

**EFFICIENCY EVALUATION OF PASSING LANE
CONFIGURATIONS ON DEDICATED LANE FOR
AUTONOMOUS VEHICLE LEVEL 3**

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ABSTRACT

A dedicated lane for autonomous vehicles (AVs) is considered as an efficient method for achieving AV's feature the most. However, slow-moving vehicles on dedicated lane might cause delaying and decrease the tailing vehicle's capacity. This study aims to evaluate different passing lane configurations on a dedicated lane in terms of capacity, traffic operation, and safety. Three configurations purposed in this study; dedicated lane without passing (scenario 1), the dedicated lane with partial passing section or the 2+1 configuration (scenario 2) and allowing AV to use a manual lane as passing lane (scenario 3). This study used microsimulation software, VISSIM, for simulation and SSAM for safety evaluation. The flow rate and heavy vehicles penetration rate vary in each simulation. Safety evaluation in this study is evaluated from the potential of rare-end and land-changing crash event in each simulation. The result showed that scenario 2 provided slightly higher capacity, higher traveling speed, and lower accident rate than other scenarios when the flow rate and the heavy vehicles penetration rate is high. Scenario 3, which AV can use both types of lanes, provide higher capacity and traveling speed than others scenario when the flow rate is low to moderate, however, this scenario causes effects to adjacent manual lanes due to mixed traffic and resulted in the highest accident rate. The AVs in this study were unable to connect to each other or infrastructures, hence, future study should consider connectivity in AVs since it can maximize the benefits of passing lane.

Keyword: Autonomous Vehicle, Passing Lane, Dedicated Lane, Heavy Autonomous Vehicle, Microsimulation

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Chapter 1 Introduction

1.1 Background

Autonomous vehicles technology has been developing throughout the past decade with the aims to improve the safety and comfort of a passenger. Automated technology such as adaptive cruise control system that is being applied in a low level of autonomous vehicles has been proven that this technology will improve traffic capacity (Kesting, 2007). Moreover, it is expected that by introducing autonomous vehicle, 90 percent of accidents on the road will be decreased since there is no drunk or distract drivers (The Future of Driving, 2019). According to the Society of Automotive Engineering (SAE), the autonomous vehicle can be divided into six levels, based on their automation. Autonomous vehicle level 2 was ready in the market in 2018; however, many autonomous manufactures expected that level 3 would be ready in 2020.

The same self-driving technology is being equipped in autonomous heavy vehicles as well. They are remarkable in effectiveness on the energy saving since they can perform platooning. Moreover, platooning is safer for surrounding vehicles since it can reduce wind drag effect. The freight companies will have a significant saving since they reduce truck drivers cost.

Autonomous vehicles are expected to be fully operated in the next decades, hence, there must be the transition period which autonomous and manual vehicle need to be operating in the same traffic. Mixing manual and autonomous vehicles can decrease the performance of autonomous vehicle due to unpredicted random human driving behavior. By dedicating some lanes on highway for an autonomous vehicle, they can operate with more efficiently since there is no uncertainty of human performance around them (Ivanchev, 2017).

1.2 Problem Statement

In the early stage of autonomous vehicle transforming, a dedicated lane is an effective way to provide safe operation for mixed traffic. It is assumed that only one out of three lanes on a highway will be dedicated for an autonomous vehicle in the early stage. However, providing just one dedicated lane can have an adverse effect on traffic operation when high traffic volume is assigned. An autonomous heavy vehicle is also assumed to be on the dedicated lane as well. They might travel at low speed due to their weight and causing platoon in the traffic. With no passing opportunity, slower-vehicles are delaying tailing vehicles and increasing tailing vehicles' time spent following.

This study aims to evaluate the efficiency of different lane configurations for providing a passing section for autonomous vehicles that are on a dedicated lane. Two additional configurations being purposed in this study; the 2+1 configuration and allowing autonomous vehicles to use the manual lane as passing lane. The flow rate and heavy vehicles penetration rate that being assigned to each scenario are varied. The efficiency of each configuration are compared with the base scenario in five dimensions;

- Determine the impact of each configuration to autonomous vehicles' capacity and manual vehicles' capacity.
- Determine the impact of each configuration to autonomous vehicles' travel speed and manual vehicles' travel speed.
- Evaluate the impact of platoon reduction for each configuration on a dedicated lane and manual lanes.
- Determine the impact of each configuration to autonomous vehicles' travel time and manual vehicles' travel time.
- Determine the safety impact of each configuration for autonomous vehicles.

1.3 Thesis Outline

This study is organized into five main chapters. The first chapter describes the problem statement and research objective. The second chapter review previous studies that are related to this study. Firstly, an autonomous vehicle is described in terms of classification, benefit, disadvantage, and their effect in mixed traffic. Next, the characteristic of a dedicated lane is described. Following by the heavy vehicles section that describes their characteristics and effect to traffic. Passing lane and passing maneuver are described respectively which is the primary process that vehicles will perform in this study. Lastly, the method of estimating freeway capacity is described.

The third chapter presents the methodology of this study. Firstly, the VISSIM microsimulation software is being mentioned as it is the primary tool for this study. The capacity evaluation from the microsimulation software method is being described next. This study also uses the Surrogate Safety Assessment Model, SSAM, as the tool for evaluating the safety, hence, the scope of this software is briefly described there. The simulation network that is created in this

study is the next topic. This section also mentioned the assumption, scenarios designing, and how to collect data from the simulation. Lastly, the procedure of this study is described.

The fourth chapter describes the result and analysis. The pattern that is used in this chapter is the same which beginning with capacity evaluation, traffic operation, and safety result. Lastly, the fifth chapter mentioned the conclusion of this study and the suggestion for future work. The reference and appendices being attached at the end of chapter five.

Chapter 2 Literature Review

2.1 Introduction

This section describes a literature review of all components of this study. Firstly, the feature of an autonomous vehicle in terms of classification, automated highway system, and characteristic of mixed traffic are reviewed. Moreover, the benefit and weakness of autonomous vehicle are provided in this section for the completeness of the literature review.

Since dedicated lane is the key for this study, this section has briefly investigated the feature of a dedicated lane. The heavy vehicle has an impact on the traffic stream, and its penetration rate is regarded as the variable for this study. Hence, the effect of the heavy vehicle is investigated in this section in terms of the effect on freeway capacity and safety.

A passing lane is used as one of the scenario configurations in this study. This section describes the 2+1 configuration and its feature to traffic capacity. Passing maneuver is briefly described for better understanding of the fundamental concept of this maneuver process. The definition of unsuccessful passing maneuver in this study also defined in this section.

Lastly, the methods of estimating freeway capacity are reviewed in this section. The conclusion of method selection is described in this section as well.

2.2 Autonomous Vehicles

The concept of an autonomous vehicle has been developing since the late 1970s and started implementing in a current traffic network. The autonomous vehicle is defined as a vehicle with fully integrated robotics directed by a human, and even there is no human on board (Forsgren, 2018). According to the Society of Automotive Engineering (SAE), there are six different levels of the autonomous vehicle from zero to level five which divide by level of automation. Most autonomous manufactures expect to release level 3 autonomous vehicles by 2020.

The autonomous vehicle is developed to provide better features than a conventional car, or manual vehicles in this study. Safety, comfort, and vehicles throughput were regarded as the primary goal for an auto manufacturer to develop automated technology (Calvert, 2017). A study predicted that it would take more than a decade to make highly autonomous vehicle sharing percentage increase up to 35 percent (Forsgren, 2018).

2.2.1 Classification of Autonomous Vehicles

The Society of Automotive Engineering (SAE) has divided the level of automation into six levels (Figure 2-1). These levels are currently used as a reference in many federal standards such as in the US Department of Transportation's Comprehensive Management Plan for automated vehicle initiatives. For better understanding in features of autonomous vehicles, SAE has defined technical terms to describe the character of each level as follows (Kelechava, 2018);

- **Dynamic Driving Task, DDT**, refers to all the real-time operational and tactile functions required to operate a vehicle in on-road traffic.
- **Operation Design Domain, ODD**, refers to the specific conditions under which a given driving automation system or feature thereof is designed to function.
- **The Automation Driving System, ADS**, refers to all the hardware and software collectively capable of performing the entire DDT on a sustained basis.

The six levels of automation can be briefly described as follows (Kelechava, 2018);

- **Level 0 No Driving Automation:** This level defined as a vehicle that required human performance of the entries DDT. This feature is currently applied to most of conventional vehicles.
- **Level 1 Driver Assistance:** This level has implemented some ODD-specific execution of either the lateral or the longitudinal vehicle control, which are subtasks of the DDT. Note that vehicle in this level 1 does not include the execution of these subtasks simultaneously. Human still expected to perform some of the DDT.
- **Level 2 Partial Driving Automation:** This level is similar to Level 1, except that the human driver is required to complete the object and event detection and response (OEDR) subtask. Moreover, the human is required to supervise the driving automation system all the time.
- **Level 3 Conditional Driving Automation:** The sustained and ODD-specific performance by the ADS of the entire DDT. However, the human driver is expected to be ready to respond when issued by the ADS. This study has selected this level of automation to apply for all autonomous vehicles.
- **Level 4 High Driving Automation:** Sustained and ODD-specific ADS performance of the entire DDT is performing without any human interaction requirement.

- **Level 5 Full Driving Automation:** A sustained and unconditional performance by the ADS of the entire DDT.



SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	You are driving whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			You are not driving when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
What do these features do?	These are driver support features			These are automated driving features		
	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/acceleration support to the driver	These features provide steering AND brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met	This feature can drive the vehicle under all conditions	
Example Features	<ul style="list-style-type: none"> • automatic emergency braking • blind spot warning • lane departure warning 	<ul style="list-style-type: none"> • lane centering OR • adaptive cruise control 	<ul style="list-style-type: none"> • lane centering AND • adaptive cruise control at the same time 	<ul style="list-style-type: none"> • traffic jam chauffeur 	<ul style="list-style-type: none"> • local driverless taxi • pedals/steering wheel may or may not be installed 	<ul style="list-style-type: none"> • same as level 4, but feature can drive everywhere in all conditions

Figure 2-1 SAE J3016 Levels of Driving Automation (SAE, 2019)

2.2.2 Automated Highway System

Automated Highway system refers to infrastructure that compatible with an autonomous vehicle's feature. The effectiveness of an Automated Highway System has been proven to improve roadway capacity. The study in Taiwan shows that the autonomous vehicle stabilized the traffic stream and provided higher capacity limit than conventional (Chang, 1997). It is essential to propose a suitable scheme of traffic control to achieve effective result during the transition stage such as a lane separation policy between conventional and autonomous vehicles.

By allocating exclusive freeway lanes to an autonomous vehicle, this lane can improve the overall traffic performance. The autonomous vehicle can operate with less spacing and headway when comparing to a conventional vehicle, therefore, the capacity of the network can be improved (Hussain, 2016).

2.2.3 Benefit of Automation

2.2.3.1 *Benefit for Traffic Operation*

Autonomous vehicles provide many features that can reduce human limitations and uncertainty. The study showed that autonomous vehicles could increase capacity by its feature (Maurer M., 2016). According to the study, two main factors were responsible for increasing of capacity; the shortening headway between autonomous vehicles, and the speed of vehicle group. Headway between autonomous vehicles can be shortening since the vehicles can anticipate the action of another vehicle's acceleration and deceleration. Autonomous vehicles also can form a group which has the same speed at a constant density. Therefore, the speed of the vehicle group can increase traffic capacity. The benefit from the existing adaptive cruise control system has shown that roads can operate at higher density and flow rate (Kesting, 2007).

2.2.3.2 *Benefit for Safety*

As the system controls the autonomous vehicles, a human error which is the main reasons that accounted for an accident can be reduced. It was estimated that accidents could be reduced by 90 percent because there is no drunk or distract driver (The Future of Driving, 2019). Autonomous vehicles level 3 allow the system to take full control of all critical safety situation, hence, it was expected that the number of crashes, injuries, and fatalities under this condition would be reduced (Anderson, 2016). Heavy vehicle platooning was also noticeably safer for surrounding vehicles (Are Self-driving Trucks Safe?, 2018). This action can reduce wind drag effect caused by heavy vehicles.

2.2.3.3 *Other Benefits*

The report pointed out that autonomous vehicles' travel time can be cut by 40 percentage which results in an expected cost-benefit saving of 1.3 trillion USD that caused congestion and fuel consumption (KPMG, 2017). The space that was used for parking can be reduced by 15 percentage since autonomous vehicles can be stacked to each other and do not need to leave space for entrance and exit (The Future of Driving, 2019). The report also pointed out that autonomous vehicles also have a positive impact on public transportation. The number of taxicabs can be reduced and replaced with a driverless car with a shorter waiting time.

2.2.4 Disadvantage of Autonomous Vehicle

2.2.4.1 *Disadvantage for Traffic Operation*

With advanced technology, autonomous vehicles can sometimes lead to negative effect on the traffic operation. Highly autonomous vehicles need to reduce the rate of acceleration and deceleration to maximize the comfort of passenger, therefore, this feature leads to slower flows for other cars (HERE, 2017). As passengers' trend to seek for greater comfort within their vehicle, the demand for the larger vehicle is likely to increase, which will reduce capacity on the road.

2.2.4.2 *Disadvantage for Safety*

One of the primary objectives for improving automate technology is to make the traffic safer, however, autonomous can sometimes lead to an accident. Dramatically increasing of autonomous vehicles in traffic will raise a risk of collision as manual vehicles lose some safety countermeasures such as eye contact (HERE, 2017). Sensors and camera technology are still unable to detect certain weather conditions accurately as human do (Are Self-driving Trucks Safe?, 2018).

The rear-end collisions that involved with autonomous vehicles were double compared to conventional vehicles (Favarò, 2017). Autonomous vehicles also have shorter mean mileage before a crash than conventional vehicles. Most of the recent incidents that involved with autonomous vehicles were found to cause by a human (Reisinger, 2018), nevertheless, autonomous vehicles technology still need to be improved to reduce all of the human constraints.

2.2.4.3 *Other Disadvantages*

Occupancy rates may drop since autonomous vehicles are only used for one-way trips (HERE, 2017). Some automate technology may lead to additional vehicle mile travel, which increasing traffic congestion and external cost (Anderson, 2016). The example of this situation is such as autonomous vehicles try to find the parking spot that has the lowest price, which is usually located far from the urban area or decide not to park and to stay in the traffic instead. The cost of autonomous vehicles can be excessively expensive due to the cost of sensors, software, and computer system (Top 5 Disadvantages of Driverless Cars, 2017). Security is also one of the concerns since the automated system technology are continuously updating (Advantages And Disadvantages Of Autonomous Car, 2018). The equipment may have faulty codes when the update is not done properly. Another critical disadvantage of driverless cars is that this technology will

take over many job positions such as truck-driver or taxi. Autonomous driving technology could replace some 294,000 long-distance truck drivers over the next 25 years, which could significantly reshape freight-industry employment, according to the new research paper (Smith, 2018).

2.2.5 Mixed Traffic

It is expected that autonomous vehicles will be fully implemented on the road network in the next few decades, however, many issues that involve with the interaction of autonomous vehicles and manual vehicles remain during the transition process. Not only the mechanism of how autonomous vehicles will respond to manual vehicles, but also their effect on the traffic operation. Many studies evaluate the characteristic of mixed flow. By installing automated equipment to enable automatic driving mode on cars, it was found that this installation enables vehicles to operate at the higher capacity limit of 2000 vphpl in ideal roadway conditions (Tang-HsienChang, 1997). Even in a single-lane problem, connected autonomous vehicles can increase capacity when their penetration rate is increasing in mixed flow (Hussain, 2016). This study also found that the need for allocated lanes for aggressive connected autonomous vehicles decreases since they can follow each other with shorter headway. Autonomous vehicles also have a positive effect on manual vehicles' driving behavior (Aria, 2016). The study found that manual driver trend to drive close to the platoon of autonomous vehicles with short time headway to reduce their time headway.

However, there was a study that addressed to the disadvantage of mixed traffic flow. The high penetration rate of autonomous vehicles in traffic flow can lead to a lower speed, higher density, and congestion due to the inability of autonomous vehicles to predict neighboring vehicles' behavior and take risks (Makridis, 2018). Manual vehicles' crashes are found to be one of the primary reason for autonomous system failure in mixed traffic (Bhavsar, 2017).

2.3 Dedicated Lane

Due to unpredicted human driving behavior, mixing conventional and autonomous vehicles in the same traffic can decrease the performance of an autonomous vehicle. Beneficial of autonomous vehicles, such as increasing traffic speed, congestion reduction, and connectivity, can be achieved by avoiding mixing these two types of vehicles. Dedicated lanes for the autonomous vehicle on highway allow the autonomous vehicle to operate more efficiently and reduce the uncertainty of human performance (Ivanchev, 2017).

Previous studies have investigated the traffic operation on the dedicated lane for autonomous vehicles. With 30%, 40%, and 50% of autonomous vehicle level 1, 2, and 3 respectively has found to be the penetration rate that the best performance is seen (Laan, 2017). Dedicated lanes not only increased occupancy on the road, but they also used for safety purposes (Princeton, 2011).

In this study, only one dedicated lane is installed on three lanes freeway in each direction. Manual vehicles are not allowed to drive on a dedicated lane, however, the autonomous vehicle may use the manual lane to perform overtaking maneuver.

2.4 Heavy Vehicle

Trucking was the main overland freight movement in the United States with the 700 billion US dollars value in 2017 (Trucking industry in the U.S. - Statistics & Facts, 2019). It was predicted that the growth rate of US truck is expected to ease to 2.3 percent per year from 2019 to 2024 (Baertlein, 2018). According to the United States Environmental Protection Agency (EPA), heavy-duty vehicle refers to a vehicle that has weight more than 8501 lbs (US: VEHICLE DEFINITIONS, 2019), which defined as heavy vehicles' in this study.

2.4.1 The Effect of Heavy Vehicles in freeway Capacity and Safety

Heavy vehicle mostly causes negative effect on the network in terms of capacity and safety. The research has investigated the difference in traffic characteristic in the vicinity of heavy vehicles and passenger cars (Moridpour, 2014). The result showed that heavy vehicles tend to leave larger gap in the traffic for safety reasons. Moreover, heavy vehicle drivers mainly keep a constant speed and do not frequently change their speed. Heavy vehicles increase average travel time and the number of lane changing maneuvers of a passenger car. As a result, these behaviors have decrease traffic capacity and safety as well.

Heavy vehicles only have a small effect on low traffic flow since drivers have relative freedom to choose their speed (Alazmi, 2018). However, the interaction between heavy vehicles and passenger car was expected to increase as the congestion level increasing. This situation also reduced opportunities for drivers to overtake slower-moving vehicles.

In order to reduce the effect of heavy vehicles on a multi-lane highway, the study suggested that all heavy vehicles should be restricted from the use of the rightmost lanes in Australia, or the

leftmost lane in the United States (Al-Kaisy, 2004). Another study has proved that traffic safety can be improved by separating truck from passenger car (Lord, 2005).

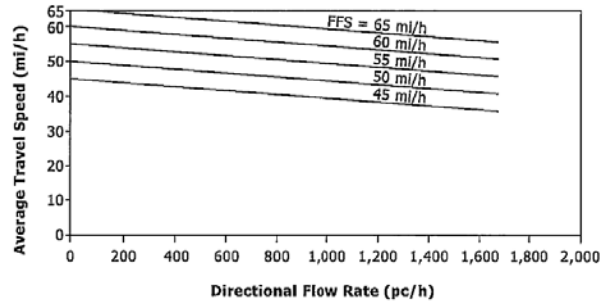
2.4.2 The Heavy Autonomous Vehicles

Autonomous technology is being developed in heavy vehicles as well as a passenger car. Autonomous trucking already applied the core sensing, communications, and software technologies in nowadays, however, it was expected that sensor technology and data processing would likely to deploy in truck with higher automation such as level 3+ (Slowik, 2018). Since retrofitted level 3 prototype trucks have been demonstrated on US road since 2015, the study expected level 4 would be ready in the next 4-10 years and level 5 in 7-20 years. Some benefits and drawbacks of the autonomous truck have revealed in this study. The autonomous trucking has significant improvement in on-road safety and reduces fuel consumption. Driving tasks can be facilitated by using automation. Real-time planning also improving operational efficiency and reduced vehicle downtime. Meanwhile, autonomous trucking will eliminate the jobs of millions of truck driver and contributes to negative macroeconomic impacts.

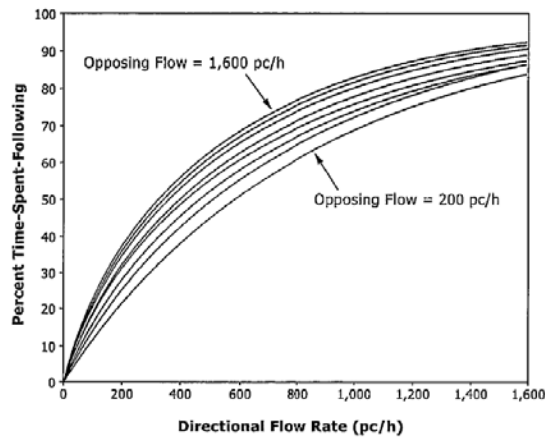
Platooning truck is remarkable in effectiveness on energy saving. Experiments of platooning three or four trucks have shown the efficiency in energy saving due to short gaps between vehicles (Tsugawa, A Review of Truck Platooning Projects for Energy Savings, 2016). The evaluation simulations showed that the platooning with the gap of 10 meters at 40% penetration of heavy vehicle could decrease carbon dioxide up to 2.1 percent along an expressway (Tsugawa, An Automated Truck Platoon for Energy Saving, 2011). The technology for same brand truck platooning is already available now in the market. Driving across Europe on a motorway should be possible with multi-brand platoons, up to SAE level 2, without needing any specific exemption by 2023 (Platooning Roadmap, 2017).

2.5 Passing Lane

Passing restriction is the main operational issue in two-lane roads. Low-speed vehicles or heavy vehicle can create platooning and delaying the trailing vehicles. An insufficient passing opportunity also has adverse effects on average travel speed (ATS) and percent time-spent-following (PTSF) depending on the direction flow rate (Figure 2-2). One solution to eliminate this problem is to provide a passing lane.



(a) ATS Versus Directional Flow Rate



(b) PTSF Versus Directional Flow Rate

Figure 2-2 Speed-Flow and PTSF Relationships for Directional Segment (Transportation Research Board, 2010)

Adding a passing lane can give many benefits for traffic performance by allowing vehicles to overtake a slower vehicle and enable the dispersion of vehicle platoons and were proved by many studies. The percentage of vehicles in platoon decreased by 14% which caused by the passing lane (Gattis, 1961). In Missouri, the level of service was improved in terms of average travel speed and the percentage of time spent following 10% to 31% by passing lane installation (Potts, 2004). Moreover, the effects of passing lane are not only alleviating vehicle delaying within its length, but also result in reducing platooning for 3 to 10 mi downstream (AASHTO, 2011).

There was an example of simulation of passing maneuver in microsimulation model (PTV Vision, 2018). The result showed that the delay has improved as look ahead distance increase (Figure 2-3). However, since the passing maneuver in this simulation has taken on the opposite lane, the main attribute that affects the result are the look ahead distance and the speed of oncoming traffic.

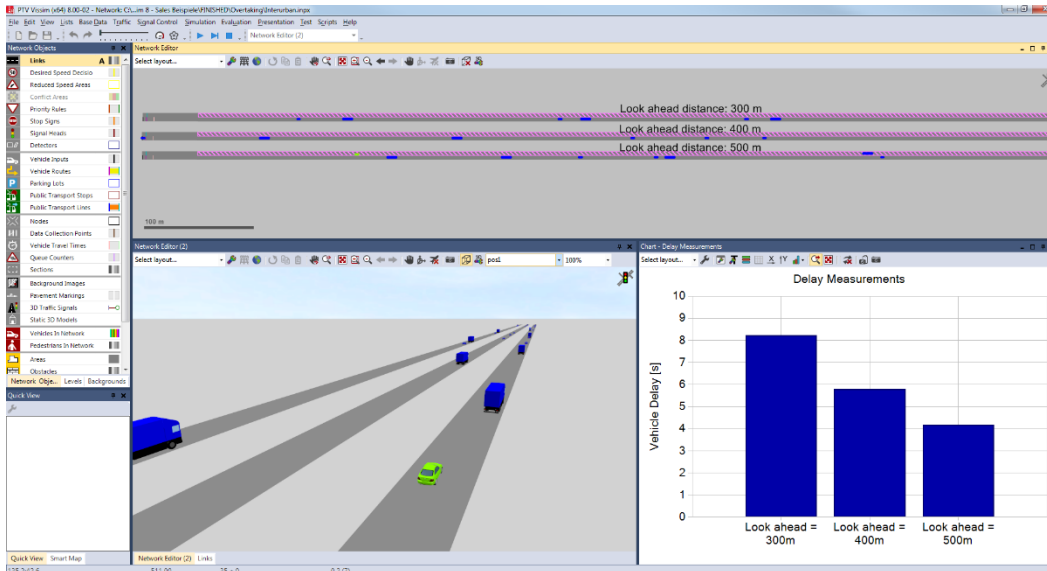


Figure 2-3 Overtaking Model in VISSIM (PTV)

AASHTO recommended that 2+1 roadway is an additional alternative method that can provide more passing opportunity (AASHTO, 2011). This configuration offers alternating passing lane in each direction throughout the section of the three-lane cross-section. A 2+1 road is suitable for roadways with high traffic volume and location where space is limited. Moreover, the 2+1 road will provide roadways with a higher level of service than a conventional two-lane highway serving the same traffic volume (Derr, 2003).



Figure 2-4 Schematic for 2+1 Roadway (AASHTO, 2011)

In terms of safety, additional passing lane decreases head-on crashes since vehicle no need to travel in the opposite direction for overtaking. However, the diverging and merging conflict at each ends off passing lane may lead to an accident. The studies showed that a longer merged section at the end of 2+1 increases the number of the conflict area, which potentially leads to accidents (Cafisoa, Safety assessment of passing relief lanes using microsimulation-based conflicts analysis, 2018).

In this study, the 2+1 roadway is used as the method for providing the passing opportunity for autonomous vehicles on a dedicated lane in scenario 2.

2.6 Passing Maneuver

Passing opportunity has a significant impact on traffic operation, especially on a two-lane highway, by allowing faster vehicles to pass slower vehicles and travel at their design speed. Many factors of passing maneuver depended on the human factor (Llorca, 2014). There are three main stages of traditionally passing maneuver as follow;

- Passing desire: Driver's design to pass or keep on following the slower vehicle.
- Passing decision (Gap Acceptance): for a driver who desired to pass, their decision to accept or reject a passing opportunity.
- Passing execution: for a driver who accepted a gap, the passing performance and the decision to complete or abort the maneuver, before reaching the critical point.

After safety conditions are checked, the performance is operating as follows (Figure 2-5) (Naranjo, 2008)

- A lane change to the adjacent lane
- Trajectory tracking in the left lane until the passing vehicle has passed the other vehicle in the right lane
- A second lane change to go back to normal lane

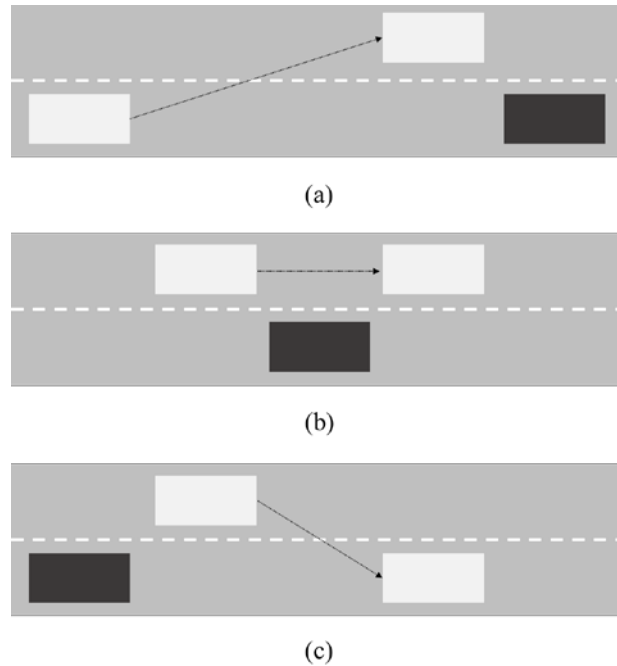


Figure 2-5 Overtaking maneuver phases

Advanced technology for passing maneuver has been employed in autonomous vehicles and being proof for better operation. A fuzzy-control-based automatic lane-change system was used as the key system installed on the autonomous vehicle to make automated passing maneuver (Naranjo, 2008). Another study also used a fuzzy-control to steer and control the speed of autonomous vehicles along with the data from multiple sensors such as a real-time vision system and a vehicle-to-vehicle communication system to facilitate to the decision-making process for passing maneuver (Chiang, 2014).

This study, however, assumed that the automation of autonomous vehicles is only applied in the following behavior. Meaning that systems are not being installed on the vehicles. Therefore, passing maneuver in this study is exclusively related to a sequence of lane changing maneuver.

2.6.1 Lane-changing Maneuver

The lane-changing maneuver is the main movement of the passing maneuver process. By applying sub-controller in autonomous vehicles, many benefits can be achieved such as minimize travel time, maintain safety, and control speed of vehicles (Du, 2018). Providing the lane-changing maneuver can produce many benefits to the traffic operation. The study showed that the flux

increases if lane changing is permitted in heterogeneous traffic that consists of vehicles with a different maximum speed (Zhang, 2009).

In contrast, lane-changing also harms traffic operation. The study found that the increase of lane-changing activity can decrease the average capacity per lane on highway (Xiao-bao, 2007). Under unsaturated flow situation, lane-changing opportunities increase the chance for the drivers to overtaking slower vehicles, however, lane-changing maneuver increase the disturbance to traffic stream in saturated flow and oversaturated flow situation, the study has shown. Moreover, improper lane-changing processes lead to accident and congestion (Zheng, 2011).

Lane changing in autonomous vehicles can sometimes led to negative effects on traffic operation (Calvert, 2017). As autonomous vehicles require a larger gap to perform the maneuver, they also tend to leave a larger gap between vehicles. This large gaps result in longer headway and can decrease capacity. The lane-changing maneuver requires vehicles to accelerate or to decelerate, hence, this can cause heterogenetic traffic which also reduces the traffic capacity.

Another study found that the lane-changing frequency between adjacent lanes is related to traffic density and have a relationship as the same as a fundamental-diagram curve (Liu, 2017). This study concluded that the impact of smart lane-changing has less effect on the traffic flow when comparing to the smart car following.

2.6.2 Unsuccess Passing

The overtaking maneuver is complicated and has an impact on traffic operation and safety. An inappropriate overtaking decision leads to road crashes (Clarke, 1998). The study found that the probability of an overtaking maneuver aborting was affected by the size of the accepted gap, the speed, types of a leaded vehicle, the waiting time to find an appropriate gap, road geometry, and driver characteristic (Farah, 2015). In order to make overtaking maneuvers safer, intelligent systems in the vehicles were found to be the possible solution that can assist drivers in performing this maneuvers better (Hegeman, 2005).

In this study, passing vehicles that are unable to complete overtaking maneuver within provided distance are not aborting the performance. Instead, they would wait at the end of passing lane until there was a sufficient gap for them to merge back. This concept resembles the late merge strategies and deployed to describe unsuccess passing event in this study.

The Michigan Department of Transportation has researched the evaluation of the late merge system at work zones (Datta, 2007). The definite merge point near the taper area is the main concept for the late merge strategy. It was found that this strategy can alleviate the congestion and queue lengths on both open and close lanes. According to the literature review, several countries have deployed the concept of late merge in terms of “zipper merge”. The zipper merge refers to a situation that each driver only changes lane when he reaches the fixed point which near the lane drop location. However, vehicles in this study did not yield to exactly one vehicle before changing lane like in zipper merging but depended on the available gap. The result of field testing by PennDOT showed that the late merge system provides higher capacity than the traditional merge system, however, this concept might not be working to its full potential (Pesti, 1999).

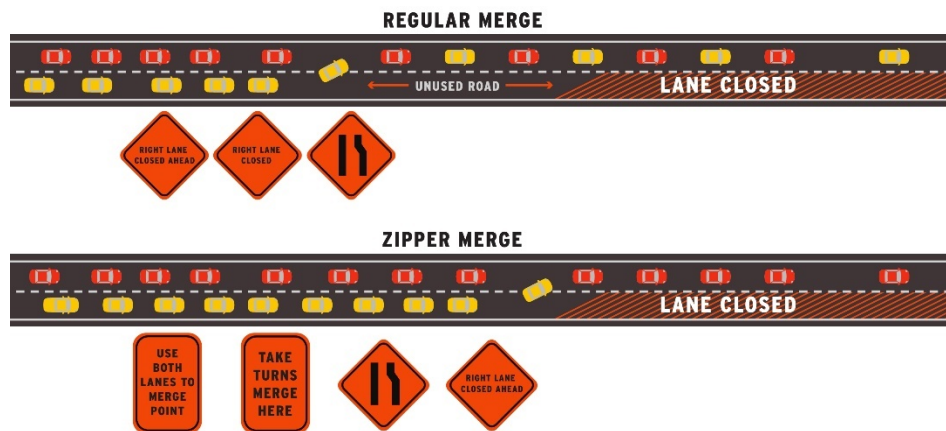


Figure 2-6 Regular Merge vs. Zipper Merge [Image]. Retrieved from <https://www.mdt.mt.gov/pubinvolve/ehelenaviaduct/zippermerge.shtml>

2.7 Methods of Estimating Freeway Capacity

Capacity is the main concept in roadway design and traffic control. Various methods could be used for estimating the capacity. Each method requires different data and is depending on circumnutate.

The previous study has investigated the usage of each capacity estimation for uninterrupted roadway section methods (Minderhoud, 1997). Estimation with headways is based on the theory that all driver-vehicle elements are constrained at the capacity level of the road, however, these models can be only applied for a single lane. Fundamental Diagram Method is another approach

to estimate capacity by using traffic volumes, speeds, and densities. This method requires a mathematical model that fits the observed data pairs which are considered as a major disadvantage.

The maximum capacity methodology is the easiest method to estimate freeway capacity (Li, 2015). This method based solely on known maximum traffic volumes obtained over a given time period as shown in equation (1).

$$C_i = \max_{i,\delta} f_{i,\delta} \quad \forall \delta = 1, 2, \dots, N, \quad (1)$$

- Where, C_i = The maximum flow rate over a given time period δ for location i
 δ = The time interval
 $f_{i,\delta}$ = The observed flow rate during time interval δ at location i
 N = The number of time periods considered

As the time interval increases, the capacity value will decrease. Thus, it is vital to use the same time duration when comparing capacity. Note that typical time duration ranges from 1 to 60 minutes. There are disadvantages of this method such as it provides little variation in capacity estimate over time and cannot be used for defending major changes in flow rate over short periods. This method also requires a high-frequency data collection for analysis. However, these advantages can be neglectable in this study and made this method the most suitable approach for determining capacity.

Chapter 3 Methodology

3.1 Introduction

Microsimulation becomes a popular tool that many researchers have been used for analyzing traffic operation in recent years. User can define geometry, volume, vehicle types, and driving behavior with close to reality. The result can be detailed as in individual vehicles level. Since this simulation is regarded as stochastic software, the result of two simulations will not necessarily match (Spack, 2016). Microsimulation traffic model is also a suitable tool for analyzing the operational effect of new geometric schemes (Austroads, 2006).

Autonomous vehicles are now in the market, but their proportion is not large enough for the researcher to conduct a study in the field. Moreover, autonomous feature and infrastructure that will compatible and maximize benefits of automation are now under development and not ready in the realistic. Therefore, it is impossible to conduct field-based studies which can be carried out when those designs are implemented. For all these reasons, many studies that conduct on autonomous vehicles have use micro-simulation software as their tool. This study, therefore, will use micro-simulation for conducting research as well.

3.2 VISSIM Microsimulation Tool

VISSIM was selected as microsimulation tool for this study since this software has many features that support autonomous vehicles simulation. Detailed of autonomous vehicle behavior can be replicated as many algorithms can be adopted within the simulation (PTV Group Traffic, 2017). One method to model autonomous vehicles is to adopt default behavior parameters such as car-following model, lane change behavior and speed. Another method is to use COM interface, the process of controlling VISSIM from externally interface such as Python, MATLAB, or Microsoft Excel.

VISSIM has categorized vehicles type by its basic behavior in traffic (PTV Vision, 2018). In this study, car and HGV represent for passenger car and heavy vehicle, respectively. Besides the physical dimension, the properties of HGV that are significantly different from a car is the acceleration. In Wiedemann 99 car-following model in the free and follow interaction states, HGV only accelerates with half the calculated acceleration. The weight and the power distribution are only applicable for HGV vehicle type. However, the occupancy in this study was set to single occupancy for both types of vehicles.

In VISSIM 11, new features for the autonomous vehicle were defined (PTV Vision, 2018). Many autonomous following parameters were defined based on prototype researches. This study chosed “the normal autonomous vehicle following behavior” as the type of the autonomous vehicle behavior since its characteristic is the closest to human driving behavior and reflect the autonomous vehicle level 3. However, the connected feature and enable variance in the car following model were disabled in this study, according to the assumption. Driving behavior parameter of manual vehicle, both passenger and heavy vehicles, are set as default value.

3.2.1 Longitudinal Control

3.2.1.1 Wiedemann Car Following Model

VISSIM's traffic flow model is a stochastic, time step based, microscopic model. The traffic flow model in VISSIM is based on Wiedemann's extensive research work. The model contains a psycho-physical car following model for longitudinal vehicle movement. The model also contains a rule-based algorithm for controlling lateral vehicle movement.

The Wiedemann 99 car following model was used in this study since it is suitable for freeway traffic. There are nine model parameters as follow (Table 3-1);

- **CC0 Standstill distance (feet):** The distance between two vehicles in standstill stage. A higher value means larger standstill distance which results in a lower capacity.
- **CC1 Headway time (seconds):** Time distribution of speed-dependent part of desired safety distance. A higher value means a more cautious driver and lower capacity. Note that this parameter has a significant impact on the safety distance and saturation flow rate. However, the headway time for manual and autonomous vehicles in this study was set as the default value.
- **CC2 Following Variation (feet):** Additional distance beyond the desired safety distance that a driver is allowed before he intentionally moves closer to the car in front. A higher value means a more cautious driver and lower capacity. This value was set to 0 feet for the autonomous vehicle, whereas 13.12 feet was set for the manual vehicle.
- **CC3 Threshold for Entering Following:** Control method for starting of deceleration process.
- **CC4 Negative Following Threshold (m/s):** Negative speed difference during the following process. Lower values mean the vehicle has a more sensitive reaction to the

acceleration or deceleration process. This value was set to -0.10 for the autonomous vehicle, whereas -0.35 was set for the manual vehicles.

- **CC5 Positive Following Threshold (m/s):** Positive speed difference during the following process. Lower values mean the vehicle has a more sensitive reaction to the acceleration or deceleration process. This value was set to 0.10 for the autonomous vehicles, whereas 0.35 was set for the manual vehicle.
- **CC6 Speed dependency of Oscillation (ft/s²):** Influence of distance on speed oscillation during the following process. For autonomous vehicle, this value was set to 0 ft/s², which means the speed oscillation is independent of the distance. The larger value was set for the manual vehicle, 11.44 ft/s², which leads to higher speed oscillation with increasing distance.
- **CC7 Oscillation Acceleration (ft/s²):** Oscillation during acceleration. This value was set to 0.33 ft/s² for the autonomous vehicle, whereas 0.82 ft/s² was set for manual vehicle
- **CC8 Standstill Acceleration (ft/s²):** Vehicle’s acceleration starting from standstill stage.
- **CC9 Acceleration with 50 mph (ft/s²):** Vehicle’s acceleration when starting at 50 mph speed.

