Center for Advanced Multimodal Mobility Solutions and Education

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IMPACT OF CONNECTED AND AUTOMATED VEHICLES ON FREEWAY CAPACITY

Final Report

by

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EXECUTIVE SUMMARY

Connected and automated vehicle (CAV) technologies are combination technologies of connected vehicle and automated vehicle. As widely known, CAVs can bring with them many benefits including improving safety, reducing emissions and increasing mobility of the transportation system. CAV only needs a smaller lane width and headway which will lead to a higher roadway capacity. CAVs may have coordinated weaving maneuvers which will increase the capacity on weaving sections. For an intersection, instead of using a stop- or signal-controlled method, CAV can have coordinated through or turning movements to avoid collisions. In short, there is no doubt that the CAV technologies will significantly change future transportation system.

As the CAVs start to penetrate into the market, the current Highway Capacity Manual (HCM) methods cannot be used to evaluate freeway capacity due to the fact that they did not account for the impacts of CAV strategies in the HCM. To quantify the impact of CAVs on freeway capacity, new guidelines should be established in order to be suitable for use in conducting various types of analyses involving CAV strategies. The impact of different CAV penetration rates in the highway system on various facilities under different scenarios should be examined. In order to be better prepared for both CAV planning and operations under varying levels of market penetration and traffic demand, there is a critical need to develop and establish the HCM capacity adjustments.

This research will develop guidelines for and make recommendations on estimating and predicting freeway capacity in the presence of CAVs or AVs, and therefore will lead to a better understanding of how CAVs or AVs improve mobility in the freeway system. In the case study conducted in this research, four different freeway scenarios are chosen from the Caltrans Performance Measurement System (PeMS). To obtain valid results, various driving behavior parameters are calibrated to the real traffic conditions for human-driven vehicles by using VISSIM, a commonly used traffic microsimulation tool. In particular, the calibration is conducted using genetic algorithm for driving behavior parameters such as standstill distance and minimum headway between vehicles. After the calibration process, the simulation is conducted on basic freeway segments in the mixed traffic environment including regular human-driven vehicles, AVs, and CAVs. Simulation results are discussed in detail. Overall, the results of this study can help traffic engineers and stakeholders better understand how different market penetration levels of CAV and AV influence freeway capacity and therefore can help improve freeway traffic management.

Chapter 1. Introduction

1.1. Problem Statement

Connected and automated vehicle technologies are among the most rapidly developing automotive technologies. Connected and automated vehicle (CAV) technologies are combination technologies of connected vehicle and automated vehicle. As widely known, CAVs can bring with them many benefits including improving safety, reducing emissions and increasing mobility of the transportation system. CAV only needs a smaller lane width and headway which will lead to a higher roadway capacity. CAVs may have coordinated weaving maneuvers which will increase the capacity on weaving sections. For an intersection, instead of using a stop- or signal-controlled method, CAV can have coordinated through or turning movements to avoid collision.

As the CAVs start to penetrate into the market, the current HCM methods cannot be used to evaluate freeway capacity due to the fact that they did not account for the impacts of CAV strategies in the HCM. The limitations of the current capacity analysis methods include, but are not limited to, the following: 1) There is no guideline related to how current HCM methods should be adjusted in order to be suitable for use in conducting various types of analyses involving CAV strategies; 2) There is no consideration of the general impact of CAV technologies on traffic congestion and delay as well as safety in the HCM analysis; and 3) There is no information about the impact of different CAV penetration rates in the highway system on various facilities under different scenarios. In order to be better prepared for both CAV planning and operations under varying levels of market penetration and traffic demand, there is a critical need to develop and establish the HCM capacity adjustments.

Connected Vehicle (CV) and Automated Vehicle (AV) technologies will change the way vehicles are driven on the highway system and have a significant impact on transportation operations, safety, and environment (Campbell and Alexiadis 2016). Driverless Cars (DLC) can keep a shorter headway and maintain consistent acceleration and deceleration rates due to the absence of perception errors and the minimal perception and reaction time. As a result, freeway operations and level of service (LOS) can be affected to a substantial but yet unknown degree by the DLC (Shi and Prevedouros 2016). Le Vine et al. (2016) mentioned that following distance between CAVs could be very short or very long (i.e., 0.85 seconds considering only vehicle ahead and 2.6 seconds if considering debris that might appear from the leading vehicle). As such, the subsequent freeway capacity could be 4247 passenger cars/hour/lane and 1367 passenger cars/hour/lane. Preliminary modeling showed that the capacity improvements can be resulted from different CAV penetration rates due to potential vehicle platooning and reduction in the space required for CAVs on the road network – a 22% capacity improvement with a 50% CAV penetration, a 50% capacity improvement with an 80% CAV penetration and an 80% capacity improvement with full CAV penetration (Shladover et al. 2012).

Minelli et al. (2015) developed an iterative methodology to examine the effects of CV on mode choice based on the changes in travel time between each origin-destination pair. The results showed that as the percentage of CVs increases, the average travel time for the whole auto mode will also increase. Litman (2014) explored the impacts of AVs on transportation planning and travel demand, such as optimal road and public transit supply. The results indicated that it may take twenty to forty years for the AVs to have a significant impact on the traffic congestion, safety, mobility, and environment. Some benefits may even require prohibiting human-driven vehicles on certain roadways. Bierstedt et al. (2014) examined the effects of AVs on travel demand and highway capacity. It was presented that with a lower penetration of AVs, there could be a reduction in vehicle average speed and vehicle density. Only when AVs are fully penetrated into the highway system, highway capacity could be improved to more than 4,000 passenger cars per hour per lane. Also, along with the improvement of highway capacity, total vehicle delay could be reduced by 45% or more.

Duncan et al. (2015) evaluated the impact of AVs on the mobility of aging population. First, a survey was conducted to examine the attitude of aging population towards the AVs. The conclusion was that over half of the attendees were interested in AVs, even though not all of them could trust AVs. Then a social media data mining analysis of public perception of AVs was done using data from twitter and other social media. The results indicated that the current travel demand of aging population has not been fully satisfied. But this mobility problem could be solved by the AV technology. Another study done by Auld et al. (2017) examined the effects of CAV technologies on people's travel demand and the vehicle miles traveled (VMT) in the Chicago area. The results indicated that an increase of 80% in highway capacity could only result in a 4% increase in induced VMT. In contrast, the reduction in travel time cost could increase the VMT by up to 59%, while the average travel time increases from about 20 min to more than 70 min.

This research will develop guidelines for and make recommendations on estimating and predicting freeway capacity in the presence of CAVs or AVs, and therefore will lead to a better understanding of how CAVs or AVs improve mobility in the freeway system. In the case study conducted in this research, four different freeway scenarios are chosen from the Caltrans Performance Measurement System (PeMS). To obtain valid results, various driving behavior parameters are calibrated to the real traffic conditions for human-driven vehicles by using VISSIM, a commonly used traffic microsimulation tool. In particular, the calibration is conducted using genetic algorithm for driving behavior parameters such as standstill distance and minimum headway between vehicles. After the calibration process, the simulation is conducted on basic freeway segments in the mixed traffic environment including regular human-driven vehicles, AVs, and CAVs. Simulation results are discussed in detail. Overall, the results of this study can help traffic engineers and stakeholders better understand how different market penetration levels of CAV and AV influence freeway capacity and therefore can help improve freeway traffic management.

1.2. Objectives

The main goal of this research project is to develop the highway capacity adjustments so that the HCM can be adapted to evaluate the impacts of CAVs at different levels of traffic volume and market penetration rates. To achieve the goal, the specific objectives of this project are to:

1. To conduct a comprehensive review of the state-of-the-art and state-of-the-practice on CAV technologies;

2. To identify suitable freeway segments as potential real-world scenarios for the conduct of case studies;

3. To develop and use a simulation-based method to measure freeway capacity at different CAV and AV penetration levels;

4. To analyze the impacts of the CAV technologies on freeway capacity and provide recommendations on future research directions.

1.3. Expected Contributions

In order to quantify the impacts of CAV and AV on freeway capacity and develop the highway capacity adjustments for HCM, modeling and simulation of CAV and AV are conducted in this research. The expected contributions from this research are summarized as follows:

1. A review of CAV technologies and freeway capacity analysis considering different levels of CAV penetration;

2. Identification and development of freeway segment scenarios and collecting the characteristics of each scenario;

3. Guideline on highway capacity adjustments at different CAV and AV penetration levels.

1.4. Report Overview

The report is structured as shown in Figure 1.1. In this chapter, the background and motivation of the study have been discussed, followed by the research objectives and expected contributions.

Chapter 2 presents a comprehensive review of the current state-of-the-art and state-of-the-practice of CAV technologies and various methodological approaches to analyze freeway capacity with or without CAVs. This chapter gives a clear picture of existing freeway capacity analysis methods with consideration of CAVs, possible modeling scenarios, and suitable parameters that can be used to estimate the freeway capacity. To get a better understanding of the capability and feasibility of the simulation methods, several previous studies using simulation methods for freeway capacity analysis are investigated and presented.

Chapter 3 presents potential freeway segments and any necessary data related to the select freeway segments. The California Department of Transportation (Caltrans) Performance Measurement System (PeMS) is a web-based database which provides users real-time and historical traffic data in different aspects, such as speed, flow, capacity, and delay. Consolidated real-time traffic data have been collected by PeMS and as such, PeMS is used as the data source for selecting potential freeway segments. Four freeway segments are selected with different scenarios, including on-ramps, off-ramps, and weaving segments. By using PeMS, researchers can conduct research with the comprehensive information about selected freeway segments, identify congestion bottlenecks, evaluate freeway performance, and make better decisions on freeway operation.

Chapter 4 discusses the calibration procedure of the microscopic traffic simulation model. VISSIM uses the Wiedemann's car following model to capture the physical and human components of vehicles. In order to minimize the discrepancy between observed and simulated traffic data, the parameters of the microscopic traffic simulation model should be calibrated. In this regard, a general optimization framework is formulated. The corresponding traffic data are collected from PeMS. Genetic Algorithm is used to achieve near-global optima during the calibration procedure of the microscopic traffic simulation model. The objective is to minimize the difference between the simulated and field traffic data (e.g., flow and speed).

Chapter 5 describes the External Driver Behavior Model (EDBM) that is used to simulate CAVs and AVs in VISSIM. VISSIM cannot simulate operations of CAVs with its internal driver model. However, VISSIM provides the option to replace the internal model with an EDBM, which is a fully user-defined driving behavior model for CAVs. The results of the four simulation scenarios are discussed in detail. The capacity under each scenario is estimated with different combinations of regular manually driven vehicles, AVs, and CAVs, so that the effects of different market penetration levels of CAVs and AVs could be quantified.

Chapter 6 concludes the report with a summary of the simulation results. Directions for future research are also provided.

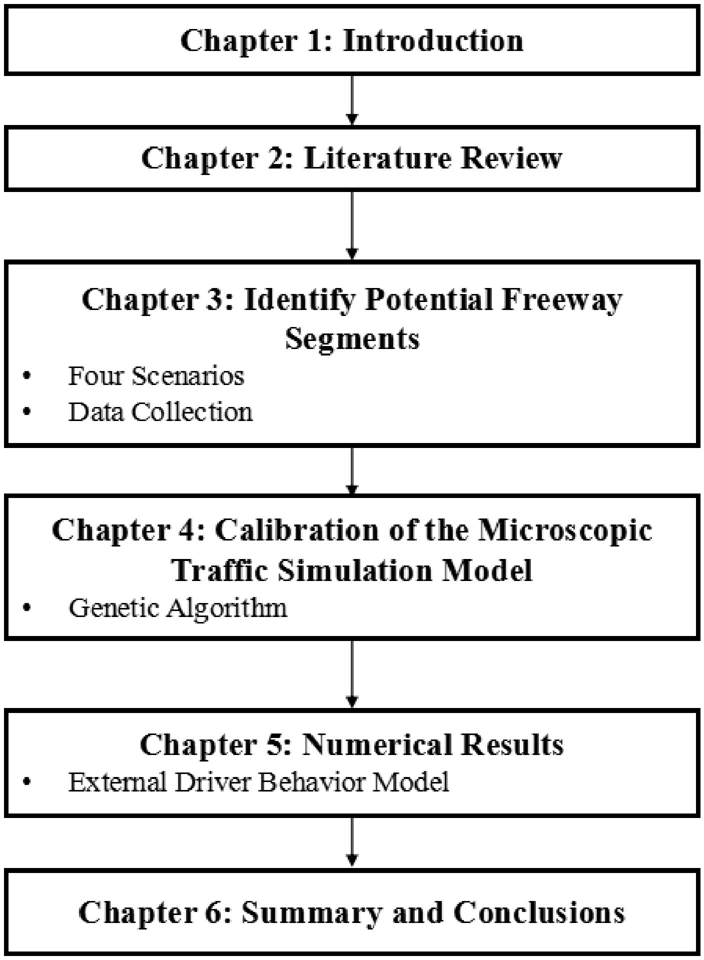

Figure 1.1 Research Structure

Chapter 2. Literature Review

2.1. Introduction

This chapter provides a comprehensive review of the current state-of-the-art and state-of-the-practice of CAV technologies and various methodological approaches to analyze freeway capacity with or without CAVs. This should give a clear picture of existing freeway capacity analysis methods with consideration of CAVs, possible modeling scenarios, and suitable parameters that can be used to estimate the freeway capacity.

The following sections are organized as follows. Section 2.2 presents definitions of connected vehicle and autonomous vehicle technologies, followed by the discussions of current technologies in use and benefits of CAVs. Section 2.3 details existing freeway capacity analysis methods with consideration of CAVs. Particular attention will be given to simulation-based approaches as they are capable of measuring freeway capacity under different modeling scenarios. A suite of possible freeway modeling scenarios and a variety of suitable parameters that can be used to assess the capacity of freeway segments are presented in section 2.4, respectively, with consideration of different CAV penetration level. To get a better understanding of the capability and feasibility of using the simulation methods, several previous studies using simulation methods for freeway capacity analysis are investigated and presented as well. Finally, section 2.5 concludes this chapter with a summary.

2.2. Connected Vehicle and Autonomous Vehicle Technology

2.2.1. Connected Vehicle Technology

Center for Advanced Automotive Technology (CAAT 2018) defines connected vehicles as vehicles that use a number of different communication technologies to communicate with the driver, other cars on the road (V2V), roadside infrastructure (V2I), and the "Cloud" (V2C). V2V technology can enable applications such as cooperative collision warnings and hazard alerts, cooperative collision mitigation or avoidance, while also incorporating active braking. V2I technology can enable vehicle probe data applications, providing detailed traffic information such as speed, volume, travel time, queue length, and stops (Shladover 2017). The U.S. Department of Transportation's Connected Vehicle program is dedicated to new technologies that will enable vehicles to communicate with each other and other infrastructures, by cooperating with state and local transportation agencies and stakeholders (Hong et al. 2014).

By applying connected vehicle technologies, drivers can be noticed in advance of the traffic information, such as traffic delay or an accident occurred ahead. Such information can greatly help drivers adjust their strategy of driving, which could reduce their travel time and also the probability of being involved in a crash. However, the overall travel times for the whole auto mode may still increase due to the increased travel demand (Minelli 2015). According to National Highway Traffic Safety Administration (NHTSA), connected vehicle technologies have the potential to reduce up to 80 percent of crashes where drivers are not impaired. Connected vehicle technologies are a combination of technologies in the following categories:

- In-vehicle or mobile equipment is the most end equipment that provides useful information to drivers, such as vehicle speed and travel time.
- Roadside equipment will interact with connected vehicles with real time information, such as the traffic signal information, and it can also collect vehicle data to support better traffic management.
- Core systems enable the data exchange process between vehicles and infrastructure.
- Support systems create and operate a security credentials management system that allows connected vehicle applications to establish trust in relationships.
- Communications systems comprise the data communications infrastructure that provides connectivity for other equipment and systems in the connected vehicle environment. Dedicated Short Range Communications (DSRC) technology was developed specifically for connected vehicle communications with 5.9 GHz frequency. DSRC provides a low-latency communications link. While the least stringent latency requirement for Active Safety is 1 second and most stringent latency requirement for Active Safety is 0.2 second, DSRC has a latency of 0.0002 second.

Applications-specific systems refer to the equipment supporting specific connected vehicle applications. For example, a software system acquires data from connected vehicles and integrates them into traffic management systems.

2.2.2. Autonomous Vehicle Technology

NHTSA defines autonomous vehicle as "those in which operation of the vehicle occurs without direct driver input to control the steering, acceleration, and braking and are designed so that the driver is not expected to constantly monitor the roadway while operating in self-driving mode." Society of Automotive Engineers (SAE) international defines six levels of vehicle automation from level 0 to level 5. Table 2-1 provides a summary of different level of vehicle automation.

Table 2.1 Summary of Different Level of Vehicle Automation

Level	Description
Level 0	No automation: The human driver does all the driving.
Level 1	Driver assistance: Human driver is assisted with either steering or acceleration/deceleration by the driver assistance system.
Level 2	Partial automation: Driver assistance system undertakes steering and acceleration/deceleration.
Level 3	Conditional automation: Automated driving system with human driver intervene to a request.
Level 4	High automation: Automated driving system undertakes all aspect of the dynamic driving task.
Level 5	Full automation: No human driver needed.

Autonomous vehicles use a "sense-plan-act" design like other robotic systems. A suite of in-vehicle sensors gather information from the surroundings of the vehicle. The automated driving system will analyze sensor data and decide actions in the next step, such as decelerating or lane changing. Autonomous vehicles use a combination of sensors to realize their automotive driving, which include radar, cameras, Lidar, GPS, and so on.

