Addressing traffic breakdown at merge sections in mixed traffic

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DELFT UNIVERSITY OF TECHNOLOGY

MASTER'S THESIS

Addressing traffic breakdown at merge sections in mixed traffic

This thesis is submitted in partial fulfilment of the requirements for the degree of

Master of Science
in
Civil Engineering
Department of Transport and Planning

To be defended publicly on 31st March 2021 at 12:00.

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Acknowledgements

This thesis marks the end of my beautiful journey at TU Delft. I want to thank all my committee members for their guidance, which helped to mold this thesis better than I could have ever imagined.

Dr. ir. S.C. (Simeon) Calvert and Dr. Jochen Lohmiller, both of you have been my constant pillars of support throughout my thesis.

Dr. ir. S.C. (Simeon) Calvert, your guidance has brought the best out of me as well as this thesis. Your advice has helped me gain an enormous amount of knowledge and confidence. Thank you for always being there for solving all my queries and lessening my burdens.

Dr. Jochen Lohmiller, thank you for patiently answering tons of questions on simulations in Vissim which aided me to thoroughly conduct the simulations in this thesis. I also want to thank you for always being there and lessening my worries.

Prof.dr.ir. J.W.C. (Hans) van Lint and Dr. L. (Laura) Ferranti, I want to thank both of you for your feedback during milestone meetings which helped me to be more concise and precise in my work. I also want to thank PTV group for giving me the opportunity to do this thesis in collaboration with them.

Most importantly, I want to thank my parents and my younger brother for their unbelievable love and support throughout my life. They mean the world to me.

Lastly, I also want to thank all my friends in Delft for making my journey at TU Delft a memorable one.

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March 2021

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Summary

The development in the vehicle automation and communication technology is expected to transform the future composition of vehicular traffic, wherein Human Driven Vehicles (HDV's) start to interact with the vehicles utilizing these automation and communication technological features while driving. Such vehicles are referred to as Automated Vehicles (AV's) and Connected AV's (CAV's). AV's refer to vehicles which have the hardware and software collectively capable of performing part/all of the real-time tactical and operational functions needed to operate a vehicle in on-road traffic on a sustained basis, whereas CAV's are AV's with added wireless communication features to foster better vehicle operation.

As HDV's start to share the road with AV's and CAV's in the future, the nature of various traffic flow phenomena can be expected to be different due to the differences in the expected driving behavior of AV's and CAV's compared to HDV's. *Traffic breakdown phenomena* was the focus of this research as literature review and analysis revealed that the nature of traffic breakdown can be expected to change when HDV's start sharing the road with AV's (ACC) and CAV's (CACC). AV's (ACC) and CAV's (CACC) refer to AV's enabled with Adaptive Cruise Control functionality and CAV's enabled with Co-operative ACC functionality respectively.

Currently, there are traffic management measures which address traffic breakdown for the current situation. With the expected changes in breakdown phenomena in the future, will the current measures be able to address the different nature of traffic breakdown in the future? This research answers this question by looking into one of the current measures. Furthermore, this research also provides insights into what future traffic management measures need to focus on to better address the expected change in the nature of traffic breakdown. The flow chart displayed at the end of the summary,
Figure 1, gives an overview of this research.

To check whether measures which are currently expected to address breakdown can be effective in addressing different nature of breakdown in mixed traffic, simulation through Vissim was conducted. The current measure whose effectiveness was analyzed is Variable Speed limits (VSL) applied through the concept of feedback Mainstream Traffic Flow Control, *MTFC-VSL*, at on-ramp merge sections. MTFC-VSL is expected to address traffic breakdown at merge sections, by regulating the mainline flow using VSL. Before conducting simulation, it was hypothesized that *MTFC-VSL control effectiveness in addressing traffic breakdown increases as CAV's (with ACC and CACC*

functionality) penetration rate increases in mixed traffic, because CAV's can be expected to precisely follow the speed limits. *Mixed traffic* in this research comprised of HDV's and CAV's (with ACC and CACC functionality). CAV's (with ACC and CACC functionality) implies that CAV's *majorly* differ with that of HDV's in car following behavior and not in lane change behavior.

Simulation results and analysis revealed that the hypothesis doesn't hold good. Improvements in average of the total average Travel Time (TT) of mainline vehicles and average network speed due to the presence of MTFC-VSL control compared to the absence of it, started to witness a decreasing trend as penetration rate of CAV's (with ACC and CACC functionality) increased until 20% in mixed traffic. For further penetration rates the improvements fluctuates. On-ramp vehicles for most of the scenarios of mixed traffic, are better off without MTFC-VSL control as the presence of it increases the vehicles average TT. MTFC-VSL control doesn't effectively address the capacity drop phenomenon for various scenarios of mixed traffic, might rather increase it compared to the absence of control. This increase in capacity drop probably has to do with MTFC-VSL control deteriorating the Average discharge rate. Lastly, it was found that for less than 20% CAV's (with ACC and CACC functionality) penetration rate in mixed traffic, MTFC-VSL control effectiveness can be expected to overall increase if Intelligent Speed Adaptation (ISA) is installed as an On-Board Unit (OBU) in HDV's as it limits HDV's exceeding the mandated speed limits.

Probable reasonings of hypothesis not being valid, indicate that, rather than having the *same* set-up of MTFC-VSL control for *all* the scenarios of mixed traffic, i.e., irrespective of the penetration rate of CAV's (with ACC and CACC functionality), it's better to tailor the set-up according to the *specific* scenarios of mixed traffic. Additionally, for *specific* scenarios of mixed traffic, may be CAV's following the speed limits exactly and HDV's following within a certain desired speed distribution might create problems. However, these are just probable reasonings which need to be further researched to confirm their validity. It must be noted that the MTFC-VSL control was set up considering the practical considerations of implementing in real life, which can also be expected to play a significant role in hypothesis not being valid. Given the ineffectiveness of MTFC-VSL control for various scenarios of mixed traffic, the future traffic management measures should focus on the causes of traffic breakdown phenomena which aren't addressed by MTFC-VSL control and better utilize the connectivity feature of CAV's. One of the new proposed measure is a combination of *a merging assistant strategy & MTFC-VSL control* to better address traffic breakdown than MTFC-VSL alone. Merging assistant strategy utilizes the connectivity feature of CAV's to foster smoother merging of on-ramp vehicles which isn't addressed by MTFC-VSL control.

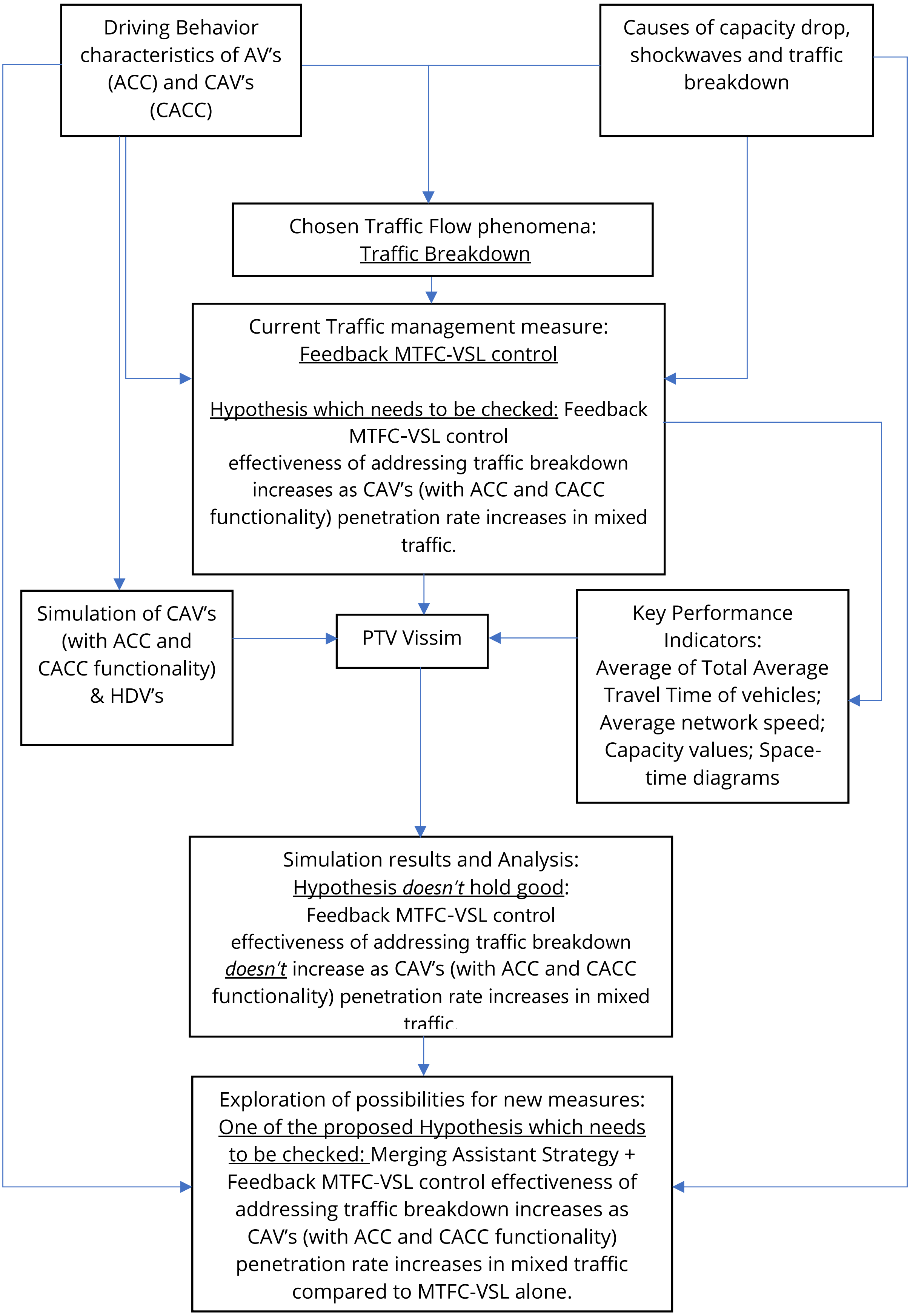


Figure 1: Flow chart representing the research overview

Contents

List of Abbreviations

RQ	Research Question
AV's	Automated Vehicles
LDW	Lane Departure Warning
ACC	Adaptive Cruise Control
AV's (ACC)	AV's enabled only with ACC
CAV's	Connected Automated Vehicles
CACC	Cooperative Adaptive Cruise Control
CAV's (CACC)	CAV's enabled only with CACC
LIDAR	Light detection and Ranging
HDV's	Human Driven Vehicles
C-ITS	Cooperative- Intelligent Transport Systems
FOT's	Field Operational Tests
RM	Ramp Metering
VSL	Variable Speed Limits
ISA	Intelligent Speed Adaptation
RM+VSL	Integration of RM & VSL
RGIS	Route Guidance and Information Systems
OBU	On Board Unit
W99	Wiedemann 99 car following model
MTFC	Mainstream Traffic Flow Control
MTFC-VSL	Mainstream Traffic Flow Control by use of VSL
MTFC-VSL-ISA	Mainstream Traffic Flow Control by use of VSL with ISA being installed as an OBU in HDV's
MTFC-VSL (150/200)	MTFC-VSL with 150m VSL application area and 200m acceleration area
MTFC-VSL-ISA (150/200)	MTFC-VSL-ISA with 150m VSL application area and 200m acceleration area
KPI's	Key Performance Indicators
TT	Travel Time
RSU	Roadside Unit
FD's	Fundamental Diagrams
V2V	Vehicle-to-Vehicle Communication
PB	Probability of traffic Breakdown
CAV's (with ACC and CACC functionality)	CAV's only differ in car following behavior with that of HDV's and have the same rules and parameters values for lane change as that of HDV's.

1. Introduction

In this chapter, the motivation behind doing this research is discussed in section 1.1, the main objective of this research and the relevant research questions which will be addressed will be elaborated in section 1.2. Later, an overview of the methodology adopted which will be followed in the entire research will be explained in section 1.3. Lastly, section 1.4 gives the outline of this report.

1.1.Research motivation

With the advancement in automation and connectivity features of vehicles, the future traffic composition and the relevant eruption of traffic flow phenomena's can be expected to be different than the current composition and phenomena.

Regarding vehicle automation features, (SAE International, 2018) defines six levels of vehicle driving automation, ranging from level 0 to level 5, with level 0 representing *no driving automation* and level 5 with *full driving automation* wherein all of the dynamic driving task is performed by *driving automation systems* on a sustained basis. *Driving automation system* refers to the hardware and software which are collectively capable of performing part/all of the dynamic driving task on a sustained basis, thereby referring to level 1-5 of driving automation (SAE International, 2018). *Dynamic Driving task* refers to all the real-time tactical and operational functions needed to operate a vehicle in on-road traffic, except strategic functions such as for instance, selection of destinations & waypoints and trip scheduling (SAE International, 2018). In this research, *Automated Vehicles (AV's)* refer to the vehicles which have these *driving automation systems.* However, whether these systems in AV's are capable of performing part/all of the dynamic driving task will be made clear in the relevant part and context of this report. One of the most popular and commercially available *driving automation system* of lower level which takes control of the *longitudinal vehicle motion control is* Adaptive Cruise Control (ACC). Based on the measurements obtained of the preceding vehicle, ACC adjust the vehicles velocity (Naus, Vugts, Ploeg, Vd Molengraft, & Steinbuch, 2009).

The next step in the advancement of automation features, is the wireless communication (such as vehicle-to-vehicle (V2V) communication) to acquire better and faster extensive information about the surrounding vehicles, fostering better vehicle control performance (Milanes et al., 2014). One of the application of these V2V communication is the extension of ACC, known as

Cooperative ACC (CACC), where in vehicles get information not just of preceding vehicle as in ACC but also vehicles ahead of preceding one (Milanes et al., 2014). In this research, Connected Automated vehicles (CAV's) refer to AV's with wireless communication, however, how and for what dynamic driving tasks these wireless communication will be utilized will be made clear in the relevant part and context of the report.

In the future, before AV's and CAV's together completely dominate the traffic, there exists a transition period during which AV's and CAV's share the road with Human Driven Vehicles (HDV's). In this research HDV's refer to vehicles where humans perform all of the dynamic driving tasks. *Currently*, there are various traffic management measures which are designed to address various traffic flow phenomena. However, looking into the future *transition period* wherein AV's, CAV's and HDV's co-exist on the same road (mixed traffic), these *current* traffic management measures might be effective or ineffective in addressing the relevant traffic flow phenomena they are designed to address for. This research provides insights into whether (one of) the current traffic management measures can be expected to be effective in the *future transition period i.e., mixed traffic.* Furthermore, based on its effectiveness this research also provides insights into what are the possibilities of better managing the mixed traffic in the future.

1.2. Research objective and research questions

Based on the motivation of this research discussed in the previous section, in this section the main objective of this research and the research questions which needs to be framed to attain the objective is elaborated.

The main objective of this research is to study how effectively a current traffic management measure can address its control objective (i.e., address a particular traffic flow phenomenon it is designed for) in mixed traffic, where in AV's, CAV's and HDV's interact and drive together. Later, based on the analysis of the effectiveness of the current measure, new possibilities will be explored from a C-ITS or vehicle-based control perspective which can better address the traffic flow phenomena which the current measure is addressing. Thereby, the main research question is:

What are the possibilities of better addressing a traffic flow phenomenon from a C-ITS or vehicle-based control perspective in mixed traffic than a current traffic management measure which addresses the same phenomena?

Given practical considerations and lesser penetration rates of AV's and CAV's in real life, this research question will be answered through simulation. The research is divided into three phases and each phase has research questions framed, which all together help to better answer the main research question.

Phase 1: Literature review and Analysis
The objective of this phase is to gain insights into:

- The expected driving behavior characteristics of AV's and CAV's
- Current traffic management measures which can hypothesized that they will be effective in mixed traffic

To simulate mixed traffic properly, it is vital to study the expected driving behavior characteristics of AV's and CAV's, leading to formulation of Research Question 1 (RQ1).

1) What are the expected driving behavior characteristics of AV's and CAV's?

Based on the answer of RQ1, the next step is to look into the second objective of this phase. *Currently*, there are various current traffic management measures which try to address various traffic flow phenomena. Before diving straight way into the measures, it is of much importance to study various traffic flow phenomena and their causes. Studying the causes of various phenomena and linking their causes with the driving behavior characteristics of AV's and CAV's will help to scope down this research to one particular phenomenon which can be hypothesized that it might be expected to be influenced/incur changes in mixed traffic because some of its causes are expected to be addressed by the driving behavior characteristics of AV's and CAV's. This leads to formulation of RQ2a.

Having chosen *a phenomenon* based on answer of RQ2a, now it's time to investigate various current traffic management measures which address this phenomenon (RQ2b). Later, these measures will be linked to the driving behavior characteristics of AV's and CAV's (RQ2) to hypothesize *which of them can be expected to be effective in achieving its control objective (i.e., address a particular traffic flow phenomenon it is designed for) in mixed traffic*. This hypothesis will be checked in phase 2. Consequently, answering RQ2 will help to scope down this research to a current traffic management measure and the relevant traffic flow phenomena it's expected to address.

2) Which of the current traffic management measures is expected to be influenced by the driving behavior characteristics of AV's and CAV's?
    a) What are the causes of different traffic flow phenomena's and which of them can be influenced by the driving behavior characteristics of AV's and CAV's?

b) What are the current traffic management measures which address various causes of traffic flow phenomena?

Phase 2: Effectiveness of current traffic management measure in mixed traffic

The objective of phase 2 is check the hypothesis of phase 1 through simulation, where in its hypothesized that a *current traffic management measure can be expected to be effective in achieving its control objective (i.e., address a particular traffic flow phenomenon it is designed for) in mixed traffic* (RQ3). To carry out the simulation and check the hypothesis correctly, four aspects need to be decided. *First*, the driving behavior characteristics of AV's and CAV's studied in RQ1 needs to be translated to the relevant parameter values in simulation (RQ3a). *Second*, various scenarios of mixed traffic for which the hypothesis will be checked needs to be decided (RQ3b). Thirdly, various Key Performance Indicators (KPI's) which will be used to quantify the effectiveness of the measure needs to be discussed (RQ3c). Lastly, how the different features of the chosen measure will be incorporated in simulation software needs to be investigated (RQ3d). Hence, answering all these sub questions will add up to investigate whether the hypothesis that a *current traffic management measure can be expected to be effective in mixed traffic* holds good or not.

3) How effective is the traffic management measure in addressing the traffic flow phenomena for various scenarios of mixed traffic?
   a) What are the characteristics of mixed traffic?
   b) What are the various scenarios of mixed traffic?
   c) What are the various Key Performance Indicators (KPI's)?
   d) What are the features of chosen traffic management measure and how it can be incorporated in simulation?

Phase 3: Exploration of possibilities of future traffic management measures in mixed traffic

The traffic management measure analyzed in phase 2 considers only certain causes of the traffic flow phenomena which it tries to address or influence. However, there are other causes of the phenomena, that aren't being taken into consideration by the measure in phase 2. Hence, based on the answer of RQ3, addressing these causes from a C-ITS or vehicle-based traffic control perspective, will facilitate to explore possibilities to address the traffic flow phenomena more effectively [RQ4]. Lastly, if time permits, one of the possibilities will be simulated and evaluated to check how effective is it in addressing the traffic flow phenomena in comparison to the current traffic management measure studied in phase 2 [RQ5].

4) What are the possibilities to address various causes of the traffic flow phenomena for mixed traffic from a C-ITS or vehicle-based traffic control perspective based on simulation results of phase 2?

5) How effective are the possibilities in addressing the traffic flow phenomena compared to the effectiveness of the measure studied in phase 2?

1.3. Research methodology

In Section 1.2 research objective and questions were elaborated. In this section, an overview of the methodology which will be followed in this research will be discussed. Figure 2 represents the flow chart of the proposed methodology.

Phase 1: Literature review and Analysis
Studying the **driving behavior characteristics** (RQ1) of AV's and CAV's and relating these characteristics with the **causes of various traffic flow phenomena** (RQ2), represented by black arrows in Figure 2, will help to analyze which of the causes of a particular traffic flow phenomena and thereby the phenomena itself might be expected to be influenced by the driving behavior of AV's and CAV's. Thereby, that phenomena will be **chosen** for further analysis in phase 2 and phase 3. Based on how well various current traffic management measures addresses the **chosen** phenomena by accounting for certain **causes** of it and also whether certain **driving behavior characteristics** of AV's and CAV's will foster the measures effectiveness, represented by dashed black arrows in Figure 2, one **current traffic management measure** will be selected for simulation and analysis in phase 2 to check whether the **current** measure is able to influence the **chosen** phenomena in mixed traffic as expected or hypothesized.

Phase 2: Effectiveness of current traffic management measure in mixed traffic
Studying **driving behavior characteristics** will also help to set driving behavior parameters of **AV's and CAV's in simulation** (RQ3), represented by orange arrow in Figure 2, which is required for simulation and analysis in phase 2 and phase 3. Having chosen the traffic flow phenomena and the measure, various **Key Performance Indicators** required to quantify the effectiveness of measures will be investigated. **PTV Vissim** is used for simulation and analysis in phase 2 and phase 3. **Simulation results and analysis Phase 2** (RQ3) indicates the effectiveness of the **current traffic management measure** (RQ2) in addressing the **chosen** phenomena.

Phase 3: Exploration of possibilities of future traffic management measures in mixed traffic

The **exploration of possibilities** to better address the **chosen** phenomena is based on three things, all of which are represented by green arrows in Figure 2 and are pointed out as follows:

1. **Simulation results and analysis Phase 2**
2. Address **causes** of the chosen phenomena which hasn't been considered in the selected measure
3. Better utilize the **driving behavior characteristics** of AV's and CAV's

If time permits, one of the explored **possibilities** will be **simulated and analyzed (RQ5) in phase 3**. Lastly, the simulation results of phase 2 and 3 which relate to **current** and **explored possibilities** respectively will be **compared** and **analyzed** to look for the expected improvements and future recommendations.

1.4. Report outline

In this section, the outline of the report is elaborated. The Literature review is conducted in Chapter 2 to understand the driving behavior characteristics of AV's and CAV's and also to understand causes of various traffic flow phenomena. Later, the causes of the phenomena will be related with the driving behavior of AV's and CAV's to select and thereby narrow down research to one phenomenon for further analysis. Chapter 3 further investigates the causes of the chosen phenomena at a deeper level. Chapter 4 describes various currently employed traffic management measures which address the traffic phenomena investigated in Chapter 3. Based on how well the traffic management measures address the causes of the phenomena, one of the current measures will be chosen for further analysis. Chapter 5 marks the start of phase 2 of this research, which addresses PTV Vissim simulation set-up pertaining to the simulation of mixed traffic. Chapter 6 presents the results and analysis of phase 2, whereas Chapter 7 discusses possibilities of better addressing the traffic based on the analysis in Chapter 6 and also proposes one possibility. Chapter 8 concludes this research by answering the main research question and lastly, Chapter 9 discusses the limitations of this research and also provides recommendations for future research on several aspects.

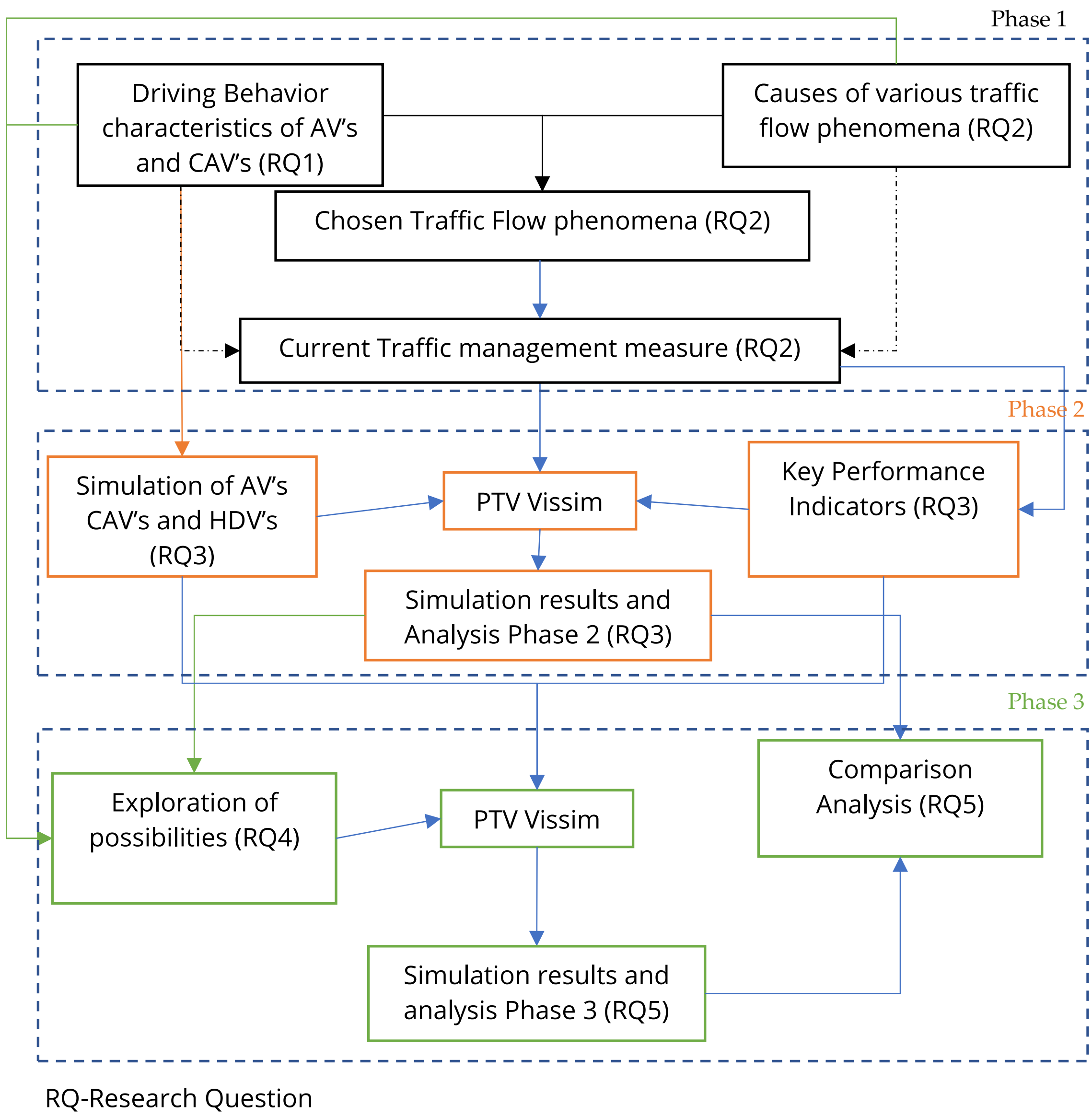


Figure 2: Flow chart of the Research Methodology

2. Literature Review

Following from Figure 3, which is derived from Figure 2, in this chapter, in section 2.1 and 2.2 literature review will be carried out to understand various driving behavior characteristics of AV's and CAV's respectively which will help to answer RQ1. Later, in section 2.3 causes of three traffic flow phenomena will be studied to understand how the causes of those phenomena's can be related to the driving behavior characteristics of AV's and CAV's, which is indicated by the arrows in Figure 3. This will help to choose one of the three traffic flow phenomena whose causes can be expected to be addressed by AV's and CAV's.

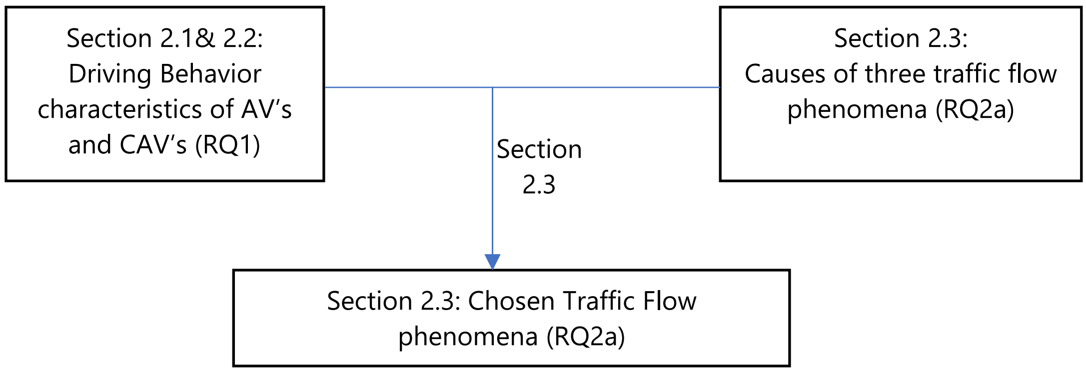


Figure 3: Part of the flow chart of the research methodology

2.1. Driving behavior characteristics of AV's

An AV drives differently than an HDV. To understand how driving behavior characteristics of an AV differ, several *empirical studies, mostly Field Operational Tests (FOT's),* are referred to in this section to gain an understanding about the difference in AV's driving characteristics. The characteristics which will be studied are *reaction times, desired time gap/headway, lane change and lateral behavior, desired and actual speed, acceleration & deceleration, heterogeneity and usage.*

2.1.1. Reaction time

One essential driving behavioral dimension is the *reaction time* of the drivers or systems in case of AV's. As per Gipps Model (Gipps, 1980), the reaction time parameter is specified as the time from the moment the leader acts to the moment the follower reacts (Makridis, Mattas, Borio, Giuliani, & Ciuffo, 2018). In theory, automated functionalities can instantly respond when required, thereby reducing the reaction time, which for humans is higher than 1 second (s) (Green, 2000; Kesting, Treiber, Schönhof, & Helbing, 2008).

Currently, Adaptive Cruise Control (ACC) is one of the automated functionality which is available in the market and regarded as the closest proxy of full automation with respect to the longitudinal movement (He et al., 2019; Makridis, Leclercq, Mattas, & Ciuffo, 2020). ACC can be enabled and disabled on request by the driver with the aim to maintain a predefined time gap with the leading vehicle or to attain a desired velocity. Light detection and Ranging (LIDAR's) or cameras are employed to detect and track the vehicle ahead (and also surrounding objects) and also to measure the actual distance and speed difference with the leading vehicle (Kesting, Treiber, Schonhof, Kranke, & Helbing, 2007). According to (Makridis et al., 2018), authors (Calvert, Van Den Broek, & Van Noort, 2012; Patel, Levin, & Boyles, 2016; Shladover, Su, & Lu, 2012; M. Wang, Daamen, Hoogendoorn, & Van Arem, 2012) mentioned delays in *ACC between 0.4 – 0.5s*, whereas in some older studies, the reaction time for ACC was of the order 0.1s - 0.2s which was negligible compared with the *1s reaction time of humans* (Green, 2000; Kesting et al., 2008).

(Makridis et al., 2018) provided insights into reaction time of an ACC system currently existing in market based on an experimental study conducted on a predefined track in the Joint Research Center in Ispra, Italy under normal traffic conditions. In the study, reaction time is defined as the time required for the ACC controller to react on the action of the leading vehicle, while initially the vehicles were in stable state i.e., when acceleration of both the vehicles are zero and speeds are roughly same. A strong linear correlation was observed between relative speed of the two vehicles and acceleration chosen by the controller. This correlation is evident only when reaction time lag is considered. *This lag can be justified because of the time needed by the ACC system to process the data and act*. Results indicated, reaction time between *0.9 – 1.3 s and 1.4 – 1.5 s for ACC systems and manual driving respectively*, which is in contrast with the prevalent opinion that the reaction time of ACC system can be regarded as negligible.

To conclude, reaction time for AV's enabled with ACC functionality is *smaller* than that of the HDV's but not negligible, as ACC systems require time to process the data and act. However, there is no one ideal value of reaction time. It can be presumed that reaction times of AV's enabled with ACC, are in the range of 0.4 – 0.5s.

2.1.2. Desired time gap or time headways

Simulation studies on ACC models conclude that setting the right parameters for desired time gap as a tedious task. For instance, in simulation conducted by (Ntousakis, Nikolos, & Papageorgiou, 2015), unless desired time gap is less than 1.10 s - 1.20 s, the capacity increases with the ACC penetration rate. (Li, Li, Wang, Wang, & Xing, 2017) shows that larger time gaps and smaller time delays enhance safety performance, however incorrect parameter settings enhance collision risks and traffic disturbances. Hence, this indicates that desired time gap/headway is an important driving characteristic which needs to be studied.

Following up from the experimental study aforementioned in section 2.1.1 conducted by (Makridis et al., 2018), desired time gap values were approximated based on estimation of time gaps as the distance between two vehicles divided by the speed of the follower. The results indicated estimated time gap values between *1.4 - 2.2 s and 0.8 – 1.3 s* for *ACC and manual driving respectively,* which indicate that ACC enabled vehicles have distinctly larger desired time gap values. (Calvert, Schakel, & van Lint, 2017) mentions that numerous simulation studies used time gaps values derived from practice for ACC in the range between *1.0 - 3.0 s as desired time gaps*, especially focusing on the range between *1.2 - 1.8 s*. For human drivers it thought of to be of the range of *0.5-1.5 s* (Calvert et al., 2017; Knospe, Santen, Schadschneider, & Schreckenberg, 2004; Treiber, Kesting, & Helbing, 2006a).

A FOT called the "*Assisted Driver*" conducted in the Netherlands indicated that more than half of the *participated drivers chose 1.0s* as the time headway which was the least headway which could be set within the vehicle Volkswagen Passat equipped with ACC with the available settings of 1.0s, 1.4s, 1.8s etc. (Alkim, Bootsma, & Hoogendoorn, 2007). Sometimes, other headways of 1.4, 1.8 and 2.2 s were also used, and hardly larger headways were utilized. *The variation in headways is smaller and also the number of shorter following headways (less than 0.7 s) decreases substantially when ACC is enabled*, which indicates less critical and harmful situations. Similarly, in the *AdaptIVe* EU-project, where drivers drove a "motorway-automation" system installed in a passenger car with included functions relevant to Level 3 (SAE, 2014), *the system maintained the correct distance* to the leader (Várhelyi, Kaufmann, Johnsson, & Almqvist, 2020) and instances where the distance close to the preceding vehicle (<1s) were 7 times more in rides without the system than with the system.

A planned pilot deployment of AV's, under the '*Drive Me*" project, where 93 Volvo cars equipped with ACC in Gothenburg were deployed to analyze the operation of these AV's in a 40km route consisting of dual carriageway. The desired time gaps could be *chosen* from 5 settings (approximately 1.0 to 3.0 seconds (Limited, 2018)) The usage probability from the pilot revealed around *0.45 for 2s, 0.2 for 1.5s, 0.3 for 1s* and remaining split between 2.5s and 3s (Zhu, Gonder, Bjarkvik, Pourabdollah, & Lindenberg, 2019).

The European project, *euroFOT* focused on Intelligent vehicles equipped with ADAS being driven by around 1200 drivers for more than 35 million km. When ACC and Forward Collison Warning (FCW) was active for passenger cars, the *average* time headway *increased* significantly (16%) while following a lead vehicle, *critical time headways (<0.5s) reduced* (73% on motorways) and frequency of harsh braking events and incidents (incidents are defined as dangerous situations which could potentially lead to accidents) decreased. The reasons for these results can be owed to *selectable ACC settings* which cannot be lower than the legally prescribed values which isn't the case while manual driving (Kessler et al., 2012).

To conclude, it is understood that there is no one exact time gap setting within ACC system, which all drivers choose as evident from Table 1, which lists the desired time gap and time headway values of ACC functionality by drivers according to various empirical tests discussed before. The values vary between drivers driving the same vehicle in a field test and also between different vehicles, as the ACC time gap/headway settings vary between car manufacturing companies. Thereby, it isn't reasonable to choose *one* exact time gap/headway as the desired ACC setting by the drivers and it's better to have a preferred *range* of desired time gaps/headways. From Table 1 it is evident that most of the drivers prefer time gap settings for ACC systems between *1.0s and 2.0s*. The staring value of the range is 1.0 s because FOT's have revealed that ACC largely decreases shorter following headways (less than 1.0s) and most of the vehicles available in market have 1.0s as the minimum setting (Limited, 2018). With regards to deviation of set time gap in an ACC system, it might be expected to be very less.

Table 1: Desired time gap and time headway values for AV's enabled with ACC functionality

Time gap (s) values	**Time headway (s) values**	**References**
1.4 -2.2	-	(Makridis et al., 2018)
-	1.0	(Alkim et al., 2007)
1.0 – 2.0	-	(Zhu et al., 2019)

2.1.3. Lane change and lateral behavior

So far in sections 2.1.1 and 2.1.2, driving behavior characteristics related to car following behavior were discussed. This section investigates how an AV executes a lane change. FOT conducted by (Gorter, 2015) indicated that regardless of the enabling of ACC, drivers perform much less lane changes in congested conditions than in the free flow or capacity conditions. A decrease in the lane change of 16.6% and 30.7% during free flow and capacity conditions was identified when ACC was active compared to when it was inactive. Even Questionnaire's study analysis indicated less lane changes when ACC is active. Hence, study by (Gorter, 2015) indicates that ACC has influence on lane changes when its enabled.

However, the FOT "Assisted Driver" in the Netherlands as mentioned in section 2.1.2. resulted in no less lane change maneuvers when Lane Departure Warning (LDW) and ACC functionalities are active which is contrary to what is expected (Alkim et al., 2007). Questionnaires were asked at the beginning, middle and end of the FOT period for the analysis of driving behavior and acceptance. The results indicated that drivers had to adjust their driving style in some instances. For example, an ACC enabled vehicle approaching a slower vehicle, the ACC might react sooner than the human drivers might think and thereby resulting in slowing down even before the driver will overtake. Hence, to avoid this, the drivers started to overtake earlier or use accelerator to temporarily override the system until they start overtaking. This was being mentioned by almost half of the participants. However, these are based on four months study and the results should be considered subjective and not necessarily true.

Looking into Level 3 automation systems, from the open questionnaires in AdaptIVe project aforementioned in section 2.1.2, some participants mentioned that the system took too much time to accelerate and overtake, thereby hampering the movement of other cars and in some cases aborted lane changes. Additionally, reckless behavior of the system by not allowing other vehicles to merge onto the motorway was noted (Várhelyi et al., 2020). The effect of LDW on driving performance was studied within the euroFOT project described in section 2.1.2, which indicated that it had an effect to stay within the lane (reduced mean steering wheel angle) and positive effect on turn indicator usage, thereby indicating increased lateral control. Some drivers perceived the association between LDW and actual risk as weaker resulting in many unnecessary warnings (Kessler et al., 2012).

Form the above results of FOT's, it is clear that there is *lacking empirical* information on *quantitative* aspects of lane change execution of AV's such as gap acceptance, acceleration, deceleration during lane change etc., which are vital components of lane change models in simulation to properly study the effects of AV's.

2.1.4. Desired and Actual Speeds

Desired Speed and actual speed of an AV during various driving conditions is also an important driving behavior characteristic which is expected to be different than HDV. When ACC and LDW is active in a FOT the "Assisted Driver" mentioned in section 2.1.2, it was found that the choice of the desired speed is based on the *speed limit* and in free flow conditions the average difference between actual speed and speed limit was 5km/hr (Alkim et al., 2007).

Following up from the AdaptIVe EU-project described in section 2.1.2, it was observed that when the Level 3 automation system was active, it always accelerated smoothly and *chose* speed according to *speed limit and traffic conditions* whereas in case of without the system enabled, the test persons drove uneven, sometimes higher, other times lower than the speed limit (Várhelyi et al., 2020). The maximum speeds driven with system active was less compared to without the system. Furthermore, the mean driving speed remained unchanged when the Level 3 automation system was active, but *lower* standard deviations in the means were identified.

Within the "Drive Me" project previously mentioned in section 2.1.2, the results indicated that the mean speed of ACC samples (81kph) is higher than non-ACC samples (78kph), significant at the 95% confidence level (Zhu et al., 2019). Similarly, a small increase in average speed is noticed when ACC+FCW is active within the euroFOT project, which cannot be attributed to the function related changes, rather gives insights on *usage behavior* (Kessler et al., 2012). In addition, A Speed Regulation System (SRS) which consists of two functions, Speed Limiter (SL), where in the driver can preset a speed limit, and when the function is on and active, it prevents the driver from exceeding the limit. And Cruise Control (CC), which maintains a constant speed preset by the driver when the function is on and active, were tested within the euroFOT project. It was observed that when SL was active, over speeding and harsh braking events were reduced by half and 30% respectively. On the contrary, with CC active, its effect on over speeding was higher, but strong jerk, critical time gap and harsh braking occurrences were reduced by one third. As CC was used at higher speeds (free flow conditions) the average speed was higher, whereas when SL was active, the average speed was similar to that without using it.