Wiedemann 99 Car Following Model	Freeway (Manual Vehicle)	AV Normal (Autonomous Vehicle)
CC0	4.92 ft	4.92 ft
CC1	0.9 s	0.9 s
CC2	13.12 ft	0.00 ft
CC3	-8.00	-8.00
CC4	-0.35	-0.10
CC5	0.35	0.10
CC6	11.44	0.00
CC7	0.82 ft/s ²	0.33 ft/s²
CC8	11.48 ft/s ²	11.48 ft/s ²
CC9	4.92 ft/s ²	4.92 ft/s ²

Table 3-1 Wiedemann 99 Car Following Model Parameters Summary

3.2.1.2 Driving behavior parameter following behavior

Seven elements can be adjusted in driving behavior parameter as follows;

- **Look ahead distance:** A distance that a vehicle can see forward in order to react to other vehicles either in front or the side of it.
 - **Observed vehicles:** The number of vehicles that vehicles in the link can predict movement and react appropriately. Observed vehicle was set to 2 default value for the freeway.
- **Look back distance:** A distance that a vehicle can see backward in order to react to other vehicles behind.
- **Temporary lack of attention:**
 - **Duration:** The period that vehicles do not react to other vehicles. However, the vehicles still react to other vehicles in emergency braking.
 - **Probability:** Chance of the lack of attention. The increasing of these value affect the capacity of the network.
- **Smooth close up behavior:** reflects how vehicle approaches a stationary obstacle. If this option is not in use, the following vehicle will determine the final approach behavior.

In this study, all of the driving behavior parameter following behavior for both manual and autonomous vehicles were the same (Table 3-2).

Following Parameter		Manual Vehicle	Autonomous Vehicle
Look ahead distance	min	0.00 ft	0.00 ft
	max	820.21 ft	820.21 ft
	Observed vehicles	2	2
Look back distance	min	0.00 ft	0.00 ft
	max	492.13 ft	492.13 ft
Temporary lack of attention	Duration	0 s	0 s
	Probability	0.00%	0.00%
Smooth closeup behavior		Applicable	Applicable

Table 3-2 Driving behavior parameter following behavior Summary

3.2.2 Lane Change

VISSIM categorizes lane changing into two types; necessary lane changes and free lane change. Necessary lane change is used when vehicles need to reach the next connector or route, while free lane change is used when there is more space and higher speed is required.

For necessary lane change, the parameters are depending on the maximum acceptable deceleration for a vehicle and its trailing vehicles on the new lane. For free lane change, the parameters are depending on the desire safety distance to the trailing vehicle on the new lane. The driving behavior parameter for lane change behavior consists of the following elements (Table 3-3);

- **General Behavior:** This study used “the slow lane rule” to allow overtaking of a vehicle from the other lane.
- **Necessary Lane Change:**
 - **Maximum deceleration (ft/s²):** Upper bound of deceleration for own vehicle and tailing vehicle for a lane change
 - **-1 ft/s²:** Value that reduces the Maximum deceleration with increasing distance from the emergency stop distance linearly until the Accepted deceleration has reached. The -1 ft/s² value of the autonomous vehicle was set lower than the manual vehicle.
 - **Accepted deceleration (ft/s²):** Lower bound of deceleration for own vehicle and trailing vehicle for a lane change.
- **Diffusion time (second):** The maximum amount of time a vehicle can wait at the emergency stop distance for a necessary change of lanes. This parameter reflects a vehicle’s tolerance on vehicles waiting for a necessary lane change.
- **Minimum headway (front/rear) (ft):** The minimum distance between two vehicles that must be available after a lane changing process.
- **Safety distance reduction factor:** This factor only uses during lane changing process to reduce safety distance.
- **Maximum deceleration for cooperative braking (ft/s²):** Specifies to what extent the trailing vehicle is braking cooperatively, to allow a preceding vehicle to change lanes into the same

lane they are traveling in. The higher the value, the stronger the braking and the greater the probability of changing lanes.

- **Advanced merging:** Option that allows vehicles to perform lane change earlier.
- **Vehicle routing decision look ahead:** Option that allows vehicles to identify routing decision in advance further downstream.
- **Cooperative lane change:** This option allows trailing vehicles to make a necessary lane change to facilitate the lane change of a leading behavior. This option is applicable for an autonomous vehicle but not for a manual vehicle.

Lane Change Parameter		Manual Vehicle	Autonomous Vehicle
General Behavior		slow lane rule	slow lane rule
Necessary lane change (route)	Maximum deceleration	Own	-13.12 ft/s ²
		Trailing vehicle	-9.84 ft/s ²
	-1 ft/s ² per distance	Own	200.00 ft
		Trailing vehicle	200.00 ft
	Accepted deceleration	Own	-3.28 ft/s ²
		Trailing vehicle	-1.64 ft/s ²
Waiting time before diffusion		60.00 s	60.00 s
Minimum headway (front/rear)		1.64 ft	1.64 ft
Safety distance reduction factor		0.60	0.60
Maximum deceleration for cooperative breaking		-9.84 ft/s ²	-9.84 ft/s ²
Advance merging		Applicable	Applicable
Vehicle routing decision look ahead		Applicable	Applicable
Cooperative lane change	Maximum speed difference	Not applicable	6.71 mph
	Maximum collision time		10.00 s

Table 3-3 Lane change parameter Summary

3.2.3 Lateral Control

The lateral behavior directly controls the lateral orientation within the vehicle's lane and overtaking orientation. In VISSIM, it is possible to allow overtaking within the same lane by assigning vehicle at a different position on the road. However, this study aimed to analyze the effect of providing distinct passing opportunity by geometry, then, overtaking within the vehicle's lane is not allowed. Hence, all vehicles were programmed to occupy the entire lane width and use default parameters in this study.

3.3 Capacity Estimation

VISSIM microsimulation can provide flow rate and speed over time at high frequency. For this reason, the maximum capacity method was chosen as the best approach to determine network capacity. The capacity of each scenario was from the highest flow rate among the three simulation runs. Each run was assigned with a different random seed, which is a random number used by the stochastic function in VISSIM which changes the traffic flow and simulation result.

3.4 Surrogate Safety Assessment Model (SSAM)

The Surrogate Safety Assessment Model (SSAM) is a software developed by the Federal Highway Administration, FHWA, which use for identifying the frequency of conflicts based on vehicle trajectory data from microscopic traffic simulation (Pu, 2008). There are four types of conflicts in SSAM: unclassified, crossing, rear-end and lane-change. SSAM classified conflicts type from link and lane information for both vehicles. Rear-end conflict refers to both vehicles that occupy the same lane at the start and end of the event, while lane-changed conflict refers to vehicles that end the conflict event in a different lane than it started. If link and lane information is not available for both vehicles, SSAM will classified conflict event based on the absolute value of the ConflictAngle. If ConflictAngle is less than 30° , SSAM classified this event as rear-end event, a crossing conflict if ConflictAngle is more than 85° , or otherwise a lane-changing conflict.

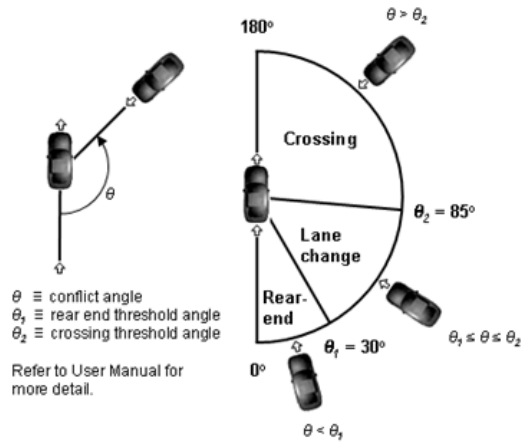


Figure 3-1 Screenshot of a Threshold Angle Diagram taken by the author from SSAM software.

3.4.1 SSAM Configuration

SSAM provides conflict thresholds configuration to allow a user to set Times To Collision (TTC) and Post Encroachment Time (PET) threshold values for the analysis process. TTC calculation is based on the current location, speed, and trajectory of two vehicles at a given instant. PET is the time between when the first vehicles last occupied a position and the second vehicle subsequently arrived at the same position. The default maximum TTC time is set to 1.5 second, while the maximum PET time is set to 5 seconds.

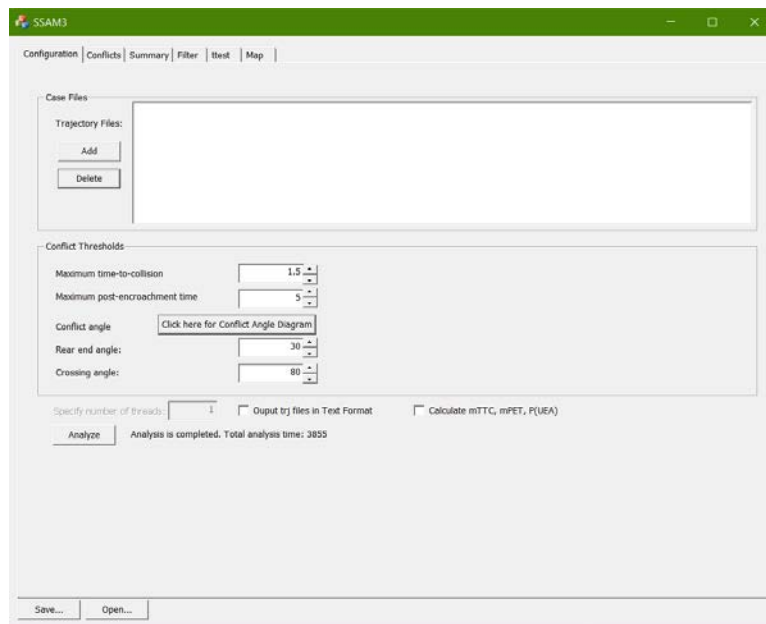


Figure 3-2 SSAM3 Configuration Page

3.4.2 Result from SSAM

The analyzed data in summary page from SSAM can be divided into two parts; the SSAM measures result and the total number of conflict event. The result of the SSAM measures consists of statistical data on the following SSAM measures; TTC, PET, a maximum speed of either vehicle in conflict event, maximum deceleration, speed different, and initial deceleration of the second vehicle. The type of conflicts classifies the total number of conflict event. Note that the user can investigate each conflict event and its detail in conflict tab.

SSAM also provided the built-in feature to visualize conflicts of each type on the map. User can easily observe both types and location of the conflict event on the map.

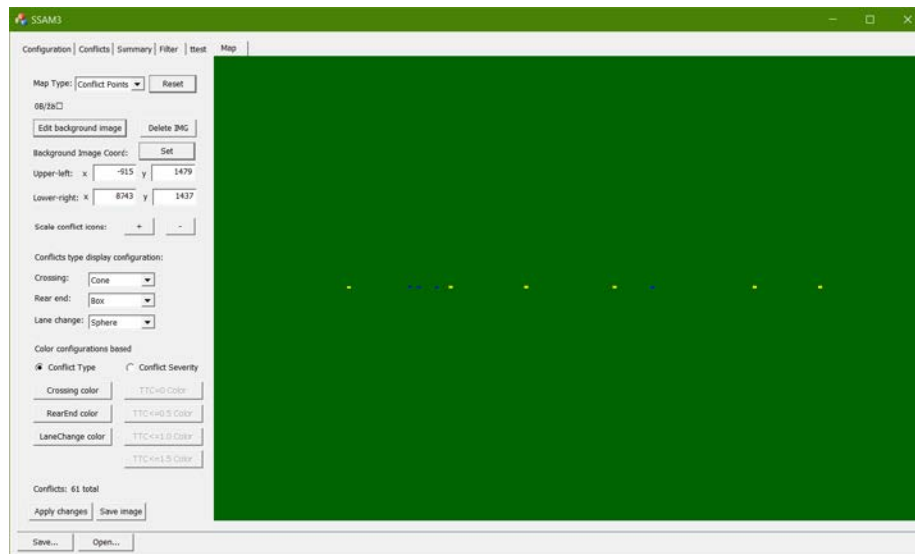


Figure 3-3 SSAM Result

3.5 Simulation Network

3.5.1 Assumption

The assumptions in this study were as follow;

- There were four types of vehicles in this microsimulation model; manual passenger vehicle, manual heavy vehicle, autonomous vehicle (level 3), and heavy autonomous vehicle (level 3).
 - Both manual passenger and heavy vehicle have the same driver behavior
 - Both autonomous vehicle and heavy autonomous vehicle have the same driver behavior

- All autonomous vehicle has zero connectivity.
- Dedicated lane was preserved for the autonomous vehicle, while 2-lane of the freeway were for manual vehicle except for the third scenario; autonomous vehicle on dedicated lane can use the freeway on the adjacent lane for overtaking.
- Heavy vehicle referred to vehicles of six wheels and above.
- No interruption; no traffic control such as traffic signal or interchange, no entrance or exit ramp in the network.
- The conditions which the full capacity of a freeway segment was achieved include good weather, good visibility, no incident or accidents, no work zone activity, and no pavement deterioration (Transportation Research Board , 2010, pp. 11-1)
- A driver population was familiar with the facility.

3.5.2 Scenario Designing

In this study, three scenarios which have different passing configurations on the dedicated lane were defined. Overall, all scenarios have three lanes; the dedicated lane in the leftmost and two manual lanes in the right. The only passing section in scenario 2 will have two dedicated lanes. The barrier between the dedicated lane and manual lanes was set to separate autonomous vehicles and the manual vehicles in scenario 1 and 2. Note that this study only simulated traffic in one direction since no scenario allows passing maneuver in the opposite direction.

The length of this microsimulation model was set to 6 miles for all of the scenarios. The length of 6 miles is the significant length of highway that passing lane can improve traffic operation in the next scenario (AASHTO, 2011). The width of the lane was set to 12-ft which is generally used for most high-speed and high-volume highway (AASHTO, 2011). This roadway has no fixed cause of delay or interruption external to the traffic stream, hence, the effect of providing passing opportunity can be observed concisely.

The speed limit is set to 70 mph based on *Wisconsin Statewide Speed Management Guideline* (WisDOT, 2009). The truck speed limit is usually equal to the passenger vehicle speed limit (Schubert, 2018). However, the-truck speed limit can be lower than passenger vehicle up to 10-15 mph in some state (U.S. Truck and Auto Speed Limits, 2019). Therefore, the passenger speed limit was set to 70 mph or 120 km/hr and the truck speed limit was set to 60 mph or 100 km/hr for this study.

In VISSIM, the specific power-to-weight ratio of a heavy vehicle can be adjusted. This study uses the default value for this value which is minimum of 7 kW/t and maximum for 30 kW/t for both heavy manual vehicles and heavy autonomous vehicles.

3.5.2.1 Dedicated Lane without Passing Lane (Base Model)

In this scenario, a dedicated lane was entirely separate from manual lanes (Figure 3-4 and Figure 3-5). By geometric of this scenario, all of the vehicles on the dedicated lane were not allowed to perform any passing maneuver. The heavy autonomous vehicles were forced to drive on the same lane as well as autonomous vehicles. Meanwhile, on the manual lanes, heavy vehicles were restricted to drive only on the rightmost lane in order to minimize the effect of itself.

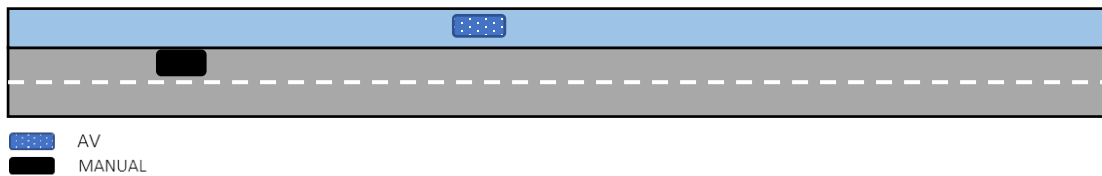


Figure 3-4 Illustration of Scenario 1



Figure 3-5 Scenario 1 in VISSIM

3.5.2.2 Dedicated lane with Passing Lane (2+1)

This scenario used the same characteristic as the “Dedicated lane” scenario but has one passing lane section installed in the middle of the network (Figure 3-6 and Figure 3-7). The detail of passing lane length was calculated in the following section.

Passing lane design

According to AASHTO, the optimum length of the passing lane is 0.5 to 2.0 mi, depending on traffic volume. The passing lane should be sufficiently long enough for passing maneuver. The width of an added lane is set to be the same as the lane widths of the dedicated lane. The flow in this study varying from 700 to 1600 vehicles per hour and the optimal passing lane is between 1.00 to 2.00 mi for this flow range. Therefore, the length of 2.00 mi was used as the passing lane length for this study.

The transition at each end of the added-lane section, or taper, is designed for efficient operation and safety purpose. The length of the taper is recommended to be half to two-thirds of the lane drop length for the posted speed limit at 45 mph or above, shown in equation (2).

$$L = WS \quad (2)$$

Where L = Length of taper, ft

W = Width, ft

S = Speed, mph

For this study, the maximum speed was 70 mph, and the width of the road was 12 ft. Thus, from equation (2), the length of taper for this study equals 840 ft. However, this study did not allow vehicles to drive on the taper.

In order to clarify the effect of passing lane at upstream and downstream location, the additional lane that defined as a passing lane in scenario 2 was set at the middle of the network length. Therefore, scenario 2 has almost the same configuration as the base scenario except for the installation of the passing lane. Heavy automated vehicles were refrained from driving on passing lane. Note that all of the results on the manual lane in this scenario was the same as scenario 1 since this configuration in scenario 2 did not affect the operation on the manual lane at all.

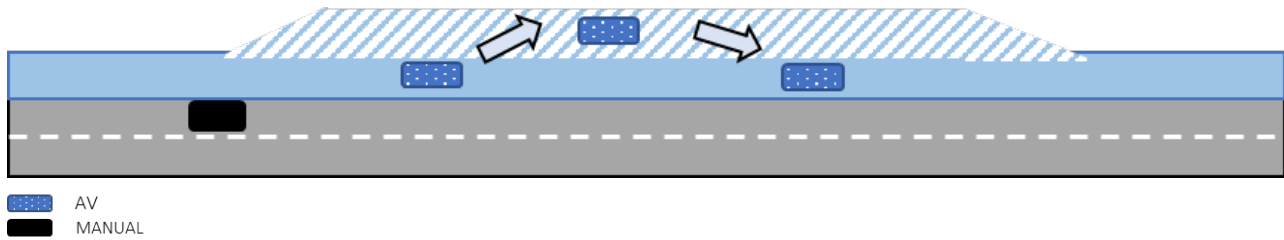


Figure 3-6 Illustration of Scenario 2

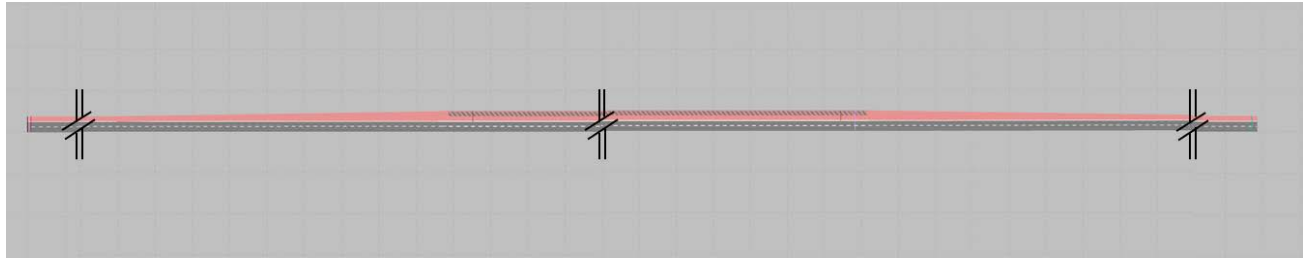


Figure 3-7 Scenario 2 in VISSIM

Modeling Passing Maneuvers in VISSIM

VISSIM can model the overtaking maneuver, or passing maneuver in this study, in the opposite lane. The passing lane will be used when there is a large enough gap downstream of the slower vehicle to change back to the normal lane (What is New in PTV VISSIM/VISWALK 8, 2015). The model was being applied to for passing maneuver in this study. There was no vehicle assigned in the opposite lane, therefore, the factor that being used in this model for vehicles to perform passing maneuver was the available gap downstream of the slower vehicle.

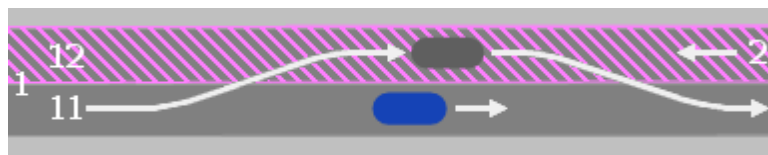


Figure 3-8 Illustration of Overtaking Model in VISSIM (PTV, 2018)

3.5.2.3 Dedicated lane with passing allowance

The geometric design of this scenario was the same as scenario 1 except the autonomous vehicles that were on the dedicated lane were allowed to drive on the adjacent manual lane for passing purpose (Figure 3-9 and Figure 3-10). Autonomous heavy vehicles were not allowed to drive on any manual lane and must drive only on a dedicated lane. Likewise, heavy vehicles were restricted to drive only on the rightmost manual lane. The result of the manual lane in this scenario

affected an autonomous vehicle. Therefore, this result was used to compare the traffic operation of manual vehicles between scenario 1 and 2.

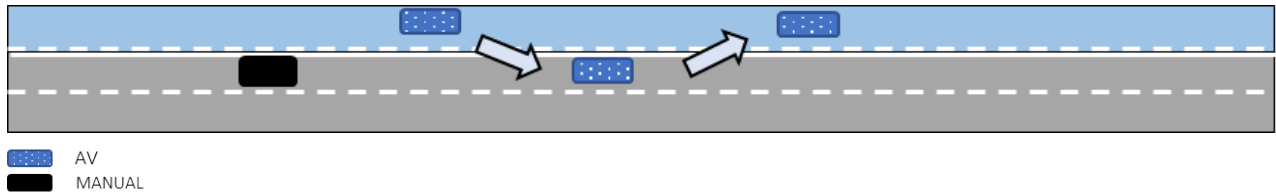


Figure 3-9 Illustration of Scenario 3

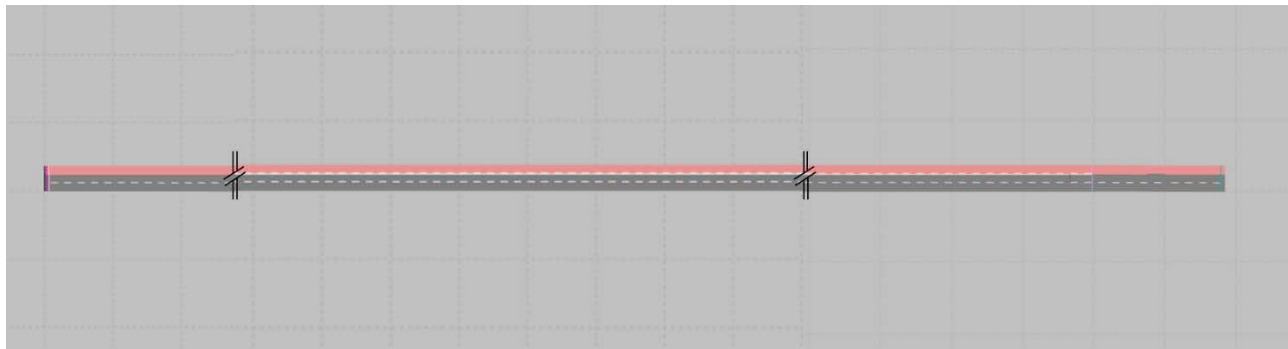


Figure 3-10 Scenario 3 in VISSIM

3.5.3 Vehicle Input

According to AASHTO, a 2+1 road should use only when the flow rate is not exceeded 1200 vehicle per hour in one direction. However, the highest flow rate in this study was set above 1200 vehicle per hour in order to investigate the impact of autonomous vehicles persistence. The flow rate in this study was varied from 800 to 1600 vehicle per hour per lane, with 200 incremental, or 5 vehicle input for each scenario.

The truck proportion was varied from 0 percent of the total number of vehicles in the network. The highest truck proportion was set at 40 percent, with ten incremental. Hence, there were five truck proportions for each scenario as well.

3.5.4 Data Collection

The study period was 2 hours, or 7200 seconds, for each scenario. The warm-up period was 300 second, which is the duration that the first vehicles completed traveling in the network. The study period was divided into eight intervals, every 15 minutes. One scenario consisted of three runs, hence, the average value among three runs was used as the value for each interval.

The following section described the methodology used for collecting simulation data for different analysis in VISSIM. The first part describes the location of the data collection point in the simulation model. The next part describes data collection for three analysis which are capacity, traffic operation, and safety.

3.5.4.1 Location of Data Collection Points

The location of data collection points in this study was based on the operational effect of a passing lane in the second scenario. Percent of time-spent-following between roadway with and without passing lane was significantly different at the starting point of the additional lane (Figure 3-12). Hence, the detectors were set at the location as follows;

- One mile upstream
- The beginning of passing lane
- The middle of the passing lane
- The end of passing lane
- One mile downstream.

Note that the data collection points on the other two scenarios, dedicated lane and dedicated lane with passing allowance, also located at the same point (Figure 3-11).

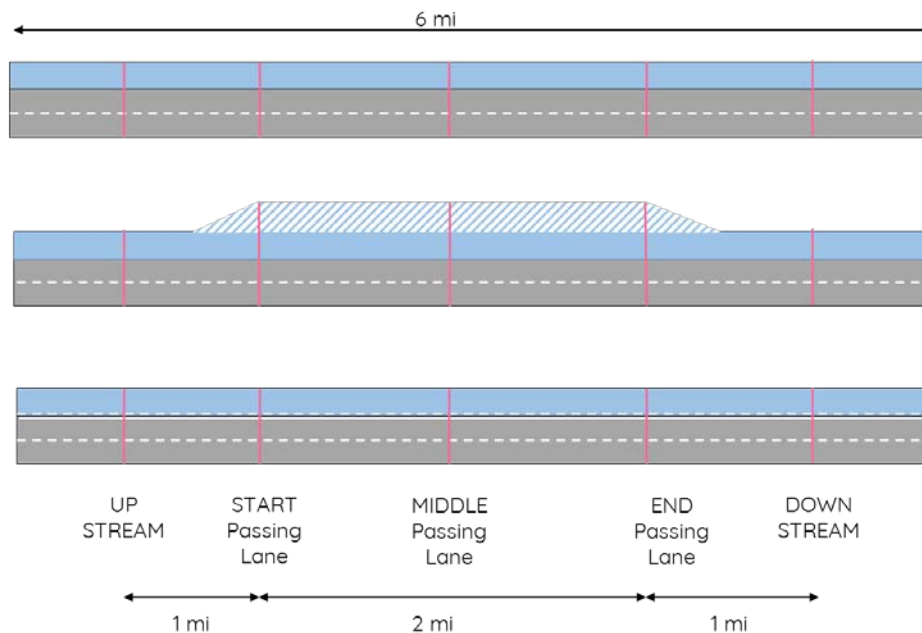


Figure 3-11 Illustration of Data Collection Points

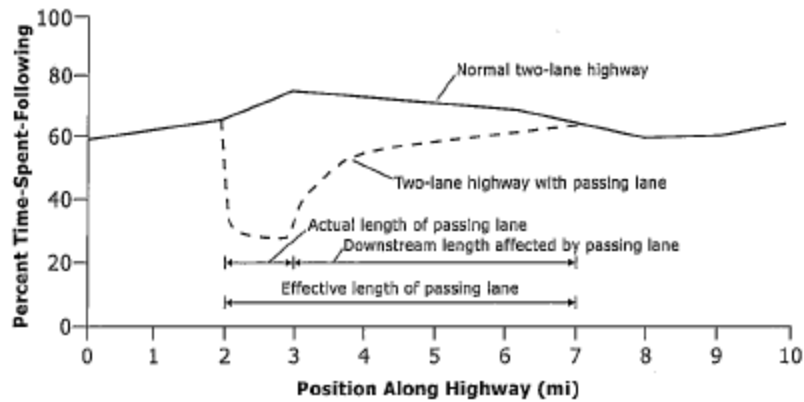


Figure 3-12 Operational Effect of a Passing Lane on PTSF (Transportation Research Board , 2010)

3.5.4.2 Data Collection for Capacity Analysis

Flow rate at each data collection points was used for capacity analysis. Total flow rate was converted to an hourly flow rate.

3.5.4.3 Data Collection for Traffic Operation Analysis

To perform traffic operation analysis, some additional variable needed to be collected: speed, travel time, passing rate, and the average percentage of vehicles in a platoon.

- **Speed:** The data collection points also collect the vehicle’s speed. The average speed in 2 hours period was used as speed data.
- **Travel Time:** The mean travel time from traversing from the beginning of the network to 1 mile downstream of the end of passing lane was used for travel time evaluation in this study.
- **Delay Measurement:** The delay of a vehicle is defined as the differential between actual travel time and the theoretical (ideal) travel time. The theoretical travel time is the travel time which could be achieved if there were no other vehicles and no signal controls or other reasons for stops.
- **Passing rate** (for scenario 2 and 3): VISSIM provides record file of the time and place where the lane changes were made. In this study, only autonomous vehicle lane change maneuvers were observed. Passing rate was calculated from the percentage share of the passing vehicle.

- **Percentage of the vehicle in a platoon:** from previous studies, the share of the platoon is defined as the vehicles that traveling a distance of 3 seconds or less between each other (Cafisoa, Investigating the influence of passing relief lane sections on safety, 2017). To evaluate headway between vehicles, data collection point can be used as a detector in the simulation.
- **Queue length:** Vehicle that fails to merge back to dedicated lane at the end of passing lane leads to queuing propagate. The queue length is defined as the maximum distance between the traffic counter and the vehicle that meets the queue condition. This study used the default value for queue condition;
 - The queue begins when speed is less than 3.1 mph, and end when speed is more than 6.2 mph
 - Maximum headway is 65.6 ft and minimum headway is 1640.4 ft

The queue length is only evaluated in scenario 2 and 3 since there is no merging in scenario 1. The location of the queue counter for scenario 2 was located at the end of passing lane, while it was located at the end of the network for scenario 3 (Figure 3-13). Note that autonomous vehicles that used the adjacent manual lane for passing purpose were forced to merge back at the end of the network.

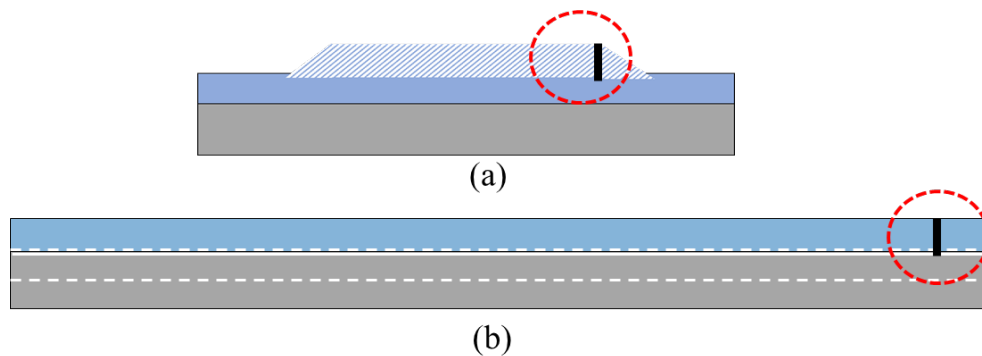


Figure 3-13 Illustration of Location of Queue Counter on (a) Scenario 1 and (b) Scenario 2

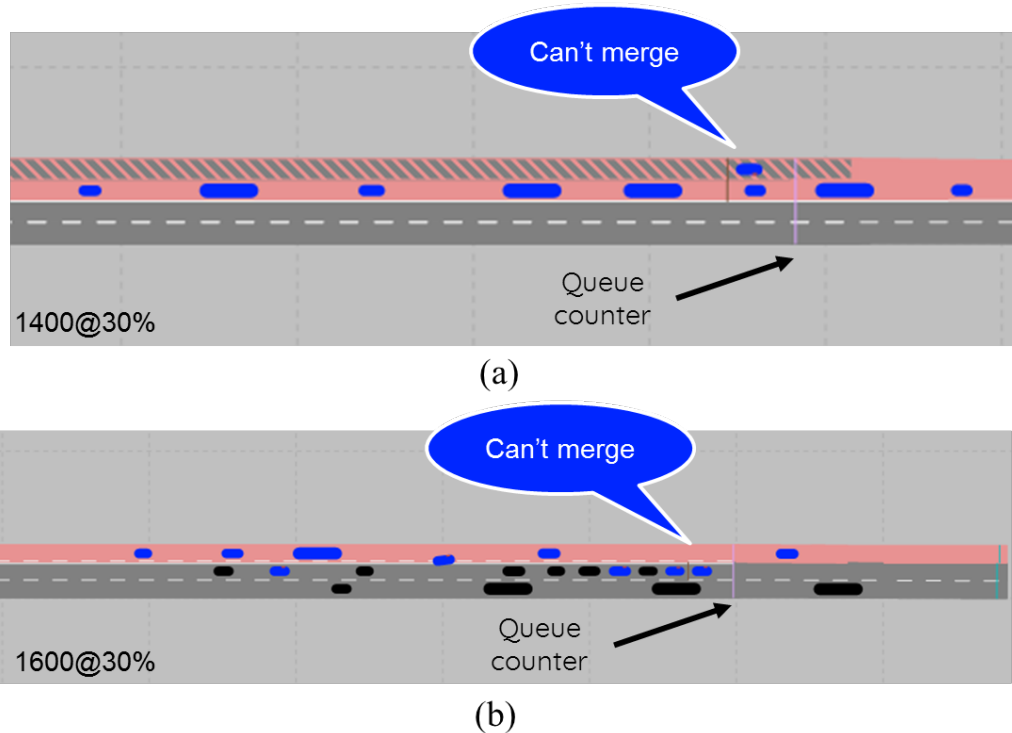


Figure 3-14 Unsuccess Passing in (a) Scenario 1 and (b) Scenario 2

3.5.4.4 Data Collection for Safety Analysis

Vehicle trajectories from VISSIM were used for safety analysis in SSAM. The conflict events consisted of rear-end conflict and lane change conflict. The number of conflict event in each scenario was used for safety analysis. Note that this study observed conflicts involved with at least one autonomous vehicle.

File	MinTTC	MinPET	MinPETA	MinPET	TTC	PETA	MaxG	DeltaS	DR	MaxD	MaxDeltaV	ConflictAngle	ClockAngle	ConflictType	PostCrashV	PostCrashA	FirstVID	FirstLin
S3_800_0_765.00	-42.60	1347.43	0.00	0.00	0.00	35.01	2.19	-5.69	-5.69	1.18	2.88	5.56	lane change	34.03	358.92	478	12	
S3_800_0_809.00	7924.66	1346.72	0.00	1.30	1.00	17.25	6.68	-6.59	-6.83	3.50	5.86	5.48	rear end	14.13	357.90	372	12	
S3_800_0_859.00	8642.09	1346.76	3.00	1.30	2.00	12.32	11.50	-6.77	-6.77	6.13	0.00	6.00	rear end	6.92	6.00	374	12	
S3_800_0_862.00	8644.42	1344.35	0.00	0.00	0.00	16.40	18.54	-2.10	-2.18	9.42	-45.56	7.31	lane change	10.03	359.24	347	12	
S3_800_0_860.00	8655.71	1344.21	0.00	1.10	3.00	4.69	3.73	-3.06	-3.08	1.92	8.45	5.43	rear end	2.77	351.18	357	12	
S3_800_0_860.00	8651.53	1343.10	3.00	0.60	0.00	26.47	24.10	8.26	0.25	12.26	-11.61	6.27	lane change	13.20	358.27	347	12	
S3_800_0_859.00	8635.89	1344.54	0.00	0.10	1.00	25.47	18.42	-5.86	-6.07	9.63	5.89	5.50	rear end	15.85	358.81	367	12	
S3_800_0_863.00	8635.26	1346.76	0.00	0.00	0.00	3.33	3.17	-7.51	-7.51	1.68	0.00	5.59	rear end	1.85	0.00	363	12	
S3_800_0_864.00	8660.76	1343.30	3.00	0.50	3.00	3.85	2.10	-0.19	-0.89	1.60	0.94	5.59	rear end	1.85	359.72	357	12	
S3_800_0_865.00	8655.35	1343.12	0.00	1.20	4.00	3.83	3.83	-1.68	-3.78	2.06	0.06	5.59	rear end	1.77	359.99	367	12	
S3_800_0_870.00	8620.86	1343.10	0.00	1.10	3.00	10.02	3.31	-2.13	-6.02	1.74	0.00	5.59	rear end	8.44	0.00	372	12	
S3_800_0_871.00	8625.61	1346.76	3.00	1.50	4.00	8.94	3.61	-3.26	-7.52	1.88	0.00	6.00	rear end	6.77	0.00	386	12	
S3_800_0_8106.00	15.59	1347.43	0.00	0.00	0.00	32.43	1.50	-0.25	-0.25	0.79	1.42	5.57	rear end	30.43	6.10	727	12	
S3_800_0_1568.00	1467.44	1342.94	0.00	0.70	1.00	17.97	12.10	-6.02	-6.46	6.05	0.00	5.59	rear end	11.92	0.00	984	12	
S3_800_0_1657.00	8664.32	1346.76	3.00	1.30	2.00	12.39	8.18	-6.62	-7.04	-6.09	0.00	5.59	rear end	8.30	0.00	903	12	
S3_800_0_1894.00	3582.63	1348.88	0.00	0.00	0.00	17.21	11.45	-6.39	-6.61	6.09	-7.02	6.14	lane change	11.77	4.61	1144	12	
S3_800_0_2375.00	4394.02	1345.81	0.00	0.00	0.00	31.38	5.05	0.10	0.10	2.61	-1.68	6.03	rear end	28.24	0.00	1428	12	
S3_800_0_2979.00	483.32	1345.32	3.00	0.00	0.00	27.88	2.15	-6.44	-6.44	1.09	-0.53	6.05	rear end	26.99	1.31	1939	10	
S3_800_0_3210.00	4619.60	1343.01	0.00	1.20	1.00	17.41	11.42	-6.67	-6.91	5.76	-0.15	6.00	rear end	11.65	359.89	1988	12	
S3_800_0_3216.00	4612.72	1345.11	0.00	0.00	0.00	5.47	1.50	-7.13	-7.13	0.81	-18.70	6.21	rear end	4.61	8.21	1981	12	
S3_800_0_3359.00	58.61	1347.84	3.00	0.00	0.00	31.47	6.82	-0.25	-8.88	3.73	2.78	5.94	lane change	28.44	358.93	2142	12	
S3_800_0_3363.00	-27.59	1347.32	0.00	1.50	1.00	18.12	7.04	-6.62	-6.86	3.85	0.41	5.59	rear end	14.93	356.70	2189	12	
S3_800_0_3370.00	199.25	1345.68	0.00	0.00	0.00	23.62	3.37	0.10	0.10	1.71	-4.22	6.08	lane change	20.99	358.90	2192	12	
S3_800_0_3598.00	27.31	1345.77	3.00	0.00	0.00	21.16	15.33	-6.47	-6.47	8.74	11.92	5.36	lane change	15.13	355.63	2235	12	
S3_800_0_3660.00	4034.80	1347.92	0.00	0.00	0.00	31.85	2.26	0.99	1.29	3.76	5.52	lane change	30.38	359.85	2289	12		
S3_800_0_4097.00	4229.13	1347.92	0.00	0.00	0.00	29.97	1.69	-1.27	-1.27	0.84	3.20	5.54	rear end	29.85	359.28	2546	12	
S3_800_0_4812.00	8322.24	1348.31	3.00	0.00	0.00	32.10	1.78	-0.41	-0.41	0.92	3.88	5.94	lane change	31.63	359.41	2950	12	
S3_800_0_4833.00	8661.45	1346.76	0.00	1.40	3.00	19.35	11.00	-4.25	-6.68	5.59	0.00	6.00	rear end	13.94	0.00	2958	12	
S3_800_0_4845.00	8660.44	1345.37	0.00	0.80	1.00	18.10	17.23	-6.90	-7.15	9.16	-17.01	6.34	lane change	10.03	357.95	2949	12	
S3_800_0_5009.00	8670.31	1346.76	3.00	1.20	3.00	3.67	1.04	-0.89	-0.89	0.27	0.00	5.59	rear end	2.59	0.00	3432	12	
S3_800_0_5818.00	-863.32	1345.34	0.00	0.00	0.00	33.32	3.38	-6.35	-6.35	1.82	-2.27	6.05	lane change	31.86	0.97	3844	10	
S3_800_0_6045.00	8680.41	1344.31	0.00	1.30	1.00	26.66	18.60	-6.15	-6.61	9.89	3.80	5.52	rear end	16.77	359.03	3779	12	
S3_800_0_6267.00	8679.13	1344.36	3.00	0.00	0.00	9.12	1.35	-6.99	-6.99	0.69	4.82	5.50	rear end	8.66	357.18	3941	12	
S3_800_0_6285.00	28.44	1343.84	0.00	0.00	0.00	20.08	0.87	-6.74	-6.74	0.49	1.34	5.57	rear end	19.27	359.44	4135	12	
S3_800_0_6581.00	4249.26	1347.30	0.00	1.10	0.00	30.77	1.36	0.79	0.79	0.71	1.77	5.56	rear end	30.25	0.04	4232	12	
S3_800_0_6620.00	3134.52	1346.63	3.00	1.50	1.00	22.43	12.00	-5.85	-6.07	6.00	0.00	5.29	rear end	16.44	0.00	4297	12	

Figure 3-15 SSAM Result in Table

3.6 Procedure

The procedures of simulation and the data collection and analysis for each scenario is the following:

1. Create the scenario, install the data collection points at the same location as others 2 scenarios.
2. Set vehicle input volume and truck penetration rate.
3. Perform three simulation runs for each scenario.
4. Record the following attribute for each scenario;
 - a. Average vehicle throughput (at each data collection points)
 - b. Average speed (at each data collection points)
 - c. Average travel time
 - d. Average delay time

- e. Average queue length (only in scenario 2 and 3)
5. Repeat step 1 to 5 for the other 2 scenarios, at different traffic volume and truck penetration rate, to gathering all of the data.
6. Convert vehicle throughput into capacity at each data collection point, plot the graph to compare the capacity of each scenario at the same traffic input and truck penetration rate (21 in total). Note that the capacity of autonomous vehicles and manual vehicles are plotted separately.
7. Plot the speed at each data collection point at the same traffic input and truck penetration rate (21 in total). Note that the speed on the dedicated lane and manual lane are plotted separately.
8. Process the data in “*.MER” file, which is the data & collection measurements output file from the simulation runs (Figure 3-16). Coding data in the file to determine average headway. Calculated percentage of platooning and plot data for the same traffic input and truck penetration rate at each data collection point. Note that the speed on the dedicated lane and manual lane are plotted separately.
9. Process the data in “*.SPW” file, which is the lane changes output file from the simulation runs. Coding data in the file to determine the average passing rate. Calculated percentage of sharing passing vehicle and plot data for the same traffic input and truck penetration rate. Note that this step only considers passing maneuver of autonomous vehicles.
10. Use trajectory file for each simulation run to do the safety analysis in SSAM. The result from three runs are average and use as the representative for each case. Note that this study only considered conflicts involved with an autonomous vehicle.
11. Average capacity result for each scenario, compare the differential between scenario 1 (base case) with other 2 scenarios, plot the result on the same graph. Note that data in each graph has the same truck penetration rate.

