Estimating the Effect of Connected and Autonomous vehicles (CAVs) on Capacity and Level of Service at Freeway Merge Segments

By

Akshay D Patel

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Chair: Dr. Alexandra Kondyli

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Dr. Steven D. Schrock

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Dr. Thomas E. Mulinazzi

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The thesis committee for Akshay Patel certifies that this is the
approved version of the following thesis:

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Chair: Dr. Alexandra Kondyli

Date Approved:

ABSTRACT

The aim of the study was to obtain Capacity adjustment factors and Break points which can be utilized for Highway Capacity Manual (HCM6) methodology in obtaining Level of Service for freeways when Connected and Autonomous Vehicles (CAVs) are present inside the traffic stream. Accordingly, various two-lane heterogeneous flow scenarios were modelled which included variations in free-flow speed and percent of heavy vehicles wherein the possible impact of the CAVs on the current traffic system was analyzed. Each scenario was first calibrated inside VISSIM to replicate the results from HCM6 and later CAVs were introduced in various proportions inside the traffic stream of conventional vehicles to access performance improvements using VISSIM. It was concluded that CAVs do improve system capacity and resulted in longer free-flow phase, which is a direct effect of the increased road capacity. Up to 25% CAV-penetration rate, the road capacity increased gradually and beyond 25%, the growth rate was largely decided by the improved capability of the CAVs compared to conventional vehicles. An improved capability corresponded to a higher capacity growth rate and a higher capacity. CAVs with higher penetration rates also resulted in longer free-flow phases but only a few of the scenarios saw a minor improvement in density, which was due to the assumptions and driving behavior parameters utilized to model driving behavior for different vehicle classes.

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1. INTRODUCTION

Automation along with connectivity between vehicles and surrounding infrastructure are being considered to solve major challenges related to traffic safety and congestion throughout the world. Experiments have been conducted on self-driving cars since at least the 1920s, which were not computer-driven, but rather remote controlled. Since then enormous advancements have been made to improve its reliability and performance with introduction of new technologies in automobile industry. Major companies and research organizations have developed working prototypes of autonomous vehicles including Google, Mercedes Benz, etc. This has led to an increase in research which studies their effects on traffic flow with conventional vehicles (i.e., having no automation and connectivity capabilities) by conducting field tests and/or by simulating them inside various software to understand their impact on microscopic and macroscopic performance measures. Connected vehicles use several different communication technologies to communicate with the driver, other cars on the road (vehicle-to-vehicle [V2V]), roadside infrastructure (vehicle-to-infrastructure [V2I]), and the "Cloud" [V2C]. The Highway Capacity Manual has been used by transportation engineers for decades but currently there are no provisions inside the manual for Connected and Autonomous vehicles [CAVs].

1.1. Objective

For this study, it is hypothesized that the introduction of CAVs will likely bring improvements for traffic stream by sustaining the FFS for higher flow rates and increasing the throughput compared to conventional vehicles traffic. This improvement should increase with higher proportions of CAVs as it can maintain shorter headways along with better reaction times than humans.

Hence, the objective of this research was to obtain capacity adjustment factors (CAFs) based on various proportions of CAVs when introduced inside the traffic stream of conventional vehicles using microsimulation software. The thesis findings may be used in the HCM6 methodologies to account for the impact of CAVs on highway capacity and level of service determination for freeway facilities.

2. LITERATURE REVIEW

This chapter presents background information on the Highway Capacity Manual 6th Edition (TRB, 2016) methods for basic, merge, and diverge segments, as well as an overview of past research that tried to quantify the impact of CAVs and proposed modifications to the HCM.

2.1. Highway Capacity Manual (HCM)

The Highway Capacity Manual, 6th Edition provides methods for quantifying highway capacity along with fundamental reference on concepts, performance measures, and analysis techniques for evaluating the multimodal operation of streets, highways, freeways, and off-street pathways. Various chapters from the HCM serve as a backbone for this research as current methodology for calculating various performance measures for a freeway serve as a guideline and its results as a benchmark when comparing against performance of CAVs.

The core methodology for estimating freeway performance measures for a single analysis period is contained in Chapter 10 of HCM6. Both undersaturated (i.e., below capacity) and oversaturated (i.e., above capacity) conditions can be evaluated. This Chapter provides guidelines on distinguishing between section and a segment for a basic freeway segment from a merge segment. It also states the criteria on influence areas for a merge segments on a freeway as shown below in Fig 2.1. With undersaturated conditions, the operational impacts of ramp–freeway junctions occur within a 1,500-ft-long influence area. It includes the acceleration/deceleration lane and the right two lanes of the freeway.

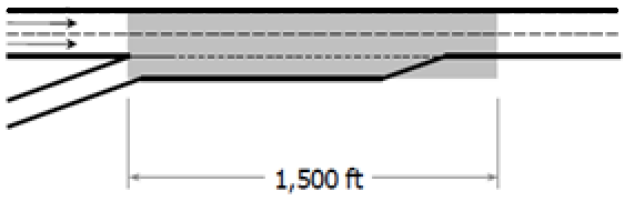

Figure 2.1 Influence Areas of Merge (TRB, 2016)

Chapter 10 provides important definitions which are mentioned below;

1. Free-flow speed (FFS): It is the average speed of vehicles on a given segment or facility, measured under low-volume conditions (up to 1300 vehicles per hour per lane (veh/h/ln)), when drivers are free to drive at their desired speed and are not constrained by the presence of other vehicles. The FFS of a basic freeway segment is sensitive to three variables:
   - Lane widths,
   - Lateral clearances, and
   - Total ramp density.

   The total ramp density is defined as the average number of on-ramp, off-ramp, major merge, and major diverge junctions per mile in the analysis direction (one side of the freeway only), measured three miles upstream and three miles downstream of the middle of the segment under investigation.

2. Demand flow rates v_d, and actual served (or observed) flow rates v_a,
3. The term capacity c, as used thus far, refers to the critical segment capacity—the maximum observed flow rate. The capacity of a basic freeway segment under base conditions varies with the free-flow speed (FFS). Table 2.1 provides capacity values under base conditions

(i.e., no heavy vehicles, drivers familiar with the facility, do not include the effects of non-recurring sources of congestion, such as severe weather, incidents, or work zones, and 12 ft lanes with adequate lateral clearances) for a selection of free-flow speeds. In all cases, capacity represents a maximum flow rate for a 15-min interval in time.

Table 2.1 Basic Freeway Segment Capacity under Base Conditions (TRB, 2016)

Free-Flow Speed (mi/h)	Capacity of Basic Freeway Segments (pc/h/ln)
75	2,400
70	2,400
65	2,350
60	2,300
55	2,250
50	NA
45	NA

4. Critical segment: It is generally defined as the bottleneck segment that will break down the earliest, given that all traffic, roadway, and control conditions do not change, including the spatial distribution of demands on each component segment,
5. Critical speed: It is defined as speed at capacity.
6. Density (k): It is defined as the number of vehicles per unit length of the roadway. In traffic flow, the two most important densities are the critical density (k_c) and jam density (k_j).
7. Active and hidden bottlenecks: An active bottleneck is defined as a segment with a demand-to-capacity ratio (v_d/c) greater than 1.0, an actual flow-to-capacity ratio (v_a/c) equal to 1.0 and queuing upstream of the bottleneck segment. A hidden bottleneck is defined as a segment with a demand-to-capacity ratio (v_d/c) greater than 1.0, but an actual flow-to-capacity ratio (v_a/c) typically less than 1.0 (or equal to 1.0 in some cases), with no queues forming upstream of the segment.

Freeway facility capacity is governed by the position and severity of active bottlenecks (i.e., segments with $v_d/c > 1.0$) along its length. Both characteristics vary over time and space, depending on the time-varying demand flow rates on each facility segment. A bottleneck that is active at one time may hide another (less severe) bottleneck further downstream, by suppressing demand flows to that downstream bottleneck. Therefore, there is no simple definition for freeway facility capacity, other than it is variable over time and influenced by the timing and location of active bottlenecks.

Chapter 12, Basic freeway and multilane highway segments from HCM6 presents methodologies for analyzing the capacity and level of service (LOS) of basic freeway and multilane highway segments. These segments are outside the influence of merging, diverging, and weaving maneuvers.

The methodologies in this chapter are limited to uncongested flow conditions which require that the demand-to-capacity ratio for the segment is less than or equal to 1.0. Uncongested flow on freeways further means that there are no queuing impacts on the segment from downstream bottlenecks.

Few important definitions from this chapter are as follows;

1. Traffic flow within a basic freeway or multilane highway segment can be categorized as one of three general types: undersaturated, queue discharge, and oversaturated as shown in Fig 2.2.
    - Undersaturated flow represents conditions under which the traffic stream is unaffected by upstream or downstream bottlenecks.
    - Queue discharge flow represents congested traffic flow that has just passed through a bottleneck and is accelerating back to the drivers' desired speeds. Assuming no other

downstream bottleneck exists, queue discharge flow will be relatively stable until the queue is fully discharged.

- Oversaturated flow represents the conditions within a queue that has backed up from a downstream bottleneck. These flow conditions do not reflect the prevailing conditions of the segment itself, but rather the consequences of a downstream problem. All oversaturated flow is considered to be congested.

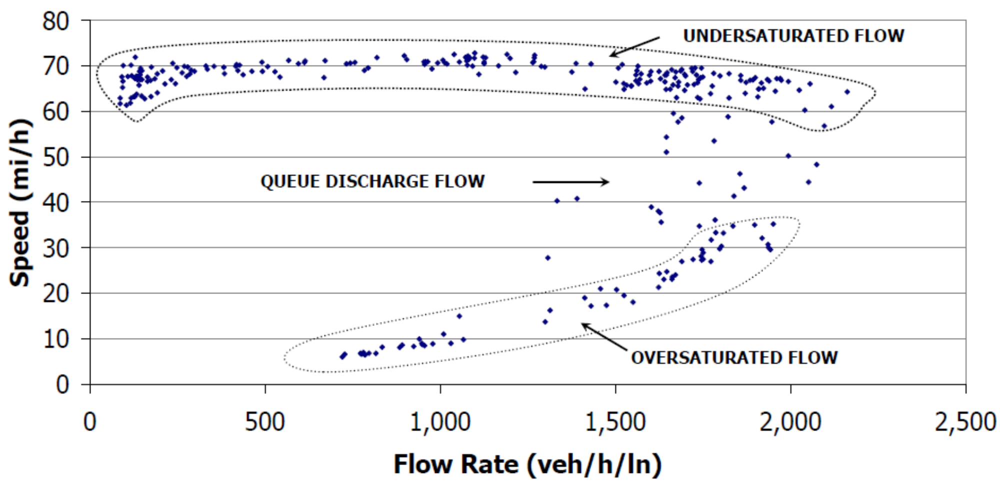

Figure 2.2 Types of Flow on a Basic Freeway Segment (TRB, 2016)

2. Capacity drop phenomenon: Previous research has shown that when oversaturation begins, queues develop, and vehicles discharge from the bottleneck at a queue discharge rate which is usually lower than the throughput rate before the breakdown.
3. Breakdown and Recovery: A breakdown event on a freeway bottleneck is defined as a sudden drop in speed of at least 25% below the FFS for a sustained period of at least 15 min that results in queuing upstream of the bottleneck. This methodology has also been implemented by Asgharzadeh and Kondyli (2018) and Kondyli et al. (2019) to identify breakdowns. The HCM defines the breakdown recovery on a freeway bottleneck as a return of the prevailing speed to

within 10% of the free-flow speed for a sustained period of at least 15 min, without the presence of queuing upstream of the bottleneck.

4. Pre-breakdown flow rate: It is defined as the 15-min average flow rate immediately prior to the breakdown event. For purpose of this research, the pre-breakdown flow rate is equivalent to the segment capacity.
5. Queue discharge rate: It is defined as the average flow rate during oversaturated conditions (i.e., during the time interval after breakdown and prior to recovery). This flow rate is usually lower than the pre-breakdown flow rate, resulting in significant loss of freeway throughput during congestion. Studies have indicated that the average difference between the post-breakdown and the pre-breakdown flow rates vary widely from as little as 2% to as much as 20%, with a default value of 7% recommended.

The relationship between speed and flow is illustrated for various speeds in Fig 2.3, where the x-axis represents the adjusted 15-min demand flow rate v_p in pc/h/ln and the y-axis represents the space mean speed (S) of the traffic stream in mi/h. The equation for the base speed–flow curve for every basic freeway segment follows this form. In all cases, the value of capacity is directly related to the FFS. Under base conditions, speed–flow curves for uninterrupted flow on basic freeway segments follow a common form i.e. it starts with a constant speed range followed by a decreasing speed range after the Break Point (BP) and ends at capacity when the traffic stream density D is 45 pc/mi/ln, indicated by the dashed line in Fig 3.

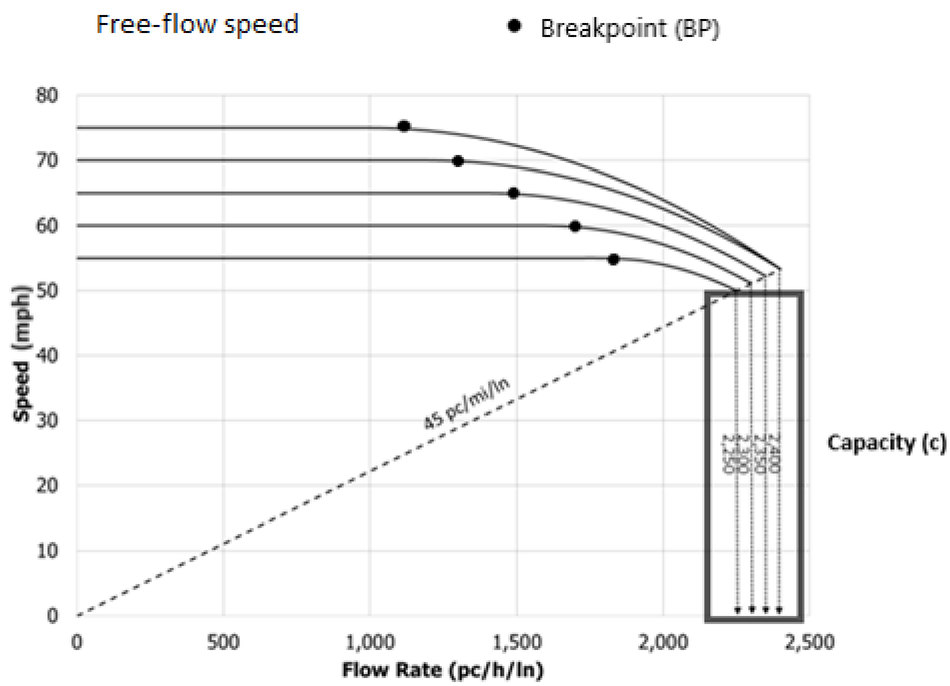

Figure 2.3 Speed–Flow Curves for Basic Freeway Segments (TRB, 2016)

6. Level of Service (LOS) on basic freeway segments is defined by density. A basic freeway segment can be characterized by two performance measures: density in passenger cars per mile per lane (pc/mi/ln) in Table 2.2, and the ratio of demand flow rate to capacity (v_d/c). Each of these measures is an indication of how well traffic is being accommodated by the basic freeway segment.