In conclusion, in an AV enabled with ACC (combined with LDW or FCW), a *desired speed* is chosen according to the *prevalent speed limit* during free flow conditions or adjusted according to the preceding vehicle's speed when in car-following mode. The AV enabled with ACC can be expected to maintain *the set speed with less variation or spread compared to HDV's*. This also holds good while driving with a Level 3 AV or a SRS functionalities. The average speeds can be expected to be higher in free flow when driving an AV enabled with ACC than driving disabled.

2.1.5. Other driving behavior aspects

ACC have *smoother* acceleration and deceleration profiles, thereby contributing to a more stable traffic flow (Hoedemaeker & Brookhuis, 1998). Furthermore, when ACC is enabled, a more *even* distribution of acceleration was observed in a FOT the "Assisted Driver" (Alkim et al., 2007). The analysis of the operation of the AV's with ACC systems within the "Drive Me" project indicated that, for traffic speeds between 40-110kph, the standard deviation of acceleration/deceleration (change of speed change) over a segment for both ACC mode and non-ACC mode indicated *smoother* driving behavior within ACC mode. The average standard deviation of deceleration/acceleration was -0.21/+0.22m/s2 and -0.29/+0.29m/s2 for ACC and non-ACC mode respectively (Zhu et al., 2019).

With regards to the aspect of heterogeneity, human behavior is inherently stochastic and includes variation in many levels. In traffic flow, human driver heterogeneity reflects in *variable gaps and intra & inter vehicle speed at varying times, lateral variations within the lane, thereby leading to heterogeneity in traffic flow which causes to reduce traffic flow capacity* (Calvert et al., 2017; Calvert, Taale, & Hoogendoorn, 2016; Vlahogianni, Karlaftis, & Golias, 2006). However, this heterogeneity aspect can be expected to be observed *less* in case of AV's as they have lesser variation in all the aspects mentioned before.

Regarding *usage* of AV functionalities, the FOT "Assisted Driver" indicated *that LDW was seldom switched off* and *ACC is mainly used on highways* and primarily during free flow (v > 90 km/hr) and heavy traffic conditions (70km/hr < v < 90km/hr), hardly during congested conditions (40km/hr < v <70km/hr) (Alkim et al., 2007). ACC usage on motorways is also confirmed by another FOT "euroFOT" as discussed in section 2.1.2 (Kessler et al., 2012). Additionally, following up from the SRS description within the euroFOT project mentioned in section 2.1.4, it was seen that the SL and CC usages depended on the driving conditions. Drivers used the CC mostly in *free flow conditions* (40%) and on *motorways* (66%), whereas SL was used less (about one third of the driven km, less on motorways).

To conclude, AV's enabled with ACC functionality can be expected to have *smoother* driving behavior i.e. lesser rate of change of (de)acceleration. It can be assumed that ACC enabled AV's behavior is *less heterogeneous* with regards to set time gap, reaction time, driving speed and lateral variations within the lane compared to *heterogeneous* behavior induced by different driving styles of human drivers. LDW is *used* in almost all the road types and ACC is used mostly on *motorways* and usually in *free flow and capacity* conditions. However, ACC usage in different driving conditions depends on the speed range within which it can be enabled.

2.1.6. Conclusion

All in all, it is evident from the literature review of this section 2.1 that most of the FOT's are conducted on <u>*ACC functionality of AV's*</u> and thereby most of the driving behavior characteristics discussed are relevant to ACC functionality.

Hence, in this research, *ACC functionality of AV's will be simulated with regards to car following and owing to lesser-known information of lane change, the lane change parameters of AV's with ACC functionality will be same as that of the HDV's*. The following driving behavior characteristics of AV's with ACC functionality concluded from the literature will be adapted in the further simulation and analysis. *Those characteristics which cannot be adapted in simulations of this research will be further reported as limitations of this research.*

- *Reaction time* for AV's enabled with ACC functionality is *smaller* than that of the HDV's. However, there is no one ideal value of reaction time. It can be presumed that *reaction times of AV's enabled with ACC, have reaction times in the range of 0.4 – 0.5s.*
- As it isn't reasonable to choose one exact *time gap/headway* as the *preferred* ACC setting by the drivers, a range of desired time gaps between 1.0s to 2.0s is chosen, as most driver preferred gaps within this range. Hence, *in this research a desired time gap range between 1.0 to 2.0 s will be used in simulation study.* With regards to the *deviation* of the set time gap in an ACC system, *it is very less and thereby can be presumed that ACC maintains set time gap with less oscillations in simulations.*
- Owing to lacking empirical information on quantitative aspects of *lane change* execution of AV's, *in this research, lane change parameters of AV's enabled with ACC functionality will be assumed to be same as that of HDV's.*
- In an AV enabled with ACC (combined with LDW/FCW), it's reasonable to presume that a *desired speed* is set according to the prevalent speed limit during free flow conditions, and it maintains the set speed with *less* variation compared to HDV's.
- In the simulation, the *smoother acceleration and deceleration* behavior of AV's with ACC functionality needs be accounted for. Within the simulation it will be assumed that ACC enabled AV's vehicle behavior is *less heterogeneous* in various driving behavior aspects compared to more heterogeneous behavior induced by different driving styles of human drivers. As this research is focused on motorways, it is good to know that ACC is used mostly on motorways.

2.2. Driving behavior characteristics of CAV's

In Section 2.1 driving behavior characteristics of AV's with ACC functionality was studied. If these AV's are connected, then their driving behavior varies and thereby needs to be studied to understand and simulate CAV's. Hence, in this section various empirical FOT's will be studied to investigate how CAV's behave with regards *to desired and actual time gaps/time headways, platoon cut-in behavior and platoon string stability.*

2.2.1. Desired and Actual Time gap/time headways

Given the relevance of time gaps/headways in simulation as mentioned in section 2.1.2, this section looks into various FOT's which focus on desired and actual time gaps/headways of CAV's enabled with CACC. CACC enabled vehicles follow each other with longitudinal automation and with the added gain of vehicle-to-vehicle (V2V) communication, which fosters short delays in information availability about the driving states of the predecessors, resulting in shorter time gaps between the vehicles (Calvert & Van Arem, 2019). Along with the V2V communication, communication can also exist with the Infrastructure (V2I). For example, intelligent Traffic Signals (iTS) receives an indication of approaching vehicles and it adjusts its signal phases accordingly for prioritization of a specific class of vehicles and also the information of signal phases can be sent to the vehicles which can adjust its driving behavior to arrive in green phase (Calvert & Van Arem, 2019; Zohdy & Rakha, 2016).

(Calvert & Van Arem, 2019) reported findings of a FOT conducted using seven CACC enabled vehicles driving in platoons and communicating through Wi-Fi on an *arterial* corridor in the Netherlands. The default setting for time gap was 0.6 s for CACC and 0.8 for ACC with an additional 5 meters as a standstill distance. The groups of CACC vehicles are defined as platoons with constant time gaps.

Time headways within the platoons were analyzed from the processed data for three driving modes i.e., HDV, ACC and CACC for three different traffic states which are, stable, acceleration and deceleration. Stable state implies traffic in which acceleration and deceleration is within the bandwidth of 0.5m/s2 and -0.5m/s2. If these bandwidths are exceeded, then the state refers to acceleration and deceleration. From the results, it can be derived that in almost all of the traffic states, CACC has shorter *(median time headway: 0.96 to 1.13 s)* and *smaller spread of time headways (i.e., more stable behavior can be observed)* compared to ACC and HDV's, and with regards to ACC, the time headways are longer, and spread is smaller compared to HDV's.

To figure out the *willingness of drivers to accept shorter following distances offered by CACC,* an ACC and CACC FOT was carried out on highways in the United States (Nowakowski, O'Connell, Shladover, & Cody, 2010). Among the two vehicles used, one was equipped with factory ACC system with gap-settings of 1.1, 1.6 and 2.2 s when the speed of the vehicle is higher than 35mph, and the other was equipped with prototype CACC system with gap-settings of 0.6, 0.7, 0.9 and 1.1 s. By default, when both the systems are enabled, the largest gap-setting was set. *The time-weighted mean following time-gap setting for ACC was found to be 1.54 (± 0.41) s while for CACC it was 0.71 (± 0.13)* s. The time-weighted mean following time-gap is a metric used to investigate following-gap setting preferences. With regards to percent of time the different setting were employed, it was clear that males preferred the *shortest setting* in either systems with the mean usage of 78% and 60% respectively for ACC and CACC systems, whereas it was evenly spread with regards to female participants, with many using 0.7s setting in CACC. *The main conclusion from this FOT is that drivers are willing to accept less than 1.0 s time gap setting and more importantly most drivers accepted 0.6s* (Nowakowski et al., 2010).

(Milanes et al., 2014) designed and implemented the CACC system in four production vehicles equipped with 5.9-Ghz (Dedicated Short-Range Communication (DSRC) for wireless communication and tested them in real traffic scenarios**.** Analysis of the CACC car-following behavior while the driver is changing the time-gap *settings* indicated *smoother* acceleration and deceleration profiles while transitioning between different time-gap *settings* available by the system. Furthermore, once the desired gap has been reached the time gap is *very well maintained*.

In conclusion, with regards to time gap values it is evident that drivers are willing to *accept* desired time gaps offered by the prototype CACC *settings* which are below 1.0s (as low as 0.6 s). Furthermore, actual time headway values obtained from the data collected in FOT's as discussed before and as evident from Table 2 wherein values are less than 1.0s further substantiate the previous statement. With regards to standard deviation i.e., variation of these desired time gap after its set, it is evident that in various driving states (stable, acceleration and deceleration) it is lesser than that of ACC and HDV. Lastly, a *smoother transition* between different desired time gaps settings can be expected for CAV's enabled with CACC vehicles.

Table 2: Desired time gap and Actual time headway values for CAV's enabled with CACC functionality

Desired Time gap (s) values	Actual Time headway (s) values	References
-	0.96 – 1.13	(Calvert & Van Arem, 2019)
0.71 (± 0.13)	-	(Nowakowski et al., 2010)

2.2.2. Platoon cut-in/cut-out behavior

Usually in many of the FOT's conducted on CAV's enabled with CACC, much of the analysis of field tests are focused on the platoon behavior of CACC enabled vehicles. Thereby, this section and the next section give insights into the platoon cut-in/cut-out behavior and platoon string stability respectively.

Platoon cut-in/cut-out behavior refers to the behavior of vehicles within the platoon, when a vehicle in the adjacent lane executes a lane change and cuts in within the platoon to join the platoon or any vehicle within the platoon cuts out (exits from the platoon) by further executing lane change.

Following up from the CACC platoon field test carried out by (Calvert & Van Arem, 2019) as described in section 2.2.1, platoon break-ups occurred due to cut-ins by other vehicles due to various reasons. It was observed that the percentage of time during which vehicles are in active CACC-mode for 3 vehicle platoons was 76%, which is larger than 7 vehicle platoons, indicating that larger platoon sizes are more vulnerable to cut-ins. This observation is also similar to ACC. A certain degree of flexibility with regards to CACC platoons after break-up was observed, where in the vehicles in some cases reconnected to a platoon (Calvert & Van Arem, 2019).

Following up from (Milanes et al., 2014) test of CACC systems as mentioned in section 2.2.1, analysis of a cut-in and cut-out maneuver between two vehicles platoon (a CACC enabled vehicle following a preceding CAV) executed in a short time by a vehicle who wants to exit the road was carried out. For safety reasons, the desired time gap is set at 1.1s which is the longest available gap. During the cut-in and cut-out behavior it was observed that deceleration and acceleration by the CACC enabled vehicle was performed smoothly to maintain the desired gap without any sudden behavior changes, and especially hardest deceleration occurs during cut-in as time gap is reduced suddenly, but it is within the comfort range of ± 0.2 g (Milanés, Villagrá, Pérez, & González, 2012). The results also holds good for four vehicle platoon (Milanes et al., 2014).

(Milanés & Shladover, 2016) presented the design, implementation and testing of a CACC controller with cut-in handling capabilities in four vehicles on public roads where HDV's were able to cut-in. In order to smoothly handle cut-ins, a transition function was introduced to regulate the time-gap when cut-in occurs until the desired time gap set by the driver is reached. When a cut-in by a HDV occurred between the first and second vehicle, with regards to the second vehicle, the time gap error increases due to sudden cut-in and it switches to ACC and brakes with a maximum deceleration of 2.5 m/s2 to recover the gap error. However, this sudden deceleration is further attenuated by the third (2.2m/s2) and fourth (1.6m/s2), indicating the lessening impact of the cut-in maneuver due to the considerable handling of the cut-in by the transition function in the second vehicle. Furthermore, the speed was almost constant in the fourth vehicle after the cut-in occurs. During the cut-out scenario, where the second vehicle in a platoon performs lane change (cut-out), the third vehicle closes the gap between it and the first vehicle and in the mean while the fourth vehicle very well maintains the desired time gap within 0.05s error and even the acceleration is smoother than the third vehicle minimizing the perturbation upstream. Later, the three vehicles form a string-stable platoon.

To conclude, higher the platoon size, more *vulnerable* is it to split up into smaller size platoons due to frequent cut-ins and cut-outs. A *three* vehicle CACC platoon has higher probability of staying as a platoon compared to higher numbers. During cut-ins and cut-outs the acceleration and deceleration behavior of the immediate follower is *smooth*. Furthermore, if the platoon size is more than two, then the acceleration and deceleration behavior of the vehicles in the platoon upstream of the immediate follower is *much smoother* than the immediate follower and those vehicles maintain desired time gaps pretty well during the cut-ins and cut-out maneuvers.

2.2.3. Platoon string-stability

One of the unique characteristics of the CACC platoons is the ability of the vehicles in the platoon to react faster to any disturbance incurred by the leader of the platoon or any downstream vehicles of the platoon, owing to the advantage of being connected to each other. Thereby, reacting earlier to the disturbance, the platoon vehicles attenuate the amplitude of the disturbance propagating upstream of the traffic flow, fostering stable traffic behavior. In this section, this stability behavior of platoons evident from FOTs will be looked into.

A comparison analysis of the ACC and CACC platoon system (four vehicle system) response to the automatic speed profile changes of the leader to mimic the frequent acceleration and deceleration usually observed in moderately congested traffic was carried out by (Milanes et al., 2014). It revealed that in case of ACC systems, once the speed profile is activated, the accelerations initiated by the leader, cause *oscillations* in speed (sometimes amplifications of overshoots in speed), acceleration/deceleration and time-gap profiles, especially in the third and fourth vehicle. This indicates there are *response delays* which lead to oscillations. However, even though the ACC was the stability-enhanced design, it couldn't overrule the problems due to *lack of information* about movements of vehicles ahead of the preceding vehicle. While in case of CACC, where in a desired time-gap setting of 0.6 seconds was set, it was worth noting that overshooting and amplification of speeds of third and fourth vehicle was *eliminated* which were observed in ACC systems, desired time gaps were very well maintained indicating good car-following behavior, and no significant response delays were observed (Milanes et al., 2014).

The previous analysis of (Milanes et al., 2014) focused on stability analysis of four vehicle platoons. (Ploeg, Scheepers, Van Nunen, Van De Wouw, &

Nijmeijer, 2011) focused on the string stability analysis of CACC platoon consisting of six passenger vehicles. A constant time headway spacing policy is adopted consisting of time-headway and standstill distance. It was found that considering the wireless communication delay of approximately *150 ms*, the minimum time headway for string stability is 0.67 s, and analysis has been performed using headway of 0.7s. Similar to the aforementioned automatic speed profile used to mimic frequent acceleration and deceleration in analysis of FOT by (Milanes et al., 2014), a test trajectory is identified as the desired acceleration of the lead vehicle and consisting of three superimposed swept sine signals. The reaction of the other five vehicles in the platoon to the test trajectory of the lead vehicle was analyzed for ACC and CACC systems. It is seen that CACC is string stable while ACC is not. Overshooting of speeds occurs in case of ACC, and it amplifies as the vehicle index increases. *The overshooting of speeds wasn't observed in CACC. This indicates that at time headway less than 1.0 s i.e., at 0.7s the CACC platoon is string stable.*

In conclusion, ACC platoons are not string stable due to void of information availability causing reaction delay of the vehicles to disturbance leading to oscillations in speed, desired time gap, acceleration and deceleration. On the other hand, these oscillations are hardly observed in case of CACC platoons of four and six vehicle platoon size leading to string stable behavior of CACC platoons at time headway of 0.7s.

2.2.4. Conclusion

All in all, it is evident from the literature review of this section 2.2 that most of the FOT's are conducted on CACC functionality of CAV's and thereby most of the driving behavior characteristics discussed are relevant to CACC functionality. *Hence, in this research, CACC functionality of CAV's will be simulated with regards to car following and owing to lesser-known information of lane change, the lane change parameters of CAV's enabled with CACC functionality will be same as that of the HDV's*. The following driving behavior characteristics of CAV's enabled with CACC functionality concluded from the literature will be adapted in the further simulation and analysis. *Those characteristics which cannot be adapted in simulations of this research will be further reported as limitations of this research.*

- Regarding *desired time gap* values, as drivers are willing to accept time gap settings offered by the CACC functionality which are below 1.0s and as low as 0.6 s, in simulation for this research desired time gaps of CAV's with CACC functionality can be set with *values less than 1.0s*. With regards to standard deviation of these time gap settings, as its evident that in various driving states (stable, acceleration and deceleration) it is *lesser* than that of AV's enabled with ACC functionality and HDV, in simulation for this research it might be *reasonable to presume that* *longitudinal oscillation of the set time gap setting of CACC vehicle is less than that of ACC and HDV settings.* Lastly, in simulation its better if *smoother transition* between different time gaps settings is considered for CACC vehicles.

- A *three*-vehicle platoon is less likely to encounter cut-ins/cut-outs compared to higher platoon size. Thereby in simulations, it's better to consider three size platoons rather than higher platoon sizes.
- In simulation of CACC enabled vehicles within the platoons which are effected by cut-ins and cut-outs, the *acceleration* and *deceleration* can be expected to be smoother and degree of smoothness increases with increase of vehicle index upstream within the platoon. Furthermore, the desired time gaps of these vehicles need to be ensured that they are pretty well maintained during the cut-in and cut-out maneuvers.
- In simulation, it needs to be ensured that CACC platoons are *string stable* at desired time gaps less than 1.0s. ACC platoons are not string stable due to void of information availability causing reaction delay of the vehicles to disturbance leading to oscillations in speed, desired time gap, acceleration and deceleration.

2.3. Relation between causes of traffic flow phenomena and the driving behavior characteristics of AV's (ACC) and CAV's (CACC)

Following up from Figure 4, after studying the driving behavior characteristics of AV's enabled with ACC functionality, referred to as *AV's (ACC)* hereafter and CAV's enabled with CACC functionality, referred to as *CAV's (CACC)* hereafter, the next steps are to first study the causes of three traffic flow phenomena which are, *Capacity Drop, Traffic Breakdown and Shockwaves,* which is carried out in section 2.3.1, 2.3.2 and 2.3.3 respectively. Later, the causes of these phenomena's are related to the driving behavior characteristics of AV's (ACC) and CAV's (CACC) in section 2.3.1.1, 2.3.2.1 and 2.3.3.1, to understand how well these phenomena can be influenced. In doing so, it will help to answer RQ2a, as framed in section 1.2 which is, *What are the causes of different traffic flow phenomena's and which of them can be influenced by the driving behavior characteristics of AV's (ACC) and CAV's (CACC)?* Finally, based on how well the causes of those phenomena can be expected to be influenced by AV's (ACC) and CAV's (CACC), one of those traffic flow phenomena will be chosen for further analysis, which is discussed in section 2.3.4.

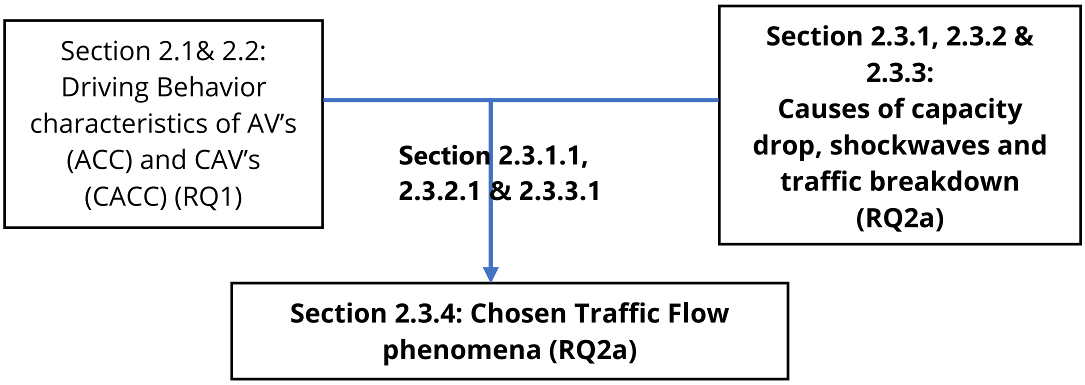


Figure 4: Part of the flow chart of the research methodology

2.3.1. Capacity Drop

Capacity drop is one of the phenomena which accounts for traffic delay. Once congestion occurs, the queue discharge rate (flow detected in the downstream of a traffic jam) is usually lower than the free-flow capacity (maximum flow that can be observed, also referred to as pre-queue capacity), causing a drop in the capacity, which leads to incomplete utilization of available road capacity. Lot of empirical observations revealed varying magnitude of capacity drop which are seen at bottlenecks when they are active, i.e. queue upstream and free flow downstream of bottlenecks (Yuan, 2016). According to (Yuan, 2016), existing proposed hypotheses about the mechanism behind the capacity drop could be divided into four categories, three of which will be discussed in this report are, *bounded acceleration capability, inter-driver spread, and intra-driver variation*. The following paragraphs explain these hypotheses as derived from (Yuan, 2016).

Bounded acceleration capability refers to the fact that vehicles can't accelerate instantaneously to their maximum potential when accelerating from low speeds, thereby creating gaps between the vehicle and the preceding vehicle. This bounded acceleration plays a major role when lane changing maneuvers are executed. (Laval & Daganzo, 2006) proposed a model that tracks lane change maneuvers precisely and experimented with that model in a simulation of lane drop scenario to explore a conjecture based on the study from (Bertini & Leal, 2005; Cassidy & Bertini, 1999) that, capacity drop at lane drops or merge sections may be caused by *lane changers*. From the results, a flow drop of 9.3% was observed which is in line with (Bertini & Leal, 2005). Additionally, a simultaneous sharp increase in density and lane changes upstream of bottleneck was observed once flow drop was noted, similar to the results of then ongoing finer-resolution empirical studies at merge bottlenecks by (Cassidy & Rudjanakanoknad, 2005). Consequently, this suggests that *lane changes* create voids (gaps) in the current lane and insertions in the target lane which cannot be filled up owing to *bounded acceleration capability* of the lane changing vehicle due to which it cannot accelerate instantaneously and thereby not catching up with its new predecessor. This causes the aggregated flow measured downstream of the queue to be lower than the capacity (Yuan, 2016). However, according to (Oh & Yeo, 2015) the capacity reduction is much larger due to *stop-and-go waves* in absence of lane changing than compared due to lane changing. In the absence of lane changing, the magnitude of capacity drop depends on the severity of congestion.

Inter-driver spread refers to the heterogeneity of various drivers in certain aspects of driving behavior. For instance, according to (M. Papageorgiou, Papamichail, Spiliopoulou, & Lentzakis, 2008) difference in acceleration between two successive vehicles can be reason for the capacity drop i.e. voids could be created for instance when a low-acceleration vehicle follows a high-acceleration vehicle. (Yuan, 2016) refers to this desired acceleration heterogeneity among vehicles as *inter-driver spread*.

The *intra-driver variation* assumes that driver behavior varies based on traffic conditions which could be the probable cause of capacity drop. For example, a driver's reaction time, desired time headway or time gap differs during acceleration and deceleration process. Various authors have proposed their hypothesis relevant to intra-driver variation on several driving behavior aspects as the probable reasons of capacity drop. (Treiber, Kesting, & Helbing, 2006b) assumes that drivers would *choose* longer time headway in congested conditions than in free flow, i.e., as density increases the *preferred* time headway increases. This assumption also known as *variance-driven headways* is based on the empirical observation by (Nishinari, Treiber, & Helbing, 2003), where in after a considerable queuing time, an increasing spacing time gap is observed. (Zhang & Kim, 2005) proposed a *multi-phase car-following traffic flow theory* where driver behavior in three phases i.e. acceleration, deceleration and coasting results in capacity drop. (Wu & Liu, 2013) developed an *asymmetric microscopic traffic flow theory* based on validation of acceleration and deceleration curves derived from an empirical data in an urban environment, where in capacity drop is the difference in maximum flow between acceleration and deceleration curves in density-flow diagram. (D. Chen, Ahn, Laval, & Zheng, 2014) described capacity drop as an outcome of intra-driver behavior variation in the form of change of aggressiveness i.e., four *different reaction patterns* to disturbances. According to (Tampere, 2004), the intra-driver variability is modeled as traffic condition dependent "*activation level*", low activation level refers to loss of motivation. (Tampère, Hoogendoorn, & van Arem, 2005) made two behavioral assumptions regarding activation level, i.e., time gaps are inversely proportional to activation level, or alternatively, the loss of motivation in low-speed condition is relatable to a reduction of maximum acceleration.

Table 3 provides a summary of the aforementioned hypothesized causes with regards to capacity drop and the relevant category they fall into, derived from (Yuan, 2016). Apart from those mentioned in Table 3, (Yuan, 2016) hypothesized that *there is a relation between congestion characteristics and capacity drop.* An empirical positive linear relation between the speed in congestion and queue discharge rate is observed, implying that as speed in congestion increases, the queue discharge rate increases. This further indicates that there could be a correlation between congestion categories (for instance, stop-and-go waves and standing queues) and queue discharge rates. (Yuan, 2016) study showed that queue discharge rate in stop-and-go waves is lower than in standing queues without any influences from the downstream, which could be the due to the reasons of the different speed in congestion. Hence, this paves the way to somewhat explain the magnitude variation in capacity drop and that it can be controlled.

Table 3: Overview of some of the hypothesized causes of the capacity drop and the relevant categories they fall into. Source: (Yuan, 2016)

Categories	Hypothesized causes	References
Bounded acceleration capability	Lane changing	(Duret, Bouffier, & Buisson, 2010; Laval & Daganzo, 2006; Leclercq, Knoop, Marczak, & Hoogendoorn, 2016; Leclercq, Laval, & Chiabaut, 2011)
Inter-driver/vehicle spread	Acceleration spread	(M. Papageorgiou et al., 2008)
Intra-driver variation	Variance-driven time headways	(Treiber et al., 2006b)
	Multi-phase car-following theory	(Zhang & Kim, 2005)
	Asymmetric driving behavior theory	(Hwasoo, 2008)
	Activation level	(Tampere, 2004)
	Reaction pattern	(D. Chen et al., 2014)

Based on the aforementioned empirical relation observed between the speed in congestion and queue discharge rate, the longitudinal behavior which could reproduce the empirical capacity drop was investigated through analytical and numerical simulations with regards to *inter-driver spread* and *intra-driver spread* by looking into desired acceleration spread and reaction time respectively

(Yuan, 2016). It was realized that *inter-driver spread* (even in combination with intra-driver spread) isn't that *significant* reason for capacity drop, while *intra-driver spread* where in reaction time decreases with increase in speed in congestion, can model the empirical relation observed. Furthermore, (Yuan, 2016) also analyzed the floating car trajectory data obtained from (Laval, Toth, & Zhou, 2014) collected in an *urban* environment and extended a car-following model to include the desired acceleration stochasticity which is hypothesized as inducing capacity drop evident from the aforementioned data. Desired acceleration refers to the acceleration the driver imposes to the vehicle when there is no vehicle ahead. Stochasticity implied that, the mean and standard deviation of a driver's desired acceleration decreases as the vehicle speed increases. The desired acceleration stochasticity justified the capacity drop. Hence, it is concluded from (Yuan, 2016) study that modelling *intra-driver variation* better represents capacity drop than *inter-driver spread*.

To conclude, *bounded acceleration capability* of the vehicle after executing a lane change or while accelerating from stop and go waves, variation *of driving behavior between drivers/vehicles* especially different desired acceleration values and finally *variation of driving behavior within a driver* depending on traffic conditions can be hypothesized as probable reasons for causing capacity drop. Furthermore, the relation between speed in congestion and consequent capacity drop i.e., higher speed relates to lesser drop, explains variation in magnitude of capacity drop observed empirically, implying that having a controlled congestion which has a higher speed is more desirable.

2.3.1.1. Relation between causes of capacity drop and driving behavior characteristics of AV's (ACC) and CAV's (CACC)

In the previous section, the various hypotheses for the probable causes of the capacity drop were discussed. In this section, whether these probable causes could be addressed by the driving behavior characteristics of AV's (ACC) and CAV's (CACC) will be discussed. Following up from Table 3, one of the hypothesized causes is *lane changing* followed by the *bounded acceleration capability* of the vehicle due to which after lane changing occurs, the vehicle cannot accelerate instantaneously to fill the gap cause due to lane change. As pointed out in sections 2.1.6 and 2.2.4 that hardly any FOT's are conducted on lane changing behavior of AV's and CAV's, it is hard to hypothesize or relate whether lane changing behavior of AV's and CAV's and thereby their acceleration capability after lane changing would influence capacity drop.

In the absence of lane change, capacity drop occurs, as indicated in Table 3 by another hypothesized cause, *acceleration spread* under the category of Inter-driver spread. In mixed traffic, when moving out of congestion, *if ACC and CACC functionality of AV's and CAV's are presumed to be enabled*, then the ACC and CACC functionality tries to catch up with the speed of the predecessor with *faster reaction time* by accelerating in the similar fashion as that of the predecessor, due to which lesser voids can be expected between vehicles. Hence, it might be expected that as penetration rate of AV's (ACC) and CAV's (CACC) increases, the acceleration spread and voids between vehicles reduces and subsequently a reduction in the magnitude of capacity drop.

Lastly, another category causing capacity drop is *intra-driver variation*. This heterogeneity within drivers in different traffic conditions, can be expected to be addressed by similar driving behavior in all the traffic states which can be expected to be achieved by AV's and CAV's as they are *system controlled* rather than by human behavior. *However, this only applies if the AV's and CAV's drive without any interruption by humans, for instance, if a driver of an AV and CAV changes the headway choice among the ones offered by the car-following system depending on the traffic conditions, then it might not influence capacity drop.* Table 4 provides an overview of the relation between proposed categories for causes of capacity drop and the relevant AV's (ACC) and CAV's (CACC) driving behavior which address the categories as discussed before.

Table 4: Relation between categories for the hypothesized causes of capacity drop and the respective AV's (ACC) and CAV's (CACC) driving behavior which address them.

Proposed categories for the hypothesized causes of the capacity drop	**AV's (ACC) and CAV's (CACC) driving behavior characteristics which address the categories**
Bounded acceleration capability	-
Inter-driver/vehicle spread	Spread reduced by ACC and CACC functionality
Intra-driver variation	Variation eliminated by system-controlled vehicles

2.3.2. Traffic Breakdown

In this section to understand traffic breakdown phenomena *three phase traffic flow theory* is referred. Traffic breakdown is onset of congestion in Free Flow (F), thereby restricting free flow conditions. Breakdown usually occurs at *effectual bottlenecks* (such as on/off ramp, lane drop, roadworks etc.), which are defined as the bottlenecks where breakdown is often observed. The onset of congestion is accompanied by an acute decrease in average vehicle speed in free flow to significantly lesser speed in congested traffic. Breakdown results in emergence of Synchronized phase (S), where in the downstream jam front is usually fixed at bottlenecks. Hence, traffic breakdown is a *first-order local phase transition from F to S phase* (Kerner & Klenov, 2009).

Traffic Breakdown is *probabilistic* in nature, implying that at the same flow rates breakdown might occur or might not. Empirical probability of breakdown is an increasing function of flow rate downstream of the bottleneck (Kerner & Klenov, 2009). Breakdown doesn't occur at all free flow rates at/downstream of the bottleneck, there is a range within which breakdown probability exists. This indicates that all the flow rates within the range represent bottleneck capacity if breakdown doesn't occur, implying the concept of *stochastic capacity*. The flow rates within this range are called *metastable free flow states* with respect to F to S transition at the bottleneck. This range is defined by the equation 1 below (Kerner, 2017).

$$C_{min} \leq q_{sum} < C_{max} \quad (1)$$

Free flow rates at/downstream of the bottleneck (q_{sum}) which are smaller than minimum capacity (C_{min}) the breakdown probability is zero and the flow rates are stable with respect to traffic breakdown. If q_{sum} is higher than maximum bottleneck capacity C_{max}, the traffic states are unstable, and the breakdown probability is one. Considering that metastable free flow states exist at/downstream of the bottleneck, there are two types of empirically observed breakdown at the bottlenecks, which are *Spontaneous traffic breakdown* and *Induced traffic breakdown.*

Before breakdown, if free flow persists at, upstream and downstream of the bottleneck, then the *occurrence* and subsequent *growth* of *speed disturbances* in free flow cause *spontaneous traffic breakdown* at the bottleneck. The growth refers to the decrease of speed within the disturbance over time followed by subsequent traffic breakdown, which happens only if the *initial speed* during the disturbance occurrence is equal to or less than the *critical speed* required for F to S transition. If the *initial speed* within the disturbance is equal to or less than the *critical speed*, then the disturbance can be regarded as a *nucleus (cause)* for F to S transition i.e., breakdown. This *critical speed* depends on the free flow rate downstream of the bottleneck, i.e., at higher flow rates, critical speed is higher and vice versa. This implies, at higher flow rates downstream of the bottleneck, a small local speed decrease in free flow at the bottleneck is sufficient for traffic breakdown (Kerner, 2009). Unexpected vehicle braking, lane changing, flow rates fluctuations upstream of the bottleneck, vehicle merging at on-ramp bottleneck etc. cause *speed disturbances* (Kerner, 2009).

Contrarily, if a moving spatiotemporal pattern, i.e., a breakdown initially occurred at a different location, travels through the bottleneck and induces F to

S transition, then the breakdown is referred to as *induced traffic breakdown*. This moving congestion pattern can be called as *external* disturbance (Kerner, 2009).

Following from the aforementioned types of breakdown it indicates that there are two occurrence possibilities for the *nucleus (cause)* required for traffic breakdown (Kerner, 2017):

1. *Random* fluctuations in *speed, density and/or the flow rate* at the bottleneck resulting in the *nucleus*, causing *Spontaneous traffic breakdown*.
2. A *local congested pattern* when reaches a bottleneck acts as a *nucleus*, which leads to *Induced traffic breakdown*.

(Kerner, 2017; Kerner, Koller, Klenov, Rehborn, & Leibel, 2015) empirically analyzed the aforementioned possibilities of *nucleus* causing traffic breakdown, which is explained in the following paragraphs.

Nucleus for Empirical Spontaneous Traffic Breakdown at Highway Bottlenecks

To study *nuclei* for spontaneous traffic breakdown, (Kerner et al., 2015) introduced the concept of *empirical waves* where values of traffic variables plotted in space-time are analyzed. To obtain traffic variables required to plot *empirical waves*, 1-minute averaged empirical data available from detectors, such as speed (v), flow (q) and flow rate of long (slow) vehicles (q_{slow}) are subtracted with the respective 20-minute average empirical data to obtain new variables, Δv_{wave}, Δq_{wave}, & Δq_{wave}^{slow}. Additionally, another variable related to the share of the long vehicles ($\Delta\psi_{wave}$), is obtained by diving Δq_{wave}^{slow} *by* Δq_{wave}. Empirical waves of these variables in free flow is achieved using an approximate wave reconstruction procedure as described in (Kerner et al., 2015).

Figure 5 shows an instance of an *empirical wave* causing traffic breakdown when propagating through an off-ramp bottleneck derived from real traffic data, thereby acting as a *nucleus*. The characteristics and structure of the wave, while propagating downstream of the bottleneck doesn't change (Kerner, 2017). However, it can't be said which exact wave causes traffic breakdown, as its *random*. Hence, a wave propagating downstream with velocity same as that of mean velocity of long (slow) vehicles (85-88 km/hour), causes breakdown *only* at the *effective location of the bottleneck*, which is a location in the neighborhood of an effective bottleneck. *This implies not many breakdowns are observed in between bottlenecks.*

To further discern the aforementioned conclusion that most breakdowns occur *at* the bottlenecks and not *in between* bottlenecks, waves of speed (*v)* averaged across lanes were analyzed for real field traffic data of a road section which consist of one off-ramp and two on-ramp bottlenecks (Kerner, 2017; Kerner et al., 2015) as shown in Figure 6. It was observed that, in addition to speed (*v)* waves propagating downstream, there exists *narrow regions* localized in the *effective location (neighborhood) of the aforementioned bottlenecks*, within which speed is lower than the outside locations. These narrow regions are termed as empirical *permanent local speed disturbances* in free flow at highway bottlenecks. Empirical observations have shown that, *only* when an *empirical wave* reaches the *narrow region,* traffic breakdown occurs, indicating that breakdown occurs at the *narrow regions* as shown in Figure 6. In other words, a decrease in speed within the empirical *permanent local speed disturbance* further decreases when an *empirical wave* reaches it, because within the wave the average speed is lower, flow rate is higher, and percentage of long vehicles (slow vehicles) is higher than outside the wave. Hence, this *empirical wave* can be termed as *nucleus* (Kerner, 2017; Kerner et al., 2015). It can be noted that, even though it hasn't been explicitly mentioned in (Kerner, 2017; Kerner et al., 2015), even in the absence of long (slow) vehicles, average speed within empirical waves could be lower due to driver heterogeneity in the presence of same vehicle class, i.e. a driver with a lower desired speed can mimic the presence of a long (vehicle) and hence influence empirical wave acting as a *nucleus*.

Nucleus for Empirical Induced Traffic Breakdown at Highway Bottlenecks: Upstream propagation of a *localized congested pattern* act as *nucleus* and cause traffic breakdown in metastable free flow state when it reaches the effective location (narrow region) of the bottleneck. Normally, a *single congested pattern* is enough for induction of traffic breakdown, whereas breakdown may not occur for *many empirical waves* which propagate through the bottleneck (Kerner, 2017).

To conclude, it is understood from this section's literature review that traffic breakdown is *probabilistic* in nature at *metastable* traffic flow rates around the *bottleneck*. For spontaneous traffic breakdown to occur, a *random critical speed disturbance* (*empirical wave) in free flow,* either due to long (slow) vehicles or slow drivers of passenger cars in absence of long vehicles, with its speed less than or equal to the critical speed for a given metastable flow rate, will act as a *nucleus* for breakdown when it reaches the *narrow regions (permanent local speed disturbance)* of the bottlenecks. For induced traffic breakdown to occur, an *upstream propagating congested pattern* which usually has lower speed acts as a *nucleus* for breakdown when it reaches the bottlenecks. Table 5 highlights these *causes (nucleus)* of traffic breakdown at bottlenecks and the *respective* conditions which should prevail at bottlenecks for the *causes* to trigger breakdown.

Table 5: Causes (nucleus) of traffic breakdown at bottleneck along with the respective required conditions at bottlenecks.

Causes of Traffic Breakdown at bottlenecks	**Other conditions required along with the standalone causes**
Random critical local disturbance a) Due to long vehicles (slow vehicles) b) Due to lower desired speed of passenger cars in absence of (a).	Metastable free flow state at/downstream of bottleneck + permanent local speed disturbance
Moving congestion pattern	Metastable free flow state at/downstream of bottleneck

2.3.2.1. Relation between causes of traffic breakdown and driving behavior characteristics of AV's (ACC) and CAV's (CACC)

In the previous section, two causes of traffic breakdown were discussed and were highlighted in Table 5. In this section, whether these causes could be addressed by the driving behavior characteristics of AV's (ACC) and CAV's (CACC) will be discussed.

Following up from Table 5, *random critical local disturbance* occurs either due to a certain *percentage of long (slow) vehicles* as analyzed empirically by (Kerner et al., 2015) or *due to lower desired speed of passenger cars* in the absence of long vehicles as hypothesized by the author.

Long vehicles cannot be related, because the driving behavior characteristics of AV's (ACC) and CAV's (CACC) studied in section 2.1 and 2.2 refer to passenger cars. Slow drivers of passenger cars are evident in traffic due to *heterogeneous* human drivers, driving with lower desired speeds (lower than the prescribed speed limits). This *heterogeneity* can be expected to be influenced by AV's (ACC), based on the conclusion from the section 2.1.6, that AV's set their desired speed according to the Speed Limit in *free flow state*. Furthermore, AV's (ACC) maintain the set speed with less variations. Hence, it can be expected that at higher penetration rates of AV's (ACC), more *homogeneous* desired speeds and less fluctuations can be observed in free flow, contributing to lesser occurrence of random critical local disturbance as summarized in Table 6. The same reasoning can also be expected to apply to CAV's (CACC). However, it can be argued that in *car following state in the context of mixed traffic,* if AV's (ACC) and CAV's (CACC) desired speed of driving at speed limit is obstructed by a slower desired speed preceding HDV, then AV's (ACC) and CAV's (CACC) are also expected to drive slower to follow the slower preceding HDV. In that case, AV's (ACC) and CAV's (CACC) *cannot* be expected to address the *random critical local disturbance* occurring due to the *lower desired speed of passenger cars.*

The second cause of traffic breakdown is *moving congested pattern* which aid in *induced traffic breakdown.* This moving congested pattern which occurred at a downstream bottleneck, propagates upstream and induces breakdown when it reaches the upstream bottleneck under study.