- Radar systems used in autonomous vehicles contain two ranges: short range and long range. Short range radar is used when vehicle speed is relatively low, detecting the vehicle's surroundings within a short distance. Long range radar is used when vehicle speed is relatively high, detecting over long distance.
- Cameras are equipped by autonomous vehicles to work as the human's eyes. Videos are captured and processed so that roadside infrastructure can be recognized, such as signage, lane markings, and traffic lights.
- Lidar creates 3D representations of the vehicle's surroundings by a pulsed laser light, measuring the reflected pulses with the sensor. Although Lidar makes high resolution profiles, it is also easily disrupted by a temporary change of the surroundings, such as rain and snow.
- GPS receives real time location of the autonomous vehicle and navigates the vehicle to its destination.

Litman (2014) explored the impacts of autonomous vehicles on travel demands and transportation planning. The analysis indicated that most impacts, including reduced traffic congestion, increased safety, and reduced pollution, will only be significant when autonomous vehicles become common and affordable, probably in the 2040s to 2060s.

2.2.3. Connected and Autonomous Vehicle Technology

Connected and autonomous vehicle technology is a combination of connected technology and autonomous vehicle technology. CAV can be self-driving and also communicate with its surroundings. Some examples of existing CAV technologies are active lane keeping assistance, active park assistance, automatic braking, blind spot detection, cross traffic alert systems, and forward collision warning. Many transportation agencies such as U. S. Department of Transportation (USDOT) are also working very closely with cities and stakeholders to create real-world test beds to ensure the timely deployment of CAV technologies (Yang et al. 2017).

By incorporating the two technologies together, CAV has many more benefits compared to CV alone, AV alone, and traditional vehicles in the following aspects:

- Increase safety. By eliminating driver errors during driving, CAVs will significantly reduce the number of crashes. CAV technologies may reduce current U.S. crash costs at least by $126 billion per year (Kockelman et al. 2016).
- Increase capacity. CAVs will allow lower headways between vehicles, which will increase roadway capacity.
- Increase mobility. CAVs can increase mobility by providing opportunities to people with disabilities, aging populations, and communities where car ownership

is prohibitively expensive, or those who prefer not to drive (Duncan 2015, NHTSA 2016).

- Reduce emissions. By communicating with each other, CAVs could drive more smoothly than human drivers, which will reduce vehicle emissions and improve air condition.
- Save time. During in-vehicle time, people can perform any activity as necessary instead of driving. When arrived, CAVs can park themselves which will also save time for the drivers and passengers.
- Improve road design. CAVs require narrower lanes and less traffic control methods such as median barriers and traffic lights, maximizing land use and increasing traffic efficiency. The need for human-centered design for parking areas will be significantly reduced (Chapin et al. 2016).

The role of state and local transportation agencies is to develop, maintain, manage, and improve the transportation system in a way that enables individual mobility, supports economic activity, and improves quality of life. State and local transportation agencies should understand the impact of CAV technologies. Planning and policy decisions should be made to maximize the positive effects on a broad public interest (Zmud 2017). Long-term fleet evolution suggests that the privately held light-duty vehicle fleet will have a 24.8% Level 4 AV penetration by 2045 under an annual 5% price drop (Bansal and Kockelman 2017).

2.3. Freeway Capacity Analysis Methods

One critical issue for connected and autonomous vehicle technology is that higher level of automation is still in its infancy. Therefore, there is inadequate empirical data about the use of CAVs and associated impacts. Most researchers used macro and micro traffic simulation, driving simulators, field experiments and analytical methods to estimate the impact of CAVs on freeway capacity (Milakis et al. 2017).

2.3.1. Empirical Based Methods

2.3.1.1. Ni et al.'s research work

Ni et al. (2012) analyzed the impact of connected vehicle technology (CVT) on highway capacity. The model formulation was derived based on Gipps' car following model. The modeling strategy was using different driver perception-reaction time for different driving modes, such as CVT-automated mode, CVT-assisted mode, and non-CVT mode. An illustrative example was provided by employing different market penetration rate of CVT. The result showed that connected vehicle technology could increase highway capacity by 20% to 50% depending on the penetration rate. One limitation of this study was that the model assumed equilibrium flow and homogeneous type of vehicles.

2.3.1.2. Shi and Prevedouros's research work

Shi and Prevedouros (2016) examined the possible impact of driverless cars on freeway capacity based on Highway Capacity Manual 2010 methodologies. The quantification analysis used adjusted average headway and traffic demand flow rate. Two case studies were conducted on a six lane basic freeway segment and a four lane freeway weaving segment. Two types of driverless cars were considered (i.e., autonomous driverless cars and connected driverless cars), by setting different headways. The results showed that the level of service can be improved by increasing penetration rate of driverless cars in traffic and shortening the driverless car following headways.

2.3.1.3. Michael et al. research work

Michael et al. (1998) presented a methodology to calculate highway capacity as a function of vehicle capabilities and control system information structure. The Automated Highway System was assumed to be dedicated for use by fully automated vehicles. The intra-platoon control laws can regulate spacing with very high precision but require additional information that is not available through sensors, such as acceleration and deceleration of the leading vehicle. As such, a high level of inter-vehicle cooperation was needed within the platoon. The authors defined the platoon brake amplification factor, which was the maximum peak braking by any follower/lead vehicle peak braking. The brake amplification factor can be used to determine the inter-platoon spacing required for safety. Under the required spacing between inter-platoon vehicles, collisions can be avoided in the Automated Highway System. Various system parameters were set for capacity calculation, including lags, deceleration capabilities, jerk limits, and vehicle lengths. The pipeline capacity for an Automated Highway System that supports platoons can thus be determined. The minimum inter-vehicle separation was constrained for safe operation. It was concluded that highway capacity increases as the degree of inter-vehicle cooperation increases. Highway capacity increases as platoon length increases and decreases as intra-platoon spacing increases.

2.3.1.4. VanderWerf et al.'s research work

VanderWerf et al. (2002) examined the effects of autonomous and cooperative adaptive cruise control systems on highway traffic flow capacity. Three mathematical models were developed and used to represent vehicles driven by human drivers, Autonomous Adaptive Cruise Control (AACC) system, and Cooperative Adaptive Cruise Control (CACC) system. Monte Carlo simulation approach was used to estimate the lane capacity with the varying proportions of vehicle control types. The highway capacity was measured on a 16-km section on a single lane highway with on- and off-ramps at nodes separated at 1.6-km intervals. The traffic volume at the beginning was set to be significantly less than a conservative estimate of capacity. At each successive node, traffic flow was incremented by a small number of entering vehicles per hour. To keep it realistic, the number of vehicles entering on-ramp and leaving off-ramp were set small enough so that they would not disturb the merging processes both upstream and downstream. It was concluded that AACC system can have only a small impact on highway capacity even under the most favorable conditions. CACC system can increase highway capacity significantly by reducing the time gap between pairs of CACC vehicles. The lane capacity with a full penetration of CACC vehicles can accommodate more than 4,200 vehicles per hour per lane.

2.3.1.5. Pinjari's research work

Pinjari (2013) pointed out that at low autonomous vehicle penetration rates, little improvement of the highway capacity and congestion reduction was expected. The reason is that human drivers would be more likely to keep a longer distance from AVs with consideration of safety. As the penetration rate of AVs increases, the impact on highway capacity could get greater. AV technology can improve traffic flow both on freeways and at highway intersections. It can also avoid traffic collisions at intersections from a safety perspective. In addition, the AV technology allows shorter headways between vehicles and smaller startup lost times at signalized intersections and a smoother stop-and-go traffic. All these benefits can lead to significant reductions in intersection delay and notable increase in highway capacity.

2.3.1.6. Tientrakool et al.'s research work

Tientrakool et al. (2011) assessed the impact of sensors and V2V communication on highway capacity. Different average safe inter-vehicle distances were calculated in different cases, such as leading vehicle can communicate, following vehicle can communicate, and neither the preceding nor following vehicle can communicate. The authors developed a Reliable Neighborcast Protocol which allows each vehicle to reliably communicate with the surrounding vehicles within a specified distance. Three types of vehicles were defined on the highway system (i.e., manual vehicles, vehicles with sensors, and communicating vehicles). The vehicles with sensors would always keep a safe following distance in order to avoid collisions with the preceding vehicle. The communicating vehicles would use the negotiated deceleration rate instead of its actual maximum deceleration rate. The estimated highway capacity will increase by about 43% if all vehicles equipped with sensors. If all the vehicles are communicating vehicles, the capacity could increase significantly by about 3.7 times compared to the highway capacity with human driver vehicles.

2.3.1.7. Treiber et al.'s research work

Treiber et al. (2000) developed an intelligent driver model (IDM) for simulating freeway conditions. The IDM model was a time-continuous car following model using information about the vehicle speed and headways, and the differences between vehicles, to decide acceleration and deceleration rates. Further, the authors developed an enhanced IDM that defines an upper limit of a safe acceleration in an Adaptive Cruise Control (ACC) environment based on the assumption that the leading vehicle will keep its speed for the next few seconds during simulation. By using the empirical boundary conditions, the experimental findings were consistent with a proposed theoretical phase diagram for traffic near on-ramps.

2.3.1.8. Le Vine et al.'s research work

Le Vine et al. (2016) evaluated the interaction between automated cars' kinematic capabilities and the standard legal requirement for operator of an automobile to avoid crashes. The authors compared the capacity values calculated from the HCM-2010 and

Wiedemann-1999 models of human driving behavior and also draw on empirical Naturalistic Driving data to further characterize human-driving behavior. The authors employed traffic microsimulation techniques, using VISSIM software, to assess the hypothesized relationship between intersection capacity and the occupants' ride experience in autonomous cars. The geometry and traffic demand of a schematic signalized intersection were defined first in the analysis. The road network consisted of a single four-way 90 degree signalized intersection with identical single lane approaches on all four legs. All traffic lanes were 12 feet in width. Free flow speed was defined at 50 km per hour for all four legs. Vehicle turning speed was defined manually because VISSIM does not calculate it automatically. Traffic demands on all four approaches were defined to be identical with a ratio of 1:3:1 between left-turning, through, and right-turning traffic. The results suggested that automated cars may sustain higher flow rates at their free-flow speed than human drivers. It is anticipated that autonomous cars will lead to increased roadway capacity and reduce congestion due to shorter headways between vehicles. The traffic streams will be controlled without conflicting and the control methods can be more flexible.

2.3.1.9. Campbell and Alexiadis's research work

Campbell and Alexiadis (2016) comprehensively assessed how connected vehicles should be considered across the range of transportation planning processes. The authors summarized the needs generated by CAV technology for new or enhanced tools, techniques, and data to support various CAV planning activities. The research focused on the needs to take place in order to adapt the Highway Capacity Manual for use in analyzing CAVs. The authors also pointed out the limitation of traffic simulation models. They cannot be used to model certain real-world driver behaviors or situations, such as inattention or collisions. Traffic simulation models require a significant level of input data, such as origin-destination tables for each travel mode. Traffic simulation models also require a substantial investment of time and efforts, including the time needed for the software to perform the simulation once the model is ready.

2.3.1.10. Talebpour and Mahmassani's research work

Talebpour and Mahmassani (2016) presented a framework that utilizes different models with appropriate assumptions to simulate connected and autonomous vehicles. This study presented an acceleration framework to address the limitations of microscopic simulation models in capturing the changes in driver behavior in a mixed environment. Drivers' behavior may change according to the amount of information they receive. Accordingly, four scenarios were defined: Active/Inactive Vehicle-to-Vehicle Communications and Active/Inactive Vehicle-to-Infrastructure Communications. This study presented an approach to model autonomous vehicles using a deterministic acceleration modeling framework due to the ability of autonomous vehicles to constantly monitor other vehicles in their vicinity. Since an autonomous vehicle can only observe vehicles that are located in its sensors detection range, the speed of the autonomous vehicle should be low enough to allow it to stop at the sensors detection range. It was found that with the increase of market penetration rate of CAVs, the throughput will increase more than 100%.

2.3.1.11. Meyer et al.'s research work

Meyer et al. (2017) used the Swiss national transport model to simulate the impact of autonomous vehicles on accessibility of the Swiss municipalities. Three scenarios were considered: advantages of autonomous vehicles can only be realized in extra-urban situations, vehicles can operate fully autonomously in every situation, and a vehicle-sharing scheme is in place. The results showed that autonomous vehicles could cause quantum leap in accessibility.

2.3.1.12. Delis et al.'s research work

Delis et al. (2015) presented two macroscopic approaches to model the dynamics of ACC and CACC traffic flows. The first approach was developed to describe the effects induced by the ACC and CACC systems due to change of the speed of the leading cars by the introduction of an acceleration/deceleration term. The second approach was a novel one and was based on the introduction of a relaxation term that satisfied the time/space gap principle of ACC or CACC systems. The conclusion made was that CACC vehicles increase the stabilization of traffic flow, with respect to both small and large perturbations, compared to ACC vehicles. The proposed CACC approach could improve the dynamic equilibrium capacity and traffic dynamics, especially at the on-ramp bottlenecks.

In summary, car following models are capable of evaluating the impacts of various types of freeway capacity analysis strategies. A variety of empirical-based freeway capacity analysis studies considering CAV technologies have been done to achieve this goal. Table 2-2 exhibits a summary of the empirical freeway analysis studies reviewed in this section.

Table 2.2 Summary of Existing Empirical Based Freeway Capacity Analysis Studies

No.	Author, Year	Vehicle Type	Model	Project Purpose	Capacity Impact
1	Ni et al., 2012	CV	Gipps' car following model	Highway capacity	Increases 20% to 50%
2	Shi and Prevedouros, 2016	CV, AV	HCM 2010	Freeway and weaving segment	Improves LOS
3	Michael et al., 1998	AV	-	Highway capacity	Increases as platoon length increases
4	VanderWerf et al., 2002	AACC, CACC	Three mathematica l models	Highway traffic flow capacity	AACC small, CACC 4,200 vph
5	Pinjari, 2013	AV	-	Highway capacity	Little improvement
6	Tientrakool et al., 2011	Sensors and V2V communicatio n	-	Highway capacity	43% for sensors and 3.7 times for V2V
7	Treiber et al., 2000	ACC	Intelligent driver model	Traffic near on-ramps	-
8	Le Vine et al., 2016	AV	Wiedemann-1999	-	Higher flow rates
9	Campbell and Alexiadis, 2016	CAV	-	Transportation planning process	-
10	Talebpour and Mahmassani, 2016	CAV	-	throughput	100%
11	Meyer et al., 2017	AV	Swiss national transport model	accessibility	Quantum leap in accessibility
12	Delis et al., 2015	ACC, CACC	-	Traffic flow	CACC increases the stabilization of traffic flow

2.3.2. Simulation Based Methods

Simulation based method has been widely used in CAV related studies. Compared to other approaches, simulation based method is imperative for practical decision making in transportation planning and operations. Several representative studies based on the simulation based methods are reviewed.

2.3.2.1. Atkins's research work

Atkins (2016) used VISSIM to explore the impact of connected and autonomous vehicles on traffic flow capacity. Various simulation models, simplified link and junction models and complex real-world situations, were developed to investigate the potential impacts of CAVs under different traffic situations. The results showed that road capacity would increase when CAVs accelerate faster and keep shorter headways. However, when CAVs are more cautious than the existing vehicle fleet, road capacity will decrease by as much as 40%.

2.3.2.2. Shelton et al.'s research work

Shelton et al. (2016) used traffic modeling software to develop and test connected and autonomous vehicle in a complex urban roadway network. In order to approximate real-world conditions, a multi-resolution model that combines aspects from three types of modeling (i.e., macroscopic, mesoscopic, and microscopic) was used. Various market penetrations were simulated to determine the total volume over one hour. The results showed that total volume increases significantly with increasing market penetration rates. Under a simplified test network, the capacity could reach 4,000 vehicles per hour per lane with 100 percent market penetration of CAVs.

2.3.2.3. Hartmann et al.'s research work

Hartmann et al. (2017) used microscopic traffic flow simulation to assess the impact of automated vehicles on freeway capacity. A number of individual freeway component segments were set as input in VISSIM for the simulation, including basic, merge, diverge, and weaving segments. The simulation results showed that an increasing share of partially and highly automated vehicles would lead to a capacity decrease up to 7%. Only with a high penetration rate of connected and automated vehicles that maximizes the cooperative maneuvering and minimizes the headways, there will be a significant increase of road capacity up to 30 %.

2.3.2.4. Shladover's research work

Shladover et al. (2012) used microscopic simulation to estimate the effect of adaptive cruise control and cooperative adaptive cruise control vehicles with varying market penetration rates. The simulation was built on AIMSUN with new driver behavioral models developed in C++ and called by AIMSUN. The results showed that the maximum lane capacity could increase up to 4,000 vph if all vehicles were CACC vehicles. However, the use of ACC was unlikely to significantly change lane capacity.

2.3.2.5. Bierstedt et al.'s research work

Bierstedt et al. (2014) conducted a series of freeway simulations in VISSIM to get an initial estimate of the impacts of adaptive cruise control on capacity. A simple congested freeway network was developed with seven segments including basic, diverge, and merge segments. The authors modified the existing Wiedemann model that exists within VISSIM. Because the operating characteristics of ACC systems are proprietary, the authors opted to initially develop conservative and aggressive scenarios which represent a wide range of possible ACC characteristics. The conservative scenario was characterized by higher headways and lower acceleration/deceleration rates than the base assumptions for manual operation, whereas the aggressive scenario was characterized by the opposite set of assumptions. The results showed that at a 10% ACC penetration, no change is observed. Even at a 75% ACC penetration, the improvements are minor.