Table 2.2 LOS Criteria for Basic Freeway (TRB, 2016)

LOS	Density (pc/mi/ln)
A	≤11
B	>11–18
C	>18–26
D	>26–35
E	>35–45
F	Demand exceeds capacity OR density >45

Chapter 14 from HCM6, Freeway and Merge and Diverge Segments, presents methodologies for evaluating roadway segments downstream of on-ramps and upstream of off-ramps, where weaving does not occur. Table 2.3 summarizes the LOS criteria for freeway merge and diverge segments.

Table 2.3 LOS Criteria for Freeway Merge and Diverge Segments (TRB, 2016)

LOS	Density (pc/mi/ln)
A	≤10
B	>10–20
C	>20–28
D	>28–35
E	>35
F	Demand exceeds capacity

2.2. Modeling the Impacts of CAVs

With the advent of driverless cars, it became imperative to know the effects these will have on uninterrupted and interrupted flow facilities on which they will be running. Currently there is a lack of thorough understanding regarding the effects of CAVs on traffic operations and transportation infrastructure.

Many researchers have estimated quantitative gains in traffic flow by introducing new variables to adjust for automated vehicles into already existing formulas in HCM6 for quantifying the improvement in LOS for the same facility traversed by conventional vehicles. Shi and Prevedouros (2016) in their research adjusted capacity, maximum service rate, and density to account for CAVs. The CAVs had significant impact on traffic efficiency under congested conditions instead of uncongested due to their capabilities of maintaining shorter headways. They considered while running Monte Carlo simulations inside the traffic stream which resulted in maximum theoretical capacity of 7200 veh/h/ln. It was concluded that if the headway of the CAV is kept similar to that of a driver, then there was negligible gain in terms of capacity. Also, CAV share below 2% were unlikely to produce detectable improvements in the quality of traffic flow.

Ye and Yamamoto (2018), developed a heterogeneous traffic-flow model to the possible impact of CAVs on the traffic flow based on two-state safe speed model (TSM) for conventional vehicles. Simulations were conducted under various CAV penetration rates in the heterogeneous flow. The simulation results indicated that the road capacity increased with an increase in the CAV penetration rate within the heterogeneous flow. Up to a CAV penetration rate of 30%, the road capacity increased gradually; the effect of the difference in the CAV capability on the capacity growth rate was insignificant as CAVs were the minority in the heterogeneous flow. When the CAV penetration rate exceeded 30%, the growth rate was largely decided by the improved capability of the CAVs in the Adaptive Cruise Control (ACC) compared to conventional vehicles.

While many considered a basic freeway segment for quantifying the throughput under different market penetration rates, Talebpour and Mahmassani (2016) considered a hypothetical one-lane highway with an on-ramp located in the middle of the segment for simulating a platoon of regular, connected, and autonomous vehicles for different market penetration rates of connected and autonomous vehicles. A gap-acceptance based lane-changing model was selected for merging maneuvers. The vehicles were classified into autonomous, connected, and regular vehicles in a highway environment. The connected vehicles had vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) capabilities where drivers were not only aware of vehicles in their vicinity, but also received information from several vehicles upstream and downstream. Regardless of the type of information, drivers were the decision makers in connected vehicles. The performance of autonomous vehicles was bounded by their sensor limitations as they did not have connectivity capabilities. The simulation results revealed that scatter in fundamental diagrams increased as market penetration rate of connected/autonomous vehicles increased from 0% to 50% and decreased after this point. However, the throughput increased as market penetration rate increased.

The simulation results also exhibited that autonomous vehicles resulted in higher throughput when compared to connected vehicles at similar market penetration rates.

Similarly, Bujanovic and Lochrane (2018) developed an analytical model to predict the capacity of basic freeway segments based on the market penetration and the maximum number of vehicles allowed in a platoon. Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) were the enabling technologies used to support vehicle platooning. A decision mechanism was created for a vehicle to decide on what headway it was supposed to keep. A leader of a platoon or a standalone platooning-enabled vehicle may be in either ACC mode (if it is following a manual vehicle) or CACC mode (if it is following another platoon which it may not join because the size of that platoon is equal to the maximum size). If the vehicle was in CACC mode, it received information from its predecessors via vehicle-to-vehicle (V2V) communication but must maintain a larger gap than it would, if it was part of the same platoon. Using an intra-platoon time headway of 0.8 s, an inter-platoon time headway of 1.3 s, and a maximum platoon size of 12 vehicles, resulted in a capacity of up to 4,237 vehicles per hour.

Other researchers have used simulation software by writing their own algorithms to simulate driver behavior based on the levels of automation that one is trying to simulate.

CAVs rely on AAC and cooperative adaptive cruise control (CACC) algorithms by adjusting the vehicle speed to maintain a safe distance from vehicles ahead. Zhao and Sun (2013) by using the application programming interface inside VISSIM simulated a platoon with six CACC vehicles and examined the interactions in a platoon and how they react to shockwaves microscopically. The traffic stream was comprised of manual vehicles, ACC-equipped vehicles, and platoons consisted with CACC vehicles on 2.49 miles stretch of road with a 2-lane freeway. The minimum desired headway of ACC in this paper is set 1.4 s while 0.5 s for CACC with a desired speed set to 49.71

mph. Results illustrated that the lane capacity increased significantly when market penetration of CACC vehicles increased (Fig 2.4), however platoon size had little impact on traffic capacity.

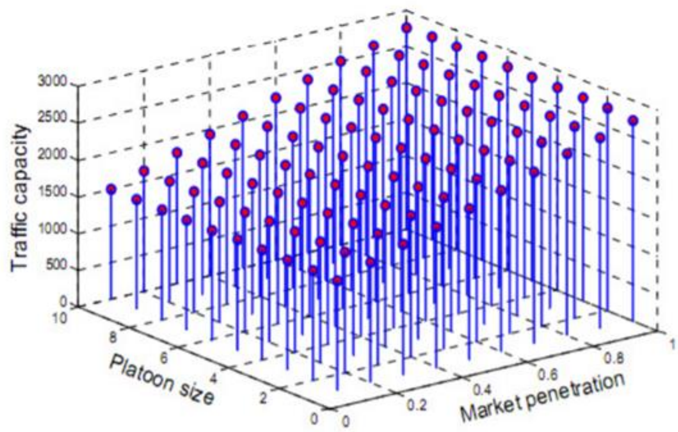

Figure 2.4 CACC on the impact of traffic capacity (Zhao and Sun (2013)

The one common result that resonates from the reviewed literature, is the improvement in traffic flow conditions because the CAVs have better response time, lane merging and weaving capabilities, and they can travel at headways closer than regular drivers are comfortable with. This also helps in better absorbing shockwaves on freeway propagating upstream due to their constant communication with the vehicles and infrastructure downstream.

3. METHODOLOGY

This chapter describes the methods undertaken in this study to model ramp merge areas on freeway segments in VISSIM and calibrate them to match the HCM6 values for capacity.

3.1.Geometry

The first step was to create a model in VISSIM of a freeway segment having a merge segment between a two 2-lane basic freeway segment and a one lane ramp as shown in Fig 3.1. The acceleration lane length L_A was 1000 ft.

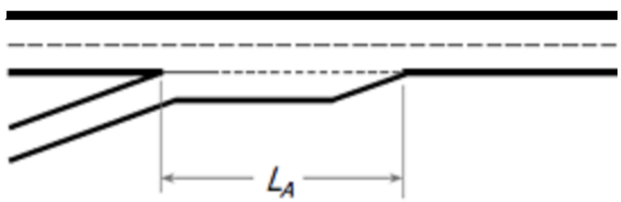

Figure 3. 1 Geometry of the freeway facility with 2-lanes and parallel acceleration lane.

In order to contain all queues within the facility, the two 2-lane basic freeway segment of the facility was constructed to be a mile long. The merge segment in between represented the bottleneck. Table 3.1 describes the base condition details of the geometry.

Table 3.1 Geometry of Freeway facility and Base condition parameters

Geometry details and Base scenario Parameters	
Freeway Lane width	12 ft
Ramp lane width	12 ft
No. of Lanes freeway	2
No. of Lanes ramp	1
% of SUTs and TTs	0
Right-side lateral clearance	6 ft
Terrain	Level
PHF	0.94
Driver population speed & capacity adjustment factor	1.00
Acceleration lane length	1000 ft
FFS for Mainline and ramp	(65,40), (70,40), (75,40)
No. of runs per scenario	10
Hourly demand volume on upstream or downstream ramp (veh/h)	None, isolated ramp
Length of basic freeway segment at the start and end of merge segment	1 mile

3.2. Calibrating for HCM6

This section discusses definitions of the parameters that were considered while calibrating in VISSIM and explains how variations in them impacts the driving behavior of a vehicle when it is in free-flow condition, merging, or following another vehicle.

3.2.1. Baseline Behavior Models

3.2.1.1. Wiedemann 99 model

Wiedemann 99 car following model is applicable to freeway links and connectors. It consists of 10 calibration parameters which are all labeled with a prefix “CC” (Table 3.2). Among this calibration parameters, CC0, CC1 and CC2 have the most impact on driving behavior (ODOT, 2011):

- **CC0 Standstill distance:** Desired distance between the rear-bumper to front bumper of the stopped cars. This parameter has greater impact to maximum flow rate when the traffic is in jam conditions.
- **CC1 Headway time:** The distance in seconds that the following driver desires to maintain with the lead vehicle. Based on the time distribution, the following distance for a vehicle is calculated. This is the distance in seconds which a driver wants to maintain at a certain speed. The higher the value, the more cautious the driver is. The safety distance is defined in the car following model as the minimum distance a driver will maintain while following another vehicle. In case of high volumes this distance becomes the value, which has a determining influence on capacity.

Note that desired safety distance = CC0 + (CC1* speed)

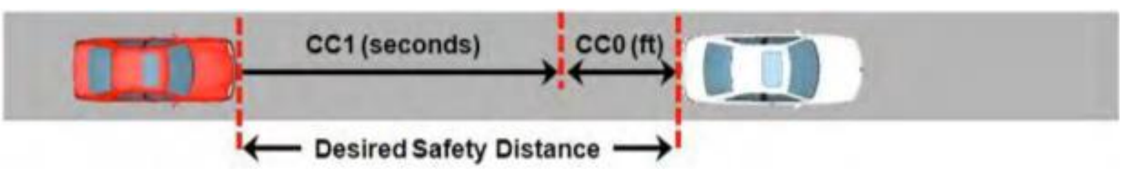

Figure 3. 2 Headway Time (CC1), ODOT (2011)

- **CC2 (Following variation):** How much more distance than the desired safety distance (CC0+CC1) before the lagging driver intentionally moves closer to the lead vehicle.

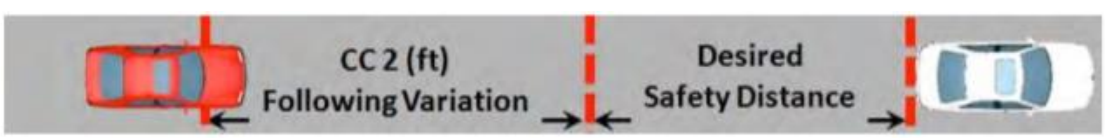

Figure 3. 3 Following Variation Parameter (CC2), (ODOT, 2011)

Table 3. 2 Wiedemann 99 car-following parameters ((PTV, 2018))

Parameter Grouping	Parameter name		
Car Following	Wiedemann 99 Car following model (applicable for freeway)	CC0 (Standstill Distance) (feet)	The average desired standstill distance between two vehicles, it has no variation. Higher value means larger standstill distance and lower capacity
		CC1 (Headway Time) (s)	Time distribution of speed-dependent part of desired safety distance. Higher value means more cautious driver and lower capacity
		CC2 (‘Following’ Variation) (feet)	Restricts the distance difference (longitudinal oscillation) or how much more distance than the desired safety distance a driver allows before he intentionally moves closer to the car in front. Higher value means more cautious driver and lower capacity
		CC3 (Threshold for Entering ‘Following’)	It controls the start of the deceleration process (i.e., the number of seconds before reaching the safety distance. At this stage the driver recognizes a preceding slower vehicle.
		CC4 (Negative ‘Following’ Threshold)	Defines negative speed difference during the following process. Low values result in a more sensitive driver reaction to the acceleration or deceleration of the preceding vehicle.
		CC5 (Positive ‘Following’ Threshold)	Defines positive speed difference during the following process. Low values result in a more sensitive driver reaction to the acceleration or deceleration of the preceding vehicle.
		CC6 (Speed dependency of Oscillation)	Influence of distance on speed oscillation while in the following process. If the value is 0, the speed oscillation is independent of the distance. Larger values lead to a greater speed oscillation with increasing distance.
		CC7 (Oscillation Acceleration) (ft/s2)	Oscillation during acceleration
		CC8 (Standstill Acceleration) (ft/s2)	Desired acceleration when starting from standstill (limited by maximum acceleration defined within the acceleration curves).
		CC9 (Acceleration with 50 mph) (ft/s2)	Desired acceleration when starting approximately 50 mph, (limited by maximum acceleration defined within the acceleration curves).

3.2.1.2. Baseline Behavior Parameters

Driving behavior parameters in VISSIM control the driver behavior characteristics of individual vehicles in the model. Driving behavior in VISSIM is primarily affected by two models: (1) the car-following model, and (2) the lane changing behavior.

These models include the parameters discussed below, which are found to be effective in impacting driver behavior for calibration purposes.

- **Advanced merging**

When this option is selected vehicles change lanes upstream of a congested on-ramp to allow more vehicles from the ramp to merge to the mainline, thus increasing capacity and reducing the likelihood of stopped vehicles waiting for a gap.

- **Safety distance reduction factor for lane changes**

A safety distance reduction factor is taken into consideration for each lane change. It affects the following parameters:

1. The safety distance of the trailing vehicle on the new lane, which determines whether a lane change will be carried out.
2. The safety distance of the lane changing vehicle itself.
3. The distance to the preceding, slower lane changing vehicle.

During the lane change VISSIM reduces the safety distance of the vehicle to the value that is calculated by multiplying original safety distance with the safety distance reduction factor. For instance, the default value of 0.6 reduces the safety distance value by 40% and then after the lane change occurs the value is changed to the original safety distance.

- **Cooperative lane change**

It is recommended to select this option for all behaviors, as it smooths transitions into more realistic driving behaviors.

- **Waiting time before diffusion**

This time is the maximum amount of time a vehicle will wait or stop for a necessary lane change before it is removed from the network. If the vehicle is removed from the network, a warning message will be written in the .err file denoting that the vehicle was removed.

- **Maximum deceleration for cooperative braking**

This value denotes to what extent the trailing vehicle is braking cooperatively in order to allow the preceding vehicle in the adjacent lane to perform a lane change and enter the lane in which the trailing vehicle is traveling. The default value for the maximum deceleration for cooperative braking is -9.84 feet/s^2 (defaulted in VISSIM).

During cooperative braking, a vehicle decelerates with the following values:

1. 0% to 50% of the desired deceleration, until the vehicle in front begins to change lanes.
2. 50% of the desired deceleration to the maximum deceleration of 100% specified in the 'Maximum deceleration field'. The deceleration during the lane change will be considerably less than the maximum deceleration, because the preceding vehicle, which changes lanes, does not expect such a high deceleration from the trailing vehicle.