12. Repeat step 10 for speed result
13. Repeat step 10 for the percentage of platooning reduction result
14. Repeat step 10 for the percentage of travel time reduction result
15. Use queue length data to analyze unsuccess passing vehicles
16. Use SSAM result to analyze safety for each scenario
17. Evaluated the result and proceeded to conclusion

Data collection (Raw Data)

File: C:\Users\jantarathane\Google Drive\Uw\THESIS\VISSIM 10\SI\800\SI_800_0.inpx
 Comment: SI 1200 10
 Date: wednesday, March 13, 2019 8:39:54 PM
 PTV Vissim 10.00-05 (64 bit) [69293]

```
Data collection point      10: Link   14 lane 1 at   5285.079 ft.
Data collection point      11: Link   16 lane 2 at   5284.984 ft.
Data collection point      12: Link   16 lane 1 at   5286.008 ft.
Data collection point      20: Link   14 lane 1 at  10649.169 ft.
Data collection point      21: Link   16 lane 2 at  10649.108 ft.
Data collection point      22: Link   16 lane 1 at  10648.596 ft.
Data collection point      30: Link   14 lane 1 at  21054.319 ft.
Data collection point      31: Link   16 lane 2 at  21053.225 ft.
Data collection point      32: Link   16 lane 1 at  21054.225 ft.
Data collection point      33: Link   14 lane 1 at  26397.270 ft.
Data collection point      34: Link   16 lane 2 at  26396.765 ft.
Data collection point      35: Link   16 lane 1 at  26396.356 ft.
Data collection point      49: Link   14 lane 1 at  15847.164 ft.
Data collection point      50: Link   16 lane 2 at  15846.069 ft.
Data collection point      51: Link   16 lane 1 at  15846.069 ft.
```

Measur.	t(Entry)	t(Exit)	vehNo	vehicle type	Line	v[mph]	b[ft/s2]	occ	Pers	tqueue	vehLength[ft]
11;	301.23;	301.33;	156;	100;	0;	85.6;	-0.00;	0.10;	1;	0.0;	13.16;
30;	301.85;	301.99;	60;	150;	0;	74.0;	-0.00;	0.14;	1;	0.0;	15.24;
31;	301.42;	301.57;	56;	100;	0;	71.3;	-0.00;	0.15;	1;	0.0;	15.62;
34;	301.92;	-1.00;	23;	100;	0;	73.3;	-0.00;	0.08;	1;	0.0;	13.82;
21;	302.12;	302.26;	122;	100;	0;	72.4;	-0.00;	0.14;	1;	0.0;	15.12;
22;	302.27;	302.40;	119;	100;	0;	69.4;	-0.00;	0.13;	1;	0.0;	13.16;
30;	302.92;	-1.00;	61;	150;	0;	73.5;	-0.34;	0.08;	1;	0.0;	15.12;
34;	-1.00;	302.05;	23;	100;	0;	73.3;	-0.00;	0.05;	1;	0.0;	13.82;
35;	302.79;	302.91;	26;	100;	0;	76.4;	-0.00;	0.12;	1;	0.0;	13.82;
21;	303.38;	303.52;	124;	100;	0;	74.5;	3.09;	0.14;	1;	0.0;	15.12;
30;	-1.00;	303.06;	61;	150;	0;	73.4;	-0.34;	0.06;	1;	0.0;	15.12;
51;	303.19;	303.32;	86;	100;	0;	68.9;	-0.00;	0.14;	1;	0.0;	13.82;
12;	304.37;	304.49;	153;	100;	0;	72.5;	-0.00;	0.12;	1;	0.0;	13.16;
31;	304.24;	304.38;	68;	100;	0;	76.0;	-0.00;	0.14;	1;	0.0;	15.12;
35;	304.22;	304.37;	19;	100;	0;	69.7;	-0.00;	0.15;	1;	0.0;	15.24;
50;	304.47;	304.61;	91;	100;	0;	71.4;	-0.00;	0.13;	1;	0.0;	13.82;
51;	304.30;	304.44;	90;	100;	0;	67.5;	-0.82;	0.14;	1;	0.0;	13.82;
21;	305.94;	-1.00;	129;	100;	0;	79.5;	-0.00;	0.06;	1;	0.0;	14.30;
50;	305.70;	305.85;	94;	100;	0;	72.0;	2.39;	0.14;	1;	0.0;	15.24;
51;	305.35;	305.49;	93;	100;	0;	67.2;	-1.40;	0.13;	1;	0.0;	13.16;

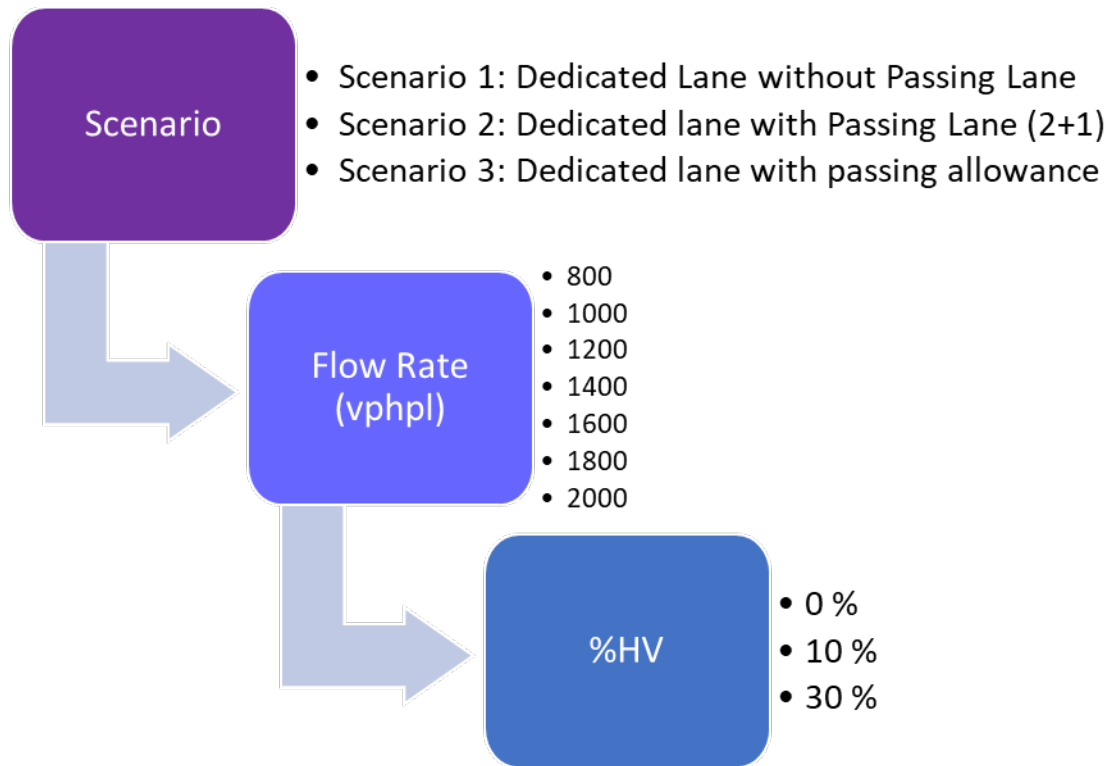
Figure 3-16 Data Collection & Measurement Output from VISSIM (*.MER)

* File: C:\Users\jantarathane\Google Drive\UW\THESIS\VISSIM 10\S1\800\S1_800_0.inpx
 * Comment: S1 1200 10
 * Date: 3/13/2019 8:39:54 PM
 * PTV Vissim: 10.00 [05]
 *
 * Table: Vehicles In Network
 *
 * SIMSEC: SimSec, Simulation second (Simulation time [s]) [s]
 * NO: No, Number (Unique vehicle number)
 * LANE\LINK\NO: Lane\Link\No, Lane\Link\Number (Unique link/connector number)
 * LANE\INDEX: Lane\Index, Lane\Index (Unique number of the lane)
 * POS: Pos, Position (Distance on the link from the beginning of the link or connector) [ft]
 * POSLAT: PosLat, Position (lateral) (Lateral position at the end of the time step. Value range 0 - 1: 0: at the right lane edge 0.5: middle of the lane 1: at the left lane edge)
 * ACCELERATION: Acceleration, Acceleration (Acceleration during the time step) [ft/s²]
 * COORDFRONT: CoordFront, Coordinate front (Coordinate of front end of vehicle at the end of the time step)
 * COORDREAR: CoordRear, Coordinate rear (Coordinate of rear end position of vehicle at the end of the time step)
 * DELAYTM: DelayTm, Delay time (Difference between optimal (ideal, theoretical) driving time) [s]
 * DESLANE: DesLane, 9999 = no desired lane)
 * DESSPEED: DesSpeed, Desired speed (Reference to the Desired speed distribution for the vehicle type) [mph]
 * DRIVSTATE: DrivState, Driving state
 * HDWY: Hdwy, Headway (Distance to the preceding vehicle before the time step) [ft]
 * LANE: Lane, Lane (Number of lane on which the vehicle is used. If a vehicle in the dynamic assignment drives away from a parking lot, the 0 is output in the Lane column)
 * LNCHG: LnChg, Lane change (Direction of the current lane change)
 * SPEED: Speed, Speed (Speed at the end of the time step) [mph]
 * TMSINCESTARTOFLASTLNCHG: TmSinceStartOfLastLnChg, Time elapsed since start of last lane change (Time since the beginning of the last lane change) [s]
 * TMINNETTOT: TmInNetTot, Time in network (total) (The total time which a vehicle is in the network. The value is saved only in the last second before the vehicle leaves the network. Also record the Delay time for the vehicle in this time step. For vehicles that are still in the network at the end of the simulation, you can determine the total time on the basis of their utilization time. The recording file contains the total time = 0.00, as long as the vehicle is still in the network.) [s]
 *
 * SimSec No Lane\Lin Lane\Ind Pos PosLat Accelerat CoordFro CoordRex DelayTm DesLane DesSpee DrivState Hdwy Lane LnChg Speed TmSincE TmInNetTot
 *
 SVEHICLE:SIMSEC NO LANE\LIN LANE\IND POS POSLAT ACCELEA COORDFR COORDRE DELAYTM DESLANE DESSPEED DRIVSTAT HDWY LANE LNCHG SPEED TMSINCES TMINNETTOT
 301 4 14 1 31146.73 0.5 0 8578.891 8574.281 0 73.34 Default 0 14-1 None 73.34 289
 301 8 14 1 29882.38 0.5 0 8193.520 8189.508 0 73.16 Default 1264.08 14-1 None 73.16 278
 301 9 14 1 29765.79 0.5 0.33 8157.983 8153.373 10.61 76.66 Default 114.1 14-1 None 71.57 276
 301 11 14 1 29657.56 0.5 -0.53 8124.992 8121.243 24.65 80.87 Default 108.45 14-1 None 71.42 274
 301 14 14 1 25767.78 0.5 0 6939.388 6934.744 0 65.29 Default 3880.52 14-1 None 65.29 269
 301 15 14 1 25662.39 0.5 4.42 6907.266 6903.055 8.54 68.17 Default 106.88 14-1 None 67.82 267
 301 18 14 1 24787.03 0.5 0 6640.456 6635.846 0 65.45 Default 874.1 14-1 None 65.45 258
 301 24 14 1 24681.9 0.5 -0.33 6608.411 6604.200 50.52 85.87 Default 105.07 14-1 None 65.3 246
 301 29 14 1 24577.23 0.5 -0.24 6576.508 6571.748 36.03 82.7 Default 105.97 14-1 None 66.22 238
 301 31 14 1 24465.06 0.5 2.36 6542.318 6537.558 60.38 96.11 Default 112.5 14-1 None 67.33 233
 301 32 14 1 24352.35 0.5 3.75 6507.964 6503.354 13.06 75.79 Default 108.27 14-1 None 64.77 232

Figure 3-17 Lane Changes Output from VISSIM (*.SPW)

3.7 Simulation Scenario

The scenarios in this study were created and based on three levels; the passing configurations, traffic flow, and heavy vehicles penetration rate (Figure 3-18). The first level, passing configuration, consists of 3 components; scenario 1: dedicated lane without passing lane, scenario 2: dedicated lane with passing lane (2+1), scenario 3: dedicated lane with a passing allowance. The second level is flow rates which range from 800 vphpl to 2000 vphpl with an increment of 200 vphpl, seven components in total. The third level is three heavy vehicle penetration rates which are 0%, 10%, and 30%.



Total = 3 x 7 x 3 = 63 Scenarios

Figure 3-18 Total Simulation Scenarios in This Study

Chapter 4 Result and Analysis

4.1 Result

This section describes result from simulation runs which consists of three part: capacity, traffic operation, and safety.

4.1.1 Capacity

4.1.1.1 Capacity of Autonomous Vehicle

The graphs show the relationship between the location of the detector and flow rate of autonomous vehicles for each scenario at different heavy penetration rate (Figure 4-1 to Figure 4-7). Note that the flow rate of autonomous vehicles in the middle lane of scenario 3 was also included.

From the result, scenario 3 provided almost the same capacity when assigned traffic volume was low, 800 to 1200 vphpl. When the assigned traffic volume increased to 1400 and 1600 vphpl, scenario 3 can provide slightly more capacity. Moreover, the flow rate that scenario 1 and 3 can provide was more than the assigned traffic volume. However, when traffic volume has assigned at or higher than 1800 vphpl, both scenario 1 and 3 has a lower capacity than scenario 2, especially scenario 3.

In contrast, scenario 2 provided a lower capacity than the assigned traffic volume, regardless of the heavy vehicles penetration rate. When the assigned traffic volume increased to 1800 vphpl, this scenario can provide better capacity than others.

The result also showed that different heavy penetration rate has no explicitly effects to capacity until the assign traffic volume is at or above 1800 vphpl. For the latter cases, capacity was decreasing when heavy penetration rates increased.

4.1.1.2 Capacity of Manual Vehicle

The graphs show the relationship between the location of the detector and flow rate of manual vehicles for each scenario at different heavy penetration rate. (Figure 4-8 to Figure 4-16). Note that the flow rate of autonomous vehicles in the middle lane of scenario 3 were excluded since this study aimed to compare capacity between autonomous vehicles and manual vehicles on all lanes. Also, the result from scenario 1 was only compared to scenario 3 since the configuration of the manual lane on scenario 1 and 2 are the same.

From the result, scenario 3 provided better capacity than scenario 1 for the manual vehicle when the assigned traffic volume was below 1800 vphpl. Scenario 3 also provided a higher flow rate than the assigned traffic volume. In contrast, scenario 1 only provide the same or lower flow rate than the assigned volume. However, when the traffic volume was assigned at 1800 vphpl or higher, scenario 3 provided traffic flow less than scenario 1. The capacity also decreased when the heavy penetration rate increased.

- Scenarios with traffic flow at 800 vehicle per hour per lane

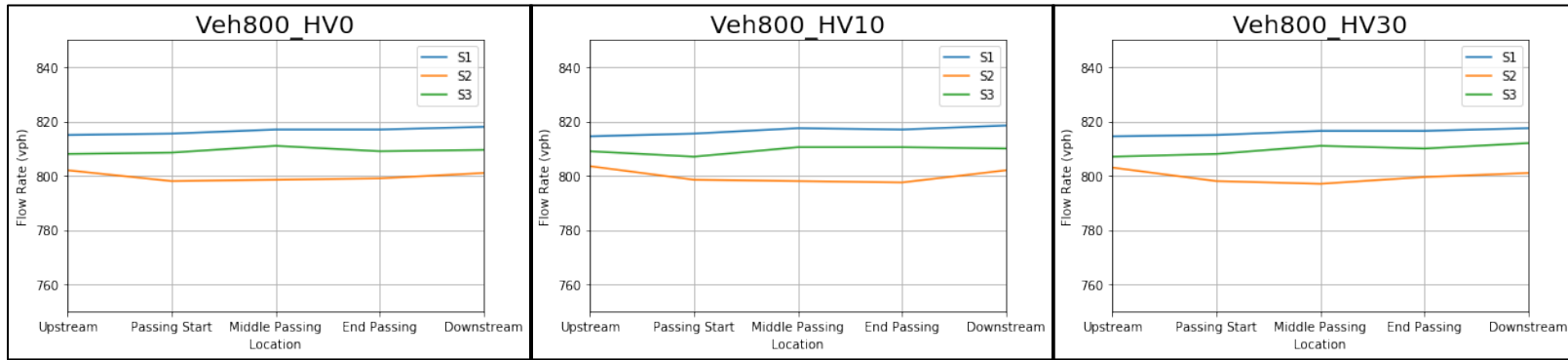


Figure 4-1 Comparison of Flow Rate at each Location with 800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Autonomous Vehicle

- Scenarios with traffic flow at 1000 vehicle per hour per lane

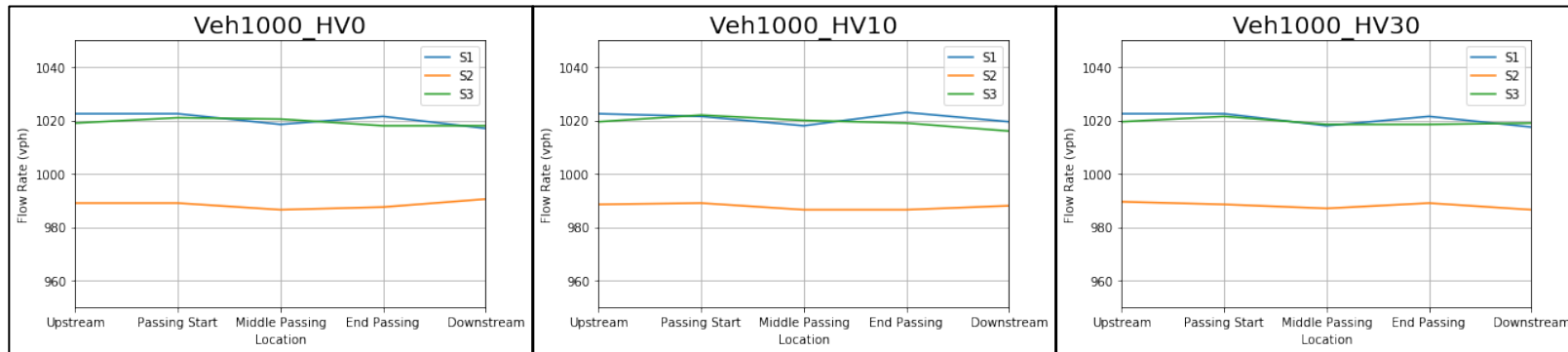


Figure 4-2 Comparison of Flow Rate at each Location with 1000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Autonomous Vehicle

- Scenarios with traffic flow at 1200 vehicle per hour per lane

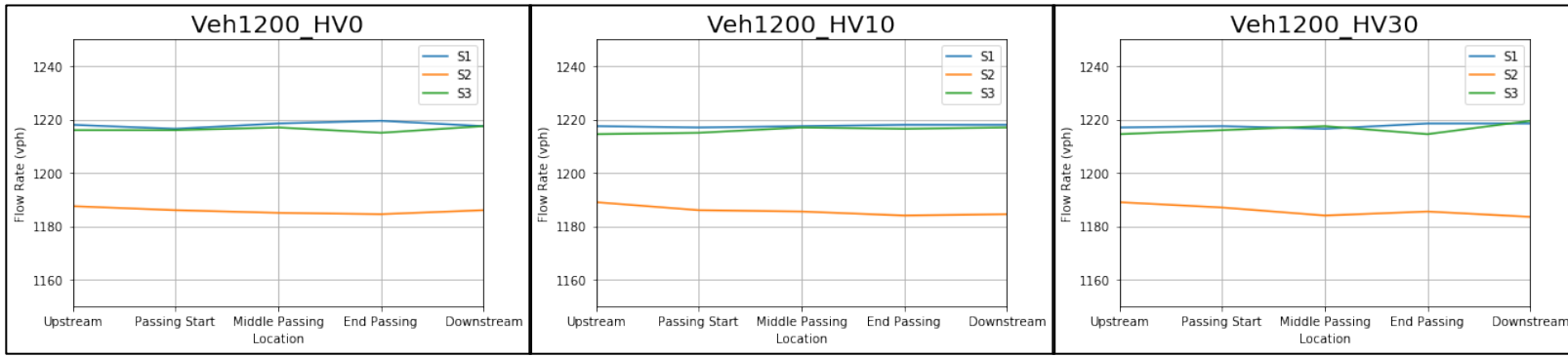


Figure 4-3 Comparison of Flow Rate at each Location with 1200 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Autonomous Vehicle

- Scenarios with traffic flow at 1400 vehicle per hour per lane

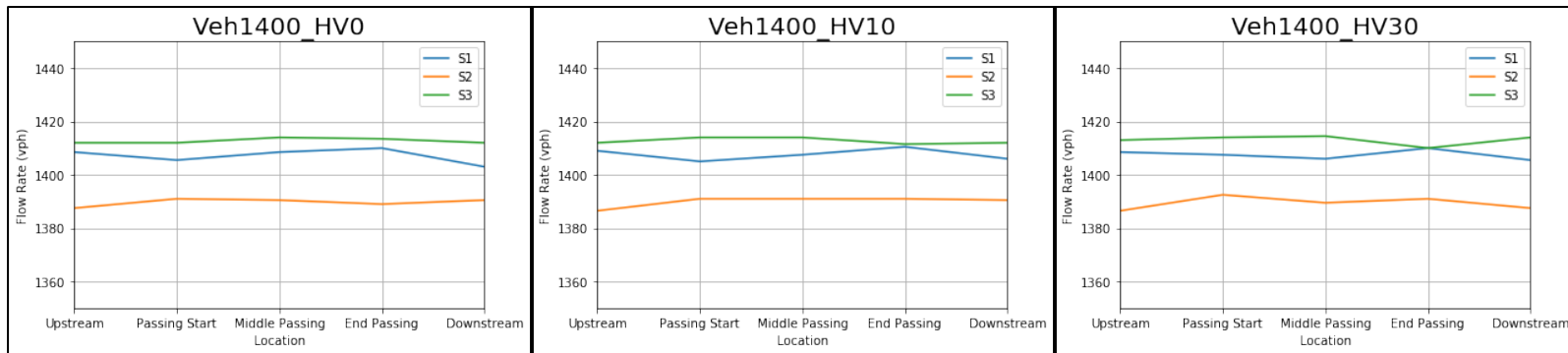


Figure 4-4 Comparison of Flow Rate at each Location with 1400 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Autonomous Vehicle

- Scenarios with traffic flow at 1600 vehicle per hour per lane

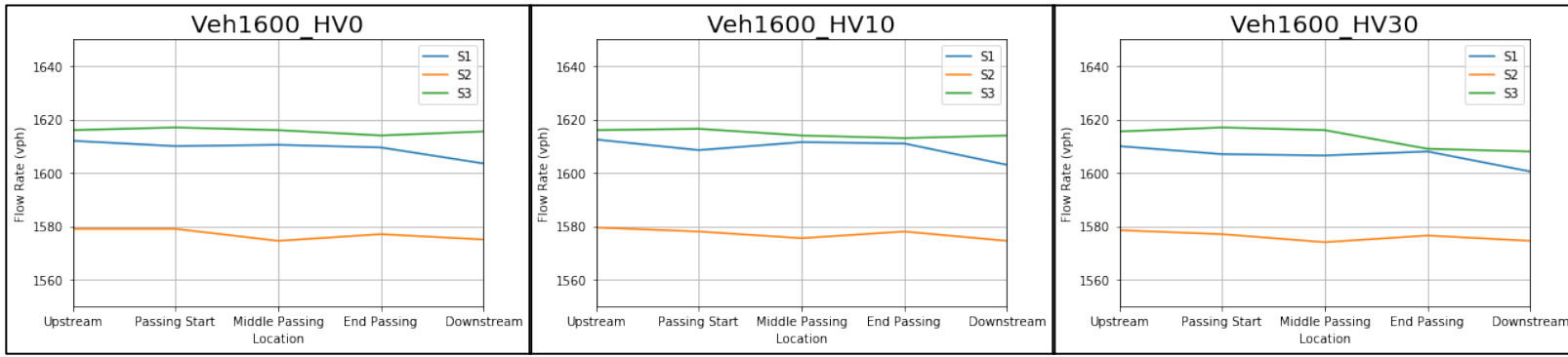


Figure 4-5 Comparison of Flow Rate at each Location with 1600 vphl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Autonomous Vehicle

- Scenarios with traffic flow at 1800 vehicle per hour per lane

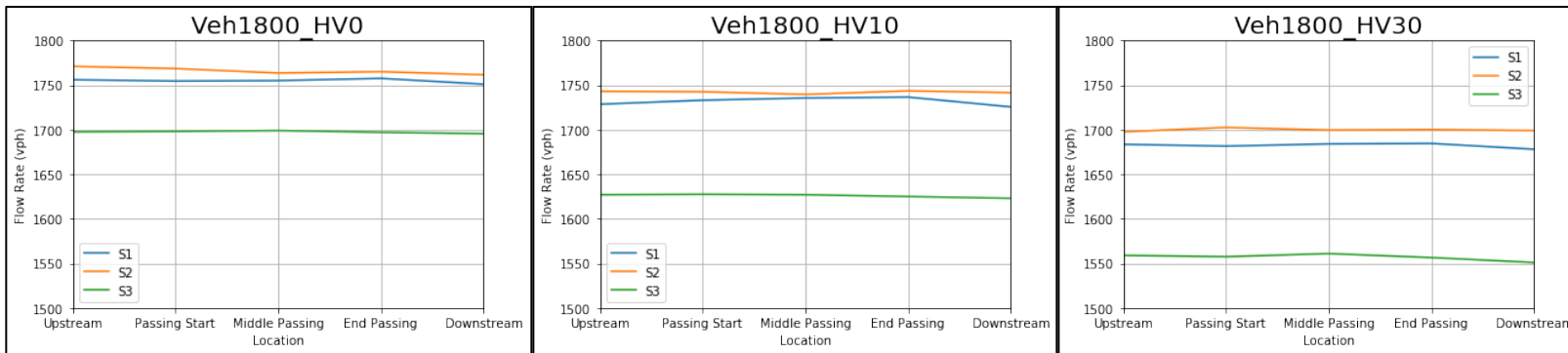


Figure 4-6 Comparison of Flow Rate at each Location with 1800 vphl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Autonomous Vehicle

- Scenarios with traffic flow at 2000 vehicle per hour per lane

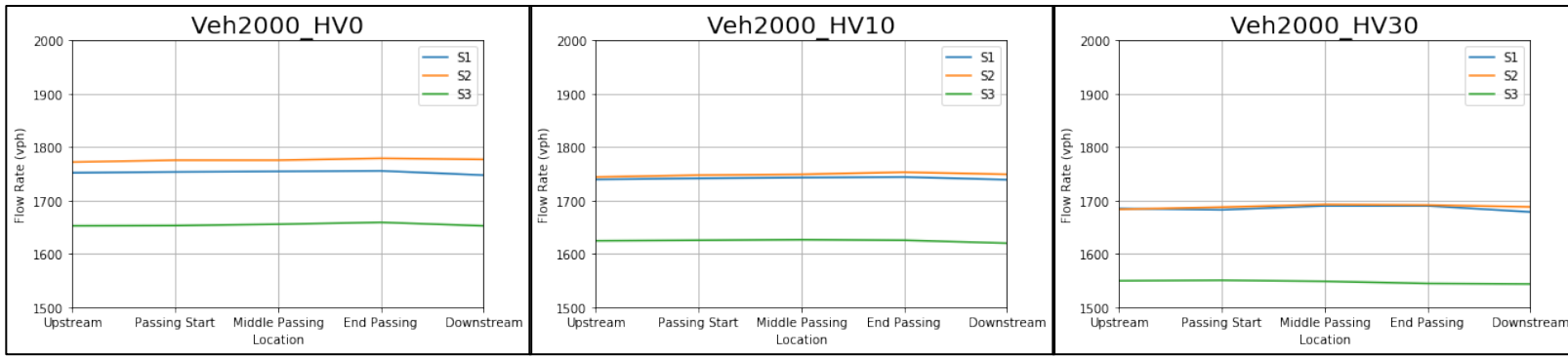


Figure 4-7 Comparison of Flow Rate at each Location with 2000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Autonomous Vehicle

- Scenarios with traffic flow at 800 vehicle per hour per lane

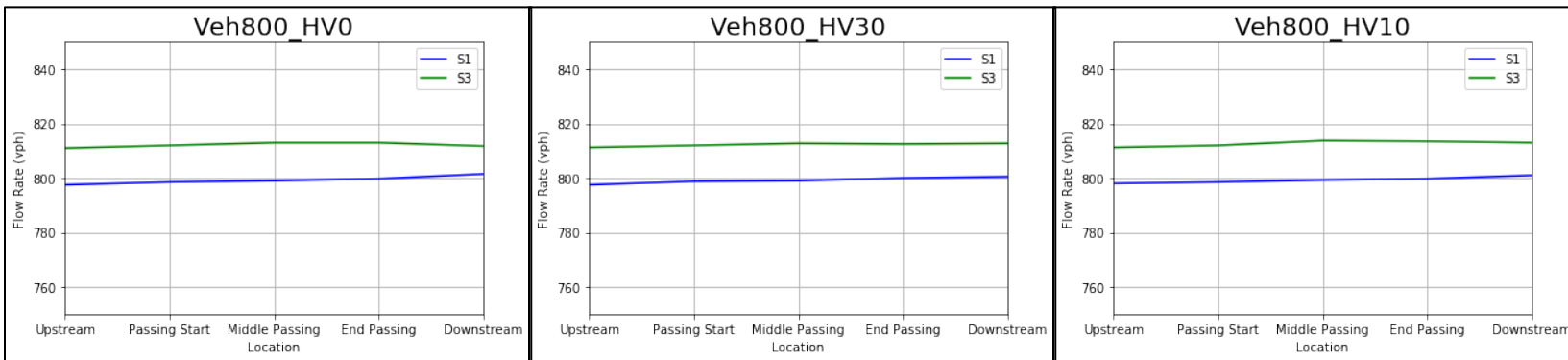


Figure 4-8 Comparison of Flow Rate at each Location with 800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Manual Vehicle

- Scenarios with traffic flow at 1000 vehicle per hour per lane

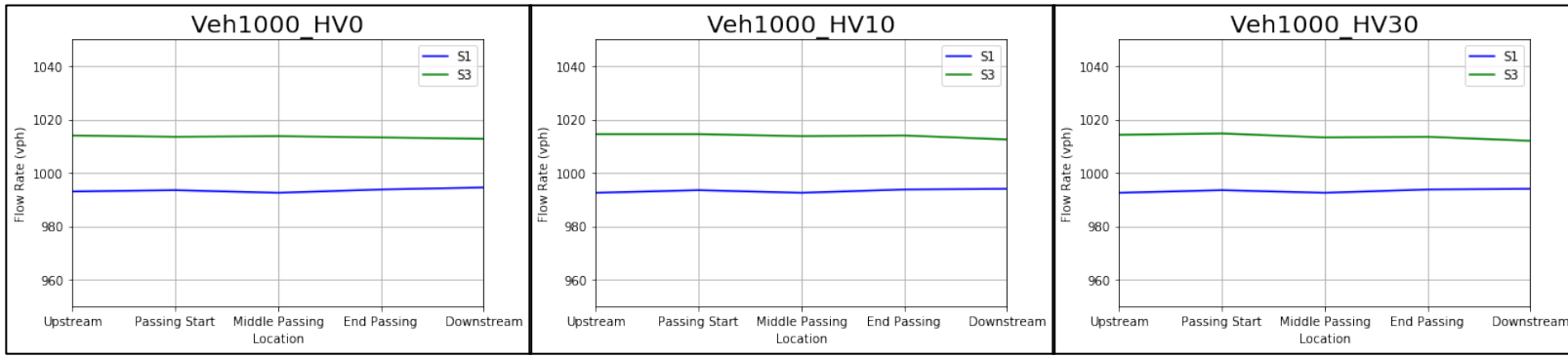


Figure 4-9 Comparison of Flow Rate at each Location with 1000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Manual Vehicle

- Scenarios with traffic flow at 1200 vehicle per hour per lane

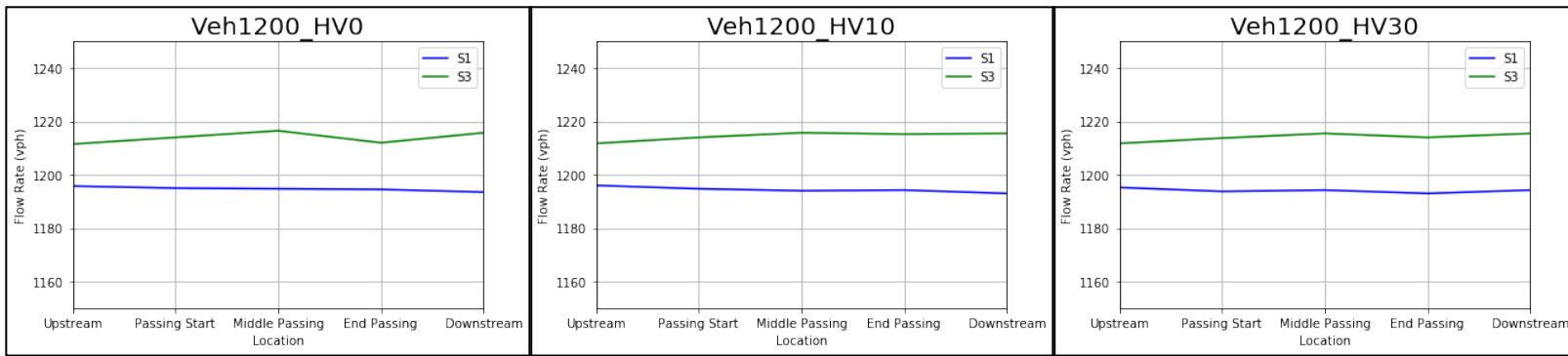


Figure 4-10 Comparison of Flow Rate at each Location with 1200 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Manual Vehicle

- Scenarios with traffic flow at 1000 vehicle per hour per lane

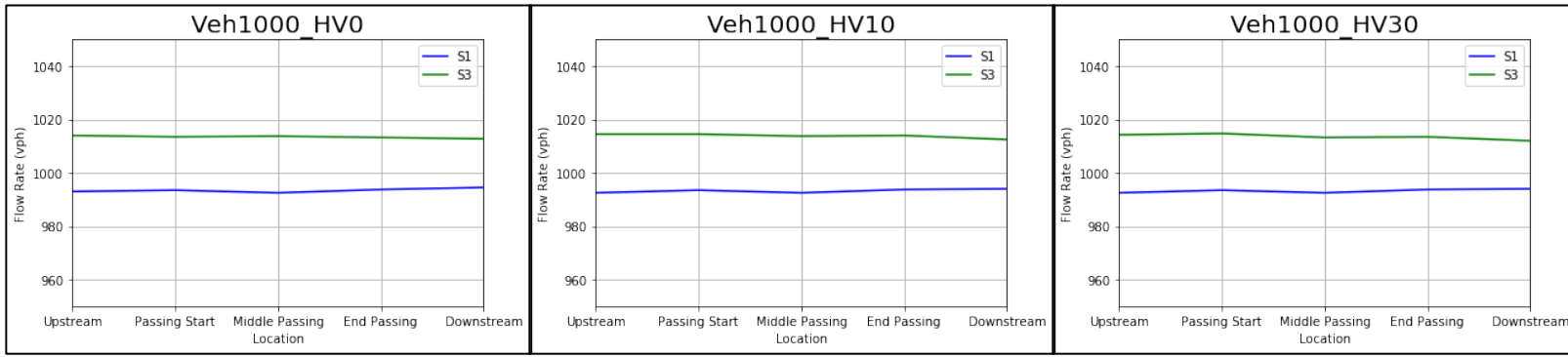


Figure 4-11 Comparison of Flow Rate at each Location with 1000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Manual Vehicle