2.3.2.6. Auld et al.'s research work

Auld et al. (2017) used an advanced transportation system simulation model named POLARIS, including co-simulation of travel behavior and traffic flow to study the potential effects of several CAV technologies at the regional level. An examination of a wide range of potential scenarios varying the market penetration, capacity changes, and travel time valuations has been conducted. The results showed that an 80% increase in capacity change can increase 4% overall VMT.

2.3.2.7. Lioris et al.'s research work

Lioris et al. (2017) assessed the potential mobility benefits of platoons of connected vehicles. A simulation study of a road network near Los Angeles was conducted using a mesoscopic simulator named PointQ. The input links had exogenous demands modeled as stationary Poisson streams and intersections regulated by fixed time controls and offsets. PointQ is a discrete event simulation that accurately models vehicle arrivals, departures and signal actuation. When a vehicle is discharged from one queue, it travels to a randomly assigned destination queue according to the probability distribution specified by the routing matrix. A standard four-legged intersection capacity can double if vehicles can cross the intersection in platoons with 0.75s headway at 45 mph to achieve a saturation flow rate of 4,800 vph per movement. CACC capability can provide shorter headway than ACC because it can keep a shorter car following distance. CACC may permit lane changing by a vehicle in a platoon. For urban mobility, the network travel demand will increase with the increase of saturation flow rate, without increasing in queuing delay or travel time or changing signal control.

2.3.2.8. Arnaout and Arnaout's research work

Arnaout and Arnaout (2014) explored the effects of cooperative adaptive cruise control on highway traffic flow characteristics of a multilane highway system. The authors used a microscopic traffic simulator, F.A.S.T. that models the interaction of intelligent vehicles on a freeway. The object-oriented model was developed using Java. The new model can manipulate the key variables of car-following model more stochastic. The initial scenario was a 6-km U-shaped four-lane freeway, with cars and trucks sharing available capacity according to a user predefined arrival rate. It was concluded that the CACC impact is not statistically significant under a low-to-moderate penetration rate of CACC. A very large improvement was noticed at a high penetration rate of CACC. A CACC advantage could be observed with a penetration rate of 40% CACC or more.

2.3.2.9. Arnaout and Bowling's research work

Arnaout and Bowling (2011) assessed the impact of CACC systems on traffic performance using microscopic agent-based simulation. The model was simulated on a 6 km highway stretch with a speed limit of 60 mph. An on-ramp was added to the system to create perturbations and provoke stop and go traffic. A constant arrival rate of 500 veh/hr was set for the vehicles entering the freeway from the on-ramp. The result showed that the impact of CACC is maximal in high traffic hours, and especially in high CACC market penetration levels, 40% or higher. The CACC could highly increase the capacity of the highway by increasing the average speed and the rate of flow.

2.3.2.10. Olia et al.'s research work

Olia et al. (2017) assessed the impact of CAVs on highway capacity. Both CAVs and AVs are simulated in a microscopic traffic simulator named PARAMICS. An analytical framework including the new car-following and automated lane-merging models, were developed and evaluated for vehicles driving on a highway segment including an on-ramp. The results indicated that a maximum lane capacity of 6,450 vph per lane is achievable if all vehicles are CACC vehicles. CACC vehicles can significantly increase highway capacity when their market penetration is higher than 30%. For ACC vehicles, the capacity remains within a narrow range of 2,046 to 2,238 vph per lane regardless of market penetration.

2.3.2.11. Monteil et al.'s research work

Monteil et al. (2014) examined the impact of vehicle to vehicle cooperation on the onset of traffic congestion analytically and through simulation. A car-following model and a lane-changing model were implemented and calibrated. The calibration process was a multi-step process. The dataset and the model parameters had to be chosen first. The measure of performance, the goodness of fit and the optimization procedure were the following choices for the quality of the parameters estimation. For the lanes to be calibrated, the trajectory of the follower was computed in each observed leader-follower couples at 15-min intervals. The calibration results enable one to run simulations with realistic synthetic data. It can be observed in simulation that cooperation has the potential to contribute to increasing traffic flow homogeneity and safety as a consequence.

In summary, simulation based models are capable of evaluating the impacts of CAV technologies on freeway capacity. A variety of simulation-based freeway analysis studies have been conducted to achieve this goal. Table 2-3 exhibits a summary of the simulation based freeway analysis studies reviewed in this section.

Table 2.3 Summary of Simulation Based Freeway Analysis Studies

No.	Author, Year	Vehicle Type	Tool	Project Purpose	Capacity Impact
1	Atkins, 2016	CAV	VISSIM	Traffic flow capacity	Decreases 40%
2	Shelton et al., 2016	CAV	Multi-resolution model	Urban roadway network	4,000 vph
3	Hartmann et al., 2017	AV	VISSIM	Freeway capacity	Decreases 7%
4	Shladover et al., 2012	ACC, CACC	AIMSUN	Lane capacity	CACC 4,000 vph
5	Bierstedt et al., 2014	ACC	VISSIM	Freeway capacity	Minor
6	Auld et al., 2017	CAV	POLARIS	Travel behavior	80% increase in capacity can increase 4% VMT
7	Lioris et al., 2017	CV	PointQ	Four-legged intersection	4,800 vph
8	Arnaout and Arnaout, 2014	CACC	F.A.S.T.	U-shaped four-lane freeway	Large improvement with high penetration rate
9	Arnaout and Bowling, 2011	CACC	-	Traffic performance	Highly increases
10	Olia et al., 2017	CAV	PARAMICS	Highway capacity	6,450 vph for CACC, 2,046 to 2,238 for ACC
11	Monteil et al., 2014	CV	-	Traffic flow	Increases traffic flow homogeneity

2.3.3. Survey Based Methods

2.3.3.1. Willke et al.'s research work

Willke et al. (2009) performed an extensive survey of inter-vehicle communication applications. The authors pointed that effective inter-vehicle communication will improve the safety, capacity, and lower traditional barriers to adoption, such as infrastructure cost and complexity.

2.3.3.2. Mahmassani et al.'s research work

Mahmassani et al. (2012) researched and developed a bundle of USDOT-identified high-priority transformative applications entitled Intelligent Network Flow Optimization (INFLO) that fully considers the impact of wireless connectivity on the surface transportation system, including queue warning, dynamic speed harmonization, and CACC. The CVs broadcast their respective speeds with the goal of harmonizing traffic flow and reducing the impending shockwaves caused by congestion in merge/weave areas, thus improving safety on the specific roadway segments.

2.3.3.3. Cregger's research work

Cregger (2015) highlighted major CAV deployment efforts throughout the world and evaluated important factors for successful deployment, using information gathered from interviews, electronic searches, and print materials. The author concluded that various regions all over the world are exploring CAV technologies, such as United States, Europe, and Japan. In the United States, the research is focused on safety, while some states currently have roadside infrastructure deployed. In Europe, normal drivers may begin benefiting from DSRC services with the introduction of the Cooperative ITS Corridor. Japan is far ahead of infrastructure deployment. The author identified best practices that will allow transportation agencies to strengthen their CAV programs.

2.3.3.4. Kockelman et al.'s research work

Kockelman et al. (2016) estimated the adoption of connected and autonomous vehicle technologies over the long term through the use of two surveys. The national survey investigated each respondent's current household vehicle inventory, their technology adoption, future vehicle transaction decisions, and so on. The Texas-based survey examined a variety of perception and attitude analyses using various econometric models. The authors believed that with more familiarity with CAV technologies, the potential behaviors are apt to change rapidly.

2.3.3.5. Schoettle and Sivak's research work

Schoettle and Sivak (2014) conducted a survey examining public opinion regarding self-driving vehicle technology in U.S., U.K., and Australia. The majority of respondents expressed a desire to have this technology in their vehicle, with a high level of concern about security issues related to self-driving vehicles and self-driving vehicle not performing as well as actual drivers.

In summary, survey based method is capable of evaluating the public attitude towards the CAV technologies. A variety of survey-based freeway analysis studies have been done to achieve this goal. Table 2-4 exhibits a summary of the empirical based freeway analysis studies reviewed in this section.

Table 2.4 Summary of Survey Based CAV Studies

No.	Author, Year	Content	Object	Findings
1	Willke et al., 2009	Inter-vehicle communication	-	Decreases 40%
2	Mahmassani et al., 2012	Wireless connectivity	-	Harmonizes traffic flow and reduces the impending shockwaves
3	Cregger, 2015	CAV	Interview, electronic searches, print materials	Identified best practices to strengthen CAV programs
4	Kockelman et al., 2016	CAV	National survey, Texas survey	Potential behaviors are apt to change rapidly
5	Schoettle and Sivak, 2014	AC	US, UK, Australia	High level of concern about security

2.4. Freeway Modeling Scenarios and Parameters

Davis (2007) examined the effect of adaptive cruise control systems on mixed traffic flow near an on-ramp. A random mixture of ACC and manually driven vehicles were simulated merging from an on-ramp to the mainline freeway. In this paper, cooperative merging was proposed to increase throughput and increase distance traveled in a fixed time (i.e., reduce travel times). In such a system, an ACC vehicle senses not only the preceding vehicle in the same lane but also the vehicle immediately in front in the opposite lane. Prior to reaching the merge region, the ACC vehicle adjusts its velocity to ensure that a safe gap for merging is obtained. If on-ramp demand is moderate, partial implementation of cooperative merging where only mainline ACC vehicles react to an on-ramp vehicle is effective. With cooperative merging being proposed, significant improvement in throughput (18%) could be achieved and up to 3 km in distance traveled in 500 seconds were found for a penetration rate of 50% ACC vehicles.

Kesting et al. (2008) proposed and simulated a modified CACC system with both V2V and V2I technologies, which optimized vehicle speed and acceleration by altering CACC driving characteristics. The authors simulated their system on a 13-km, three-lane stretch of the German Autobahn during rush hour conditions. The results showed that even a small percent of CACC vehicles can lead to an improvement of traffic flow quality and reduce the travel time.

Hussain et al. (2016) defined three different CAV technology scenarios, neutral, conservative, and aggressive, in two operational environments: single-lane and managed lane. The results showed that as the CAV penetration rate increases, the freeway capacity also increases. More aggressive CAV technologies need less specifically allocated lanes because they can follow the vehicles with less headway.

Fernandes and Nunes (2010) used new models to conduct research of cooperative and autonomous communication-enabled vehicles platoon in SUMO (Simulation for Urban MObility). The platoon leaders' parameters were controlled externally with the TraCI package. The remaining vehicles were controlled by the SUMO itself. The microscopic simulation scenario consisted of a lane with approximately 5 kilometers long. The platoon contained eight vehicles with a length of 3 meters each. The leading vehicle maintained a speed of 5 m/s. The following vehicles adapt their acceleration patterns to approach their precedent vehicle by accelerating first then braking slightly afterwards to conclude the approaching procedure. After the platoon formation stabilizes, the eight vehicles would follow the leader with one meter apart.

Fernandes and Nunes (2015) proposed multi-platooning leaders positioning and cooperative behavior strategies to improve the efficiency of a traffic system of communicant automated vehicles evolving on dedicated lanes. The platooning system was implemented in the SUMO traffic simulator. The scenario consisted of a dedicated track 3,965 m long with ten offline stations. The maximum number of vehicles of each platoon was eight. Three transportation modes were simulated, including platoon vehicle, bus, and light rail. The results suggested that the CAV platooning performs better in both capacity and travel time metrics. The capacity would be 7,200 passengers per hour. Platooning may help improve lane capacity, particularly if constant vehicles' spacing is used in the platoons.

Past research has sought better understanding of how freeway capacity is simulated. Based on the literature review as presented above, Table 2-5 exhibits a summary of the existing freeway modeling scenarios using simulation methods. Note that the following parameters were used in the simulation models.

- CC0 standstill distance (ft)
- CC1 headway time (sec)
- CC2 following variation (ft)
- CC3 threshold for entering following
- CC4 negative following threshold
- CC5 positive following threshold
- CC6 speed dependency of oscillation
- CC7 oscillation acceleration (ft/sec^2)
- CC8 standstill acceleration (ft/sec^2)
- CC9 acceleration at 50 mph (ft/sec^2)

Table 2.5 Summary of Freeway Modeling Scenarios

No.	Author, Year	Vehicle Type	Scenarios	Findings
1	Davis, 2007	ACC	Mixed traffic near on-ramp	18% improvement in throughput
2	Kesting et al., 2008	CACC	13-km, three-lane stretch	Improvement traffic flow quality and reduce travel time
3	Hussain et al., 2016	CAV	Single-lane and managed lane	Less specifically allocated lanes needed
4	Fernandes and Nunes, 2010	CAV	5-km lane	Platoon stabilized at eight vehicles with one meter apart

2.5. Summary

A comprehensive review and synthesis of the current state-of-the-art and state-of-the-practice of past research efforts related to connected and autonomous vehicle technology, freeway capacity analysis methods, simulation scenarios, and parameters have been discussed and presented in the preceding sections. This is intended to provide a solid reference and assistance in formulating freeway capacity analysis methods and developing effective simulation strategies for future tasks.

Chapter 3. Identify Potential Freeway Segments

3.1. Introduction

As discussed in the literature review conducted in Chapter 2, this chapter will identify potential freeway segments and collect necessary data related to the select freeway segments. Based on the literature review in Chapter 2, a set of freeway segments will be selected with different scenarios, such as on-ramp(s), off-ramp(s), and lane drop(s). The California Department of Transportation (Caltrans) Performance Measurement System (PeMS) database is used as the source to determine the potential freeway segments.

The following sections are organized as follows. Section 3.2 presents information about the Caltrans Performance Measurement System. Section 3.3 details potential freeway segments with necessary data related to the select freeway segments. Finally, section 3.4 concludes this chapter with a summary.

3.2. The Caltrans Performance Measurement System

In this chapter, the Caltrans Performance Measurement System is used to select potential freeway segments. The PeMS is briefly introduced in this section.

3.2.1. Introduction to PeMS

PeMS was first started in 1999 as a university research project and now has been deployed statewide across California. There are over 35,000 detectors which can report real-time traffic data every 30 seconds. To use PeMS, users have to apply for an online account through the PeMS homepage. Then users are able to access the PeMS database via a standard internet browser with no charge generated.

PeMS is a web-based database which provides users real-time and historical traffic data in different aspects, such as speed, flow, capacity, and delay. By using PeMS, researchers can conduct research with the comprehensive information on selected freeway segments, identify congestion bottlenecks, evaluate freeway performance, and make better decisions on freeway operation.

A consolidated real-time traffic data can be collected by PeMS. The raw data sent to PeMS are from the following sources (PeMS 2001):

- Intelligent Transportation System Vehicle Detector Stations
- Traffic Census Stations
- Weight-In-Motion Sensors
- California Highway Patrol Incident data
- The Caltrans Traffic Accident Surveillance and Analysis System accident data
- The Caltrans Photolog
- Lane Closure information from the Caltrans Lane Closure System
- Electronic Toll Collection Reader data

- Changeable Message Signs
- Arterial Detector data and Timing Plans
- Transit data such as routes and schedules, Automated Vehicle Location and Automated Passenger Count data

3.2.2. PeMS Data Sources

Data are collected by PeMS from various types of vehicle detector stations, including inductive loops, side-fire radar, and magnetometers. The inductive loops are the most common detection devices used by PeMS. The inductive loops are installed at specific locations on the freeways, with a controller in a cabinet at the roadside recording the data. The inductive loops collect traffic flow and vehicle occupancy data and then send the information to PeMS through the controller every 30 seconds.

There are also other data sets that can provide information to the PeMS database. The detector configuration information is provided by the Caltrans Districts. Caltrans Headquarters provide freeway configuration information (i.e., number of lanes), and incident information (i.e., number of collisions and type of collisions).

3.2.3. Functionality of PeMS

Users can query real-time and historical traffic data from PeMS to conduct analyses. PeMS provides users summary reports on current freeway information, historical freeway performance, freeway detectors health, and freeway incidents information. Several freeway performance data can also be obtained, such as traffic volume, vehicle speed, traffic delay, vehicle miles traveled (VMT), vehicle hours traveled (VHT), and annual average daily traffic (AADT). With the assistance of PeMS, users can conduct both simple and advanced traffic analyses, such as Highway Capacity Manual analyses, Synchro analyses, and traffic simulations. The PeMS data can be used as an input to the simulation models for research projects and other transportation planning objectives. Users can also use PeMS data for model calibration so that more accurate results can be achieved under the real-world traffic condition. Below are some examples of what PeMS can do (PeMS 2001):

- Export data in different formats including Excel file, CSV text file, HTML tables, and plots.
- Integrate with current internet-based mapping tools, such as Google Maps and Google Earth.
- Compute basic freeway performance measures, such as flow, speed, truck volume, delay, and Level of Service.
- Compute advanced freeway performance measures, such as VMT ratio and VHT ratio, by vehicle occupancy for a designated lane facility (i.e. High Occupancy Vehicle lanes).
- Conduct special freeway system analyses including managed facility performance measures, Lane Closure System (LCS) analysis, and Corridor System Management Plan (CSMP) analysis.
- Provide users with incident information from third-party sources through a modular framework.

- Identify freeway bottlenecks, recurrent or non-recurrent congestion through a special algorithm.
- Produce summary reports of different variables with animated graphics to visualize freeway conditions.