After understanding how these parameters affect the driving behavior of a vehicle in VISSIM, the next steps involved creating the model geometry, calculating demand volumes based on different LOS and free-flow speed. And finally, replicating the results resembling the boundary conditions by adjusting various car-following and lane-changing parameters based on flow rates and mean speed for various LOS as shown in HCM6 (Fig 3.4).

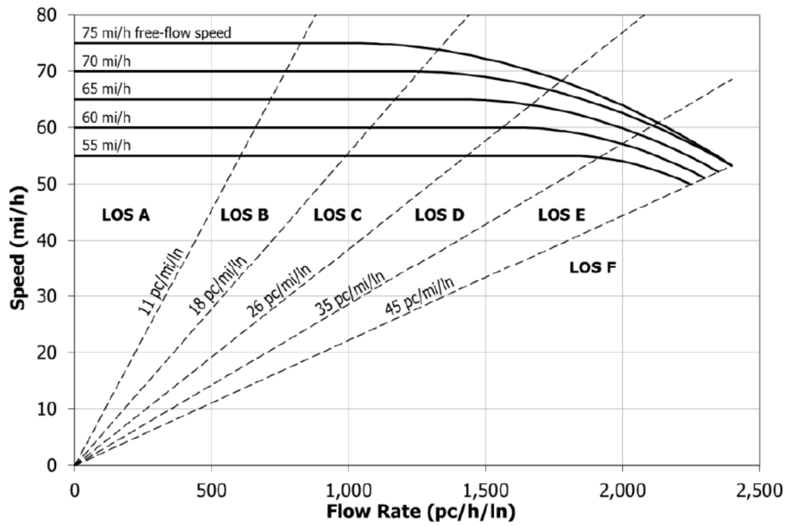

Figure 3.4 LOS Criteria and Speed-Flow Curves for Basic Freeway Segments (TRB, 2016)

The input volumes for scenarios with 0%, 5%, and 15% heavy vehicles are mentioned Table 3.3. Note, that the values for Max service flow rate are in passenger car per hour per lane (pc/h/ln).

Table 3. 3 Input volumes for 2-lane freeway

LOS	**FFS**					
	65		**70**		**75**	
	Max service flow rate (pc/h/ln) I Avg Speed (mph)					
A	**1430**	65.00	**1540**	70.00	**1650**	75.00
B	**2340**	65.00	**2520**	69.93	**2660**	73.06
C	**3330**	62.95	**3470**	64.10	**3550**	64.33
D	**4120**	52.28	**4230**	52.75	**4260**	52.31
E	**4324**	48.04	**4416**	49.07	**4416**	49.07

But, the input volumes inside VISSIM are in vehicles per hour and therefore each calculated total input volume from Table 3.3 is multiplied with the heavy vehicle adjustment factor (f_{HV}) of 0.95 for 5% heavy vehicles and 0.87 for 15% heavy vehicles which was calculated based on Equation 3.1 obtained from Chapter 12 of HCM6 in order to get the values in vehicles per hour.

$$f_{HV} = \frac{1}{1+P_T(E_T-1)}$$ **Equation 3. 1**

where, f_{HV} = heavy-vehicle adjustment factor (decimal), P_T = proportion of heavy vehicles in traffic stream (decimal), and E_T = 2.0 (passenger-car equivalent of one heavy vehicle in the traffic stream on level terrain (PCEs)). Whereas, the scenarios comprising of no trucks in them used the exact values from Table 3.3 as input volumes for VISSIM, because all the vehicles inside the traffic were passenger cars.

The ratio of mainline volume to on-ramp volume was 4:1. The scenarios including trucks, had the same ratio of mainline to on-ramp volume and both mainline and on-ramp traffic were assigned same percentage of trucks (i.e., 5% and 15%).

The research from Leyn and Vortisch (2015) served as guideline where they utilized VISSIM to replicate results from the German version of the HCM for a basic and merge freeway segment by changing driver behavior parameters. After calibrating to achieve the densities for the boundary conditions of LOS with the conventional vehicles, CAVs were introduced into the traffic stream in different proportions ranging from 5% to 100% to observe the improvement in capacity on the freeway facility along with its respective segments. These proportions were the same for both the mainline and the on-ramp traffic.

The specific driving behavior for the merge area begins for the modeled freeway lanes and the on-ramp at the gore point. It continued until the end of the merging lane. The lane change distance for the connectors upstream of the end of the merging lane was set at 800ft with one exception for the scenario having a free-flow speed of 75mph and 15% trucks for which it was set at 810ft with a default emergency stop value of 16.4ft. In addition, no lane change was set for the rightmost freeway lane to prevent vehicles from getting on the acceleration lane. Heavy vehicles on mainline could change lanes to the left throughout the merge area.

To reproduce speed profiles of entering and merging vehicles, desired speed decisions were made on the on-ramp, starting with 40mph for both passenger cars and heavy vehicles just before the beginning of the acceleration ramp. About 200ft before the gore point, both passenger cars and heavy vehicles were assigned desired speeds based on the free-flow speed of mainline vehicles in order for them to accelerate to achieve free-flow speed after leaving the on-ramp and getting on the acceleration lane to merge.

Table 3.4 presents 270 scenarios which were generated by variations in parameters with their specific range of values.

Table 3. 4Total number of scenarios based on various parameters.

Considered Parameters							**No. of Scenarios**
LOS Scenario	A	B	C	D	E		5
FFS Mainline (mph)	65	70	75				3
FFS Ramp roadway (mph)	40						
% of CAVs	0	5	25	50	75	100	6
% of trucks	0	5	15				3
No. of Lanes on Freeway	2						1
No. of Lanes on Ramp	1						1
Ratio of Mainline demand volume to on-ramp demand volume	4:1						1
Total							270

The FFS criteria for mainline and on-ramp formed the three major groups i.e., (65, 40), (70, 40), and (75, 40). The remaining parameters varied within each FFS group. Each of the 180 scenarios run initially 10 times. For each run there were six 15-minute intervals where the first 15-minute served as warm-up period and each remaining interval represented the demand volume for each of the five LOS boundary conditions.

Initially, each scenario were run 10 times, in order to get the required number of runs based on the standard of deviation and 95% confidence based on equation 3.2:

$$\mathbf{R} = \left(\frac{\boldsymbol{s.t\alpha/2}}{\boldsymbol{\bar{x}\ .\varepsilon}}\right) \qquad \textbf{Equation 3.2}$$

where, R is required number of model runs; s is standard deviation of the examined traffic measure; $\overline{x}$ is the mean of the traffic measure; ε is the required accuracy specified as a fraction of $\overline{x}$, and $t_{\alpha/2}$ is the critical value of Student's t-test at confidence level α.

The Root Mean Squared Error (RMSE) was applied for measuring the goodness of fit for comparison between simulation outputs and observed measurements of various traffic measures because large errors are heavily penalized by this measure and therefore, this metric improves the consistency of the calibrated results. Calibration targets for both flow rate and speed were set at 5% and 11% of the target value for RMSE.

$$\mathbf{RMSE} = \sqrt{\frac{\mathbf{1}}{\boldsymbol{N}}\sum_{\boldsymbol{i=1}}^{\mathbb{N}}\left(\frac{\boldsymbol{x_i - y_i}}{\boldsymbol{y_i}}\right)^{\mathbf{2}}} \qquad \textbf{Equation 3.3}$$

Where x_i is the simulated measurement, y_i is the observed measurement, and N is the number of measurements.

As mentioned in the objective of this research introduction of CAVs most likely will bring improvements to the traffic stream by sustaining the FFS for higher flow rates and increasing the throughput compared to conventional vehicles traffic. This improvement should increase with higher proportions of CAVs. This is because CAVs can manage shorter headways along with better reaction times than humans.

3.3. Performance measures

As mentioned in the literature review, density determines the LOS for freeways. In order to obtain density, speeds and flow rates were used as performance measures and these data were collected close to the bottleneck location i.e., 100ft downstream of the end of the merge segment. It is important that the measurements of flows, speeds, and densities used to estimate capacity and LOS were carried out at a correct location for which Section 5 from Chapter 26 in HCM6 provides insight. Data were obtained at a bottleneck location, just downstream at the end of acceleration lane, as shown in Fig. 3.5.

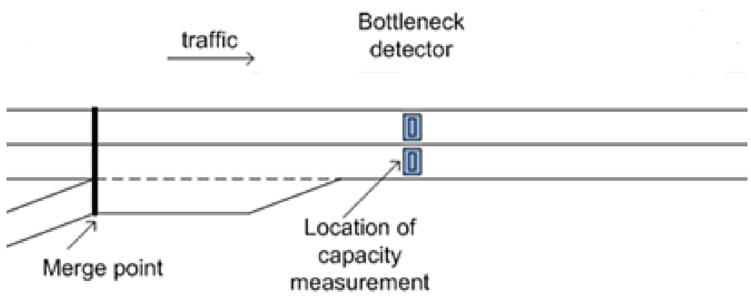

Figure 3.5 Recommended Capacity Measurement Location

Once breakdown events were identified as queues start to form upstream from the bottleneck location, the pre-breakdown condition was determined to estimate segment capacity based on speed and flow rate obtained from the data collection point.

While calibrating in VISSIM, the boundary condition for flow rates for LOS E could not be achieved and sustained for the whole 15-minute interval as breakdown conditions were seen after 5 minutes into simulation run. Therefore, an 8% demand volume drop was applied to resemble the LOS E condition throughout all the scenarios in order to access the improvements and to avoid application of additional capacity adjustment factors during the final calculations. This also brought down the critical speed in order to match the density at capacity of 45pc/mi/ln.

3.4. Calibration Results

In order to obtain the required speeds and flow rates to replicate the results from HCM6, various driver behavior parameters present inside the “Driving behavior” tab in VISSIM were calibrated. The selected ranges of calibration values are provided in Table 3.5. These values only apply to the merge segment whereas the basic segment on both sides of the merge follow Freeway (Free-lane selection) follow driving behavior using default settings provided in VISSIM.

Table 3.5 Range of values applied for driving behavior attributes for calibrating merge section

Car Following					***Defaults***	
No. of interaction objects	3				2	
No. of interaction vehicles	4				99	
Wiedemann 99	**Min**	**Max**			***Wiedemann 99***	
CC0 (Standstill Distance) (ft)	4.00	7.00			4.92	
CC1 (Headway Time) (s)	1.10	1.18			0.9	
CC2 (Following Variation) (ft)	13.12	13.12			13.12	
Lane Change						
	Own (Min)	**Own (Max)**	**Trailing Vehicle (Min)**	**Trailing Vehicle (Max)**	**Own**	**Trailing Vehicle**
Max deceleration (ft/s2)	-13.12	-12	-9.84	-8	-13.12	-9.84
-1ft/s2 per distance (ft)	185	260	100	155	200	200
Accepted deceleration (ft/s2)	-4.92	-3.25	-3.28	-2	-3.28	-1.64
	Min	**Max**			***Defaults***	
Waiting time before diffusion (s)	60	60			60	
Min. net headway (front to rear) (ft)	1.64	1.8			1.64	
Safety distance reduction factor	0.33	0.50			0.60	
Max deceleration for cooperative braking (ft/s2)	-9.84	-9.84			-9.84	
Cooperative Lane change	On				Off	
Max speed difference (mph)	6.71	7.2			6.71	
Max collision time (s)	10	10			10	
Advance merging	On				On	
Vehicle routing decision look ahead	On				On	
Connector Lane change (ft)	800	810			656.2	

Table 3.5 provides comparison between calibrated values to the defaults one. For simulating merging behavior, the ‘Safety distance reduction factor’ was set lower than the default value of 0.6. The scenarios involving heavy vehicles were modelled for more aggressive merging behavior for the on-ramp traffic to avoid queueing on the acceleration lane. VISSIM driving behavior parameters that were considered adjusting during calibration were kept within suggested ranges presented in Iowa DOT’s Microsimulation Guidance document (IowaDOT, 2017).

While calibrating each scenario, few key points were taken into consideration:

- Creation of a bottleneck by the end of the merge segment, where the data were collected and nowhere else throughout the site,
- Obtaining mean values for both flow rate and speed within 5% and 11% of target values for RMSE for each LOS intervals,
- Avoiding queue formation on the on-ramp by vehicles who were unable to find acceptable gaps to merge to mainline.

The following sections present the calibration results for the three FFS studied (65 mi/h, 70mi/h, and 75 mi/h) and for different truck percentages (0%, 5%, 15%).

3.4.1. Scenarios with FFS=65mph

As observed from Fig 3.6 and Table 3.6, the resulting mean values for flow rate (pc/h/ln) and speed (mph) were within the acceptable margin of error, as RMSE for both flow rate and speed were within 5% and 11% respectively of the target values for each LOS. In the Table 3.6 for LOS E condition, the flow rate was set at 2162 pc/h/ln instead of 2350 pc/h/ln (which is the flow-rate at capacity when free-flow speed is 65mph) which was a result of 8% drop applied in flow rate to all scenarios with 65mph as FFS. Similarly, 8% capacity drop was applied for FFS of 70mph and

75mph, resulting in 2208 pc/h/ln instead of 2400 pc/h/ln for LOS E interval. Rest of the LOS input volumes remain unchanged.

Table 3.6 Calibration data for 65mph FFS, and 0% Heavy vehicles.

LOS	Flow Rate (pc/h/ln)	Speed (mph)	Calibrated Flow (pc/h/ln)			Calibrated Speed (mph)		
			Flow rate	Std Dev.	RMSE	Speed	Std Dev.	RMSE
A	715	65.00	722	11.499	9.406	64.29	0.238	0.573
B	1170	65.00	1156	15.197	10.621	63.43	0.392	1.301
C	1665	62.95	1648	16.092	11.786	61.38	0.841	1.314
D	2060	52.28	2042	15.609	9.183	55.58	3.131	3.224
E	2162	48.04	2168	17.895	12.922	52.03	3.605	4.199

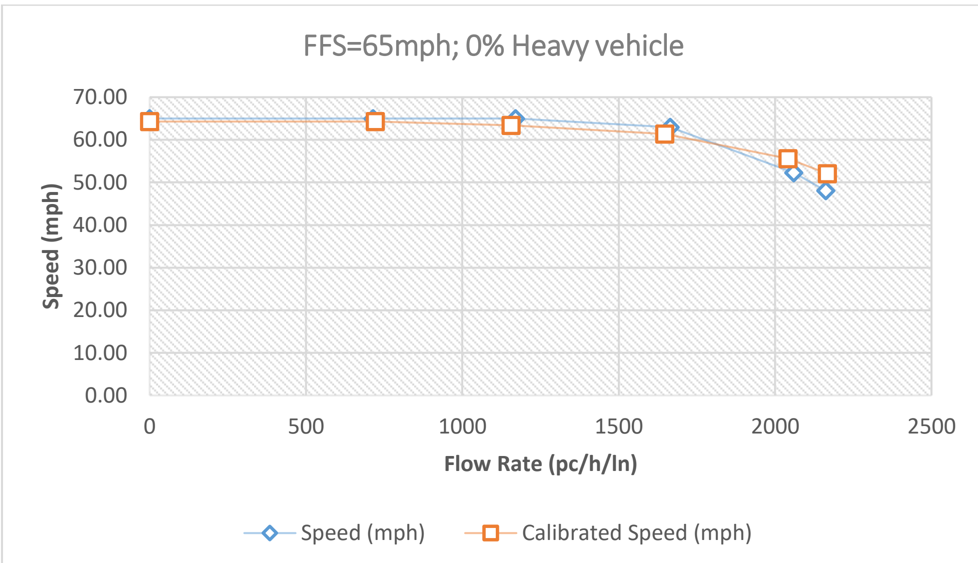

Figure 3.6 Speed-Flow Curves for 65mph FFS, and 0% Heavy vehicles.