The *amplitude* of the congested pattern propagation upstream might be lessened if it encounters a CACC platoon, owing to the *platoon string stability* behavior of CACC equipped vehicles. As discussed in 2.2.3, CACC vehicles in a platoon foster in dampening of the disturbance while the disturbance propagates within the platoon. Thereby, if CACC platoon encounters a congested pattern before the pattern reaches the bottleneck, then the amplitude of the moving congestion pattern can be alleviated by the string stability of CACC vehicles within the platoon. This might lead to congestion pattern reaching the bottleneck with lesser amplitude then required for the breakdown at the bottleneck. However, it is to be noted that it is less probable for the CACC vehicles to form a platoon at lower penetration rates of CAV's (CACC). Table 6 provide an overview of the previously described relation between causes of traffic breakdown at bottlenecks and the respective AV's (ACC) and CAV's (CACC) driving behavior which address them.

Table 6: Causes of traffic breakdown at bottleneck and the respective AV's (ACC) and CAV's (CACC) driving behavior characteristics which address them.

Causes of Traffic Breakdown at bottlenecks	**AV's (ACC) and CAV's (CACC) driving behavior characteristics which address the causes**
Random critical local disturbance a) Due to long vehicles (slow vehicles) b) Due to lower desired speed of passenger cars in absence of (a).	At higher penetration rates, homogeneous driving of AV's and CAV's addresses (b) in free flow states
Moving congestion pattern	String stability of CACC vehicle platoon

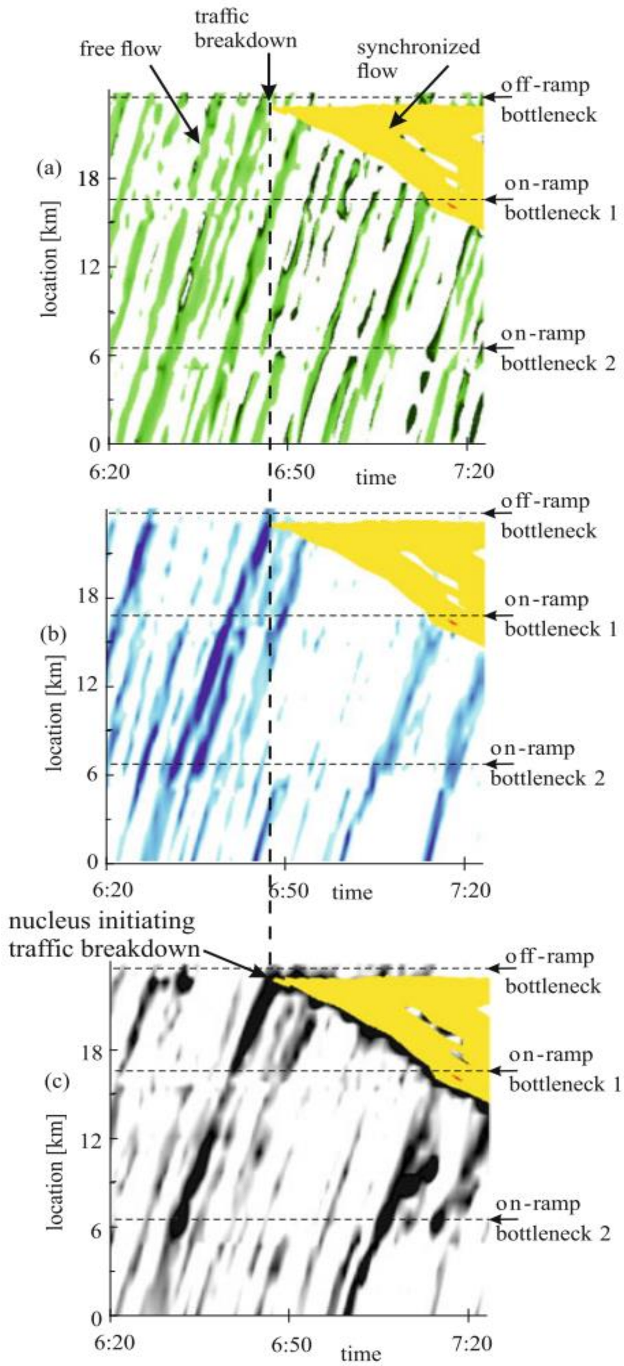


Figure 5. Empirical waves of $\Delta\psi_{wave}$ (a), Δq_{wave} (b), and Δv_{wave} (c) in free flow averaged across the road. In (a–c), region labeled by "synchronized flow" shows symbolically synchronized flow. Waves of $\Delta\psi_{wave}$ are presented by regions with variable shades of green (in white regions $\Delta\psi_{wave} \leq 0.1$, in black (dark green) regions $\Delta\psi_{wave} \geq 1$). (b) Waves of regions with variable shades of blue (in white regions $\Delta q_{wave} \leq 700$ vehicles/h, in black (dark blue) regions $\Delta q_{wave} \geq 2000$ vehicles/h). (c) Waves of Δv_{wave} are presented by regions with variable shades of gray (in white regions $\Delta v_{wave} \leq 2$ km/h, in black regions field traffic data measured on $\Delta v_{wave} \geq 15$ km/h). Real field traffic data measured by road detectors on September 03, 1998. Source: (Kerner, 2017)

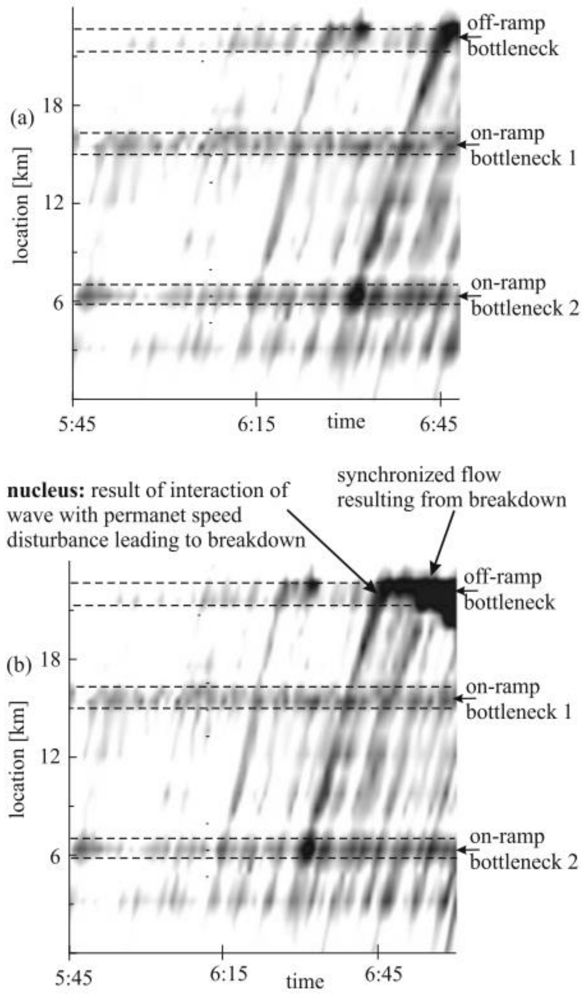


Figure 6: (a) Empirical permanent local speed disturbances in free flow at highway bottlenecks for the real field traffic data measured on September 03, 1998. (b) The same data as in (a), however, for a longer time interval showing that the nucleus for the breakdown at the off-ramp bottleneck appears due to some interaction of the wave with a permanent speed disturbance at the bottleneck. In (a, b), empirical data for the speed v(x,t) *presented by regions with variable shades of gray; in white regions $v \geq 115$ km/h, in black regions $v \leq 80$ km/h. Narrow road regions of a smaller speed (permanent local speed disturbances), which are localized in neighborhoods of the effective locations of the bottlenecks, are marked by double dashed lines. Source: (Kerner, 2017)*

2.3.3. Shock waves

Shockwaves occur at the transition from one traffic state to another (Schroeder, 2016). The main cause of the occurrence of shock waves is the combination of *higher traffic demand* and *unexpected driver actions* (Forster, Frank, Gerla, & Engel, 2014), implying that in *denser* traffic, a *minor mistake in driver behavior* or *traffic along the path* can instigate a temporary overload that leads to the occurrence of a shock wave travelling upward of the traffic stream. Shockwaves commonly occur at freeway bottlenecks (on-ramps, construction sites, reduction of lanes or an increase in traffic) and incidents, which induce vehicles to drastically slow down or come to a stop (Schroeder, 2016).

Congestion in freeways usually occurs by the interactions of different drivers and vehicles in near-capacity situations. So, instead of having a clear bottleneck followed up by clear congestion pattern, the disturbance in heavy traffic stream on freeways is usually more *random*, sometimes leading to congestion without any apparent cause. One such consequence is Phantom or ghost traffic jams which are a specific form of congestion (Calvert, Van Den Broek, & Van Noort, 2011). Phantom traffic jam phenomena was illustrated at a smaller scale by (Sugiyama et al., 2008) using *a large group of vehicles* driving on a circular road without any bottleneck where shockwaves occurred *due to a disturbance created by a driver*, resulting in phantom traffic jam. The mechanism behind the occurrence of jam is string stability (Calvert et al., 2011). Hence, the random variation of vehicle headways and random disturbances can result in breakdown even without any apparent incident, bottleneck or any other reason of congestion. The speed of the congestion shockwave gives the speed at which congestion i.e. back of queue travels upstream from the bottleneck location (Schroeder, 2016). From the trajectory data observations, it is observed that the drop or valley in the speed is evident when a shock wave occurs and the depth of the speed drop indicates the effect of shock waves, i.e. whether it was short-term fluctuation or long-term congestion (Lu & Skabardonis, 2007).

(Ahn & Cassidy, 2007) provided an empirical evidence regarding the important role of *lane-changing maneuvers* on multi-lane freeways as the cause of oscillations. Contrarily, oscillations have also been observed on single roads, test tracks or in tunnels where lane changing was prohibited and these oscillations may be explained by the interactions detailed in car-following models to a certain extent. Empirical data was collected on both directions of freeway during rush hours where in queues emerged due to a bottleneck downstream. For the *macrolevel* assessment, loop detector data and for *micro level*, video surveillance system for a part of the highway stretch were utilized.

From the microlevel analysis, the cause of oscillation *formation and growth* were realized. An oscillation *formation* was evident when a vehicle's speed starts to change whereas its leader's speed doesn't (Ahn & Cassidy, 2007). The oscillation *growth* is evident when a kinematic wave carries speed variations which increase at upstream locations. It was found that *lane changes* which were executed into *smaller* vehicle spacings were the *triggering* events of oscillation *formation* as well as oscillation *growth*. It can be concluded from the study by (Ahn & Cassidy, 2007) that *lane changes trigger formation and growth of oscillations within queued traffic.*

In conclusion, one of the causes of shockwaves is an unexpected driver action during high dense/inflow traffic conditions. Another cause relates to the lane changing maneuvers within queued traffic which is also responsible for growth of the shockwaves. Table 7 summarizes these causes of shockwaves as discussed previously with the relevant references.

Table 7: Causes of shockwaves

Causes of Shockwaves	**References**
Within queued traffic, *lane changing* causes *occurrence* and *growth* of shockwaves.	(Ahn & Cassidy, 2007)
A disturbance *by an unexpected driver action* causes the *occurrence* of shockwave and *high inflow* influences the *propagation* of shockwaves.	(Sugiyama et al., 2008) (Forster et al., 2014) (Schroeder, 2016)

2.3.3.1. Relation between causes of shockwaves and driving behavior characteristics of AV's (ACC) and CAV's (CACC)

In the previous section, two causes of shockwaves were discussed and were highlighted in Table 7**.** In this section, whether these causes could be addressed by the driving behavior characteristics of AV's (ACC) and CAV's (CACC) will be discussed.

Following up from Table 7, *lane changing* causes *occurrence and growth* of shockwaves in queued traffic. As pointed out in sections 2.1.6 and 2.2.4 that hardly any FOT's are conducted on lane changing behavior of AV's and CAV's, it is hard to hypothesize or relate whether lane changing behavior of AV's and CAV's would influence the *occurrence* and *growth* of shockwaves.

Another cause for the *occurrence* of shockwaves is a *disturbance by an unexpected driver action*. The disturbance caused by driver behavior (for instance, sudden braking or slowing down) is very *random* (due to heterogeneous human driving) and is unpredictable. Hence, in mixed traffic when HDV's are still on the road, this random disturbance occurrence cannot be eliminated, which indicates that AV's and CAV's driving behavior has no relation with this cause of shockwave occurrence. However, it is can be expected that at higher penetration rates (>70 or 80%) of AV's and CAV's, homogeneous driving behavior of AV's and CAV's might eliminate this randomness to a certain extent.

Next to the *occurrence* of shockwaves, high *inflow* of vehicles and their *reactions* to the *disturbance* influence the *growth* of shockwaves and thereby causing jams. It is pointed out in section 2.3.3 that the mechanism behind the occurrence of jam is string stability (Calvert et al., 2011). Hence, this string stability required to hamper the growth of shockwaves and thereby jam, can be expected to be addressed by the string stability characteristic of CACC vehicles within a platoon as discussed in section 2.2.3. Thereby, *inflow* cannot be influenced directly by driving behavior of CAV's, however, given the inflow, CACC platoon string stability can be expected to hinder the growth of shockwaves. However, it is to be noted that it is less probable for the CACC vehicles to form a platoon at lower penetration rates of CAV's (CACC).

Table 8 gives an overview of the previously discussed relation between causes of shockwaves and the respective AV's (ACC) and CAV's (CACC) driving behavior characteristics which address them.

Table 8: Causes of shockwaves and the respective AV's (ACC) and CAV's (CACC) driving behavior characteristics which address them.

Cause of Shockwaves	**AV's (ACC) and CAV's (CACC) driving behavior characteristics which address the causes**
Within queued traffic, *lane changing* causes *occurrence* and *growth* of shockwaves.	-
A disturbance *by an unexpected driver action* causes the *occurrence* of shockwave and *high inflow* influences the *growth* of shockwaves.	Shockwave *occurrence*: - Shockwave *growth*: CACC string stability

2.3.4. Conclusion

To conclude, from Table 8, it is evident that driving behavior of AV's (ACC) and CAV's (CACC) cannot be expected to address the expected causes of *occurrence* of shockwaves. On the other hand from Table 4 and Table 6, certain (hypothesized) causes of capacity drop and traffic breakdown can be expected to be addressed by the driving behavior characteristics of AV's (ACC) and CAV's (CACC) to a certain extent. Thereby, it can be hypothesized that capacity drop and breakdown phenomena might be influenced to certain extent by the expected driving behavior of AV's (ACC) and CAV's (CACC) as their penetration rate increases in mixed traffic. However, given the time limit of this research, one of the two phenomena, i.e., either capacity drop or traffic breakdown needs to be chosen for further investigation. Based on the mechanism of those phenomena's, *capacity drop (and congestion shockwaves)* are by-products of *traffic breakdown*. In addition, traffic breakdown i.e., onset of congestion is one of the significant problems in traffic flow theory which needs to be addressed daily, otherwise its by-products capacity drop and congestion shockwaves occur. *Hence, in this research, the phenomena of* ***traffic breakdown*** *will be studied and addressed*. Following up from Figure 7, the next step is to investigate current traffic management measures which address *traffic breakdown*. However, before that, it is of greater importance to study traffic breakdown mechanism in greater detail which will be dealt in Chapter 3.

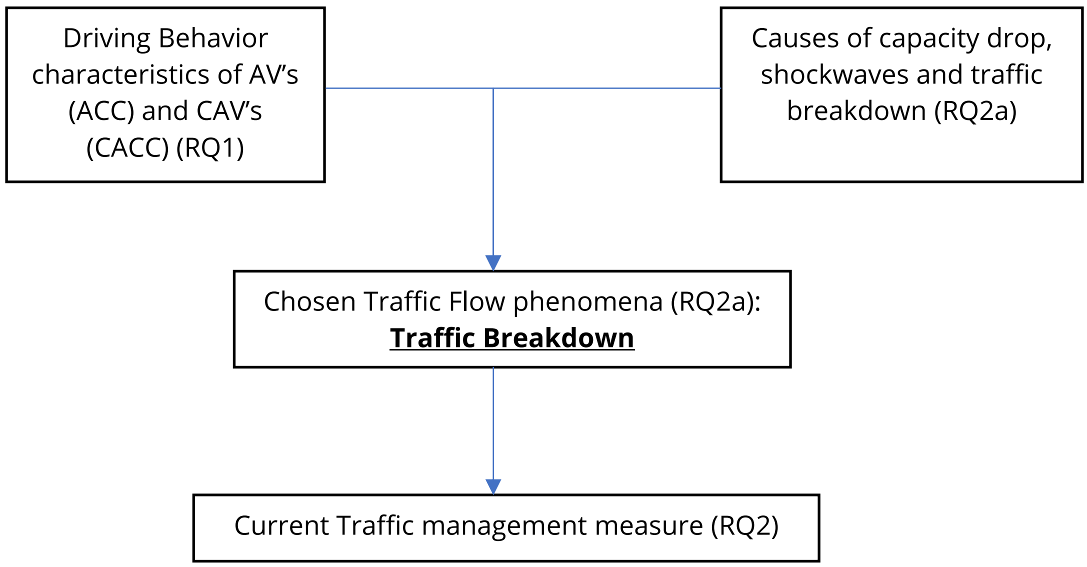


Figure 7: Part of the flow chart of the research methodology.

3. Microscopic Analysis of Traffic Breakdown mechanism

In section 2.3.2, traffic breakdown mechanism was analyzed from the three-phase traffic flow theory perspective and the causations studied were at a more macroscopic level. However, given that the driving behavior characteristics are described at a microscopic level (reaction times, desired/actual time headways, acceleration etc.) and it is these microscopic driving behavior characteristics of different drivers and vehicles which interact and lead to these amazing traffic flow phenomena which are evident at a macroscopic level, it is necessary to analyze breakdown mechanism from a microscopic level.

The benefit of conducting this microscopic analysis is *three-fold*.

1. Knowing the microscopic influencing factors of traffic breakdown helps to carefully adjust the values of those factors in driving behavior of HDV, AV's (ACC) and CAV's (CACC) in simulation.
2. It helps to relate the driving behavior of AV's (ACC) and CAV's (CACC) with the microscopic subtleties which influence breakdown mechanism, giving insights into addressing breakdown mechanism just by expected driving behavior of AV's (ACC) and CAV's (CACC).
3. Knowledge of these microscopic influencing factors also helps to know which of them are being addressed by current traffic management measures and which of them needs to be handled by the new measures to lessen the occurrence of traffic breakdown.

Thereby, this chapter will investigate different theories which describe the traffic breakdown mechanism from a microscopic level. Later, section 3.1 elaborates on the second benefit of conducting microscopic analysis mentioned before.

(Han & Ahn, 2018) developed stochastic traffic breakdown model at a merge bottleneck. The breakdown process is divided into two process, *trigger (*initiation of speed disturbance*)* and *propagation (*transition of disturbance into congestion*)*. These processes vary based on the *distribution of spacing/headway of the vehicles in the mainstream*. For a given flow rate, breakdown probability is formulated by integrating probabilities of *trigger* and *propagation* depending on microscopic car-following behavior, which is that of simplified model by (Newell, 2002).

(Han & Ahn, 2018) assumed that disturbances are triggered only by merging vehicles from an on ramp on a single lane freeway section. Once a merging vehicle (vehicle M in Figure 8), enters the mainstream traffic at a *lower speed* (v_{in}) than the *free flow speed* (u) in the mainstream as shown in Figure 8, the intensity of the speed disturbance leading to *trigger* event depends on the spacing, S_F , between the immediately following vehicle (vehicle F in Figure 8), and the merging vehicle, at the time of merge. If S_F *is greater than or equal to, among others, desired spacing for the desired speed of the follower,* $S_F^*(u)$, as shown in Figure 8a, then *no trigger or mild trigger* may occur. However, if S_F is smaller than, among others, $S_F^*(u)$ as shown in Figure 8b, then the following vehicle finds itself suddenly in Car Following mode (CF mode in Figure 8) causing *moderate to severe trigger* and thereby increasing the magnitude and duration of the disturbance. Along with S_F, the *time duration* for which the merging vehicle maintains the lower speed at which it merges influences *trigger* as well.

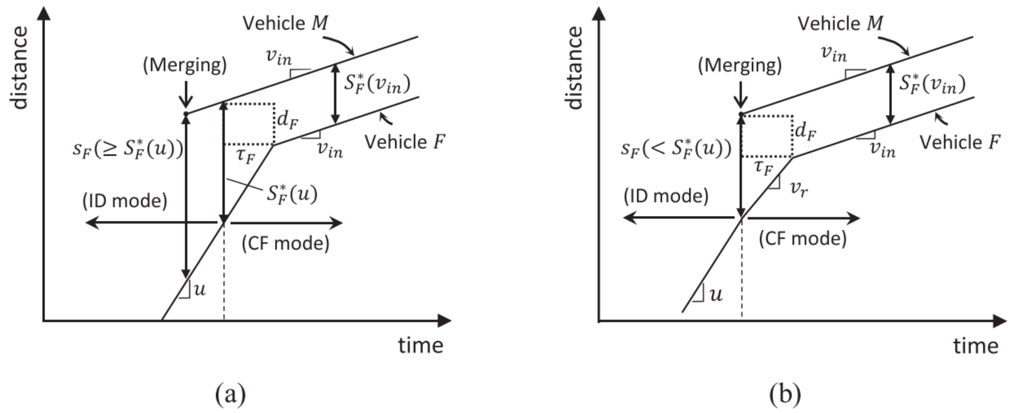


Figure 8: Behavior between merging and following vehicle. a) Merging spacing larger than desired spacing; b) Merging spacing is smaller than desired spacing. Source: (Han & Ahn, 2018)

According to (Son, Kim, Kim, & Lee, 2004), if the initial triggered disturbance doesn't dissipate before the next merging vehicle then, it is likely that the disturbances will cumulate over time leading to traffic breakdown. If the initial headways of the vehicles in the mainstream before the next merging vehicle are large enough [higher than *desired time headway* (*desired time headway is obtained by dividing the desired spacing for the considered desired speed)* also known as *buffer headways,* as shown in Figure 9a) then the initial disturbance dissipates. However, if the buffer headways are less, then the vehicles (F_4 and F_5 in Figure 9b) will lose the buffer headways once they encounter the initial disturbance and later with the shorter headways encounter the second disturbance initiated by merging vehicle M_2, thereby increasing the probability of its further consistent propagation (both in magnitude and duration). Hence, the probability of *propagation* depends mainly on *number of mainline vehicles and their actual headways before the next merging vehicle, the time required for the* *triggered disturbance dissipation which depends on the free flow speed, magnitude and duration of the speed disturbance.*

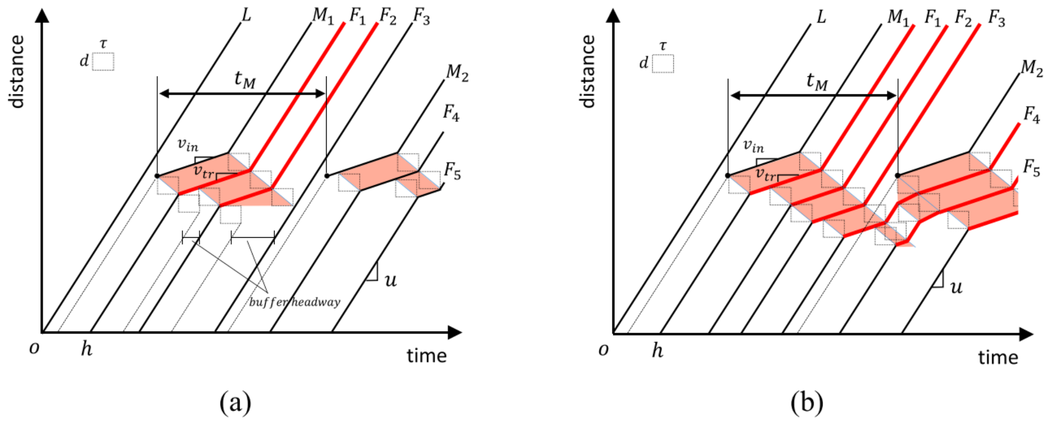


Figure 9: Traffic breakdown propagation a) insufficient propagation; b) sufficient propagation over next merge maneuver. Source: (Han & Ahn, 2018)

The influencing factors for the probability of traffic breakdown according to (Han & Ahn, 2018):

- For a given mainline flow rate, as *merge flow rate* increases, probability increases.
- For a given merge flow rate, as *mainline flow rate increases*, probability of breakdown increases, as triggers are severe, and propagation is consistent because actual headways aren't sufficient to dissipate the triggered disturbance.
- For a given mainline flow rate, as *speed* of the merging vehicle increases, the breakdown probability decreases, as it triggers less severe disturbances.
- Lower the *reaction time* of the mainline vehicles to the disturbance, lower the breakdown probability, as more aggressive drivers cause lesser disturbance or respond faster in the propagation of disturbance than timid drivers with more reaction time.
- Below the critical value (near capacity), lower the *deviation of headways distribution* for the entire mainline flow range, lower the breakdown probability due to larger buffer headways. On the contrary, beyond the critical value, the lesser the deviation the more the probability of breakdown, as buffer headways are insufficient to dissipate the merging disturbance, thereby larger deviation increases probability of larger buffer headways which help in dissipating the merging disturbance and decreasing the probability of breakdown.
- However, According to (X. (Michael) Chen, Li, Li, & Shi, 2014), rather than vehicle headway distribution, *average headway* which changes with mainline flow determines the S-shape breakdown probability curve.

Hence, as average headway decreases, queue exists for a longer time which increases the probability of breakdown.

Consequently, from the stochastic breakdown model proposed at on ramp scenario with a single mainline lane by (Han & Ahn, 2018), it can be hypothesized that, *spacing between the immediate follower and the merging vehicle (disturbance), which can be ≥ or < than desired spacing for the desired speed of the follower, the magnitude and duration of the lower speed of the disturbance (merging vehicle), reaction time of the immediate follower to the disturbance and thereby which decides the deceleration rate, all contribute to the* _trigger_ *for the traffic breakdown.*

Whereas *actual headways (better if they are higher than desired time headway for the desired speed) between mainline vehicles behind the immediate follower (which influences the mainline flow rate), actual headways between merge vehicles (which influences the merge rate), reaction time of the mainline vehicles to the response of the immediate follower to the disturbance, free flow speed on the mainline, contribute to the* _propagation_ *of the trigger and hence breakdown.*

It is to be noted that, very similar to the previously discussed concept of stochastic breakdown model by (Han & Ahn, 2018), (Son et al., 2004) used *wave propagation model* developed by (Kim & Zhang, 2004) to propose a probabilistic model of traffic breakdown on a single lane freeway at an on-ramp where in the breakdown is triggered by the merging vehicles (disturbance).

According to the model by (Son et al., 2004), a merging vehicle merges and travels at a lower speed and then accelerates to free flow speed, i.e. following from Figure 10 there exists a *duration* (T_0) and *speed* (v_0) of initial disturbance caused by the merging vehicle. (X. (Michael) Chen et al., 2014) in their *Queueing Model* for traffic breakdown probability considered the *duration* of merging disturbance as *stochastic* as it is influenced by many factors such as merging velocity, accepted gap etc. The following vehicles react to the disturbance created by the merging vehicle, leading to deceleration and then acceleration, i.e., formation of deceleration and acceleration waves as shown by dotted lines in Figure 10, which are *stochastic* in nature owing to the reason of *distribution of gap time*. This *stochastic* distribution of gap times of mainline vehicles is also in line with the *Queueing Model* for traffic breakdown probability proposed by (X. (Michael) Chen et al., 2014).

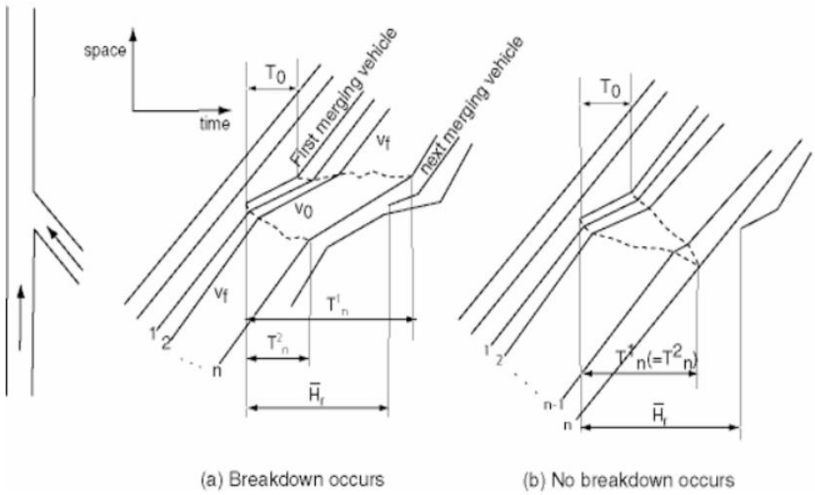


Figure 10:Breakdown on a freeway. Source: (Son et al., 2004)

While the deceleration disturbance created by the first merging vehicle exits and, in the meantime, a second vehicle from the on-ramp merges as shown in Figure 10a, then the merging vehicle and the following vehicles would decelerate much stronger than earlier. Hence, as more vehicles merge, traffic breakdown finally occurs (Son et al., 2004). However, if the deceleration wave caused by the first merged vehicle dissipates before the second vehicle merges as shown in Figure 10b, breakdown wouldn't occur, i.e., to say that breakdown is prevented when acceleration and deceleration waves *meet* before the merging of the second vehicle from the on-ramp. These acceleration and deceleration waves are defined as *reaction times* of drivers to speed drop (deceleration) and speed increase (acceleration). According to the breakdown probability analysis by (Xu, Hao, Peng, & Sun, 2013) the speed and direction of acceleration wave are determined by the driver characteristics such as, *drivers attention to the situation* and thereby they can drive out of the disturbance as early as they can, given that there is no congestion at the downstream of the bottleneck.

Hence, probability of traffic breakdown on a single lane on-ramp bottleneck according to the probabilistic model developed by (Son et al., 2004) depends on, the *duration* and *speed* of the initial disturbance caused by the merging vehicle, the *free flow speed*, the *reaction time of drivers of the mainline vehicles* to decelerate and then to accelerate (which depend on *stochastic distribution of gap time* before meeting, during and after recovering from the disturbance) and the *average time headway* of the on-ramp vehicles. *All these factors are also mentioned in similar fashion by that of (Han & Ahn, 2018) in their previously discussed breakdown model.*

So far, models by (Han & Ahn, 2018) and (Son et al., 2004) focused on single mainline lane. To get insights into breakdown mechanism from a multi-lane perspective, the study by (Sun, Zhao, & Zhang, 2014) is looked into. (Sun et al., 2014) studied the mechanism of *early-onset breakdown* phenomena at on-ramp bottlenecks based on the detailed traffic data obtained from videos. Studies revealed that the Pre-Queue Flow (PQF) i.e. flow before breakdown observed at two bottlenecks in Shanghai expressway was on average 20% lower than the Queue Discharge Flow (QDF's) at those bottlenecks (Sun et al., 2014). (Sun, Zhang, & Zhang, 2013) refer to the breakdown phenomena where in the lower PQF and higher QDF is observed as *early-onset breakdown.*

From the observational and empirical analysis of early-onset of traffic breakdown mechanism conducted by (Sun et al., 2014) it can be derived that, as *mainline flow rate* and *merge rate* increases, *platoon* formation occurs in mainline due to which lane changes of the merging vehicles increasingly occur at the end of the acceleration lane i.e. downstream end of the bottleneck. Most of these lane changes are of the type mandatory (forced) which act as a *trigger* for breakdown (congestion) firstly in acceleration and shoulder lane at the downstream end of the bottleneck, as shown in Figure 11c. Owing to higher density in shoulder lane, drivers execute *secondary lane changes* at the end of the bottleneck from shoulder/acceleration lane to middle and median lane, causing *lateral* migration of congestion across other lanes (refer Figure 11d and Figure 11e) and then the congestion propogates upstream (refer Figure 11f), and thereby even though expected capacity of the bottleneck isn't reached, due to intense lane changes in the downstream area of the bottleneck, breakdown occurs at lower PQF.

A comparison of this *early-onset breakdown phenomena* as described earlier and as shown in Figure 11, was conducted with that of an on-ramp site in Los Angeles by (Sun et al., 2014). It was analyzed that congestion starts at the acceleration and shoulder lane and spreads laterally and longitudinally, i.e., congestion in the site in Los Angeles is roughly contained in certain lanes unlike in Shanghai case as shown in Figure 11 where congestion spread quickly from right to left. The lane change distribution indicated that unlike lane changes focused at one location (at downstream end of bottleneck) in case of Shanghai, they were evenly distributed in space or time and much smaller percentage of forced or cooperative lane changes leading to less disruption in Los Angeles site than in Shanghai. *These differences revealed that location and type of lane change plays a profound role on the breakdown process.*

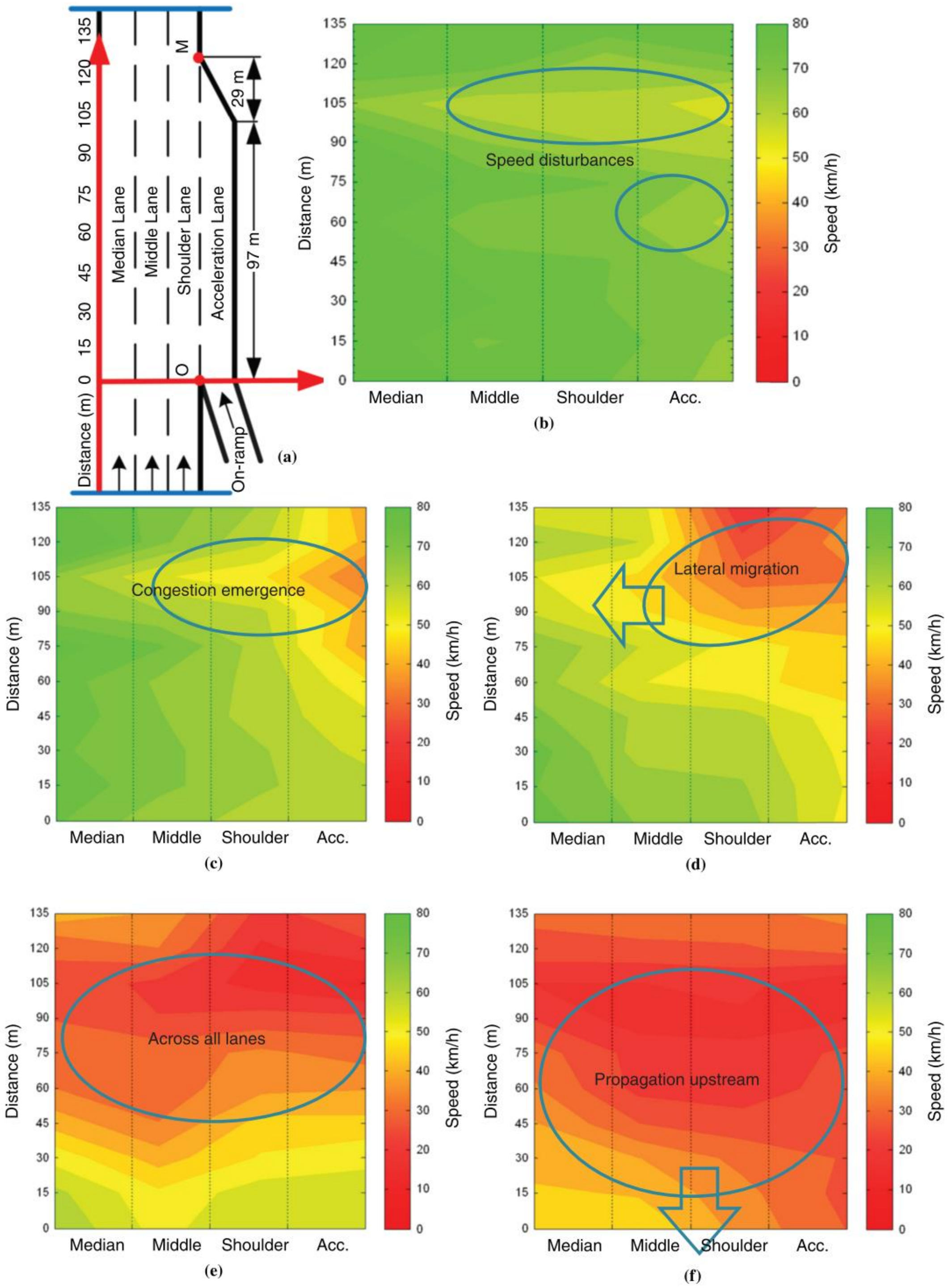


Figure 11: Mechanism of traffic breakdown at an on-ramp site in Hongjing, Shanghai. b) time: 16:54, c) 16:55, d) 16:56, e) 17:01, f) 17:05. Source: (Sun et al., 2014)

Until now, (X. (Michael) Chen et al., 2014; Han & Ahn, 2018; Sun et al., 2014) breakdown models gave a good understanding of the influencing factors of traffic breakdown at merge bottlenecks, where in the *main initial disturbance* was created by *lane changes of merging vehicles*. To gain insights of breakdown *irrespective of the bottleneck type*, investigation of breakdown mechanism by (Shiomi, Yoshii, & Kitamura, 2011) is referred.

(Shiomi et al., 2011) developed a traffic flow model which simulates the dynamic and stochastic traffic flow process at a bottleneck focusing on *single-lane* expressway sections based on (Koshi, 1986) conjecture. The conjecture is "a platoon is formed by *slow vehicles* that form moving bottlenecks. A vehicle with a higher desired speed catches up with a slow vehicle and is forced to follow it. The number of following vehicles behind the moving bottleneck increases, generating a platoon in which traffic density is locally high. Once a vehicle within a platoon decelerates at a bottleneck section for some reason, the deceleration wave propagates upstream, and a traffic flow breakdown is likely to occur" as its recognized that breakdown at freeway bottlenecks is mainly related to platoons (Koshi, 1986; Mahnke, Kaupužs, & Lubashevsky, 2005). It is to be noted that this conjecture is very similar to the *nucleus* for *spontaneous traffic breakdown* according to three phase traffic flow theory as discussed and concluded in Section 2.3.2.

The traffic flow dynamics within the model by (Shiomi et al., 2011) consists of two stochastic processes, *platoon formation model* and *speed transition model* within the platoon. Bottleneck refers to sections such as sag sections or tunnel entrances where in fractional lowering of vehicle speed causes breakdown (Koshi, Iwasaki, & Ohkura, 1983; Shiomi et al., 2011). Within the model its assumed that, traffic flow complexity originates from the *desired speed heterogeneity* of drivers and *platoons form stochastically* due to the heterogeneity and the random arrivals at the target section. Furthermore, probability of breakdown is greater when a platoon passes through a bottleneck.

Based on study by (Koshi, 1986; Oguchi, Katakura, & Shikata, 2001), (Shiomi et al., 2011) conjectured that when a platoon passes through a bottleneck, speed reduction within the platoon occurs stochastically. In case of small platoon, deceleration wave due to speed reduction won't propagate upstream, while in large platoon's, deceleration wave propagates upstream, and breakdown occurs. Hence, from the (Shiomi et al., 2011) model, it can be assumed that *desired speed heterogeneity* among the vehicles which stochastically causes platoon formation and the presence of a *bottleneck*, which induces a stochastic speed drop/transition within the platoon causes traffic breakdown in a probabilistic manner.