3.3. Potential Freeway Segments

Three different freeway segments are selected through the PeMS database as potential simulation scenarios. In order to identify the impact of CAV technology under different freeway scenarios, the selected freeway segments contain a mix of configurations, such as on-ramp, off-ramp, and weaving area. All three freeway segments are selected around the City of Los Angeles, a large population area. These sites are selected because their preexisting congestion issues during the peak hour, as well as the fact that they are the major interstate freeways with high traffic volumes. According to the literature review in Chapter 2, each selected freeway segment has a length of around 3 miles. Table 3-1 provides a summary of the length of the simulation scenarios in previous studies. The following sections will describe each freeway segment in detail.

Table 3.1 Summary of the Length of Simulation Scenarios in Previous Studies

Authors	Length of Scenarios
Atkins (2016)	1 km Single-lane link
Atkins (2016)	1 km Multi-lane link
Bierstedt, J. et al. (2014)	3.2 mi Mix of merge, diverge and weaving area
Arnaout, G., and Bowling, S. (2011)	6 km
Olia et al. (2017)	20 km Two-lane with an on-ramp
Kesting et al. (2008)	13 km
Shelton (2016)	12 mi Corridor
Fernandes and Nunes (2010)	5 km
Arnaout and Arnaout (2014)	6 km U-shaped four-lane freeway
Fernandes and Nunes (2015)	4 km

3.3.1. I10 EB Postmile 7.36 – 10.08

The first freeway segment is a mainline segment of I-10 freeway eastbound in the west of downtown LA. It has a total length of 2.72 miles including three weaving sections with distances of 2,700 ft, 2,200 ft, and 2,800 ft, respectively. Figure 3.1 shows the location of the freeway segment. Figure 3.2 provides a detailed configuration of the freeway segment. The selected freeway segment is inside the orange square. The blue lines in the freeway segment are vehicle detector stations, including vehicle detectors in each lane of the freeway. These vehicle detectors collect, store, and process real-time traffic data and send them to PeMS. Table 3-2 shows an example of the roadway information provided by the vehicle detector station VDS 717022.

Figure 3.1 Freeway Segment at I-10 EB

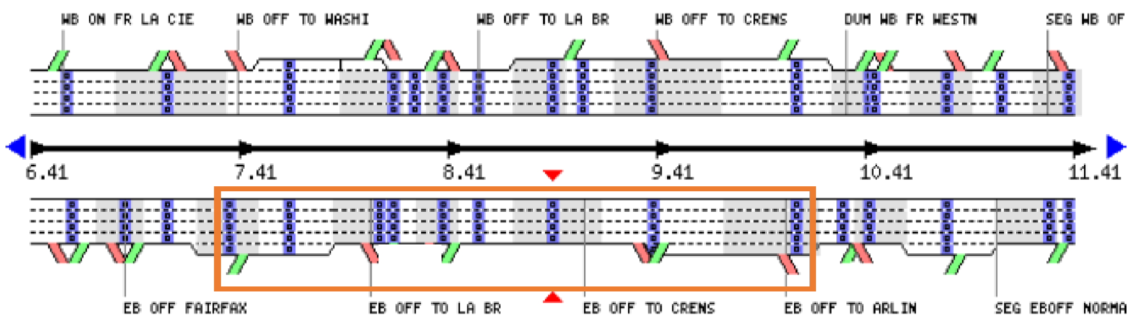

Figure 3.2 Configuration of Freeway Segment at I-10 EB

Table 3.2 Roadway Information Provided by VDS 717022

Roadway Information	
Road Width	60 ft
Lane Width	12.0 ft
Inner Shoulder Width	10 ft
Inner Shoulder Treated Width	10 ft
Outer Shoulder Width	10 ft
Outer Shoulder Treated Width	10 ft
Design Speed Limit	70 mph
Functional Class	Principal Arterial W/ C/L Prin Arterial
Inner Median Type	Paved - No Roadway Use
Inner Median Width	22 ft
Terrain	Flat
Population	Urbanized
Barrier	Concrete Barrier
Surface	Concrete

Figure 3.3 shows the daily traffic flow collected by VDS 717022 on Monday 02/19/2018.

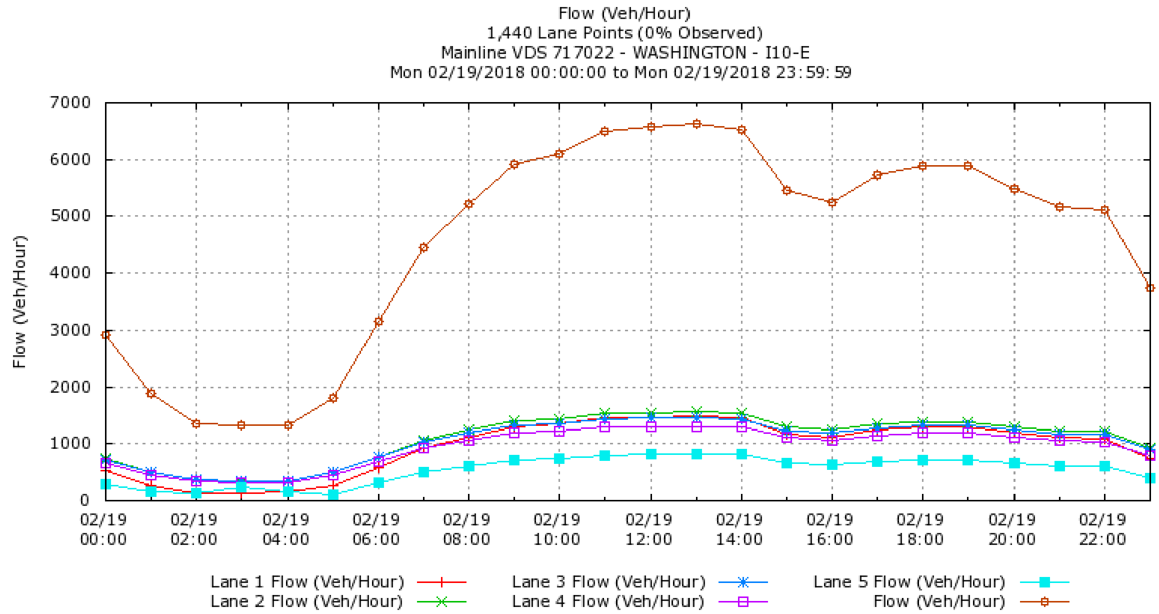

Figure 3.3 Daily Traffic Flow Example at VDS 717022

Figure 3.4 shows the daily traffic speed collected by VDS 717022 on Monday 02/19/2018.

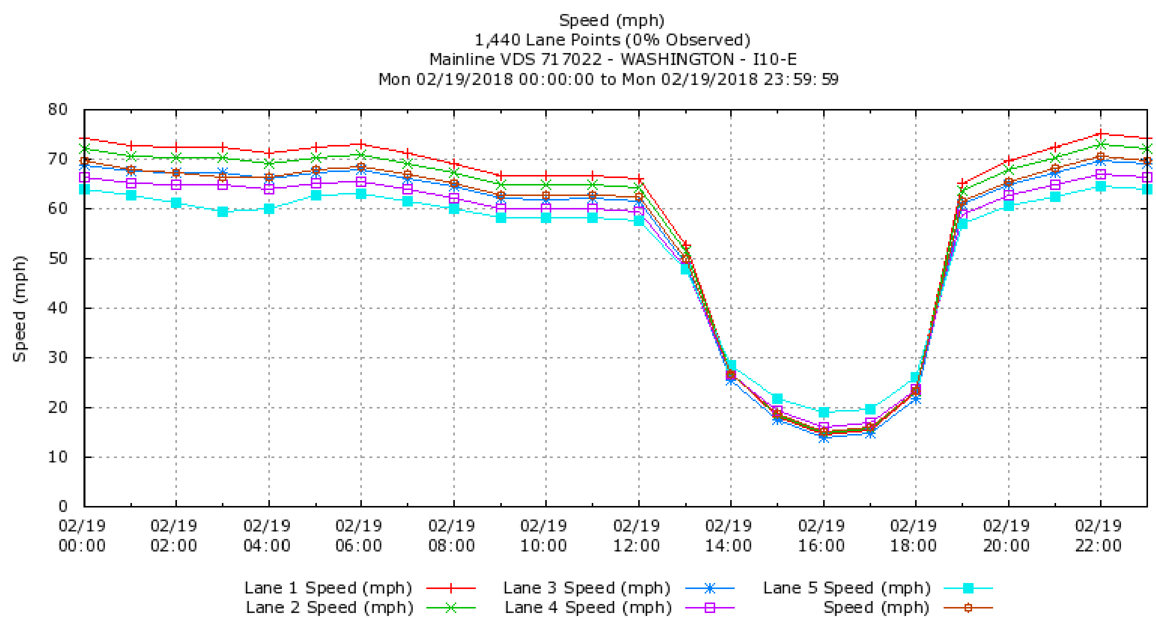

Figure 3.4 Daily Traffic Speed Example at VDS 717022

3.3.2. I-110 North Bound Postmile 15.03 – 17.90

The second freeway segment is a mainline segment of I-110 freeway northbound in the south of downtown LA. It has a total length of 2.87 miles including four weaving sections with distances of 2,900 ft, 1,500 ft, 650 ft, and 550 ft, correspondingly. FIGURE 3.5 shows the location of the freeway segment. FIGURE 3.6 provides a detailed configuration of the freeway segment. Table 3-3 shows an example of the roadway information provided by the vehicle detector station VDS 763384.

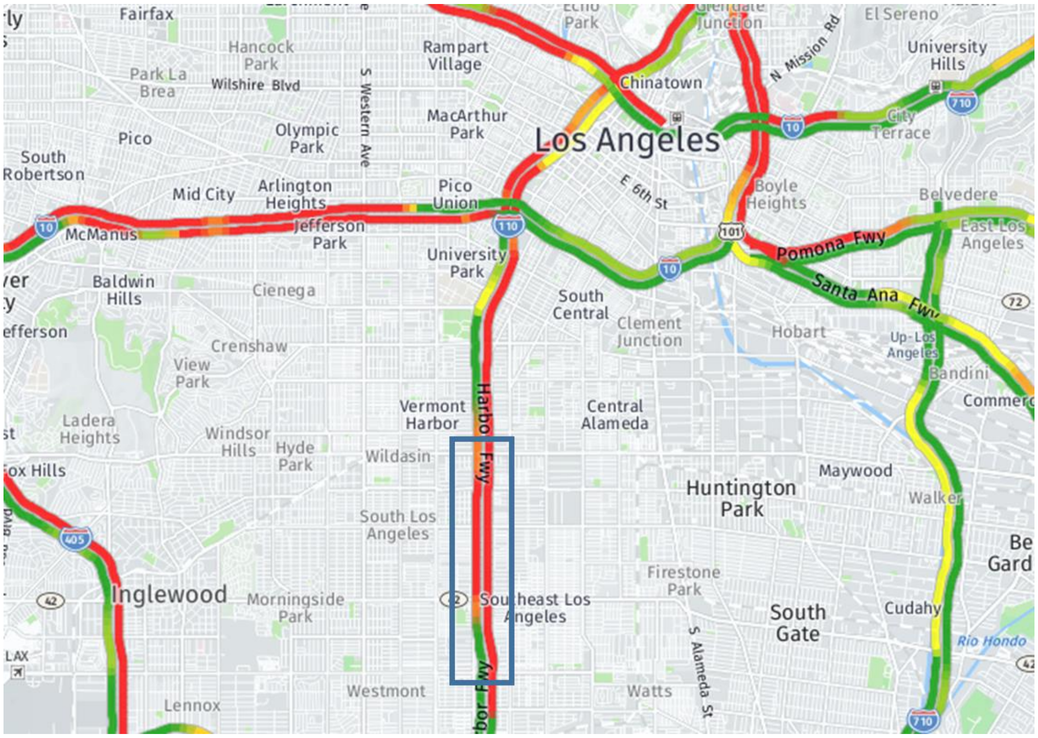

Figure 3.5 Freeway Segment at I-110 NB

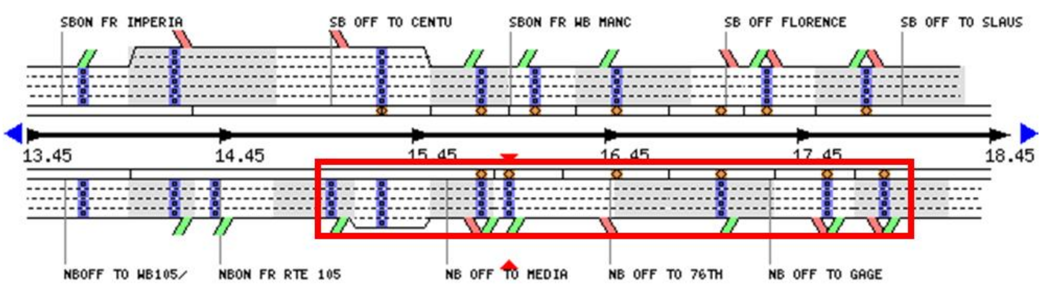

Figure 3.6 Configuration of Freeway Segment at I-110 NB

Table 3.3 Roadway Information Provided by VDS 763384

Roadway Information	
Road Width	48 ft
Lane Width	12.0 ft
Inner Shoulder Width	7 ft
Inner Shoulder Treated Width	7 ft
Outer Shoulder Width	10 ft
Outer Shoulder Treated Width	10 ft
Design Speed Limit	70 mph
Functional Class	Principal Arterial W/ C/L Prin Arterial
Inner Median Type	Paved - No Roadway Use
Inner Median Width	16 ft
Terrain	Flat
Population	Urbanized

Barrier	Concrete Barrier w/Glare Screen
Surface	Concrete

FIGURE 3.7 shows the daily traffic flow collected by VDS 763384 on Monday 02/19/2018.

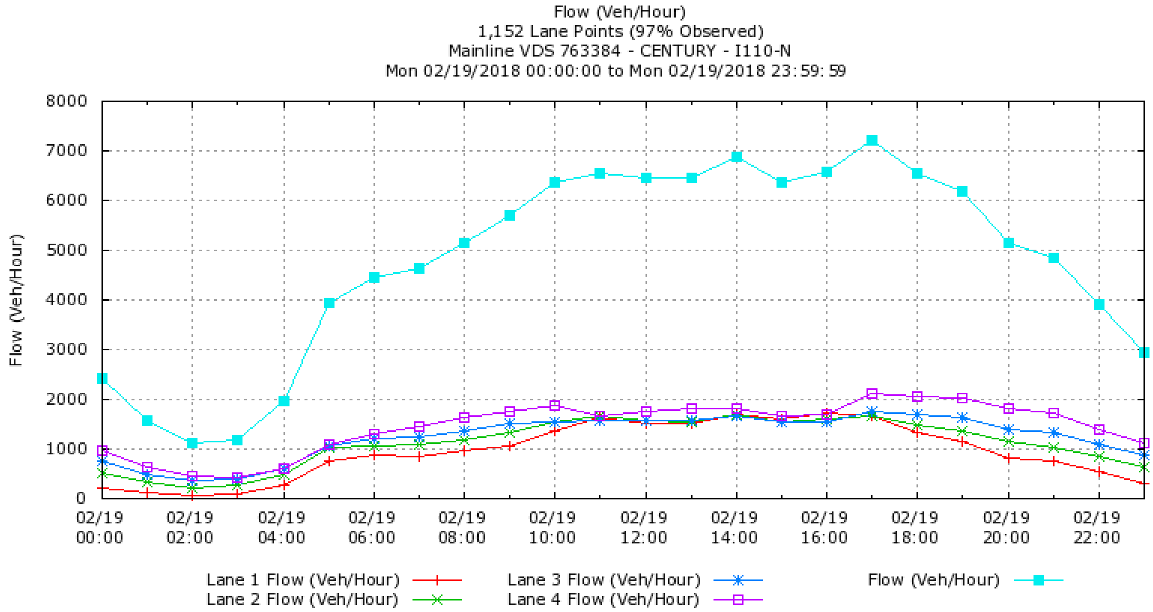

Figure 3.7 Daily Traffic Flow Example at VDS 763384

FIGURE 3.8 shows the daily traffic speed collected by VDS 763384 on Monday 02/19/2018.

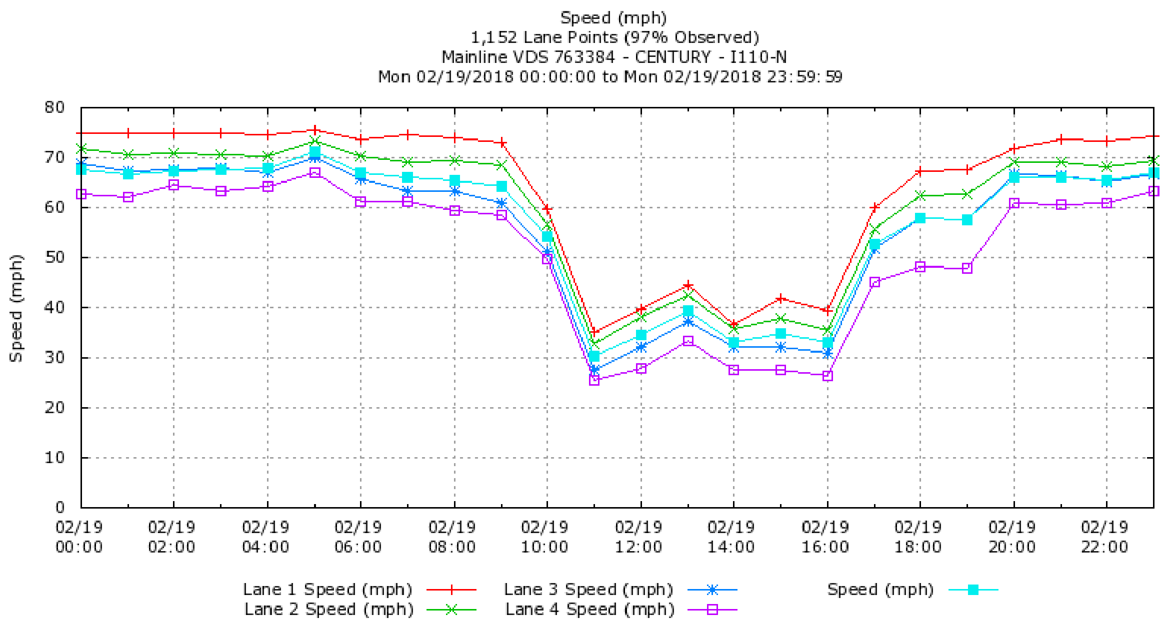

Figure 3.8 Daily Traffic Speed Example at VDS 763384

3.3.3. I-405 South Bound Postmile 69.87 – 66.22

The third freeway segment is a mainline segment of I-405 freeway southbound in the northwest of downtown LA. It has a total length of 3.65 miles including three on-ramp and off-ramp pairs with distances of 5,700 ft, 3,100 ft, and 5,100 ft, respectively. Also, this freeway segment has a lane drop from six lanes to four lanes. FIGURE 3.9 shows the location of the freeway segment. FIGURE 3.10 provides a detailed configuration of the freeway segment. Table 3-4 shows an example of the roadway information provided by the vehicle detector station VDS 737529.