- Scenarios with traffic flow at 1200 vehicle per hour per lane

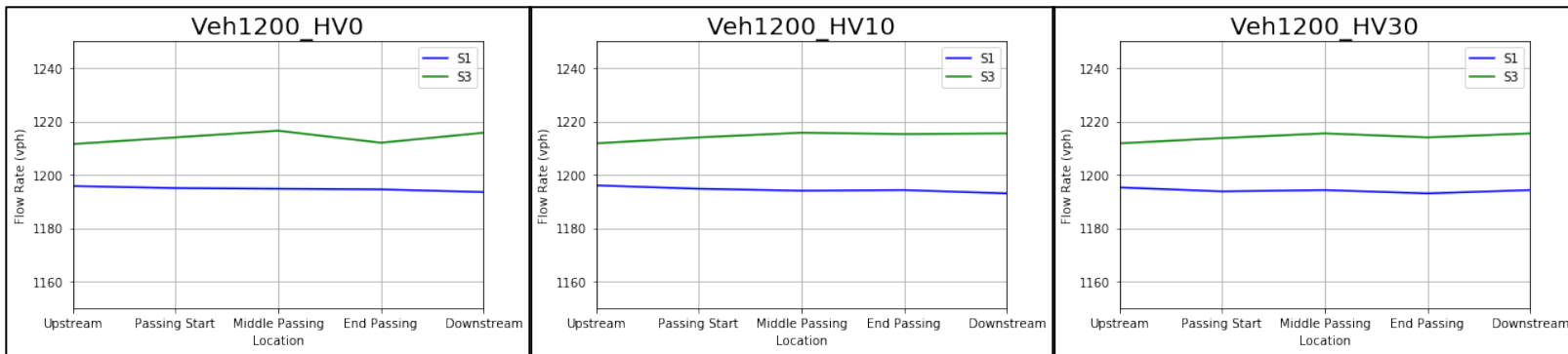


Figure 4-12 Comparison of Flow Rate at each Location with 1200 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Manual Vehicle

- Scenarios with traffic flow at 1400 vehicle per hour per lane

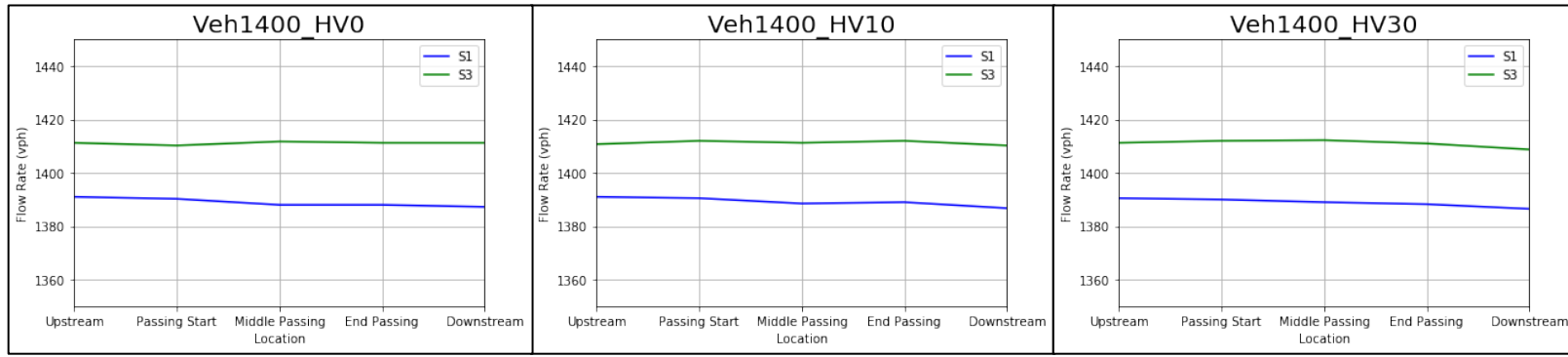


Figure 4-13 Comparison of Flow Rate at each Location with 1400 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Manual Vehicle

- Scenarios with traffic flow at 1600 vehicle per hour per lane

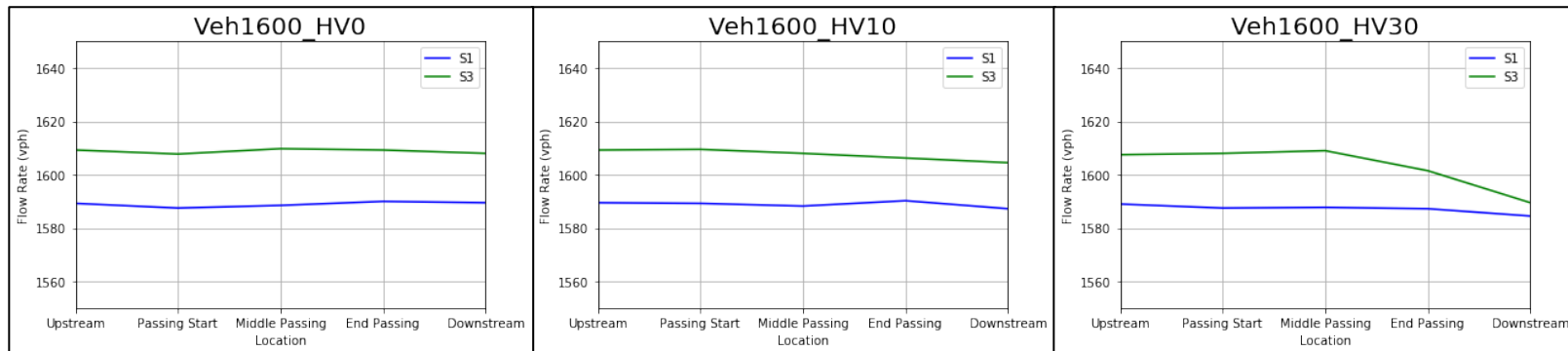


Figure 4-14 Comparison of Flow Rate at each Location with 1600 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Manual Vehicle

- Scenarios with traffic flow at 1800 vehicle per hour per lane

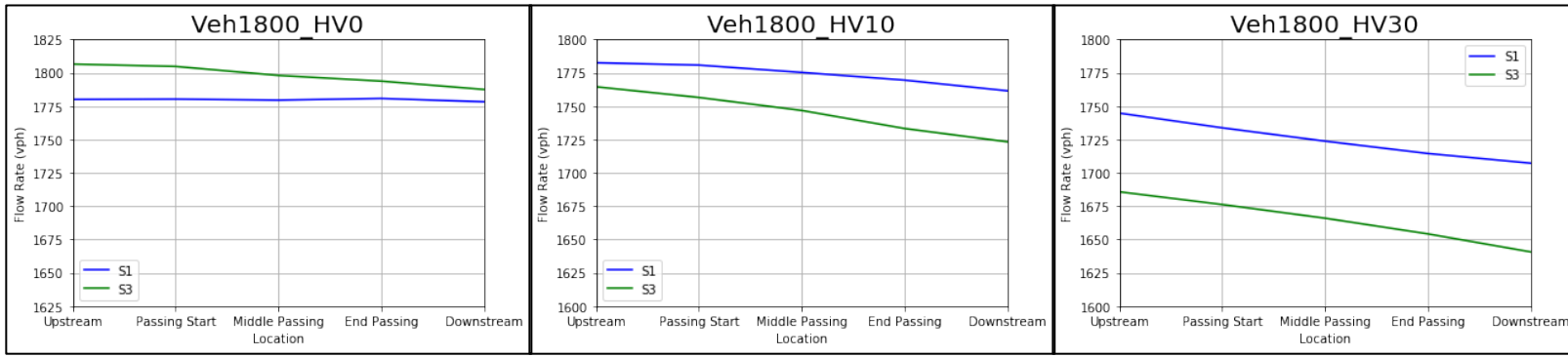


Figure 4-15 Comparison of Flow Rate at each Location with 1800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Manual Vehicle

- Scenarios with traffic flow at 2000 vehicle per hour per lane

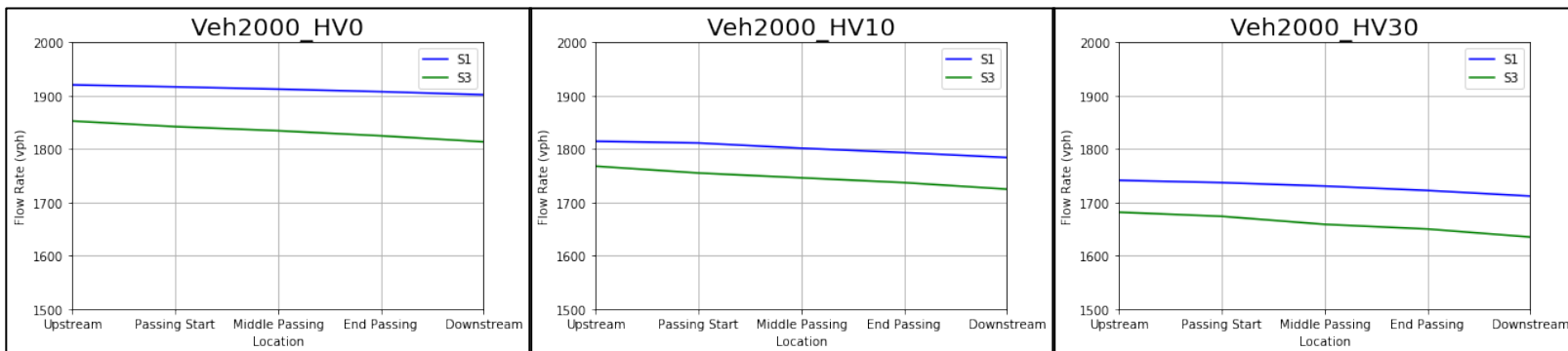


Figure 4-16 Comparison of Flow Rate at each Location with 2000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate for Manual Vehicle

4.1.2 Traffic Operation

The traffic operation attribute consists of speed, travel time, delay, passing rate, percentage of vehicles in the platoon, and queue length.

4.1.2.1 Speed

A) Speed on Dedicated Lane

The graphs show the relationship between the location of detector and speed on the dedicated lane for each scenario at different heavy penetration rate. (Figure 4-17 to Figure 4-23). Note that the speed of autonomous vehicles in the middle lane of scenario 3 was not used for average speed calculation.

As a result, when the assigned traffic volume was below 1800 vphpl, scenario 3 provided the highest speed on the dedicated lane at all location. Scenario 1 and 2 provided almost the same travel speed except at the middle of passing lane location, which scenario 2 can provide higher travel speed. Moreover, scenario 3 was the only scenario that can provide travel speed at or above post speed, which is 70 mph for passenger car and 60 for heavy vehicle. When the assigned traffic was at 1800 vphpl or above, scenario 3 provided lower travel speed, and in some case provided the lowest. On the other hand, scenario 2 provided the highest travel speed in the middle of the passing lane location. However, scenario 2 has the lowest travel speed at the end of passing lane location. Also, travel speed was slightly decreased when the heavy penetration rate increase.

B) Speed on Manual Lane

The graphs show the relationship between the location of the detector and speed on the manual lane for each scenario at different heavy penetration rate. (Figure 4-24 to Figure 4-30). Note that the result from scenario 1 was only compared to scenario 3 since the configuration of the manual lane on scenario 1 and 2 are the same.

From the result, scenario 1 provided travel speed as same as scenario 3 for manual vehicles at equal or higher than post speed. However, when the assigned traffic volume was more than 1600 vphpl, scenario 3 provides lower travel speed than scenario 1. Both scenarios provided travel speed lower than post speed when the assigned traffic volume and heavy penetration rate increase.

- Scenarios with traffic flow at 800 vehicle per hour per lane

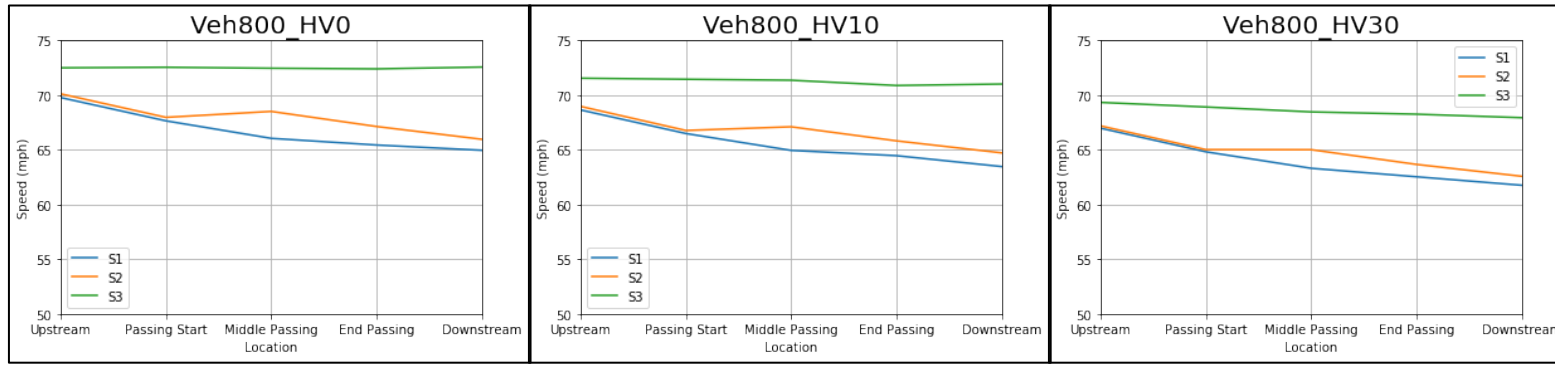


Figure 4-17 Comparison of Speed at each Location with 800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 1000 vehicle per hour per lane

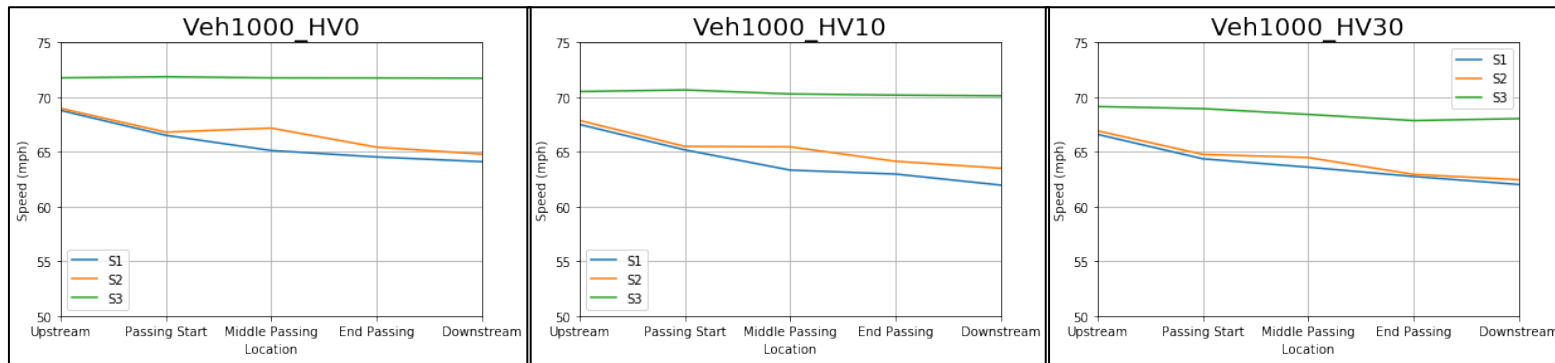


Figure 4-18 Comparison of Speed at each Location with 1000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 1200 vehicle per hour per lane

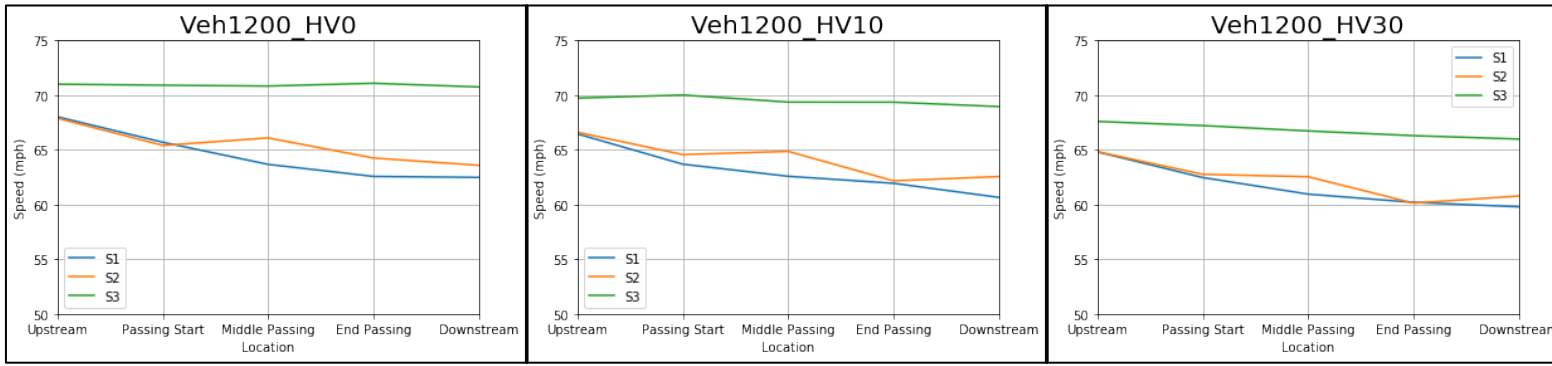


Figure 4-19 Comparison of Speed at each Location with 1200 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 1400 vehicle per hour per lane

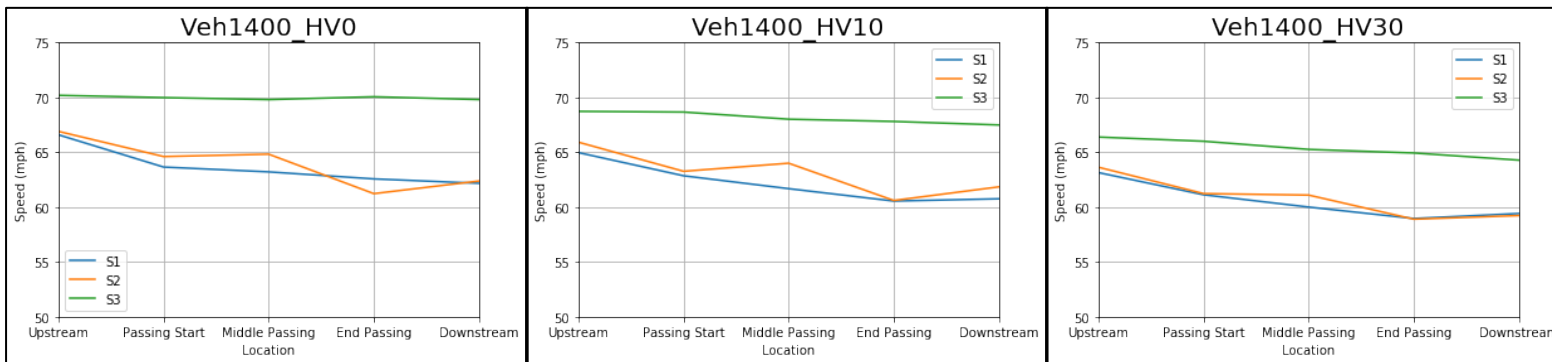


Figure 4-20 Comparison of Speed at each Location with 1400 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated

- Scenarios with traffic flow at 1600 vehicle per hour per lane

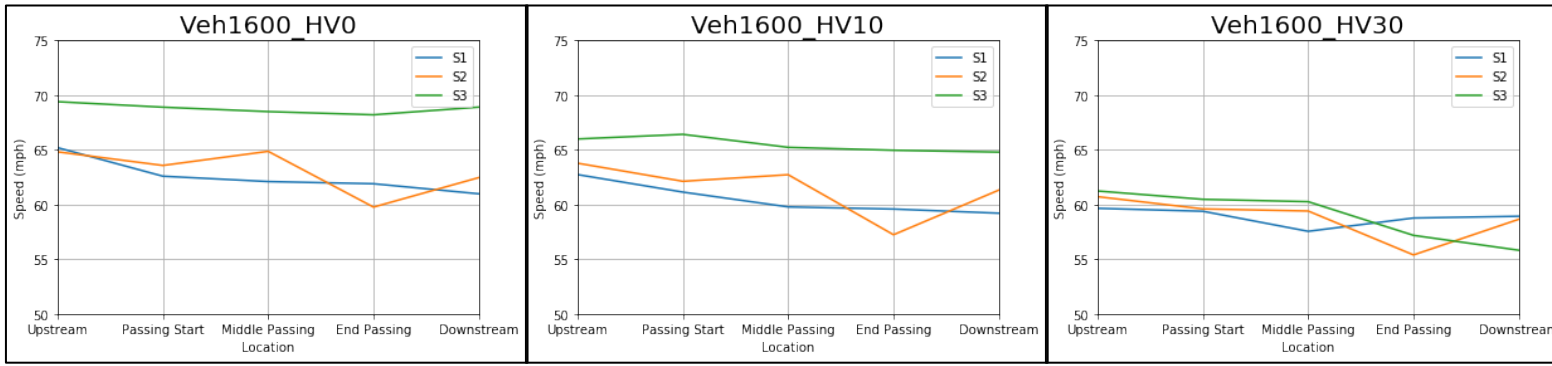


Figure 4-21 Comparison of Speed at each Location with 1600 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 1800 vehicle per hour per lane

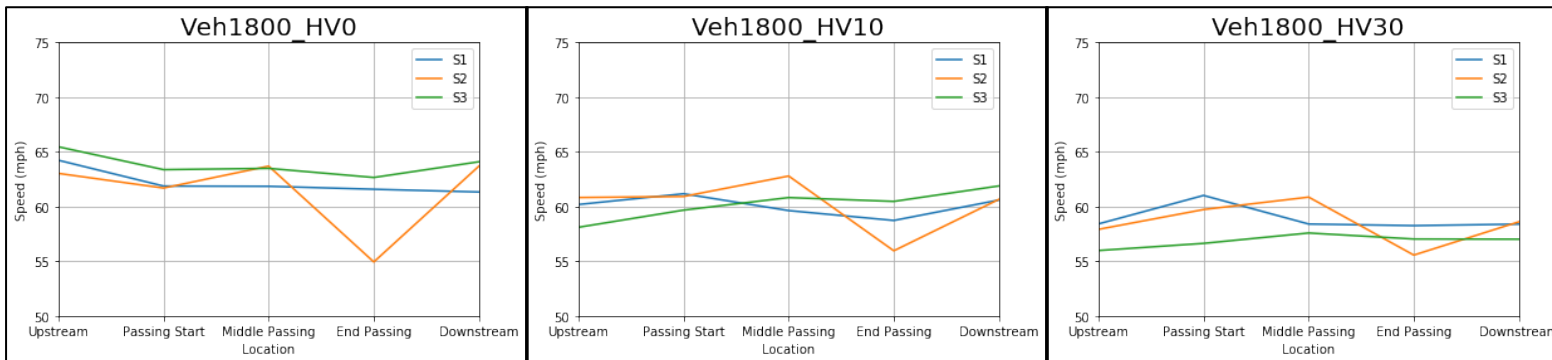


Figure 4-22 Comparison of Speed at each Location with 1800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 2000 vehicle per hour per lane

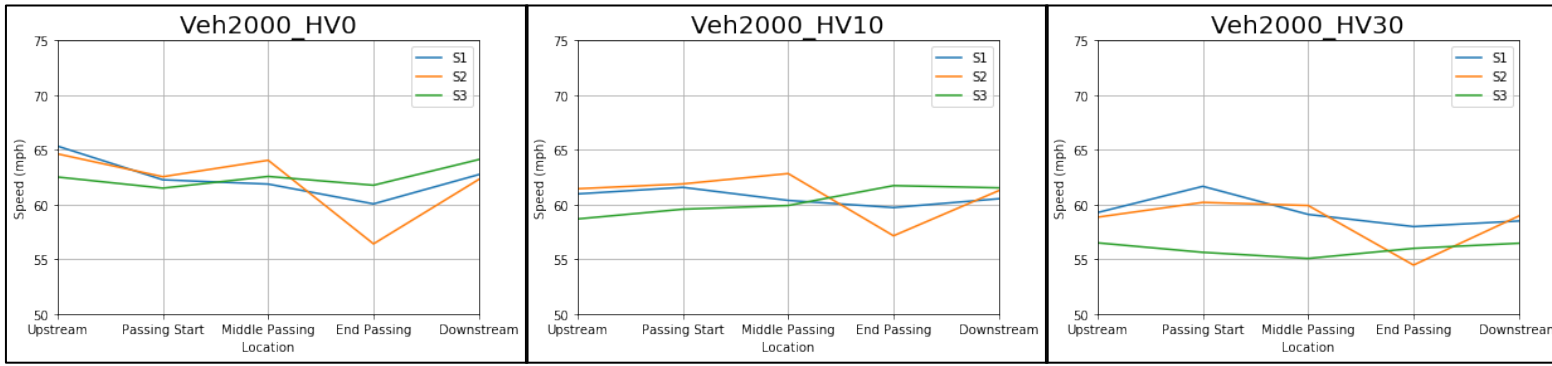


Figure 4-23 Comparison of Speed at each Location with 2000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 800 vehicle per hour per lane

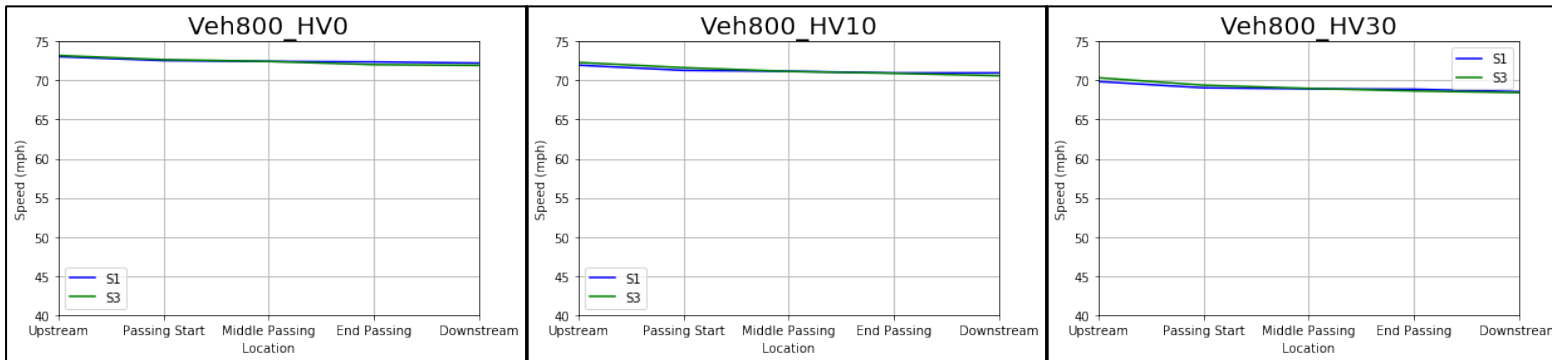


Figure 4-24 Comparison of Speed at each Location with 800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lane

- Scenarios with traffic flow at 1000 vehicle per hour per lane

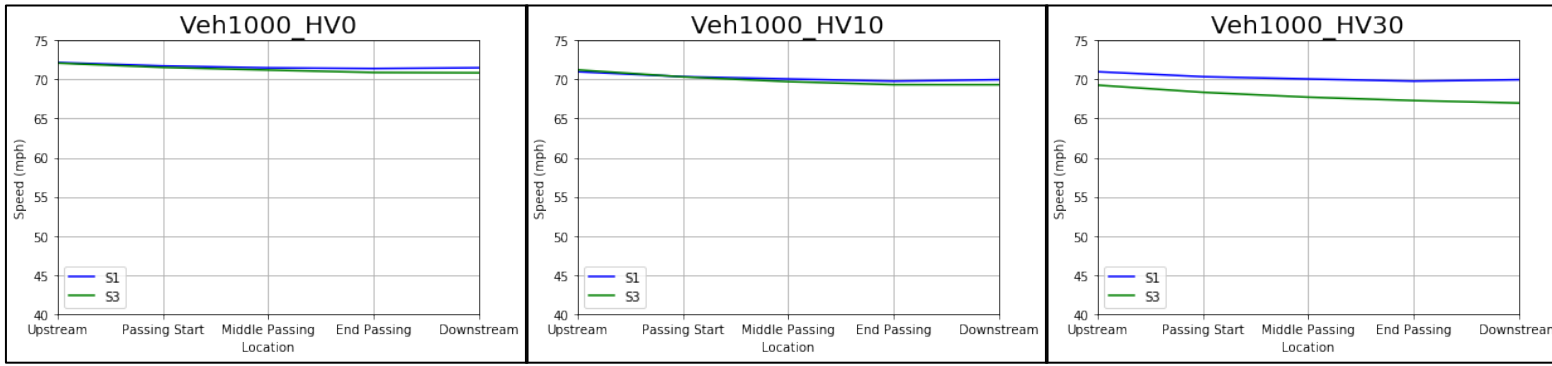


Figure 4-25 Comparison of Speed at each Location with 1000 vphl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lane

- Scenarios with traffic flow at 1200 vehicle per hour per lane

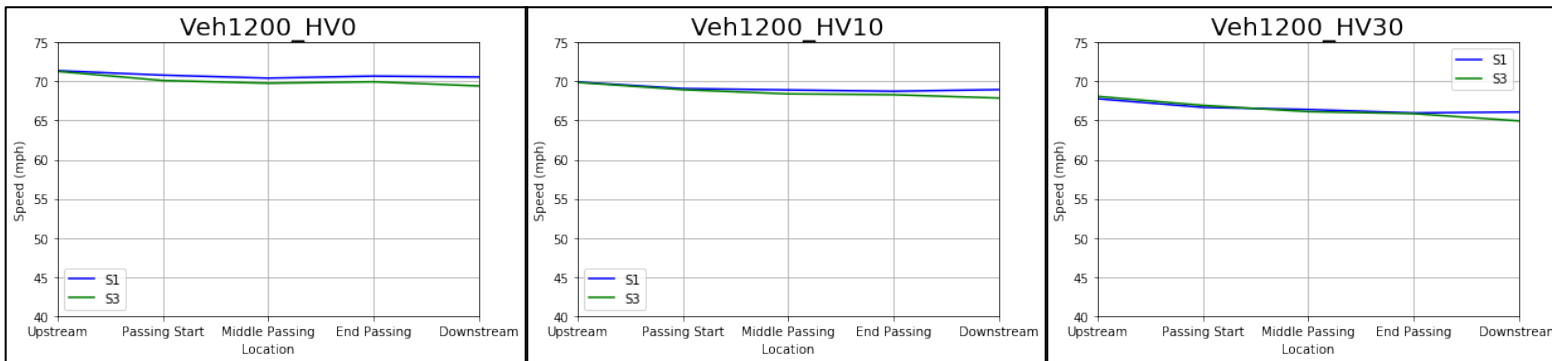


Figure 4-26 Comparison of Speed at each Location with 1200 vphl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lane

- Scenarios with traffic flow at 1400 vehicle per hour per lane

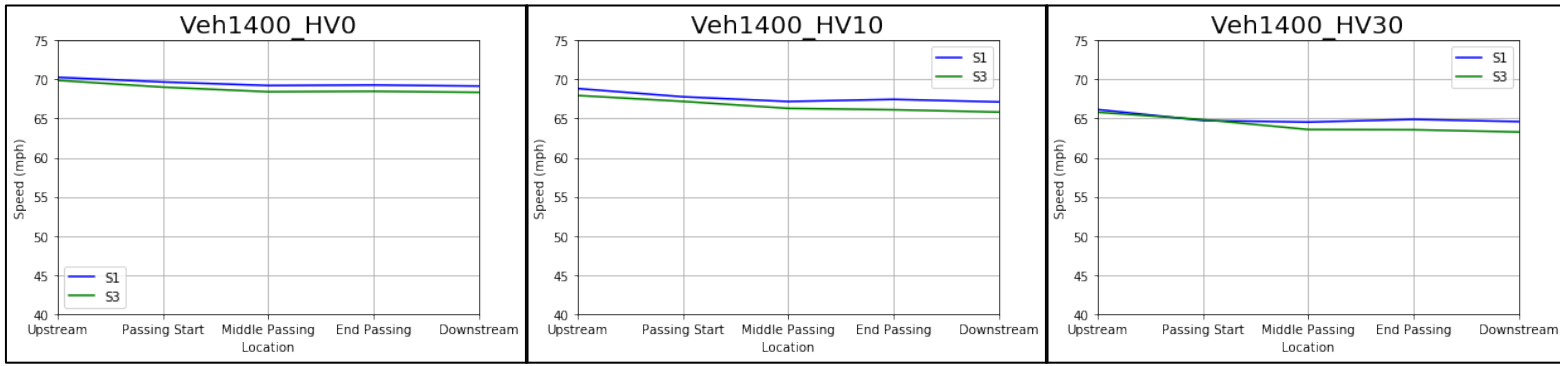


Figure 4-27 Comparison of Speed at each Location with 1400 vphl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lane

- Scenarios with traffic flow at 1600 vehicle per hour per lane

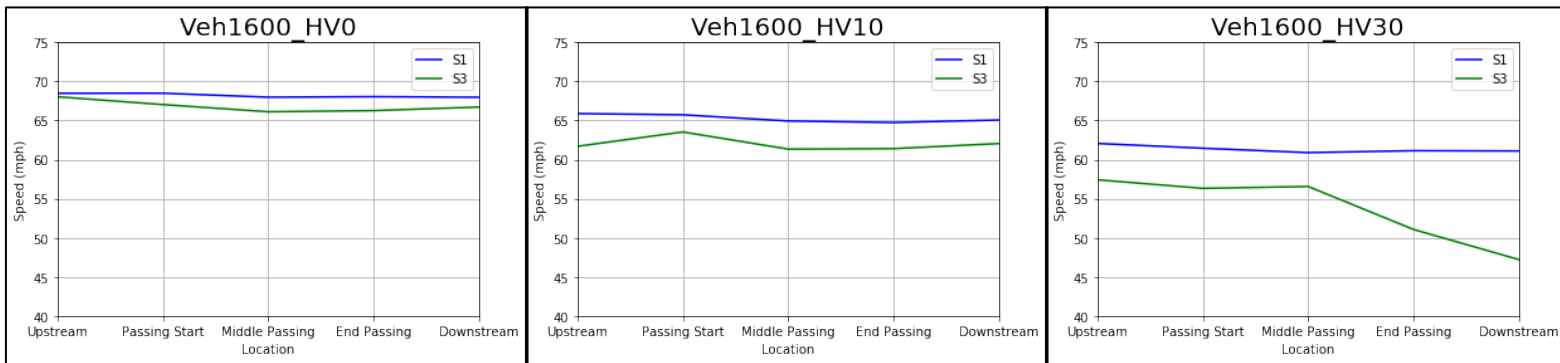


Figure 4-28 Comparison of Speed at each Location with 1600 vphl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lane

- Scenarios with traffic flow at 1800 vehicle per hour per lane

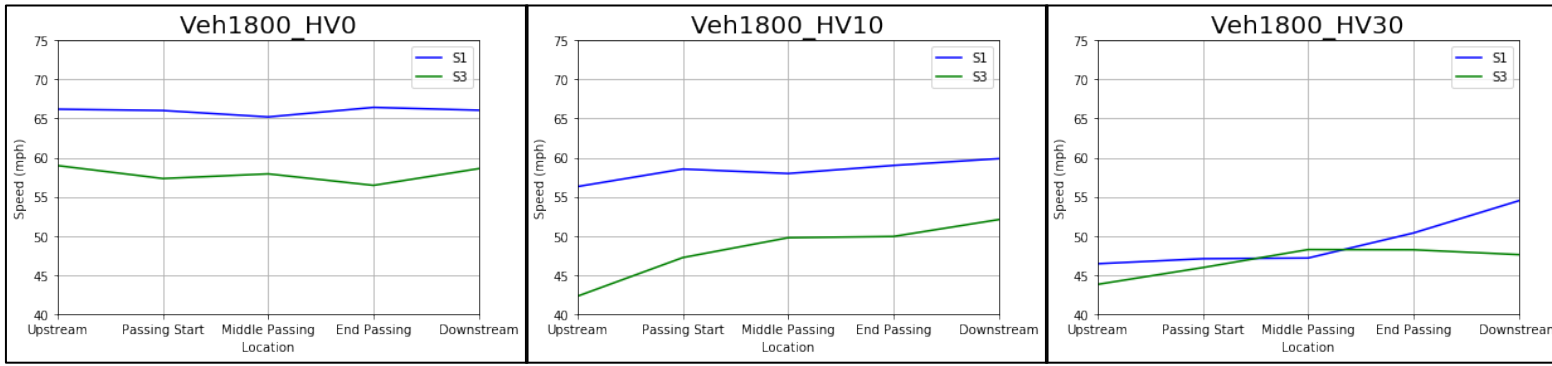


Figure 4-29 Comparison of Speed at each Location with 1800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lane

- Scenarios with traffic flow at 2000 vehicle per hour per lane

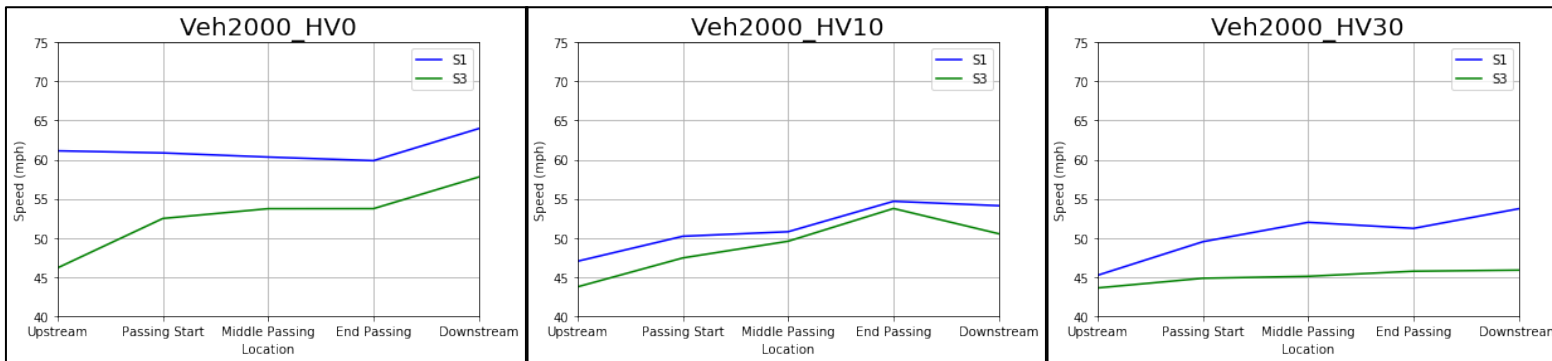


Figure 4-30 Comparison of Speed at each Location with 2000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lane

4.1.2.2 Percentage of Vehicles in Platoon

A) Percentage of Vehicles in Platoon on Dedicated Lane

The graphs show the relationship between the location of the detector and the percentage of vehicles in a platoon on the dedicated lane for each scenario at different heavy penetration rate. (Figure 4-31 to Figure 4-37).

It was found that scenario 1 create the highest platoon in the traffic stream on a dedicated lane. Scenario 2 also created the same percentage of the vehicle in the platoon as in scenario 1 except in the middle of the passing lane, which percentage of platoon dropped at this location. Scenario 3, then, created the lowest percentage of vehicle sharing in a platoon on the dedicated lane. Note that the heavy vehicle penetration rate has almost no effect on the percentage of sharing vehicle in a platoon of all scenarios. In the case of high assigned traffic volume, the percentage of vehicles sharing in a platoon is increasing to more than 80 percent, even in scenario 3.

B) Percentage of Vehicles in Platoon on Manual Lane

The graphs show the relationship between the location of the detector and the percentage of vehicles in a platoon on the manual lane for each scenario at different heavy penetration rate (Figure 4-38 to Figure 4-44). Note that autonomous vehicles that used manual lane in scenario 3 were included in platoon determination. The average headway between two of manual lanes in scenario 1 and 3 was used for platoon determination.