In conclusion, from the microscopic analysis of different theories discussed before, the expected microscopic influencing factors for Probability of traffic Breakdown (PB) are:

- For a given mainline flow rate, as the *magnitude and duration of the disturbance (merging vehicles in case of lane drop or on-ramp scenario)* decreases and increases respectively, PB increases. The magnitude and duration can be considered stochastic owing to its dependency on many other factors. In case of lane drop/on-ramp scenarios, along with duration and magnitude of the merging vehicle, *merging position* influences PB.
- *Actual time Headways between mainline vehicles* influences PB. As actual time headways between mainline vehicles decreases, the average headway decreases and thereby mainline flow rate increases. If the actual headways between vehicles are not large enough, then disturbance propagation triggered by the merging vehicle increases and thereby PB increases. It needs to be considered that *deviation* of these actual headways distribution should be less for near capacity flow situations near bottleneck and more for higher than capacity flow scenarios to have lesser PB at bottlenecks.
- Along with the actual headways, the *reaction time* of the mainline vehicles *to* the disturbance decides the *deceleration rate* and thereby the speed of the propagation of the disturbance. As reaction time increases, deceleration rate increases and thereby disturbance propagates upstream at faster pace and thereby increasing PB.
- Similar to the previous point, the *reaction time* of the vehicles *moving out* of the disturbance influences acceleration rate of congestion front. Thereby, lesser reaction times increases acceleration rate contributing in resolving congestion faster.
- At an onramp junction, for a given mainline flow rate, as *actual time headways between merge vehicles decreases,* the average headway decreases and thereby merge flow rate increases. As *actual* time *headways between merge vehicles decreases*, there are more merging vehicles triggering disturbances leading to increase in PB.
- For a given speed of the disturbance, as the *Desired speed of the mainline vehicles* increases, PB increases. Furthermore, as the *desired speed heterogeneity* increases, platoons form stochastically owing to drivers driving at higher desired speed forced to follow drivers driving at lower desired speed. Thereby as these platoons (moving bottlenecks) are susceptible to breakdown once they incur speed changes (at bottlenecks), increase of desired speed heterogeneity increases PB.
- Lastly, *Secondary Lane changes* which are undertaken by drivers from a slower lane (due to disturbance propagation) to a faster adjacent lane, the speed disturbance spreads laterally, thereby increasing PB.

The above mentioned microscopic influencing factors of traffic breakdown even though they are discussed separately they are correlated and thereby influence one another. All the above discussed factors are listed in Table 9 with the relevant references they are derived from. In the next section, these microscopic influencing factors will be related to driving behavior characteristics of AV's (ACC) and CAV's (CACC) as concluded in section 2.1.6 and 2.2.4, to understand how well breakdown mechanism is expected to be influenced by expected driving behavior characteristics of AV's (ACC) and CAV's (CACC).

Table 9: Overview of Expected Microscopic influencing factors of traffic breakdown with the relevant references they are derived from

Expected Microscopic influencing factors (Causes) of Traffic Breakdown	**References**
Actual time headways between mainline vehicles (which influences Mainline flow rate)	(Han & Ahn, 2018) (Sun et al., 2014) (Son et al., 2004) (X. (Michael) Chen et al., 2014) (Xu et al., 2013)
Duration and Magnitude (lower speed) of the disturbance	(Han & Ahn, 2018) (Son et al., 2004) (X. (Michael) Chen et al., 2014) (Xu et al., 2013)
Merging position of the merging vehicle	(Han & Ahn, 2018)
Reaction time of the mainline vehicles to the disturbance (and thereby which influences deceleration rate)	(Han & Ahn, 2018) (Son et al., 2004)(X. (Michael) Chen et al., 2014) (Xu et al., 2013)
Reaction time of the vehicles moving out of the disturbance (and thereby which influences acceleration rate)	(Son et al., 2004) (X. (Michael) Chen et al., 2014) (Xu et al., 2013)
Desired speed on the mainline	(Han & Ahn, 2018) (Son et al., 2004) (Xu et al., 2013)
Actual time headways between on-ramp vehicles (which influences merge flow rate)	(Han & Ahn, 2018) (Sun et al., 2014) (Son et al., 2004)
Secondary Lane changes	(Sun et al., 2014)
Desired speed heterogeneity	(Shiomi et al., 2011)

3.1. Relation between causes of traffic breakdown mechanism and driving behavior characteristics of AV's (ACC) and CAV's (CACC)

In the previous section, different expected microscopic influencing factors from various theoretical perspectives which might influence traffic breakdown mechanism were studied. Relating these factors with the AV's (ACC) and CAV's (CACC) driving behavior helps to know which of them can be influenced by AV's (ACC) and CAV's (CACC) driving behavior, and those which can't be addressed, indicate that the traffic management measure needs to address them, so that the traffic management measure in combination with the AV's (ACC) and CAV's (CACC) driving behavior in mixed traffic, together influence the traffic breakdown mechanism as much as possible. Hence, in this section, the relation will be studied, an overview of which is given in Table 10.

Actual time headways between vehicles on the mainline are stochastic in nature. The larger the headways between mainline vehicles, average headway increases and mainline flow rate decreases. Especially the larger the actual headways (better if they are higher than desired time headway for the desired speed) between the vehicles immediately upstream of the follower of the merging vehicle, the higher the probability of disturbance decay. Because the large headways are enough to absorb the disturbance created by the merging vehicles. Because of the *CACC platoon string stability,* CACC platoon vehicles can be expected to influence actual headways between vehicles and as well decrease probability of disturbance decay. Due to *CACC platoon string stability* as discussed in section 2.2.3, CACC platoon vehicles even though they drive at very small headways they are expected to be capable of dissipating the disturbance as the disturbance travels upstream within the platoon. However, this is only possible at higher penetration rates of CAV's (CACC).

Duration and magnitude (lower speed) of the disturbance, are another two variables which influences traffic breakdown. The higher the duration of the lower speed of the disturbance, higher the PB. Disturbances here refer to that caused due to bottleneck configuration of lane drops, merging, diverging or weaving sections, where lane changing is the source of the disturbance. Driving behavior of AV's and CAV's cannot be expected to address these variables, simply because as pointed out in sections 2.1.6 and 2.2.4 hardly any FOT are conducted to know how lane changing of AV's and CAV's would be different than HDV's. *Hence, the duration and magnitude of disturbance (lane changing) needs to be influenced by traffic management measure.*

In an on-ramp merging scenario (also applies to lane drop and weaving scenarios), the *merging position of the merging vehicle within the accepted headway* acts as a trigger for the breakdown mechanism along with the magnitude and duration of its lower merging speed. If merging position necessitates the immediate follower to decelerate harder than necessary to avoid collision then, the impact of the disturbance is amplified. *Driving behavior of AV's and CAV's cannot be expected to influence the merging position due to lesser knowledge of merging process of AV's and CAV's, indicating a need for a traffic management measure to address it.*

Reaction time of the mainline vehicles (drivers in case of HDV's) *to* the disturbance is another contributing factor for traffic breakdown probability. The mainline actual time headway distribution and the speeds (vehicle speed and speed within the disturbance) influences the reaction time and the reaction time further influences the deceleration rate of the vehicles. In other words, a vehicle which has a larger headway can react earlier to the disturbance and decelerate at a much smoother pace than by a vehicle with a shorter headway. The *reaction time* can be influenced by AV's (ACC) and CAV's (CACC) driving behavior because as concluded in section 2.1.6 that AV's (ACC) react faster than HDV's and in case of CAV's if a CACC platoon exists immediate upstream of the disturbance, then the vehicles in the farther upstream of the platoon can get information of the disturbance and hence can react early and decelerate smoothly lessening the magnitude of the disturbance propagation upstream and thereby reducing PB.

Reaction time of the vehicles while moving *out* of the disturbance influences breakdown, because the faster the vehicles react i.e., accelerate/move out after experiencing the disturbance, the higher the chances of acceleration and deceleration wave meet each other and thereby congestion being resolved. The reaction time also depends on the driver's awareness of the situation. *Presuming that ACC and CACC functionality of AV's and CAV's are enabled* when moving out of congestion, they react faster to the movement of vehicles ahead as they are completely aware of the situation than compared to HDV's. *Hence, AV's (ACC) and CAV's (CACC) can be expected to influence the reaction time and thereby the acceleration wave*.

Desired speed on the mainline influences the traffic breakdown mechanism. Irrespective of the cause of the disturbance, for a given magnitude (lower speed) of the disturbance, the higher the desired speed of vehicles, the higher the PB, as sufficient space (headway) and time is required to undergo the speed transition, if not, then deceleration takes place at a higher magnitude, amplifying the lower speed of the disturbance. Following from 2.1.6, within AV's (ACC), a *desired speed* is expected to be set according to prevalent speed limit during free flow conditions or adjusted according to the preceding vehicle's speed when in car-following mode. Similar behavior can be assumed for CAV's (CACC). Thereby, to influence the desired speed of AV's (ACC) and CAV's (CACC), it's through the *traffic management measure* which sets the Speed limits based on traffic conditions, *after* which AV's (ACC) and CAV's (CACC) follow the speed limits with less variations. Hence, it's the *traffic management measure* which is expected to address the *desired speed on the mainline* to decrease PB.

Actual Headways between on-ramp vehicles influence the breakdown mechanism at on-ramp merge bottlenecks. The shorter the actual headways between on-ramp vehicles, the overall merge flow rate increases, i.e., the number of merging vehicles increases. Thereby the vehicles on the mainline have to decelerate and lower their speed much than in case of one merging vehicle. *The Actual Headways between on-ramp vehicles can't be expected to be influenced by AV's (ACC) and CAV's (CACC) driving behavior and hence can be expected to be addressed by traffic management measure in case of higher merge flow rate*.

Secondary lane changes are carried out by drivers to the adjacent lanes, for instance in case of an on-ramp junction, as the shoulder lane density increases due to the merging vehicle, secondary lane changes might occur from the shoulder lane to the middle and median lane owing to the reason of higher speeds on those lanes. This similar situation also holds good at weaving and lane drop sections. These secondary lane changes contribute to lateral spread of congestion across lane, increasing the PB. These lane changes can't be expected to be addressed by driving behavior of AV's and CAV's because as pointed out in sections 2.1.6 and 2.2.4 hardly any FOT are conducted to know how lane changing of AV's and CAV's would be different than HDV's. *Hence, secondary lane changes can be expected to be addressed by traffic management measure.*

Desired speed heterogeneity influences breakdown in a way that due to heterogeneity, if a desired speed of a vehicle is less than other vehicles, then the other vehicles need to follow the slower vehicle resulting in a platoon (moving bottleneck) with high density and for instance while passing through a bottleneck, the vehicles in the platoon need to slow down, then breakdown might occur. This *heterogeneity* can be expected to be influenced by AV's (ACC), based on the conclusion from the section 2.1.6, that AV's set their desired speed according to the Speed Limit in *free flow state*. Furthermore, AV's (ACC) maintain the set speed with less variations. Hence, it can be expected that at higher penetration rates of AV's (ACC), more *homogeneous* desired speeds and less fluctuations can be observed in free flow, contributing to lesser occurrence of platoons. The same reasoning can also be expected to apply to CAV's (CACC). However, it can be argued that in *car following state in the context of mixed traffic,* if AV's (ACC) and CAV's (CACC) desired speed of driving at speed limit is obstructed by a slower desired speed preceding HDV, then AV's

(ACC) and CAV's (CACC) are also expected to drive slower to follow the slower preceding HDV. In that case, AV's (ACC) and CAV's (CACC) *could be expected to be part of the platoon (moving bottleneck)* thereby not addressing the desired speed heterogeneity factor.

Thus, it can be concluded that *Actual time headways between mainline vehicles (which influences Mainline flow rate)*, *Reaction time of the mainline vehicles to the disturbance* (and thereby which influences *deceleration rate*), *Reaction time* of the mainline vehicles when *moving out of the disturbance* (and thereby which influences *acceleration rate*) and *Desired speed heterogeneity* might be expected to be influenced by the expected AV's (ACC) and CAV's (CACC) driving behavior as highlighted in Table 10. Other influencing factors which are indicated by (-) in Table 10, imply they are expected to be addressed by the traffic management measures.

Table 10: Overview of the relation between the expected microscopic influencing factors (causes) of traffic breakdown and the relevant AV's (ACC) and CAV's (CACC) driving behavior which address the factors.

Expected Microscopic influencing factors (causes) of Traffic Breakdown	**AV's (ACC) and CAV's (CACC) Driving Behavior which address the factors**
Actual time headways between mainline vehicles (which influences Mainline flow rate)	CACC string stability
Duration and Magnitude (lower speed) of the disturbance	-
Merging position of the merging vehicle	-
Reaction time of the mainline vehicles to the disturbance (and thereby which influences deceleration rate)	Faster reaction time
Reaction time of the vehicles when moving out of the disturbance (and thereby which influences acceleration rate)	Faster reaction time
Desired speed on the mainline	-
Actual time headways between on-ramp vehicles (which influences merge flow rate)	-
Secondary Lane changes	-
Desired speed heterogeneity	Homogeneous driving of AV's and CAV's in free flow states (At higher penetration rates)

4. Current traffic management measures

In Chapter 3 various expected microscopic influencing factors (i.e., causes) which might influence traffic breakdown mechanism were studied. Following from Figure 12, the next step is to investigate *current* traffic management measures which are expected to address traffic breakdown and be influenced by AV's (ACC) and CAV's (CACC) driving behavior. First, a brief information on various current traffic management measures which are expected to address traffic breakdown are discussed in section 4.1. Next, in section 4.2, these traffic management measures are related to various microscopic influencing factors (i.e., causes) of traffic breakdown studied in chapter 3, yellow arrow in Figure 12, to get insights into how well these measures can be expected to influence traffic breakdown. In doing so, this helps to answer the RQ2b as framed in section 1.2 which is, *What are the current traffic management measures which address various causes of traffic flow phenomena?* This RQ after deciding upon the traffic flow phenomena i.e., traffic breakdown, is reframed as, *What are the current traffic management measures which address various causes of traffic breakdown phenomena?*

Furthermore, after relating the *causes* to the *measures*, section 4.2 analyzes which of the measures can be positively influenced by AV's (ACC) and CAV's (CACC) driving behavior, orange arrow in Figure 12, which will lead to *hypothesize* which of the current measure will be effective in mixed traffic while addressing traffic breakdown. In doing so, this helps to answer RQ2 as framed in section 1.2 which is, *Which of the current traffic management measures is expected to be influenced by the driving behavior characteristics of AV's (ACC) and CAV's (CACC) driving?*

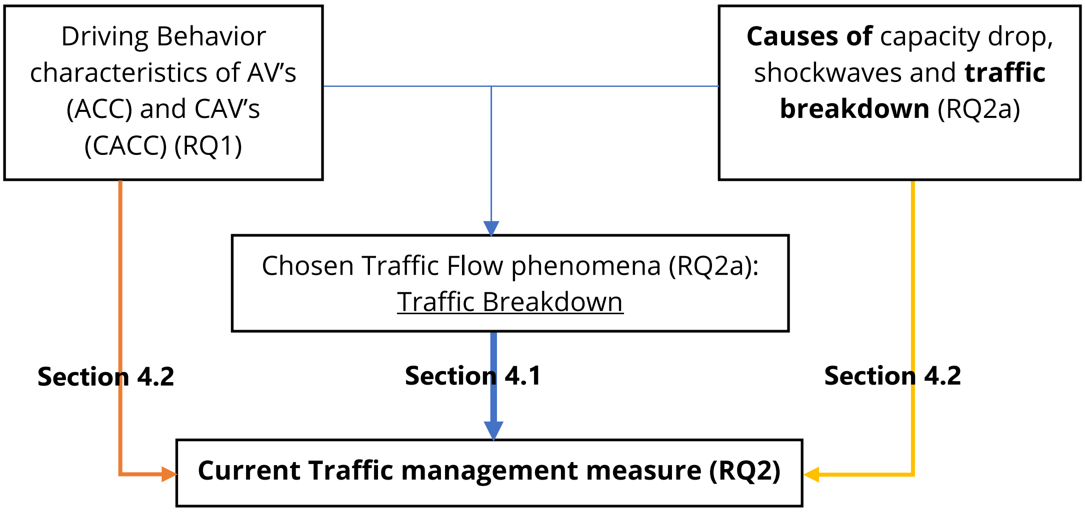


Figure 12: Part of the flow chart of the research methodology

4.1. Traffic management measures

In this section a brief information on the four of the current traffic management measures which are expected to address traffic breakdown will be elaborated.

Variable Speed Limits (VSL)

VSL is a prominent freeway traffic control whose aim is to limit traffic speed in real-time to adapt to various situations such as weather, *congestion*, accidents, etc. through displaying speed limit at the variable message signs (Martínez & Jin, 2020). With regards to traffic operation, VSL control strategies can be divided into two categories. The first category's goal is to attain *homogenization effect* among and within the lanes (Martínez & Jin, 2020; Markos Papageorgiou, Kosmatopoulos, & Papamichail, 2008; Smulders, 1990; Zackor, 1991). Speed limits are imposed around the speed at which capacity is observed (critical speed) and is based on the premise that lower speed limits decrease the heterogeneity in speed, flow and occupancy. The second category's goal is to limit the *demand* to the bottleneck section from exceeding its capacity, also known as *Mainstream Traffic Flow Control (MTFC*). In the absence of the control, demand exceeds bottlenecks capacity and queues arise upstream of the bottleneck, which further fosters capacity drop (Martínez & Jin, 2020).

Ramp Metering (RM)

One of the freeway traffic control methods to address *congestion* at merging regions is Ramp Metering (RM). The intention of RM is to utilize the freeway capacity by regulating the traffic flow from the on-ramp to the mainline freeway, otherwise, there is a possibility that if the on-ramp flow and upstream mainline flow are high, then the total flow exceeds the bottleneck capacity and then congestion occur which ensues capacity drop (Baskar, De Schutter, Hellendoorn, & Papp, 2011). Hence, installation of RM prevents traffic flow breakdown and thereby the subsequent capacity drop.

Integration of RM and VSL (RM+VSL)

At lower on-ramp demand, RM is not required and on the other hand, if its high, then RM needs to be deactivated as the on-ramp queues would spill back (X. Wang & Niu, 2019) because of limited storage space, indicating that RM alone wouldn't be sufficient for freeway control in a lot of cases. On the other hand, with regards to VSL which carries more controllable traffic, over-control may lead to upstream queue propagation which might block off-ramps. Hence, recent research is focused on RM+VSL (X. Wang & Niu, 2019).

Route Guidance and Information Systems (RGIS)

Providing drivers with real-time information supports them in better travel decision making during and before the trip (Ben-Akiva, Bottom, & Ramming, 2001). Based on time and content of the information provided, it may affect, *whether* to travel, *where and how (mode and path)* to travel. Certain systems only give information related to path choice decision, informing the driver that his/her current route is blocked due to an accident (*information*) and recommend (*guidance*) about alternative route with shorter travel times. Thereby, these systems are called as Route Guidance and Information systems (RGIS) (Ben-Akiva et al., 2001).

4.2. Comparison and analysis of measures

In the previous section 4.1, current measures such as VSL, RM, RM+VSL and RGIS which address congestion (traffic breakdown) are introduced. To hypothesize which of them will be effective in mixed traffic, wherein HDV's, AV's (ACC) and CAV's (CACC) coexist, first each measure will be compared based on how well they score on addressing the microscopic influencing factors of traffic breakdown as discussed in chapter 3 and later, how driving behavior characteristics of AV's (ACC) and CAV's (CACC) as highlighted in section 2.1.6 and 2.2.4, foster the effectiveness of each of those measures will be discussed.

Following up from Table 11, **VSL** address three influencing factors of traffic breakdown. *Homogenization* category of VSL as discussed earlier addresses *desired speed heterogeneity*. The category of *MTFC* addresses *actual time headways between mainline vehicles (which further influences mainline flow rate).* Lastly, both categories of VSL have an influence on the *desired speed on the mainline* which is another influencing factor for breakdown.

In current practice, the main issue with regards to effectiveness of VSL in achieving its control objective is *compliance rate* to the posted speed limits which varies and is less in case of HDV's (unless mandated). Thereby, VSL effectiveness is not completely achieved as desired. However, as concluded in section 2.1.6, that in AV's (ACC) the *desired speed* is set according to prevalent speed limit (if any) during free flow conditions and the AV maintains *the set speed with less variation or spread compared to HDV's*. This AV's (ACC) driving behavior can also be assumed to hold good for CAV's (CACC). Thereby, it can be expected that AV's and CAV's comply with the speed limit posted by the Variable Message sign, and further increase the effectiveness of VSL. *Consequently, it can be hypothesized that, VSL's effectiveness of addressing traffic breakdown increases as AV's (ACC) and CAV's (CACC) penetration rate increases in mixed traffic.*

Regarding **RM,** it is straightforward that RM addresses actual time headways between on-ramp vehicles (which further influences merge flow rate) which is one of the influencing factors of traffic breakdown at merge bottlenecks as listed in Table 11.

RM is a proven effective strategy in addressing traffic breakdown and consequent capacity drop at on-ramp bottlenecks because, it hinders platoons of on-ramp vehicles from merging by regulating them at bottleneck capacity situations. However, when looked in microscopically, as discussed in chapter 3, merging vehicle is the main *trigger* for traffic breakdown, which the ramp metering doesn't address. Furthermore, as pointed out in sections 2.1.6 and 2.2.4 hardly any FOT are conducted to know how different merging behavior of AV's and CAV's would be compared to HDV's. Thereby, it's hard to hypothesize that when AV's and CAV's are released from RM signals, how efficiently they would merge thereby fostering the effectiveness of RM. On the other hand, one might argue that the disturbance caused by the merging vehicle, can be better dissipated by the faster reaction times of AV's (ACC) and CAV's (CACC) on the mainline, especially the string stability characteristic of CACC platoons, and thereby the RM would be effective in addressing traffic breakdown. But probability of having AV's or CAV's as immediate follower of merging vehicles or formation of CACC platoons depends *highly* on higher penetration rate of AV's and CAV's. *Consequently, it can't be clearly hypothesized whether driving behavior of AV's (ACC) and CAV's (CACC) increase or decrease the effectiveness of RM in mixed traffic.*

In the context of **RM+VSL,** all the influencing factors addressed by standalone RM and VSL measures discussed before, apply to this integrated measure as shown in Table 11. RM+VSL has been researched a lot and because as introduced earlier how limitations of standalone RM and VSL measures are addressed by integration of these measures, simulations have revealed that integration is effective than standalone measures. *Furthermore, in mixed traffic, it can be hypothesized that the effectiveness of the integration will increase, as discussed* *earlier that* AV's (ACC) and CAV's (CACC) *can be expected to follow the speed limit set by VSL.*

RGIS addresses traffic breakdown more at a macroscopic level by addressing *mainline flow rate or merge flow rate* as shown in Table 11, where in by giving information about the current state of a certain route, the vehicles can be guided to other routes, thereby influencing route flow rates, which otherwise would increase and foster breakdown. In mixed traffic, AV's and CAV's can be expected to comply with the route guidance and information received by them and thereby the effectiveness of RGIS can be hypothesized to increase in mixed traffic. *However, the decision of choosing alternative routes takes place at a more strategic level. This research deals with more operational and tactical driving level decision and congestion is focused more at local bottlenecks using microscopic simulation rather than at network levels assessed by macroscopic simulations. Hence, RGIS won't be considered as a probable measure for further analysis.*

In conclusion, from the comparison of all the measures above, based on how well they score on addressing the influencing factors of traffic breakdown, from Table 11 it is evident that *RM+VSL followed by VSL* address more of the influencing factors of traffic breakdown compared to RGIS and RM. Furthermore, based on how well driving behavior of AV's (ACC) and CAV's (CACC) in mixed traffic foster the effectiveness of these measures, as discussed before, both RM+VSL and VSL effectiveness can be hypothesized to increase with increase in penetration rate of AV's (ACC) and CAV's (CACC) in mixed traffic, as they are expected to follow the speed limit of VSL with less variations. Given the time limit and motive of this research to analyze effectiveness of a traffic management measure, *VSL is chosen over RM+VSL* owing to the reason that the unclarity which might arise whether the integration of RM+VSL is effective in mixed traffic because of VSL or RM or both. Hence, the hypothesis which will be checked through simulation is as follows:
"*VSL's effectiveness of addressing traffic breakdown increases as AV's (ACC) and CAV's (CACC) penetration rate increases in mixed traffic.*"

In addition, from Table 11 it is evident that there are five influencing factors of traffic breakdown which aren't influenced by any the studied measures. They are, *duration and magnitude of the disturbance, merging position of the merging vehicle, Secondary Lane changes, reaction time of the mainline vehicles to the disturbance, reaction time of the vehicles moving out of the disturbance.* Among these five, as highlighted in Table 10, AV's (ACC) and CAV's (CACC) driving behavior address the latter two. Consequently, this indicates that the new traffic management measures should focus on addressing *duration and magnitude of the disturbance, merging position of the merging vehicle and Secondary*

Lane changes to utmost influence breakdown phenomena in mixed traffic in conjunction with the current measures mentioned in Table 11.

Table 11: Various traffic management measures and the expected microscopic influencing factors of traffic breakdown they address.

	Traffic Management Measures			
Expected Microscopic influencing factors of Traffic Breakdown	VSL	RM	RM+VSL	RGIS
Actual time headways between mainline vehicles (which influences Mainline flow rate)	+		+	+
Duration and Magnitude of the disturbance				
Merging position of the merging vehicle				
Reaction time of the mainline vehicles to the disturbance				
Reaction time of the vehicles moving out of the disturbance				
Actual time headways between on-ramp vehicles (which influences merge flow rate)		+	+	+
Secondary Lane changes				
Desired speed on the mainline	+		+	
Desired speed heterogeneity	+		+	

4.3. Variable Speed Limits

Previously it was hypothesized that "*VSL's effectiveness of addressing traffic breakdown increases as AV's (ACC) and CAV's (CACC) penetration rate increases in mixed traffic.*". The next step is to investigate which of the *currently* employed VSL control law addresses traffic breakdown and then choose a suitable one to check the aforementioned hypothesis. When looked into currently used VSL algorithms, most of the algorithms used in real life are *reactive rule-based approaches* and the objectives which they focus on varies between *safety, efficiency, environmental benefits* or *multi-objective focusing on multiple aspects*. As they are reactive algorithms, they lessen the congestion propagation rather than preventing it. Furthermore, most of the algorithms are *rule-based*, where in speed limits are set if the real time speed or flow data collected, falls within certain speed or flow thresholds. The thresholds are selected based on historical data. However, when looked into the completeness of one of these algorithms to be selected as a suitable one, no complete information is available either regarding the *thresholds* being currently used, the *demand* for which the thresholds are tuned for, whether the algorithm objective is to address traffic breakdown. Thereby, Mainstream Traffic Flow Control (MTFC) concept by use of VSL (referred to as MTFC-VSL hereafter) which specifically addresses traffic breakdown is found suitable to check the aforementioned hypothesis.

MTFC Concept

According to (Carlson, Papamichail, & Papageorgiou, 2013; M Papageorgiou & Kotsialos, 2002) congestion (traffic breakdown) at an active bottleneck has two negative effects on freeway throughput and capacity, which are, *capacity drop* at the congestion head and *blocking of off-ramp upstream* due to upstream congestion propagation. To prevent these effects, MTFC is activated when inflow (q_{in}) is higher than bottleneck capacity (q_{cap}^{down}) as shown in Figure 13. MTFC regulates mainstream traffic flow *adequately* upstream of bottlenecks to have enough "acceleration area" for vehicles to accelerate sufficiently before reaching the bottleneck and after driving out from the "controlled congestion" area as shown in Figure 13. This ensures a controlled flow (q_c) which is equal to q_{cap}^{down}. As $q_{in} > q_{cap}^{down}$, congestion is unavoidable, however, the "controlled congestion" by MTFC as shown in Figure 13, has outflow higher than in no MTFC activation case where in capacity drop would prevail. Furthermore, the controlled congestion has higher internal speed and is shorter in space-time lessening the blocking effect of off-ramp as visualized in Figure 13 (Carlson et al., 2013).

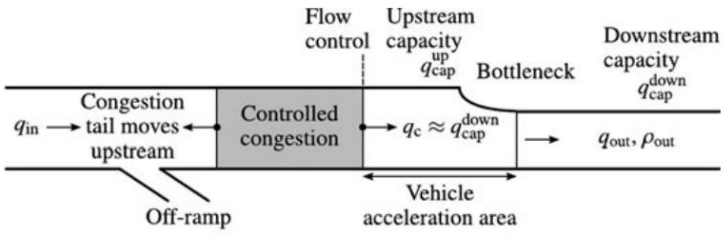


Figure 13: An example of MTFC. Source: (Carlson et al., 2013)

For regulating the mainstream control and to create a "controlled congestion" area as shown in Figure 13, VSL can be used at the *start* and *end* of the "controlled congestion" area as shown in Figure 14. The VSL at the end (VSL sign 2 in Figure 14) won't have any speed limits and will be present to indicate the end of the "controlled congestion" area. The speed limit at the start of the controlled congestion (VSL sign 1 in Figure 14) should be such that the outflow from area should be equal to the bottleneck capacity. To set the speed limit for VSL at the start of the controlled congestion area, *a feedback based MTFC-VSL control derived from (Müller, Carlson, Kraus, Jr, & Papageorgiou, 2015) will be used in this research*. Hence, thereby the hypothesis as described previously will translate to:
"*Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as AV's (ACC) and CAV's (CACC) penetration rate increases in mixed traffic.*"

Figure 14 represents the hypothetical network derived from (Müller et al., 2015) similar to which will be used in this research to apply the Feedback MTFC-VSL. Figure 14 is similar to Figure 13 with "controlled congestion" area renamed as VSL application area which consists of VSL signs at start and end of the area as described before.

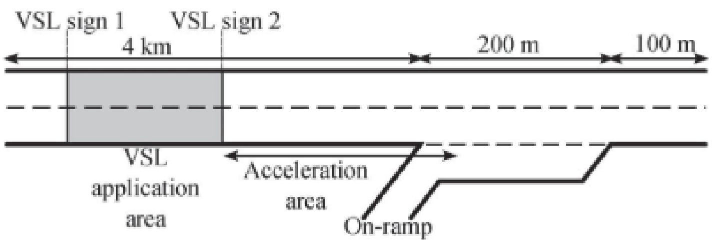


Figure 14: Hypothetical network (not to scale) Source:(Müller et al., 2015)

Feedback MTFC-VSL control by (Müller et al., 2015)***:***
The control problem which the Feedback MTFC-VSL addresses is to *regulate occupancy* (%) of the merge bottleneck, o_{out}, to a reference value, $\hat{o}_{out}$, by controlling the mainstream flow upstream of the bottleneck using VSL. Hence, it a Single-Input-Single-Output (SISO) control problem where, the *VSL rate* is control action and the *occupancy* at the bottleneck is controlled variable. Based on a discrete time linear model, an I-type control structure is developed to

determine the $VSL\ rate\ b$ at time instant k (to be set at the VSL sign 1 as shown in Figure 14) which is formulated as follows:

$$b(k) = b(k-1) + K_I e_o(k)$$

where,

VSL rate = $b = \frac{Current\ Speed\ Limit}{Nominal\ Speed\ Limit}$ where $0 \leq b \leq 1$

K_I= integral gain of the controller

$e_o(k)$ = $\hat{o}_{out}$ - $o_{out}(k)$, which is occupancy control error

$\hat{o}_{out}$ = in this research is set equal to *critical occupancy* of the bottleneck to maximize throughput.

As the previous equation of VSL rate b is a linear control law, for the suitable application of this algorithm, the linearity of the capacity flow for allowable speed limits needs to be checked in Vissim. In other words, whether flow at the bottleneck increases linearly with increase in speed limits at VSL sign 1 based on the above equation needs to be checked, which is carried out in section 6.2.1. If linear relationship is obtained, then *fixed* integral gain, K_I, as indicated in the previous equation will be used. If non-linearity is obtained, then piecewise linear regression needs to be carried out, where in allowable speed limits will be split up in multiple ranges and each range will be assigned a different integral gain K_I (Müller et al., 2015).

To conclude, in this chapter, four current traffic management measures which are expected to address traffic breakdown were discussed. Later, after comparison and analysis of these measures it was hypothesized that, *VSL's effectiveness of addressing traffic breakdown increases as AV's (ACC) and CAV's (CACC) penetration rate increases in mixed traffic* based on the reasoning of how well VSL is expected to address traffic breakdown and how well expected driving behavior characteristics of AV's (ACC) and CAV's (CACC) influence VSL's effectiveness in mixed traffic. Lastly, to check the aforementioned hypothesis in simulation, the concept of feedback MTFC-VSL control was elaborated, based on which the aforementioned hypothesis translates into, *Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as AV's (ACC) and CAV's (CACC) penetration rate increases in mixed traffic.*

5. Vissim simulation set-up

In section 4.3, its hypothesized that, *Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as AV's (ACC) and CAV's (CACC) penetration rate increases in mixed traffic.* Following from Figure 15, the next step is to check the hypothesis through simulation which will be carried out through Vissim, which is a microscopic simulation software designed by the PTV group. To check the hypothesis, two things need to be set-up in Vissim. One relates to the set-up of *Feedback MTFC-VSL control* and the other *relates to the following five topics.* The set-up of *Feedback MTFC-VSL control* in Vissim is elaborated in section 6.2.1, as shown by red arrow in Figure 15.

This chapter addresses the following five topics:

1 *Driving behavior parameters within Vissim*. To have reliable simulation results, the vital aspect is to set appropriate values of driving behavior parameters of AV's (ACC) and CAV's (CACC) and HDV's. So first, the driving behavior parameters within Vissim will be elaborated in section 5.1 and then following from green arrow in Figure 15, insights gained into the driving behavior characteristics of AV's (ACC) and CAV's (CACC) studied earlier in sections 2.1 and 2.2, will be used to a certain extent to set the *values* of the driving behavior parameters for AV's (ACC) and CAV's (CACC) in simulation, which will be used for the further analysis. These *values* together with the values for HDV's will be discussed in section 5.2.

2 Various *scenarios* of mixed traffic for which the hypothesis will be analyzed is discussed in section 5.3

3 Following from yellow arrow in Figure 15, various Key Performance Indicators (KPI's) used to get insights into the effectiveness of Feedback MTFC-VSL control in addressing traffic breakdown is elaborated in section 5.4.

4 Number of simulation runs required to get statistically significant results is discussed in section 5.5

5 and lastly, the hypothetical network characteristics which will be used to test the hypothesis is discussed in section 5.6

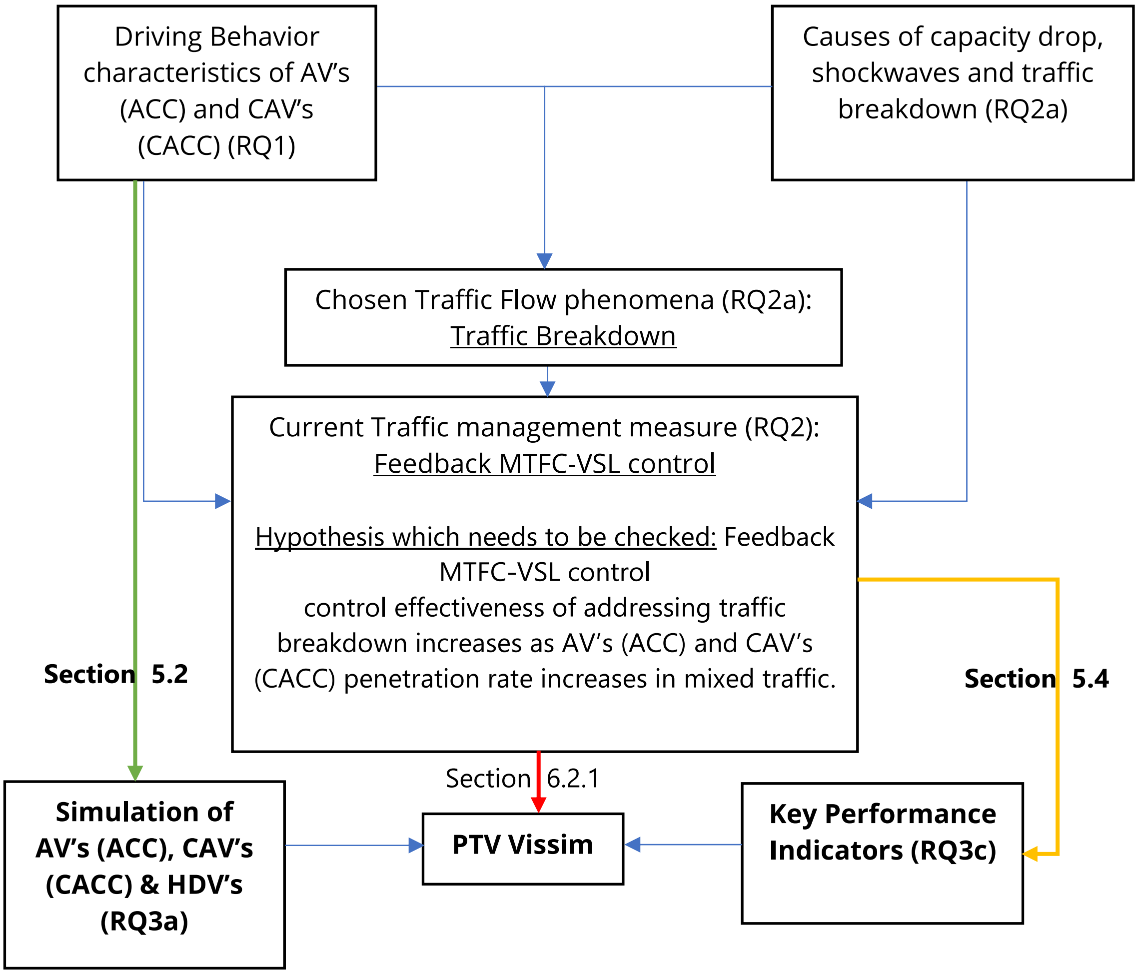


Figure 15: Part of the flow chart of the research methodology

5.1.Driving behavior parameters within Vissim

Within Vissim, two of the important components of the driving behavior of vehicles is the parameters related to *car following* and *lane change and lateral behavior*. First, parameters related to *car following* and *lane change and lateral behavior* will be elaborated in this section in subsequent manner. Next, *functions and distributions* which also play a vital part in driving behavior is described. Lastly, *built-in driving behavior parameters specially for AV's and CAV's* within Vissim will be described.

Car Following driving behavior parameters

The car following model within Vissim is a *psycho-physical model* which is based on drivers *physical* restrictions - imperfect perception of distance (Δx) and speed difference (Δv) with respect to the front vehicle, and *psychological* basis - desired speed and distance to the front vehicle (Zeidler, 2018). There are two car following models within Vissim, Wiedemann 74 (W74) and Wiedemann 99

(W99). W74 was developed by Rainer Wiedemann as part of his doctorate (Zeidler, 2018) and for a better version, W99 was further developed as private research and the source code of it was handed over to PTV group without any theoretical justifications and no scientific publication (Zeidler, 2018).

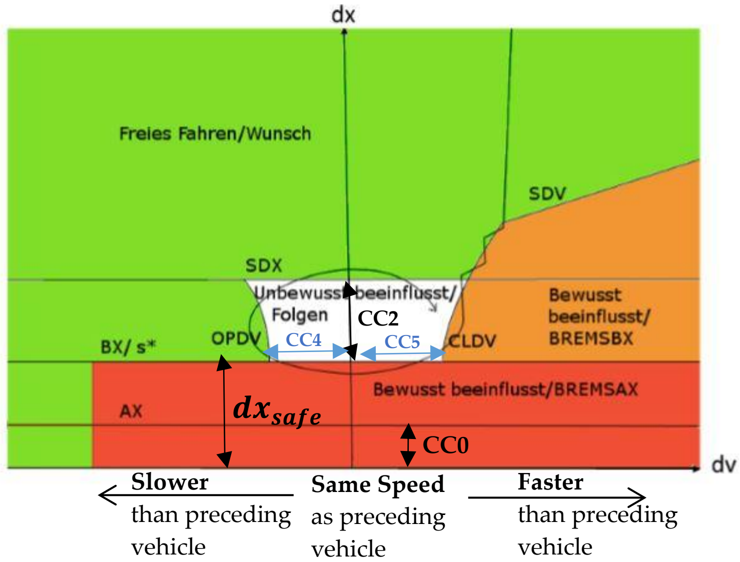


Figure 16: dx-dv diagram of a vehicle depicting various driving states. Source: (Zeidler, 2018)

As this research is focused on motorways, W99 is recommended for its usage by the PTV group. W99 contains 10 car following parameters which are explained as follows. Some general notations to guide for better understanding of the W99 parameters are (Zeidler, 2018):

$dv \text{ or } \Delta v = v_f - v_l$, $dv \text{ or } \Delta v$: speed difference; v_f: speed of the follower; v_l: speed of the leader.
$dx \text{ or } \Delta x$ = distance from front bumper of the follower to the rear bumper of the leader.

CC0, Standstill Distance (unit: meters): Desired standstill distance between two vehicles (PTV AG, 2020). Standstill distance can only be modelled as a fixed value. CCO of a vehicle with respect to its preceding vehicle is shown in Figure 16.

CC1, Desired time gap (unit: seconds): This time gap represents the speed dependent part of the desired safety distance as shown in the below equations 1 and 2 (PTV AG, 2020). This time gap can either be modelled as *fixed* value for all vehicles or if desired time gap data of drivers is available, then can be modelled as a *distribution*. With regards to the usage of distributions, each vehicle at the start of simulation is assigned a *random* safety variable as a *fractile*, which will be used to derive the corresponding desired time gap values from the distribution.