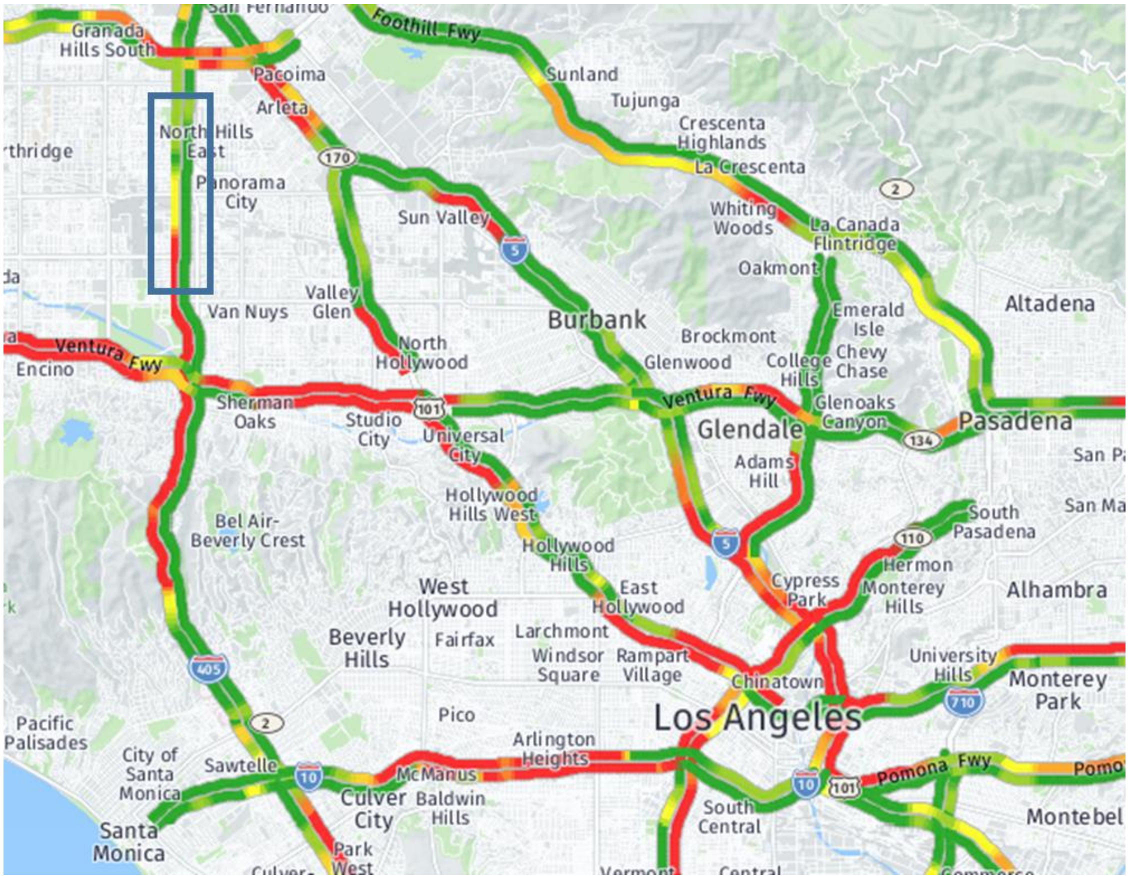

Figure 3.9 Freeway Segment at I-405 SB

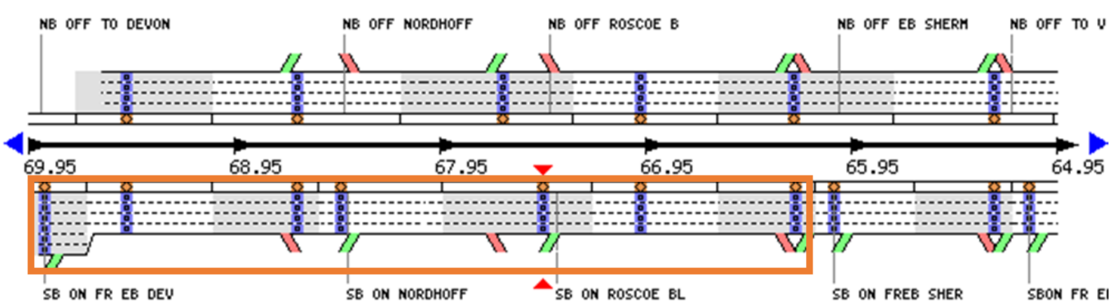

Figure 3.10 Configuration of Freeway Segment at I-405 SB

Table 3.4 Roadway Information Provided by VDS 737529

Roadway Information	
Road Width	56 ft
Lane Width	11.2 ft
Inner Shoulder Width	1 ft
Inner Shoulder Treated Width	1 ft
Outer Shoulder Width	0 ft
Outer Shoulder Treated Width	0 ft
Design Speed Limit	70 mph
Functional Class	Principal Arterial W/ C/L Prin Arterial
Inner Median Type	Paved - No Roadway Use
Inner Median Width	6 ft
Terrain	Flat
Population	Urbanized
Barrier	Concrete Barrier
Surface	Bridge Deck

FIGURE 3.11 shows the daily traffic flow collected by VDS 737529 on Monday 02/19/2018.

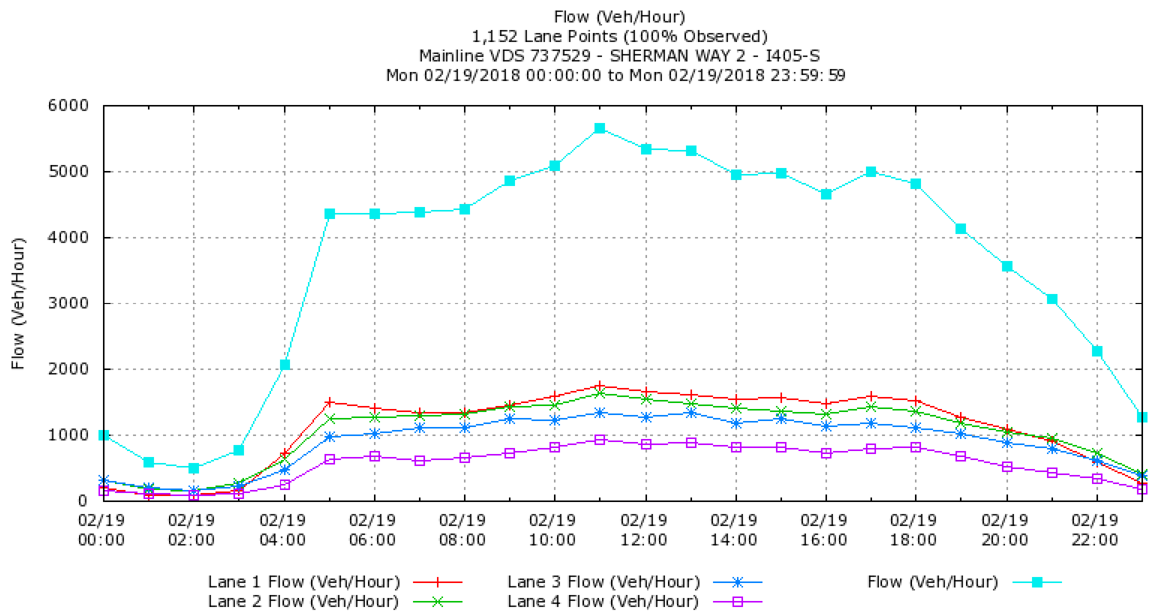

Figure 3.11 Daily Traffic Flow Example at VDS 737529

FIGURE 3.12 shows the daily traffic speed collected by VDS 737529 on Monday 02/19/2018.

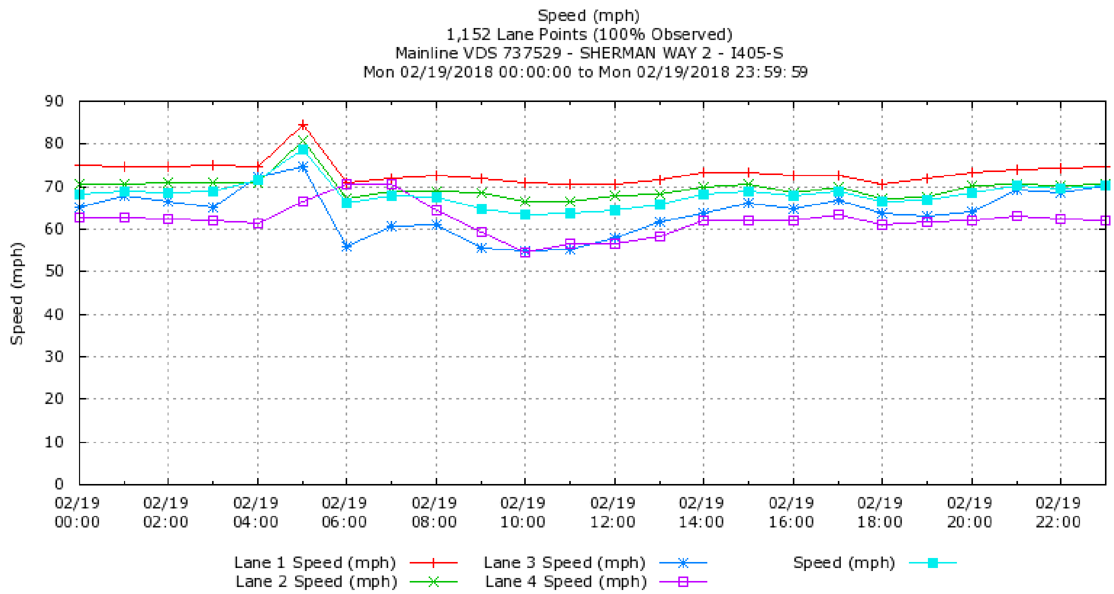

Figure 3.12 Daily Traffic Speed Example at VDS 737529

3.4. Summary

PeMS provides real-time traffic data across the state of California. A comprehensive introduction to PeMS has been presented in the preceding section. After examining the PeMS database, three freeway segments have been selected as potential simulation scenarios. The selected freeway segments contain a mix of merging, diverging, and weaving area. There are vehicle detector stations before and after each merging, diverging, and weaving area. The basic information about the selected freeway segments is discussed and traffic speed and flow data from three vehicle detector stations are shown as an example of the necessary data related to the selected freeway segments. This is a basic preparation for simulating freeway capacity with CAV technologies in the future tasks.

Chapter 4. Calibration of the Microscopic Traffic Simulation Model

4.1. Introduction

Microscopic simulation models have been widely employed in transportation planning and operational analysis. Compared to field testing, simulation provides a safer, faster, and costless environment for researchers. However, in order to obtain reliable results through simulation, the parameters of microscopic simulation models need to be calibrated. The calibration procedure can minimize the differences between the simulation results and the realistic field data, such as traffic volumes and speed. This chapter presents the calibration procedure for the microscopic simulation model built in VISSIM by a case study from a freeway segment selected from PeMS. VISSIM contains numerous default parameters to describe traffic flow characteristics and driver behavior. It also allows users to input other values for the parameters. To obtain a better match between the simulation results and the observed data, a proper calibration of the VISSIM parameters needs to be conducted. Genetic Algorithm (GA) is employed to find the optimal set of parameters being calibrated so that the objective function can be minimized. GA has been used by many researchers as a calibration method for micro-simulation models and it has been proven that near-global optima can be obtained.

This chapter is organized as follows. Section 4.2 presents the study site selected through PeMS for conducting the calibration procedure. Section 4.3 describes the objective function used in the calibration including proper performance measures. Section 4.4 introduces the GA process and section 4.5 presents the set of parameters in VISSIM being calibrated. Section 4.6 shows the calibration results. Finally, in section 4.7, a summary concludes this chapter.

4.2. Study Site

The study site used for the conduct of case study in this paper is a basic freeway segment that is selected through the PeMS database. The freeway segment is a portion of the I-405 freeway located in the city of Los Angles, California, as shown in Figure 4.1 (within the rectangular area). This freeway stretch is a four-lane basic freeway segment with a total length of 2100 ft. The study period spans 1 hour of the a.m. peak, from 7:00 to 8:00 a.m. on May 16th, 2018, and the field traffic data (i.e. flow and speed) are aggregated into 5-min counts. Table 4-1 shows the traffic flow and speed in each lane during a 5-min interval. And the right two columns show the total traffic flow and the average traffic speed of four lanes.

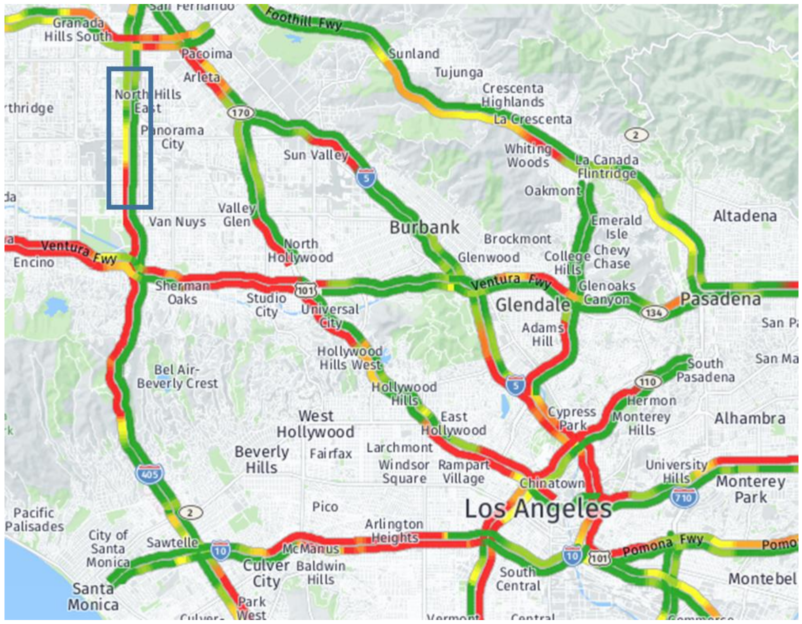

Figure 4.1 Map of the Study Site at I-405 from the PeMS

Table 4.1 Traffic Flow and Speed throughout the Study Period

Time	**Lane 1 Flow (Veh/5 Minutes)**	**Lane 1 Speed (mph)**	**Lane 2 Flow (Veh/5 Minutes)**	**Lane 2 Speed (mph)**	**Lane 3 Flow (Veh/5 Minutes)**	**Lane 3 Speed (mph)**	**Lane 4 Flow (Veh/5 Minutes)**	**Lane 4 Speed (mph)**	**Flow (Veh/5 Minutes)**	**Speed (mph)**
7:00	98	73.70	114	67.60	113	60.10	75	57.00	400	65.00
7:05	132	73.20	134	68.00	116	57.80	77	55.60	459	64.80
7:10	116	73.00	122	66.50	120	56.00	85	52.70	443	62.70
7:15	122	71.90	141	66.00	136	57.30	92	56.60	491	63.30
7:20	135	69.60	153	65.30	133	56.30	116	54.30	537	61.80
7:25	139	69.50	158	65.10	132	55.20	114	53.80	543	61.40
7:30	131	70.00	148	64.80	150	56.20	110	55.40	539	61.80
7:35	154	69.90	155	64.40	142	56.80	113	54.10	564	61.90
7:40	150	71.00	142	63.90	135	54.80	113	52.80	540	61.30
7:45	146	68.60	159	62.90	140	54.70	127	52.10	572	60.00
7:50	136	70.30	152	64.50	155	52.80	111	50.80	554	59.90
7:55	136	70.90	145	66.10	152	56.10	115	53.80	548	61.90

4.3. Objective Function

In order to minimize the discrepancy between observed and simulated traffic data, the parameters of the microscopic traffic simulation model should be calibrated for the existing human driven vehicles. In this regard, the general optimization framework is formulated as follows.

$$min\, f(\boldsymbol{V}^{obs}, \boldsymbol{V}^{sim})$$

Subject to the constraints:

$$\boldsymbol{l}_{x_i} \leq \boldsymbol{x}_i \leq \boldsymbol{u}_{x_i}, i = 1 \ldots n,$$

where

$\boldsymbol{x}_i$= the model parameters to be calibrated.
$f(.)$= objective function.
$\boldsymbol{V}^{obs}, \boldsymbol{V}^{sim}$= observed and simulated value of model parameters being calibrated.
$\boldsymbol{l}_{x_i}, \boldsymbol{u}_{x_i}$= the respective lower and upper bounds of model parameter $\boldsymbol{x}_i$.
n = number of variables.