The required number of model runs was set to 15 runs based on Equation 1 for a 95% confidence interval. It was not possible to achieve speeds lower than 52.03mph as that was causing an increase in RMSE as well as a standard of deviation leading to less consistent results as the congested conditions were observed.

Table 3.7 and Figure 3.7 present the calibration results for 5% heavy vehicles in the traffic stream, assuming a 65mph free-flow speed.

Table 3.7 Calibration data for 65mph FFS with 5% Heavy vehicles

LOS	Flow Rate (pc/h/ln)	Speed (mph)	Calibrated Flow (pc/h/ln)			Calibrated Speed (mph)		
			Flow rate	Std Dev.	RMSE	Speed	Std Dev.	RMSE
A	715	65.00	728	9.483	22.053	64.09	0.309	0.719
B	1170	65.00	1152	11.821	38.590	63.18	0.508	1.474
C	1665	62.95	1648	14.550	29.472	61.38	0.810	1.453
D	2060	52.28	2048	15.470	18.138	56.40	2.031	3.519
E	2162	48.04	2158	15.340	13.975	52.74	3.856	4.759

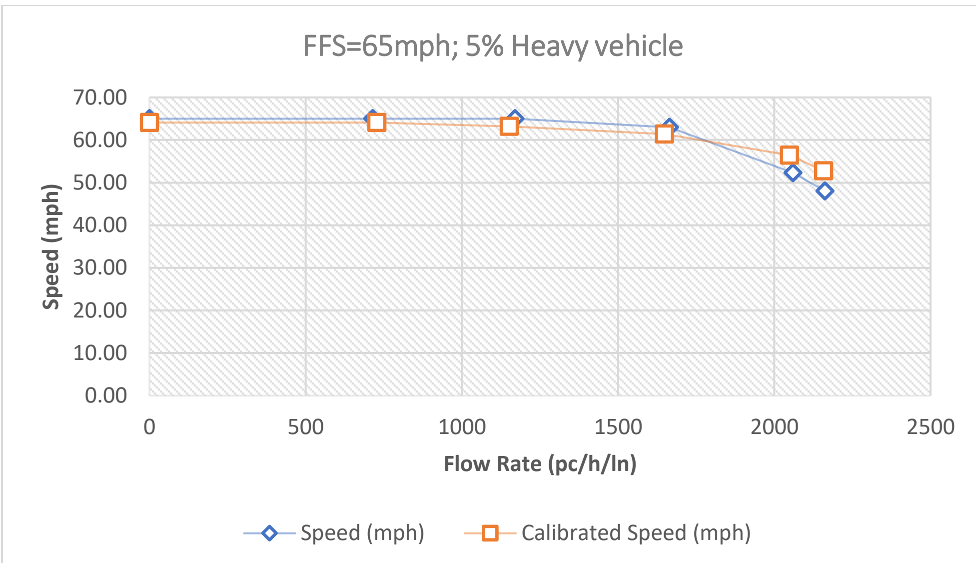

Figure 3.7 Speed-Flow Curves for 65mph FFS with 5% Heavy vehicles.

VISSIM considers the presence of trucks in the traffic stream, therefore, despite of setting the Desired speed distribution at 65mph for both cars and trucks, slightly lower free-flow speeds than 65mph were obtained, but still within the acceptable error margins. Both the scenarios for 65mph FFS with heavy vehicles required 18 and 20 runs for 5% and 15% respectively. The calibration results for 15% heavy vehicles are presented in Table 3.8 and Figure 3.8.

Table 3.8 Calibration data for 65mph FFS with 15% Heavy vehicles

LOS	Flow Rate (pc/h/ln)	Speed (mph)	Calibrated Flow (pc/h/ln)			Calibrated Speed (mph)		
			Flow rate	Std Dev.	RMSE	Speed	Std Dev.	RMSE
A	715	65.00	724	10.476	10.725	63.74	0.400	1.272
B	1170	65.00	1152	13.164	11.243	62.79	0.509	2.213
C	1665	62.95	1653	15.452	13.833	60.15	1.085	2.557
D	2060	52.28	2048	15.795	16.517	55.08	2.590	3.620
E	2162	48.04	2170	15.378	17.048	51.75	3.886	4.387

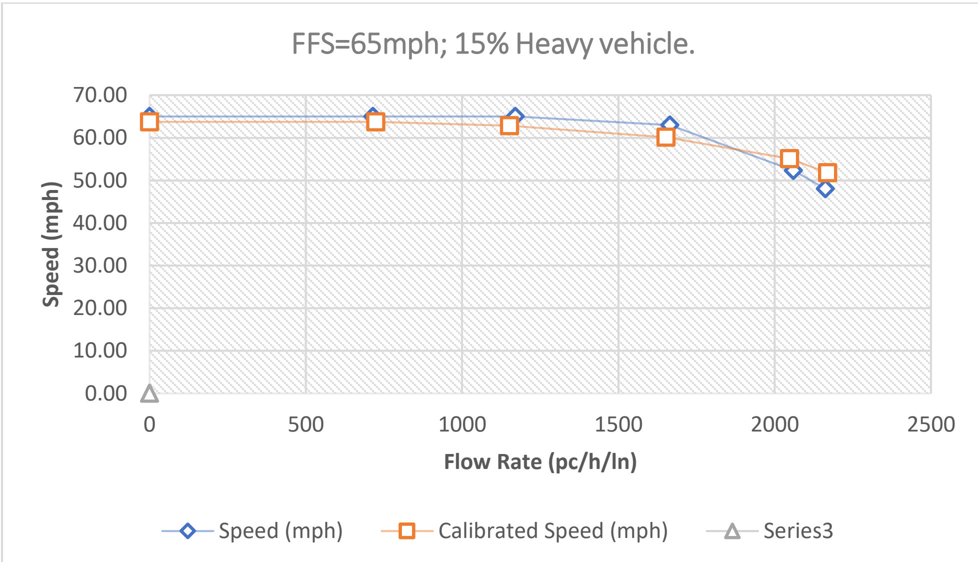

Figure 3.8 Speed-Flow Curves for 65mph FFS with 15% Heavy vehicles

When trucks were modelled for a FFS of 65mph, the CC0 (Standstill Distance) parameter in VISSIM was increased to 7ft and 5.5ft for 5% and 15% trucks, respectively. As trucks from the on-ramp required longer gaps in order to merge, the CC1 (Headway Time) parameter was also increased for the scenarios with 15% trucks to avoid formation of queues on the on-ramp. This meant that traffic on the mainline did not have to decelerate aggressively in order to create gaps for the on-ramp traffic. The “Cooperative lane change” and “Advance merge” functions in VISSIM also aided in acceptable gap creation between the mainline vehicles for the on-ramp traffic to merge to complete the maneuver.

3.4.2. Scenarios with FFS=70mph

The calibration results for the 70mph scenario and 0% heavy vehicles are presented in Figure 3.9 and Table 3.9. A total of 15 runs were performed for this scenario. The calibrated values are again within the set margin of error; therefore, the goodness of fit condition was satisfied. The Standstill Distance (CC0) was set at 5ft and the Headway time (CC1) was set at 1.13s, although the critical speed at LOS E was higher than the required one, i.e., 52.34mph instead of the 49.07mph target value. Similar condition was observed for LOS D as well. Table 3.9 shows that the resulting mean speed value for LOS A was almost 70mph because there are no heavy vehicles involved. The table also shows the speed and flow RSMEs are within the acceptable ranges.

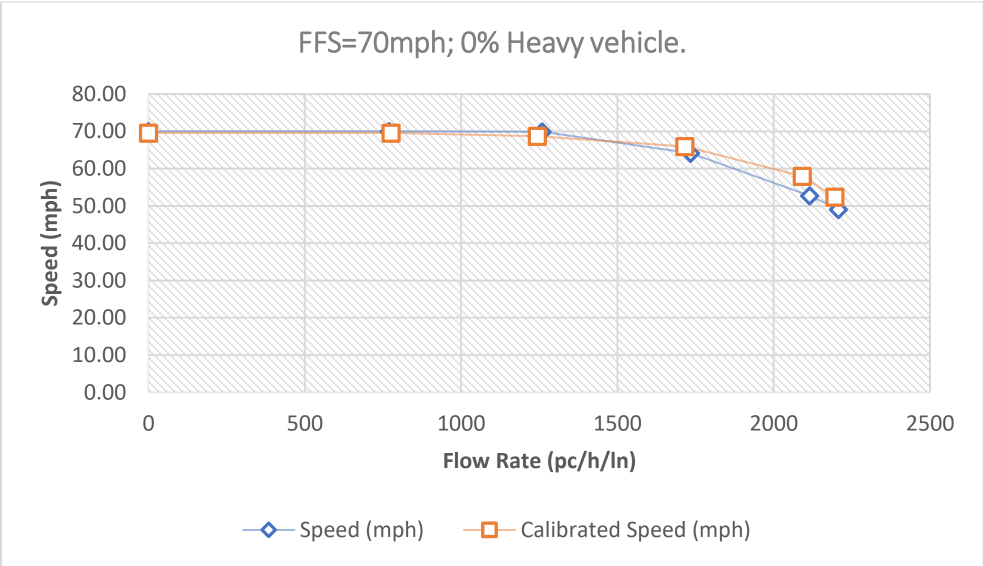

Figure 3.9 Speed-Flow Curves for 70mph FFS, and 0% Heavy vehicles.

Table 3.9 Calibration result for 70mph FFS, and 0% Heavy vehicles

LOS	Flow Rate (pc/h/ln)	Speed (mph)	Calibrated Flow (pc/h/ln)			Calibrated Speed (mph)		
			Flow rate	Std Dev.	RMSE	Speed	Std Dev.	RMSE
A	770	70.00	776	10.082	12.803	69.58	0.234	0.305
B	1260	69.93	1244	12.830	20.562	68.65	0.455	1.081
C	1735	64.10	1716	13.000	13.232	65.95	0.741	1.694
D	2115	52.75	2092	17.702	13.714	57.97	2.794	4.622
E	2208	49.07	2196	19.732	10.146	52.34	4.413	4.777

Fig. 3.10 and Table 3.10 show the calibration results for the 70mph FFS and 5% heavy vehicles scenario. In this scenario, the critical speeds for LOS D and E were higher than the target values. The obtained FFS was also slightly lower than 70mph due to the presence of heavy vehicles. However, the two speed-flow graphs seem to be close and the speed and flow RSMEs are within the acceptable ranges.

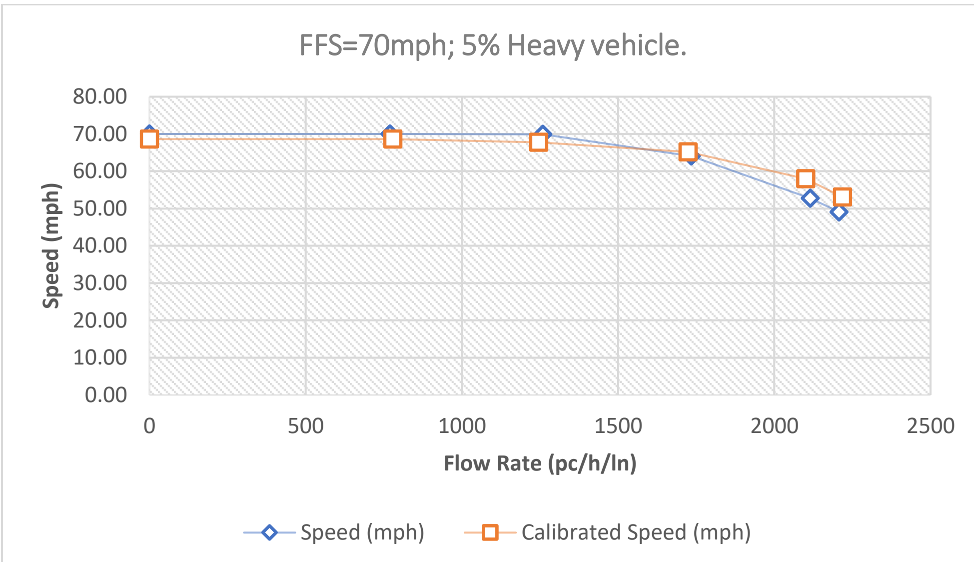

Figure 3.10 Speed-Flow Curves for 70mph FFS with 5% Heavy vehicles.

Table 3.10 Calibration result for 70mph FFS with 5% Heavy vehicles.

LOS	Flow Rate (pc/h/ln)	Speed (mph)	Calibrated Flow (pc/h/ln)			Calibrated Speed (mph)		
			Flow rate	Std Dev.	RMSE	Speed	Std Dev.	RMSE
A	770	70.00	779	11.632	9.618	68.62	0.294	1.183
B	1260	69.93	1246	14.105	11.001	67.73	0.509	1.882
C	1735	64.10	1724	16.570	11.376	65.16	1.370	1.533
D	2115	52.75	2101	17.495	10.471	57.98	3.174	4.883
E	2208	49.07	2219	18.529	11.200	53.05	4.757	4.853

Figure 3.11 and Table 3.11 present the calibration results for the 70mph FFS and 15% trucks scenario. In this scenario, a similar trend with the speeds being higher than 52.75mph and 49.07 for LOS D and LOS E, respectively, was observed. The values for CC0 and CC1 used to calibrate

the 70mph FFS with 15% heavy vehicles was 5.45ft and 1.16s, respectively, along with a Safety distance reduction factor of 0.40 to help with the merging behavior, especially for heavy vehicles because of longer gaps between mainline vehicles.

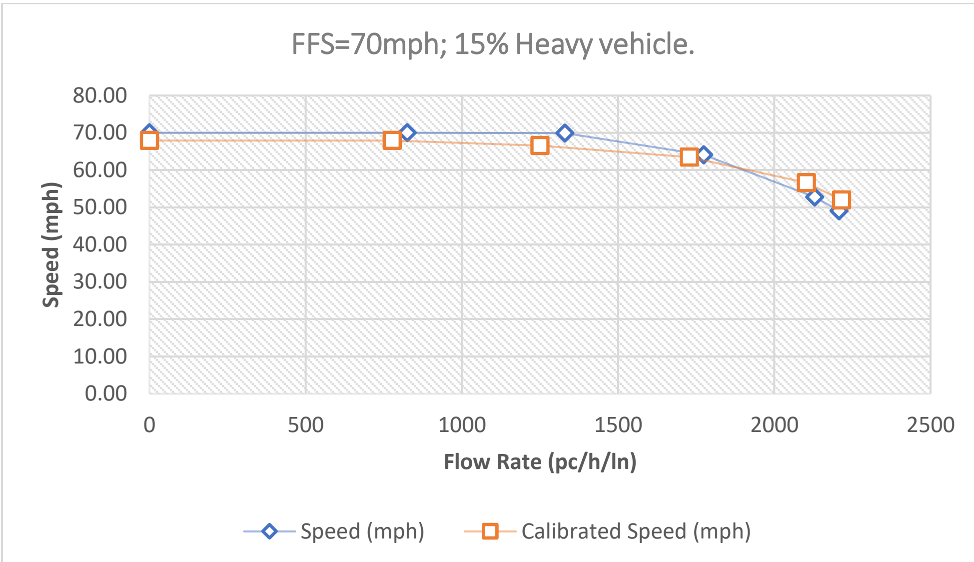

Figure 3.11 Speed-Flow Curves for 70mph FFS with 15% Heavy vehicles.