CCO and CC1 together decide the *minimum* desired safety distance of the vehicle, dx_{safe}, which the vehicle maintains. In Figure 16, dx_{safe} of a vehicle to its preceding vehicle is the distance between the front of the vehicle to the back of the preceding vehicle, which is calculated from the following equations (Zeidler, 2018):

$$dx_{safe} = \text{CC0} + \text{CC1} * v_f \text{ for } \Delta v < 0 \quad (1)$$

$$dx_{safe} = \text{CC0} + \text{CC1} * (v_l + \Delta v * (0.5 - R_{est,f})) \text{ for } \Delta v \geq 0 \quad (2)$$

Where,
$R_{est,f}$ = models the driver specific individual estimation accuracy when evaluating the speeds and distances

CC2, Longitudinal oscillation (unit: meters): This defines the *maximum* threshold of the desired safety distance at a speed v. Hence, *the safety following distance of a vehicle varies between* dx_{safe} *and* dx_{safe}+ *CC2*. Unless the vehicle safety distance is within this range, the vehicle doesn't respond to changes of the preceding vehicle and is considered to be in "following" driving state as highlighted by white color region in Figure 16.

CC3, Perception threshold for following (unit: seconds): This parameter defines the time *before* the safety distance range of a vehicle as defined before is reached. The *before* indicates that this parameter has a negative value. CC3 defines the threshold for entering "following" driving state from "free" state. This is shown in Figure 16 by a path which traverses from "free" driving state highlighted in green color and ends in "following" state. The larger the value, the earlier the vehicle recognizes the preceding vehicle (slower) and reacts to it (decelerate). CC3 is part of calculation of *sdv* in Figure 16 as (Zeidler, 2018):

$$sdv = -\frac{\Delta x - sdx}{\text{CC3}} - CC4$$

Where,
sdx = dx_{safe}+ CC2

CC4 and CC5, Negative and positive speed difference (unit: meters/second): These define the negative and positive speed difference of a vehicle with respect to the preceding vehicle, within which the vehicle assumes that it is in "following" driver state and doesn't *perceive* the speed differences. Once, the speed difference exceeds the mentioned values in CC4 and CC5, then driver perceives the speed difference and thereby will accelerate or decelerate. Lower

CC4 and CC5 values indicate that the vehicle is more sensitive to changes in speed of the preceding vehicle. CC4 and CC5 are visualized in Figure 16.

CC6, Influence of distance on speed oscillation, (unit: 1/[meters*second]): As distance to vehicle ahead increases, it's hard to *perceive* the speed of the leader. CC6 accounts for this, by defining the rate at which CC4 and CC5 change with the change in the safety distance. Referring to Figure 16, CC6 accounts for the curves OPDV and CLDV. As the value of CC6 increases, these curve more outwards increasing the "following" driving state area (white color region). A value of zero indicates speed oscillation is independent of distance.

OPDV and CLDV in Figure 16 are thereby determined using the formula (Zeidler, 2018):

$$CLDV = \frac{CC6}{17000} * (\Delta x)^2 - CC4$$

$$OPDV = \begin{cases} -\frac{CC6}{17000} * (\Delta x)^2 - CC5 & for\ v_f > CC5 \\ -\frac{CC6}{17000} * (\Delta x)^2 & for\ v_f \leq CC5 \end{cases}$$

CC7, Oscillation acceleration (unit: Meter/[second]^2): This indicates the absolute acceleration/deceleration value used by a driver when in "following" driving state, i.e., white color region in Figure 16.

CC8, Acceleration starting from standstill, (unit: Meter/[second]^2): Desired acceleration of a vehicle starting from standstill, bounded by the maximum acceleration defined by *Maximum Acceleration* function.

CC9, Acceleration at 80 kilometer/hour (km/hr), (unit: Meter/[second]^2): Desired acceleration at 80km/h, bounded by the maximum acceleration defined by *Maximum Acceleration* function. For accelerations between 0 (CC8) and 80 km/hr (CC9), interpolation is used and for speeds above 80 km/hr, the acceleration value of CC9 applies and is constant (Zeidler, 2018).

Alongside W99 parameters discussed before, there are *four* input parameters which help to simulate the *perception of surrounding vehicles and infrastructure* (Aria, 2016). Those are, *look ahead distance (*minimum and maximum), *Look back distance (*minimum and maximum), *Number of interaction objects and Number of interaction vehicles. Minimum and Maximum look ahead and look back distance* refers to the distance downstream and upstream that a vehicle can see in order to react to vehicles and network objects (red signal heads, reduced speed areas) (PTV AG, 2020). *Number of interaction objects and interaction vehicles* refers to the preceding vehicles or objects downstream or adjacent to the vehicle on the link, the vehicle interacts with taking into consideration of the look ahead distance specified (PTV AG, 2020).

Furthermore, in Vissim, after defining the aforementioned car following behavior parameters for a certain vehicle type, for instance a CAV, certain parameters of this vehicle car following behavior can be changed based on the *preceding vehicle type* the CAV is following. The parameters which can be changed are *CC0, CC1 and increased acceleration,* rest other parameters will remain the same (PTV AG, 2020). *Increased Acceleration* refers to the increased acceleration of a following vehicle by a certain percentage with which it follows an accelerating preceding vehicle. The values range from 100% to 999% (PTV AG, 2020). The default value is 100%. Any value greater than 100%, the follower doesn't fall back when the leader accelerates. This parameter influences Desired acceleration function, CC8, CC9 and jerk limitation.

Lane change and lateral driving behavior parameters

One of the two *rules* that can be used in Vissim for lane change are, *Free lane selection,* where lane changes are executed on each lane, and another is *Slow lane and Fast lane rule,* where in lane changes are executed according to the German Traffic Code (StVO) (PTV AG, 2020). After selecting the lane change rule, there are two possibilities of executing a lane change, which are, *Necessary lane change and Free lane change.*

Necessary lane change is carried out to reach the next connector of a route (PTV AG, 2020). The parameters of interest which needs to be set within Vissim for necessary lane change are *maximum and accepted deceleration of own vehicle and trailing vehicle on the target lane* which depict the upper and lower bound of deceleration for a necessary lane change to occur. To account for linear transition from *accepted* deceleration to *maximum* deceleration, a *change of -1* m/s^2 *per* <u>*meters*</u> *needs* to be specified (PTV AG, 2020). Furthermore, there is an option named *Advanced Merging,* which if opted for, then more earlier lane changes are executed, and lesser vehicles come to a stop to wait for a gap.

Free lane change on the other hand is carried out if there is more space on the new lane or if the driver wants to drive at desired speed (PTV AG, 2020). The parameter of concern during free lane change is the *maximum deceleration of the trailing vehicle,* which acts as a limit for the desired deceleration of the trailing vehicle used during Co-operative braking (PTV AG, 2020).

Before executing both the lane changes, the safety distances of the trailing vehicle on the target lane and of the lane changing vehicle will be checked with a certain percent reduction, defined by *safety distance reduction factor* i.e. *original safety distance * safety distance reduction factor,* needs to be satisfied (PTV AG, 2020). After the lane change, original safety distance comes into picture. The *safety distance reduction factor* is one of the main parameters which can be used to set higher or lower gap acceptance as desired. For instance, setting a factor of 0.75 indicates that the trailing and lane changing vehicle are willing to accept execution of lane changes with their respective safety distances reduced by 75% (presuming the deceleration is within the maximum specified limits). Hence, a factor of 0.75 calls for more execution of lane changes compared to 0.5. Lastly, within Vissim, there is an option to switch on *Cooperative lane change*, where in a trailing vehicle on a target lane recognizes a lane changing vehicle and changes its lane to make room for the lane changing vehicle (PTV AG, 2020).

Functions and Distributions

Functions as curves are defined in Vissim to account for the heterogeneity of acceleration and deceleration behavior of drivers and vehicle properties, rather than using individual acceleration and deceleration data (PTV AG, 2020). The acceleration and deceleration of a vehicle are functions of current speed of the vehicle (PTV AG, 2020). The four relevant functions useful in this research are, *Maximum acceleration and deceleration function* and *Desired acceleration and deceleration function.*

Maximum acceleration/deceleration function depicts the maximum acceleration/deceleration technically possible. Especially at inclines and downgrades, where higher acceleration/deceleration is required, this function is automatically adjusted (PTV AG, 2020). *Desired acceleration/deceleration* cannot exceed the *maximum acceleration/deceleration* values (PTV AG, 2020). These functions consist of a maximum, median and minimum value for a certain speed as shown in Figure 17, which depicts an example of desired acceleration function. The red dots denote the median and the green dots represent the minimum and maximum thresholds. Regarding the usage of the function, apart from heavy goods vehicle, every vehicle is assigned a random fractile value and if the random value is less than 0.5, then linear interpolation between minimum and median value occurs and for greater than 0.5 the same reasoning holds (PTV AG, 2020). For random value equal to 0.5, median value of the function at the given speed is selected. The x- axis in Figure 17 describes the maximum desired speed range.

It is to be noted that in Vissim, the change in acceleration and deceleration per time step is limited by *jerk limitation*. Jerk limitation is derivative of acceleration, and its value is twice the time step (considering more than two-time steps per second) (PTV AG, 2020). For instance, if simulation time step is 0.1s (ten-time steps per second), then due to jerk limitation, 20% of the intended change in acceleration occurs (PTV AG, 2020).

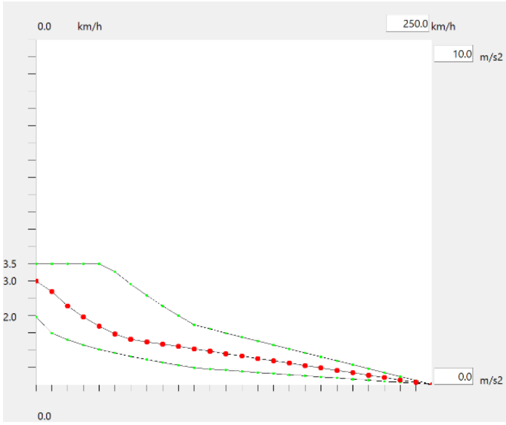


Figure 17: An example of desired acceleration function

Distributions are used in Vissim to model any type stochastic distributions (PTV AG, 2020). Two of the important distributions relevant for this research are the *desired speed distribution and time distribution*. *Desired speed distribution* is a cumulative probability distribution where in a minimum and maximum value of desired speed are specified along with mentioning the curvature of the distribution. Figure 18 shows an example of desired speed distribution. If vehicles aren't hindered by other vehicles or traffic signals, they drive at their desired speed (PTV AG, 2020). Like the usage of function described earlier, every vehicle will be assigned a fractile value between 0 and 1 which remains unchanged during the entire simulation time and based on the fractile value, the desired speed will be assigned (PTV AG, 2020). Thereby, this distribution helps to bring in the desired speed heterogeneity within vehicles.

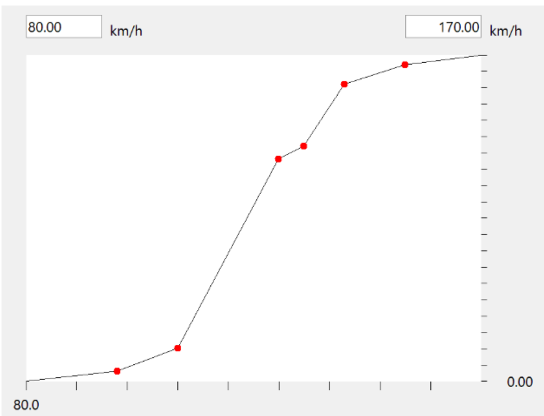


Figure 18: An example of desired speed distribution

Within *time distribution* it's possible to define either a normal or an empirical distribution. Defining empirical distribution is same as desired speed distribution i.e., cumulative probability. However, for normal distribution, a mean and standard deviation needs to be defined. Empirical time distribution in this research is utilized to define the various probabilities of time gaps i.e., as described in CC1, with which vehicles drive. Finally, like usage of desired speed distribution, every vehicle's fractile value is used to assign a desired time gap to a vehicle from the distribution.

Built-in driving behavior parameters for AV's and CAV's

Implicit stochastics: In Vissim, there are implicit stochastic components which bring the heterogeneity of the human driving perception and behavior in simulation, by assigning a random fractile value between 0 and 1 for each driver and for all those components (PTV AG, 2020). In case of AV's and CAV's, this heterogeneity is lessened as the human driver is replaced by a system. To account for this, there is an option in Vissim known as Implicit Stochastics, which, if not opted for, then all the drivers for all the relevant stochastic components are assigned a *fractile value of 0.5,* causing homogeneity (PTV AG, 2020). For instance, following from desired acceleration function as shown in Figure 17, if implicit stochastics is turned off, the maximum and minimum thresholds (green dots) become irrelevant and only the *median* values (red dots) which are assigned for fractile value of 0.5 become relevant. Thereby, all the vehicles desired acceleration for a particular speed will be the same rather than having different values for the same speed.

Lastly, there is a *platooning possibility* option, which if enabled then, vehicles drive in platoons (PTV AG, 2020).

5.2. Values of driving behavior parameters for HDV's and CAV's.

In the previous section 5.1, relevant driving behavior parameters within Vissim were discussed. In this section the values of those parameters will be set for different vehicle types. This section answers RQ3a, *What are the characteristics of mixed traffic?*

In this research, two vehicle types and their driving behavior will be simulated. One relates to HDV and the other to CAV. It is to be noted that in mixed traffic, where CAV's and HDV's co-exist, the car following behavior of these vehicles will depend on the *preceding vehicle type*, as listed in Table 12. If a CAV follows another CAV, then the CACC car following behavior holds for the following vehicle. On the other hand, if it follows an HDV, then ACC car following behavior holds for the following vehicle. *It's assumed that following behavior of HDV is the same irrespective of the preceding vehicle type*. Hence, this indicates that parameters relevant to car following behavior (especially W99) needs to be set for HDV's, ACC and CACC systems. On the other hand, parameters relevant to lateral and lane change, function & distributions and built-in driving behavior parameters will be set based on vehicle types i.e., CAV's and HDV's.

Table 12: Various car following behaviors of the following vehicle based on the preceding vehicle

Following vehicle	Preceding vehicle	Car following behavior of the Following vehicle
CAV	HDV	ACC
CAV	CAV	CACC
HDV	CAV	HDV
HDV	HDV	HDV

5.2.1. Car Following driving behavior parameters values

In this research its assumed that car following behavior of all the vehicles is executed by W99 car following model, with reasonable changes in the parameter's values of W99 to differentiate between the three car following behavior of the following vehicle i.e. ACC, CACC and HDV. Thereby, first, W99 car following parameter values relevant to HDV, CACC and ACC will be discussed followed by other relevant car following parameters as discussed in section 5.1.

W99 parameter values for HDV's

For *HDV's* the W99 car following parameters are obtained from (Durrani, Lee, & Maoh, 2016), where in vehicle trajectory data on a 640m segment of US-101 freeway in Los Angeles, California was used to calibrate and validate the W99 parameters for a *passenger car following another passenger car*. The studied segment consists of five lanes on the mainline and an auxiliary lane between an on-ramp and an off-ramp. However, only the mainline trajectories were used for calibration and validation.

The calibrated and validated car following parameters values suggested by (Durrani et al., 2016) is chosen, because these values refer to passenger car following another passenger car, unlike many other calibrated and validated studies which suggest values for passenger car irrespective of leading vehicle type. Considering that this research focusses on passenger cars, *it's reasonable to consider values from the study of (Durrani et al., 2016) as values for HDV's.* For further information on how the different values of W99 car following model were obtained from the trajectory data and the assumptions there in, the reader is referred to (Durrani et al., 2016). Table 13 lists the calibrated and validated mean values for W99 parameters for HDV's obtained from (Durrani et al., 2016) along with the default values available within Vissim.

<u>W99 parameter values for CACC and ACC</u>

<u>CC0:</u> Referring to the driving behavior study of AV's and CAV's conducted in section 2.1 and 2.2 respectively, standstill distance hasn't been studied. To obtain values for standstill distance, the empirical data analysis of Co-exist project is referred to. Empirical analysis of standstill distance between CAV's enabled with CACC indicated to be on average *4m* and the distance between a CAV and a HDV which is same as between an AV enabled with ACC and a HDV was derived to be around *6m* (Zeidler, 2018). Hence, given that these values are suggested considering PTV Vissim as micro-simulation software, *it seems reasonable to use 4m and 6m as CC0 values for CACC and ACC respectively in this research.*

<u>CC1:</u> Following from the conclusion of expected driving behavior characteristics of AV's enabled with ACC in section 2.1.6, time gap range of 1.0 to 2.0 s was considered as desired time gaps by drivers of the ACC systems, indicating that there isn't one time gap which is preferred by all the drivers. To account for the range of 1.0-2.0s, desired time gaps will be modelled as a *time distribution* as discussed in section 5.1. Within the time distribution, probabilities need to be specified to assign certain percentage of drivers to certain desired time gaps within the specified range. To obtain the probabilities and the exact desired time gap values, "Driver Me" project mentioned in section 2.1.2 is referred, where in the probability from the field test revealed around 0.45 for 2s, 0.2 for 1.5s, 0.3 for 1s and remaining split between 2.5s and 3s for AV's enabled with ACC. *Hence, in this research, CAV's with ACC car following behavior have desired time gaps of 1.0, 1.5 and 2.0 s. The probabilities with which these time gaps are allocated to vehicles, is described in the next paragraph.*

For CACC systems, following from the conclusion of expected driving behavior characteristics of CAV's enabled with CACC in section 2.2.4, drivers accept time gaps less than 1.0s. However, there is no one value which the drivers within the experiments choose. Similar to the ACC systems, *time distributions* will be used to model desired time gaps for CACC systems. Within the time distribution, probabilities need to be specified to assign certain percentage of drivers to certain desired time gaps within the specified range. The empirical study of prototype CACC systems by (Nowakowski et al., 2010) as mentioned in section 2.2.1 is referred to obtain probabilities and exact desired time gaps values required to model *time distributions.* Based on this study and the authors reasoning, *in this research, 53.33% of CAV's enabled with CACC car following behavior drive with desired time gaps of 0.6s, 33.33% and 13.34% drive with desired time gaps of 0.7 and 0.9s respectively. Similarly, in this research, 53.33% of CAV's with ACC car following behavior drive with desired time gaps of 1.0s, 33.33% and 13.34% drive with desired time gaps of 1.5 and 2.0s respectively.* In other words, for any given penetration rate of CAV's in mixed traffic, for instance 50%, then 26.66% CAV's (53.33% of 50%) drive with CC1 value of 0.6s if it's following another CAV or drive with 1.0s if its following HDV. 16.66% (33.33% of 50%) of CAV's drive with CC1 value of 0.7s if it is following another CAV or drive with 1.5s if its following HDV. Lastly, remaining 6.68% of CAV's drive with CC1 value of 0.9s if it's following another CAV or drive with 2.0s if its following HDV.

CC2: For ACC systems, following from the section 2.1.6, it is concluded that with regards to *deviation* of set time gap in an ACC system*, it is very less and thereby can be presumed that ACC maintains set time gap with less oscillations in simulations.* Thereby, it's reasonable to presume that an ACC system will maintain the exact distance (time gap). *Hence, for ACC systems, CC2 is set zero, thereby no longitudinal oscillation*. For CACC systems, following from the section 2.2.4, the standard deviation of set time gap is less than that of ACC, *hence in this research even for CACC systems, CC2 is set to zero*. This presumption with regards to CACC can also be confirmed with the data analysis within the Co-exist study where in within different test scenarios consisting of different time gaps, the distance between vehicles was *slightly* above the desired distance (Zeidler, 2018). To conclude, in simulation within this research, CAV's (with ACC and CACC systems) are expected to drive perfectly at the set time gap without any longitudinal oscillation.

CC3: As explained in section 5.1, this parameter defines the transition from the "free" state to "following" state. This hasn't been studied in section 2.1 and 2.2, as the various FOT studied in those sections, analyzed *reaction time* when the vehicles are already in "following" state and define their reaction time when the leader changed speed. Thereby, to set the value for this parameter, the *simulation analysis* by Co-exist project is referred, which was carried out to set the parameters values based on empirical data. The analysis concluded that below -40s, no behavioral change was identified with regards to better adaptation to the desired distance (Zeidler, 2018). *Hence, in this research, for both CACC and ACC systems enabled vehicles i.e., CAV's, -40s will be used as a parameter value for CC3.*

CC4 and CC5: CC4 and CC5 relate to the speed differences between follower and preceding vehicle i.e., *dv*, which isn't perceived by the follower and thereby doesn't react to the speed changes of the preceding vehicle. This speed oscillation induced by CC4 and CC5, wasn't observed in the empirical data analysis within the Co-exist project and thereby both CC4 and CC5 were set to the value of zero for both ACC and CACC systems. *Hence, in this research too, CC4 and CC5 will be set to zero for ACC and CACC car following behavior, this indicates perfect perception of any speed change of the preceding vehicle by the follower after the time step.*

CC6: CC6 parameter value has an effect when CC2, CC4 and CC5 have certain value. However, as CC2, CC4 and CC5 are set to zero for both AV's and CAV's, CC6 doesn't have an effect. *Hence, in this research, CC6 is set to zero for both ACC and CACC system enabled vehicles.*

CC7 represents acceleration during 'following' state, ***CC8 and CC9*** represent acceleration at standstill and at 80km/hr respectively. It is to be noted that CC8 and CC9 just represent another upper bound to vehicle acceleration in addition to the accelerations defined in *desired and maximum acceleration functions*. *For vehicles enabled with ACC and CACC systems all these three parameter values are assumed to be same as HDV's*, because the author couldn't find specific empirical acceleration values for different speeds for ACC and CACC systems. Even though CC8 and CC9 for ACC and CACC systems are assumed same as the HDV's, CACC systems differ in their acceleration behavior due to the change *in increased acceleration which is elaborated in further sections*. Table 13 summarizes the W99 car following parameters which will be used in this research for simulating HDV's, ACC and CACC systems in comparison with the default values given in Vissim.

In addition to the above-mentioned changes in the W99 parameters for ACC and CACC systems, *Increased Acceleration* as defined in section 5.1, needs to be altered as well. In vissim, with default value of 100% increased acceleration, the following vehicle falls back in distance when the preceding vehicle accelerates, and the following vehicle approaches the preceding only when the preceding vehicle stops accelerating (PTV AG, 2020). However, this increase in distance between following and preceding vehicle wasn't observed for CACC systems within the Co-Exist project. Thereby with the use of >100% increased acceleration, the follower makes up for the distance increment and this sort of helps to mimic simultaneous accelerations in case of CACC. Hence, in this research *110% value* of increased acceleration will be used for CACC systems *only when* a CAV with CC1 value of 0.6, 0.7 and 0.9 i.e., any CAV follows another preceding CAV which is driving with CC1 of 0.6 s (or 1s if the preceding CAV follows HDV).

However, when CAV follows a HDV, i.e. for ACC systems, within the Co-Exist project it was observed that while accelerating, the desired distance wasn't maintained by follower, thereby, the default value of *100%* will be used for ACC systems. For HDV's, the default value of 100% will be used. Table 14 summarizes the increased acceleration values for HDV, CACC and ACC systems.

Table 13: W99 Default values in Vissim and values for HDV's, ACC and CACC systems

W99 car following parameters	**Default values**	**Values for HDV's** (Durrani et al., 2016)	**Values for ACC systems (CAV's follow HDV's)**	**Values for CACC systems (CAV's follow CAV's)**
CC0 (m)	1.50	4.0	6.0	4.0
CC1 (s)	0.9	1.5	[1.0, 1.5, 2.0]	[0.6, 0.7. 0.9]
CC2 (m)	4.00	11.6	0	0
CC3 (s)	-8.00	-4.00	-40	-40
CC4 (m/s)	-0.35	-1.65	0	0
CC5 (m/s)	0.35	1.65	0	0
CC6 (1/(m*s))	11.44	11.44	0	0
CC7 (m/s^2)	0.25	0.090	0.090	0.090
CC8 (m/s^2)	3.5	0.5	0.5	0.5
CC9 (m/s^2)	1.5	0.45	0.45	0.45

Table 14: Increased acceleration values for HDV's, ACC and CACC systems.

	Default value	**Value for HDV's**	**Values for certain CACC systems (CAV's follow CAV's)**	**Values for ACC systems (CAV's follow HDV's)**
Increased Acceleration	100%	100%	110%	100%

Along with W99 car following parameters, as discussed in section 5.1, there are *four* input parameters which help to simulate the *perception of surrounding vehicles and infrastructure* (Aria, 2016). Those are, *look ahead distance (*minimum and maximum), *Look back distance (*minimum and maximum), *Number of interaction objects and Number of interaction vehicles.* As these parameters relate to vehicle types, these parameters need to be set for HDV's and CAV's.

In mixed traffic, the CAV's constantly use their inbuilt sensors to sense the surrounding traffic. Connectivity comes into its effect when there is another source of connectivity available. Hence, to determine the *maximum look ahead and look back distance* for CAV's, the measurement range of LiDAR and millimeter-wave radar (MWR) is referred to, which spans up to 200m (Yoneda, Suganuma, Yanase, & Aldibaja, 2019). *Thereby, for CAV's the maximum look ahead and back distance is set as 200m. The minimum look ahead and look back distance for CAV's is set as zero.* In Vissim, for example, specifying number of interaction vehicles as two for a CAV, the CAV will respond to the behavior of preceding two vehicles, *irrespective of the vehicle type.* In other words, a CAV will get information of the preceding vehicles (except its immediate one) even though they are HDV, which are void of communication features. Considering this reasoning, *Number of interaction vehicles for CAV's is set as 1.* Thereby, in this research connectivity is presumed to exist between CAV's only when CAV's follow each other. *The number of interaction objects for CAV's is set as two,* to react to any traffic signals or infrastructure in front of the leading vehicle.

For HDV's, the default values are used for look ahead and look back distance. The number of interaction vehicles and interaction objects are set same as CAV's. Table 15 gives an overview of the car following parameters apart from W99 for CAV's and HDV's.

Table 15: Car Following parameter values for CAV's and HDV's

Car Following parameters (units)		**Default values**	**Values for HDV's**	**Values for CAV's**
Look ahead distance (m)	Maximum	250	250	200
	Minimum	0	0	0
Number of interaction vehicles		99	1	1
Number of interaction objects		2	2	2
Look back distance (m)	Maximum	150	150	200
	Minimum	0	0	0

5.2.2. Lane change and lateral parameter values

Lane change rule of *Slow lane and fast lane* will be used within this research owing to the reason that the calibrated and validated W99 parameters for HDV's were obtained from California, where in "keep right" unless overtaking or passing another vehicle in the same direction applies (Matthiesen, Wickert, & Lehrer, 2020).

Necessary lane change and Free lane change

In this research, both CAV's and HDV's execute the lane change with the same set of rules and parameter values. The parameters and their respective values relevant for necessary lane change are given in Table 16 and the values for other lane change parameters in general are given in Table 17. The values in both the tables represent the default values given in Vissim. *These default values will be used for HDV's in this research*. In addition, *for CAV's these default values will be* *used as well,* as highlighted in section 2.2.4 that not much empirical information is available how CAV's would perform a lane change. The Advanced merging option is switched *on* for both HDV and CAV, as this option holds good for necessary lane change, and it's assumed that both HDV and CAV know their route in advance and hence can merge earlier. Cooperative lane change option holds good for CAV's if a CAV communicates its intent to change lanes to another CAV (trailing vehicle) on the target lane. However, in Vissim this is not the case i.e., Cooperative lane change works irrespective of the trailing vehicle type where in a HDV gets the information that a CAV is intending to change lanes, which doesn't make sense as communication doesn't prevail in HDV. Hence, considering this reasoning, the *Cooperative lane change is switched off* for CAV's. *For HDV*, it is switched *off* by default.

Table 16: Parameter values for necessary lane change applicable to both CAV's and HDV's.

Parameter	Own vehicle	Trailing vehicle
Maximum deceleration (m/s^2)	-4.00	-3.00
-1 m/s^2 per distance(m)	100	100
Accepted deceleration (m/s^2)	-1.00	-1.00

Table 17: Other lane change parameter values applicable to both CAV's and HDV's

Parameter	Values/option
Safety distance reduction factor	0.6
Minimum headway (front/rear) (m)	0.5
Maximum deceleration for cooperative braking (m/s^2)	-3.00
Advanced Merging (option)	on
Cooperative lane change (option)	off

5.2.3. Functions and Distributions

The *default* functions of maximum acceleration, maximum deceleration, desired acceleration and desired deceleration within Vissim will be used both for CAV's and HDV's. Time distributions for ACC and CACC systems as defined by CC1 parameter values as discussed before in section 5.2.1 will be modelled.

The usage of desired speed distributions is used during the set-up of feedback MTFC-VSL control.

5.2.4. Built-in driving behavior parameters for AV's and CAV's

In this research, its assumed that for CAV's the *implicit stochastics* is turned off to mimic the homogeneous driving behavior of CAV's and it's turned on for HDV's to account for heterogeneity. Regarding *platooning possibility* option, it is switched off for HDV's and CAV's.

5.2.5. Conclusion and limitations

To conclude, in this research mixed traffic comprises of two vehicle types, CAV's and HDV's. With regards to *car following behavior* of CAV's and HDV's, both use the **same** W99 car following model with the reasonable changes in the parameters values to differentiate between HDV's and CAV's. CAV's use the W99 parameter values of ACC systems as listed in Table 13, if CAV's follow a HDV's, where as if CAV's follow CAV's, the follower CAV's use W99 parameter as shown in Table 13 pertaining to CACC systems.
Furthermore, if CAV's follow a preceding CAV's which is driving with CC1 value either of 0.6s or 1.0 s, then the follower CAV's accelerates with 10% higher acceleration to mimic simultaneous acceleration observed in CACC systems.
Lastly, *implicit stochastic* option in Vissim is switched off for CAV's which brings in homogeneity especially with regards to desired acceleration and deceleration compared to heterogeneity in HDV's with the stochastics component switched on.
Regarding lane change behavior, both HDV's and CAV's execute lane change with the same set of rules and parameter values.

Consequently, this indicates that in this research, CAV's in simulation majorly differ from HDV's in car following behavior as they change lanes using the same parameters and rules as that of HDV's. Hereafter, CAV's (with ACC and CACC functionality) indicate that CAV's only differ in car following behavior with that of HDV's and have the same rules and parameters values for lane change as that of HDV's.

Thereby, the hypothesis framed in section 4.3 as *Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as AV's (ACC) and CAV's (CACC) penetration rate increases in mixed traffic* will be reframed and further checked as
Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic.

Figure 19 shows the updated content in the part of the flow chart of research methodology based on the conclusion discussed before.

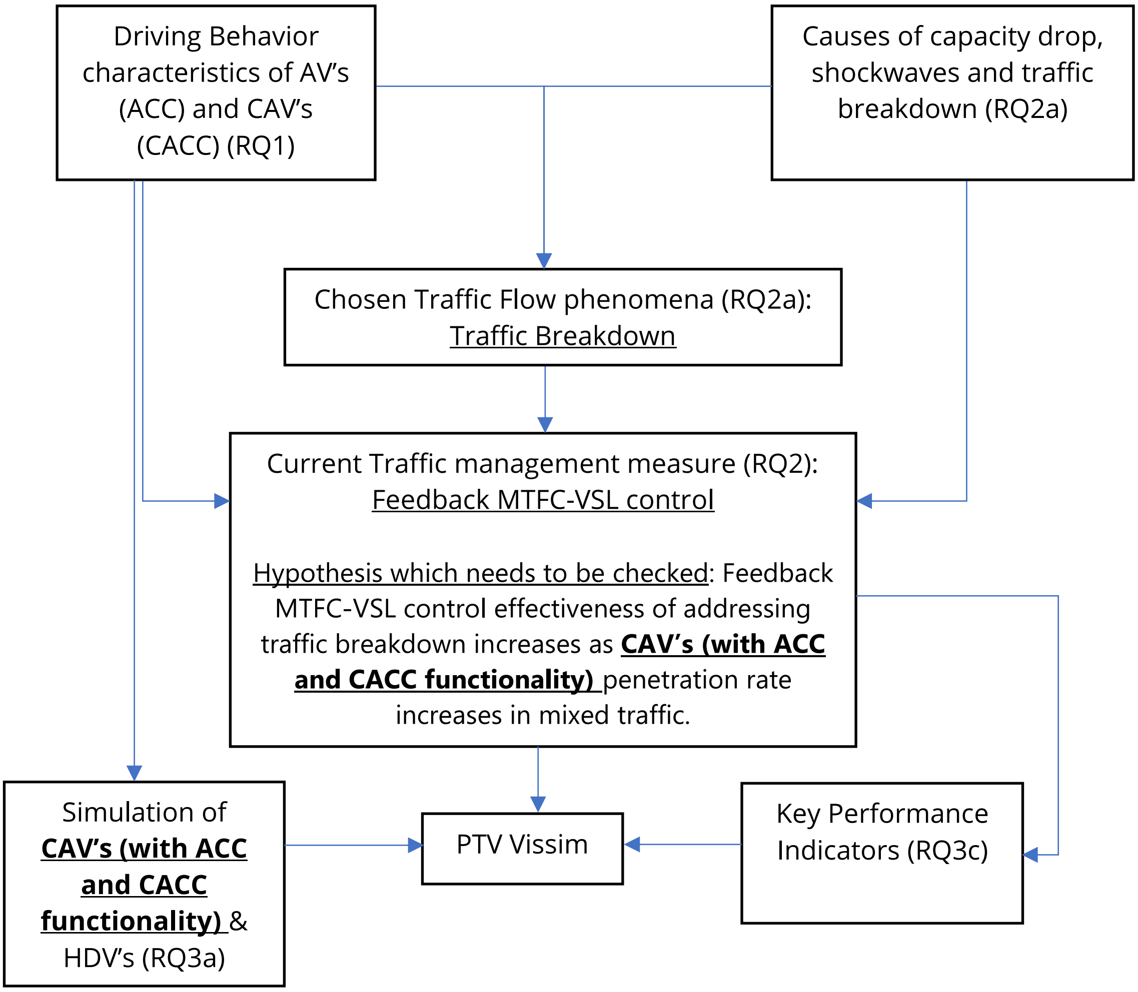


Figure 19: Part of the flow chart of research methodology

So far, driving behavior parameter values for HDV's CAV's (with ACC and CACC functionality) were discussed. However, there are certain aspects of driving behavior which aren't addressed by this research, and thereby account for limitations of this research. These limitations/assumptions are mentioned below:

1. Connectivity is not modelled between two CAV's and is presumed to exist. Thereby, packet loss of communication between CAV's and between CAV and other network element within traffic system isn't considered in simulation of this research.
2. Communication is presumed to exist only between a CAV following another CAV. Apart from this other V2V communication isn't presumed to exist in this research.
3. It is assumed that HDV's drive the same in mixed environment and thereby no behavioral adaptation is taken into consideration.
4. It is to be noted that empirical data analysis within the Co-Exist project indicated that the standstill distances (CC1 parameter of W99) for ACC

and CACC systems varied *randomly* around the values mentioned before for CCO in Table 13. However, as CCO value in vissim can only entered as a value rather than a distribution, which would then account for randomness observed in empirical data, the stochasticity in standstill distances is not taken into account in this research (Zeidler, 2018).

5. CAV's with CACC functionality can be expected to react faster to the changes of preceding vehicle when in car following mode, than CAV's with ACC functionality. Furthermore, CAV's with ACC functionality can be expected to react faster than HDV's as concluded in section 2.1.6. In this research, this difference of reaction times isn't considered, owing to the reason that in this research built-in driving behavior models of Vissim are used, where in there is no reaction time variable which can be changed based on the vehicle type. Thereby, in this research, all the vehicles, i.e., CAV's (with ACC and CACC functionality) and HDV's are simulated with simulation resolution of 10-time steps/simulation second.
6. As some of the W99 car following parameter values for ACC and CACC systems are based on (Zeidler, 2018) study, the limitations and assumptions used in that study to derive those values apply to this research as well. Specifically, (Zeidler, Buck, Kautzsch, Vortisch, & Weyland, 2018) highlight that the driving behavior of ACC systems are much more complicated to be reproduced by W99 in Vissim than CACC system driving behavior which can be modelled realistically.
7. Following from section 2.1.6, vehicles with ACC functionality can be expected to have *smoother acceleration and deceleration* behavior. However, this smoother acceleration and deceleration behavior of CAV's with ACC functionality is not adopted in simulation owing to lesser-known empirical quantitative information of acceleration and deceleration values for various vehicle speeds of vehicles with ACC functionality, because, in Vissim acceleration and deceleration functions are defined with respect to various vehicle speeds.
8. Irrespective of preceding vehicle type, CAV's (with ACC and CACC functionality) were presumed to have connectivity feature which can be used for Infrastructure to Vehicle or Vehicle to Infrastructure (I2V/V2I) if there is any.

5.3. Mixed traffic Scenario formulation

In this section, various scenarios of mixed traffic for which the effectiveness of feedback MTFC-VSL control will be analyzed in chapter 6, will be discussed. This section answers RQ3b, which is, *what are the various scenarios of mixed traffic?*

The effectiveness of feedback MTFC-VSL control will be analyzed for different scenarios of varying penetration rate of CAV's (with ACC and CACC functionality) as shown in Table 18. Scenario number 1 represents 100 % HDV's and the vice-versa for scenario number 7. The scenarios in between refer to *mixed traffic*. Alongside checking the effectiveness of the feedback MTFC-VSL control for these scenarios, the different scenarios will help to understand the changes in traffic breakdown phenomena, which is hypothesized to improve (lesser spatio-temporal extent of congestion) with increase in penetration rate of CAV's (with ACC and CACC functionality) owing to their driving behavior characteristics set in simulation as explained in section 5.2.

Table 18: Various scenarios of varying penetration rate of CAV's.

Scenario No	1	2	3	4	5	6	7
Penetration rates (% CAV's)	0	10	20	30	40	50	100

5.4.Key Performance Indicators (KPI's)

To quantitatively and qualitatively get insights into the changes of traffic breakdown phenomena for various scenarios as listed in Table 18, several Key Performance Indicators (KPI's) are required. The KPI's analyzed in this research are defined and elaborated in this section in the following paragraphs. This section answers RQ3c, which is, *what are the various Key Performance Indicators (KPI's)?*

Travel Time (TT)

TT gives a quantitative indication of how much time does it take for vehicles to travel form an origin to a destination. When traffic breakdown occurs, vehicles spend time in congestion travelling at lower speed, thereby, increasing their travel time. Whereas, in the absence of breakdown they would travel at higher speed and thereby reach destination faster. As this research is focused at highway merging sections, *average TT (unit: seconds) per 5-minute interval is measured for mainline vehicles and on-ramp vehicles* starting from their respective origin, TT1 and TT2 respectively as shown in Figure 25, and ending at a common destination at the end of the network, TT3 as shown in Figure 25. *The total average TT for mainline and on-ramp vehicles, which is defined as the summation of all average TT measured per 5-minute intervals covering the entire simulation period, is used for the analysis*. Hence, Total average TT for mainline and on-ramp vehicles are among others, the two KPI's which will be used in the further analysis.

Average Network Speed
Speed is an important variable which varies depending on traffic conditions. Due to traffic breakdown, the speed of vehicles and thereby the average network speed drops. The higher the spatio-temporal extent of congestion, the lower the average network speed. Hence, in this research *average network speed (unit: km/hr)* is used as another KPI, which is derived by dividing the total distance travelled by total travel time.

Space-time diagrams
Space-time diagrams of the entire network guide to qualitatively get insights into the spatio-temporal extent of traffic breakdown and how it varies for various scenarios of increasing penetration rate of CAV's. Furthermore, it might also help to reveal some aspects of traffic breakdown, which aren't revealed by quantitative KPI's. Hence, Space-time diagrams is a qualitative KPI which will be used in this research.

Capacity estimation
One of the important reasons of traffic breakdown at bottlenecks, is that capacity of the bottleneck is exceeded, and once breakdown occurs, capacity drop might prevail. Thereby, two types of capacity are important to be studied in this research, they are, *Breakdown capacity flow* and *Discharge capacity flow*. The difference between these two capacities represents *Capacity drop*. There are various ways to obtain these capacity values in simulation.