As a result, scenario 3 create a higher percentage of sharing vehicle in a platoon than in scenario 1. When the assigned traffic volume increased, the percentage of the vehicle in platoon also increased in both cases. The heavy penetration rate has almost no effect on the percentage of the vehicle in the platoon for both scenarios.

- Scenarios with traffic flow at 800 vehicle per hour per lane

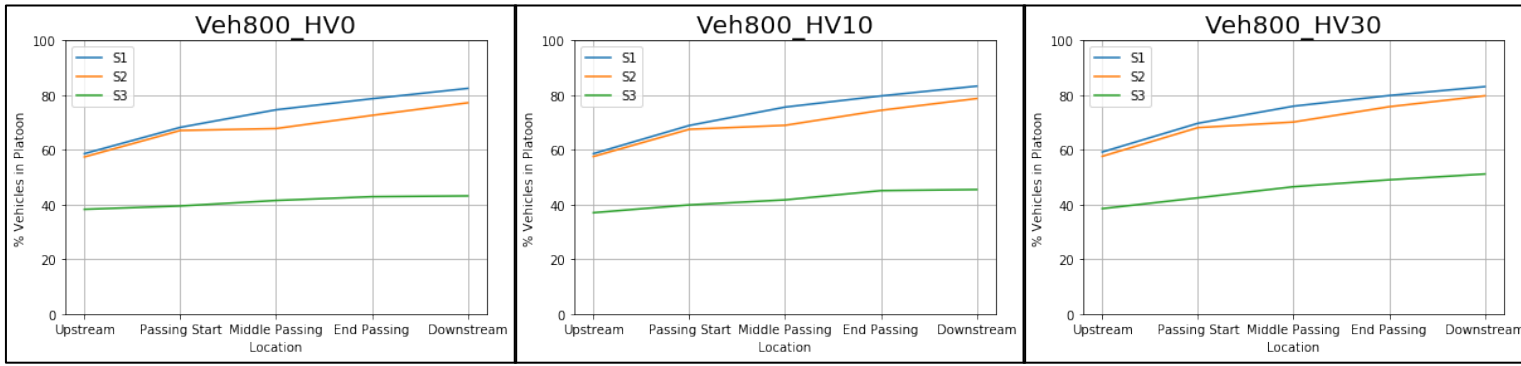


Figure 4-31 Comparison of % Vehicles in Platoon at each Location with 800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 1000 vehicle per hour per lane

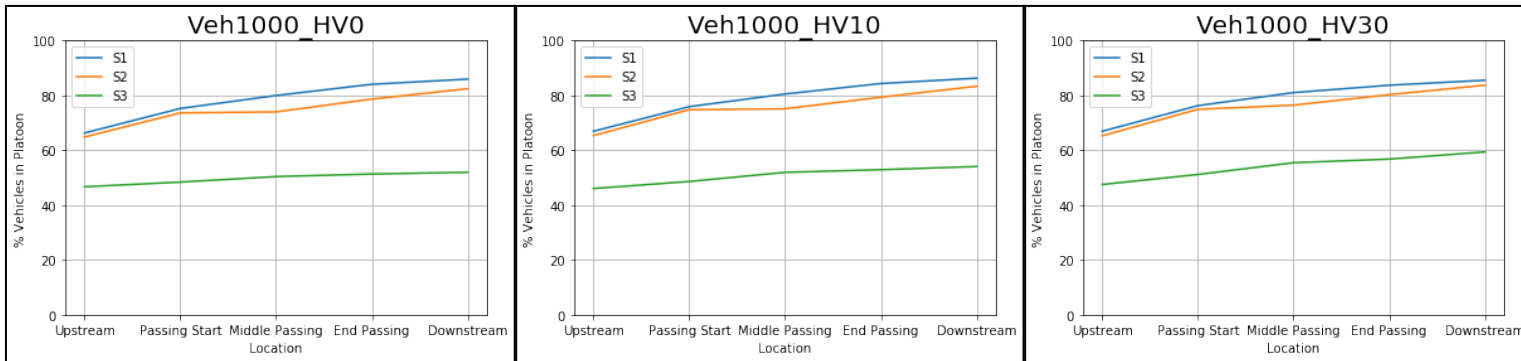


Figure 4-32 Comparison of % Vehicles in Platoon at each Location with 1000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 1200 vehicle per hour per lane

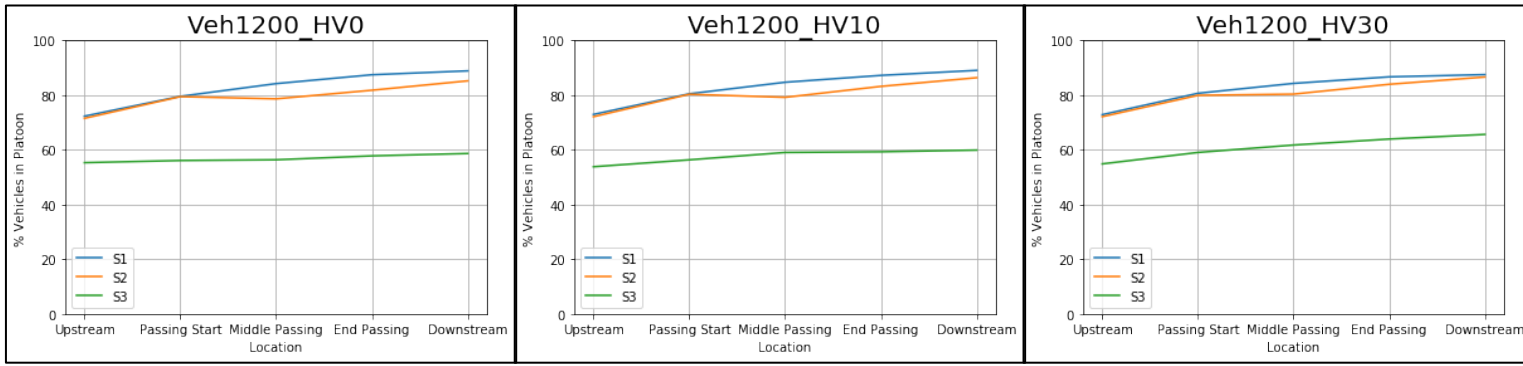


Figure 4-33 Comparison of % Vehicles in Platoon at each Location with 1200 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 1400 vehicle per hour per lane

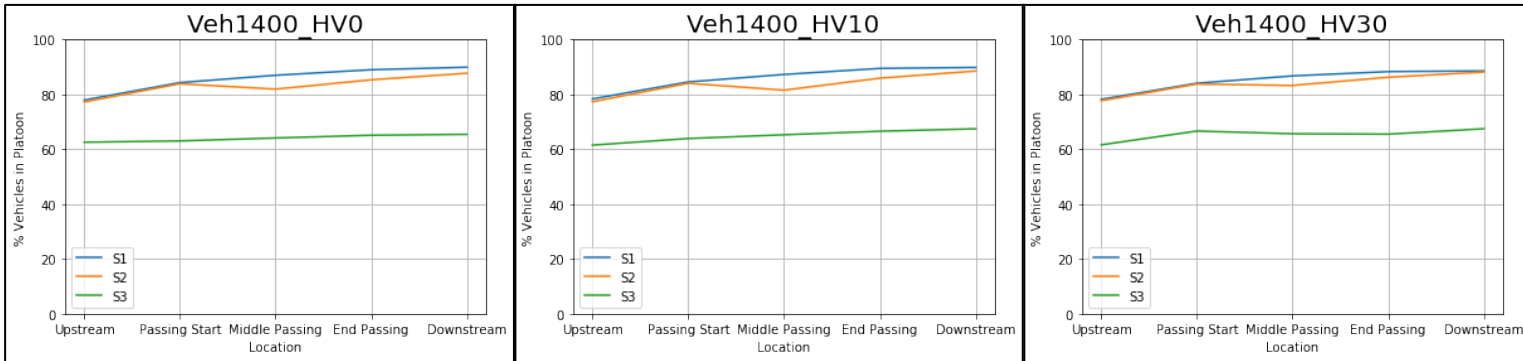


Figure 4-34 Comparison of % Vehicles in Platoon at each Location with 1400 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 1600 vehicle per hour per lane

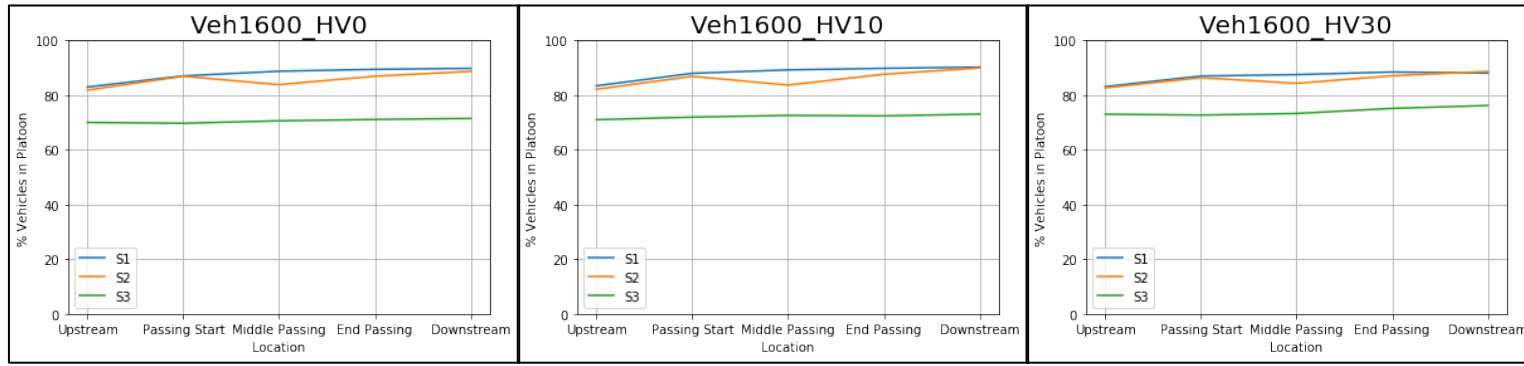


Figure 4-35 Comparison of % Vehicles in Platoon at each Location with 1600 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 1800 vehicle per hour per lane

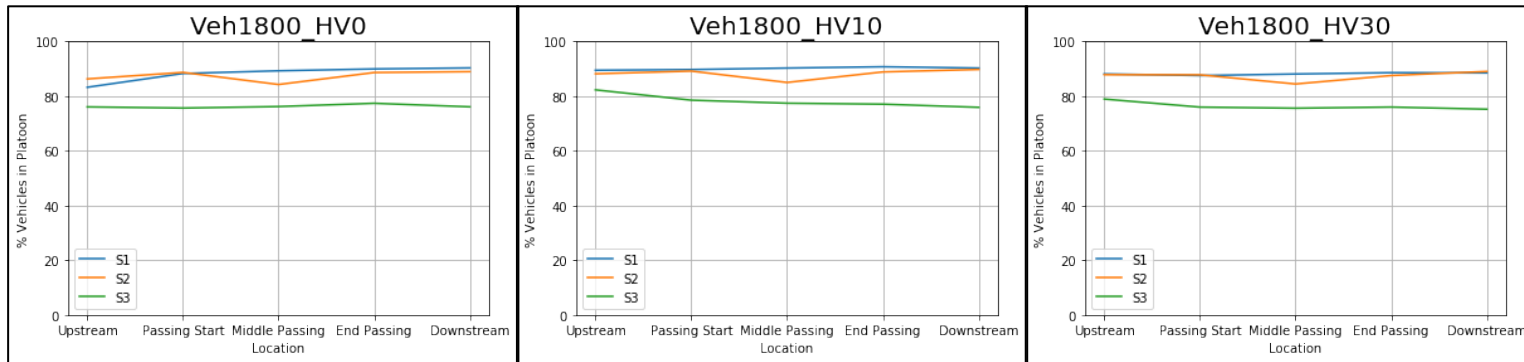


Figure 4-36 Comparison of % Vehicles in Platoon at each Location with 1800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 2000 vehicle per hour per lane

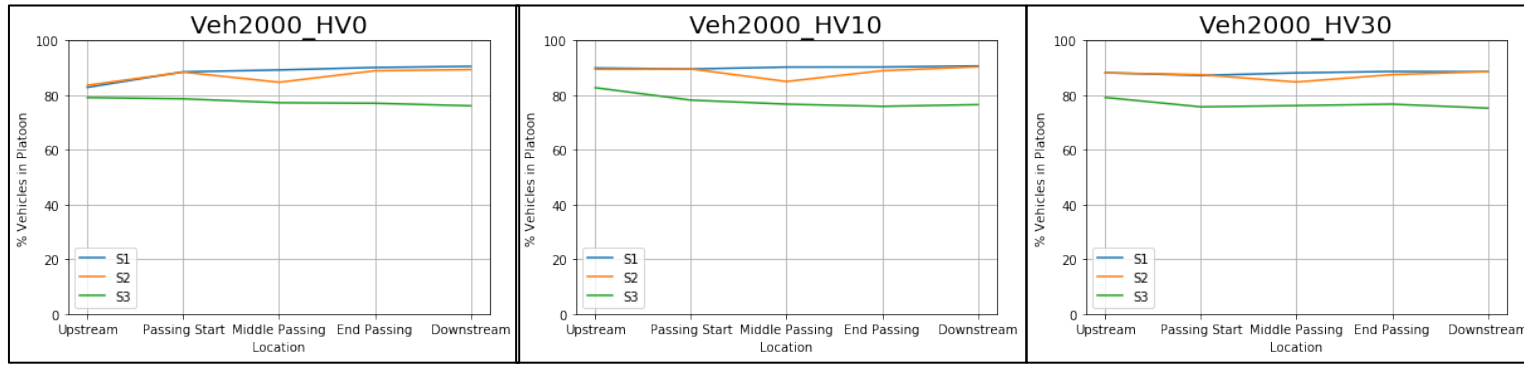


Figure 4-37 Comparison of % Vehicles in Platoon at each Location with 2000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Dedicated Lane

- Scenarios with traffic flow at 800 vehicle per hour per lane

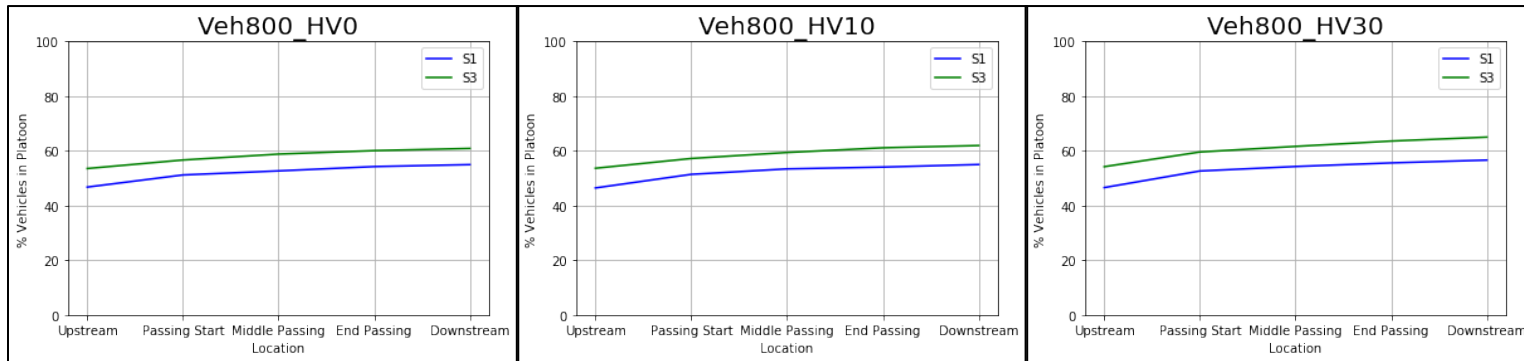


Figure 4-38 Comparison of % Vehicles in Platoon at each Location with 800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lanes

- Scenarios with traffic flow at 1000 vehicle per hour per lane

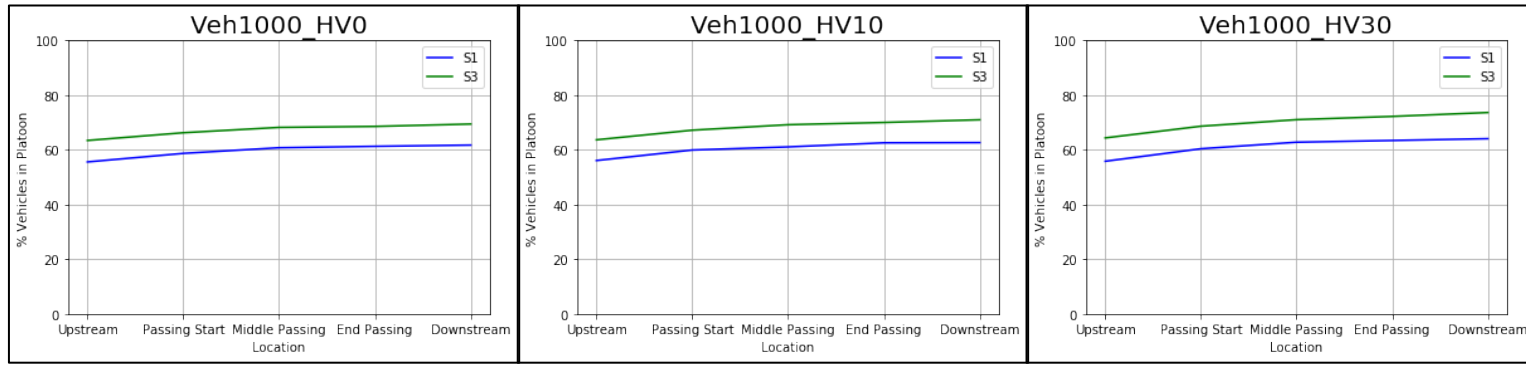


Figure 4-39 Comparison of % Vehicles in Platoon at each Location with 1000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lanes

- Scenarios with traffic flow at 1200 vehicle per hour per lane

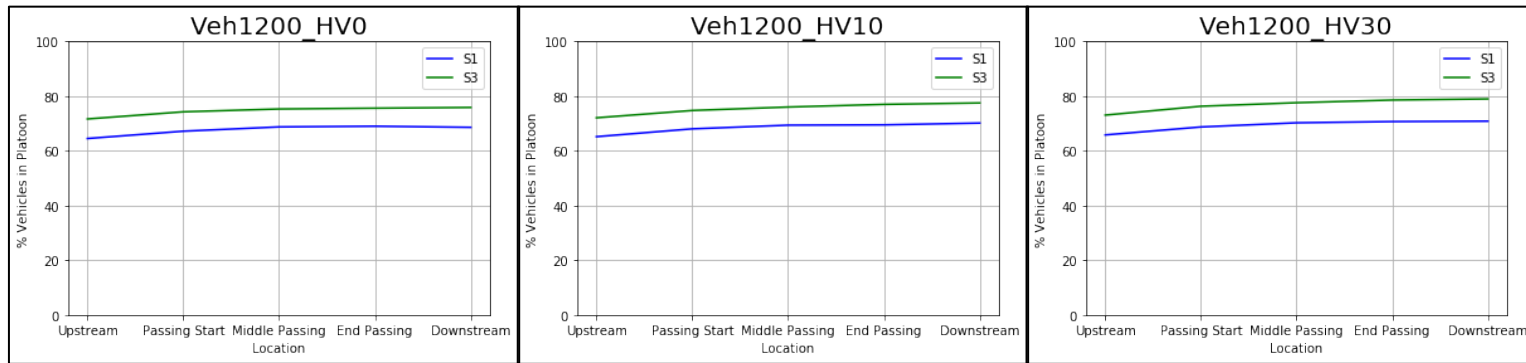


Figure 4-40 Comparison of % Vehicles in Platoon at each Location with 1200 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lanes

- Scenarios with traffic flow at 1400 vehicle per hour per lane

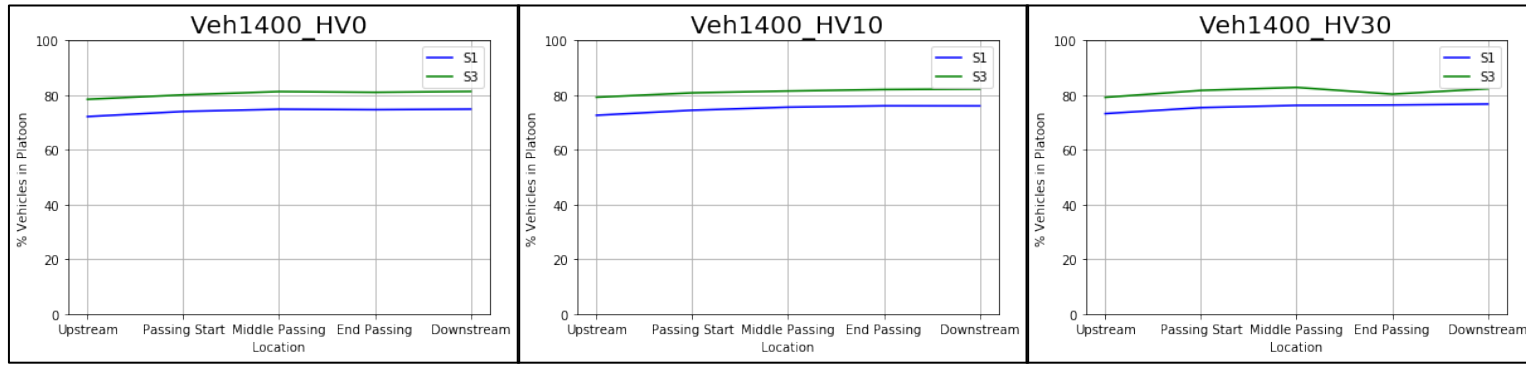


Figure 4-41 Comparison of % Vehicles in Platoon at each Location with 1400 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lanes

- Scenarios with traffic flow at 1600 vehicle per hour per lane

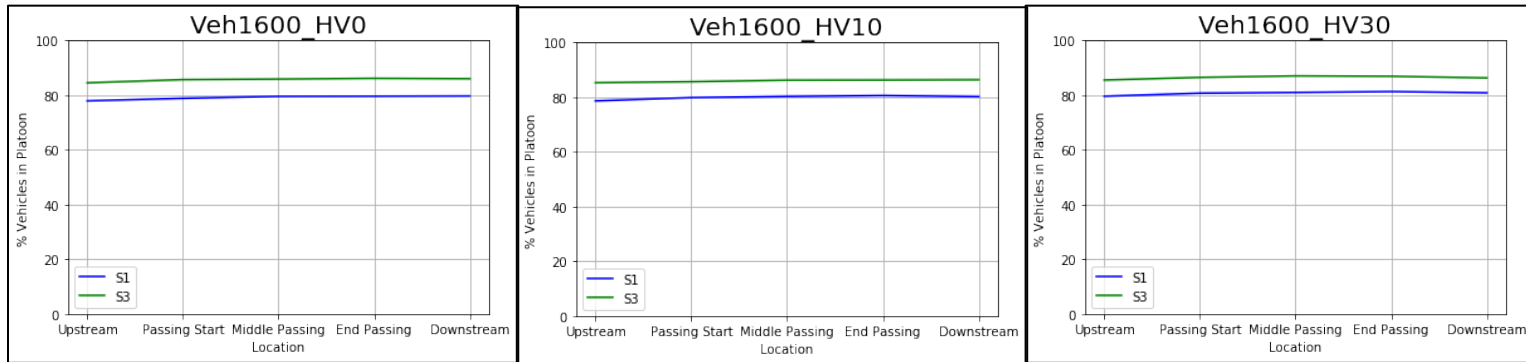


Figure 4-42 Comparison of % Vehicles in Platoon at each Location with 1600 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lanes

- Scenarios with traffic flow at 1800 vehicle per hour per lane

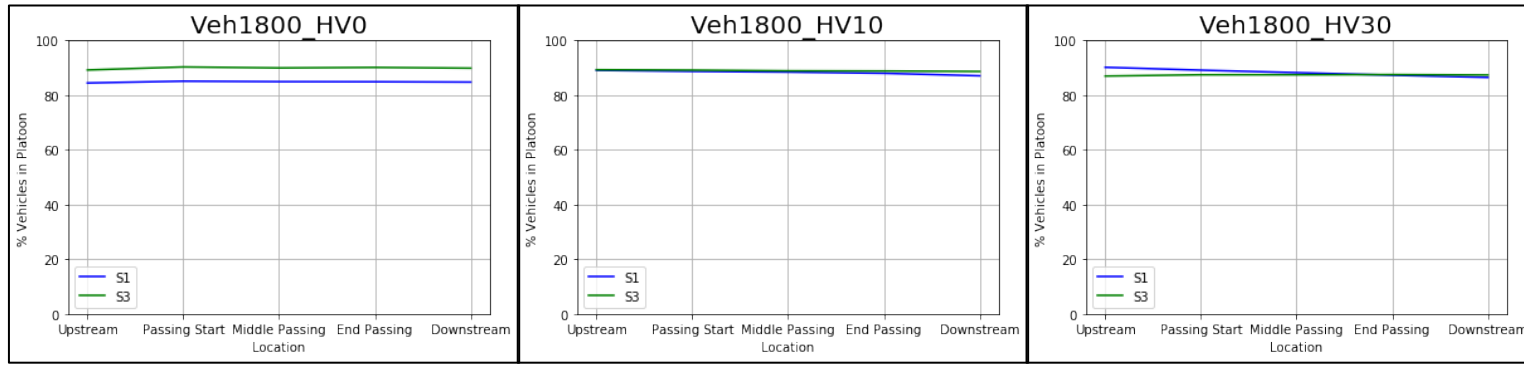


Figure 4-43 Comparison of % Vehicles in Platoon at each Location with 1800 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lanes

- Scenarios with traffic flow at 2000 vehicle per hour per lane

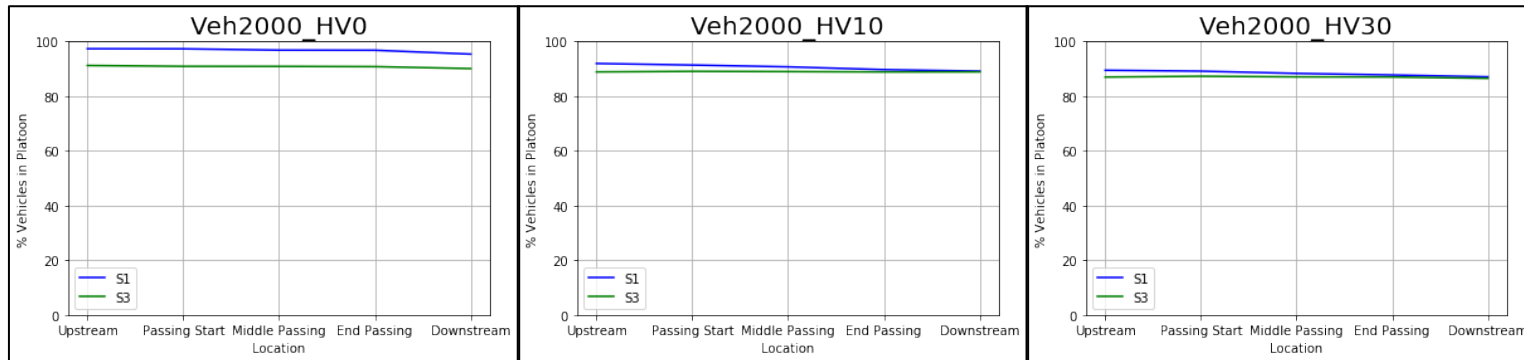


Figure 4-44 Comparison of % Vehicles in Platoon at each Location with 2000 vphpl Traffic Volume at 0%,10%, and 30% HV Penetration Rate on Manual Lanes

4.1.2.3 Travel Time

The graphs show the relationship between flow rate and travel time for autonomous vehicle and manual vehicle for each scenario at different heavy penetration rate. (Figure 4-45 to Figure 4-47). Note that the result from scenario 1 was only used for manual travel time comparison to scenario 3 since the configuration of the manual lane on scenario 1 and 2 are the same.

It was obvious that scenario 3 can provide the shortest travel time for an autonomous vehicle in light to moderate traffic assignment. Scenario 1 and 2 both provide a slightly longer travel time than scenario 3 at all heavy vehicle penetration rate. When traffic assignment is more than 1600 vphpl, scenario 3 provided the longest travel time.

For manual vehicle travel time on the rest of the manual lane, scenario 3 increased travel time on the manual lane. The increasing of heavy vehicle penetration rate also increased manual vehicle travel time.

- Scenarios with 0% Heavy Vehicle

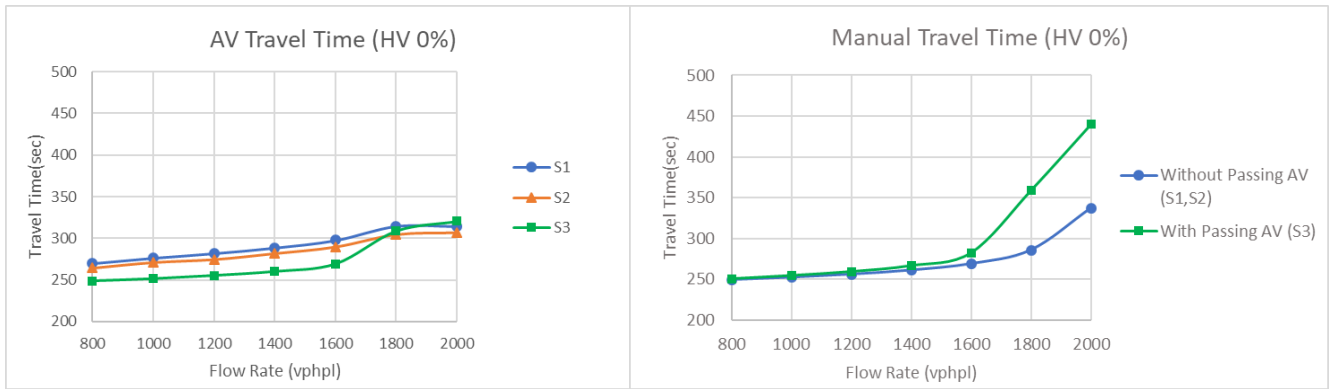


Figure 4-45 The Relationship between Flow Rate and Travel Time at 0% HV Penetration Rate for Autonomous Vehicle and Manual Vehicle

- Scenarios with 10% Heavy Vehicle

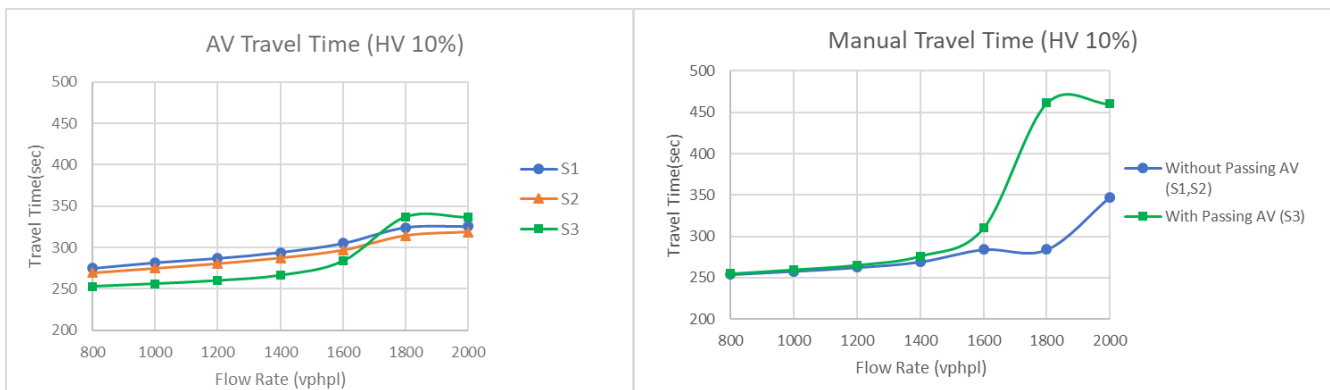


Figure 4-46 The Relationship between Flow Rate and Travel Time at 10% HV Penetration Rate for Autonomous Vehicle and Manual Vehicle

- Scenarios with 30% Heavy Vehicle

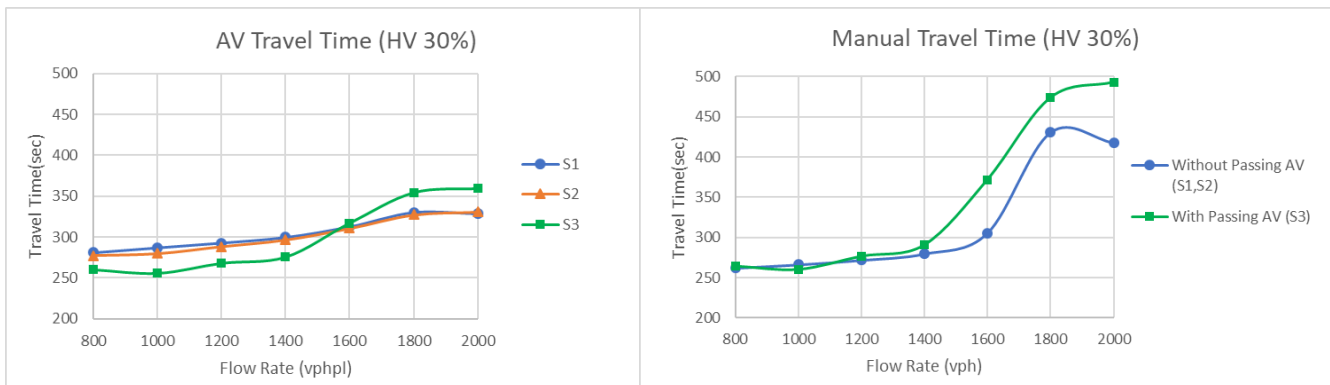


Figure 4-47 The Relationship between Flow Rate and Travel Time at 30% HV Penetration Rate for Autonomous Vehicle and Manual Vehicle

4.1.2.4 Delay

The graphs show the relationship between flow rate delay time for autonomous vehicle and manual vehicle for each scenario at different heavy penetration rate. (Figure 4-48 to Figure 4-50). The result from scenario 1 was only used for comparison to scenario 3 for manual vehicle delay. The result also has the same trend as the vehicle travel time result.

- Scenarios with 0% Heavy Vehicle

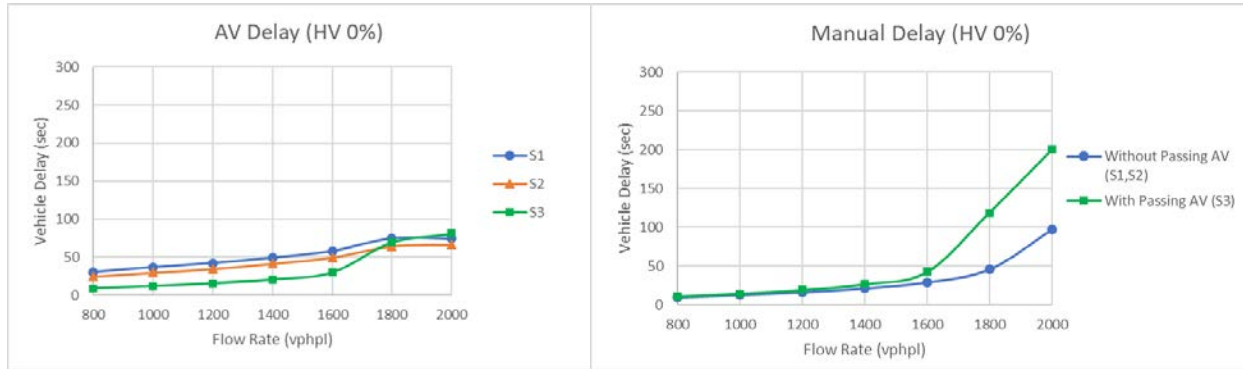


Figure 4-48 The Relationship between Flow Rate and Delay Time at 0% HV Penetration Rate for Autonomous Vehicle and Manual Vehicle

- Scenarios with 10% Heavy Vehicle

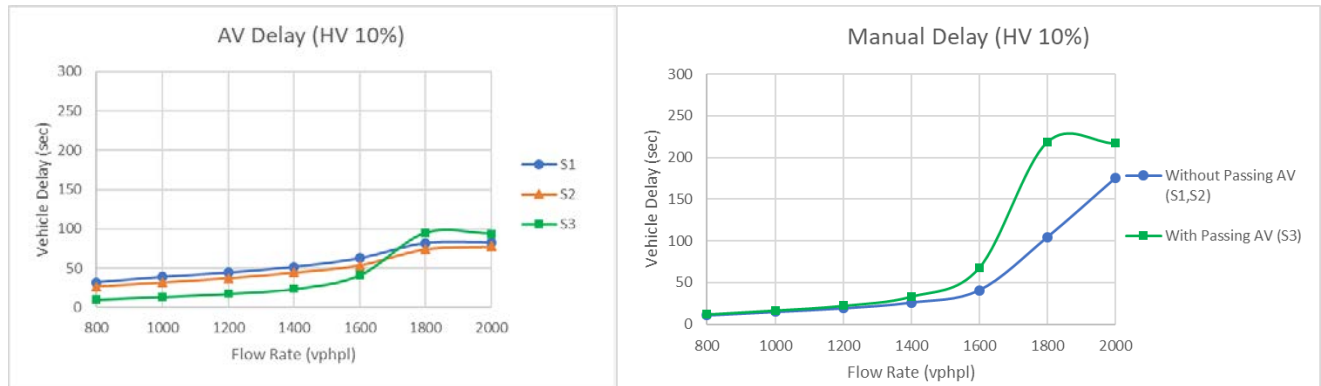


Figure 4-49 The Relationship between Flow Rate and Delay Time at 10% HV Penetration Rate for Autonomous Vehicle and Manual Vehicle

- Scenarios with 30% Heavy Vehicle

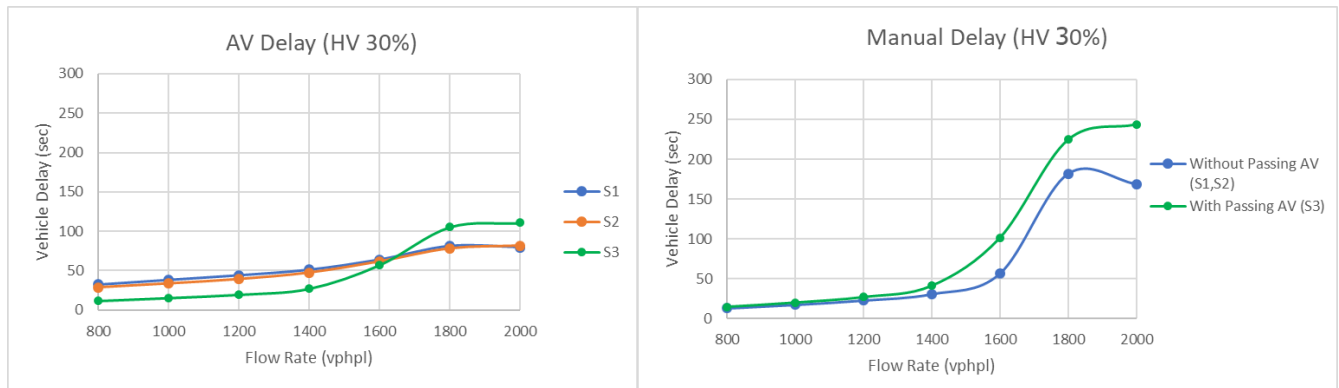


Figure 4-50 The Relationship between Flow Rate and Delay Time at 30% HV Penetration Rate for Autonomous Vehicle and Manual Vehicle

4.1.2.5 Passing Rate

The graphs show the relationship between flow rate and passing rate percentage, comparing between scenario 2 and 3, at different heavy penetration rate (Figure 4-51 to Figure 4-53). Overall, scenario 3 provided more passing opportunities than scenario 2, regardless of traffic assignment volume and heavy penetration rate. When the assigned traffic volume was increasing above 1400 vphpl, the passing rate still constant. This phenomenon also happened in scenario 2 except at 0% of heavy penetration rate, which the passing rate suddenly dropped after the assigned traffic volume was more than 1600 vphpl.