In this study, the objective function uses the Mean Absolute Normalized Error (MANE), which is provided by following equation. The calibration problem using the flow and speed data as performance measures is formulated as follows:

$$Minimize\ MANE(\boldsymbol{q}, \boldsymbol{v}) = \frac{1}{N}\sum_{i=1}^{N}(\frac{|\boldsymbol{q}_{obs,i} - \boldsymbol{q}_{sim,i}|}{\boldsymbol{q}_{obs,i}} + \frac{|\boldsymbol{v}_{obs,i} - \boldsymbol{v}_{sim,i}|}{\boldsymbol{v}_{obs,i}})$$

where

$\boldsymbol{q}_{obs,i}, \boldsymbol{q}_{sim,i}$= observed and simulated traffic flow for a given time period i.
$\boldsymbol{v}_{obs,i}, \boldsymbol{v}_{sim,i}$= observed and simulated traffic speed for a given time period i.
N = total number of observations.

4.4. Genetic Algorithm

Genetic Algorithm is available to achieve near-global optima during the calibration procedure of the microscopic traffic simulation model. The GA is an inspiration of biological evolution process with selection, crossover and mutation as its three steps. The GA starts from a random population set. For each generation, the better solutions have higher probabilities to be selected and used to generate new populations after crossover and mutation within the selected solutions. In this study, the population size is set to be 10, and the crossover and mutation rate are set to be 0.8 and 0.2, respectively. The max generation number is 20. The GA-based calibration is conducted through MATLAB. A population of binary chromosomes is generated randomly at the very beginning and each represents a feasible solution. Then the chromosomes are decoded to relative model parameters and passed onto the VISSIM for simulation. The objective function value is calculated based on the simulated traffic flow and speed data. The calibration process will not stop until the maximum number of generation is reached or the stopping criterion is met. Figure 4.2 shows the GA calibration process.

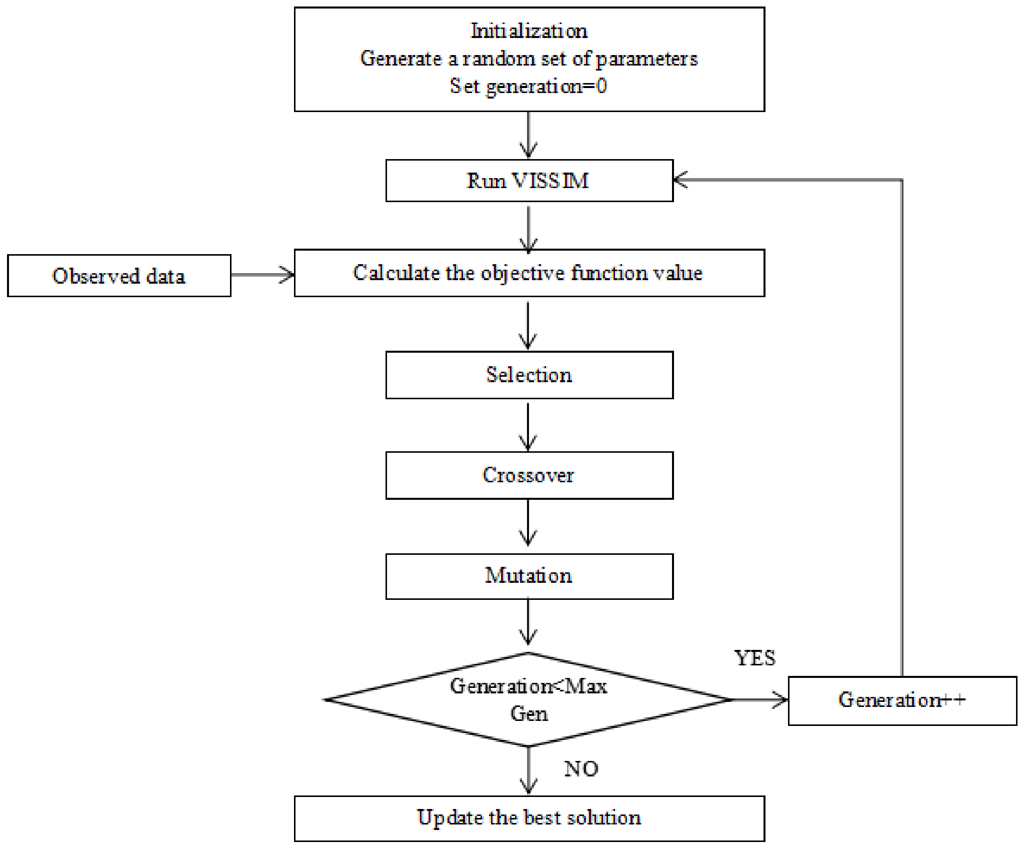

Figure 4.2 GA Calibration Process

4.5. VISSIM Calibration Parameters

VISSIM uses the Wiedemann's car following model to capture the physical and human components of vehicles. As the Wiedemann model stated, a vehicle has four driving modes: free driving, approaching, following and braking. The Wiedemann 99 car following model was developed in 1999 to provide better control of the car following characteristics for freeway modeling in VISSIM. The model consists of ten unique parameters (i.e. CC0, CC1, …, CC9) representing the car following characteristics. CC0 (standstill distance) defines the desired distance between stopped cars. CC1 (headway time) is the time that a driver wants to keep. The higher the value, the more cautious the driver is. Thus, at a given speed v, the safety distance *dx_safe* is defined as follows:

$$dx\_safe = CC0 + CC1 \times v$$

The safety distance is defined in the model as the minimum distance a driver will keep while following the preceding car. In case of high volume, this distance decided by CC0 and CC1 becomes the value with the strongest influence on capacity. Other than CC0 and CC1, CC2-CC5 and CC7 can also significantly affect the simulation flows (Lownes and Machemehl, 2006). So, in this study, CC0-CC5 and CC7 are selected as the model parameters for calibration.

4.6. Calibration Results

The optimized value of CC0 calibrated by the GA is 2.20 ft compared to the default value of 4.92 ft. And the optimized value of CC1 calibrated by the GA is 1.2 seconds compared to the default value of 0.9 seconds. Figure 4.3 presents the GA objective function MANE values during the optimization period. The y-axis represents the minimum objective function value up to every generation and the x-axis denotes the number of generations. Table 4-2 shows all the calibration results for the car following model parameters.

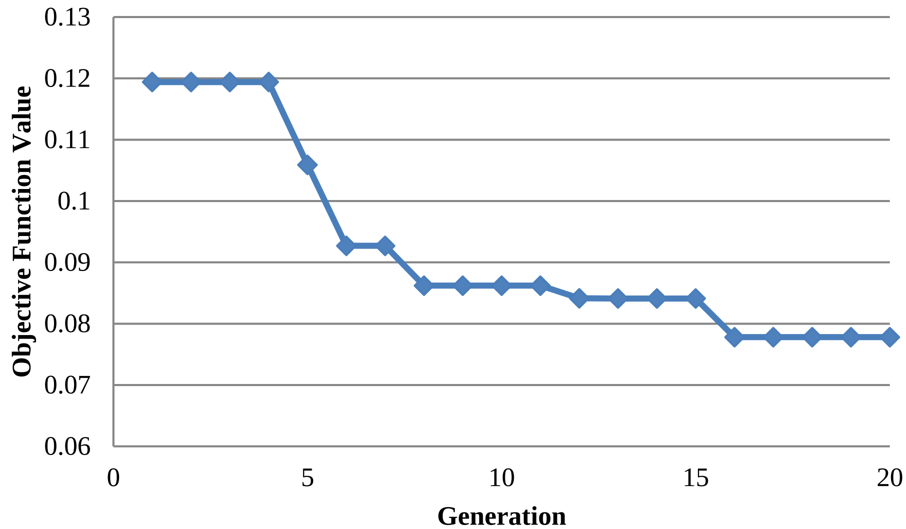

Figure 4.3 GA Objective Function Value vs. Generation

Table 4.2 Calibration Results of the Car Following Model Parameters

Parameter	**Default Value**	**Calibrated Value**
CC0-Standstill distance (ft)	4.92	2.12
CC1-Headway time (gap between vehicles) (seconds)	0.9	1.2
CC2-Car-following distance/following variation (ft)	13.12	11
CC3 - Threshold for entering following (seconds)	-8	-13
CC4 - Negative following threshold (ft/s)	-0.35	-0.8
CC5 - Positive following threshold (ft/s)	0.35	1.3
CC7 - Oscillation during acceleration (ft/s^2)	0.82	1.5

4.7. Summary

This chapter presents the calibration procedure of the microscopic simulation model. The GA is adopted to find optimized values of calibrated parameters which can reduce the differences between field and simulated data. It should be mentioned that only local optimal solutions can be obtained due to the inherent characteristics of GA and limited generations. It is noted that, with more generations, the solution can be further improved to approach closer to global optimal.

Chapter 5. Numerical Results

5.1. Introduction

This chapter presents the numerical results of the simulation. An External Driver Behavior Model (EDBM) is employed to simulate the CAVs and AVs. Four different freeway scenarios are selected based on the results of Chapter 3. The impacts of CAVs and AVs on the freeway segments are evaluated under different penetration level of CAVs and AVs.

The chapter is organized as follows. Section 5.2 describes the External Driver Behavior Model. Section 5.3 shows the numerical results of the analysis conducted on the four freeway segments collected from PeMS. Finally, in section 5.4, a summary concludes this chapter.

5.2. External Driver Behavior Model

VISSIM cannot simulate operations of connected and autonomous vehicles with its internal driver model. However, VISSIM provides the option to replace the internal model with an External Driver Behavior Model (EDBM), which is a fully user-defined driving behavior model for connected and autonomous vehicles. The EDBM is implemented as a C++ Dynamic Link Library (DLL) plug-in, which contains specific algorithms for connected and autonomous vehicles. These algorithms can determine the next step maneuver (i.e. acceleration, lane change) for each affected vehicle. During each simulation time step, VISSIM calls the DLL file to determine the behavior of the vehicle by passing the current state of the vehicle and its surroundings to the DLL and retrieving the updated state calculated by the DLL.

The EMDB model is developed by the Open Source Application Development Portal (OSADP) sponsored by the Federal Highway Administration (FHWA). The code is written in C# and needs to be compiled to generate a DLL file. The DLL file can be implemented as a V2V communication device, wherein the leading vehicle informs the following vehicle of its location, speed and acceleration. The following vehicle can adjust its speed quickly to reduce the risk of rear-end collisions. The algorithm continuously adjusts the acceleration rates by measuring the headways between the leading vehicles and following vehicles to keep short time headways. The headway between CAVs is set 0.6 s and the headway between CAVs/AVs and AVs or regular vehicle is set 0.9 s.

5.3. Numerical Results

Based on the potential freeway segments identified from Chapter 3, four freeway segments are finally selected from PeMS to conduct the analysis. The selected freeway segments represent four different freeway scenarios including basic freeway segment, on-ramp, off-ramp, and weaving segment. The impacts of CAVs and AVs on each freeway segment is examined under different CAV/AV penetration levels. The numerical results are discussed in detail in the following sections.

5.3.1. Basic Freeway Segment

The basic freeway segment is obtained from a portion of the I-405 freeway identified in Chapter 3, as shown in Figure 5.1 (in red). The study period spans 1 hour of the a.m. peak, from 7:00 to 8:00 a.m. on May 16th, 2018. The traffic flow data are collected from PeMS and entered into VISSIM as the demand input. This freeway segment stretch is a four-lane basic freeway segment with a total length of 2500 ft.

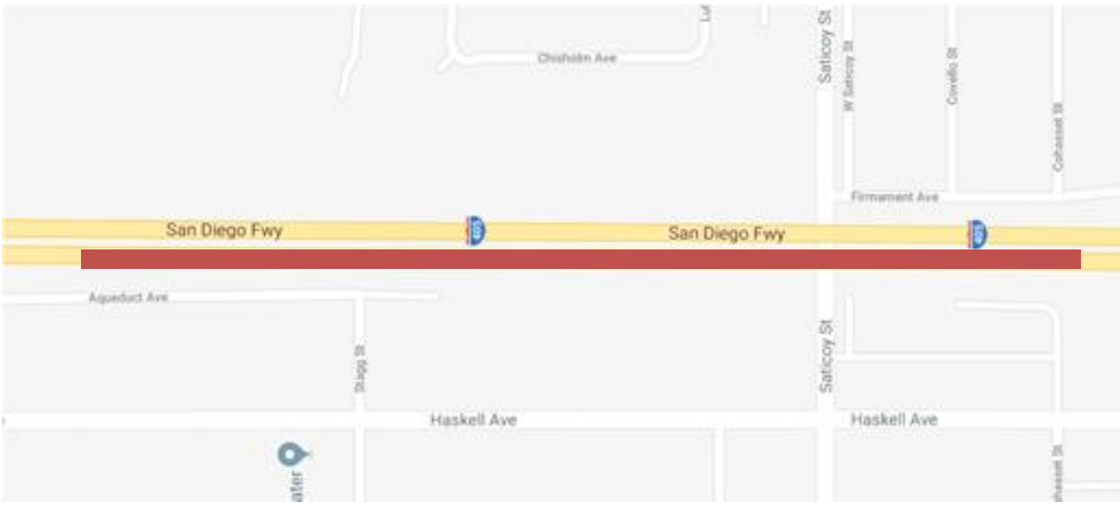

Figure 5.1 Location of the Basic Freeway Segment

The freeway capacity for different penetration level of CAVs and AVs are shown in Table 5-1. The speed limit on the tested freeway segment is 104 km/h (65 mph). Figure 5.2 plots the tendency of the capacity change with different penetration level of CAVs and AVs. And the simulations are also conducted under other three speed limits, which are 80 km/h, 90 km/h, and 120 km/h, respectively. The results are shown in Table 5-2, Table 5-3, and Table 5-4, respectively.

Table 5.1 Capacity Analysis on Basic Freeway Segment under Speed Limit 104 km/h

Basic Freeway Segment with Speed Limit 104 km/h							
		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2160	2209	2305	2371	2472	2537
	20%	1798	2092	2272	2464	2699	
	40%	2603	3067	3472	3705		
	60%	3902	3838	3856			
	80%	3927	3929				
	100%	3980					

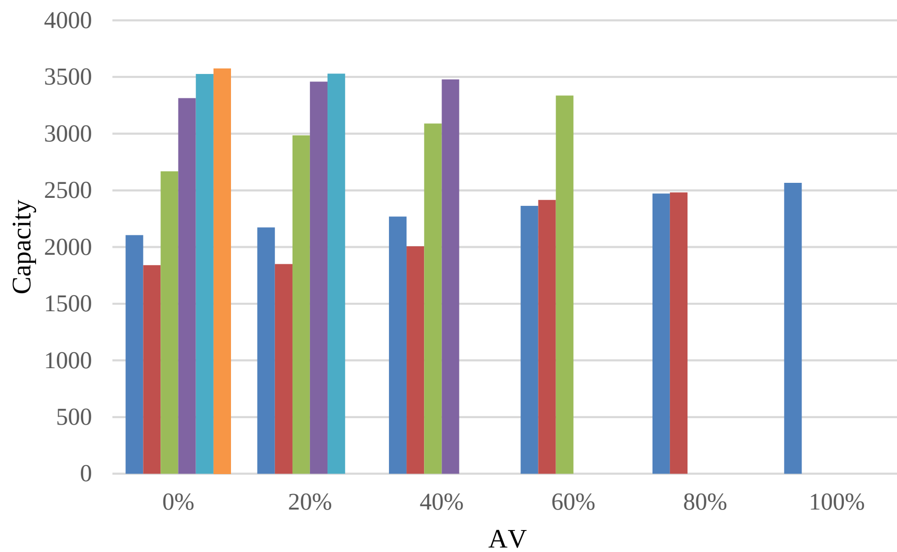

Figure 5.2 The Capacity Tendency on Basic Freeway Segment under Speed Limit 104 km/h

Table 5.2 Capacity Analysis on Basic Freeway Segment under Speed Limit 80 km/h

Basic Freeway Segment with Speed Limit 80 km/h							
		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2105	2173	2269	2363	2472	2567
	20%	1840	1850	2007	2416	2482	
	40%	2668	2985	3090	3336		
	60%	3314	3459	3479			
	80%	3526	3530				
	100%	3575					

Table 5.3 Capacity Analysis on Basic Freeway Segment under Speed Limit 90 km/h

Basic Freeway Segment with Speed Limit 90 km/h							
		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2134	2211	2289	2378	2469	2576
	20%	1745	2075	2085	2402	2498	
	40%	2666	2827	3296	3543		
	60%	3716	3747	3750			
	80%	3806	3813				
	100%	3854					

Table 5.4 Capacity Analysis on Basic Freeway Segment under Speed Limit 120 km/h

Basic Freeway Segment with Speed Limit 120 km/h							
		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2162	2234	2321	2382	2454	2566
	20%	1895	2130	2289	2537	2829	
	40%	2674	2942	3438	3712		
	60%	4117	4234	4214			

80%	4297	4300
100%	4345	

The all-manual case can be seen as a base case with a nominal capacity around 2,200 vehicles per hour per lane (vphpl). With 100% penetration level of CAVs, freeway capacity can be increased by 101%, 84.3%, 80.6%, and 69.8% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively. With 100% penetration level of AVs, freeway capacity can be increased by 18.7%, 17.5%, 20.7%, and 21.9% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively.