In this research, Breakdown capacity is defined as the *highest* observed aggregated flow observed during a 5-minute simulation period prior to traffic breakdown (Calvert et al., 2017). Traffic breakdown is presumed to persist when average speed is less than 60 km/hr. It is to be noted that the *aggregated flow and average speed* are measured at a section, 40m, upstream from the end of acceleration lane (approximately the section corresponds to the pair of detectors place at the end of the merging section as shown in Figure 25), owing to the reason that it is observed in simulations that perturbations occur at the end of the acceleration lane when on-ramp vehicles wait for a gap to merge onto the mainline lanes. As seen in Figure 25, the merging section consists of three lanes (two mainline and an acceleration lane). The *aggregated flow* is measured across all the three lanes, to account for the on-ramp vehicles which might not cross the data collection point at 40m if only two mainline lanes are considered. Whereas the average speed is the average speed across the two mainline lanes (excluding the acceleration lane) at the same cross section, because there might be vehicles waiting on the acceleration lane and this should not affect the average speed of the bottleneck, where in free flow speed might persist on the two mainlines.

On the other hand, Discharge Capacity is defined as the *highest* observed aggregated flow measured during 5-minute simulation period out of the congested bottleneck (Calvert et al., 2017). The aggregated flow is measured 100 m downstream of the end of the acceleration lane, when average speed measured at the bottleneck section as described before is less than 60 km/hr.

5.5.Number of Simulation runs

As Vissim is a stochastic microsimulation model, simulation runs with different random seeds yield different values for the KPI's discussed in the previous section. To get statistically significant values of the quantitative KPI's, certain number of simulations runs needs to be run per scenario of varying traffic composition. Thereby, to determine the minimum number of simulations runs required, the formula obtained from (Tian, Urbanik, Enqelbrecht, & Balke, 2002) as written as follows will be used.

$$n = \left(\frac{z_{\frac{\alpha}{2}}\sigma}{E}\right)^2$$

where,
n – required number of simulations runs
σ – sample standard deviation
$z_{\alpha/2}$ – threshold value for 100(1-α) % confidence interval
E – allowed error range

As a sample, 10 simulation runs for scenario 1 (0% CAV's) with different random seeds were run to get mean sample KPI's and the aforementioned formula was applied to each of the KPI's to derive the minimum number of simulation runs required for each KPI to be statistically significant at 95% confidence (α = 5%) with allowed error range of 10% of the mean of the respective KPI's. Table 19 lists the number of simulations runs required per KPI, along with the mean and Standard Deviation (SD) of the KPI's of 10 simulation runs. From the table it is evident that the required runs for scenario 1 is two simulation runs. Furthermore, in-order to check whether two runs are sufficient for other scenarios such as scenario 2,3,4,5, 6 and 7 as highlighted in Table 18, number of simulation runs required per KPI are also calculated for Scenario 3,4,5 and 6. It is found out that for these scenarios higher number of runs are required to get statistically significant results compared to scenario 1. Among Scenario 3,4,5 and 6, Scenario 5 requires highest runs, which is 19 as listed in Table 19. *Hence, all the scenarios will be run for 20 replications with different random seeds and the average values of KPI's of those 20 runs represent the values of KPI's for every scenario.* As Breakdown capacity flow and Discharge Capacity flow aren't checked for statistically significance, Boxplots will be plotted for them which gives an insight into their spread and outliers.

Table 19: Mean and Standard Deviation of 10 runs for respective KPI's and the required simulation runs for Scenario 1 and 5

KPI	Scenario No	Mean of 10 runs	SD of 10 runs	Minimum simulation runs required (n)
Total Average TT of mainline vehicles (seconds)	1	25687.49	1808.29	2
	5	10328.55	2051.06	16
Total Average TT of on-ramp vehicles (seconds)	1	3197.58	67.96	1
	5	2402.24	530.87	19
Average Network Speed (km/hr)	1	53.29	2.75	1
	5	90.31	9.97	5

5.6.Network characteristics

The network chosen for further analysis is that of a hypothetical merge section, the details of which are shown in Figure 25. The mainline length of 7 km is chosen such that congestion doesn't propagate beyond the hypothetical network. To facilitate in the occupancy measurement of the merging bottleneck required for the feedback MTFC-VSL control, four pairs of detectors spaced 40 m apart are placed on the mainline within the 200 m of the merging bottleneck. The demand chosen for the simulation period of 2.5 hours for the hypothetical network is as shown in Figure 20. After 2.5 hours the simulation is run for another 20 minutes with no demand, so that the no vehicles remain in the network at the end of the simulation. The demand for both on-ramp and mainline flow is selected such that congestion occurs at the merging bottleneck for scenario 1 (0% CAV) in the absence of any traffic management control. The nominal speed limit of the network is set as 100 km/hr.

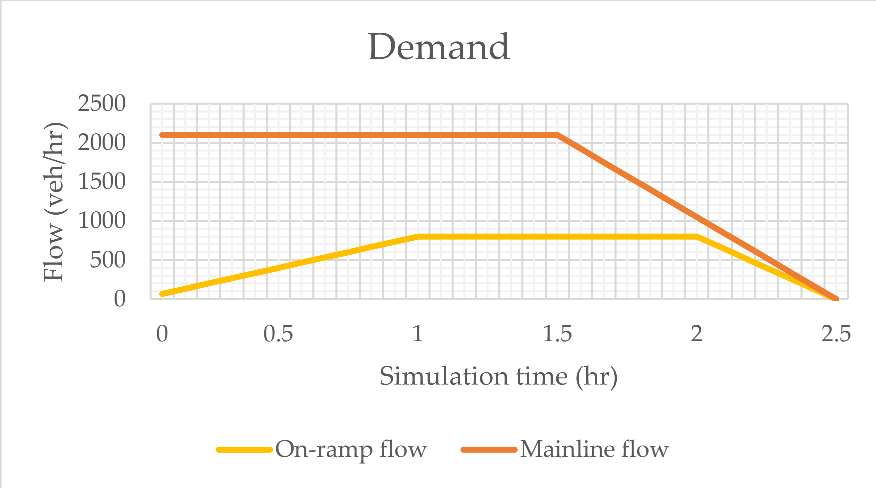


Figure 20: Demand at on-ramp and mainline at the hypothetical network for the simulation period.

6. Results and Analysis: Phase 2

In the previous chapter, chapter 5, driving behavior parameters of HDV's and CAV's to be used in simulation, various scenarios of mixed traffic and different KPI's which will be used to get insights into traffic breakdown were discussed. Following from Figure 21, the next step (yellow arrow in Figure 21) is to analyze the effectiveness of feedback MTFC-VSL control, i.e. to check the hypothesis framed in Section 5.2.5, that "*Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic*", through simulation using the previously discussed KPI's. However, before moving straightway to the next step, looking into the changes in traffic breakdown phenomena for different scenarios of penetration rate of CAV's (with ACC and CACC functionality) in the *absence of any traffic management measure/control* gives insights into how well CAV's driving behavior addresses traffic breakdown. Hence, in this chapter, first, traffic breakdown phenomena will be analyzed for all the scenarios of traffic composition in the absence of any traffic control (Section 6.1), later the hypothesis will be checked in Section 6.2. Finally, based on the results and gathered insights in Section 6.1 and 6.2, conclusions are discussed in Section 6.3. *All the quantitative values of KPI's discussed hereafter refer to average of 20 simulation runs executed per scenario.*

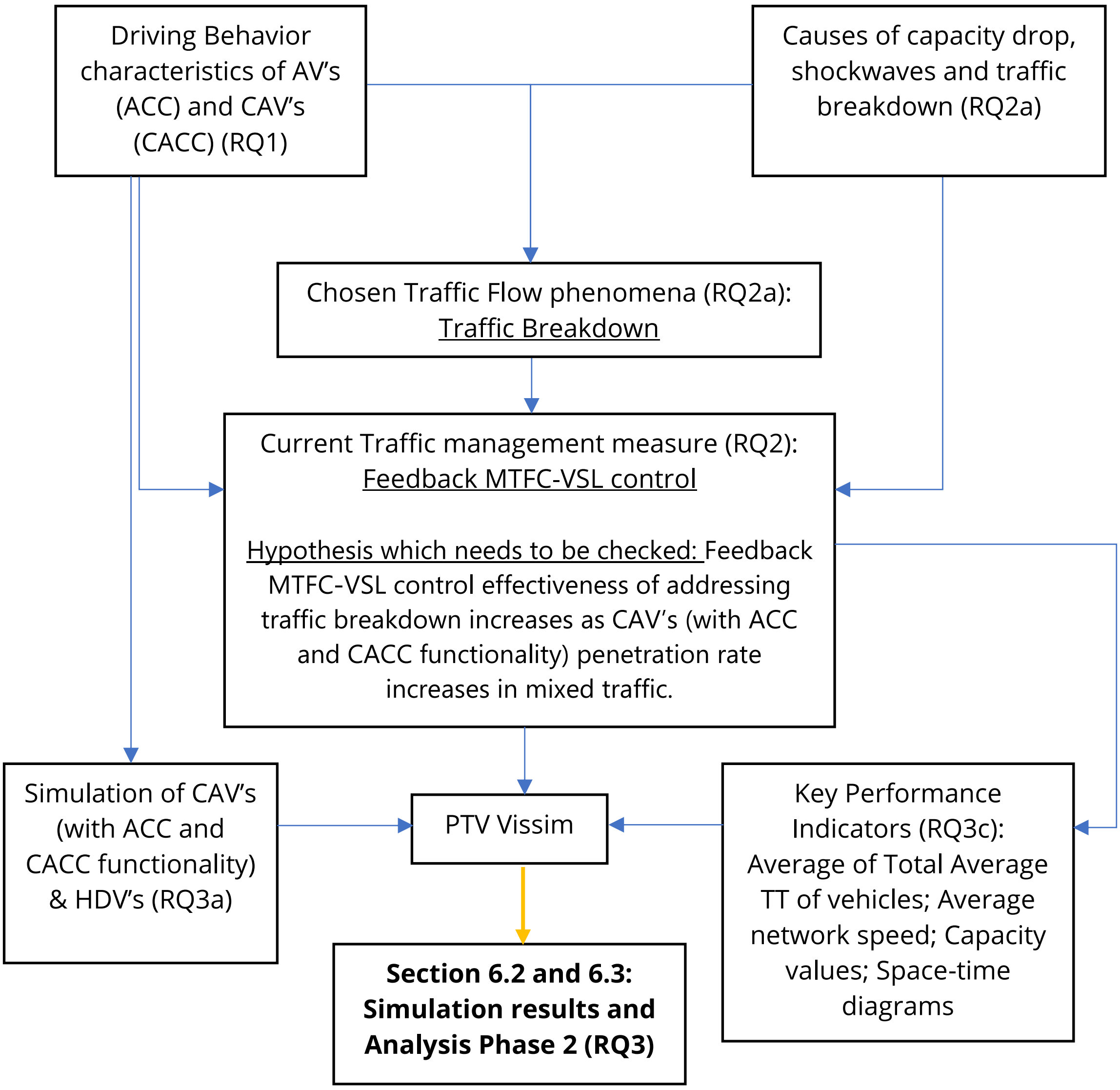


Figure 21: Part of the flow chart of research methodology

6.1. Traffic Breakdown analysis (absence of traffic control)

In this section, the traffic breakdown phenomenon will be analyzed through various KPI's described before in section 5.4 for all the scenarios of traffic listed in Table 18, in the *absence of any traffic management measure/control*. This analysis will help to get insights into the changes of KPIs' for various scenarios compared to scenario 1 where only HDV's drive and will also help to later compare these KPI's with that when feedback MTFC-VSL control exists.

TT measurements

Table 20 lists the average of the total average TT of mainline and on-ramp vehicles for various scenarios of traffic. Additionally, *percentage (%) improvement* of these TT values for all the scenarios are listed with respect to scenario 1 as reference. With regards to the average of the *total average TT of* *mainline vehicles*, it's clear that as penetration rate of CAV's (with ACC and CACC functionality) increases in mixed traffic, TT decreases. The same holds good for on-ramp vehicles except Scenario 2, where in TT increases by 0.2%. Overall, the reduction in travel times with increase in penetration rate of CAV's can be attributed to the driving behavior parameters of CAV's being set in Vissim as discussed in Section 5.2 which bring in more homogeneity and stability compared to HDV's.

Lastly, there is one significant point which needs be discussed. For scenario 2 and 3, it is very less probable for CAV's follow another CAV, leading to most of the CAV's driving with ACC functionality as car following behavior. From Table 20 it's evident that for these two scenarios there is a reduction in average of the total average TT for both mainline and on ramp vehicles. However, this might seem a bit unrealistic as empirically cars driving with ACC functionality are expected to have higher desired time gaps than HDV's. However, in this research at any given scenario of traffic, HDV's drive with 1.5s and 53.33% of CAV's drive with 1.0s, 33.33% drive with 1.5s and rest with 2.0s as desired time gaps *when following an HDV* Hence, it can be expected that scenarios 2 and 3 have reduction in travel times. This reasoning also holds good to the reduction in average network speed and spatio-temporal extent of congestion for these two scenarios discussed in the subsequent paragraphs.

Table 20: Average of the Total Average TT of on-ramp and mainline vehicles for various scenarios in the absence of traffic control.

Scenario no (% CAV)	Average of Total Average TT of mainline vehicles (seconds)		Average of Total Average TT of on-ramp vehicles (seconds)	
	Values	**% improvement with respect to Scenario 1**	**Values**	**% improvement with respect to Scenario 1**
1 (0%)	25512.9	-	3198.3	-
2 (10%)	22973.3	10%	3206.1	-0.2%
3 (20%)	18870.9	26%	3169.7	0.9%
4 (30%)	15259.5	40.2%	3070.8	4%
5 (40%)	11175.0	56.2%	2654.1	17%
6 (50%)	9856.3	61.4%	2339.4	26.9%
7 (100%)	8866.6	65.2%	1870.5	41.5%

Average Network speed

Table 21 shows the average network speed for various scenarios of traffic. It also shows the *percentage (%) improvement* of average network speed with respect to Scenario 1 as reference. From the table it is evident that, as penetration rate of CAV's (with ACC and CACC functionality) increases, average network speed increases, indicating lesser spatio-temporal extent of traffic breakdown. It is to be noted that there is significant improvement of speed during the transition from scenario 4 to scenario 5. Furthermore, for scenario 7 congestion hardly occurs as the average network speed is almost equal to the nominal speed limit of the highway which is 100 km/hr. This is further clear in space-time diagrams which are discussed in the next paragraph.

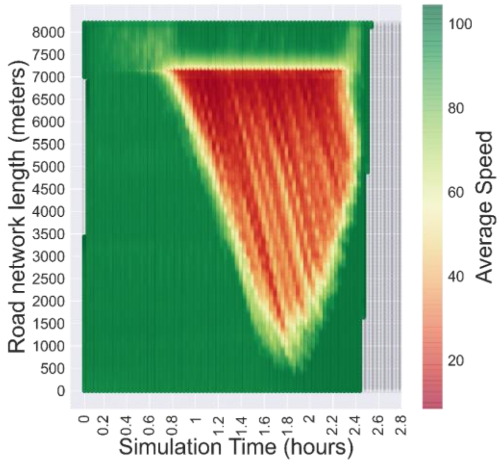
Table 21: Average network speed for various scenarios in the absence of traffic control

Scenario no (% CAV)	Average network speed (km/hr)	
	Values	% improvement with respect to Scenario 1
1 (0%)	53.56	-
2 (10%)	57.07	6.6
3 (20%)	63.69	18.9
4 (30%)	71.57	33.6
5 (40%)	85.89	60.4
6 (50%)	92.32	72.4
7 (100%)	99.78	86.3

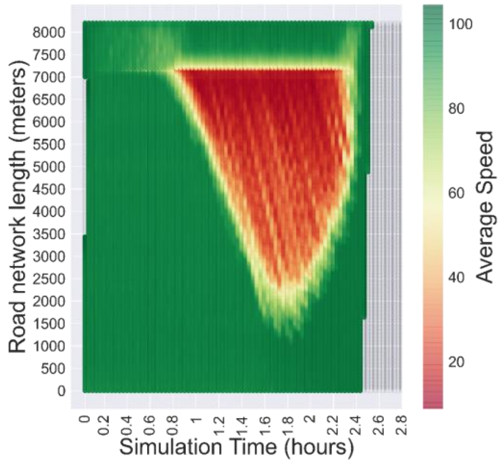
Space-time diagrams

Figure 22 depicts the space time diagrams for various scenarios of traffic in the absence of traffic control. The road network length in the figure represents the 8.2 km straight stretch of the road section as shown in Figure 25, excluding the on-ramp lane. From the figure, it is evident that as penetration rate of CAV's (with ACC and CACC functionality) increases, the spatial and temporal extent of congestion decreases. It's clear that breakdown occurs at the merging section (7000m to 7200m) specifically almost at the end of the acceleration area. For Scenario 7 breakdown isn't evident at all, which is in line with the value of average network speed given in Table 21. It is to be noted that the grey part at the edge of each space time diagrams refers to the time period during which no flow is present, just to ensure that all the vehicles clear the network, thereby ensuring valid comparison among various scenarios.

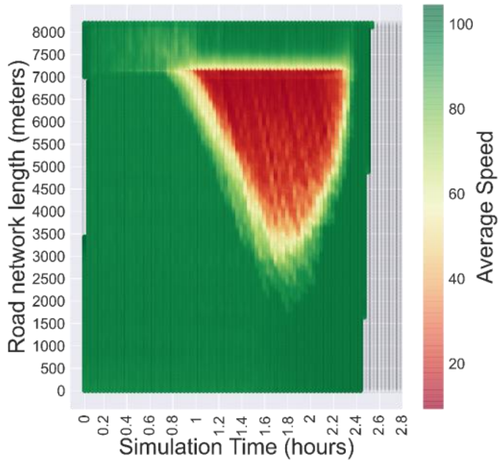
Scenario 1 (0% CAV)



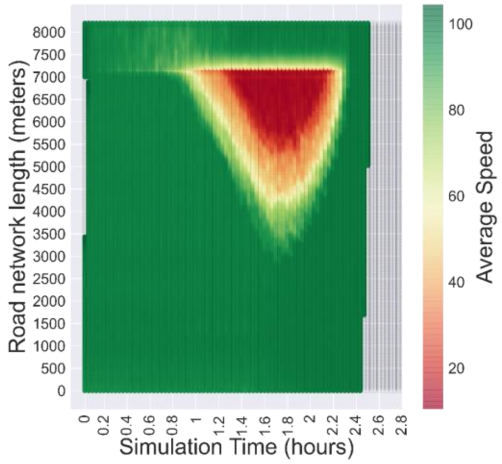
Scenario 2 (10% CAV)



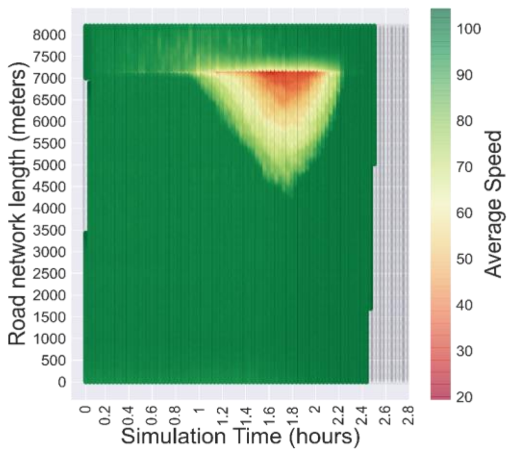
Scenario 3 (20% CAV)



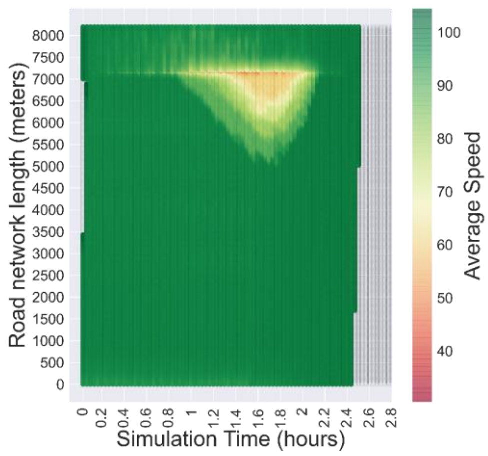
Scenario 4 (30% CAV)



Scenario 5 (40% CAV)



Scenario 6 (50% CAV)



Scenario 7 (100% CAV)

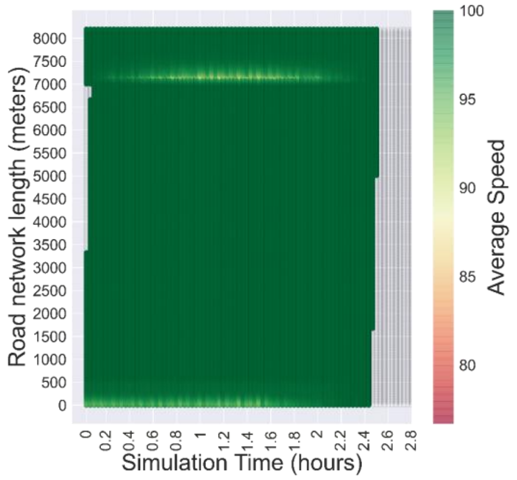


Figure 22: Space-time diagrams for various scenarios of traffic in the absence of traffic control

Capacity analysis

Table 22 lists the average values of breakdown capacity, discharge capacity and capacity drop for various scenarios of traffic in the absence of traffic control. It is to be noted that in case of scenario 7 (100% CAV's) as breakdown doesn't occur, only average breakdown capacity is shown in the table which represents the average of the *highest* flow observed in the entire simulation period. Figure 23 and Figure 24 depict the box plot of both the capacity flows with boundaries of the boxplot representing the 25 and 75 percentile and the whiskers representing the maximum and minimum values. The average is represented by 'x'. As penetration rate of CAV's (with ACC and CACC functionality) increases, breakdown capacity flow increases. The increase has to do with the fact that, at any given scenario of mixed traffic, 53.33% of CAV's drive with 1.0s as desired time gaps, 33.33% drive with 1.5s and rest with 2.0s, *when following an HDV* and on the other hand, *in case of following a CAV*, 53.33% of CAV's drive with 0.6s and 33.33% drive with 0.7 and rest with 0.9s.

However, the discharge capacity doesn't increase to the same extent as the breakdown capacity. This could be attributed to the reason that, the acceleration parameters of CAV's (with ACC and CACC functionality) and HDV's, especially CC8 and CC9, which are relevant to acceleration from standstill and at 80km/hr respectively, are set the same in simulation. Hence, when investigated into the average acceleration values at the section between end of the acceleration lane and Discharge capacity measurement, i.e., 100m, it's found that for Scenario 1 to 4 the acceleration values are similar. Thereby, even at different penetration rates, they accelerate out of congestion with similar values. Scenario 5 and 6 have higher increase in discharge which might be due to the reason of lesser instance of congestions and increases in % of CAV following CAV's and thereby smaller time gaps. Overall, an increase in Bottleneck Capacity and Discharge Capacity remaining more or less the same, leads to an increase in Capacity drop values as penetration rate of CAV's (with ACC and CACC functionality) increases as seen from Table 22.

One thing to be discussed is that the average capacity values mentioned in the Table 22 is very less compared to the theoretical capacity value. For instance, Scenario 1 where in HDV's drive with desired time gaps of 1.5s, the theoretical capacity value for this time gap yields around 2400 veh/hr/lane whereas, the average value obtained across the whole merging section is 2663 veh/hr. One of the reasons for such a difference, is that in simulation, the CC8 and CC9 which relate to acceleration from standstill and at 80 km/hr, as discussed in section 5.2, are set less than 1.0 m/s2 for both HDV's and CAV's (with ACC and CACC functionality). When *higher* mainline flow persists at the merging section, on-ramp vehicles are unable to find safe gaps to merge, due to which they wait standstill at the end of the acceleration lane and when they find a safe gap, they execute the lane change and accelerate with values less than 1.0 m/s2 from very low speeds. Thereby, due to lower speed and acceleration values of on-ramp vehicles after lane change, the on-ramp vehicles act as a disturbance which stays for some time, and the vehicles upstream of this disturbance decelerate leading to breakdown at lower flow values. When default values of CC8 (3.5 m/s2) and CC9 (1.5m/s2) are used, breakdown hardly occurs.

Table 22: Average Breakdown capacity, Discharge capacity and Capacity drop for various scenarios of mixed traffic in the absence of traffic control

Scenario no (% CAV)	**Average Breakdown Capacity (veh/hr)**		**Average Discharge Capacity (veh/hr)**		**Average Capacity Drop (veh/hr)**
	Values	**% increase with respect to Scenario 1**	**Values**	**% increase with respect to Scenario 1**	
1 (0%)	2663	-	2558	-	105
2 (10%)	2704	1.5	2585	1.1	119
3 (20%)	2792	4.8	2590	1.3	202
4 (30%)	2840	6.6	2585	1.1	255
5 (40%)	2902	9.0	2614	2.2	288
6 (50%)	2960	11.2	2736	7.0	224
7 (100%)	3007	13	unknown	unknown	unknown

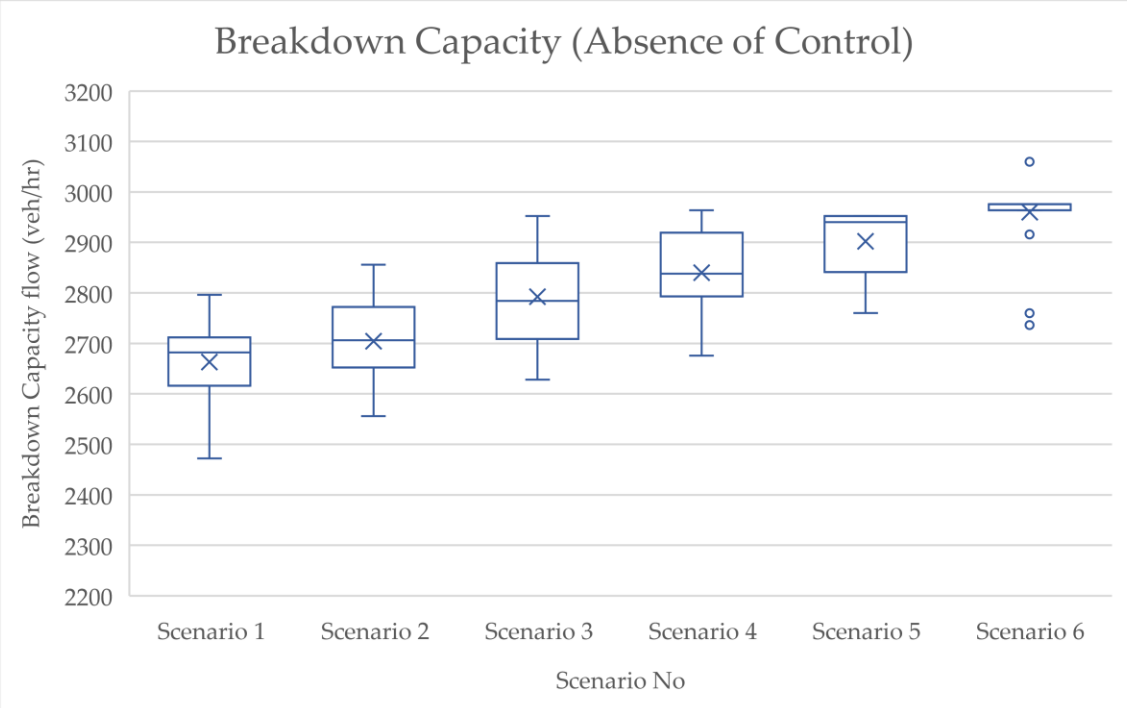


Figure 23: Boxplot of Breakdown Capacity values for various scenarios of traffic in the absence of control.

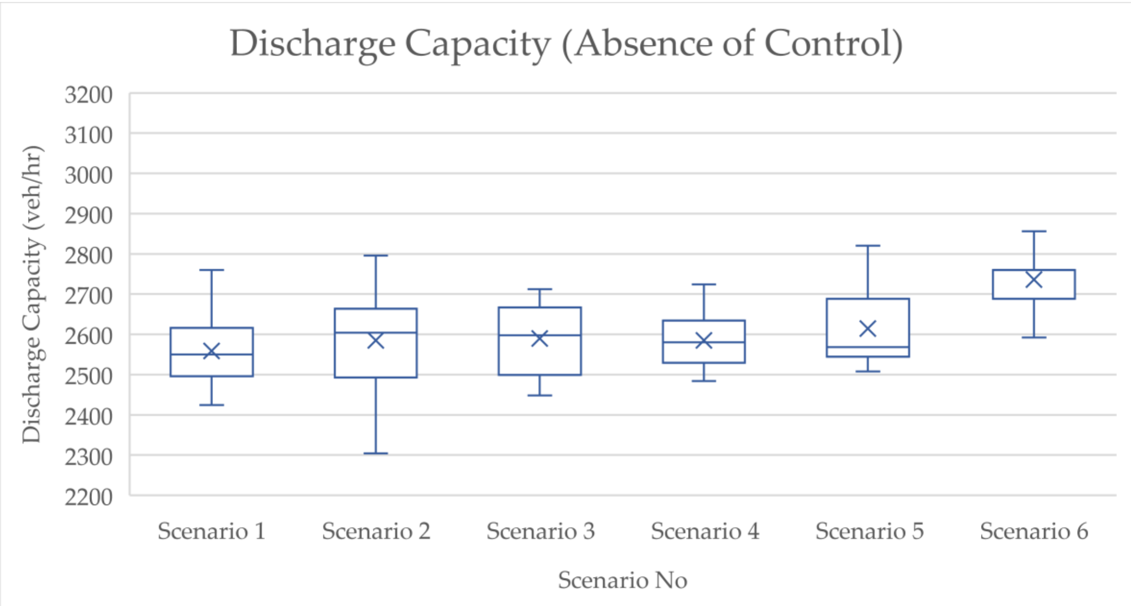


Figure 24: Boxplot of Discharge Capacity values for various scenarios of traffic in the absence of control.

6.2. Traffic breakdown analysis (presence of feedback MTFC-VSL control)

In the previous section traffic breakdown was analyzed using KPI's for various scenarios of traffic in the *absence of traffic control*. In this section, traffic breakdown will be examined in the presence of feedback MTFC-VSL control.

The feedback MTFC-VSL control as discussed in section 4.3, is set up in Vissim using VisVAP. Using VisVAP, control logics can be created and edited as flow charts, which after checking for structural correctness of the flow chart, it will be exported to a VAP (Vehicle Actuated Programming) file which can be used in Vissim (PTV AG, 2019). For the proper set-up of the feedback MTFC-VSL control in Vissim and VisVAP, the following five points needs to be addressed.

- The *practical considerations* of implementing the algorithm in real life.
- As discussed in section 4.3, that for the suitable application of the linear MTFC-VSL control law, the *linearity of the capacity flow induced by the allowable speed limits* needs to be checked in Vissim.
- *Critical speed* of the bottleneck (merging section) needs to be determined, as vehicles driving out of the VSL application area as shown in Figure 25 need to drive around the critical speed of the bottleneck when they reach the bottleneck location.
- *Critical occupancy* of the bottleneck needs to be determined as the feedback MTFC-VSL control tries to maintain critical occupancy at the bottleneck.
- *Length of VSL application area* and *acceleration area* as shown in Figure 25.

These points will be further elaborated in Section 6.2.1 and later based on that section's findings the effectiveness of the feedback MTFC-VSL control will be discussed in section 6.2.2.

6.2.1. Feedback MTFC-VSL control set-up

Practical considerations

The feedback MTFC-VSL control can be implemented in two possible ways (Müller et al., 2015). Point-level VSL (P-VSL), where in vehicles adjust their speed *while passing by a VSL sign* and keep the same speed until a new VSL sign is displayed further downstream. On the contrary, Section-level VSL (S-VSL) refers to the whole section for which *VSL sign holds good.* During S-VSL, *all vehicles* in that whole section adjust their speed *immediately* to the new speed limit (Müller et al., 2015). Considering current practical considerations, its highly probable that P-VSL set up is currently being employed in most of the countries then S-VSL, thereby P-VSL setup will be used in this research. Furthermore, along with P-VSL, there are certain practical aspects mentioned in (Müller et al., 2015) which will be considered in this research with some modifications as listed below, which will help to capture the effectiveness of the feedback MTFC-VSL control to a certain extent as if its implemented in real-life situations.

- *Discrete VSL values:* The Feedback MTFC-VSL control output values aren't discrete values of speed limits. However, they need to be rounded off to discrete values of allowable speed limits to be displayed on the VSL gantries. In this research, the nominal speed limit of the hypothetical network is 100 km/hr. Thereby, the allowable speed limits belong to the set *{50, 60, 70, 80, 90, 100}* km/hr. The rounding off of the algorithm obtained values to discrete values is carried out, for instance, if [($b(k)$ * 100) > 75 & ($b(k)$ * 100) ≤ 85] then speed limit of the VSL application area, i.e. at VSL sign b in Figure 25 is set as 80 km/hr, where in $b\ (k) = \frac{Current\ Speed\ Limit}{Nominal\ Speed\ Limit}$

- *Spatial Constraint:* Considering safety concerns, vehicles &drivers should undergo a smooth transition to changes of the speed limits in the VSL application area as shown in Figure 25. Thereby, to account for the smooth transition to lower speed limits in the VSL application area, two VSL gantries, named as VSL sign c and sign d as shown in Figure 25, are situated upstream of the VSL application area. The value of Speed Limit at sign c and d is 20km/hr more than that displayed at the downstream VSL sign. For instance, if the VSL sign b displays 50 km/hr, then sign c displays 70 km/hr and sign d displays 90km/hr. In this way, smooth transition of vehicle speed is ensured before they enter lower speed limits at the VSL application area.
- *Temporal Constraint*: In addition to the spatial constraint, temporal constraint can also be argued that it ensures safety. This constraint puts a limit on not having more than 20 km/hr change at every VSL sign in consecutive control time interval (1 min). For instance, if for the current time interval the Speed Limit at VSL sign b is 80 km/hr and in the next time interval the Speed Limit calculated by the feedback MTFC-VSL control equation to be set at VSL sign b is 50 km/hr, however due to temporal constraint, instead of setting 50km/hr, 60 km/hr is being set at VSL sign b.
- *Compliance rate and desired speed distribution*: HDV's compliance to the speed limit depends on the type of Speed Limit enforcement. In this research it is presumed that the speed limit is *mandatory* and HDV's and CAV's need to adhere to the speed limits. However, HDV's cannot be expected to exactly follow the displayed speed limit, thereby to account for this, HDV's desired speed is obtained from a distribution of ± 5 km/hr of the displayed and nominal speed limit, whereas CAV's exactly follow the displayed and nominal speed limit.

It is to be noted that VSL sign a in Figure 25 will always display 100 km/hr i.e., the nominal speed limit of the network, indicating the end of the VSL application area.

Linearity check

Following up from the discussion of the feedback MTFC-VSL control in section 4.3, the feedback control law follows as,

$$b(k) = b(k-1) + K_I e_o(k)$$

where,
VSL rate = $b = \frac{Current\ Speed\ Limit}{Nominal\ Speed\ Limit}$ where $0 \le b \le 1$
K_I= integral gain of the controller
$e_o(k)$ = $\hat{o}_{out}$ - $o_{out}(k)$, which is occupancy control error
$\hat{o}_{out}$ = in this research is set equal to critical occupancy of the bottleneck to maximize throughput.

As the above equation is linear, to effectively use it in simulation studies, the linear relationship between capacity flow for the allowable speed limits needs to be checked (Carlson et al., 2013). If the relationship is linear, then the feedback control law can be used with one integral gain (K_I) for all the allowable speed limits. Otherwise, gain scheduling needs to be considered, where in multiple integral gains, K_I, are allocated for different ranges of speed limits (Müller et al., 2015). In this thesis, the allowable speed limits to be used within the feedback MTFC-VSL control are *{50, 60, 70, 80, 90, 100}* km/hr, as it might be argued that having speed limits lower than 50 km/hr might lead to more congestion problems than left alone without any speed limits.

To check the linear relationship between the allowable speed limits and the capacity flow induced by them, a simple freeway stretch same as the one shown in Figure 25 without any on/off ramps is simulated (Carlson et al., 2013). The VSL application area length is set as 150 m, the demand is set equal to the capacity of the stretch (2450 veh/hr) and the stretch outflow for each allowable speed limit is measured downstream (150 m) of the application area. Capacity flow are also measured for speed limits less than 50 km/hr just to get insights into the non-linearity. Figure 26 shows the capacity flow obtained for discrete values of speed limits. It is evident from the figure that the relationship is non-linear, i.e., as speed limits decrease the capacity doesn't decrease linearly. This indicates that the traffic response is different for different speed limits, which is similar to the study conducted on feedback MTFC-VSL control in Aimsun by (Müller et al., 2015). Given the non-linear relationship obtained between speed limits and the capacity flow induced by them, gain scheduling needs to be considered, where in multiple integral gains (K_I) are allocated for different ranges of speed limits. This can be obtained by carrying out piecewise linear regression for multiple speed ranges (Müller et al., 2015).

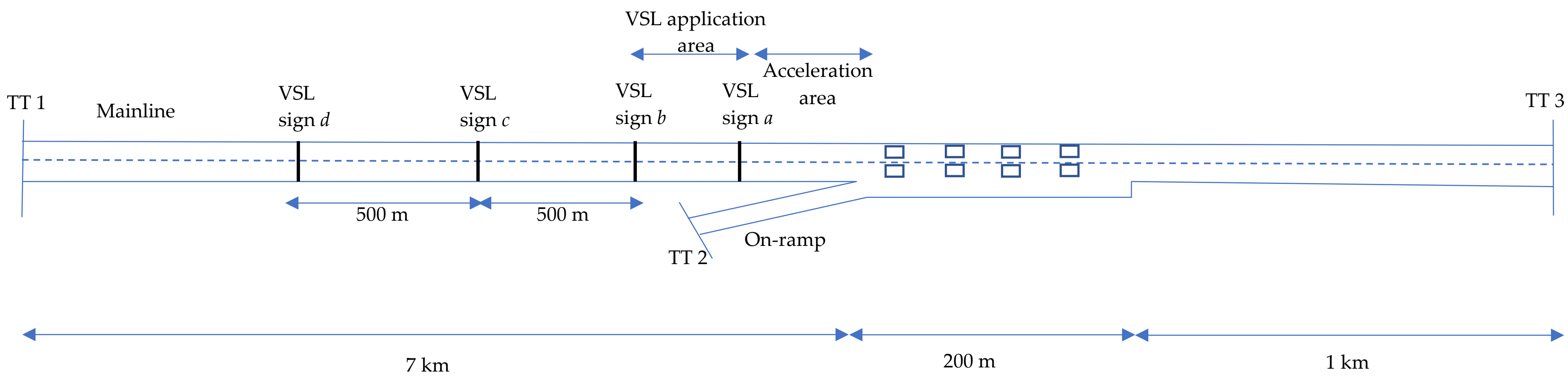


Figure 25: Hypothetical network set-up for feedback MTFC-VSL control (not to scale)

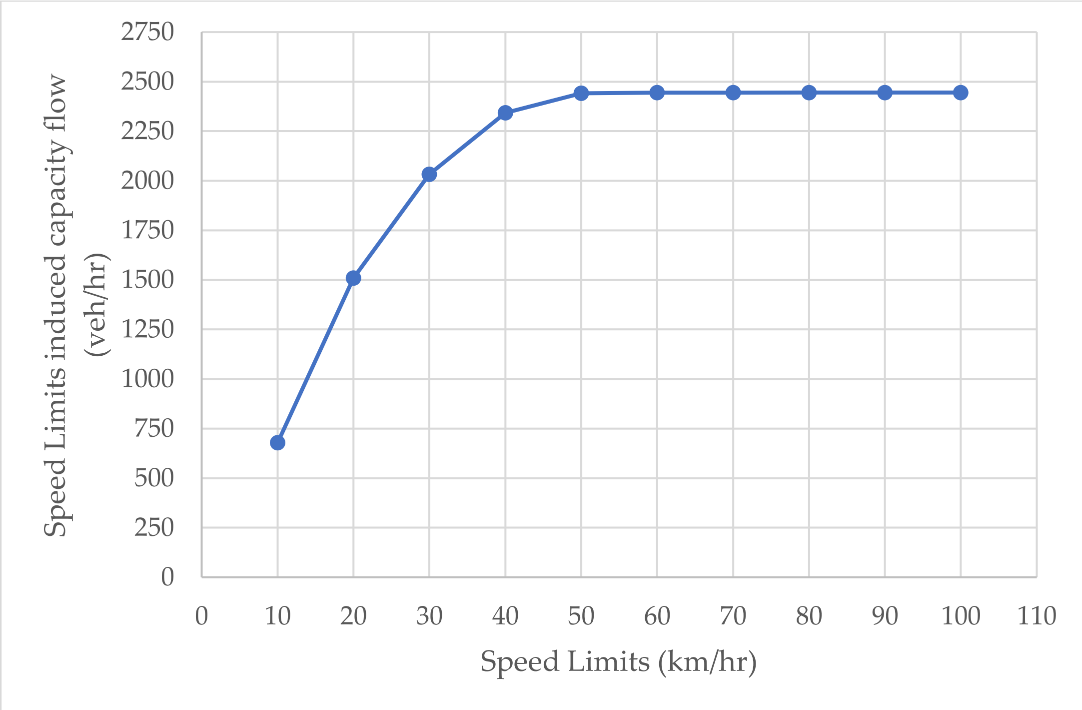


Figure 26: Capacity flow induced by Speed limits

It is seen from the Figure 26, that for all the *allowable* speed limits, i.e., from 50 to 100 km/hr, the induced capacity is almost the same, around 2445 veh/hr. From 50 km/hr to 30 km/hr the decrease in capacity flow with decrease in speed limit is significant and furthermore when speed limit is less than 30 km/hr, the decrease is more significant. This indicates that the algorithm needs to react faster for speed limits between 50 and 100 km/hr and less fast for less than 50 km/hr as traffic flow response is faster for change in speed limits there on. After carrying out piecewise linear regression, as speed limit range of 50 to 100 km/hr is the focus of this research, integral gain (K_I) for this speed limit range is obtained by trying out different reasonable values and finally choosing the one where the algorithm produces positive improvements for the *KPI's for Scenario 1*. It is found that an integral gain (K_I) of 0.08 gives good results compared to other values. Hence, the control law of the feedback MTFC-VSL control boils down to,

$$b(k) = b(k-1) + 0.08 * e_o(k)$$

It is to be noted that the linearity check is carried out with VSL application area of 150m, and different application area might slightly change the linear relationship obtained in Figure 26. Similarly, the effect of the different reasonable values of integral gains (K_I), before deciding on 0.08, were carried out for the VSL application area of 150m and acceleration area of 200m for Scenario 1. Other values of application and acceleration area lengths might yield different integral gains.