- Scenarios with 0% Heavy Vehicle

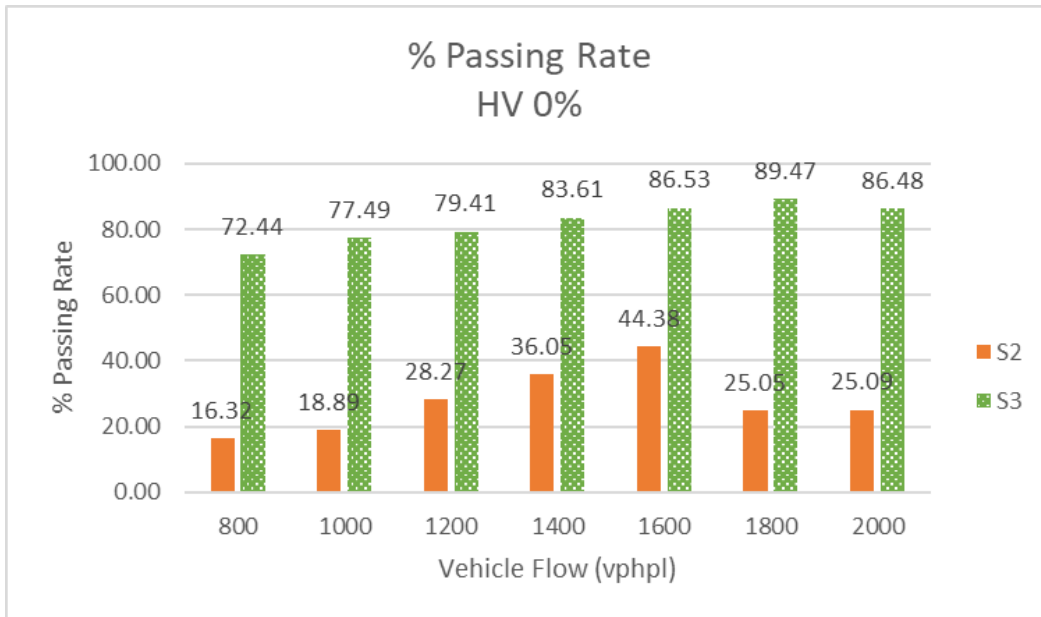


Figure 4-51 The Relationship between Flow Rate and %Passing Rate at 0% HV Penetration Rate on Scenarios 2 and 3

- Scenarios with 10% Heavy Vehicle

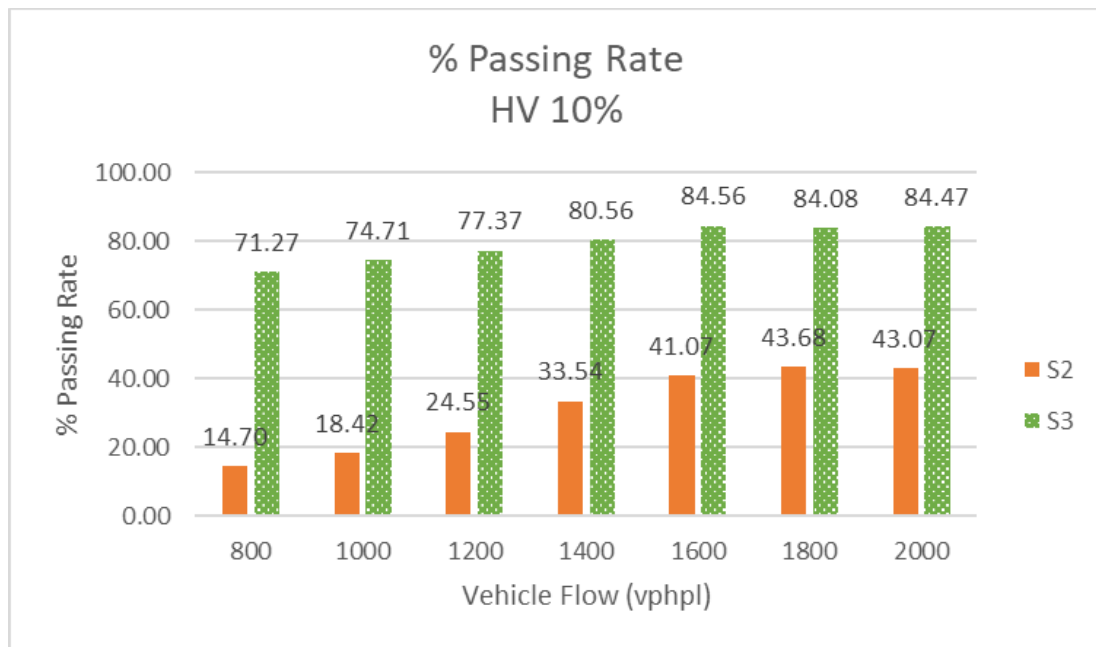


Figure 4-52 The Relationship between Flow Rate and %Passing Rate at 10% HV Penetration Rate on Scenarios 2 and 3

- Scenarios with 30% Heavy Vehicle

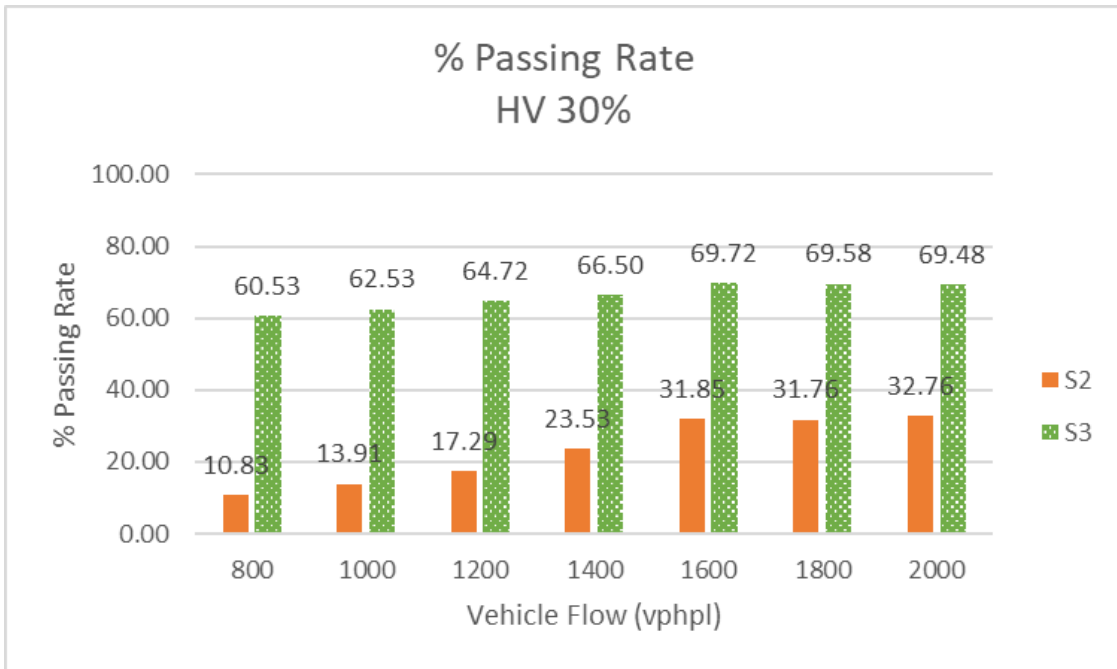


Figure 4-53 The Relationship between Flow Rate and %Passing Rate at 30% HV Penetration Rate on Scenarios 2 and 3

4.1.2.6 Queue Length

The graphs show the relationship between flow rate and queue length at the merging area in scenario 2 and 3, at different heavy penetration rate. (Figure 4-54 to Figure 4-56). The result showed that the higher traffic volume and percentage of heavy vehicle penetration rate were assigned, the higher queue length on scenario 3 would be propagated. In contrast, the queue was rarely propagated at the merging area in scenario 2 regardless of traffic volume and truck volume.

- Scenarios with 0% Heavy Vehicle

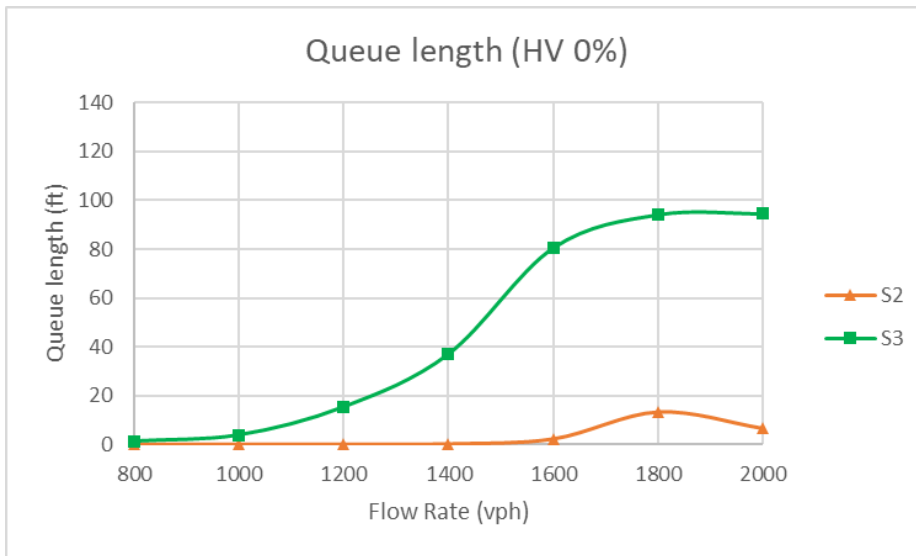


Figure 4-54 The Relationship between Flow Rate and Queue Length at 0% HV Penetration Rate on Scenarios 2 and 3

- Scenarios with 10% Heavy Vehicle

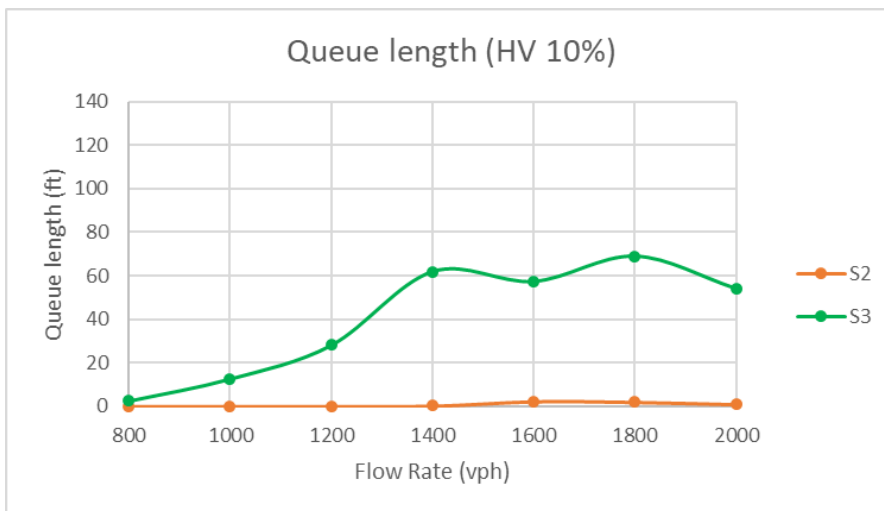


Figure 4-55 The Relationship between Flow Rate and Queue Length at 10% HV Penetration Rate on Scenarios 2 and 3

- Scenarios with 30% Heavy Vehicle

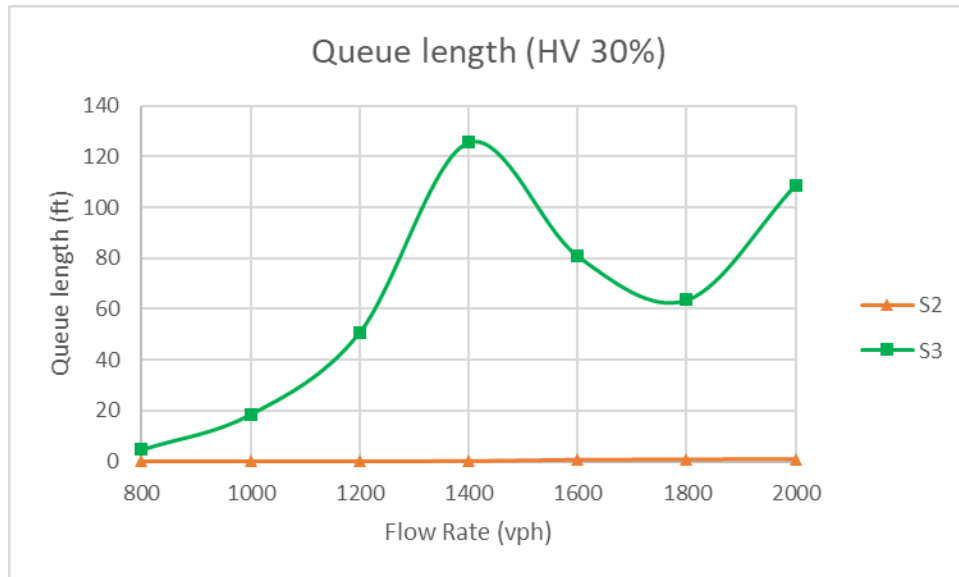


Figure 4-56 The Relationship between Flow Rate and Queue Length at 30% HV Penetration Rate on Scenarios 2 and 3

4.1.3 Safety

The safety attribute consisted of the number of rear-end conflict and lane changing conflict.

4.1.3.1 Rear-end Conflict

The tables show the number of rear-end conflict events in each scenario with different traffic flow and heavy vehicle penetration rate. (Table 4-1 to Table 4-3)

Rear-end Conflict				
0% HV	Flow Rate (vphpl)	Scenario 1	Scenario 2	Scenario 3
	800	46	16	27
	1000	115	46	120
	1200	243	134	494
	1400	460	301	1270
	1600	976	730	3564
	1800	1805	1819	12955
	2000	1817	1555	21930

Table 4-1 Number of Rear-end Conflict of 0% HV rate scenario

Rear-end Conflict				
% 10 HV	Flow Rate (vphpl)	Scenario 1	Scenario 2	Scenario 3
	800	39	9	69
	1000	81	29	262
	1200	160	96	662
	1400	282	205	1826
	1600	653	488	4692
	1800	1082	1136	19303
	2000	1092	948	17546

Table 4-2 Number of Rear-end Conflict of 10% HV rate scenario

Rear-end Conflict				
% 30 HV	Flow Rate (vphpl)	Scenario 1	Scenario 2	Scenario 3
	800	12	9	91
	1000	30	29	381
	1200	78	70	1025
	1400	182	135	2954
	1600	433	407	10565
	1800	544	594	16060
	2000	481	586	18357

Table 4-3 Number of Rear-end Conflict of 30% HV rate scenario

4.1.3.2 Lane Changing Conflict

The tables show the number of lanes changing conflict events in each scenario with different traffic flow and heavy vehicle penetration rate (Table 4-4 to Table 4-6). Note that scenario 1 did not have a lane changing conflict event for the autonomous vehicle since no passing maneuver was allowed in this scenario.

Lane Changing Conflict			
% 0 HV	Flow Rate (vphpl)	Scenario 2	Scenario 3
	800	4	18
	1000	4	44
	1200	12	108
	1400	25	247
	1600	31	601
	1800	44	1501
	2000	44	1867

Table 4-4 Number of Lane Changing Conflict of 0% HV rate scenario

Lane Changing Conflict			
% 10 HV	Flow Rate (vphpl)	Scenario 2	Scenario 3
	800	2	25
	1000	4	64
	1200	13	141
	1400	21	330
	1600	28	826
	1800	36	2084
	2000	32	1982

Table 4-5 Number of Lane Changing Conflict of 10% HV rate scenario

Lane Changing Conflict			
% 30 HV	Flow Rate (vphpl)	Scenario 2	Scenario 3
	800	0	20
	1000	2	68
	1200	4	170
	1400	12	349
	1600	18	1211
	1800	24	1678
	2000	16	1726

Table 4-6 Number of Lane Changing Conflict of 30% HV rate scenario

4.2 Analysis

The analysis of this study is divided into the main three parts based on the objectives of this study. Firstly, the capacity analysis evaluates the capacity improvement of scenario 2 and 3 on both dedicated lane and manual lanes. Next, traffic analysis evaluates the speed improvement, the percentage of platoon reduction, and the percentage of travel time reduction. The unsuccessful passing maneuver result also analyzes here. Lastly, the safety analysis summarizes the result from SSAM.

4.2.1 Capacity Analysis

The first objective of this study is to compare the capacity of the dedicated lane in difference passing configuration. The manual lanes capacity is also observed since the third scenario allowed the autonomous vehicle to use those lanes as a passing lane.

The figures show the percentage of flow rate that has changed from scenario 1, which is the base case with no passing opportunity on a dedicated lane, with difference truck penetration rate for autonomous vehicles and manual vehicles (Figure 4-57 to Figure 4-62). The flow rate from all of 5 locations was averaged and used for comparison. A positive percentage means scenario capacity was more than the base scenario, while a negative percentage means scenario provided less capacity than the base scenario.

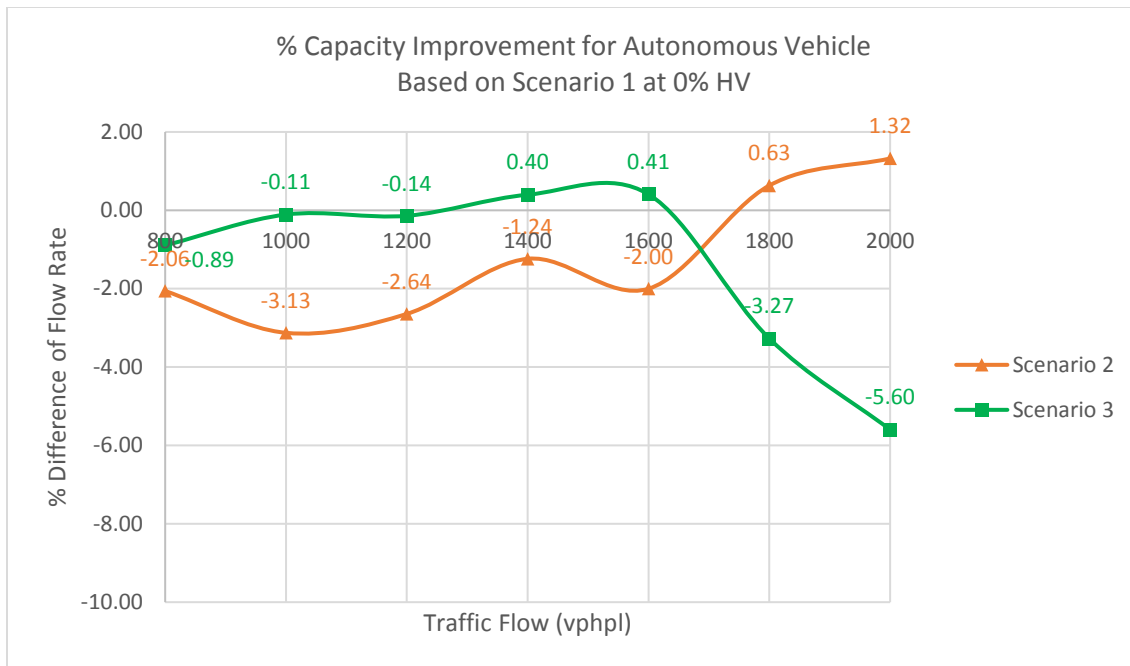


Figure 4-57 Capacity Improvement for Autonomous Vehicle (Based on Scenario 1) at 0% HV

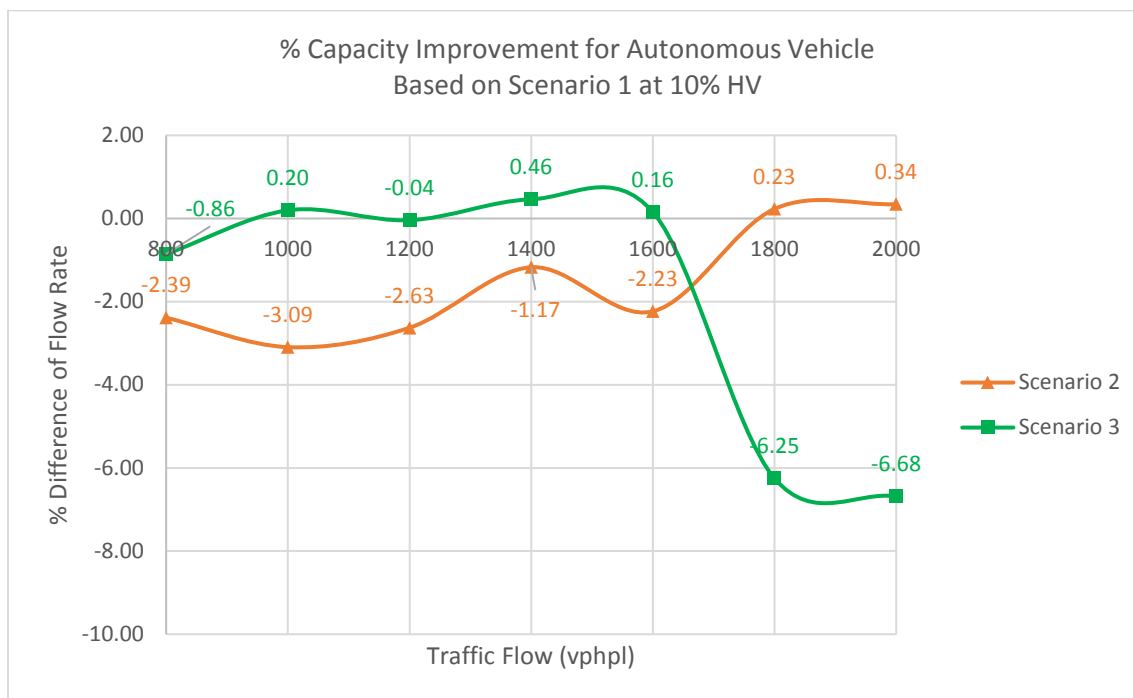


Figure 4-58 Capacity Improvement for Autonomous Vehicle (Based on Scenario 1) at 10% HV

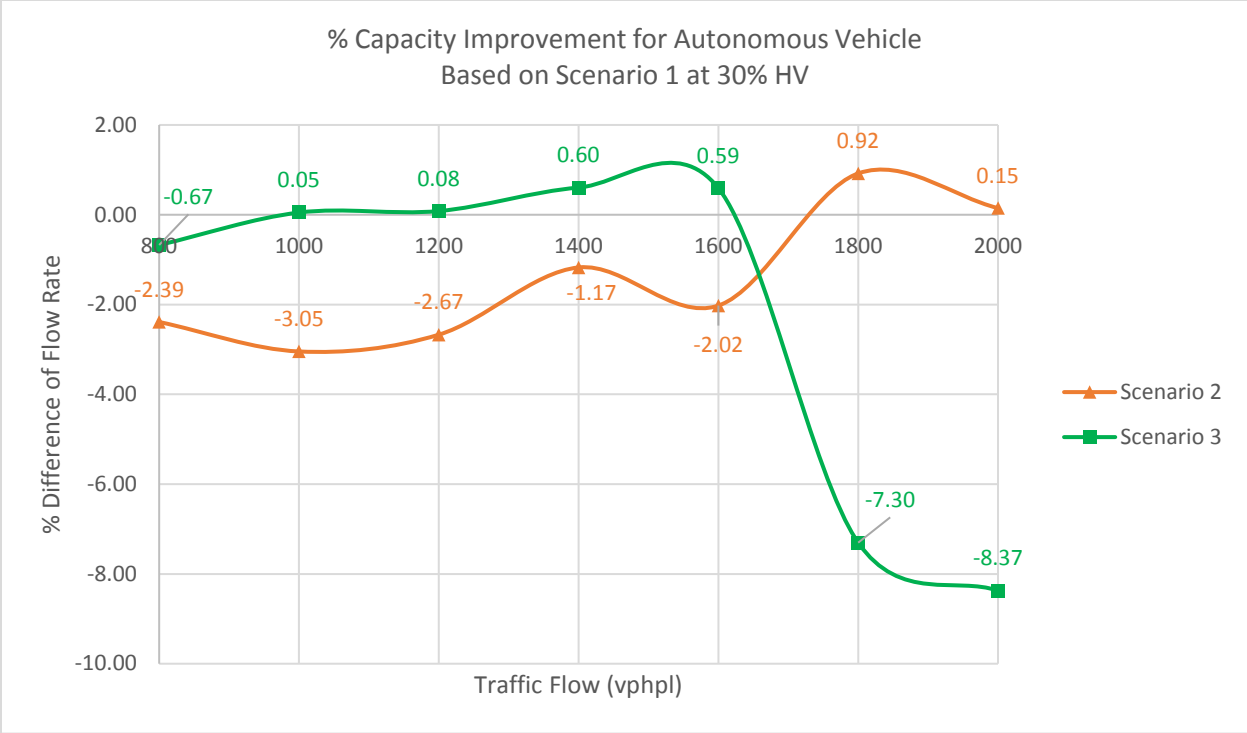


Figure 4-59 Capacity Improvement for Autonomous Vehicle (Based on Scenario 1) at 30% HV

It was proven that the capacity on the dedicated lane does not only depend on passing opportunity but also the flow rate that has assigned to the network. The third scenario was the best option for an autonomous vehicle when it comes to low flow rate, however, the second scenario provides better capacity when the flow rate was exceeding 1600 vphpl.

The heavy vehicle penetration rate affected the capacity of all scenarios when the assigned flow was at or above 1800 vphpl. When the traffic volume was low, vehicles can choose their speed at the desired speed. However, when there were more heavy vehicles in the traffic, those vehicles have greater interaction with surrounded vehicles such as larger space between a passenger car and heavy vehicle. Passenger cars, therefore, has a smaller opportunity to pass slower moving vehicle and need to leave larger space between them and heavy vehicles. As a result, the capacity of the network noticeably decreases when a heavy vehicle penetration rate was increased at high traffic flow.

For manual vehicles, scenario 3 also provided better capacity when the flow rate was between 800 to 1600 vphpl. The capacity of the manual vehicle dropped dramatically when the flow was over 1800 vphpl. The heavy penetration rate also has an effect on the capacity of all scenario when the assigned flow was at or above 1800 vphpl as same as analyzation for autonomous vehicles.

The value used for capacity analysis can be found in the table at the end of this section (Table 4-7).

4.2.2.1 Capacity Analysis for Autonomous Vehicle in Scenario 2

When low to moderate flow rate was assigned in scenario 2, the capacity of the network was lower than the capacity in the based case. With a limited and short length of passing lane, vehicles on this scenario performed less passing maneuver than in scenario 3 (Figure 4-51 to Figure 4-53). The capacity was lower than the based case due to lane changing effect that occurred on scenario 2. Lane changing maneuver contributed to traffic heterogeneity on a dedicated lane. Unlike vehicles in the base case, lane changing maneuver in scenario 2 led to uncertainty of acceleration and deceleration rate. Therefore, the capacity of this scenario was notably lower than the based case.

When the flow rate increased to 1800 vphpl and above, the capacity on scenario 2 was better than the other scenarios. Providing a passing opportunity can alleviate the effect of platooning in the based case. In sum, a passing opportunity may cause negative effect when traffic volume was too low, and the positive result would occur if the suitable traffic assignment was implemented in the network.

4.2.2.2 Capacity Analysis for Autonomous Vehicle in Scenario 3

At a flow rate of 800 vphpl, the based case provided slightly more capacity than scenario 3 since the vehicles on the base case has more homogeneity than scenario 3. Vehicles on the base case can follow the leader vehicle in less headway with less space, hence, more vehicles can pass through the network. Passing maneuver has changed accelerate and decelerate behavior of others surrounded the vehicle, therefore, vehicles on scenario 3 have loosed their homogeneity. Moreover, it was found that the capacity in both scenario 1 and 3 are higher than the assigned traffic flow. The high capacity could occur from the effect of implementing autonomous vehicle in the traffic as mentioned in [chapter 2](#).

When the flow rate increase to 1000 and 1200 vphpl, lane changing maneuver did not cause an effect on the traffic stream since vehicles still have a large space under unsaturated condition. Therefore, the result from scenario 3 was close to the base case.

When the flow rate increase to 1400 and 1600 vphpl, the capacity from scenario 3 is slightly higher than the base case. This situation reveals the effect of a platoon in the base case which has no passing opportunity. In contrast, scenario 3 provided more lane change and passing opportunity. It can be concluded in the same way as the conclusion from the previous study in [chapter 2](#) that a scenario with passing opportunity can provide more capacity than scenario without passing opportunity when the density of the network is lower than the critical density. Besides, these scenarios still provide the capacity higher than assigned traffic flow.

Even though the scenario 3 provided higher passing opportunity and higher passing rate, this configuration can cause drawback to the network capacity when the flow rate is high. At this stage, vehicles tended to use the manual vehicle lane as a travel lane, not for passing purpose. The vehicle passing rate for scenario 3 was almost the same when traffic flow was at or above 1600 vphpl (Figure 4-51 to Figure 4-53) which means the lane changing maneuver that occurred in scenario 3 was also not different when the flow rate was increasing. Lane changing maneuver of

autonomous vehicles typically require longer gap, therefore, the capacity of the network was dramatically decreasing when the flow rate is oversaturated because the network is not able to provide any gap and space for lane changing. Since vehicles on the manual lane in this scenario must interact with manual vehicles, which has unpredictable behavior, this may decrease efficiency of the lane changing maneuver of the autonomous vehicle. The autonomous vehicle also has a feature that reduces the rate of acceleration and deceleration to maximize the comfort of the passenger. This feature could be another reason that made capacity for scenario 3 even worse when there was high traffic volume. Lastly, scenario 1 and 3 neither provided capacity higher than the assigned volume at this stage. One possible reason was that there was congestion occurred. It can be concluded that improper lane changing does not only have negative effect on traffic flow but also leads to congestion and accidents.

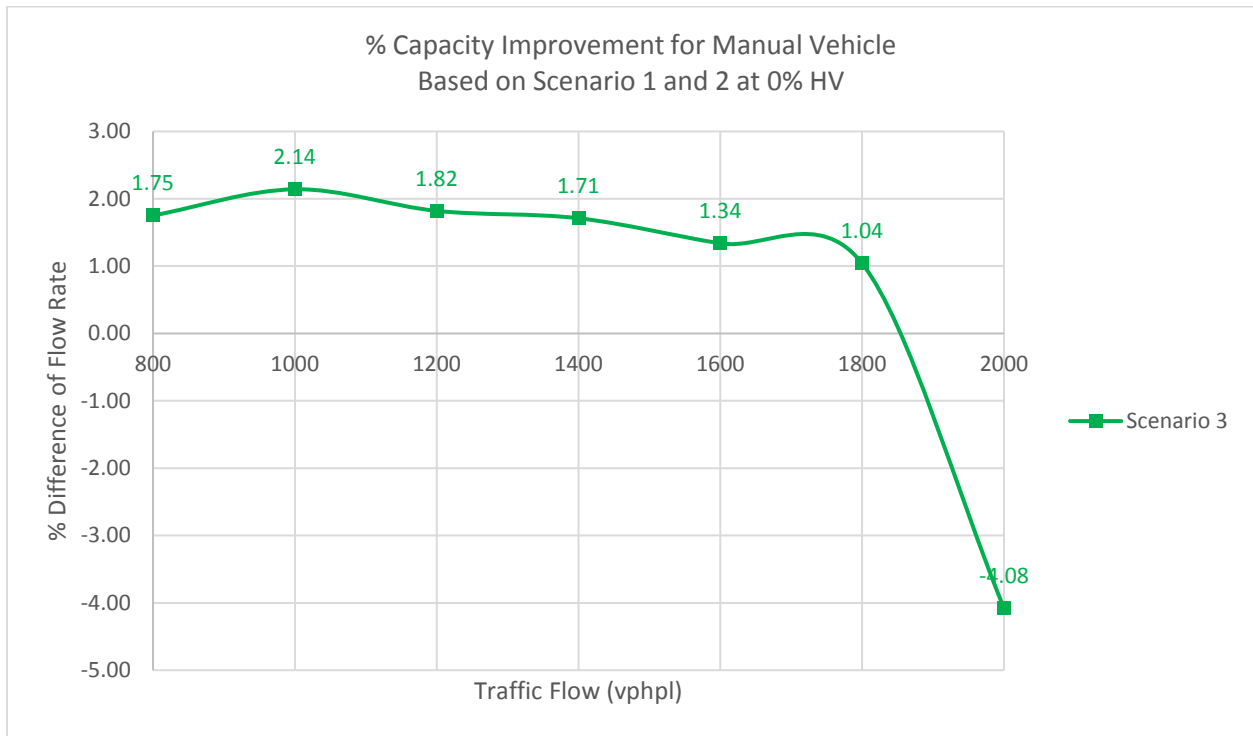


Figure 4-60 Capacity Improvement for Manual Vehicle (Based on Scenario 1 and 2) at 0% HV

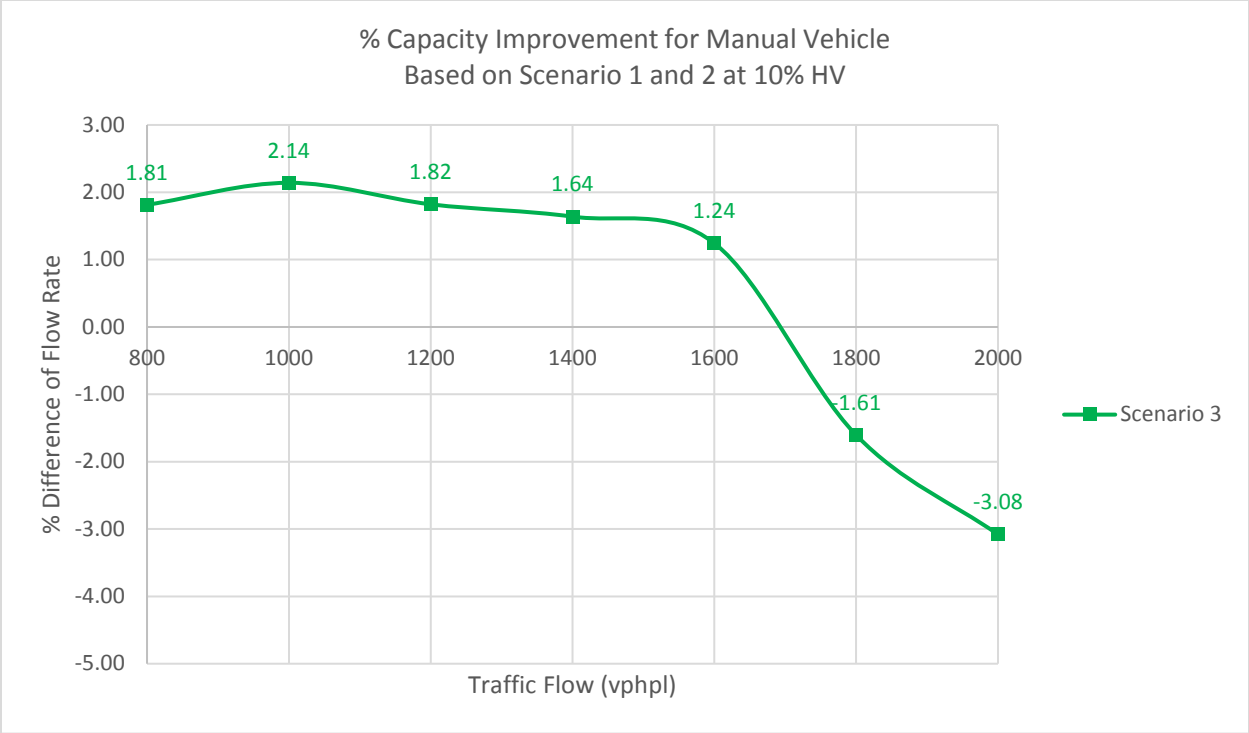


Figure 4-61 Capacity Improvement for Manual Vehicle (Based on Scenario 1 and 2) at 10% HV

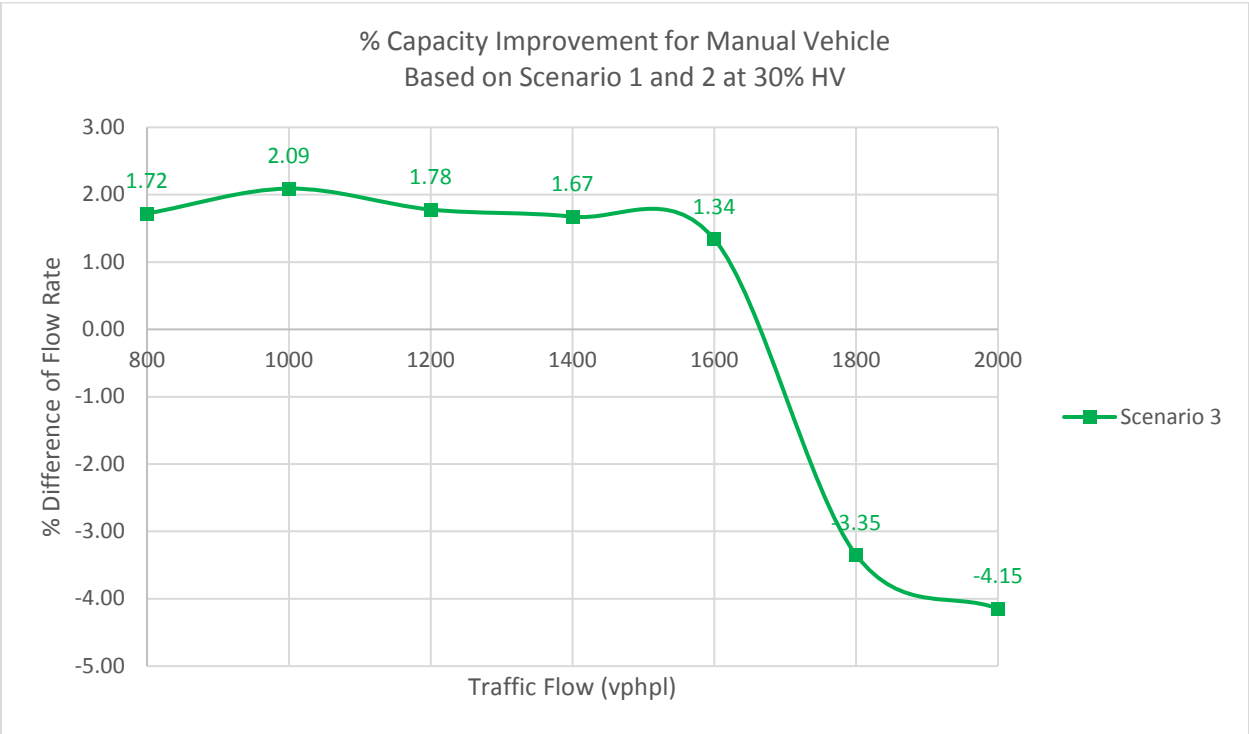


Figure 4-62 Capacity Improvement for Manual Vehicle (based on Scenario 1 and 2) at 30% HV

4.2.2.3 Capacity Analysis for Manual Vehicles in Scenario 3

The result showed that at a flow rate between 800 to 1600 vphpl, the capacity of scenario 3 was higher than the base case. The possible explanation is that manual vehicles trend to driving close to a platoon of an autonomous vehicle with short time headway, as mentioned in [chapter 2](#). This behavior can reduce manual vehicle's time headway and result in higher capacity.

When the flow exceeded 1600 vphpl, the capacity of scenario 3 trends to decrease. It can be concluded that there was congestion occurred in the network. The mixed traffic of the autonomous vehicle and the manual vehicle can also result in negative effect. As the passing rate was almost the same for the scenario with 1600 to 2000 vphpl, the autonomous vehicle required a larger space to perform lane-changing maneuver. Therefore, as the space decrease, capacity trend to decrease as well.