5.3.2. On-ramp Freeway Segment

The on-ramp freeway segment is obtained from a portion of the I-405 freeway identified in Chapter 3, as shown in Figure 5.4 (in red). The study period spans 1 hour of the a.m. peak, from 7:00 to 8:00 a.m. on May 16th, 2018. The traffic flow data are collected from PeMS and entered into VISSIM as the demand input. This freeway segment stretch is a four-lane freeway segment with an on-ramp with a total length of 2000 ft.

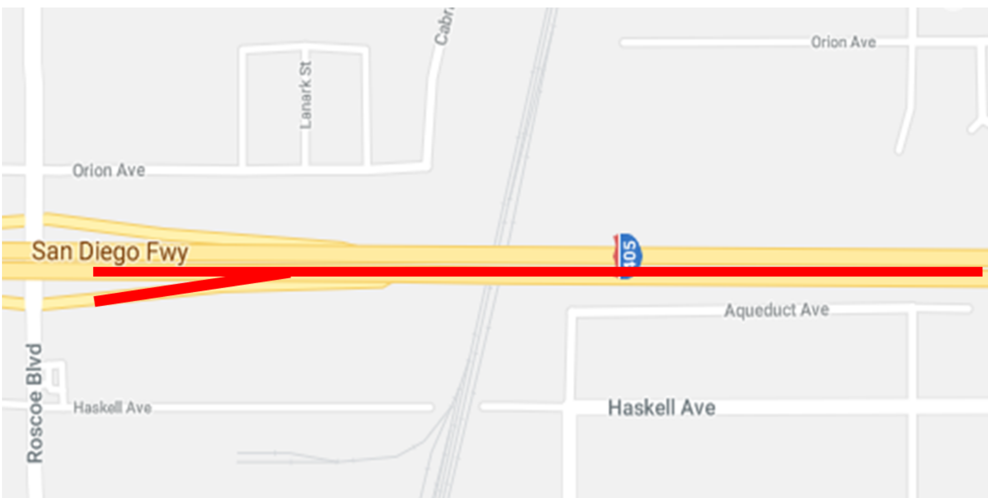

Figure 5.3 Location of the On-ramp Freeway Segment

The freeway capacity before and after the on-ramp for different penetration level of CAVs and AVs are shown in Table 5-5. Figure 5.4 plots the tendency of the capacity change before the on-ramp with different penetration level of CAVs and AVs. Figure 5.5 plots the tendency of the capacity changes after the on-ramp with different penetration level of CAVs and AVs. The simulations are also conducted under other three speed limits, which are 80 km/h, 90 km/h, and 120 km/h, respectively. The capacity results before and after the on-ramp are shown in Table 5-6, Table 5-7, and Table 5-8, respectively.

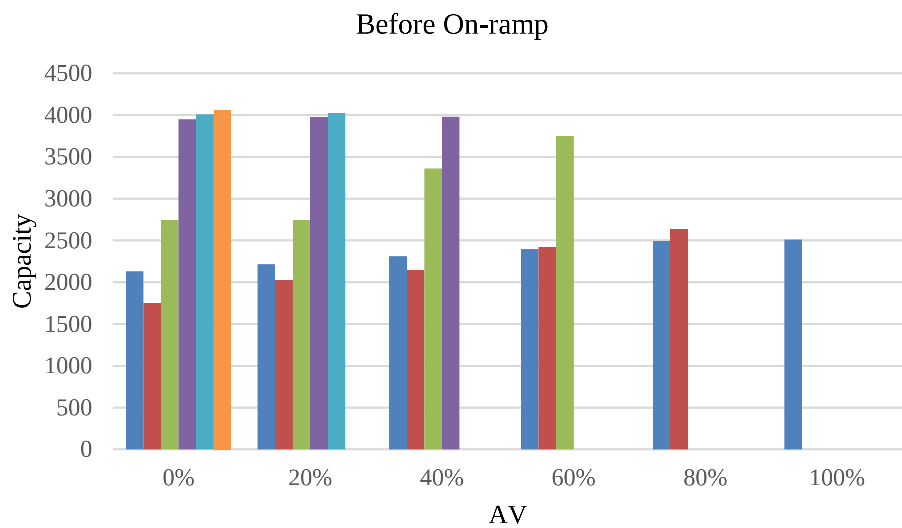

Figure 5.4 The Capacity Tendency before On-ramp under Speed Limit 104 km/h

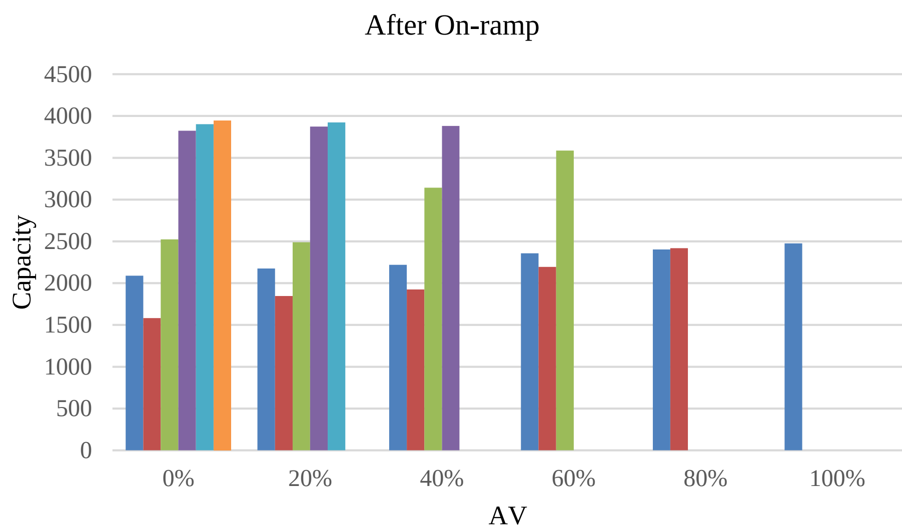

Figure 5.5 The Capacity Tendency after On-ramp under Speed Limit 104 km/h

Table 5.5 Capacity Analysis on Freeway On-ramp Segment under Speed Limit 104 km/h

Freeway On-ramp Segment with Speed Limit 104 km/h							
Before On-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2131	2214	2310	2394	2493	2511
	20%	1752	2028	2149	2421	2635	
	40%	2746	2744	3361	3751		
	60%	3948	3980	3981			
	80%	4008	4025				
	100%	4058					
After On-ramp		AV					
		0%	20%	40%	60%	80%	100%

CAV	0%	2089	2175	2220	2357	2404	2476
	20%	1582	1847	1925	2195	2418	
	40%	2524	2490	3142	3587		
	60%	3823	3874	3882			
	80%	3902	3924				
	100%	3947					

Table 5.6 Capacity Analysis on Freeway On-ramp Segment under Speed Limit 80 km/h

Freeway On-ramp Segment with Speed Limit 80 km/h							
Before On-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2121	2176	2270	2357	2444	2497
	20%	1652	1920	2268	2286	2619	
	40%	2643	3147	3244	3402		
	60%	3499	3491	3531			
	80%	3559	3574				
	100%	3611					
After On-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2048	2104	2195	2292	2385	2438
	20%	1447	1700	2042	2071	2413	
	40%	2460	2950	3014	3242		
	60%	3377	3350	3418			
	80%	3441	3451				
	100%	3487					

Table 5.7 Capacity Analysis on Freeway On-ramp Segment under Speed Limit 90 km/h

Freeway On-ramp Segment with Speed Limit 90 km/h							
Before On-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2127	2207	2302	2404	2482	2515
	20%	1872	2004	2042	2377	2457	
	40%	2705	3094	3425	3609		
	60%	3791	3810	3816			
	80%	3840	3859				
	100%	3887					
After On-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2096	2157	2266	2333	2409	2463
	20%	1701	1809	1846	2191	2246	
	40%	2462	2922	3221	3417		
	60%	3676	3697	3706			
	80%	3731	3750				
	100%	3777					

Table 5.8 Capacity Analysis on Freeway On-ramp Segment under Speed Limit 120 km/h

Freeway On-ramp Segment with Speed Limit 120 km/h							
Before On-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2140	2221	2332	2434	2480	2534
	20%	1876	2067	2172	2487	2716	
	40%	2689	3083	3442	3746		
	60%	4108	4246	4290			
	80%	4327	4337				
	100%	4370					
After On-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2132	2197	2287	2369	2418	2506
	20%	1685	1841	1937	2284	2517	
	40%	2474	2877	3245	3529		
	60%	3940	4120	4189			
	80%	4224	4244				
	100%	4272					

With 100% penetration level of CAVs, freeway capacity before on-ramp can be increased by 104%, 90.4%, 82.7%, and 70.2% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively. And with 100% penetration level of CAVs, freeway capacity after on-ramp can be increased by 100%, 88.9%, 80.2%, and 70.3% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively.

With 100% penetration level of AVs, freeway capacity before on-ramp can be increased by 18.4%, 17.8%, 18.2%, and 17.7% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively. And with 100% penetration level of AVs, freeway capacity after on-ramp can be increased by 17.5%, 18.5%, 17.5%, and 19.0% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively.

5.3.3. Off-ramp Freeway Segment

The off-ramp freeway segment is obtained from a portion of the I-405 freeway identified in Chapter 3, as shown in Figure 5.6 (in red). The study period spans 1 hour of the a.m. peak, from 7:00 to 8:00 a.m. on May 16th, 2018. The traffic flow data are collected from PeMS and entered into VISSIM as the demand input. This freeway segment stretch is a four-lane freeway segment with an off-ramp with a total length of 2000 ft.

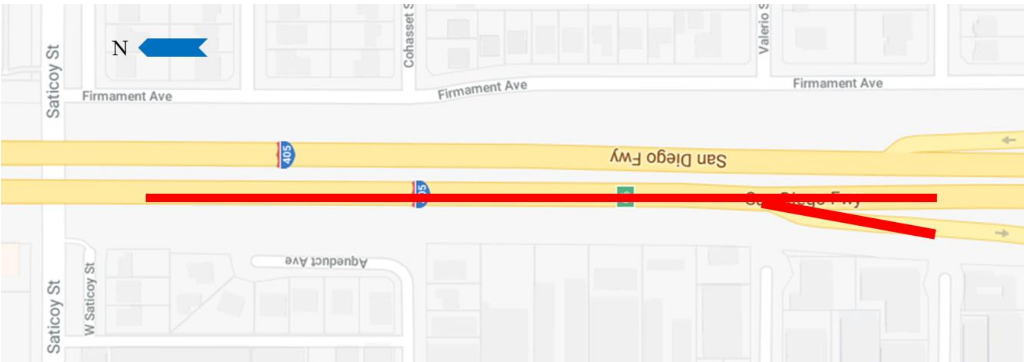

Figure 5.6 Location of the Off-ramp Freeway Segment

The freeway capacity before and after the off-ramp for different penetration level of CAVs and AVs are shown in Table 5-9. Figure 5.7 plots the tendency of the capacity change before the off-ramp with different penetration level of CAVs and AVs. Figure 5.8 plots the tendency of the capacity change after the off-ramp with different penetration level of CAVs and AVs. The speed limit on the tested freeway segment is 104 km/h (65 mph). And the simulations are also conducted under other three speed limits, which are 80 km/h, 90 km/h, and 120 km/h, respectively. The results before and after the on-ramp are shown in Table 5-10, Table 5-11, and Table 5-12, respectively.

Table 5.9 Capacity Analysis on Freeway Off-ramp Segment under Speed Limit 104 km/h

Freeway Off-ramp Segment with Speed Limit 104 km/h							
Before Off-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2003	1963	2164	2396	2303	2473
	20%	1681	1798	1892	1856	2160	
	40%	2133	2332	2739	3065		
	60%	3666	3894	4002			
	80%	4034	4044				
	100%	4086					
After Off-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1706	1717	1785	2087	2040	2235
	20%	1264	1474	1506	1409	1707	
	40%	1738	1800	2202	2545		
	60%	3172	3377	3685			
	80%	3750	3749				
	100%	3791					

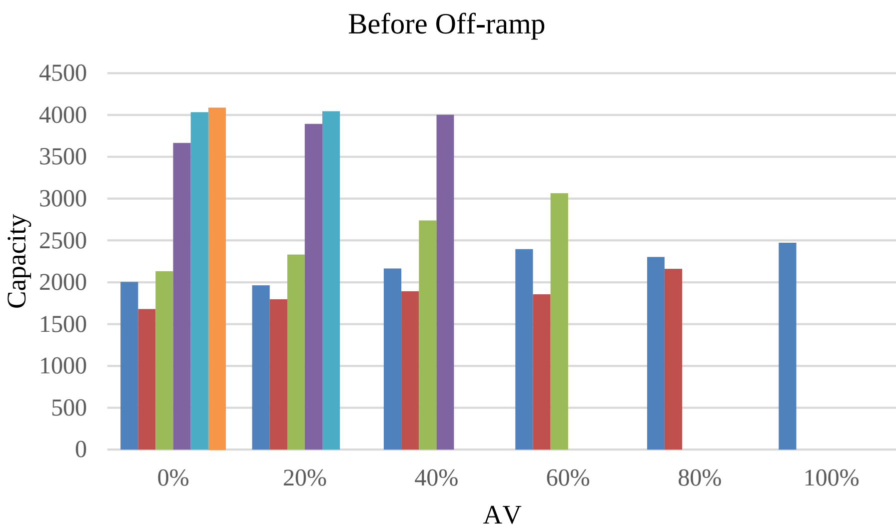

Figure 5.7 The Capacity Tendency before Off-ramp under Speed Limit 104 km/h

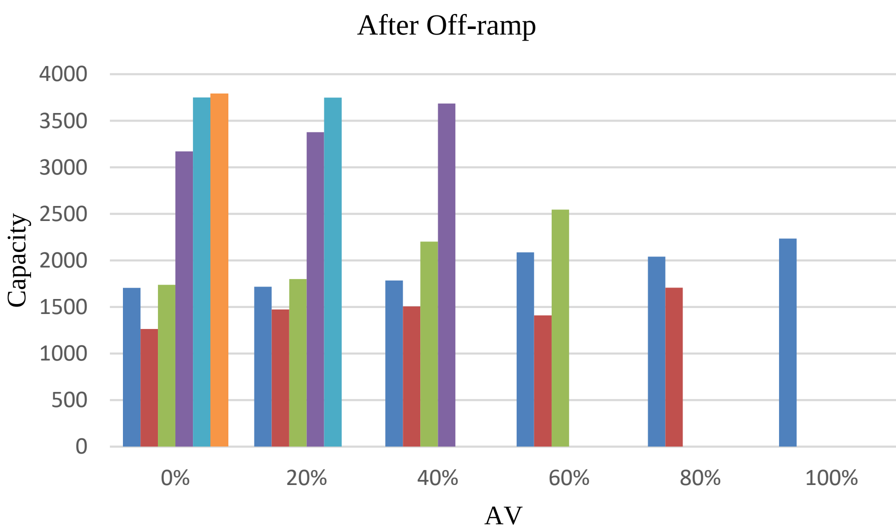

Figure 5.8 The Capacity Tendency after Off-ramp under Speed Limit 104 km/h

Table 5.10 Capacity Analysis on Freeway Off-ramp Segment under Speed Limit 80 km/h

Freeway Off-ramp Segment with Speed Limit 80 km/h							
Before Off-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1843	1930	1894	2012	2025	2116
	20%	1749	1749	1799	2053	2219	
	40%	2223	2372	2455	2856		
	60%	3427	3419	3498			
	80%	3546	3558				
	100%	3596					
After Off-ramp		AV					
		0%	20%	40%	60%	80%	100%

CAV	0%	1537	1554	1572	1698	1605	1826
	20%	1343	1430	1421	1544	1723	
	40%	1782	1845	2052	2308		
	60%	2940	2873	3066			
	80%	3256	3266				
	100%	3317					

Table 5.11 Capacity Analysis on Freeway Off-ramp Segment under Speed Limit 90 km/h

Freeway Off-ramp Segment with Speed Limit 90 km/h							
Before Off-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1907	1934	2030	2120	2235	2204
	20%	1757	1879	1872	1915	2375	
	40%	2248	2501	2634	2887		
	60%	3511	3762	3796			
	80%	3817	3837				
	100%	3873					
After Off-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1552	1663	1730	1848	1846	1814
	20%	1372	1491	1428	1555	1892	
	40%	1798	1974	2202	2297		
	60%	2995	3343	3478			
	80%	3526	3536				
	100%	3603					

Table 5.12 Capacity Analysis on Freeway Off-ramp Segment under Speed Limit 120 km/h

Freeway Off-ramp Segment with Speed Limit 120 km/h							
Before Off-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	2035	2227	2085	1907	2176	2538
	20%	1748	1882	1851	1984	2211	
	40%	2249	2411	2534	2856		
	60%	3363	4104	4267			
	80%	4295	4322				
	100%	4352					
After Off-ramp		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1728	1866	1808	1648	1835	2315
	20%	1337	1479	1423	1560	1702	
	40%	1819	1996	1935	2348		
	60%	2923	3622	3953			
	80%	4023	4034				
	100%	4088					

With 100% penetration level of CAVs, freeway capacity before off-ramp can be increased by 114%, 104%, 103%, and 95.1% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively. And with 100% penetration level of CAVs, freeway capacity after off-ramp can be increased by 137%, 122%, 132%, and 116% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively.