Table 3.11 Calibration result for 70mph FFS with 15% Heavy vehicles.

LOS	Flow Rate (pc/h/ln)	Speed (mph)	Calibrated Flow (pc/h/ln)			Calibrated Speed (mph)		
			Flow rate	Std Dev.	RMSE	Speed	Std Dev.	RMSE
A	825	70.00	777	11.095	9.696	67.92	0.487	1.780
B	1330	69.93	1251	13.235	10.913	66.52	0.861	2.585
C	1775	64.10	1729	16.138	11.206	63.46	1.383	2.487
D	2130	52.75	2103	18.514	11.794	56.60	3.419	3.528
E	2208	49.07	2216	16.123	12.385	51.94	4.117	3.931

3.4.3. Scenarios with FFS=75mph

Figure 3.12 and Table 3.12 present the calibration results for the 75mph FFS and 0% trucks. The resulted curve based on the calibration gives higher values for speed for LOS C and LOS D. The values for CC0 and CC1 used to obtain acceptable results were 5.25ft and 1.12s respectively, with a Safety distance reduction factor of 0.35. This meant on-ramp vehicles were modeled to accept shorter gaps in order to obtain speeds for LOS E and LOS D within the acceptable calibration target.

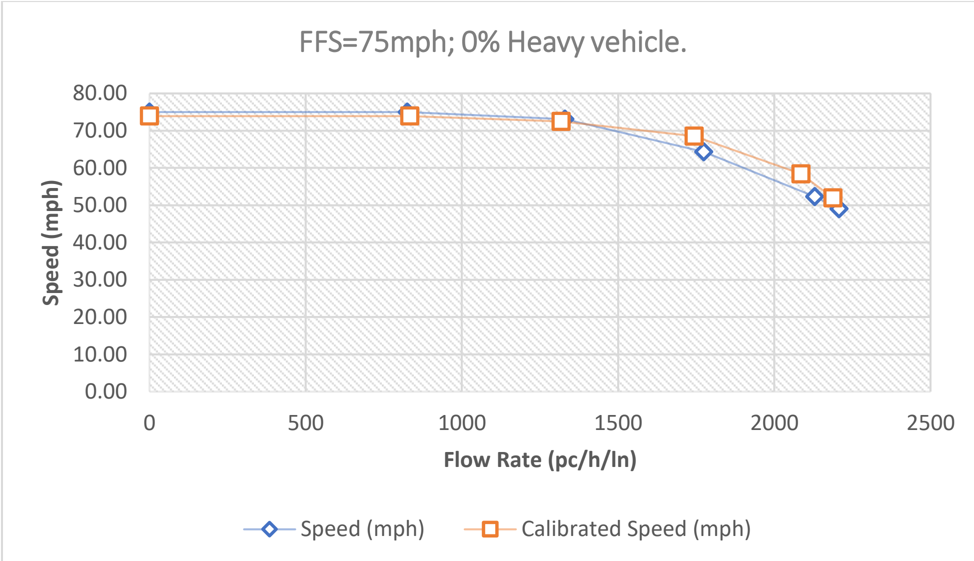

Figure 3.12 Speed-Flow Curves for 75mph FFS, and 0% Heavy vehicles.

Table 3.12 Calibration result for 75mph FFS, and 0% Heavy vehicles.

LOS	Flow Rate (pc/h/ln)	Speed (mph)	Calibrated Flow (pc/h/ln)			Calibrated Speed (mph)		
			Flow rate	Std Dev.	RMSE	Speed	Std Dev.	RMSE
A	825	75.00	834	14.029	10.363	73.91	0.210	0.858
B	1330	73.06	1318	14.722	10.219	72.51	0.580	0.627
C	1775	64.33	1744	15.779	10.629	68.51	1.398	4.032
D	2130	52.31	2086	18.860	15.786	58.39	3.378	5.774
E	2208	49.07	2188	20.132	11.895	51.93	5.016	4.781

For the 75mph FFS with 5% heavy vehicles scenario, although the calibrated model is good fit, the highest RMSE is observed for LOS D instead of LOS E condition. The values obtained are average of 15 runs and the results are shown in Figure 3.13 and Table 3.13 below.

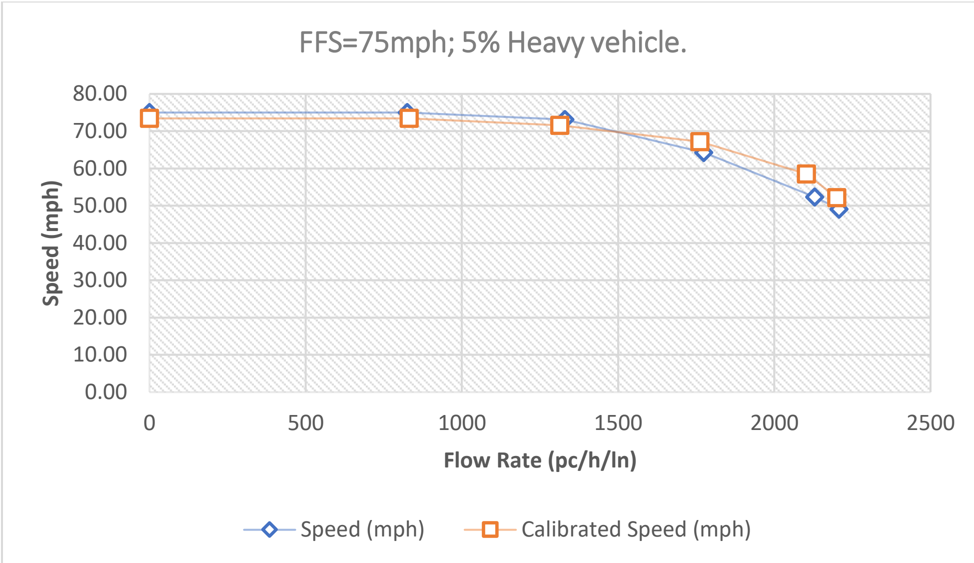

Figure 3.13 Speed-Flow Curves for 75mph FFS with 5% Heavy vehicles.

Table 3.13 Calibration result for 75mph FFS with 5% Heavy vehicles.

LOS	Flow Rate (pc/h/ln)	Speed (mph)	Calibrated Flow (pc/h/ln)			Calibrated Speed (mph)		
			Flow rate	Std Dev.	RMSE	Speed	Std Dev.	RMSE
A	825	75.00	832	11.734	9.043	73.43	0.582	1.357
B	1330	73.10	1314	15.731	10.654	71.54	0.818	1.496
C	1775	64.30	1762	15.240	8.153	67.20	1.639	2.835
D	2130	52.30	2103	17.090	12.303	58.49	3.134	5.471
E	2208	49.10	2200	22.280	12.222	52.16	4.548	4.780

Scenarios with 75mph FFS gives similar result as it did for 70mph and 65mph scenarios, but here there is a larger gap within mean speed values for the LOS C and LOS D condition. However, the obtained values are still within the error margins set for RMSE. The calibrated results were good fit for the 15% trucks and 75mph FFS scenario as shown in Figure 3.14 and Table 3.14.

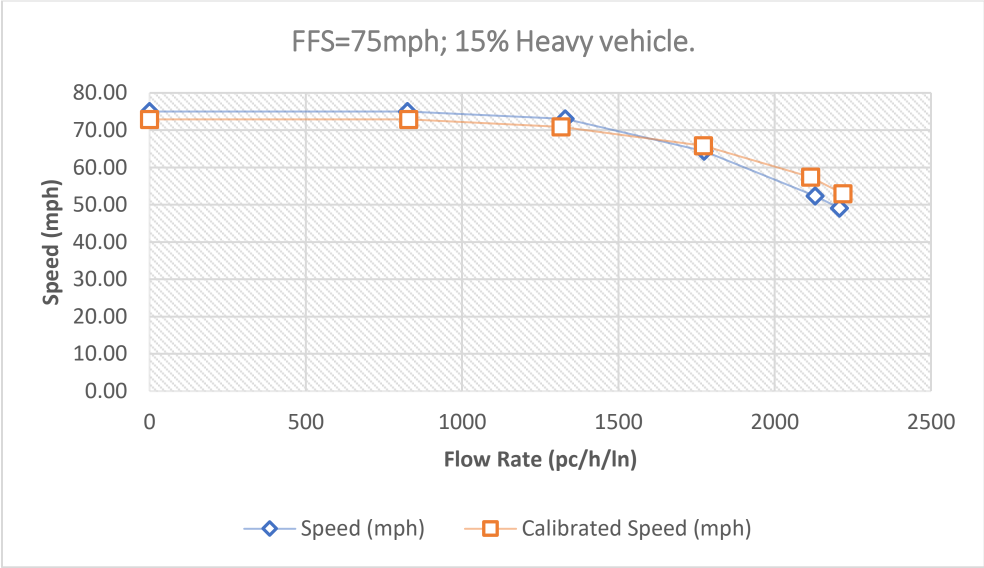

Figure 3.14 Speed-Flow Curves for 75mph FFS with 15% Heavy vehicles.

Table 3.14 Calibration result for 75mph FFS with 15% Heavy vehicles.

LOS	Flow Rate (pc/h/ln)	Speed (mph)	Calibrated Flow (pc/h/ln)			Calibrated Speed (mph)		
			Flow rate	Std Dev.	RMSE	Speed	Std Dev.	RMSE
A	825	75.00	830	12.859	11.770	72.89	0.615	2.014
B	1330	73.06	1317	15.733	12.837	70.88	1.197	2.349
C	1775	64.33	1772	15.409	11.517	65.84	2.333	2.757
D	2130	52.31	2115	18.224	11.160	57.39	3.894	5.601
E	2208	49.07	2218	18.899	12.511	52.93	5.195	4.555

All the scenarios that had some proportion of heavy vehicles saw a slight reduction in speed for the free-flow condition (i.e., LOS A) but that also assisted in getting lower speed values for LOS E. The calibration effort resulted in acceptable results with good fit.

3.5. Modelling CAVs in PTV VISSIM ver.11.0

PTV VISSIM is a microscopic traffic simulation tool, which provides a virtual testbed to evaluate the coexistence of autonomous and conventional vehicles either in the transition phase or when vehicle fleets are fully autonomous. VISSIM was used to address the evidence gap around the potential impacts of CAVs, on traffic flow, free-flow speed, and capacity.

VISSIM 11.0 simulates CAVs using two attributes: *"Number of interaction objects"* refers to vehicles and internal objects (reduced speed areas, stop signs, priority rules, red signal heads), and *"Number of interaction vehicles"* refers only to actual vehicles (Figure 3.15).

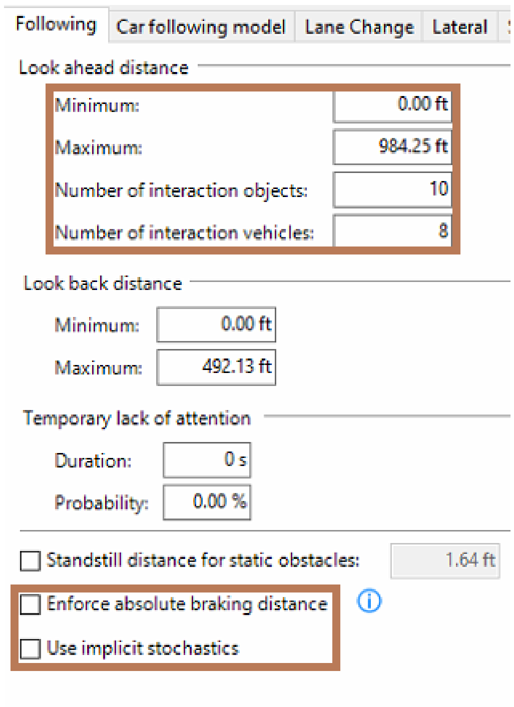

Figure 3.15 Calibration parameters for CAV using AV all-knowing (CoEXist) driving behavior in VISSIM.

The number of interaction vehicles defines an upper limit for the observed leading vehicles, therefore, this could be set to '1' for autonomous vehicles with sensor equipment that cannot see through the leading vehicle, or higher than '1' in order to model connectivity between multiple autonomous vehicles. The values used for this study were taken from that recommended by CoExist (CoExist, 2017) project which is shown in the Figure 3.15. This values also align with the study conducted by Bujanovic and Lochrane (2018), where they did not test platoon sizes greater than 12 vehicles with CACC technologies because of current technological communication constraints, as all vehicles must be able to communicate with the leader.

The attribute ‘*Enforce absolute breaking distance*’ and ‘*Use implicit stochastic*’ are both turned off by default. If the attribute *“Enforce absolute braking distance”* (a.k.a. brick wall distance) is checked, vehicles using this driving behavior will always make sure that they could brake without a collision, if the leading vehicle comes to an immediate stop (turns into a brick wall). This condition applies also to lane changes (for the vehicle itself in the new lane and for the trailing vehicle in the new lane) and to the conflict areas (for the following vehicle on the major road). But due to the connectivity between the vehicles, this feature is turned off.

The other attribute ‘*Use implicit stochastic*’ when turned off, aids in eradicating the stochastic imperfection of human driving by deterministic machines. In the internal behavior model (for humans), there are several stochastic values indicating the spread of human behavior:

- Risk acceptance,
- Ability to estimate distance and speed difference, and
- Precision when operating the throttle and braking pedals.

As the ‘*Use implicit stochastic*’ attribute is unchecked, a deterministic average value is used instead of such a stochastically distributed value whenever the distribution is not set by the VISSIM user. This option affects:

- Desired safety distance,
- Desired acceleration,
- Desired deceleration, and
- Decision points (when to start braking/accelerating).

Another attribute, ‘Increased acceleration’, is introduced in VISSIM 11.0, in order to allow vehicles with V2V communication capabilities to keep small headway even during an acceleration process because conventional vehicles tend to fall behind when the leading vehicle is accelerating. The default value recommended for this attribute is 110% as shown in Fig 3.16.