Autonomous Vehicle							Manual Vehicle				
%HV	Flow Rate (vphpl)	Scenario 1	Scenario 2		Scenario 3		%HV	Flow Rate (vphpl)	Scenario 1	Scenario 3	
		Capacity (vphpl)	Capacity (vphpl)	% Different	Capacity (vphpl)	% Different			Capacity (vphpl)	Capacity (vphpl)	% Different
0%	800	817	800	-2.06	809	-0.89	0%	800	799	812	1.61
	1000	1020	989	-3.13	1019	-0.11		1000	993	1013	2.01
	1200	1218	1186	-2.64	1216	-0.14		1200	1195	1214	1.61
	1400	1407	1390	-1.24	1413	0.40		1400	1389	1411	1.60
	1600	1609	1577	-2.00	1616	0.41		1600	1589	1609	1.25
	1800	1755	1766	0.63	1697	-3.27		1800	1780	1798	1.03
	2000	1753	1776	1.32	1655	-5.60		2000	1912	1833	-4.09
10%	800	817	800	-2.05	809	-0.88	10%	800	799	813	1.68
	1000	1021	988	-3.25	1019	-0.16		1000	993	1014	2.07
	1200	1218	1186	-2.61	1216	-0.13		1200	1194	1214	1.68
	1400	1408	1390	-1.25	1413	0.36		1400	1389	1411	1.59
	1600	1609	1577	-2.00	1615	0.34		1600	1589	1608	1.17
	1800	1732	1742	0.59	1626	-6.12		1800	1774	1745	-1.64
	2000	1741	1749	0.41	1624	-6.72		2000	1801	1746	-3.04
30%	800	816	800	-2.00	810	-0.78	30%	800	799	812	1.64
	1000	1020	988	-3.17	1019	-0.10		1000	993	1014	2.04
	1200	1218	1186	-2.61	1216	-0.10		1200	1194	1214	1.67
	1400	1408	1389	-1.29	1413	0.40		1400	1389	1411	1.60
	1600	1606	1576	-1.89	1613	0.42		1600	1587	1603	1.00
	1800	1682	1700	1.03	1557	-7.45		1800	1725	1665	-3.49
	2000	1690	1693	0.15	192	-8.44		2000	1731	1660	-4.09

Table 4-7 Data for Capacity Analysis

4.2.2 Traffic Operation Analysis

The second objective of this study is to compare the traffic operation on a dedicated lane in difference passing configuration. The traffic operation on manual lanes is also observed since some passing configuration allowed an autonomous vehicle to use those lanes as a passing lane.

In this study, average speed throughout the network, platoon reduction percentage, and travel time reduction percentage were used to defined traffic operation. The result from scenario 2 and 3 are compared to scenario 1 which defined as the base case.

4.2.2.1 Speed Analysis

The figures show the percentage of speed that has changed from the base case with difference truck penetration rate for autonomous vehicles and manual vehicles (Figure 4-63 to Figure 4-65). The speed of vehicles that passed detectors at five different locations was averaged and used for comparison. A positive percentage means that scenario can provide higher speed than the base scenario, while negative percentage means that scenario provided lower speed than the base scenario.

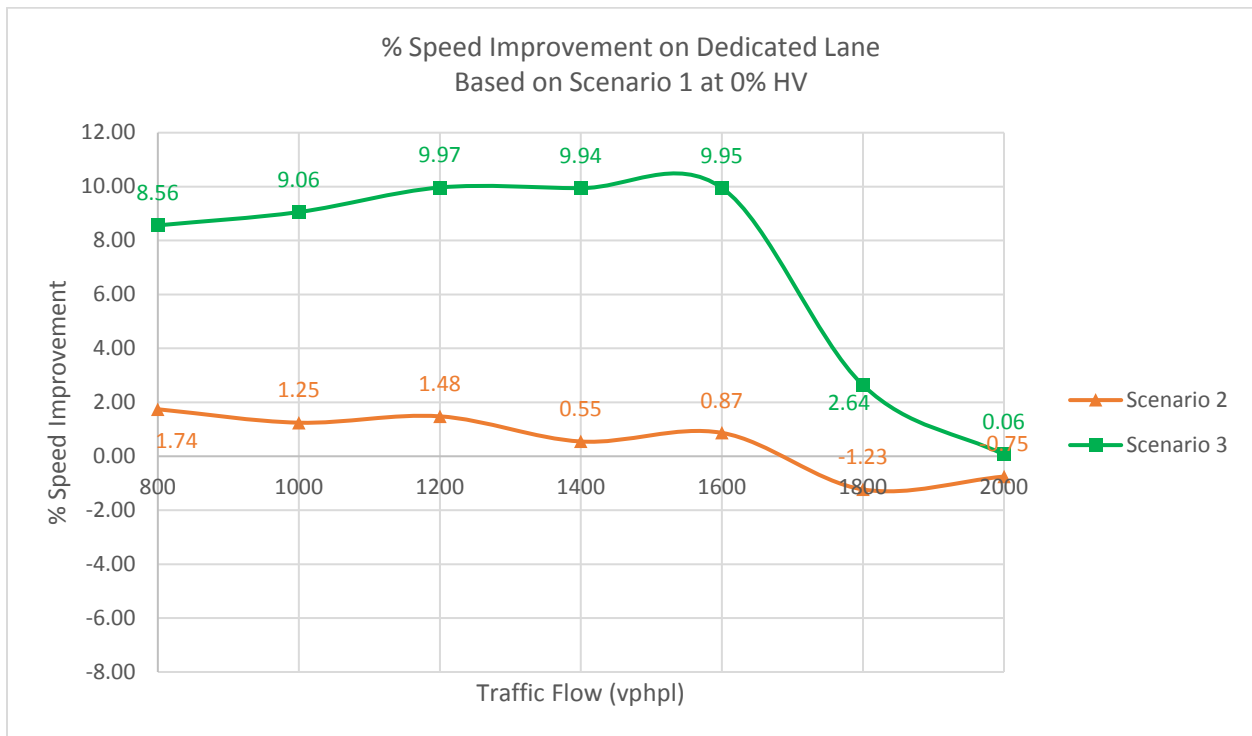


Figure 4-63 Speed Improvement on Dedicated Lane (Based on Scenario 1) at 0% HV

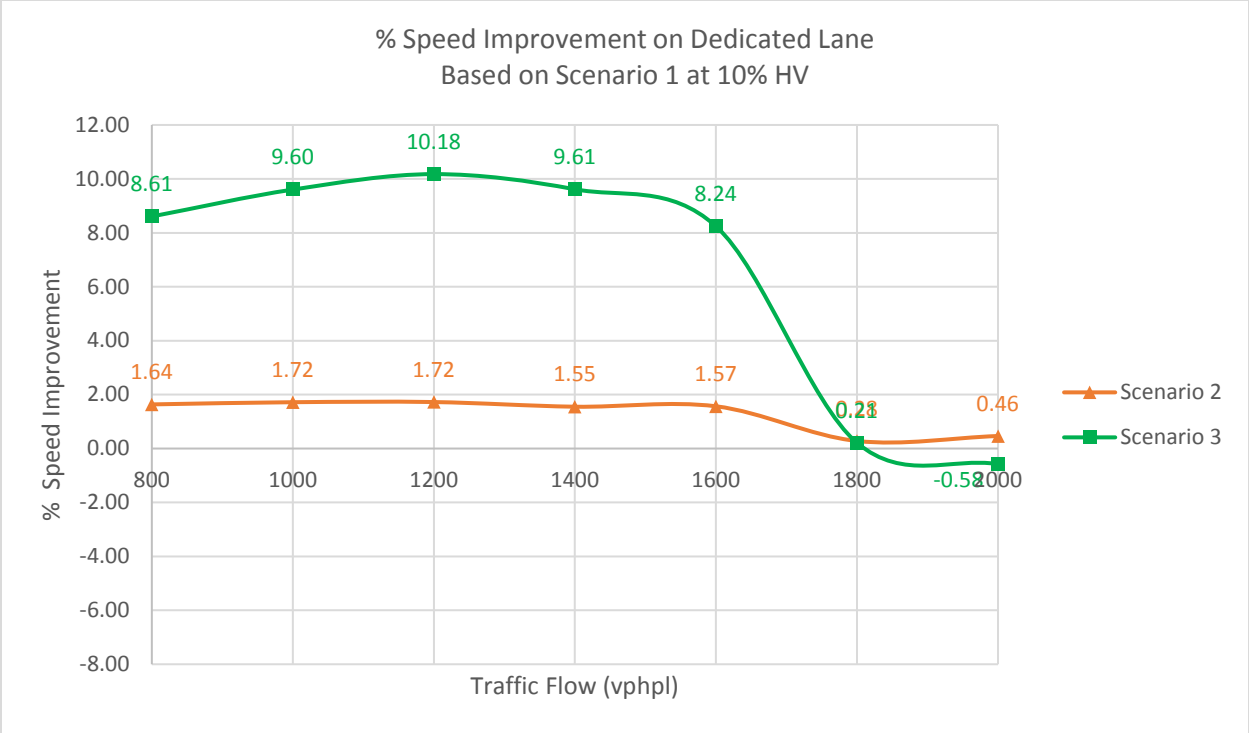


Figure 4-64 Speed Improvement on Dedicated Lane (Based on Scenario 1) at 10% HV

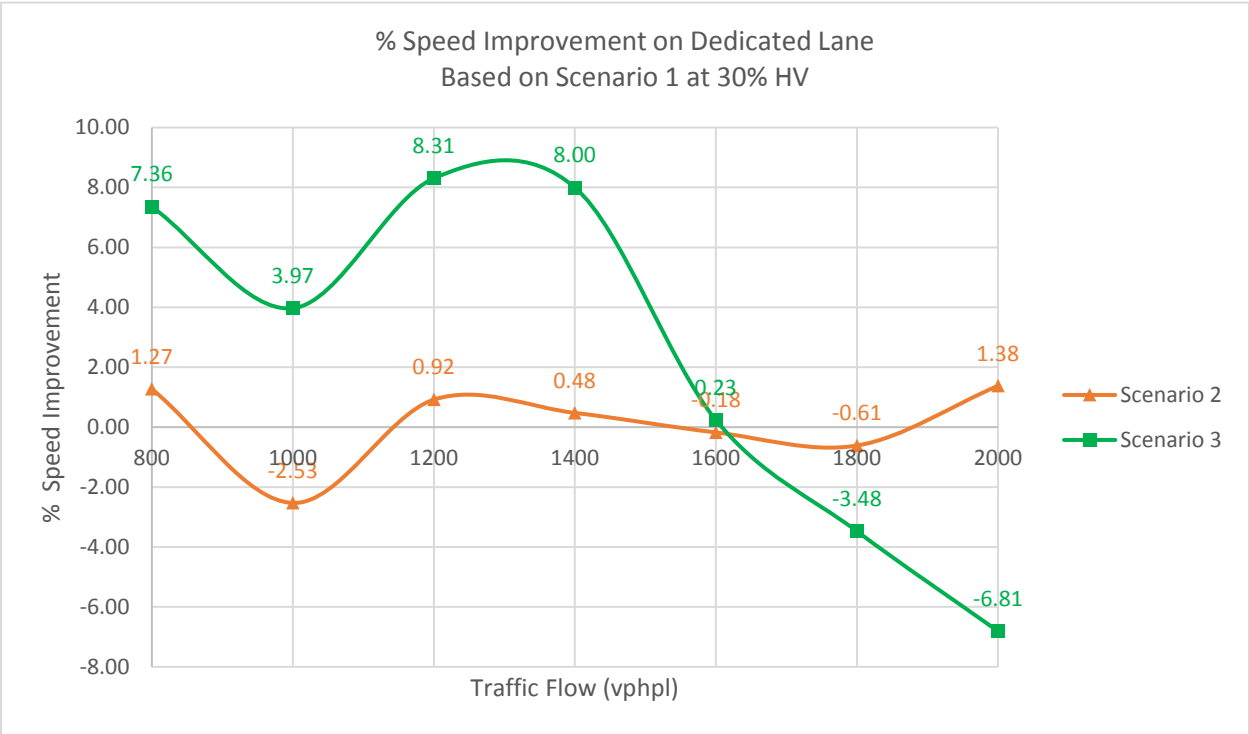


Figure 4-65 Speed Improvement on Dedicated Lane (Based on Scenario 1) at 30% HV

It was proven that scenario 3 can provide the highest speed when traffic flow was below 1800 vphpl. When the traffic flow was at or above 1800 vphpl, the speed on scenario 3 was depended on the heavy penetration rate. With high heavy vehicle penetration rate, the speed on scenario 3 dramatically decreased.

Scenario 2 provided a slightly higher speed than the base case for almost all of the traffic flow rate and heavy vehicle penetration rate. It was also highlighted that vehicles on scenario 2 also performed the highest speed at higher flow. The speed of vehicles on scenario 2 and the base case was almost the same throughout the network except at the middle location of the passing lane, shown in Figure 4-17 to Figure 4-23. It can be concluded that by installing the passing lane, the overall speed was increasing.

The value used for speed analysis can be found in the table at the end of this section (Table 4-8).

A) Speed on Dedicated Lane for Scenario 2

As mentioned above, the speed in scenario 2 was mostly slightly higher than the base case. When there was no truck and traffic flow was 1800 vphpl and above, as shown in Figure 4-51, the autonomous vehicle has difficulty in finding a suitable gap for passing, hence, the passing rate decreased. When more vehicles were not able to pass the slow vehicle, the travel speed decreased, as shown in Figure 4-63. As heavy vehicle penetration rate increased, vehicles on scenario 2 tend to have a slightly higher speed than the base case. In sum, by providing passing opportunity, vehicles on dedicated lane can have higher speed.

B) Speed on Dedicated Lane for Scenario 3

As mentioned earlier, scenario 3 only provide the highest speed when traffic flow was low to moderate. At this stage, vehicles can pass slower vehicles almost throughout the network length. Longer passing section that available in scenario 3 provides a higher passing rate when comparing to scenario 2, shown in Figure 4-51 to Figure 4-53. However, when the flow rate increase to 1600 vphpl, the travel speed drop especially at heavy penetration rate of 30%. The dropped travel speed was the result of congestion that occurred when the flow rate was high.

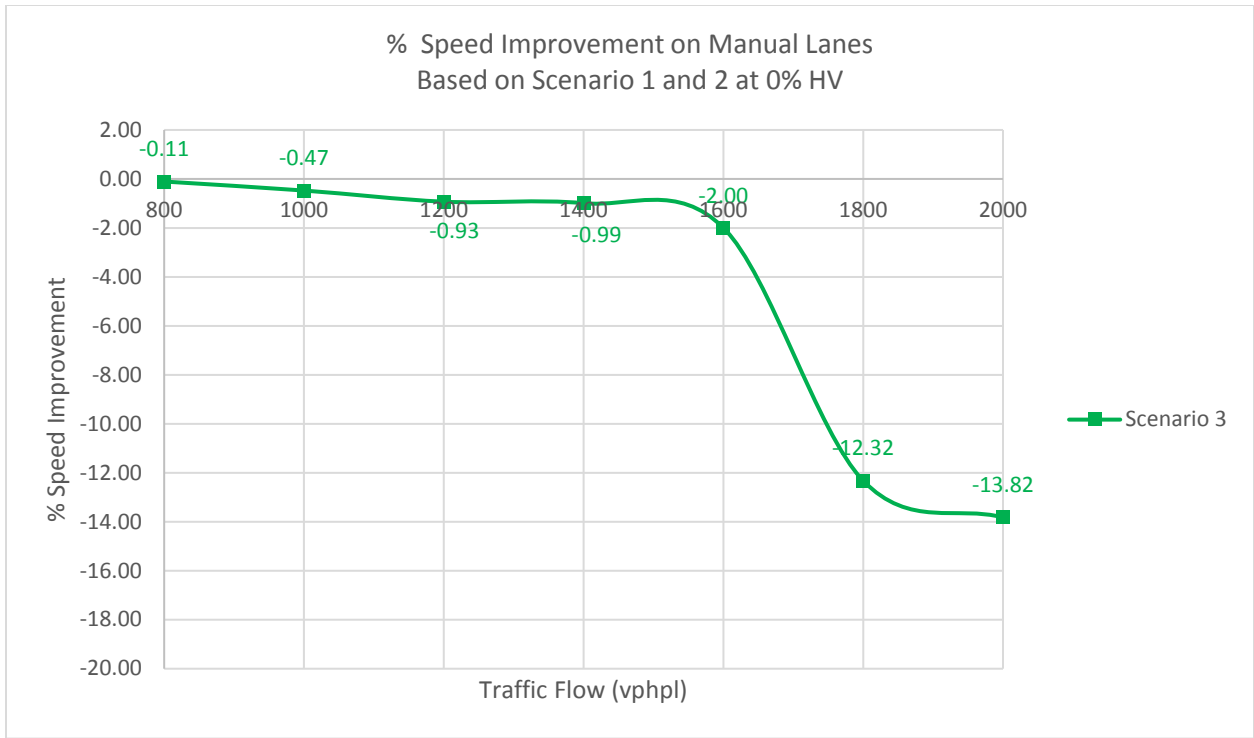


Figure 4-66 Speed Improvement on Manual Lanes (Base on Scenario 1 and 2) at 0% HV

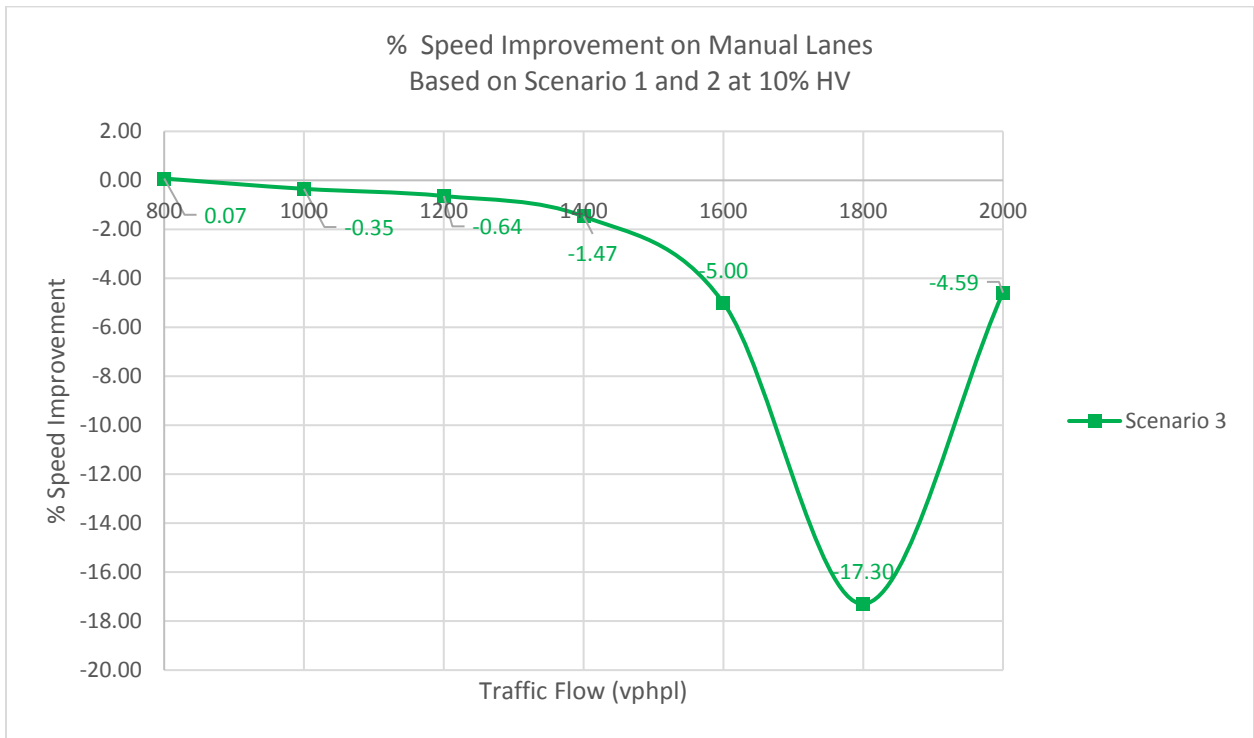


Figure 4-67 Speed Improvement on Manual Lanes (Base on Scenario 1 and 2) at 10% HV

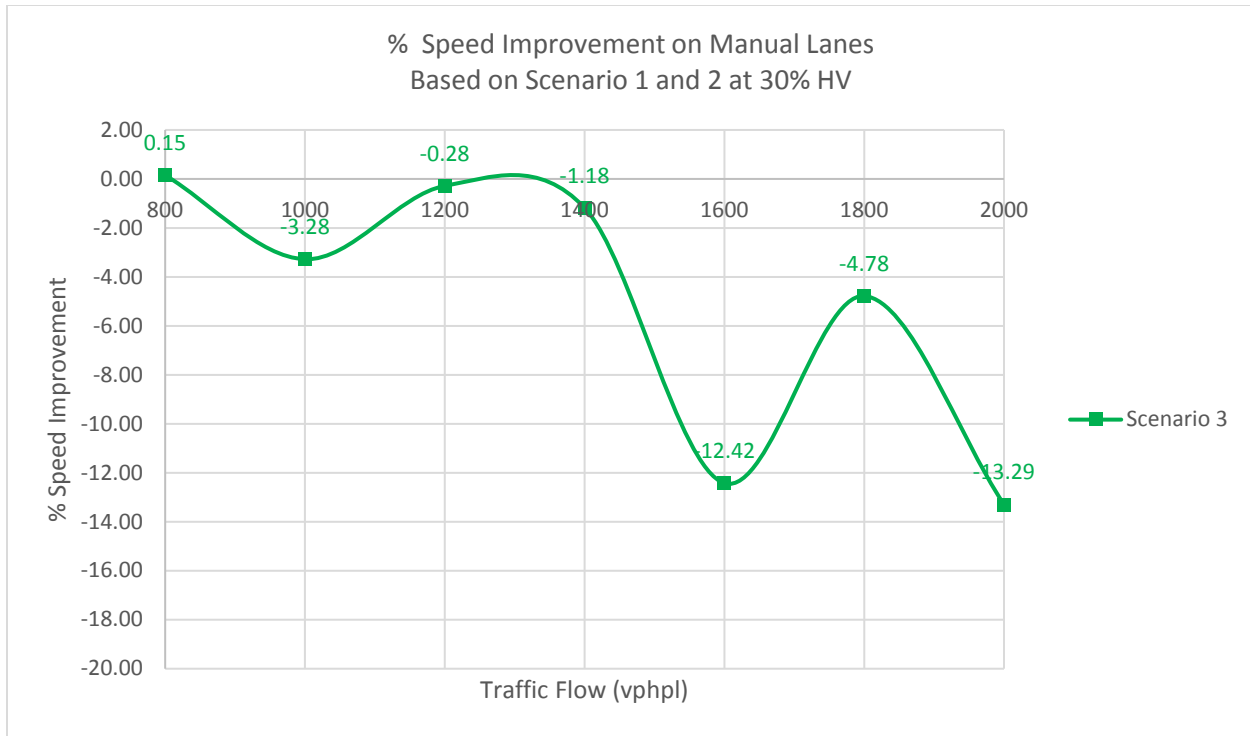


Figure 4-68 Speed Improvement on Manual Lanes (Base on Scenario 1 and 2) at 30% HV

C) Speed on Manual Lane for Scenario 3

It was proven that scenario 3 provided a lower speed on the manual lane in all cases (Figure 4-66 to Figure 4-68). The platoon results also reinforced this analyze (Figure 4-38 to Figure 4-44). It showed that the percentage of the vehicle in a platoon was increasing when both flow rate and vehicle penetration rate are increased and increase up to almost 100 percent. The reasons were that autonomous vehicles, which shared one of the manual lanes as passing lane, tried to adapt their acceleration and deceleration rate with the surrounded vehicle to maximize the comfort of passengers. Therefore, the overall speed of vehicles in the network was incredibly decreased due to the feature of an autonomous vehicle. This behavior was also likely to make autonomous vehicle formed a platoon when the flow rate increased. All the mentioned reasons made the speed operational on the manual lane in scenario 3 even worse.

Dedicated Lane							Manual Lane				
%HV	Flow Rate (vphpl)	Scenario 1	Scenario 2		Scenario 3		%HV	Flow Rate (vphpl)	Scenario 1	Scenario 3	
		Speed (mph)	Speed (mph)	% Different	Speed (mph)	% Different			Speed (mph)	Speed (mph)	% Different
0%	800	66.78	67.94	1.74	72.49	8.56	0%	800	72.53	72.45	-0.11
	1000	68.74	66.63	1.25	71.77	9.06		1000	71.66	71.32	-0.47
	1200	67.63	65.44	1.48	70.91	9.97		1200	70.78	70.12	-0.93
	1400	66.58	63.99	0.55	69.97	9.94		1400	69.53	68.84	-0.99
	1600	65.38	63.10	0.87	68.78	9.95		1600	68.20	66.84	-2.00
	1800	64.08	61.41	-1.23	63.81	2.64		1800	65.99	57.86	-12.32
	2000	61.84	61.98	-0.75	62.49	0.06		2000	61.24	52.77	-13.82
10%	800	68.44	66.68	1.64	71.25	8.61	10%	800	71.28	71.33	0.07
	1000	67.21	65.29	1.72	70.35	9.60		1000	70.24	69.99	-0.35
	1200	66.10	64.15	1.72	69.48	10.18		1200	69.13	68.69	-0.64
	1400	64.92	63.13	1.55	68.14	9.61		1400	67.68	66.68	-1.47
	1600	62.89	61.44	1.57	65.48	8.24		1600	65.28	62.01	-5.00
	1800	59.20	60.23	0.28	60.19	0.21		1800	58.34	48.25	-17.30
	2000	55.99	60.92	0.46	60.28	-0.58		2000	51.35	49.00	-4.59
30%	800	66.47	64.69	1.27	68.58	7.36	30%	800	69.06	69.17	0.15
	1000	67.68	63.47	-2.53	67.71	3.97		1000	70.24	67.93	-3.28
	1200	64.12	62.21	0.92	66.76	8.31		1200	66.60	66.41	-0.28
	1400	62.76	60.82	0.48	65.37	8.00		1400	64.99	64.23	-1.18
	1600	60.10	58.75	-0.18	59.00	0.23		1600	61.34	53.72	-12.42
	1800	54.00	58.53	-0.61	56.85	-3.48		1800	49.10	46.75	-4.78
	2000	54.81	58.47	1.38	55.93	-6.81		2000	50.32	45.01	-13.29

Table 4-8 Data for Speed Analysis

4.2.2.2 Percentage of Platoon Reduction Analysis

The figures show the percentage of platoon reduction that has changed from the base case with difference truck penetration rate for autonomous vehicles and manual vehicles (Figure 4-69 to Figure 4-71). The time headway between vehicles that passed each detector was used for platoon determination at each location. Finally, the percentage of the vehicle in a platoon at each location was average and used for comparison. A positive percentage means that scenario can provide a lower share of platoon than the base scenario, while a negative percentage means that scenario provided a higher share of platoon than the base scenario.

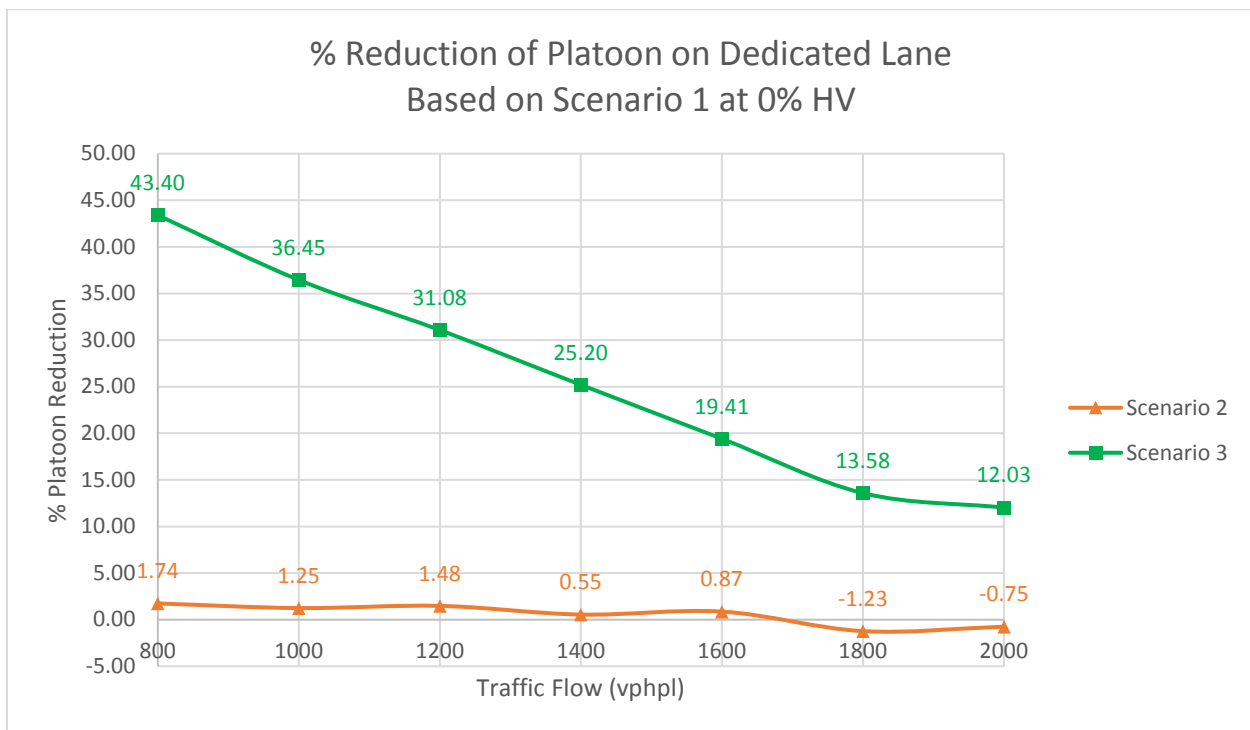


Figure 4-69 Percentage of Platoon Reduction on Dedicated Lane (Based on Scenario 1) at 0% HV

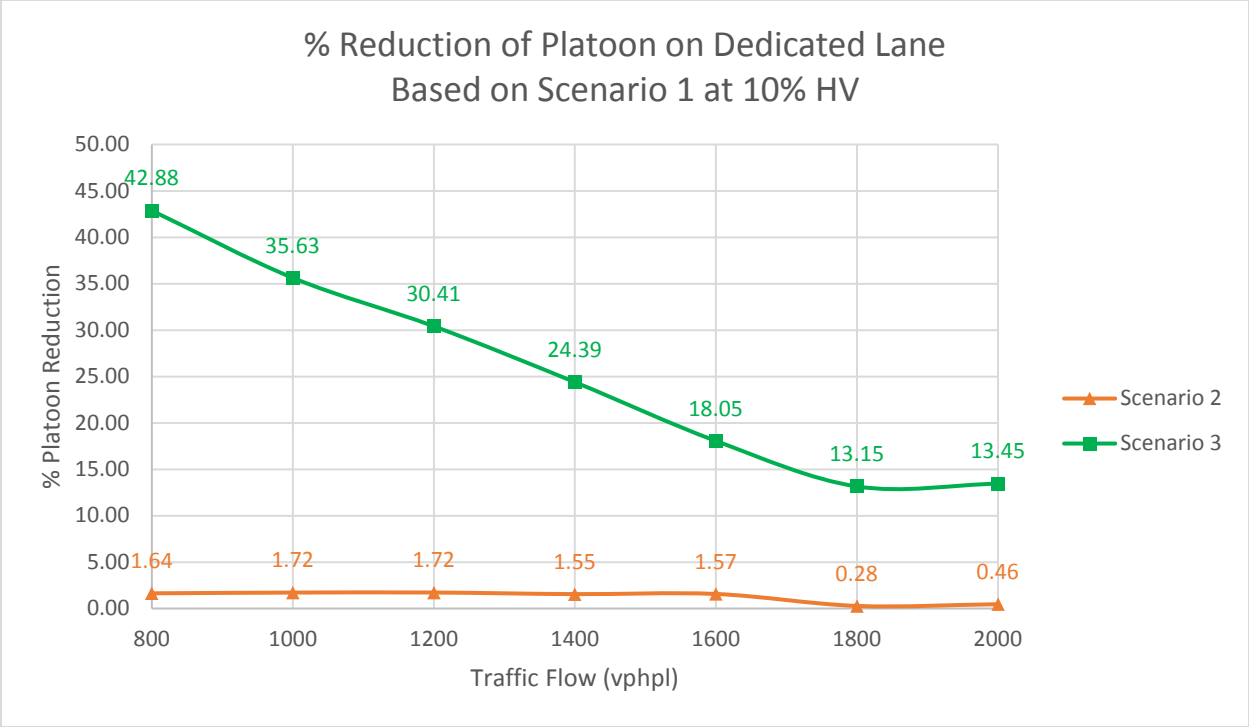


Figure 4-70 Percentage of Platoon Reduction on Dedicated Lane (Based on Scenario 1) at 10% HV

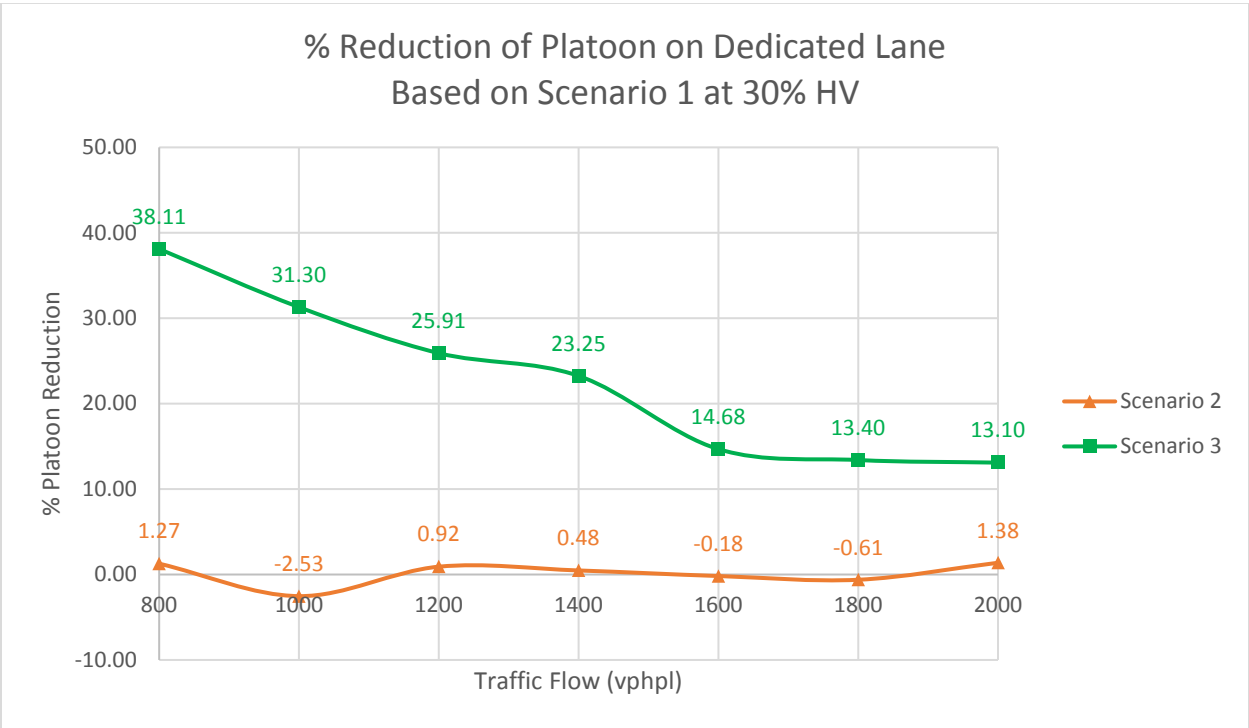


Figure 4-71 Percentage of Platoon Reduction on Dedicated Lane (Based on Scenario 1) at 30% HV

It was proven that scenario 3 can reduce the share of a platoon on the dedicated lane the most. When the traffic increase, the reduction rate decreases and constant in high traffic volume. Heavy vehicle penetration rate has no effect on the sharing of platoon reduction trend for this scenario.

Scenario 2 can slightly decrease the share of platooning vehicle on the dedicated lane. When the heavy vehicle penetration rate increase to 30%, the percentage of sharing vehicles in platoon was sometimes lower than the base case. Heavy vehicle penetration rate did not affect the sharing of platoon reduction trend for this scenario.

In contrast, the traffic on the manual lane tend to has more group of platooning vehicles. Manual lanes in scenario 3 have a higher percentage of sharing vehicle in a platoon than the base case. However, when the traffic flow was increasing, scenario 3 tend to have less platooning. Heavy vehicle penetration rate slightly has a minor effect on the sharing of platoon reduction trend for the based case and scenario 3. For the scenario with high traffic flow, as the percentage of heavy vehicle increase, the percentage of the vehicle in platoon decrease.

The value used for platoon analysis can be found in the table at the end of this section (Table 4-9).

A) Percentage of Platoon reduction on Dedicated Lane for Scenario 2

As mention above, the percentage vehicle in a platoon on a dedicated lane in scenario 2 slightly less than the base case. Percentage of the vehicle in a platoon was almost the same as in the base case except at the middle location, which notably decreased (Figure 4-31 to Figure 4-37). This result was proven that platooning can be decreased when the passing section was provided.

B) Percentage of Platoon reduction on Dedicated Lane for Scenario 3

Percentage of the vehicle in a platoon on the dedicated lane in scenario 3 enormously decreased when comparing to the base case. However, when the flow rate was increasing, more vehicles were forming the platoon in this scenario. At high flow rate, 1800 to 2000 vphpl, percentage of the platoon was not able to decrease and remain constant. However, scenario 3 always be the best option for reducing platooning. The longer passing section not only made scenario 3 provided a high rate of passing maneuver, but also alleviated percentage of the vehicle in platooning.