With 100% penetration level of AVs, freeway capacity before off-ramp can be increased by 24.7%, 23.5%, 15.6%, and 14.8% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively. And with 100% penetration level of AVs, freeway capacity after off-ramp can be increased by 34.0%, 31%, 16.9%, and 18.8% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively.

5.3.4. Weaving Freeway Segment

The weaving freeway segment is obtained from a portion of the I-110 freeway identified in Chapter 3, as shown in Figure 5.9 (in red). The study period spans 1 hour of the a.m. peak, from 7:00 to 8:00 a.m. on May 16th, 2018. The traffic flow data are collected from PeMS and entered into VISSIM as the demand input. This freeway segment stretch is a four-lane freeway segment with a weaving area with a total length of 2000 ft. The weaving area has a total length of 700 ft.

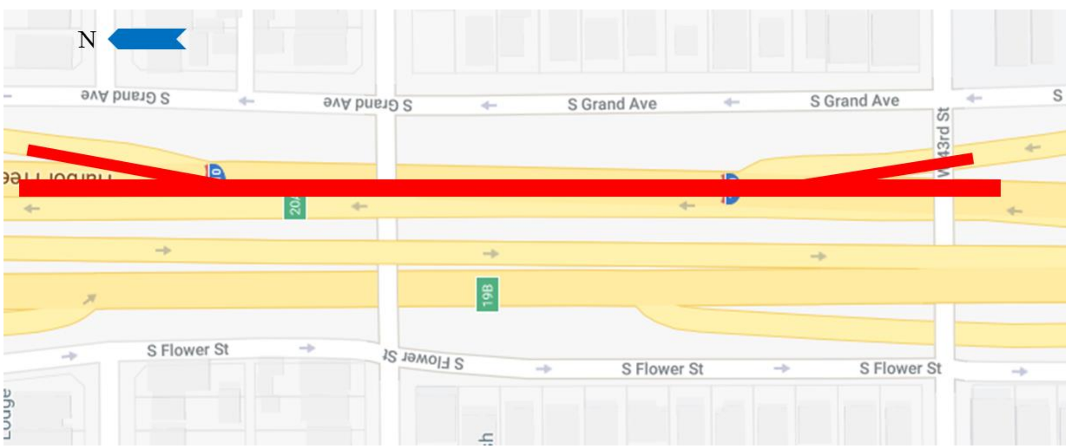

Figure 5.9 Location of the Weaving Freeway Segment

The freeway capacity before and after the weaving area for different penetration level of CAVs and AVs are shown in Table 5-13. Figure 5.10 plots the tendency of the capacity change before the weaving area with different penetration level of CAVs and AVs. And Figure 5.11 plots the tendency of the capacity change after the weaving area with different penetration level of CAVs and AVs. The speed limit on the tested freeway segment is 104 km/h (65 mph). And the simulations are also conducted under other three speed limits, which are 80 km/h, 90 km/h, and 120 km/h, respectively. The results before and after the weaving area are shown in Table 5-14, Table 5-15, and Table 5-16, respectively.

Table 5.13 Capacity Analysis on Freeway Weaving Segment under Speed Limit 104 km/h

Freeway Weaving Segment with Speed Limit 104 km/h							
Before Weaving Area		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1674	1699	1757	1843	1955	1858
	20%	1586	1803	1828	1980	1961	
	40%	2390	2237	2465	3076		
	60%	3674	3719	3921			
	80%	3961	3981				
	100%	4019					
After Weaving Area		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1565	1572	1680	1721	1807	1728
	20%	1396	1616	1637	1750	1739	
	40%	2107	1968	2214	2786		
	60%	3349	3379	3575			
	80%	3632	3646				
	100%	3682					

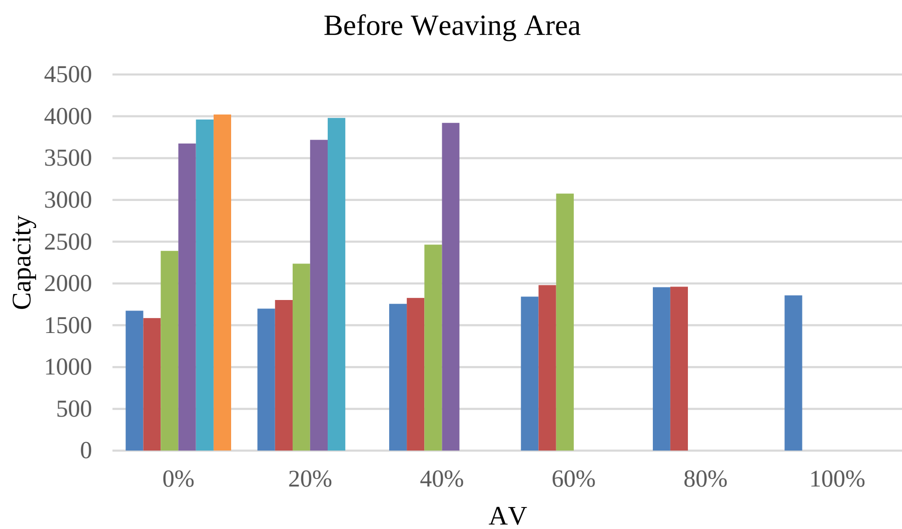

Figure 5.10 The Capacity Tendency before Weaving Area under Speed Limit 104 km/h

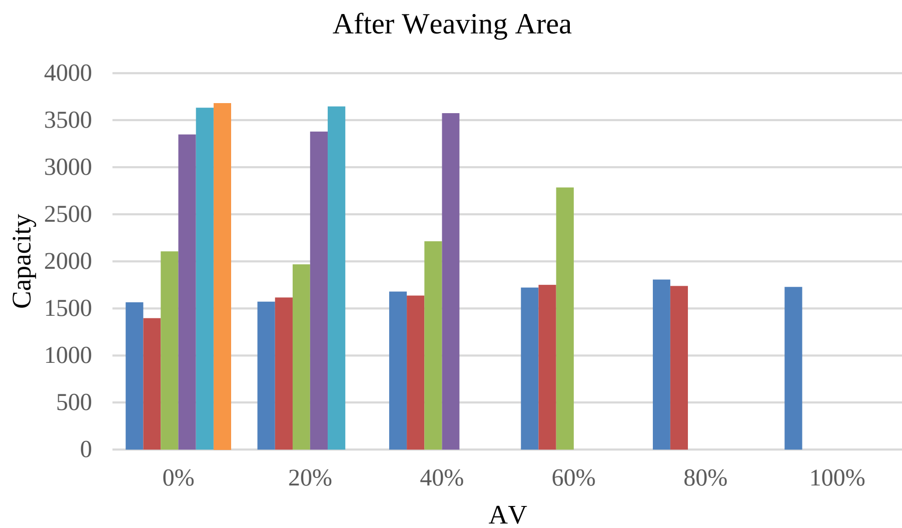

Figure 5.11 The Capacity Tendency after Weaving Area under Speed Limit 104 km/h

Table 5.14 Capacity Analysis on Freeway Weaving Segment under Speed Limit 80 km/h

Freeway Weaving Segment with Speed Limit 80 km/h							
Before Weaving Area		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1630	1642	1760	1889	1892	1925
	20%	1475	1722	1937	1642	1905	
	40%	2084	2410	2682	2776		
	60%	3346	3339	3394			
	80%	3444	3453				
	100%	3496					
After Weaving Area		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1508	1538	1640	1759	1740	1767
	20%	1319	1530	1702	1520	1712	
	40%	1873	2189	2414	2471		
	60%	3027	3009	3104			
	80%	3141	3154				
	100%	3179					

Table 5.15 Capacity Analysis on Freeway Weaving Segment under Speed Limit 90 km/h

Freeway Weaving Segment with Speed Limit 90 km/h							
Before Weaving Area		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1619	1595	1800	1842	1802	1876
	20%	1634	1685	1832	1951	2134	
	40%	2299	2378	2540	2745		
	60%	3542	3581	3698			
	80%	3715	3737				

	100%	3776					

After Weaving Area		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1518	1477	1662	1711	1676	1726
	20%	1448	1504	1635	1746	1867	
	40%	2034	2128	2248	2439		
	60%	3208	3238	3355			
	80%	3397	3409				
	100%	3454					

Table 5.16 Capacity Analysis on Freeway Weaving Segment under Speed Limit 120 km/h

Freeway Weaving Segment with Speed Limit 120 km/h							
Before Weaving Area		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1702	1798	1771	1837	1922	1939
	20%	1705	1800	1791	1828	1947	
	40%	2330	2542	2755	2881		
	60%	3565	3722	4106			
	80%	4187	4200				
	100%	4245					
After Weaving Area		AV					
		0%	20%	40%	60%	80%	100%
CAV	0%	1591	1683	1623	1730	1756	1811
	20%	1535	1588	1540	1626	1746	
	40%	2053	2255	2446	2596		
	60%	3250	3346	3728			
	80%	3858	3877				
	100%	3907					

With 100% penetration level of CAVs, freeway capacity before weaving area can be increased by 149%, 140%, 133%, and 114% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively. And with 100% penetration level of CAVs, freeway capacity after weaving area can be increased by 146%, 135%, 128%, and 111% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively.

With 100% penetration level of AVs, freeway capacity before weaving area can be increased by 13.9%, 11.0%, 15.9%, and 18.1% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively. And with 100% penetration level of AVs, freeway capacity after weaving area can be increased by 13.8%, 10.4%, 13.7%, and 17.2% under speed limits of 120 km/h, 104 km/h, 90 km/h, and 80 km/h, respectively.

5.4. Summary

This chapter describes the numerical results of the capacity analysis under the selected freeway scenarios. The External Driver Behavior Model used to simulate CAV and AV is presented. For each scenario, the freeway capacities under different CAV and AV penetration rate and speed limits are evaluated. The freeway capacities before and after on-ramp, off-ramp, and weaving area are also compared. The numerical results show that CAVs can significantly increase the freeway capacity under the four freeway scenarios. And the improvement of capacity increases with the increase of freeway speed limit. With 100% penetration level of CAVs, freeway capacity can be increased by over 100%. Compared to CAVs, there is no significant impact of AVs on freeway capacity. With 100% penetration level of AVs, freeway capacity can be increased by around 20%.

Chapter 6. Summary and Conclusions

6.1. Introduction

Connected and automated vehicle (CAV) technologies are combination technologies of connected vehicle and automated vehicle. As widely known, CAVs can bring with them many benefits including improving safety, reducing emissions and increasing mobility of the transportation system. CAV only needs a smaller lane width and headway which will lead to a higher roadway capacity. As one of the most rapidly developing automotive technologies, the impact of CAVs on the freeway capacity needs to be examined.

As the CAVs start to penetrate into the market, the current HCM methods cannot be used to evaluate freeway capacity due to the fact that they did not account for the impacts of CAV strategies in the HCM. The limitations of the current capacity analysis methods include, but are not limited to, the following: 1) There is no guideline related to how current HCM methods should be adjusted in order to be suitable for use in conducting various types of analyses involving CAV strategies; 2) There is no consideration of the general impact of CAV technologies on traffic congestion and delay as well as safety in the HCM analysis; and 3) There is no information about the impact of different CAV penetration rates in the highway system on various facilities under different scenarios. In order to be better prepared for both CAV planning and operations under varying levels of market penetration and traffic demand, there is a critical need to develop and establish the HCM capacity adjustments.

The main objective of this research project is to develop the highway capacity adjustments so that the HCM can be adapted to evaluate the impacts of CAVs at different levels of volume and market penetrations. By using VISSIM, a traffic microsimulation tool, four different freeway scenarios are chosen from the Caltrans Performance Measurement System (PeMS). To obtain valid results, various driving behavior parameters are calibrated to the real traffic conditions for human-driven vehicles. In particular, the calibration is conducted using genetic algorithm for standstill distance and minimum headway between vehicles. After the calibration process, the simulation is conducted on the basic freeway segment in mixed traffic environment including regular human-driven vehicles and connected and autonomous vehicles. Simulation results are discussed in detail. Overall, the results of this study can help traffic engineers and stakeholders better understand how different market penetration levels of connected and autonomous vehicles influence freeway capacity and therefore can help improve freeway traffic management.

The following sections are organized as follows. In section 6.2, the principal procedure of selecting potential freeway segments, calibration, and simulation are reviewed and a summary of the numerical results is discussed. Section 6.3 presents a brief discussion of the possible directions for further research.

6.2. Summary and Conclusions

Through a comprehensive review of the current state-of-the-art and state-of-the-practice of CAV technologies, various methodological approaches to analyze freeway capacity with or without CAVs are summarized. Simulation-based method has been widely used in CAV related studies. Compared to other approaches, simulation-based method is imperative for practical decision making in transportation planning and operations. To conduct analysis using microsimulation models, potential scenarios need to be selected.

The Caltrans Performance Measurement System (PeMS) is used to select potential freeway segments. PeMS is a web-based database which provides users real-time and historical traffic data in different aspects, such as speed, flow, capacity, and delay. By using PeMS, researchers can conduct research with the comprehensive information on selected freeway segments, identify congestion bottlenecks, evaluate freeway performance, and make better decisions on freeway operation. Three different freeway segments are selected through the PeMS database as potential simulation scenarios. In order to identify the impact of CAV technology on different freeway scenarios, the selected freeway segments contain a mix of configurations, such as on-ramp, off-ramp, and weaving area. All three freeway segments are selected around the city of Los Angeles, an area with large population. These sites are selected because their preexisting congestion issues during the peak hour, as well as the fact that they are the major interstate freeways with high traffic volumes. The traffic flow and speed data can be collected from PeMS and used to calibrate the microsimulation model.

Microscopic simulation models have been widely employed in transportation planning and operation analysis. Compared to field testing, simulation provides a safer, faster, and costless environment for researchers. However, in order to obtain reliable results through simulation, the parameters of microscopic simulation models need to be calibrated. The calibration procedure can minimize the differences between the simulation results and the realistic field data, such as traffic volumes and speeds. Genetic Algorithm is available to achieve near-global optima during the calibration procedure of the microscopic traffic simulation model. The GA is an inspiration of biological evolution process with selection, crossover and mutation as its three main steps. The GA starts from a random population set. For each generation, the better solutions have higher probabilities to be selected and used to generate new populations after crossover and mutation within the selected solutions. In this study, the population size is set to be 10, and the crossover and mutation rate are set to be 0.8 and 0.2, respectively. The max generation number is 20. The GA-based calibration is conducted through MATLAB. A population of binary chromosomes is generated randomly at the very beginning and each represents a feasible solution. Then the chromosomes are decoded to represent the model parameters and passed onto the VISSIM for simulation. The objective function value is calculated based on the simulated traffic flow and speed data. The calibration process will not stop until the maximum number of generations is reached, or the stopping criterion is met.

VISSIM uses the Wiedemann's car following model to capture the physical and human components of vehicles. As the Wiedemann model stated, a vehicle has four driving modes: free driving, approaching, following and braking. The Wiedemann 99 car following model was developed in 1999 to provide better control of the car following characteristics for freeway modeling in VISSIM. The model consists of ten unique parameters (i.e. CC0 and CC1) representing the car following characteristics. CC0 (standstill distance) defines the desired distance between stopped cars. CC1 (headway time) is the time that a driver wants to keep. The safety distance is defined in the model as the minimum distance a driver will keep while following the preceding car. In case of high volume, this distance decided by CC0 and CC1 becomes the value with the strongest influence on capacity. Based on the literature review, CC0-CC5, and CC7 are selected as the model parameters for calibration. The calibration results can effectively reduce the differences between field and simulated data.

VISSIM cannot simulate operations of connected and autonomous vehicles with its internal driver model. However, VISSIM provides the option to replace the internal model with an External Driver Behavior Model (EDBM), which is a fully user-defined driving behavior model for connected and autonomous vehicles. The EDBM is implemented as a C++ Dynamic Link Library (DLL) plug-in, which contains specific algorithms for connected and autonomous vehicles. These algorithms can determine the next step maneuver (i.e. acceleration, lane change) for each affected vehicle. During each simulation time step, VISSIM calls the DLL file to determine the behavior of the vehicle by passing the current state of the vehicle and its surroundings to the DLL and retrieving the updated state calculated by the DLL.

The EMDB model is developed by the Open Source Application Development Portal (OSADP) sponsored by the Federal Highway Administration (FHWA). The code is written in C# and needs to be compiled to generate a DLL file. The DLL file can be implemented as a V2V communication device, wherein the leading vehicle informs the following vehicle of its location, speed and acceleration. The following vehicle can adjust its speed quickly to reduce the risk of rear-end collisions. The algorithm continuously adjusts the acceleration rates by measuring the headways between the leading vehicles and following vehicles to keep short time headways. The headway between CAV/AV is set 0.6 s and the headway between CAV/AV and regular vehicle is set 0.9 s.

For each scenario, the freeway capacity under different CAV and AV penetration rate and speed limit is evaluated. The freeway capacity before and after on-ramp, off-ramp, and weaving area is also compared. The numerical results show that CAVs can significantly increase the freeway capacity under the four freeway scenarios. And the improvement of capacity increases with the increase of freeway speed limit. With 100% penetration level of CAVs, freeway capacity can be increased by over 100%. Compared to CAVs, there is no significant impact of AVs on freeway capacity. With 100% penetration level of AVs, freeway capacity can be increased by around 20%.

6.3. Directions for Future Research

In this study, the capacity analysis is only conducted on one freeway segment at a time. In the future, more complicated freeway scenarios can be examined with a mix of different scenarios. The External Driver Behavior Model is used in this study to simulate the CAVs. In the future, other car-following model will also be studied and adapted to model the car-following characteristics of CAVs. Besides freeways, the impact of CAVs on local roadways will also be studied, such as intersections and arterials.

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