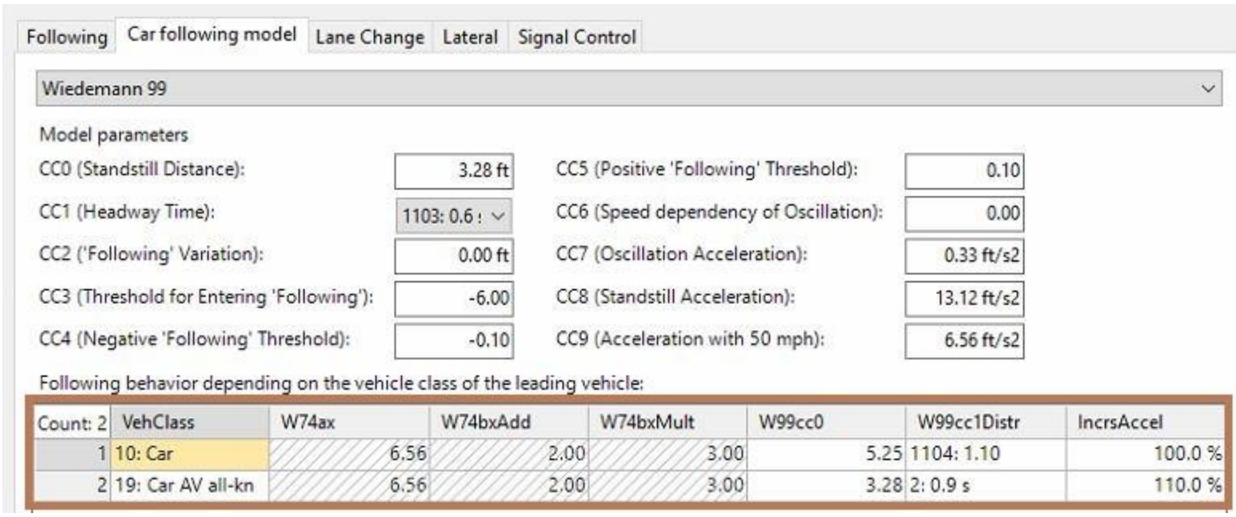

Figure 3.16 Car following parameters for CAV inside VISSIM

On the tab page "*Car following model*" (Figure 3.16) some of the parameter values affecting the desired safety distance can be specified per vehicle class of the leading vehicle. This can be utilized to model connected vehicles using a smaller safety distance when following another connected vehicle, but a larger safety distance when following a human driver. As shown in the figure above, CC0 (Standstill Distance) and CC1 (Headway Time) while following a CAV is lower than a conventional vehicle. Both CC0 and CC1 are kept the same for CAVs and conventional vehicles when following a conventional vehicle, which is more conservative due to the lack of connectivity with the vehicle leading.

Under the Lane change tab shown in Fig. 3.17 only the '*Safety distance reduction factor*' is reduced to 0.5 from the default value 0.75, as this suited the HCM calibrated scenarios best when simulating mixed traffic conditions.

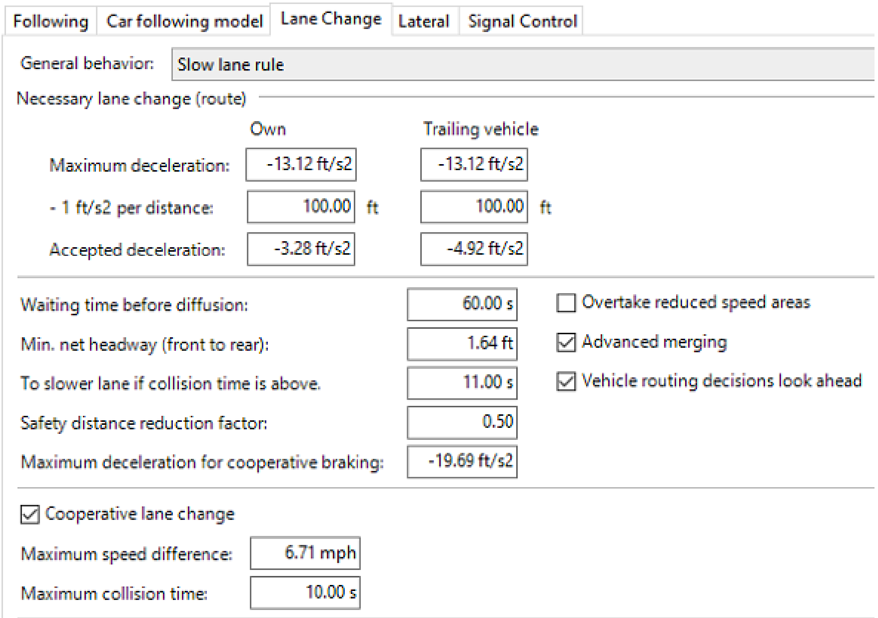

Figure 3.17 Lane changing behavior parameters used for CAVs

In VISSIM 11.0, there are three predefined driving behaviors for different types of autonomous vehicles: “AV Cautious” enforces absolute braking distance, “AV Normal” is similar to a human driver but without the stochastic spread, and “AV All knowing” uses smaller safety distances and has cooperative behavior. In this research the “AV All knowing” driving behavior logic was used, which is built on top of the Wiedemann driving behavior model but without the stochasticity of a human driver. The vehicle following this driver model can interact with up to 8 vehicles and 10 objects which are the values recommended by the European project named CoEXist (2017), aimed at preparing the transition phase during which automated and conventional vehicles will co-exist on cities’ roads. CoEXist developed a specific framework and both microscopic and macroscopic traffic models that take into account the introduction of automated vehicles.

The other recommendation from the CoEXist project was to set the Desired Speed distribution having less variability as CAVs can strictly adhere and maintain the speed limits set for a route.

Figure 3.18 shows comparison between a CAV and conventional vehicle's desired speed distributions for the same free flow speed of 75mph.

Figure 3.18 Desired Speed Distribution comparision between CAV (left) and conventional vehicle (Right)

As mentioned before, CAVs when following other CAVs can keep shorter headways than following conventional vehicles. In order to simulate this following behavior in VISSIM, Table 3.15 shows the values of Standstill distance 'CC0' and Headway Time 'CC1' implemented when a CAV is following other vehicle classes.

Table 3. 15 Car following parameters of CAVs with various vehicle class

Leading vehicle	CC0	CC1
Car	4	1.10 s
Heavy vehicle	5	1.10 s
CAV Car	3.28	0.8 s
CAV Heavy Vehicle	3.28	0.9 s

All the scenarios used the same values when modeling car-following behavior for CAV. The CC0 and CC1 values used for Car and Heavy vehicles are either less or similar to the values used to calibrate 0% CAV scenarios because CAV even without connectivity with the vehicle in front can keep smaller gaps due to better response times than human drivers. A conservative value for Headway time (CC1) was assigned for CAVs following autonomous heavy vehicles. Although CoEXist project suggests 0.6s for Headway Time (CC1) for autonomous vehicles with connectivity, slightly higher values were selected for this study leading to improved factor of safety. In the study by Ye and Yamamoto (2018), considered a 0.8s headway for Adaptive Cruise Control parameter for a CAV with advanced capabilities. Therefore, applying 0.8s for CC1 was justified. Although with connected and autonomous heavy vehicle, we did select a conservative value of 0.9s for CC1. Also, the values for a CAV following passenger cars and trucks were assumed and are mentioned in Table 3.15. These values were based on the reasoning that CAVs when following conventional vehicles can keep smaller headways even though there is lack of connectivity between them due to their faster response times than human drivers.

Also, when modeling 100% CAV, the starting point for lane change is moved 100ft further upstream from the end of the merge making it 900ft because of their better merging capabilities. Therefore, CAVs start merging behavior sooner than convention vehicles when driving in an acceleration lane.

3.6. Calculation of Adjustment Factors for CAVs

Once the base scenarios were calibrated, CAVs were introduced in various proportions in the traffic stream: 5%, 10%, 25%, 50%, 75%, and 100%. In this case, the same calibration models were used, and the input volumes were gradually increased to simulate conditions up to LOS E. Once LOS E was reached, the speed and volume and, hence, density were calculated. The ratio of the new maximum flow rate at LOS E with CAVs to the maximum flow rate with conventional vehicles was the CAF for that specific scenario. In addition, since CAVs are supposed to improve traffic conditions, it is possible that at 45pc/mi/ln (LOS for 0% CAVs) capacity is not reached. In this case, the input volume was increased until congestion started. The capacity at the point before congestion would be considered for the CAF calculation. Therefore, each scenario included two CAF values, one for density at 45pc/mi/ln i.e., CAF_{45} and other beyond the density 45pc/mi/ln i.e., CAF_{cap}. Free-flow speed adjustment factors (SAFs) were also estimated as the ratio of the FFS with CAVs to the FFS with conventional vehicles.

Apart from CAFs, the adjusted break point of the speed-flow curve was also estimated for all the proportions of CAVs given by the equation below.

$$\mathbf{BP_{adj} = [1{,}000 + 40 \times (75 - FFS_{adj})] \times CAF_{cap}^2} \qquad \textbf{Equation 3. 4}$$

Where, FFS_{adj} is the observed free-flow speed and the CAF is CAF_{cap} obtained from 100% CAVs in the base model.

4. RESULTS

Once the calibrated results within the acceptable calibration targets were achieved, each of scenarios were modelled with 5%, 25%, 50%, 75%, and 100% CAVs to observe for improvements, if any, when it comes to speed and capacity and finally calculating CAFs and adjusted Break Points (BP_{adj}) based on the CAV market penetration. The input volumes were increased gradually to access improvements. Once LOS E conditions were identified for given input volume, flow rate and speed were recorded in order to calculate CAF at capacity and another CAF was obtained when density is 45pc/mi/ln.

4.1. Capacity and Speed Analysis

This section discusses the improvements observed in performance measures i.e., speed and flow rates after CAVs were introduced at various proportions. Simulation runs for every scenario was set to 10 times. The figures in this section shows the simulated speed-flow relationship as a function of CAV market penetration. It also displays the speed-flow curve based on HCM6 values and 0% CAV (i.e., HCM calibrated results) for better understanding the improvements for each scenario. Lastly, all the figures include a dashed line representing the boundary condition of density for LOS E at 45pc/mi/ln.

4.1.1. Scenarios with 0% Heavy vehicles

When CAVs were introduced into the 65mph FFS scenarios, significant improvements for both speed and capacity were observed when CAV penetration rate was above 25% inside traffic stream.

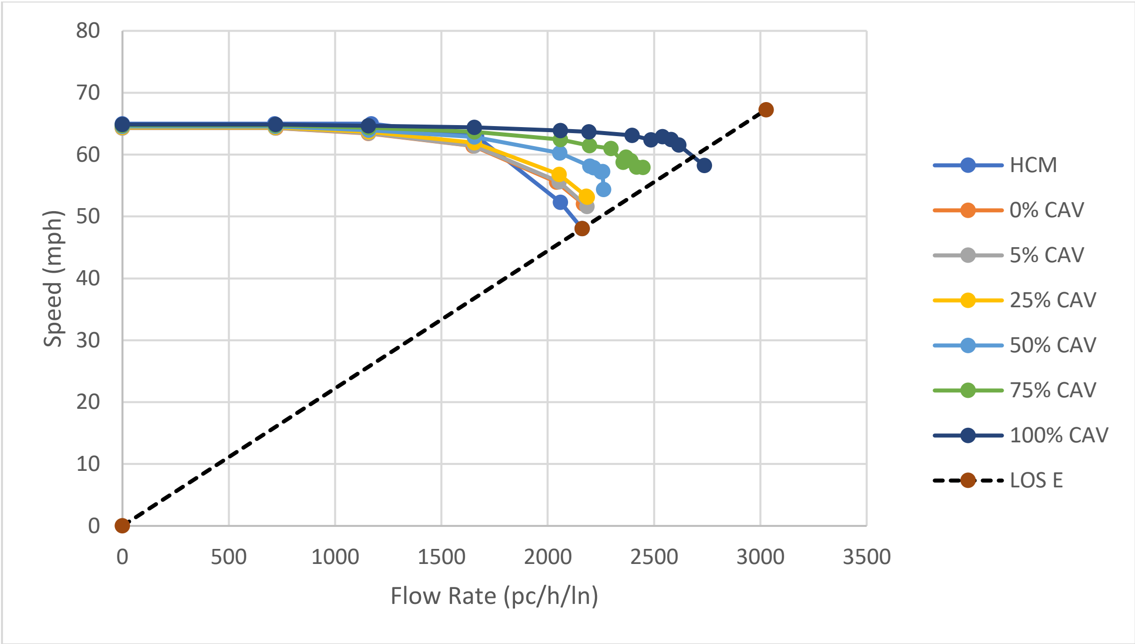

Figure 4.1 Speed-Flow relationship based on CAV-penetration rate for FFS=65mph; 0% Heavy vehicle

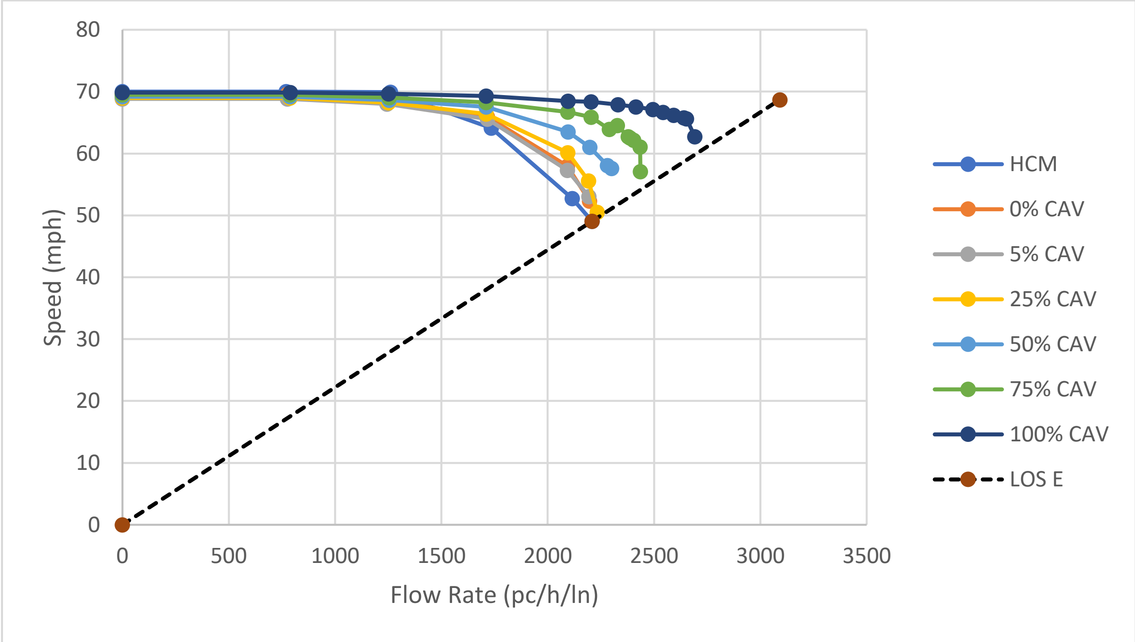

Figure 4.2 Speed-Flow relationship based on CAV-penetration rate for FFS=70mph; 0% Heavy vehicle