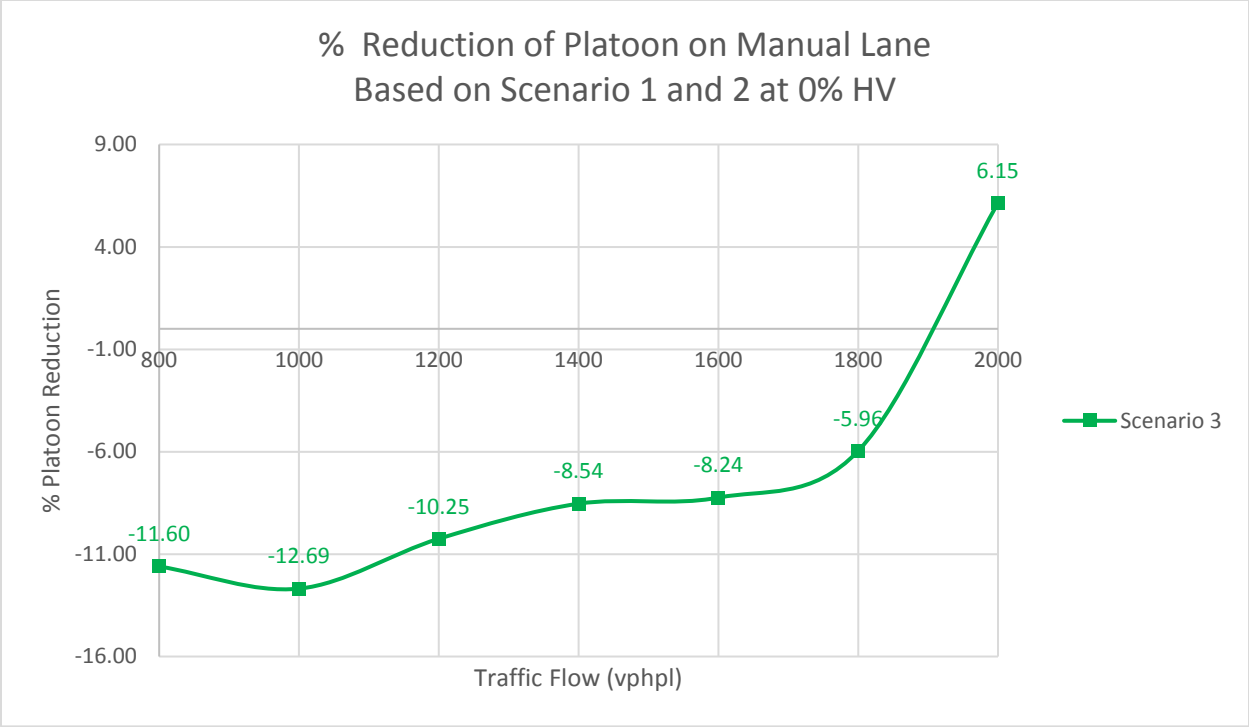


Figure 4-72 Percentage of Platoon Reduction on Manual Lane (Based on Scenario 1) at 0% HV

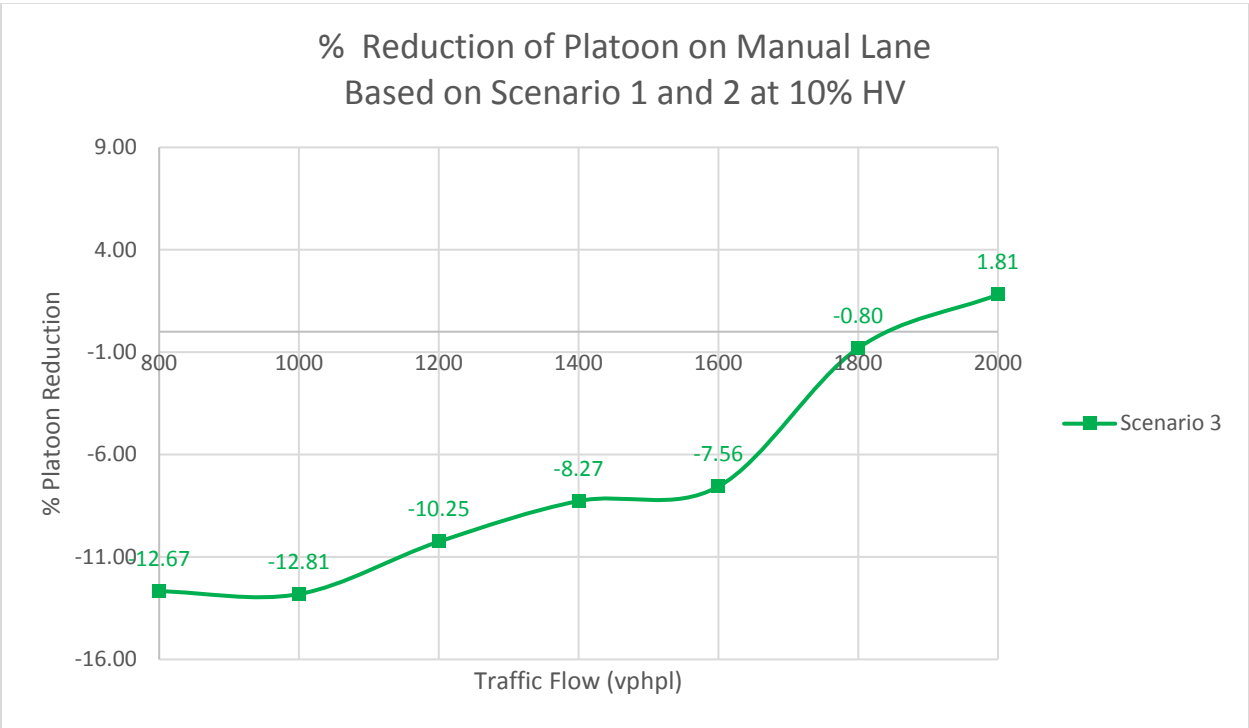


Figure 4-73 Percentage of Platoon Reduction on Manual Lane (Based on Scenario 1) at 10% HV

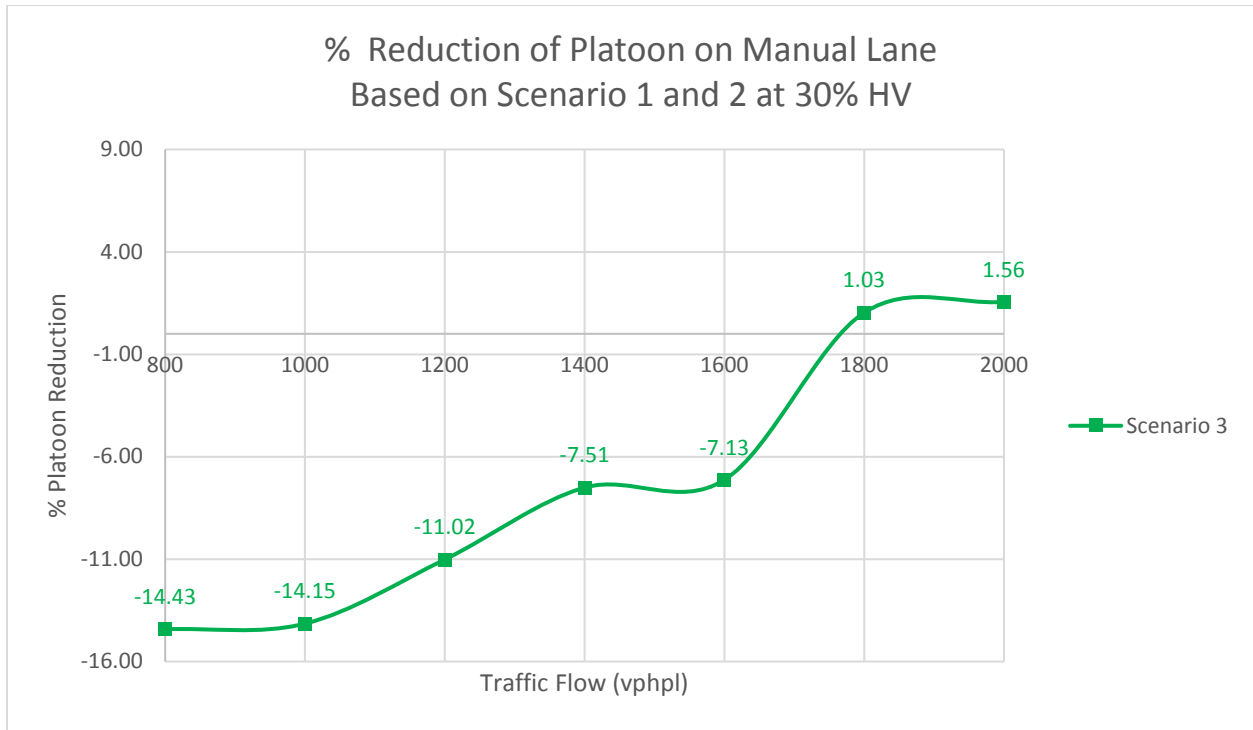


Figure 4-74 Percentage of Platoon Reduction on Manual Lane (Based on Scenario 1) at 30% HV

C) Percentage of Platoon reduction on Manual Lane for Scenario 3

It was obvious that the percentage of the vehicle in a platoon on the manual lane in scenario 3 should be higher than the based case for the scenario with low traffic volume (Figure 4-72 to Figure 4-74). Additional autonomous vehicles that were on the dedicated lane used the manual lanes too. However, when the traffic flow increased to 1800 vphpl, scenario 3 tend to decrease the percentage of platooning base on scenario 1 slightly. The possible reason was that there was congestion that occurred in the network which made traffic throughput in scenario 3 less than the base case (Figure 4-60 to Figure 4-62). Therefore, when there was less vehicle in the network, there was more space for a vehicle which leads to longer time headway and fewer vehicles would be in a platoon.

Dedicated Lane							Manual Lane				
%HV	Flow Rate (vphpl)	Scenario 1	Scenario 2		Scenario 3		%HV	Flow Rate (vphpl)	Scenario 1	Scenario 3	
		% Platoon	% Platoon	% Different	% Platoon	% Different			% Platoon	% Platoon	% Different
0%	800	0.73	0.68	5.67	0.41	43.40	0%	800	0.52	0.58	-11.60
	1000	0.78	0.75	4.59	0.50	36.45		1000	0.60	0.67	-12.69
	1200	0.82	0.79	3.82	0.57	31.08		1200	0.68	0.75	-10.25
	1400	0.86	0.83	2.82	0.64	25.20		1400	0.74	0.80	-8.54
	1600	0.88	0.86	2.24	0.71	19.41		1600	0.79	0.86	-8.24
	1800	0.88	0.87	1.02	0.76	13.58		1800	0.85	0.90	-5.96
	2000	0.88	0.87	1.41	0.78	12.03		2000	0.97	0.91	6.15
10%	800	0.73	0.69	5.16	0.42	42.88	10%	800	0.52	0.59	-12.67
	1000	0.79	0.76	4.06	0.51	35.63		1000	0.60	0.68	-12.81
	1200	0.83	0.80	3.19	0.58	30.41		1200	0.68	0.75	-10.25
	1400	0.86	0.83	2.82	0.65	24.39		1400	0.75	0.81	-8.27
	1600	0.88	0.86	2.36	0.72	18.05		1600	0.80	0.86	-7.56
	1800	0.90	0.88	2.12	0.78	13.15		1800	0.88	0.89	-0.80
	2000	0.90	0.89	1.63	0.78	13.45		2000	0.91	0.89	1.81
30%	800	0.74	0.70	4.46	0.46	38.11	30%	800	0.53	0.61	-14.43
	1000	0.79	0.76	3.27	0.54	31.30		1000	0.61	0.70	-14.15
	1200	0.82	0.81	2.18	0.61	25.91		1200	0.69	0.77	-11.02
	1400	0.85	0.84	1.59	0.65	23.25		1400	0.76	0.81	-7.51
	1600	0.87	0.86	1.16	0.74	14.68		1600	0.81	0.86	-7.13
	1800	0.88	0.87	0.95	0.76	13.40		1800	0.88	0.87	1.03
	2000	0.88	0.87	0.96	0.77	13.10		2000	0.88	0.87	1.56

Table 4-9 Data for Platoon Analysis

4.2.2.3 Percentage of Travel Time Reduction Analysis

The figures show the percentage of travel time reduction that has decreased from the base case with difference truck penetration rate on the dedicated lane and manual lanes (Figure 4-75 to Figure 4-80). The travel time was determined from the average time that vehicles used for traversing throughout the network in each scenario. A positive percentage means that the scenario has a shorter travel time than the base scenario, while a negative percentage means that the scenario has longer travel time than the base scenario.

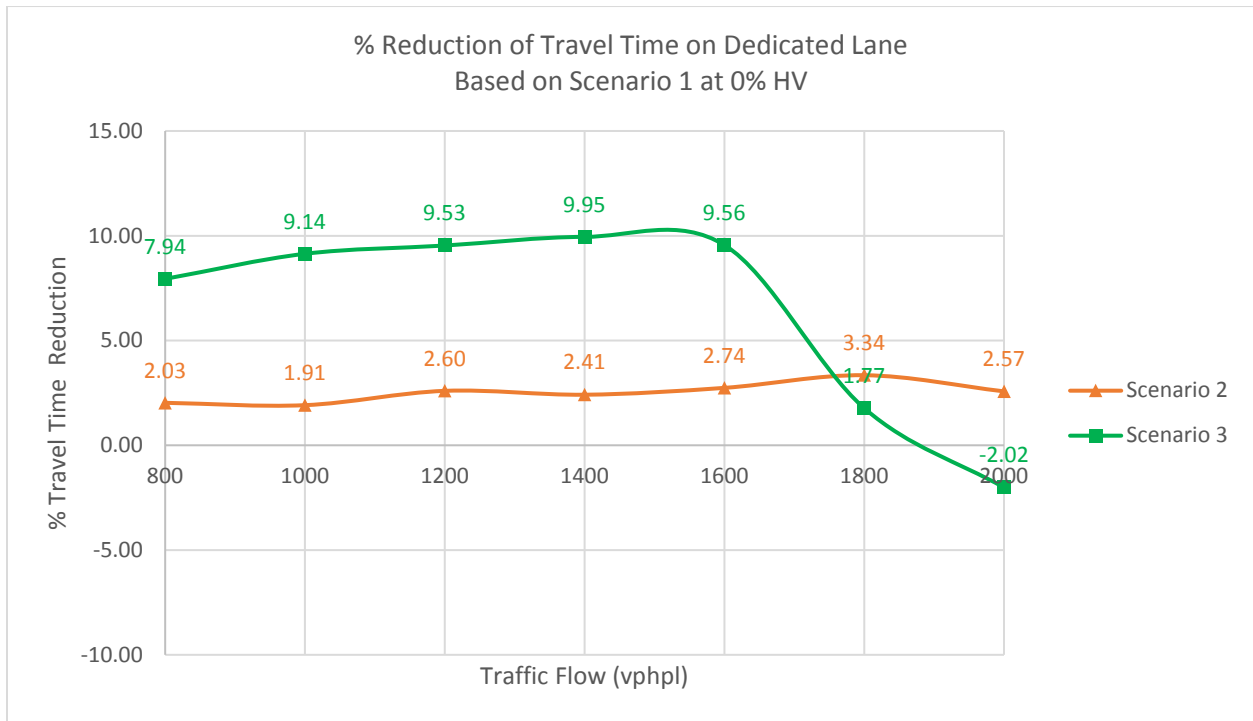


Figure 4-75 Percentage of Travel Time Reduction on Dedicated Lane (Based on Scenario 1) at 0% HV

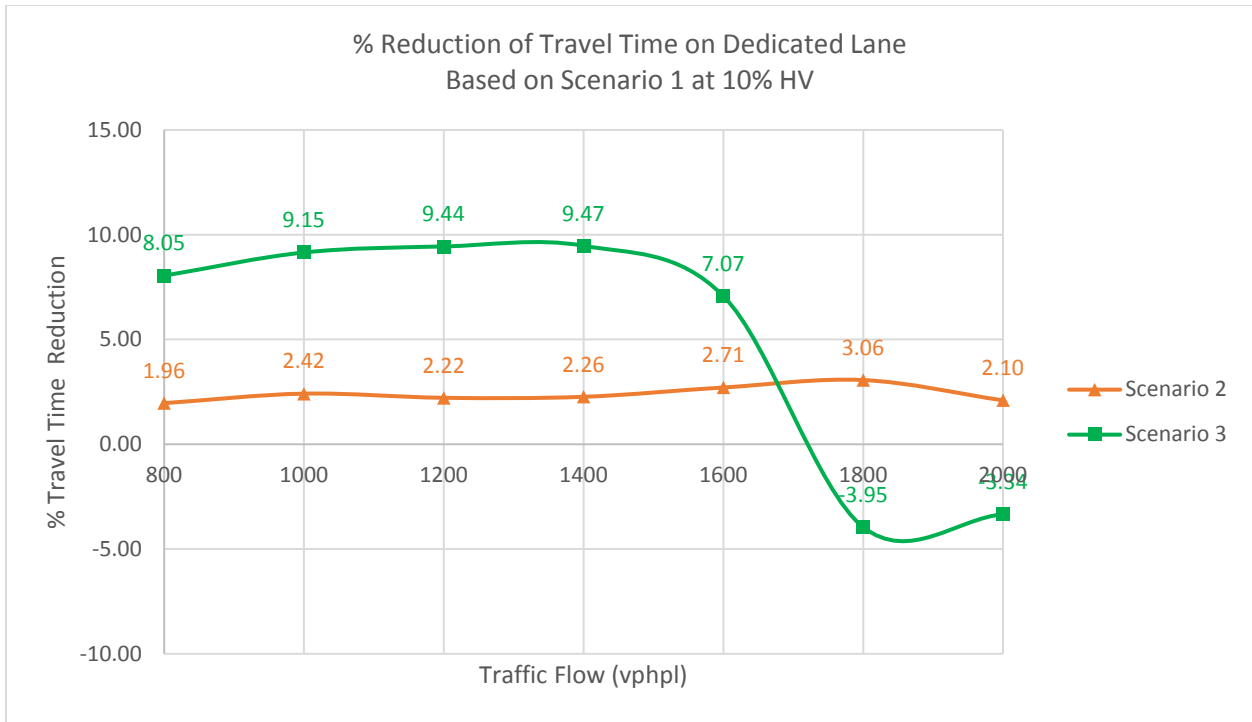


Figure 4-76 Percentage of Travel Time Reduction on Dedicated Lane (Based on Scenario 1) at 10% HV

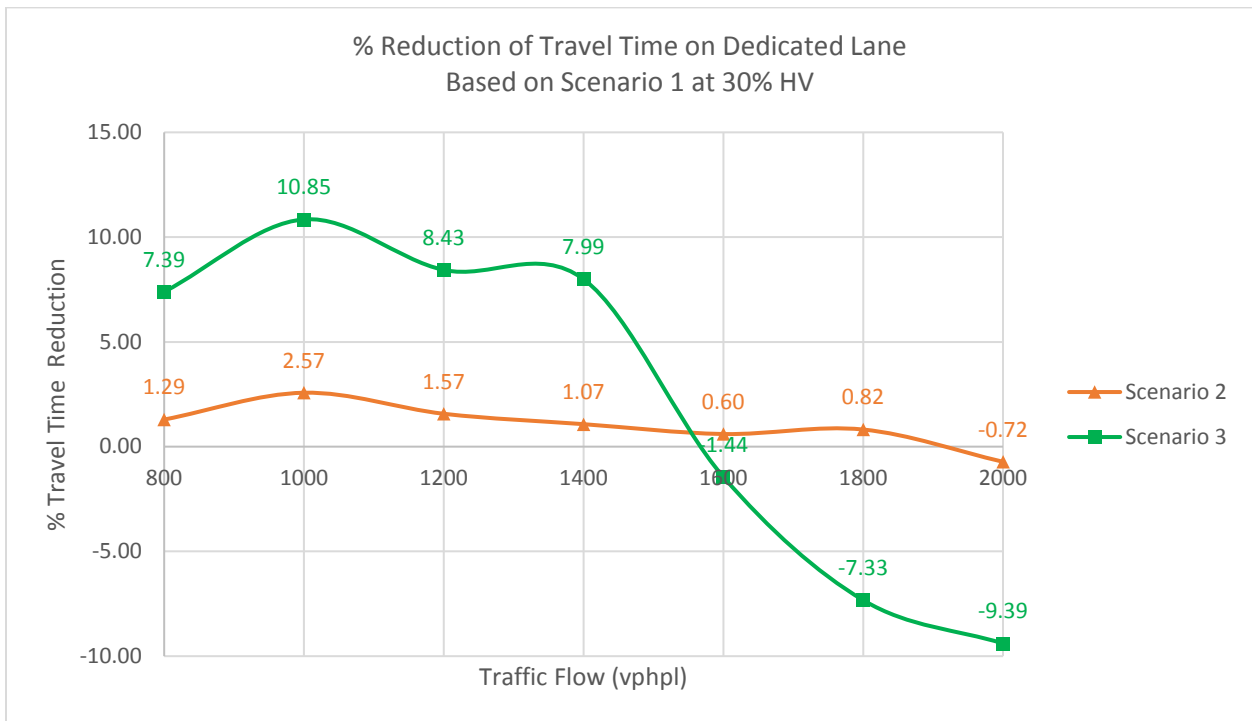


Figure 4-77 Percentage of Travel Time Reduction on Dedicated Lane (Based on Scenario 1) at 30% HV

As a result, scenario 3 can provide the shortest travel time for autonomous vehicles on the dedicated lane when the flow rate was low to moderate, 800 to 1600 vphpl. However, when the flow rate increased, travel time of vehicles in this scenario enormously increased which made it longer than the based case. Heavy vehicles penetration rate also affected the travel time. As the percentage of truck increasing, vehicles on this scenario tend to have longer travel time.

Scenario 2 provided slightly shorter vehicle travel time on a dedicated lane. It was pointed out that even the flow rate is increasing to 1800 vphpl, this scenario provided shorter travel time than the based case. Heavy vehicle penetration rate only has a negative effect when the traffic flow was at 2000 vphpl and the percentage is 30%. At this stage, the travel time of vehicles in this scenario was slightly longer than the base case.

For travel time on manual lanes, scenario 3 had made a negative effect when comparing to the base case. When the traffic flow increased, travel time also increased as well. However, as the traffic volume was high, the trend of travel time reduction depended on heavy vehicle penetration rate.

The value used for platoon analysis can be found in the table at the end of this section (Table 4-10).

A) Percentage of Travel Time reduction on Dedicated Lane for Scenario 2

Unlike the result from scenario 3, Scenario 2 can provide shorter travel time even though the traffic volume was high. One possible explanation was that there was a suitable passing maneuver occurred in scenario 2. Speed of vehicles in this scenario was almost the same as the base case, except at the middle location of the passing lane (Figure 4-17 to Figure 4-23).

B) Percentage of Travel Time reduction on Dedicated Lane for Scenario 3

This scenario can reduce enormously travel time for vehicles on a dedicated lane when the speed was low to moderate, 800 to 1400 vphpl. It was possible that fast vehicles have to change to the adjacent lane for passing purpose and spent most of their time traveling on that lane. Therefore, the speed difference on this lane was low and the autonomous vehicle can adjust their speed and travel smoother. However, when the traffic increased, there was congestion occurred. Therefore, travel time at this stage increased. Moreover, higher heavy vehicle penetration rate also increased the travel time of the vehicle on this lane. It was possible that autonomous vehicles need to adjust

their acceleration rate and deceleration rate with more frequency when there is more truck in traffic. Therefore, their speed was not constant which made them used longer time to traverse.

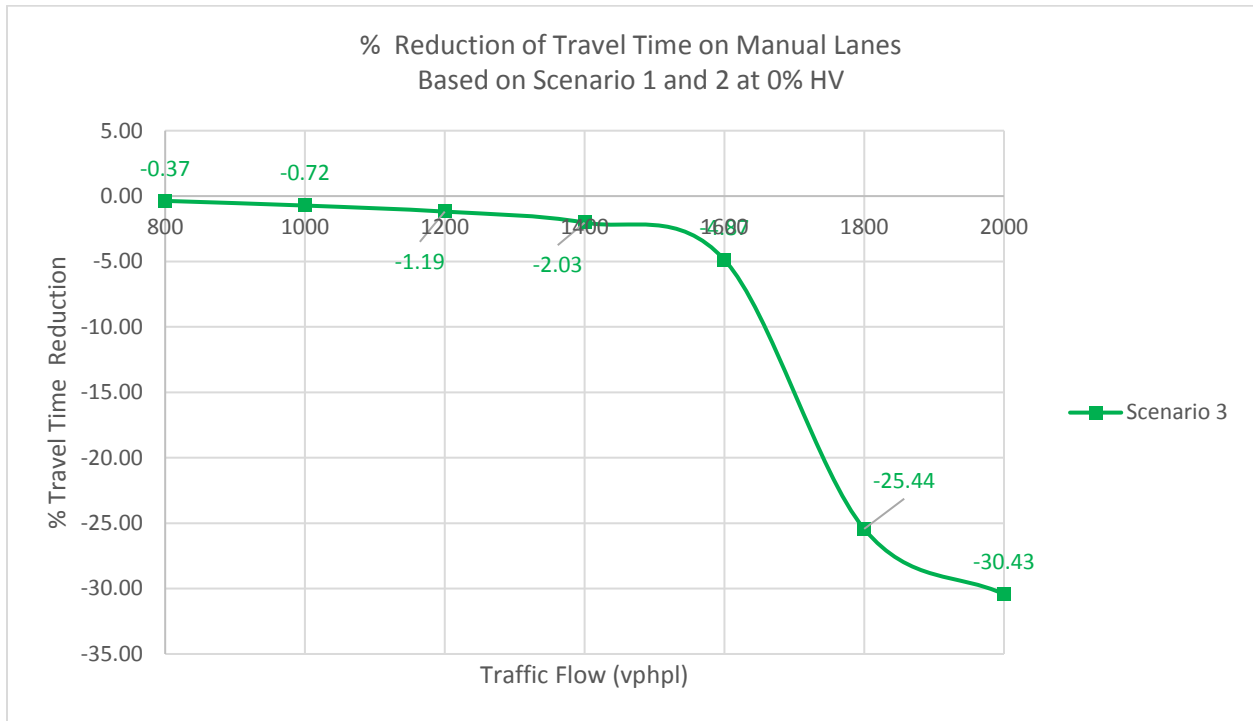


Figure 4-78 Percentage of Travel Time Reduction on Manual Lane (Based on Scenario 1) at 0% HV

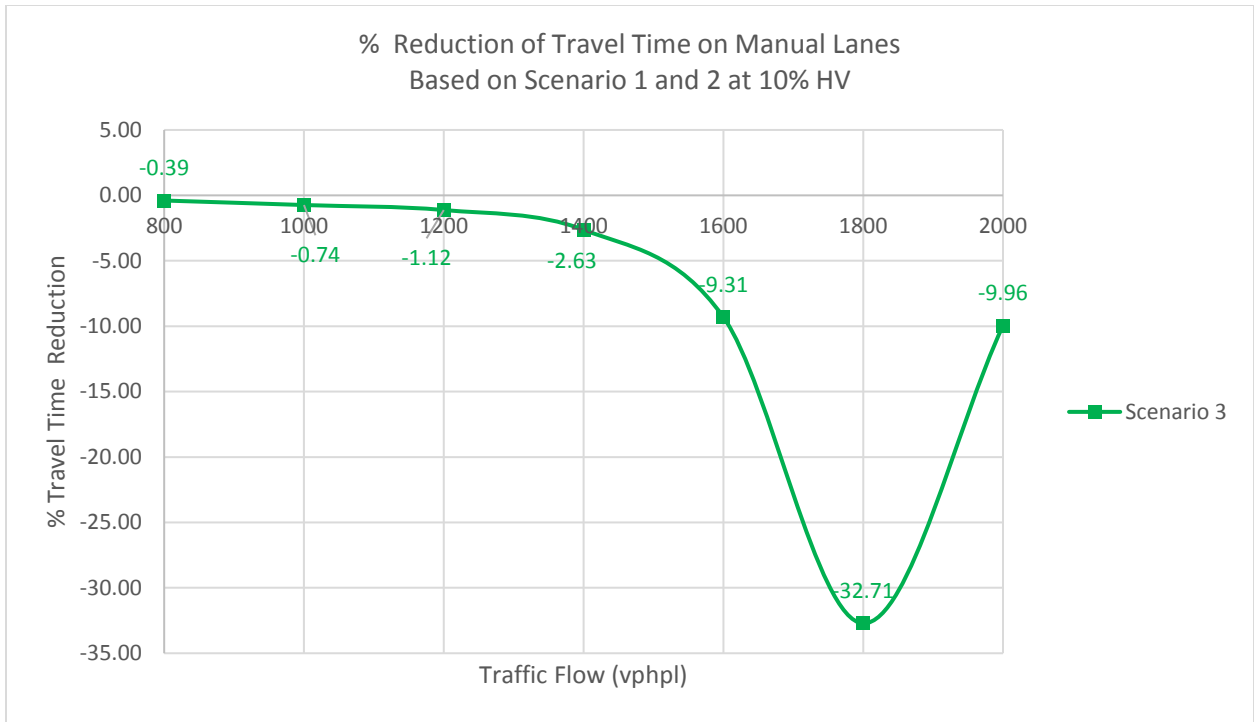


Figure 4-79 Percentage of Travel Time Reduction on Manual Lane (Based on Scenario 1) at 10% HV

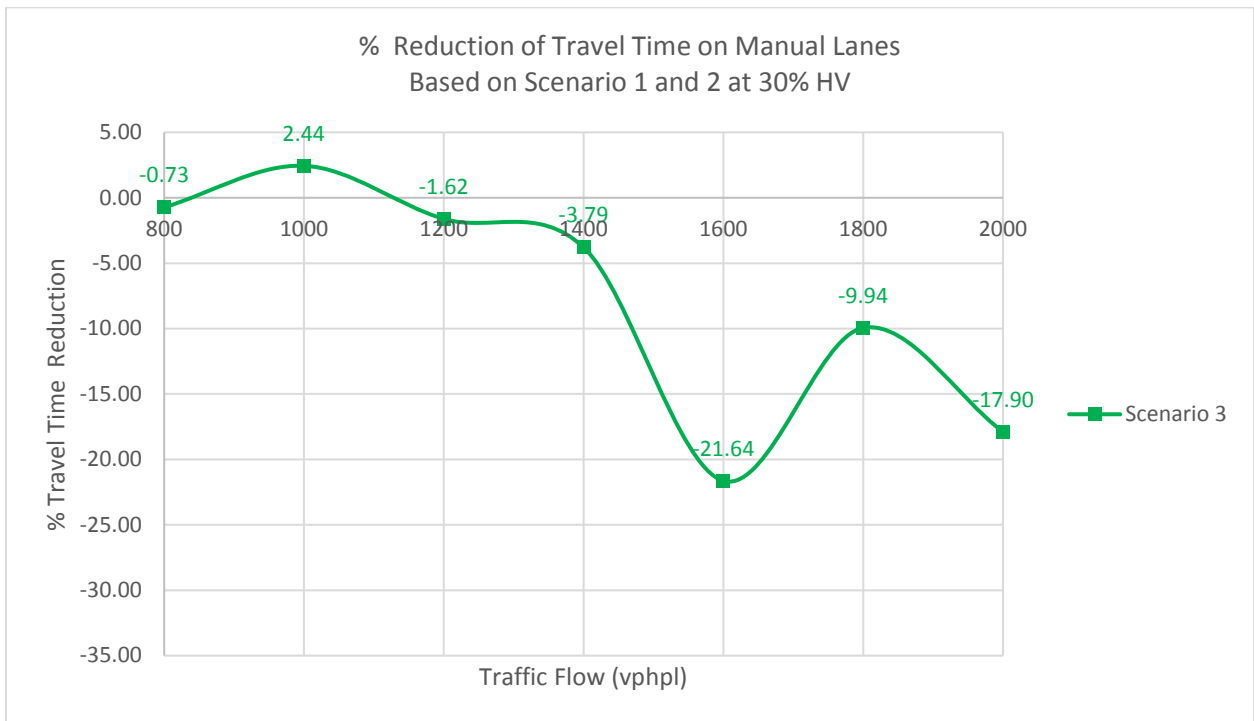


Figure 4-80 Percentage of Travel Time Reduction on Manual Lane (Based on Scenario 1) at 30% HV

C) Percentage of Travel Time reduction on Manual Lane for Scenario 3

Vehicle travel time on manual lanes in scenario 3 was generally longer than travel time in the base case. It was possible that presented of autonomous vehicles in mixed traffic had made fluctuated in the traffic stream. Autonomous vehicles may attempt to adjust their acceleration rate and deceleration rate with surrounded vehicles for comfort and safety reason. When the traffic flow increased to 1600 vphpl, there was congestion occurred which made overall vehicles slow down. Therefore, scenario 3 made a negative effect on the travel time of vehicles on manual lanes.

Dedicated Lane							Manual Lane				
%HV	Flow Rate (vphpl)	Scenario 1	Scenario 2		Scenario 3		%HV	Flow Rate (vphpl)	Scenario 1	Scenario 3	
		Travel Time (sec)	Travel Time (sec)	% Different	Travel Time (sec)	% Different			Travel Time (sec)	Travel Time (sec)	% Different
0%	800	269.94	264.46	2.03	248.49	7.94	0%	800	249.41	250.33	-0.37
	1000	276.44	271.15	1.91	251.17	9.14		1000	252.51	254.34	-0.72
	1200	281.97	274.64	2.60	255.09	9.53		1200	256.13	259.17	-1.19
	1400	288.71	281.74	2.41	259.99	9.95		1400	261.14	266.44	-2.03
	1600	297.69	289.53	2.74	269.23	9.56		1600	269.06	282.16	-4.87
	1800	314.70	304.18	3.34	309.13	1.77		1800	285.87	358.59	-25.44
	2000	314.48	306.39	2.57	320.82	-2.02		2000	337.09	439.68	-30.43
10%	800	274.70	269.32	1.96	252.60	8.05	10%	800	253.86	254.86	-0.39
	1000	281.64	274.84	2.42	255.87	9.15		1000	257.85	259.76	-0.74
	1200	286.89	280.53	2.22	259.80	9.44		1200	262.34	265.28	-1.12
	1400	294.09	287.43	2.26	266.24	9.47		1400	269.18	276.26	-2.63
	1600	305.08	296.81	2.71	283.51	7.07		1600	296.81	310.38	-9.31
	1800	324.34	314.40	3.06	337.16	-3.95		1800	314.40	461.20	-32.71
	2000	325.55	318.73	2.10	336.43	-3.34		2000	318.73	460.05	-9.96
30%	800	280.95	277.31	1.29	260.18	7.39	30%	800	262.00	263.92	-0.73
	1000	286.99	279.61	2.57	255.87	10.85		1000	266.26	259.76	2.44
	1200	292.83	288.23	1.57	268.13	8.43		1200	271.80	276.19	-1.62
	1400	299.66	296.44	1.07	275.71	7.99		1400	279.73	290.33	-3.79
	1600	312.47	310.59	0.60	316.99	-1.44		1600	305.59	371.72	-21.64
	1800	329.99	327.30	0.82	354.17	-7.33		1800	430.77	473.60	-9.94
	2000	328.50	330.87	-0.72	359.36	-9.39		2000	417.90	492.69	-17.90

Table 4-10 Data for Travel Time Analysis

4.2.2.4 Unsuccess passing vehicle

Unsuccess passing vehicle in this study was defined as autonomous passing vehicles that were unable to complete overtaking maneuver within provided distance. Instead, they will wait at the end of passing lane until there was a suitable gap for them to merge back to the dedicated lane. This attribute can be evaluated by the queue length at a merging point at the end of the passing length for each scenario (Figure 4-54 to Figure 4-56).

As a result, scenario 2 rarely produced the queue at the merging point. Passing vehicles in this scenario have shorter passing length. Therefore, they also have a lower chance to perform passing maneuver too (Figure 4-51 to Figure 4-53). Thus, the chance that they would perform the queue at the end of the passing lane also lower. However, when there was no heavy vehicle in traffic, there was noticeably queue length at a flow rate of 1800 vphpl or above. This queue propagated since the vehicles on passing lane tended to increase their speed so that they could not find a suitable gap and decelerate within the provided length.

In contrast, the queue length in scenario 3 was longer than scenario 2 and depended on the heavy vehicle penetration rate. The length of the queue in this scenario tended to increase when the flow rate increased. It was evident that when the flow increased, there would be congestion and vehicles will find difficulty trying to merge back. The queue length from the scenario with no heavy vehicle was longer than a scenario with 10 percent of heavy vehicle, however, queue tended to be longest when the penetration rate of the heavy vehicle was up to 30 percent. When there was no heavy vehicle in the traffic, autonomous vehicles tended to keep the gap between vehicles close to each other. Therefore, vehicles that need to merge would find difficulty in merging back in time. The scenario with a high percentage of heavy vehicles also produced the longest queue length, especially when the flow rate was 1400 vphpl. At this flow rate, vehicle on the dedicated lane still has a high speed which made it difficult for merging (Figure 4-17 to Figure 4-30). However, when the flow increased to 1600 vphpl and above, the speed on both dedicated and manual lanes dropped dramatically which made lane changing possible.

4.2.3 Safety Analysis

For safety analysis, this study has observed the number of conflicts that occurred only on the dedicated lane for each scenario. Two types of conflict were defined in this study; the rear-end conflict and the lane changing conflict. The number of conflicts events in each scenario was previously mentioned in the previous section.

As a result (Table 4-1 to Table 4-3), scenario 2 can provide the lowest number of rear-end conflict when traffic flow is at or below 1600 vphpl. However, when traffic increased, scenario 1 has less rear-end conflict than other scenarios. The possible explanation is that there was a passing opportunity in scenario 2 which made vehicles in the stream has larger gap between each other. As a result, the vehicle can safely make lane changing. However, when more traffic flow was assigned to this scenario, the gap between vehicles decreased. The heavy penetration rate also affected the number of conflicts. When the heavy vehicles were not present in the stream, the rear-end conflict events tended to occur with more frequently. The possible reason is that vehicles in this stage can leave a smaller space to the vehicle in front. Hence, there was more chance that an accident was likely to occur.

In contrast, scenario 3 has an extremely high number of rear-end conflicts events. According to the passing rate result (Figure 4-51 to Figure 4-53), more than 60% of vehicles on the dedicated lane have made lane-changing maneuvers. This behavior can make traffic fluctuate, and autonomous vehicles attempted to adjust their speed to the vehicle in front. Higher speed might be another reason that made scenario 3 have extremely high rear-ended conflicts. Therefore, there was a high chance that an accident would occur in this scenario.

Lane changing conflicts were only observed on the dedicated lane in scenario 2 and scenario 3. It was proven that scenario 2 has a fewer number of lane-changing conflict events than scenario 3. The fewer passing rate and opportunities in the scenario could be the reason that made scenario 2 safer for lane-changing maneuvers. Higher speed might be another reason that made scenario 3 have extremely high lane-changing conflicts.

Chapter 5 Conclusion

The introducing of autonomous vehicles has brought a lot of significant changes and effect on the current traffic operation. During the early transition stage from manual to autonomous vehicles, dedicated lanes for autonomous vehicles are needed in order to achieve maximize benefit from the technology and prevent the negative effect from mixed traffic. With the limitation of space and low autonomous vehicles penetration in early stage, only one dedicated lane was assumed to be installed out of three lanes freeway road. However, slow-moving vehicle on a dedicated lane might delay the tailing vehicles and cause negative effect for traffic operation

In the literature review section, autonomous vehicles were the first topic. The characteristic of dedicated land and passing lane were described to define the scope of geometric design for the simulations. The passing maneuver was briefly described to the process and its effect. This study used VISSIM microsimulation software for all of the simulations along with SSAM for safety analysis.

This study has evaluated traffic operation and safety of different method to provide a passing section on a dedicated lane. The first scenario was used as the base case which has no passing opportunities. The second scenario has an additional passing lane but in limited length. The third scenario allowed autonomous vehicles to use a manual lane for passing purpose. Traffic flow was assigned from low to high volume, along with the increase of heavy vehicles penetration rate. The result was evaluated in terms of capacity, traffic operation such as speed and reduction of platoon rate, and safety result.

As a result, the conclusion from this study can be drawn as follows;

- Passing opportunity mostly provided higher speed on the dedicated lane which results in better traffic operation, however, providing passing opportunities do not always increase capacity on the dedicated lane. For low traffic volume, scenario 3 provided a result with better traffic operation and capacity since it allowed autonomous vehicles to use both lanes. When traffic volume increase, the effect of lane changing has decreased the scenarios' efficient.
- Scenario 2 provided slightly better traffic operation and capacity when compared with the based case. This option is suitable for the scenario which has high traffic flow and heavy

vehicles penetration rate. It was highlighted that scenario 2 is safer than scenario 3. The cost of installing the passing lane is the primary constraint for selecting this scenario as the solution.

- Suitable autonomous vehicles flow in mixed traffic has a positive effect on manual driver behavior. As seen in scenario 3, the manual vehicles have negative effect when there was low autonomous vehicles volume present in their lanes. The capacity of manual vehicles increased when the autonomous flow rate was moderate before it became worse when there were exceeding autonomous vehicles volume.

The limitations of the study are that all of the vehicles were unable to connect to each other. The process of passing required detailed data of surrounded vehicles in order to perform that maneuver efficiently and safely, hence, the scenarios in this study should conduct with connected vehicles for better evaluation. Moreover, the application of dynamics traffic should also be applied in this study to reflect the result in more realistic. The benefit of dynamic traffic information can be used to control passing maneuver and reduce negative effect and conditions that have been found in this study.

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