After deciding the integral gain of the control law, the next step is to decide the critical speed and critical occupancy of the bottleneck (merging section).

Critical speed

It is essential to estimate the critical speed of the bottleneck, because as per the prerequisites of the feedback MTFC-VSL control, vehicles after exiting the VSL application area as shown in Figure 25, should reach the bottleneck at the critical speed of the bottleneck, so that capacity flow is maintained at the bottleneck. Thereby, knowing the critical speed will help to determine the length of the acceleration area as shown in Figure 25, which should be sufficient for the vehicles exiting the application area to reach the critical speed of the bottleneck. To determine the critical speed of the bottleneck, the speed corresponding to the highest flow observed at a cross section of the bottleneck (cross section corresponds to the location of detectors placed at the end of the acceleration lane in Figure 25) in multiples runs for scenario 1 (0% CAV) in the absence of any control is looked into. It is found that highest flow before breakdown is observed for speeds in the range between 85 km/hr to 95km/hr.

Critical Occupancy

Critical occupancy of the bottleneck is required by the feedback control law so that it can regulate it at the bottleneck to maintain the bottleneck to function efficiently. The critical occupancy is determined by simulating Scenario 1 (0% CAV) in the absence of any traffic control for 20 simulation runs. Occupancy of the bottleneck is measured by four pair of detectors on the mainline as shown in Figure 25, *per minute*. *The average occupancy of each pair is obtained by averaging the occupancy measured by each detector on the two mainstream lanes*. The critical occupancy is determined by two ways.

First, based on plotting *maximum average occupancy measured per minute among the four pair of detectors per simulation run*. An example of which is shown in Figure 28 which represents the simulation run 18 among 20 runs simulated, where in 20% is a good estimate for critical occupancy. Similar results are found for other runs as well. This way is considered because in the control law of the algorithm, the maximum average occupancy among the four pair of detectors measured per minute is used as $o_{out}(k)$. Second way of obtaining critical occupancy is based on plotting *maximum average occupancy value per minute among the 20 simulation runs at each detector locations*. An example of occupancy values obtained by this way at the pair of detectors at the end of the acceleration lane is shown in Figure 27. Similar plots are obtained at other three pair of detectors. To conclude, from both ways it is evident that 20% average occupancy is a good estimate to segregate the free flow occupancies from the congested occupancies.

Hence, the control law of the feedback MTFC-VSL control now boils down to,

$$b(k) = b(k-1) + 0.08 * e_o(k)$$
$$b(k) = b(k-1) + 0.08 * (\hat{o}_{out} - o_{out}(k))$$
$$b(k) = b(k-1) + 0.08 * (20 - o_{out}(k))$$

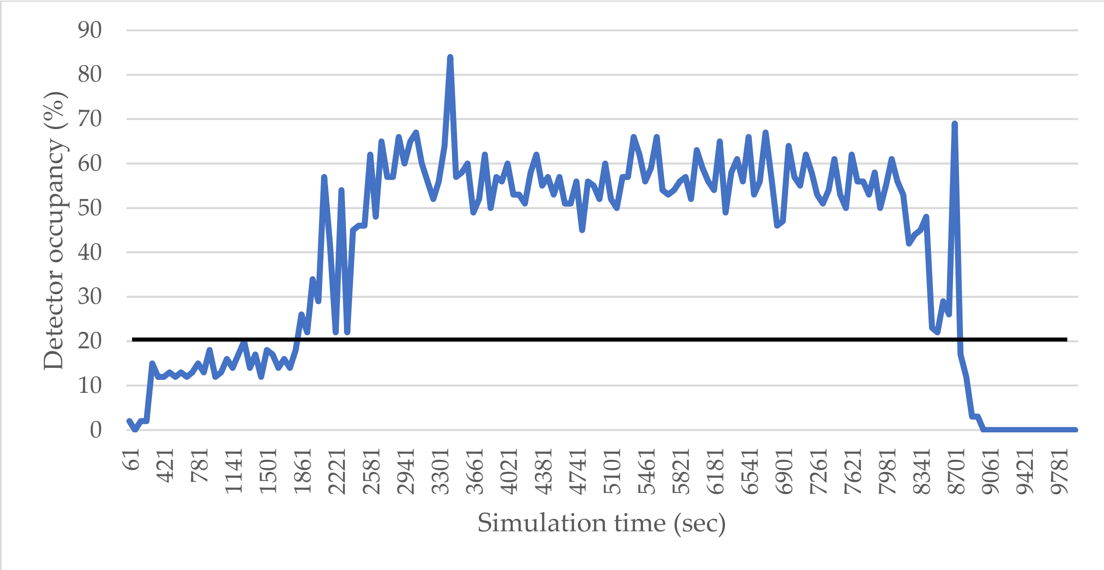


Figure 27: Maximum average occupancy rates (%) of 20 runs at one of the four pair of detectors placed at the bottleneck for scenario 1 in the absence of traffic control

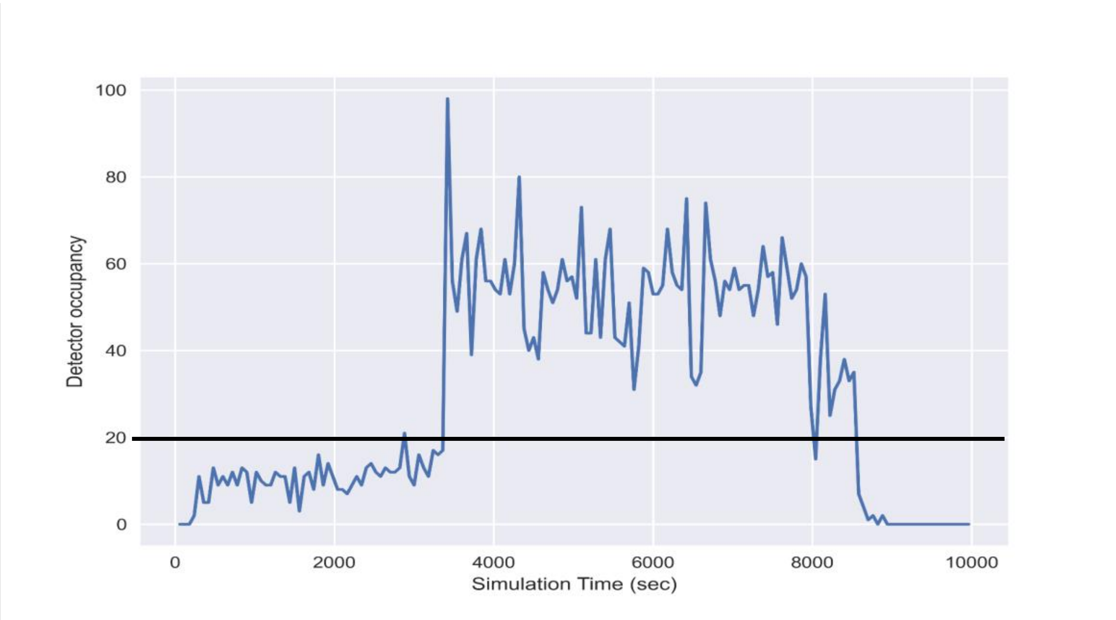


Figure 28: Maximum average occupancy rates (%) obtained for simulation run 18 for scenario 1 in the absence of traffic control

VSL application and acceleration area

Having discussed and decided upon practical considerations of implementing the algorithm, reasonable values of integral gain of the control law, critical occupancy and critical speed of the bottleneck, the next step in set-up of the feedback MTFC-VSL control, is to choose the length of the VSL application area and acceleration area as shown in Figure 25.

As both these areas influence the effectiveness of the feedback MTFC-VSL control in addressing traffic breakdown, choosing the right area lengths is of utmost concern. To find the proper values for these areas, various combinations of reasonable values of application and acceleration areas are simulated for *Scenario 1 (0% CAV).* From trial and error, it's found that the acceleration area length in the range of 175 to 225 m might be required for vehicles moving out of the application area to accelerate to critical speed range while reaching the bottleneck even from the lowest allowable speed limit of 50km/hr. On the other hand, for VSL application area, lengths of 100, 150 and 200m are chosen. Thereby, this leads to 9 combinations of VSL application and acceleration areas lengths as shown in Table 23. Table 23 and Table 24 shows the average of the total average TT values of mainline and on-ramp vehicles for Scenario 1 for various combination of application and acceleration area alongside the values with absence of any control. Similarly, Table 25 represents average network speed values. In every table, the best performing combination of application and acceleration area is highlighted in grey color, which overall, is for application area of 150m and acceleration area of 200m, whereas the worst performing is highlighted in black, which is the combination of application area of 150m and acceleration area of 175m.

To get a better understanding of how different combinations effect the effectiveness of the algorithm, the values shown in Table 23, Table 24 and Table 25 are plotted in Figure 29, Figure 30 and Figure 31 respectively. From the first glance of the figures, there is no linear trend as such with which can be derived with respect to the increase or decrease of acceleration or/and application areas. *Overall*, for all the VSL application areas studied, 225 m acceleration area performs better than other acceleration areas. This could be due to the reason that irrespective of the changes of the application area length, vehicles reach the critical speed range of the bottleneck when they reach the bottleneck with acceleration area of 225m. On the other hand, 100m VSL application area (blue color series line) performs better overall at different acceleration areas studied. This could be due to the reason that the 100m is sufficient enough to control mainstream flow as well as not increase the travel time by not having larger lengths of application area which would then let vehicles drive at lower speed for a longer stretch.

However, not every combination of application and acceleration area can be studied for other scenarios of traffic given the time limit of this research. Thereby, for further analysis of feedback MTFC-VSL control effectiveness, the best performing combination, i.e., 150 m application area and 200 m acceleration area will be studied in detail in section 6.2.2 for other scenarios of traffic, to check whether it still performs better for other scenarios. Later, some insights will also be discussed in section 6.2.3. into the feedback MTFC-VSL control effectiveness with respect to the worst performing combination, i.e. 150 m application area and 175 acceleration area to check whether it still performs the worst for other scenarios as well.

Table 23: Average of Total average TT of mainline vehicles for various combinations of application and acceleration areas for Scenario 1

		Acceleration area (meters)		
		175	**200**	**225**
Application area (meters)	**100**	25106.9	25554.4	25440.1
	150	26454.2	25031.1	25372.9
	200	25286.0	26274.1	25778.0
Absence of control (Scenario 1)		25512.9		

Table 24: Average of Total average TT of on-ramp vehicles for various combinations of application and acceleration area for Scenario 1

		Acceleration area (meters)		
		175	**200**	**225**
Application area (meters)	**100**	3197.9	3238.4	3226.1
	150	3299.3	3188.0	3239.7
	200	3186.6	3285.4	3254.3
Absence of control (Scenario 1)		3198.3		

Table 25: Average network speed for various combinations of application and acceleration area for Scenario 1

		Acceleration area (meters)		
		175	**200**	**225**
Application area (meters)	**100**	54.18	53.77	53.79
	150	52.84	54.19	53.81
	200	54.07	52.98	53.54
Absence of control (Scenario 1)		53.56		

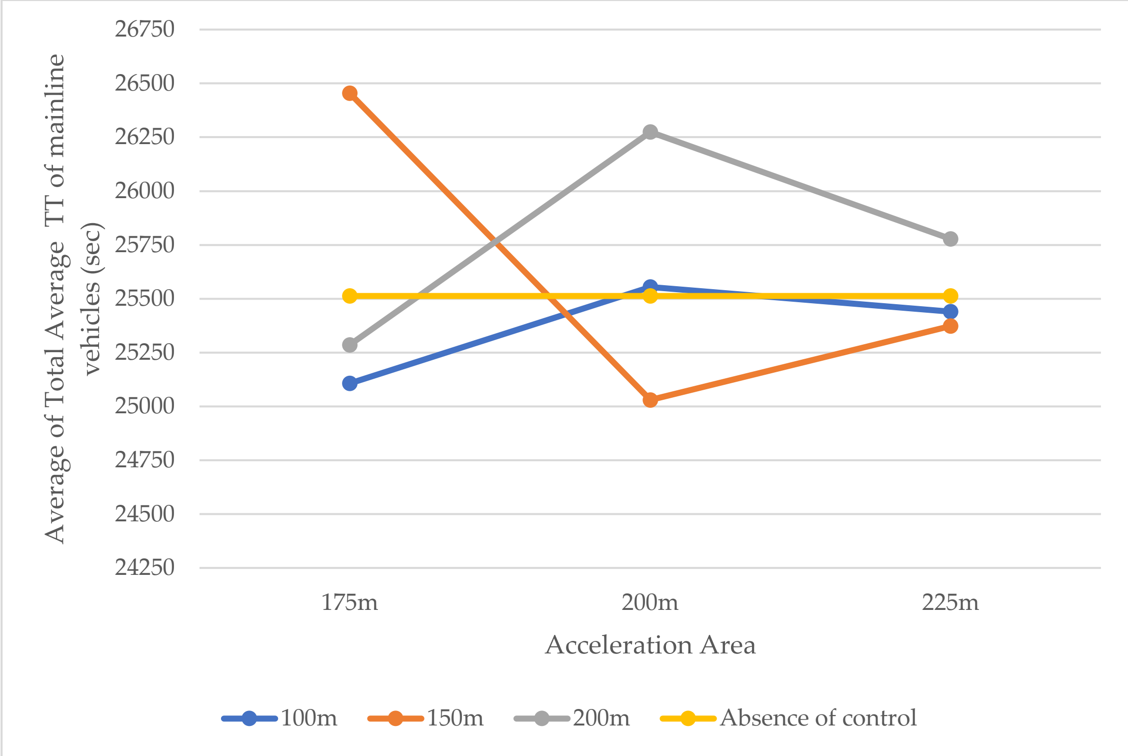


Figure 29: Values of Average of Total Average TT of mainline vehicles for various acceleration areas plotted for different VSL application areas

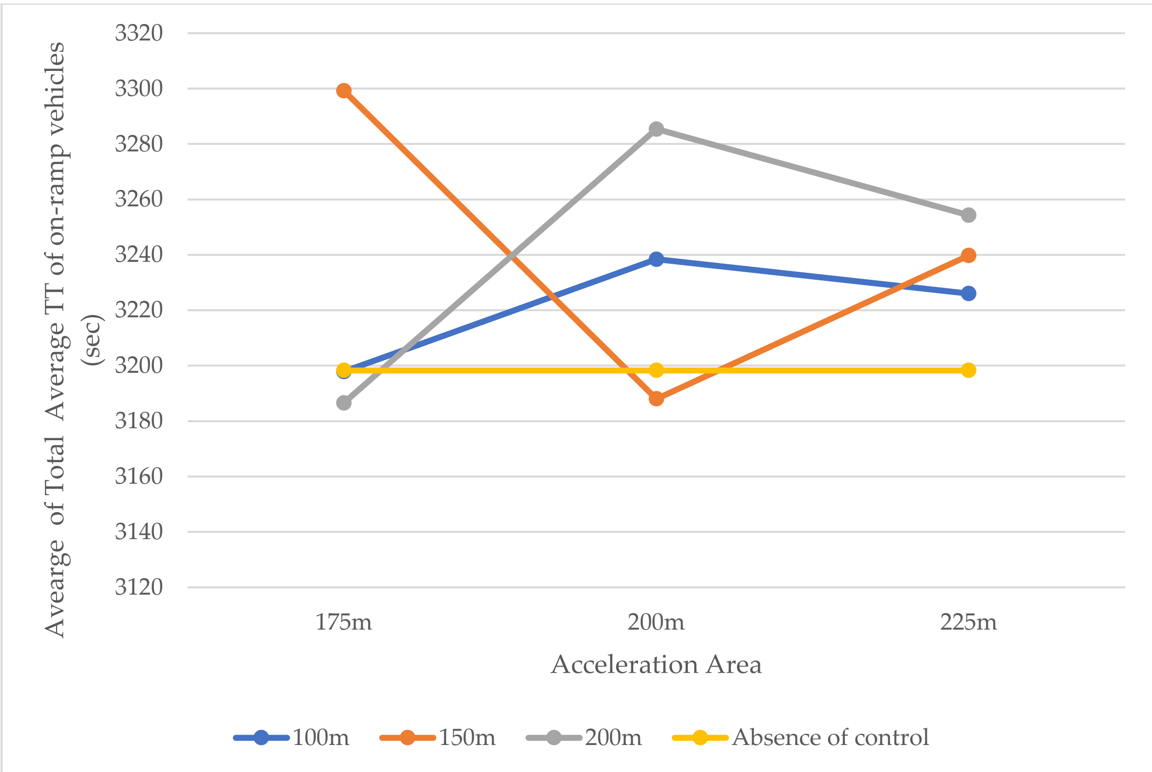


Figure 30: Values of Average of Total Average TT of on-ramp vehicles for various acceleration areas plotted for different VSL application areas

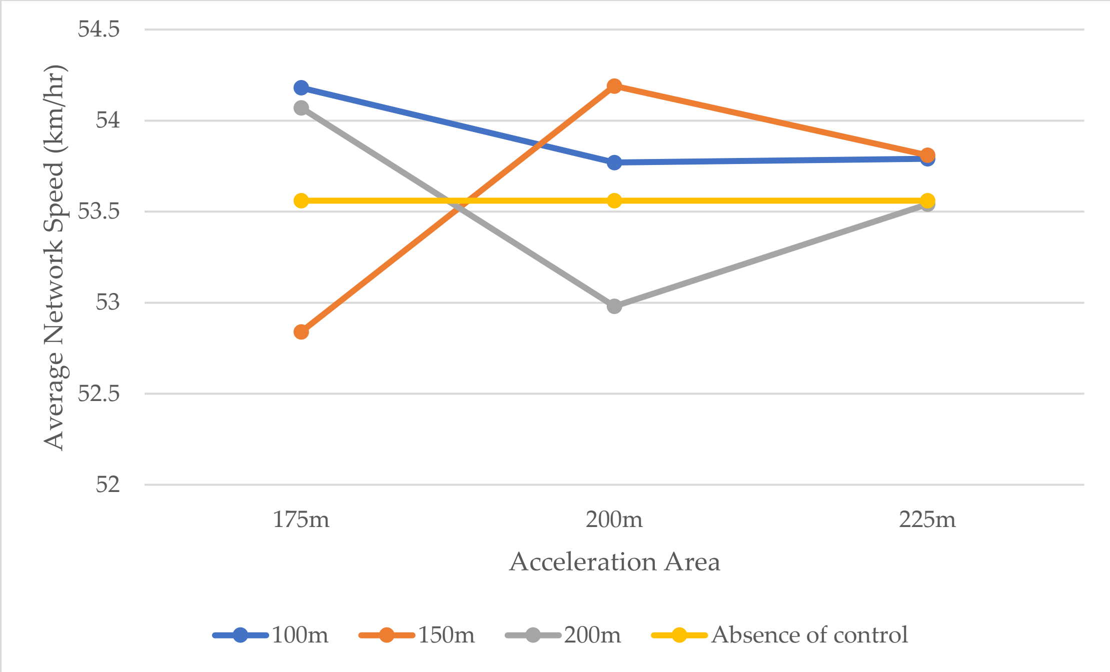


Figure 31: Values of Average Network Speed for various acceleration areas plotted for different VSL application areas

6.2.2. Feedback MTFC- VSL control effectiveness

Following up from the analysis carried out in the previous section, in this section, the effectiveness of MTFC-VSL control with the best performing combination for Scenario 1 with the application and acceleration area lengths of 150 and 200 m respectively, will be analyzed for other scenarios of mixed traffic, except scenario 7 (100% CAV's). Because, as evident from section 6.1 for Scenario 7 in the absence of control, breakdown doesn't occur. After analyzing the effectiveness, the effectiveness of another variant of the same algorithm with some modifications with respect to the desired speed distribution of HDV's to the speed limits will be elaborated as well.

Feedback MTFC-VSL control

Peculiarities of the control:

Application area:	150m
Acceleration area:	200m
Control law:	$b(k) = b(k-1) + 0.08 * (20 - o_{out}(k))$
Other information:	All the *practical considerations* elaborated in section 6.2.1 are considered.

<u>*Average of Total Average TT measurements*</u>

Table 26 and Table 27 lists the average of the total average TT of mainline and on-ramp vehicles respectively for various scenarios of traffic during MTFC-VSL control with all the aforementioned peculiarities compared to that during the absence of control. It is evident from Table 26 and Table 27 that improvement in TT as penetration rate of CAV's increases isn't straightforward. In other words, the hypothesis framed in 5.2.5 that "*Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic"* **isn't true.** In fact, for 3 out of 6 scenarios studied, the presence of control worsens the traffic situation for mainline vehicles and for 4 scenarios the traffic conditions worsen for on-ramp vehicles.

Table 26: Average of Total average TT of mainline vehicles (seconds) for various scenarios of traffic in the presence of MTFC-VSL control with 150/200 m (application/acceleration area) in comparison to that of the absence of control.

Scenario no (% CAV)	Average of Total Average TT of mainline vehicles (seconds)		
	MTFC-VSL control (150/200 m)	Absence of control	% Improvement due to MTFC-VSL control
1 (0%)	25031.1	25512.9	1.9
2 (10%)	23025.6	22973.3	- 0.2
3 (20%)	19168.7	18870.9	- 1.6
4 (30%)	14626.4	15259.5	4.1
5 (40%)	11531.4	11175	- 3.2
6 (50%)	9765	9856.3	0.9

Table 27: Average Total Average TT of on-ramp vehicles (seconds) for various scenarios of traffic in the presence of MTFC-VSL control with 150/200 m (application/acceleration area) in comparison to that of absence of control.

Scenario no (% CAV)	Average of Total Average TT of on-ramp vehicles (seconds)		
	MTFC-VSL control (150/200 m)	Absence of control	% Improvement due to MTFC-VSL control
1 (0%)	3188.0	3198.3	0.3
2 (10%)	3220.3	3206.1	- 0.4
3 (20%)	3245.7	3169.7	- 2.4
4 (30%)	3028.0	3070.8	1.4
5 (40%)	2717.2	2654.1	- 2.4
6 (50%)	2342.5	2339.4	- 0.1

Average network speed measurements

Table 28 lists average network speed values for various scenarios of traffic in case of feedback MTFC-VSL control as well in the absence of any control. It also includes % improvement values, which indicates how much % did average network speed improve or degrade, when control was used in comparison to the absence of control. Average speed almost remains the same with or without control, which indicates that the control doesn't have significant effect on the average network speed. *Hence, this further strengthens that the framed hypothesis mentioned earlier isn't true.*

Table 28: Average network speed (km/hr) for various scenarios of traffic in the presence of MTFC-VSL control with 150/200 m (application/acceleration area) in comparison to that of absence of control.

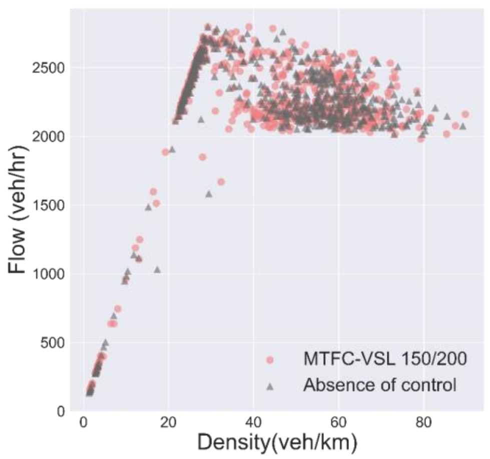
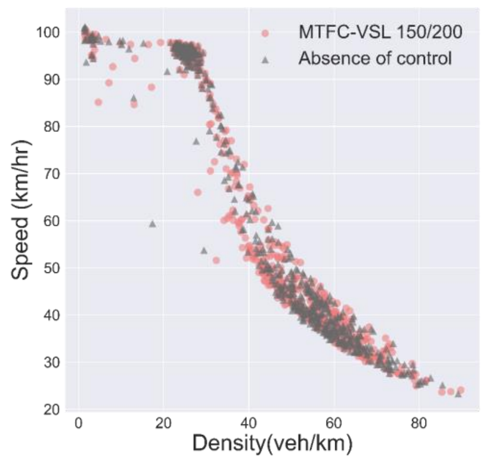
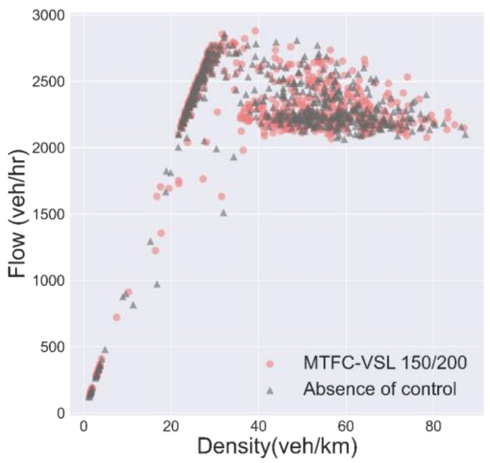
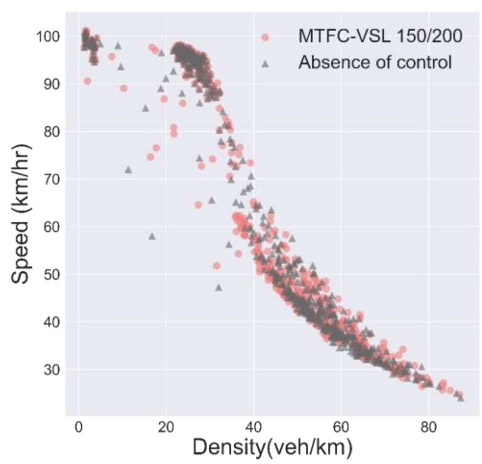
Scenario no (% CAV)	Average Network Speed (km/hr)		
	MTFC-VSL control (150/200 m)	Absence of control	% Improvement due to MTFC-VSL control
1 (0%)	54.2	53.6	1.2
2 (10%)	57.1	57.1	0.1
3 (20%)	63.5	63.7	- 0.2
4 (30%)	73.8	71.6	3.1
5 (40%)	84.2	85.9	- 1.9
6 (50%)	92.8	92.3	0.5

Capacity measurements

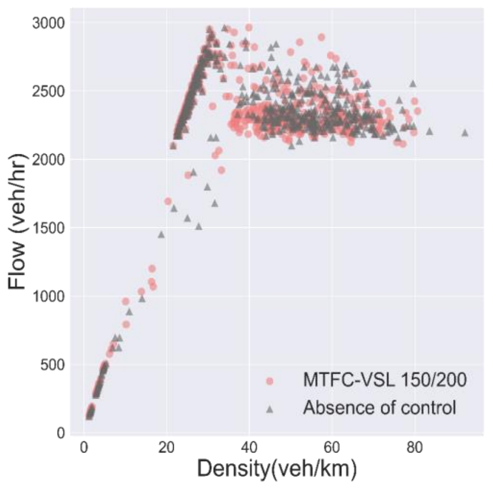
To get better insights into the capacity values, alongside presenting the average breakdown capacity and discharge capacity, Fundamental diagrams (FD's) and boxplots are presented as well. FD's of Average Flow v/s Average Density and Average Density v/s Average Speed help to get insights into the changes of the shape of the FD's in the presence and absence of MTFC-VSL control.

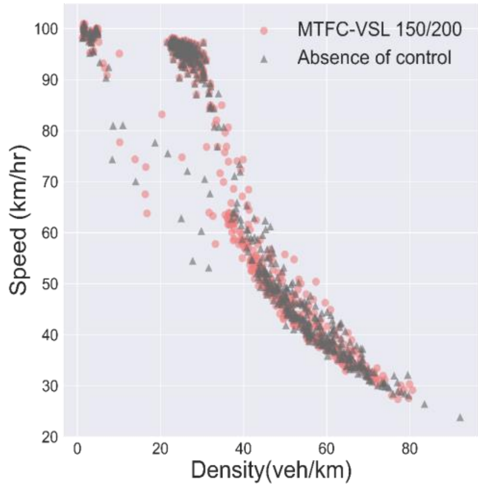
FD's for various scenarios are shown in Figure 32, where data points are obtained from all the 20 simulation runs per scenario and each data point refers to the traffic state measured per 5 minute interval at the bottleneck section (including acceleration lane) positioned at the pair of detectors at the end of the acceleration lane as shown in Figure 25. It's evident from the FD's that the Feedback MTFC-VSL control influences the congested states of the FD. This is intuitive because the control becomes effective once critical occupancy has been reached at the bottleneck, indicating no influence of the control on most of the free flow states. Additionally, the congested states during MTFC-VSL control are more widespread than without the control, but later become streamlined as penetration rate of CAV's increases. *It is to be noted that MTFC-VSL control remains activated unless average bottleneck occupancy is higher than critical occupancy.*

Table 29 lists the average breakdown & discharge capacity and Table 30 lists average capacity drop in the presence and absence of control. In both the cases, Average breakdown capacity almost remains the same, with a slight increase for scenario 3 and 4 during the presence of control compared to the absence. This increase might be attributed to the postponement of traffic breakdown by the feedback MTFC-VSL control, due to which higher number of vehicles are counted at the bottleneck location. With regards to the discharge capacity, scenarios 3,4 and 5 incur decrements during the control compared to the absence. This leads to increase in capacity drop for these scenarios during the presence of control compared to the absence of it.

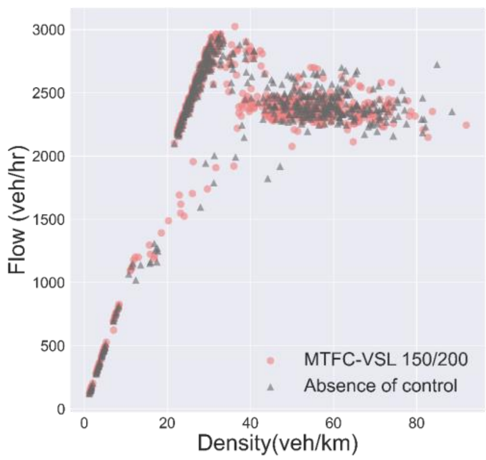
Scenario 1 (0% CAV)	
	
Scenario 2 (10% CAV)	
	

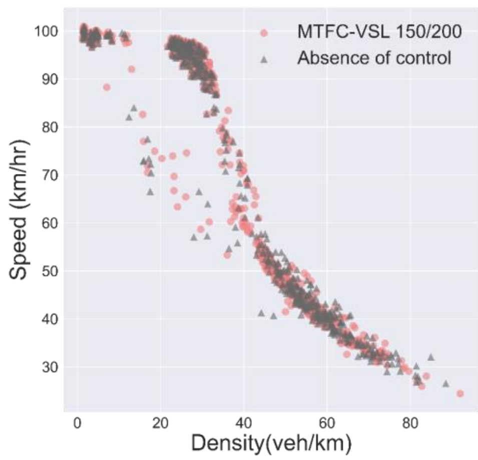
Scenario 3 (20% CAV)



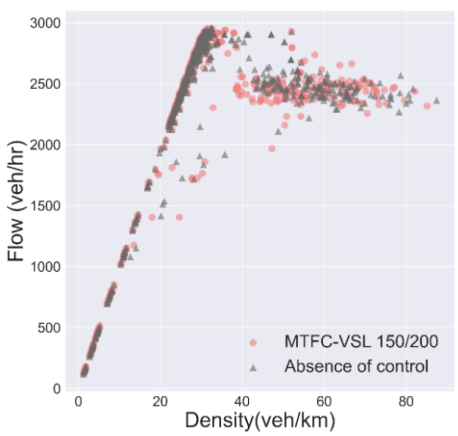


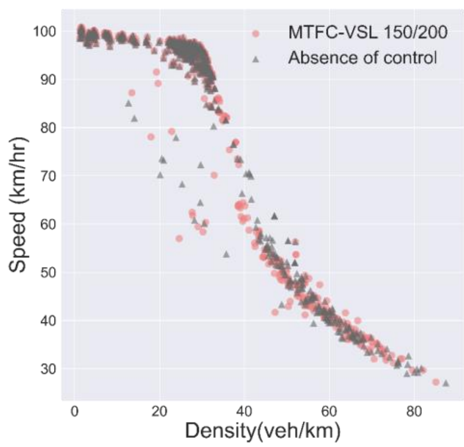
Scenario 4 (30% CAV)





Scenario 5 (40% CAV)





Scenario 6 (50% CAV)

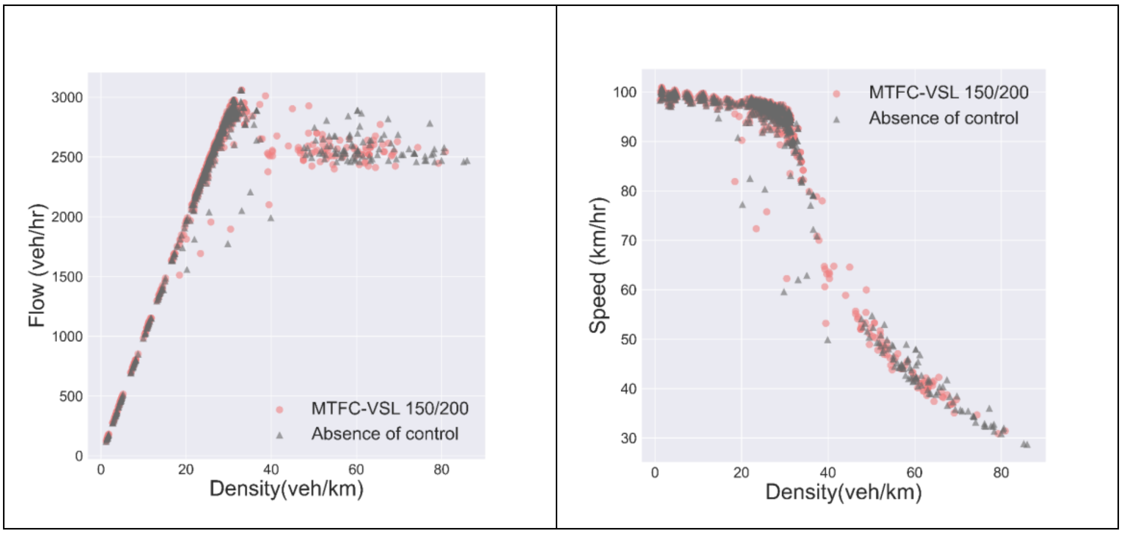


Figure 32: Fundamental Diagrams (FD)'s of Average Flow v/s Average Speed and Average Speed v/s Average Density for various scenarios of traffic in the presence and absence of MTFC-VSL (150/200) control

Overall, it can be concluded that feedback MTFC-VSL control with the peculiarities mentioned before, doesn't have a major influence on addressing capacity drop phenomenon.

Figure 33 and Figure 34 show the boxplot of Breakdown and Discharge Capacity Flow in the presence and absence of control. Boxplots have been plotted just give insights into the spread and outliers, which further gives a perspective on interpreting average values discussed before and listed in Table 29. Except Scenario 6 in case of Breakdown capacity, in other scenarios there are no outliers.

Table 29: Average Breakdown Capacity and Discharge Capacity values for various scenarios of traffic in the presence and absence of MTFC-VSL control (150/200)

Scenario no (% CAV)	Average Breakdown Capacity (veh/hr)			Average Discharge capacity (veh/hr)		
	MTFC-VSL control (150/200 m)	**Absence of control**	**% improv-ement due to control**	**MTFC-VSL control (150/200 m)**	**Absence of control**	**% improv-ement due to control**
1 (0%)	2678	2663	0.6	2560	2558	0.1
2 (10%)	2705	2704	0	2592	2585	0.3
3 (20%)	2828	2792	1.3	2627	2590	1.4
4 (30%)	2871	2840	1.1	2538	2585	-1.8
5 (40%)	2897	2902	-0.2	2586	2614	-1.1
6 (50%)	2951	2960	-0.3	2687	2736	-1.8

Table 30: Average Capacity drop values for various scenarios of traffic in the presence and absence of MTFC-VSL control (150/200)

Scenario no (% CAV)	Average Capacity Drop (veh/hr)		
	MTFC-VSL control (150/200 m)	**Absence of control**	**% improvement due to control**
1 (0%)	118	105	-12
2 (10%)	113	119	5
3 (20%)	201	202	0.5
4 (30%)	333	255	-30.6
5 (40%)	311	288	-8.0
6 (50%)	270	224	-20.5

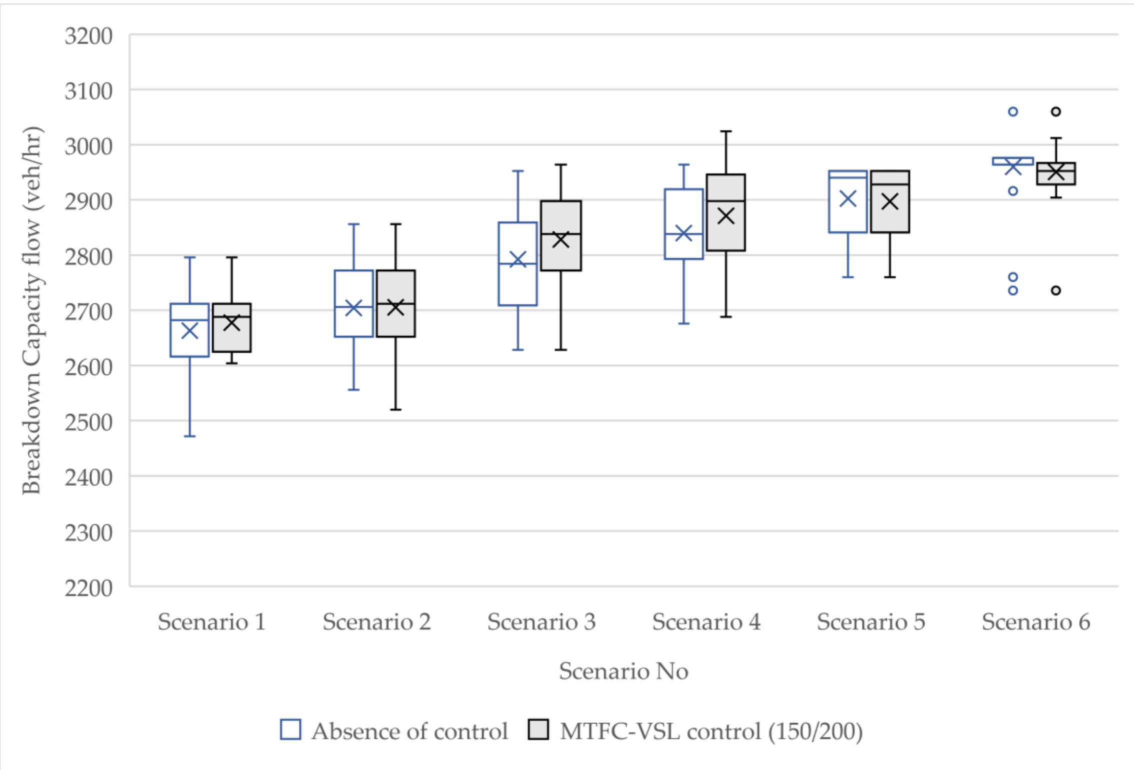


Figure 33: Boxplot of Breakdown capacity flow for various scenarios of traffic in the presence and absence of MTFC-VSL control (150/200)

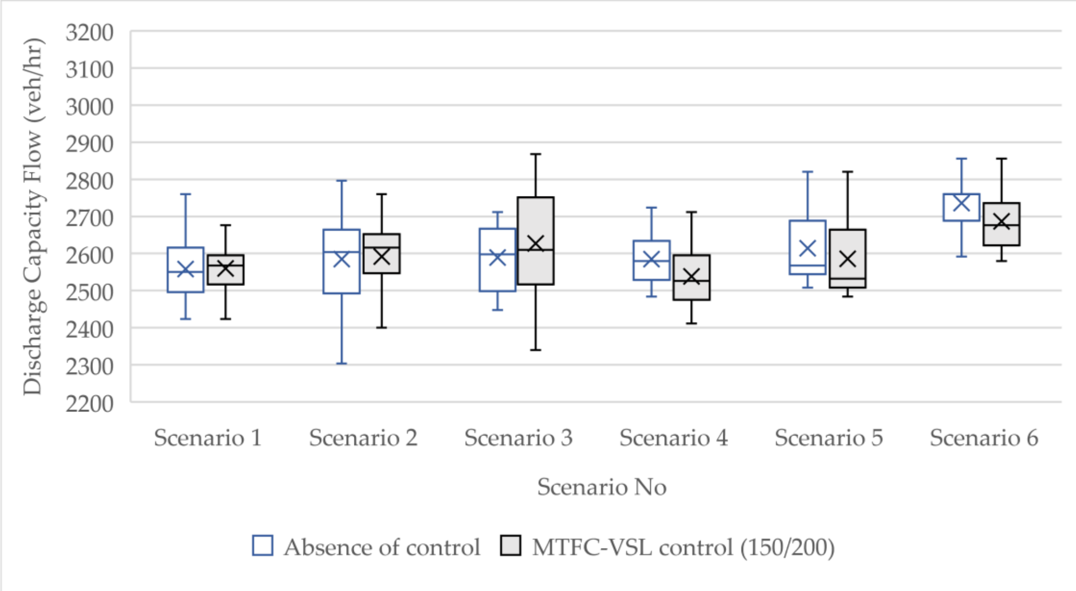


Figure 34: Boxplot of Discharge capacity flow for various scenarios of traffic in the presence and absence of MTFC-VSL control (150/200)

So far, how the presence of feedback MTFC-VSL control effects the various KPI's compared to the absence of control was discussed. Now, how the presence of another variant of the same MTFC-VSL control with the only modification with respect to the *desired speed distribution of HDV's* to the speed limits, effects the KPI's compared to the absence of the control will be discussed. In the new variant of the feedback MTFC-VSL control, the desired speed distribution of HDV's to the displayed and nominal speed limit is changed from ±5km/hr to ≤ 5 km/hr. The main reason of the change is to mimic the effect of Intelligent Speed Adaptation (ISA) being installed in HDV's.