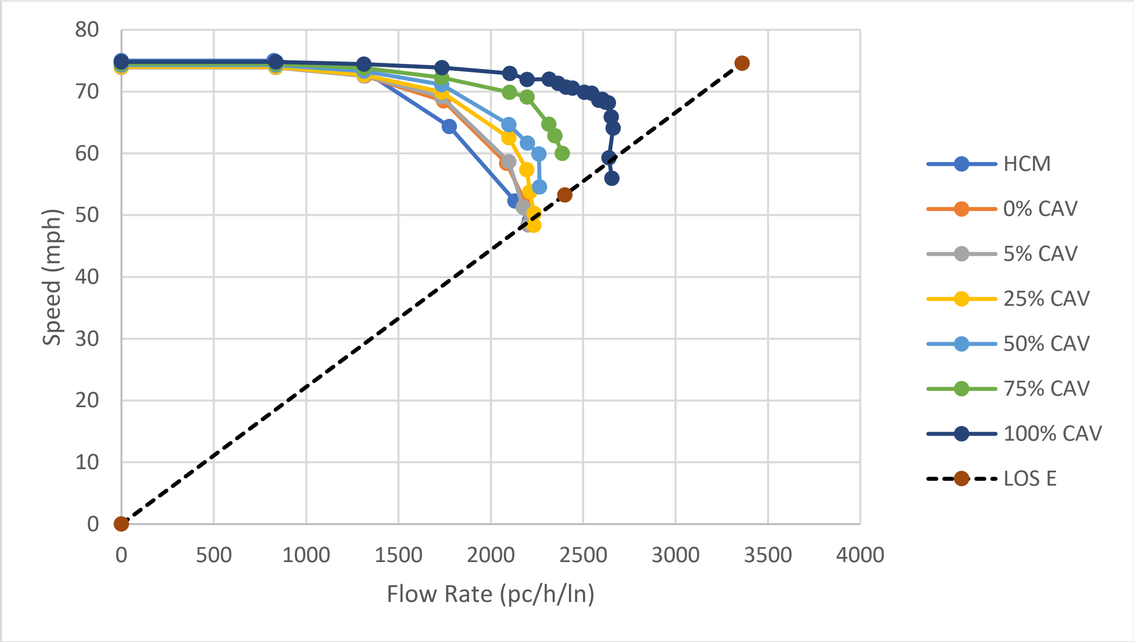

Figure 4.3 Speed-Flow relationship based on CAV-penetration rate for FFS=75mph; 0% Heavy vehicle

The free flow speeds were also sustained for higher flow rates with highest gains in this category observed for the 65mph FFS scenarios as is shown in Fig. 4.1. Also, higher CAV penetration rates lead to higher critical speeds. Although both capacity and speed saw improvements only one of the scenarios having 100% CAV for a 65mph free-flow speed and without heavy vehicles was able to maintain LOS E condition beyond the density of 45pc/mi/ln. This has to do with the values that were considered for Headway time (CC1) of CAVs as density is inversely proportional to time headway. Therefore, smaller CC1 values may have led to LOS E conditions for densities higher than 45pc/mi/ln.

4.1.2. Scenarios with 5% and 15% Heavy vehicles

For both the 5% and 15% scenarios, similar results were obtained, although this time, more scenarios were able to maintain LOS E beyond the 45pc/mi/ln density (Fig. 4.4). When comparing Fig 4.3 to Fig 4.6, for 75mph FFS, most of the CAV penetration rates saw an improvement in density for LOS E condition.

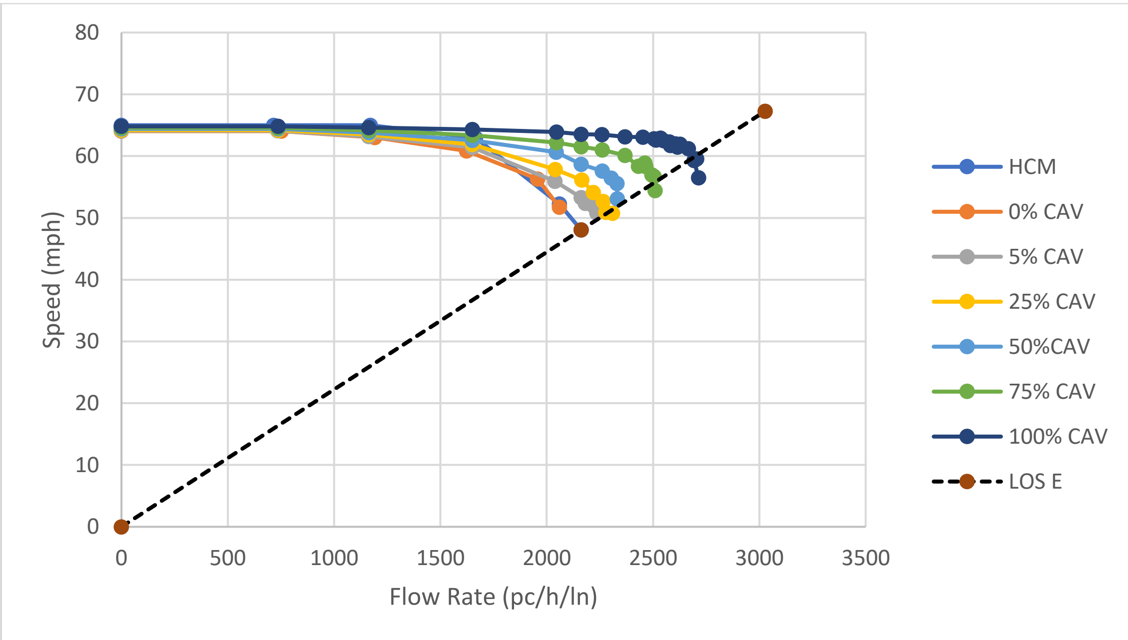

Figure 4.4 Speed-Flow relationship based on CAV-penetration rate for FFS=65mph; 5% Heavy vehicle

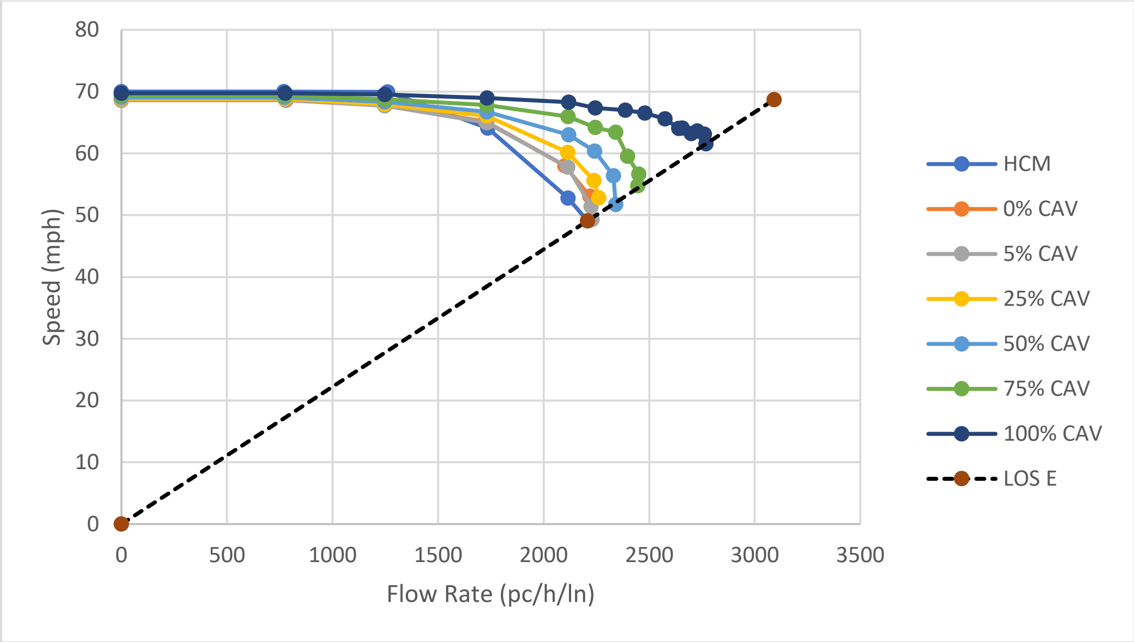

Figure 4.5 Speed-Flow relationship based on CAV-penetration rate for FFS=70mph; 5% Heavy vehicle

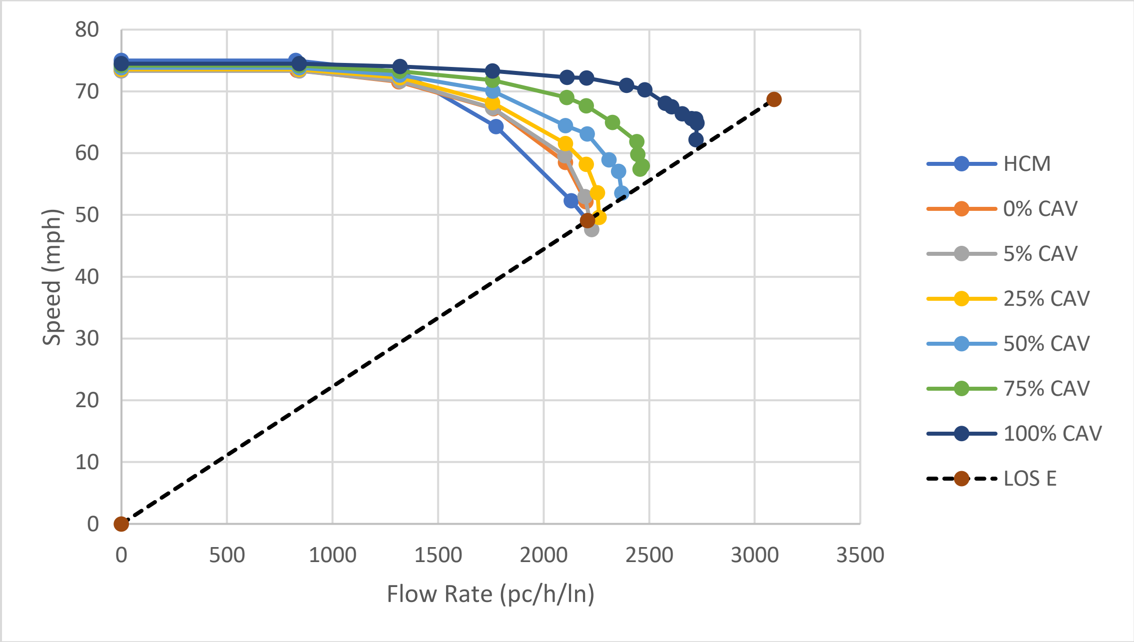

Figure 4.6 Speed-Flow relationship based on CAV-penetration rate for FFS=75mph; 5% Heavy vehicle

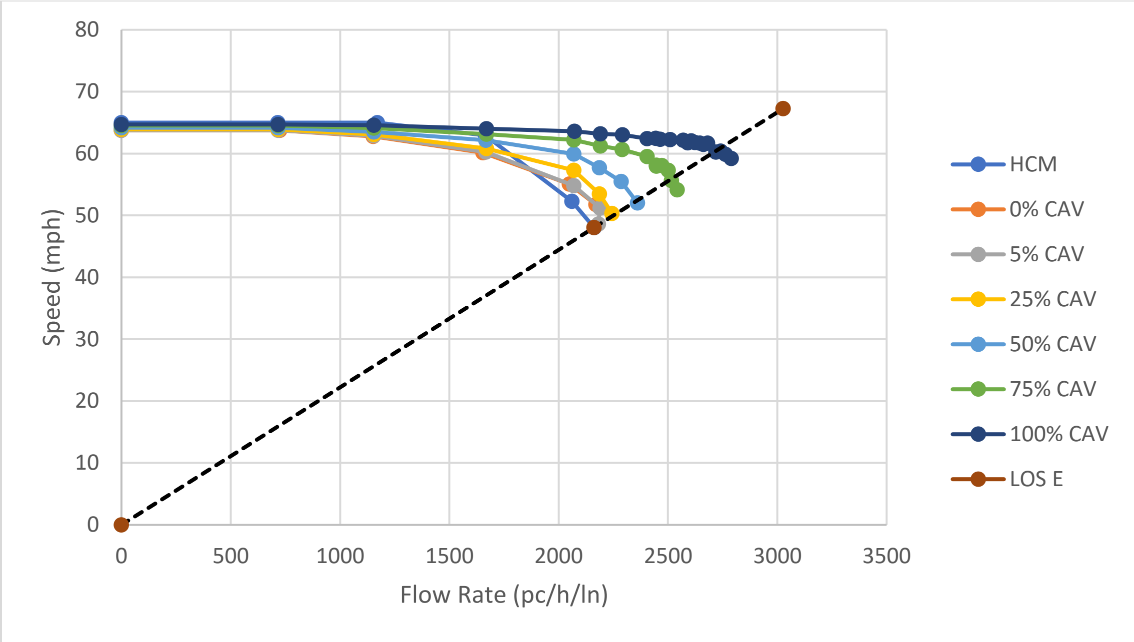

Figure 4.7 Speed-Flow relationship based on CAV-penetration rate for FFS=65mph; 15% Heavy vehicle

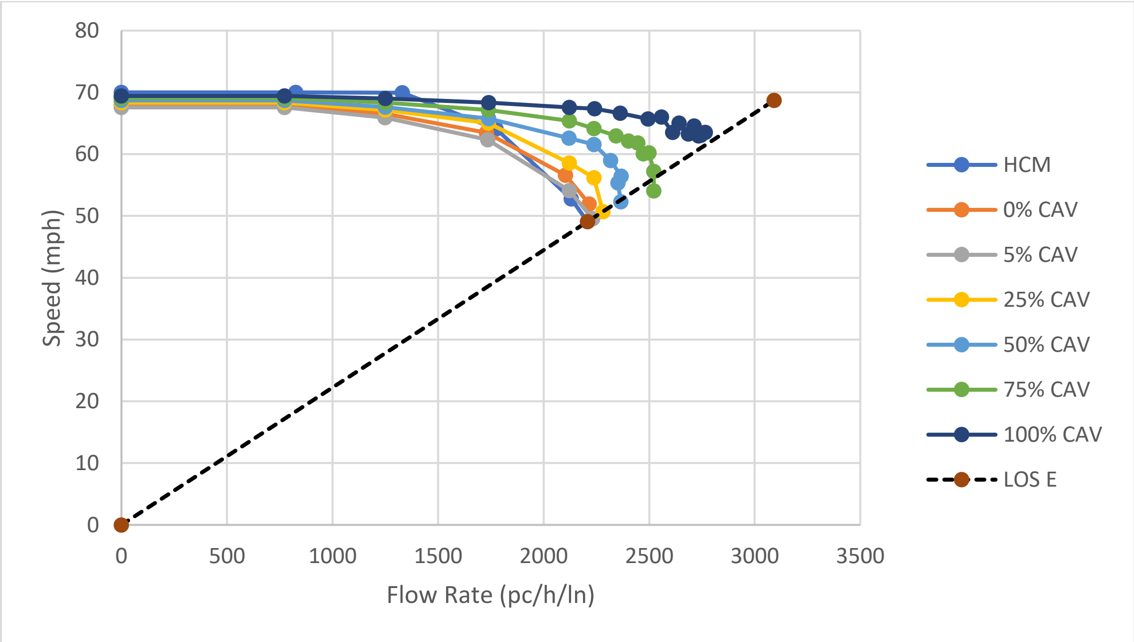

Figure 4.8 Speed-Flow relationship based on CAV-penetration rate for FFS=70mph; 15% Heavy vehicle

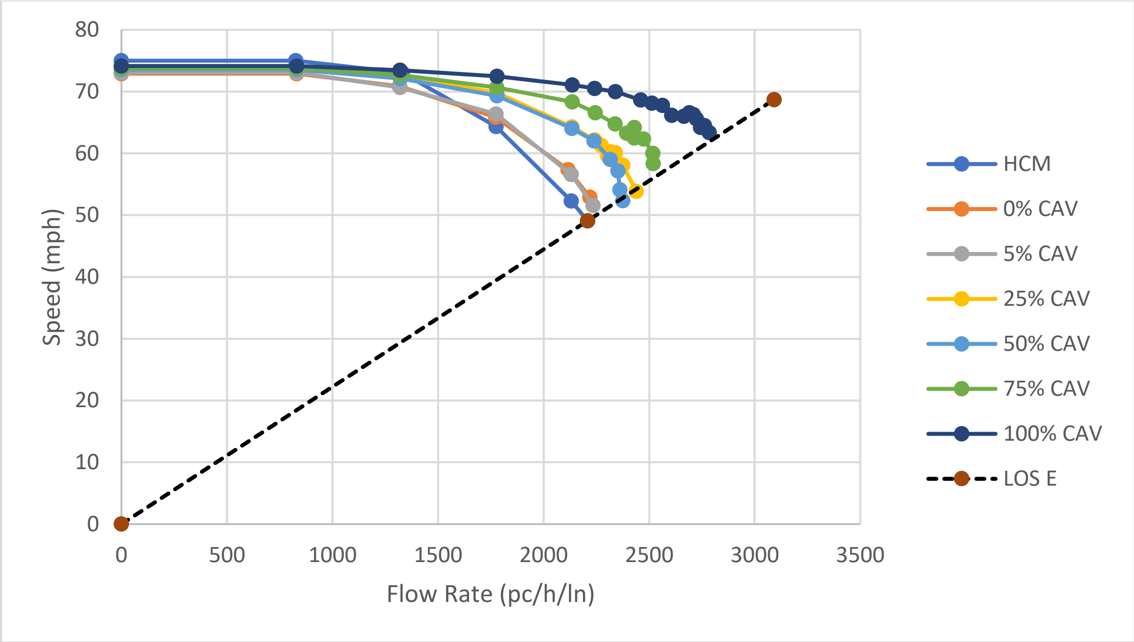

Figure 4.9 Speed-Flow relationship based on CAV-penetration rate for FFS=75mph; 15% Heavy vehicle

Scenarios with 15% heavy vehicles saw most improvement for density while sustaining LOS E condition for almost all CAV penetration rates.

Under different CAV penetration rates, the road capacity varies. In other words, a higher penetration rate corresponds to a higher capacity, indicating that the presence of CAVs can increase the road capacity. In the free-flow phase, the effect of the CAVs on the performance of the system is negligible. The conventional vehicles and CAVs were able to operate at maximum velocity. Moreover, situations with a higher CAV penetration rate result in a longer free-flow phase, which is a direct effect of the increased road capacity.

Before the CAV penetration rates reaches a rate of 25%, the road capacity increases gradually. The effect of the difference in the CAV capability on the capacity growth rate is negligible. At this stage, with CAVs being the minority in the heterogeneous flow, the connected condition is rarely fulfilled, and only autonomous driving is fully realized. As the conventional vehicles are in majority, the increase in the road capacity resulting from the CAVs is limited. When the CAV penetration rate exceeds 25%, the growth rate is largely decided by the improved capability of the CAVs compared to conventional vehicles. An improved capability corresponds to a higher capacity growth rate and a higher road capacity.

4.2. Capacity Adjustment Factors

After obtaining the results for CAVs at different penetration rates, two types of CAFs were calculated as shown in Table 4.1. CAF_{cap} represents the highest throughput that was observed to maintain LOS E condition for full 15-minute interval when input volumes were gradually increased to get LOS E. CAF_{45} is obtained to quantify an improvement if observed, while the density is 45pc/mi/ln.

Table 4. 1 Capacity adjustment Factor for each scenario based on CAV penetration rate

% CAV	CAF_{45}	CAF_{cap}	CAF_{45}	CAF_{cap}	CAF_{45}	CAF_{cap}
	65mph; Pt=0%		**70mph; Pt=0%**		**75mph; Pt=0%**	
5%	N/A	1.007	N/A	0.999	1.006	1.006
25%	N/A	1.008	N/A	1.016	1.021	1.020
50%	N/A	1.043	N/A	1.047	N/A	1.035
75%	N/A	1.129	N/A	1.109	N/A	1.090
100%	1.243	1.262	N/A	1.226	1.206	1.214
	65mph; Pt=5%		**70mph; Pt=5%**		**75mph; Pt=5%**	
5%	N/A	1.086	1.005	1.005	1.008	1.012
25%	1.122	1.122	N/A	1.019	1.028	1.029
50%	N/A	1.122	1.055	1.055	N/A	1.078
75%	1.218	1.219	1.102	1.102	N/A	1.117
100%	1.297	1.318	1.248	1.248	N/A	1.237
	65mph; Pt=15%		**70mph; Pt=15%**		**75mph; Pt=15%**	
5%	1.005	1.005	1.007	1.007	1.010	1.010
25%	1.034	1.034	1.029	1.029	1.099	1.099
50%	1.088	1.088	1.067	1.067	1.070	1.070
75%	1.159	1.172	1.138	1.138	N/A	1.136
100%	1.253	1.285	N/A	1.248	N/A	1.255

In Table 4.1, many of the scenarios do not have CAF_{45} values because those scenarios reached LOS E condition before reaching the density of 45pc/mi/ln. The ones that did reach that density while maintaining LOS E are mentioned in the table.

The highest capacity improvements were observed for scenarios with 65mph as FFS with the largest being 31.8% which had 5% heavy vehicles. Also, with the increase in FFS, the CAFs are getting lower because of the values used for Headway time (CC1) as it has the highest impact on capacity while calibrating for HCM6 (Table 4.2). The scenarios with FFS 65mph used higher CC1 values for the driving behavior than scenarios with FFS 70mph and 75mph. Now, because the CAVs were set to follow the CC1 values of 0.8s for cars and 0.9s for heavy vehicles once CAVs form 100% of the traffic, the headway for 65mph FFS scenarios with 100% CAV effectively becomes half when compared to the other two FFS scenarios and, hence, higher capacity gains were seen for FFS 65mph than 70mph and 75mph.

Table 4. 2 Standstill distance (CC0), Headway Time (CC1) parameter values, and Safety distance reduction factor (SF_r) for all scenarios

Percent of heavy vehicles (P_t)	65mph			70mph			75mph		
	CC0 (ft)	CC1 (s)	SF_r	CC0 (ft)	CC1 (s)	SF_r	CC0 (ft)	CC1 (s)	SF_r
P_t = 0%	5.00	1.14	0.45	5.00	1.13	0.40	5.25	1.12	0.35
P_t = 5%	7.00	1.10	0.40	4.00	1.13	0.48	5.50	1.14	0.40
P_t = 15%	5.50	1.18	0.50	5.45	1.16	0.40	5.45	1.16	0.33

The same reason exists when the capacity increases for scenarios with FFS of 70mph and 75mph with heavy vehicles when compared to scenarios with 0% heavy vehicle in them. Moreover, the 65mph as FFS with 5% heavy vehicles scenario, saw the highest gains as it was modelled for aggressive merging behavior than with 0% and 15% heavy vehicle for the same 65mph FFS by using safety distance reduction factor of 0.4 (Table 4.2).

4.3. Break Point

As it was observed, CAVs improve capacity of a road, and, with increase in its penetration rate, they can also maintain free-flow speeds for higher flow rates. Therefore, based on the CAFs that were obtained and the FFS recorded from LOS A intervals, the break points using Equation 3.3 were calculated and are shown in Table 4.3, where P_t means Percent of heavy vehicles inside the traffic stream. The break points help determine the shape of the speed-flow curve for each market penetration rate that was studied in this research.

Table 4. 3 Break points for each scenario based on CAV penetration rate

CAV%	Breaking Point (pc/h/ln)		
	65mph; Pt=0%	**70mph; Pt=0%**	**75mph; Pt=0%**
0%	1288	1104	920
5%	1448	1245	1057
25%	1447	1282	1083
50%	1544	1353	1095
75%	1799	1502	1213
100%	2238	1813	1535
	65mph; Pt=5%	**70mph; Pt=5%**	**75mph; Pt=5%**
0%	1288	1104	920
5%	1693	1265	1094
25%	1801	1294	1119
50%	1827	1378	1216
75%	2104	1489	1289
100%	2445	1884	1562
	65mph; Pt=15%	**70mph; Pt=15%**	**75mph; Pt=15%**
0%	1288	1104	920
5%	1465	1316	1100
25%	1543	1341	1256
50%	1696	1426	1212
75%	1948	1601	1354
100%	2331	1904	1629

It was observed in Table 4.3 that scenarios with 65mph FFS, had the highest break points when compared to 70mph and 75mph FFS speed scenarios. This result is consistent with HCM6 when only conventional vehicles are considered. Also, almost all the scenarios involving heavy vehicles have higher break points as well when compared to 0% heavy vehicle conditions for their respective CAV penetration rates. The reason being lower Safety distance reduction factor applied for scenarios with heavy vehicles (Table 4.2) when compared to their 0% trucks counterparts, because it affects both volumes and speeds. Reduction of the safety distance reduction factor leads to more aggressive driving and increase in speed and volume. The values obtained after applying the formula for Break point are consistent with the speed-flow relations depicted through figures in Section 4.1.

4.4. Density

From Table 4.4, it can be observed that density of 45 pc/mi/ln was not achieved even with 100% CAV penetration-rate except for scenarios with 65mph of free-flow speed.

Table 4. 4 Flow-rate, speed, and density at capacity as function of CAV penetration rate.

CAV %	65mph; Pt=0%			70mph; Pt=0%			75mph; Pt=0%		
	Flowrate (pc/h/ln)	Speed (mph)	Density (pc/mi/ln)	Flowrate (pc/h/ln)	Speed (mph)	Density (pc/mi/ln)	Flowrate (pc/h/ln)	Speed (mph)	Density (pc/mi/ln)
0%	2168	52.03	41.7	2196	52.34	42.0	2188	51.93	42.1
5%	2184	51.64	42.3	2194	53.02	41.4	2202	48.41	45.5
25%	2186	53.14	41.1	2232	50.53	44.2	2232	48.36	46.2
50%	2262	54.38	41.6	2300	57.62	39.9	2258	49.98	45.2
75%	2448	57.93	42.3	2436	57.08	42.7	2386	60.01	39.8
100%	2736	58.24	47.0	2692	62.73	42.9	2656	55.98	47.4
	65mph; Pt=5%			**70mph; Pt=5%**			**75mph; Pt=5%**		
0%	2059	51.75	39.8	2219	53.05	41.8	2200	52.16	42.2
5%	2236	50.81	44.0	2229	49.29	45.2	2227	47.66	46.7
25%	2309	50.73	45.5	2261	52.83	42.8	2263	49.62	45.6
50%	2333	53.06	44.0	2341	51.74	45.2	2371	53.55	44.3
75%	2509	54.43	46.1	2446	54.77	44.7	2457	57.40	42.8
100%	2714	56.49	48.0	2768	61.55	45.0	2722	62.21	43.8
	65mph; Pt=15%			**70mph; Pt=15%**			**75mph; Pt=15%**		
0%	2170	51.75	41.9	2216	51.94	42.7	2218	52.93	41.9
5%	2182	48.61	44.9	2232	49.54	45.1	2241	50.33	44.5
25%	2244	50.34	44.6	2280	50.71	45.0	2439	53.85	45.3
50%	2361	52.00	45.4	2366	52.31	45.2	2375	52.36	45.4
75%	2543	54.12	47.0	2522	54.08	46.6	2520	58.35	43.2
100%	2789	59.23	47.1	2766	63.51	43.5	2784	63.35	43.9

Scenarios with 75mph as FFS saw the highest critical speed because lower Safety distance reduction factors were applied along with the Increased acceleration attribute value of 110% for CAVs. Whereas, for 65 mph FFS, because we started with lower free-flow speeds, the desired safety distance reduces and hence resulted in higher densities.

5. SUMMARY AND CONCLUSIONS

This section presents the summary of this research, followed by the major conclusions regarding modeling CAV using VISSIM. Recommendations regarding limitations of the study and future work are also offered.

5.1. Summary

In this study, two-lane heterogeneous flow microscopic models were established wherein the possible impact of the CAVs on the current traffic system was analyzed. Each scenario was calibrated in VISSIM to replicate the results from HCM6. Next, CAVs were introduced in various proportions inside the traffic stream of conventional vehicles using microscopic simulation to access improvements, if any, to the performance of the system. Such mixed traffic scenarios were especially important because they correspond to likely evolutionary paths for the introduction and market penetration of these vehicle capabilities. The improvements were analyzed by obtaining Capacity adjustment factors and Break points.

5.2. Conclusions

The following conclusions are drawn from the analysis of results:

- The simulations revealed that connected and autonomous vehicles can improve the capacity and aid in achieving longer free-flow phase.
- Before the CAV-penetration rates reaches a rate of 25%, the road capacity increased gradually. When the CAV-penetration rate exceeds 25%, the growth rate is largely decided by the improved capability of the CAVs compared to conventional vehicles. An improved capability corresponds to a higher capacity growth rate and a higher road capacity.

- CAVs with higher penetration rates saw longer free-flow phases than the ones without them. The scenarios with heavy vehicles saw even more improvement for the Break point than their 0% heavy vehicles counterparts because heavy vehicle scenarios were modeled to behave aggressively while merging to find an acceptable merge gap.
- There were only minor improvements in densities for LOS E conditions because at capacity, we had higher flow rates and critical speeds when modeling CAVs, resulting in either similar or slightly higher densities. The reason is because CAVs were simulated to have better acceleration capabilities as they were simulated with the 110% desired acceleration while following vehicles of any class/type i.e., conventional vehicles or CAVs both including heavy vehicles and passenger cars. The other reason for lower densities, is the value of CC1 that we used to model CAVs. Perhaps, lower values for CC1 than 0.8s for CAVs may lead to higher densities.
- Higher heavy vehicle percentages sustained LOS E condition for densities larger than 45pc/mi/ln because those scenarios were modeled for aggressive merging behavior while calibrating for HCM.

5.3. Recommendations

The following points describe recommendations for future studies that could enhance this research:

- Utilizing VISSIM External Driver Model (VEDM), an add-on for Connected Automated Vehicle (CAV) to better model connectivity in CAVs as well as platooning capabilities, because currently there are only few parameters that one can change. This may help in sustaining LOS E conditions for higher flow rates even for lower critical speeds.

- Evaluating Interrupted flow facilities, i.e., intersections can be modelled with CAVs to analyze improvements in delay.
- Using different geometry (i.e., greater number of lanes, varying acceleration lane length, etc.) for the mainline segment to compare the improvements with the two-lane facility.
- Sensitivity analysis based on the variation of headway time (CC1), Safety distance reduction factor, Increased acceleration, and the number of objects and vehicles that a CAV can interact with, can help in better understanding performance improvements for a system for various traffic penetration. As it was seen from the results, lower safety distance reduction factor along with Increased acceleration parameter led to higher critical speed. Although, we used the recommended values from the CoEXist project it still will be helpful to understand how each of the driving parameters can affect the performance of a facility.
- Simulating different vehicle classes/types by using their actual sizes and weight to horsepower ratios can make this model more realistic.

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