ISA are in-vehicle systems which ensure safety on roads by continuous improvement of driver compliance with speed limits. They can either be *mandatory* or *voluntary* and foster speed limit compliance by giving speed limit information to the driver, excess speed warning, and/or automatic throttle and brake control to regulate speed (Blum & Eskandarian, 2006). ISA can be categorized based on three different criteria: *the calculation of the system speed limit, warning/control type, and the user interface*. Among these, the first two are of significant relevance in this research. With regards to *the calculation of the system speed limit,* the ISA systems can have one speed limit at which it gets activated (*fixed*), or system which changes its speed limit based on the current road (*variable*), the speed limit of which can either be communicated through road side beacon-based wireless communication or autonomously by equipping vehicles with GPS and digital maps or along with adjusting speed along the roadway, speed limits can be adjusted depending on weather conditions or congestion (*dynamic*). With regards to *warning/control type*, the system can be *advisory* (provide info/warnings), *voluntary* (can be overridden by the driver) or *mandatory* (cannot be overridden) (Blum & Eskandarian, 2006).

Thereby, for this new variant of MTFC-VSL control, it can be presumed that *all* HDV's have ISA installed as an On-Board Unit (OBU) and the category of ISA with regards to *the calculation of the system speed limit,* is presumed of the type *variable,* where in the vehicle adapts to the speed limits displayed by the VSL as they travel along the network. With regards to the *warning/control type,* ISA *is* presumed of the type *mandatory* with automatic throttle/brake control, which indicates that ISA is activated all the time and it limits exceeding the displayed and nominal speed limits. Consequently, given this presumption of ISA, for this new variant of feedback MTFC-VSL control the desired speed distribution of HDV's to the displayed and nominal speed limit is changed from ±5km/hr to ≤ 5 km/hr. For example, in simulation HDV's are assigned a desired speed between 85 to 90km/hr if 90km/hr speed limit is displayed rather than desired speed being assigned between 85 to 95 km/hr. This new variant of feedback MTFC-VSL control is hereafter named as MTFC-VSL-ISA control.

Feedback MTFC-VSL-ISA control

Peculiarities of the control:

Application area:	150m
Acceleration area:	200m
Control equation:	$b(k) = b(k-1) + 0.08 * (20 - o_{out}(k))$
Others:	All the practical consideration elaborated 6.2.1 are considered with the change in *desired speed distribution* of all HDV's to the displayed and nominal speed limit from ± 5 km/hr to ≤ 5 km/hr

Average of the Total average TT measurements

From the Table 31 and Table 32, which represent average of the total average TT of mainline and on-ramp vehicles values for various scenarios of traffic, it's clear that the with the presence of MTFC-VSL-ISA control, hypothesis stated before in 5.2.5, that "*Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic"* **doesn't hold good** even when the speed heterogeneity is reduced by 5 km/hr for HDV's. Mainline vehicles in scenarios 3, 5 and 6 are better off in the absence of control compared to the presence, whereas the control algorithm is very effective for Scenario 1 which shows the best improvement among other scenarios compared to the absence of control.

With regards to on-ramp vehicles, except scenario 1, on-ramp vehicles of all scenarios incur delays. This probably indicates that more on-ramp vehicles have to slow down/come to a stop at the end of the acceleration lane to merge during the control than in the absence of control. Scenario 5 performs worst among other scenarios.

It must be taken into account that as the desired speed distribution of HDV's has been reduced by 5 km/hr, the free flow travel time increases, compared to travel times in the case of absence of control where HDV's have desired speed distribution of ±5km/hr when following nominal speed limit of 100km/hr. Hence, considering this, it is reasonable to consider that an increase in travel time by 200 seconds for mainline vehicles and 45 seconds for on-ramp vehicle is due to decreased desired speed heterogeneity. Thereby, in that case, scenario 6 both in case of on-ramp vehicles and mainline vehicles, and scenario 2 & 4 in case of on-ramp can be considered as neither improvement nor degradation. Overall, it can be said that with respect to Average of the total average TT, apart from scenario 3 and 5, this combination seems to show positive improvements.

Average Network Speed measurements

Based on the values presented in Table 33 and given that desired speed of HDV's is decreased by 5 km/hr, Scenario 1 incurs highest and noticeable positive improvement compared to others, while the vice-versa occurs for Scenario 5. For other scenarios the average speed more or less remains similar to that of the absence of control, indicating lesser influence of feedback MTFC-VSL-ISA control on network speed, similar to that of feedback MTFC-VSL control.

Table 31: Average of Total average TT of mainline vehicles (seconds) for various scenarios of traffic in the presence of MTFC-VSL-ISA control with 150/200 m (application/acceleration area) in comparison to that of the absence of control.

Scenario no (% CAV)	**Average of Total average TT of mainline vehicles (seconds)**		
	MTFC-VSL-ISA control (150/200 m)	**Absence of control**	**% Improvement due to MTFC-VSL-ISA control**
1 (0%)	23880.7	25512.9	6.4
2 (10%)	22548.0	22973.3	1.9
3 (20%)	19407.5	18870.9	-2.8
4 (30%)	15167.8	15259.5	0.6
5 (40%)	12824.8	11175	-14.8
6 (50%)	9939.7	9856.3	-0.8

Table 32: Average of Total average TT of on-ramp vehicles (seconds) for various scenarios of traffic in the presence of MTFC-VSL-ISA control with 150/200 m (application/acceleration area) in comparison to that of the absence of control.

Scenario no (% CAV)	Average of Total average TT of on-ramp vehicles (seconds)		
	MTFC-VSL-ISA control (150/200 m)	Absence of control	% Improvement due to MTFC-VSL-ISA control
1 (0%)	3183.75	3198.3	0.5
2 (10%)	3248.06	3206.1	-1.3
3 (20%)	3221.36	3169.7	-1.6
4 (30%)	3115.87	3070.8	-1.5
5 (40%)	3002.54	2654.1	-13.1
6 (50%)	2372.36	2339.4	-1.4

Table 33: Average network speed for various scenarios of traffic in the presence of MTFC-VSL-ISA control with 150/200 m (application/acceleration area) in comparison to that of the absence of control.

Scenario no (% CAV)	Average Network Speed (km/hr)		
	MTFC-VSL-ISA control (150/200 m)	Absence of control	% Improvement due to MTFC-VSL-ISA control
1 (0%)	55.8	53.6	4.2
2 (10%)	57.5	57.1	0.8
3 (20%)	62.7	63.7	-1.6
4 (30%)	72.0	71.6	0.7
5 (40%)	78.5	85.9	-8.6
6 (50%)	91.3	92.3	-1.1

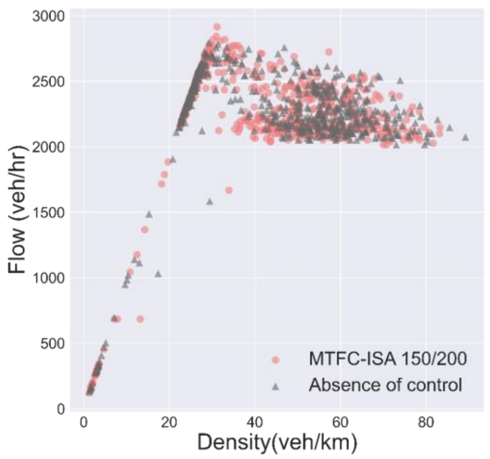
<u>*Capacity measurements*</u>

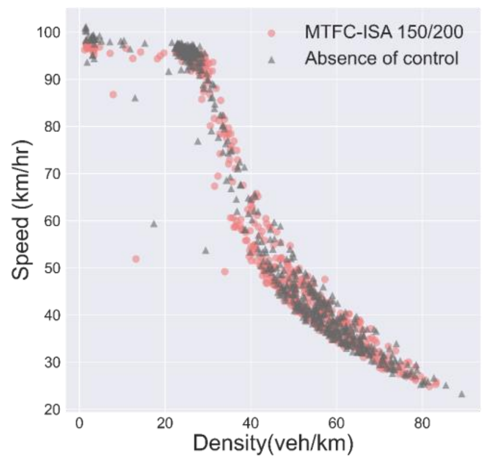
From the Average Speed v/s Average Density FD's for all the scenarios displayed in Figure 35, it's clear that MTFC-VSL-ISA shifts downwards compared to that of absence of control, owing to the reason that the desired speed of distribution has been decreased by 5 km/hr for HDV's. Additionally, congested states occur more frequently and are more spread out, compared to the absence of control.

Before discussing about the average breakdown capacity and discharge capacity values, the boxplots of them are looked into as shown in Figure 36 and Figure 37. Apart from scenario 6 with regards to breakdown capacity, other scenarios have no effect of outliers on the average breakdown and discharge capacity values listed in Table 34. Scenario 6 has outliers due to the reason that not all of 20 runs simulated undergo breakdown leading to lesser and varying values for breakdown capacity.

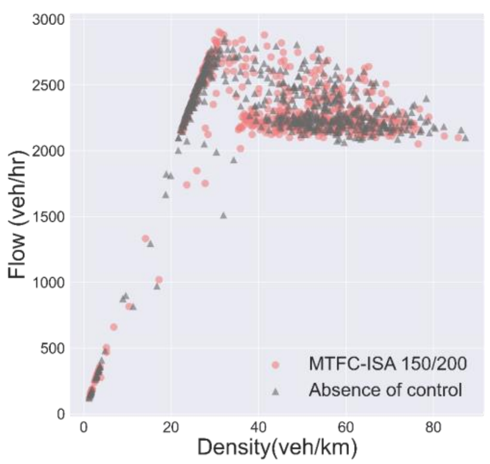
With regards to average breakdown capacity and discharge capacity values shown in Table 34, Scenario 5 and 6 experience a decrement in breakdown capacity, other scenarios show an increase in breakdown capacity. With regards to discharge capacity, 5 out of 6 scenarios, experience lesser discharge rate. Overall, it can be concluded that with increase in breakdown capacity for most of the scenarios and decrease in discharge capacity for those scenarios, leads to increasing the value of Capacity drop in the presence of MTFC-VSL-ISA control, the values of which are shown in Table 35.

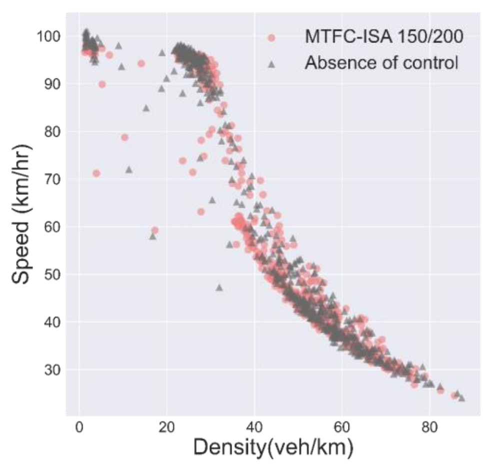
Scenario 1 (0% CAV)



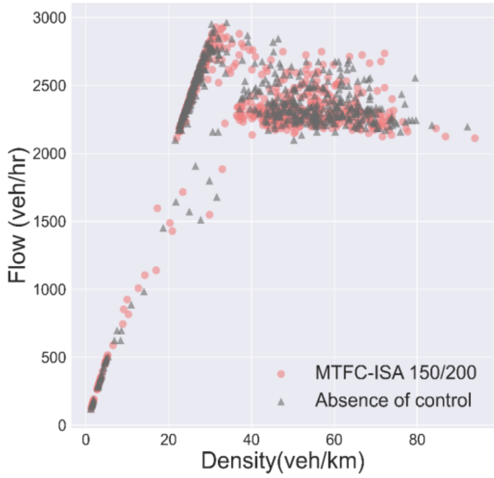


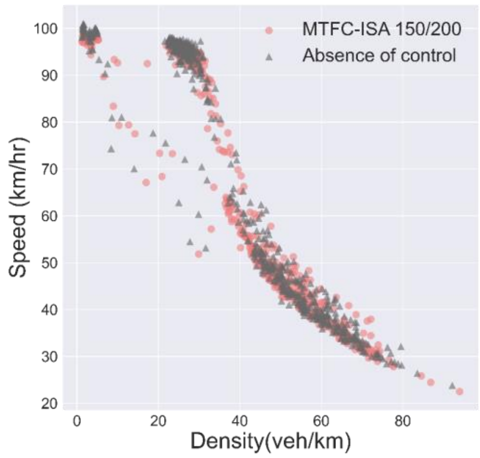
Scenario 2 (10% CAV)



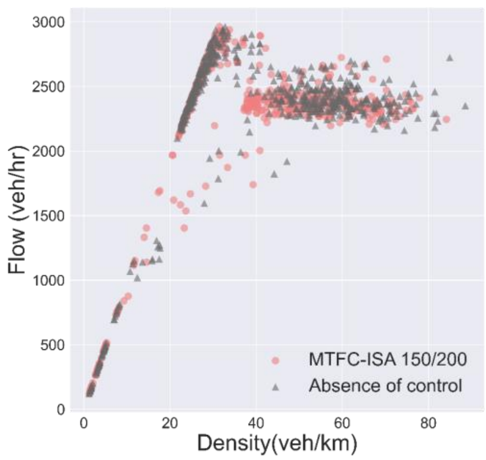


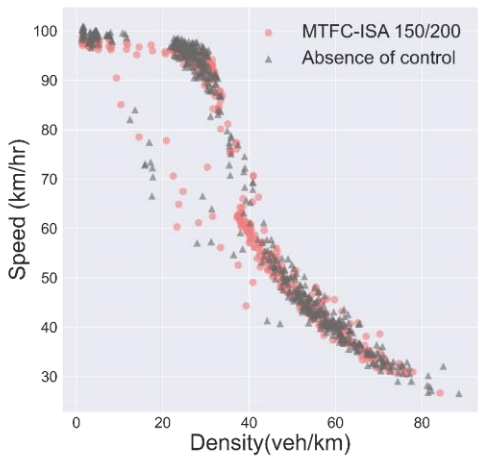
Scenario 3 (20% CAV)



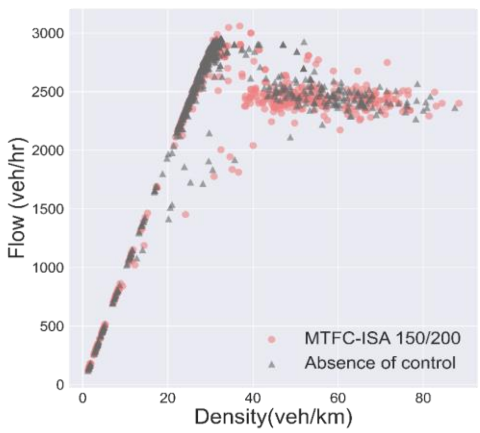


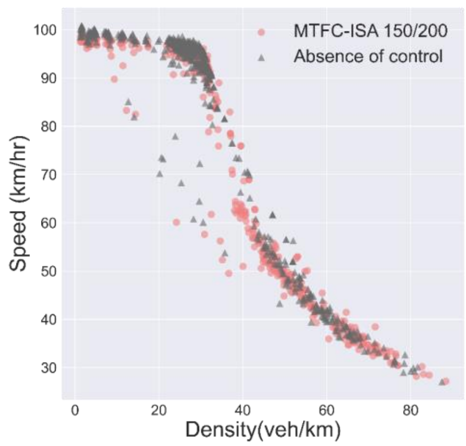
Scenario 4 (30% CAV)





Scenario 5 (40% CAV)





Scenario 6 (50% CAV)

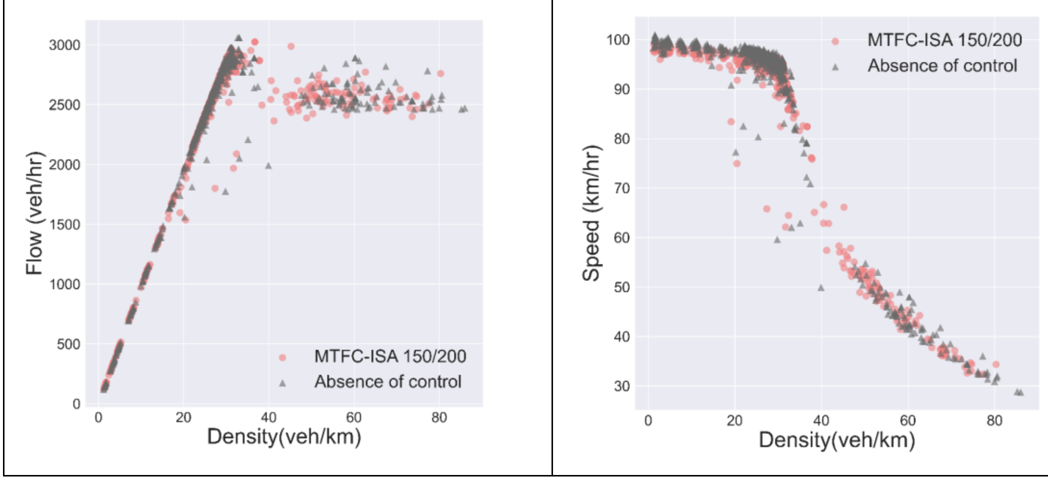


Figure 35: Fundamental Diagrams (FD)'s of Average Flow v/s Average Speed and Average Speed v/s Average Density for various scenarios of traffic in the presence and absence of MTFC-VSL-ISA (150/200) control

Table 34: Average Breakdown Capacity and Discharge Capacity values for various scenarios of traffic in the presence and absence of MTFC-VSL-ISA control (150/200)

Scenario no (% CAV)	**Average Breakdown Capacity (veh/hr)**			**Average Discharge capacity (veh/hr)**		
	MTFC-VSL-ISA (150/200 m)	**Absence of control**	**% improv-ement due to control**	**MTFC-VSL-ISA (150/200 m)**	**Absence of control**	**% improv-ement due to control**
1 (0%)	2734	2663	2.7	2518	2558	-1.6
2 (10%)	2742	2704	1.4	2600	2585	0.6
3 (20%)	2790	2792	-0.1	2585	2590	-0.2
4 (30%)	2853	2840	0.5	2557	2585	-1.1
5 (40%)	2885	2902	-0.6	2596	2614	-0.7
6 (50%)	2932	2960	-0.9	2709	2736	-1.0

Table 35: Average Capacity drop values for various scenarios of traffic in the presence and absence of MTFC-VSL-ISA control (150/200)

Scenario no (% CAV)	Average Capacity Drop (veh/hr)		
	MTFC-VSL-ISA (150/200 m)	Absence of control	% improvement due to control
1 (0%)	216	105	-105.7
2 (10%)	142	119	-19.3
3 (20%)	205	202	-1.5
4 (30%)	296	255	-16.1
5 (40%)	289	288	-0.3
6 (50%)	223	224	0.4

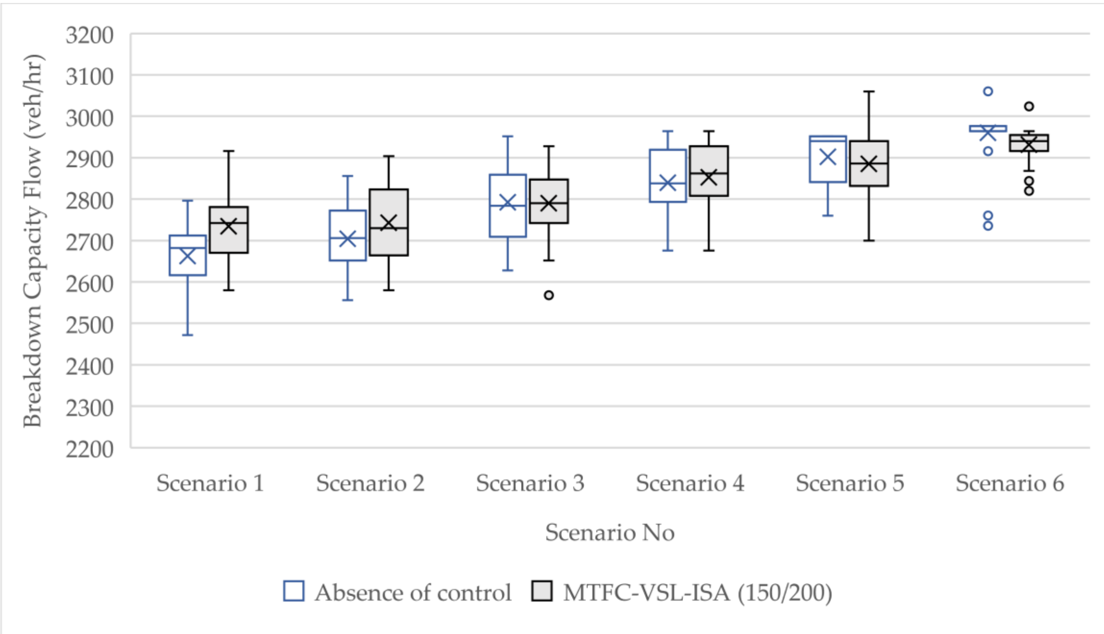


Figure 36: Boxplot of Breakdown capacity flow for various scenarios of traffic in the presence and absence of MTFC-VSL-ISA control (150/200)

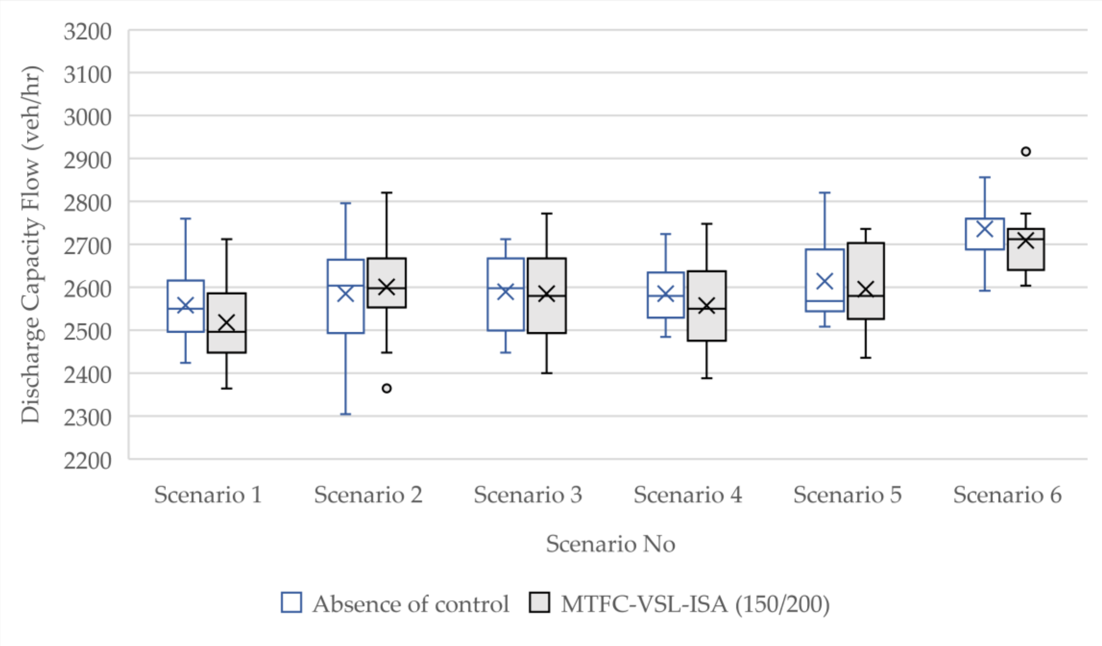


Figure 37: Boxplot of Discharge capacity flow for various scenarios of traffic in the presence and absence of MTFC-VSL-ISA control (150/200)

6.2.3. Comparison Analysis

Having discussed the effectiveness of feedback MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200) control in addressing traffic breakdown, (150/200 stands for lengths of VSL application/acceleration area), based on various KPI's in the previous section, in this section, comparison analysis between those two variants of Feedback MTFC-VSL control will be discussed which will help to give a good overview about the suitability of the variants (also to deduce some overall trends). Lastly, as discussed in section 6.2.1, these aforementioned two variants will be compared with the MTFC-VSL (150/175) and MTFC-VSL-ISA (150/175) control to see if the worst performing combination of acceleration/application area of 150/175 for Scenario 1 performs worst for other scenarios as well and if not, how better than 150/200 variants.

Comparison between MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200)

Average of Total average TT and Average Network Speed measurements

Figure 38 and Figure 39 show the % improvement of Average of the total average TT of mainline and on-ramp vehicles in the presence of MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200) with respect to the absence of control for various scenarios of traffic. From both the figures one thing is straightway clear that the hypothesis that *"Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic"* **doesn't hold good** for both the variants of Feedback MTFC-VSL controls studied. Thereby, this indicates that the best performing set-up of MTFC-VSL for Scenario 1 (0% CAV), i.e., with application and acceleration area of 150 and 200 m respectively as discussed in section 6.2.1 cannot be presumed that it will perform best for other scenarios with increasing penetration rate of CAV's (with ACC and CACC functionality).

For the both the variants of Feedback MTFC-VSL control, with regards to the quantitative improvements of average of the total average TT of mainline vehicles, a decreasing trend is observed as penetration rate of CAV's (with ACC and CACC functionality) increases, until 20% penetration rate. Further, the decreasing trend is interrupted by Scenario 4 where an improvement is evident. Later, the decreasing trend is back for Scenario 5, which is the worst performing scenario among others under the influence of both the Feedback MTFC-VSL control variants. Further on, there is an improvement for Scenario 6. MTFC-VSL-ISA shows significant improvements for Scenario 1 and 2. This gives some positive indication that for traffic mostly comprising of HDV's or with less than 20% CAV (with ACC and CACC functionality) penetration rate, having ISA installed in HDV's which is activated all the time where in it adjusts the vehicle speed to the different speed limits available along the road and also limits exceeding the speed limits with automatic throttle/brake control might positively effect safety as well as traffic performance in the presence of Feedback MTFC-VSL control compared to the absence of control as well as absence of ISA installed as an OBU in HDV's in presence of Feedback MTFC-VSL control.

Figure 40 depicts the % improvement in average network speed in the presence of MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200) with respect to the absence of control for various scenarios of traffic. As the trend in Figure 40 is similar to that of the average of the Total average TT of mainline vehicle i.e., of Figure 38, the analysis in the previous paragraph holds good to Average network speed as well.

With regards to the average of the total average TT of on-ramp vehicles, irrespective of the type of Feedback MTFC-VSL control, overall, the TT of on-ramp vehicles degrades.

Based on the discussion carried out so far, two questions arise. Why is there a decreasing trend of average of the total average TT and network speed? Why does the aforementioned hypothesis doesn't hold good? There could be a lot of reasons which could be hypothesized why this could be the case. These reasons can be divided into two broad categories. One relates to the peculiarities of the *set-up of the Feedback MTFC-VSL control* and other relates to peculiarities of *set up of driving behavior of HDV's and CAV's (with ACC and CACC functionality)* in *simulation*.

Regarding the peculiarities of the *set-up of the Feedback MTFC-VSL control,* one of the major influences on the effectiveness of the control is related to the various aspects of *practical considerations* as discussed in section 6.2.1. These practical considerations hinder the effectiveness of the control by imposing *spatial and temporal constraints* of applying the speed limits, translation of speed limit values given as the output of the Feedback MTFC-VSL control law into *discrete values* due to which the effectiveness is not pronounced to its full extent. Apart from the *practical considerations,* the control depends on several parameters as discussed in section 6.2.1. Two among them which *might* vary as penetration rate of CAV's (with ACC and CACC functionality) increases in mixed traffic are, *Linearity check (Linear relationship between capacity flow induced by speed limit)* and the suitable *combination of application and acceleration area*. Based on Linearity check, the integral gain of the feedback control law K_I is decided, thereby, it could be that Figure 26 which is based on Scenario 1 might look different for other Scenarios. Considering combination of application area and acceleration area lengths, it might be that other combination of application and acceleration area apart from 150/200 might be better for other scenarios.

With regards to the peculiarities of *driving behavior set up of HDV's and CAV's (with ACC and CACC functionality) in simulation*, it *might* be that the difference between parameters values of W99 which are set differently for CAV's (with ACC and CACC functionality) and HDV's and also the *implicit stochastics* which is switched off for CAV's and on for HDV's in Vissim, might worsen the traffic performance under the presence of Feedback MTFC-VSL control as penetration rate of CAV's increases. Furthermore, it might also be that the different *desired speed distribution* of CAV's and HDV's which is set in simulation while following the speed limits might cause a degradation in traffic performance in the presence of Feedback MTFC-VSL control. In other words, in simulation, CAV's (with ACC and CACC functionality) exactly follow the speed limits, whereas HDV's desired speed is allocated from a distribution of ±5km/hr of the speed limit (in case of absence of control and in the presence of MTFC-VSL control) and from a distribution of ≤ 5 km/hr of the speed limit (in the presence of MTFC-VSL-ISA control). Having this difference of how the speed limit is followed *might* cause a degradation in traffic performance in the presence of Feedback MTFC-VSL control.

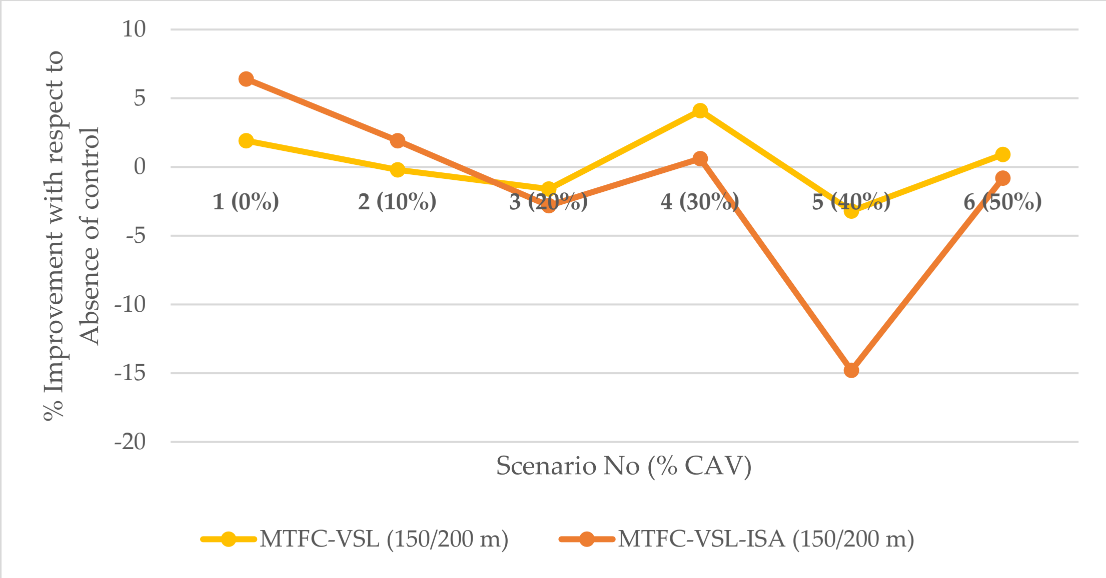


Figure 38: % improvement of Average of Total average TT of mainline vehicles for various scenarios of traffic in the presence of MTFC-VSL (150/200) & MTFC-VSL-ISA (150/200) control with respect to absence of control.

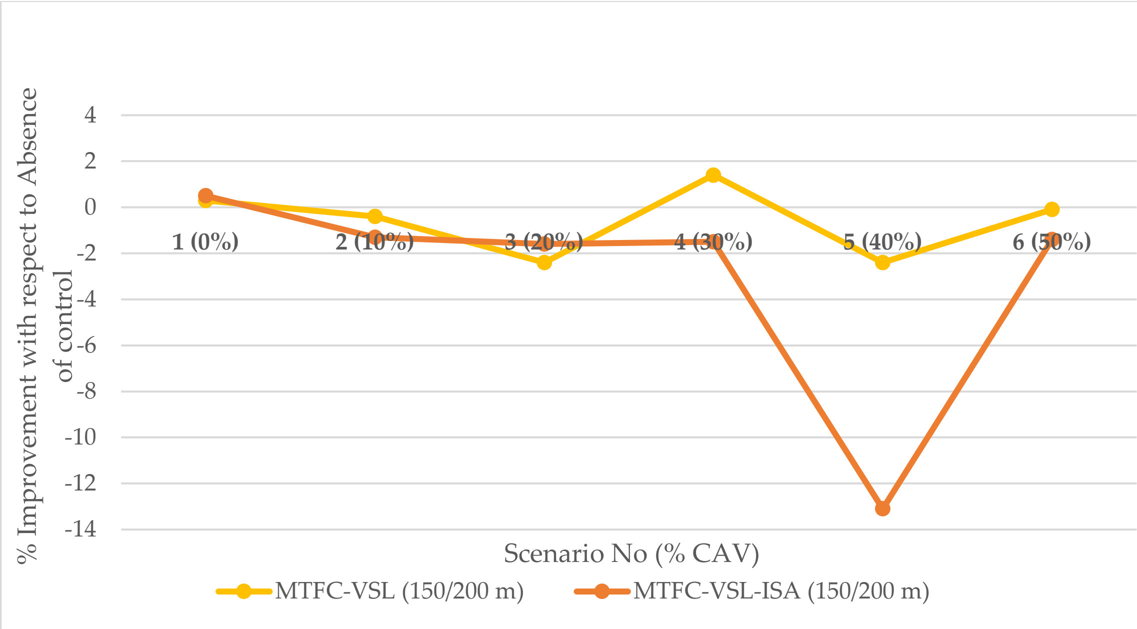


Figure 39: % improvement of Average of Total average TT of on-ramp vehicles for various scenarios of traffic in the presence of MTFC-VSL (150/200) & MTFC-VSL-ISA (150/200) control with respect to absence of control.

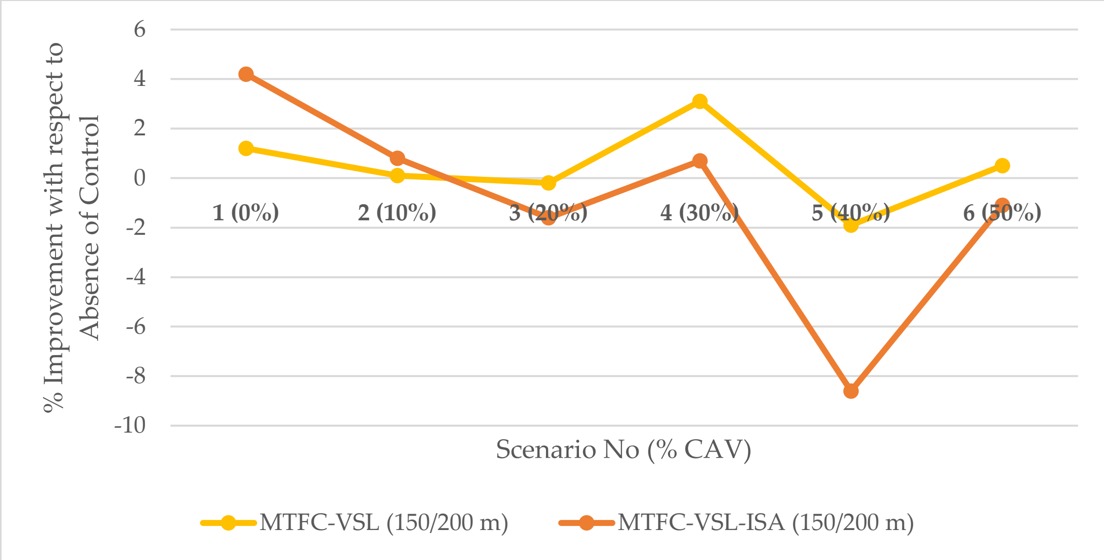


Figure 40: % improvement of Average Network speed for various scenarios of traffic in the presence of MTFC-VSL (150/200) & MTFC-VSL-ISA (150/200) control with respect to absence of control.

Capacity measurements

From the first glance of Figure 41, from the trends of both the Feedback MTFC-VSL control variants, it's probable that for certain scenarios where Average Breakdown Capacity has improved, that MTFC-VSL postpones the traffic breakdown occurrence. From Scenario 4 (30% CAV's), the trend is similar for both the variants of Feedback MTFC-VSL control, with ISA variant being less effective. Before, 30% CAV's, the trend is quite different for both the variants of Feedback MTFC-VSL control. Overall, Feedback MTFC-VSL control compared to the absence of control can be expected to either increase the average breakdown capacity or have no effect for various scenarios of traffic studied.

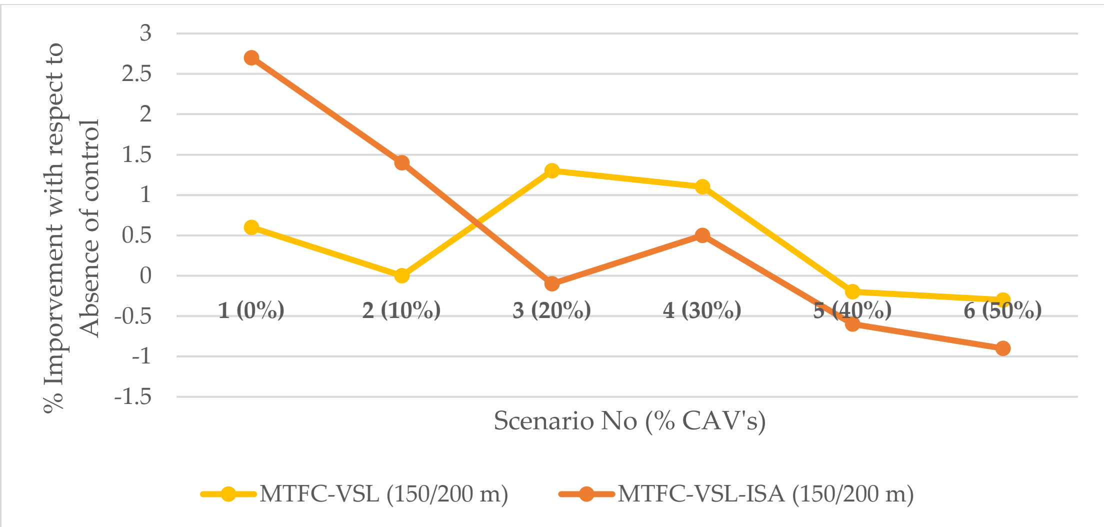


Figure 41: % improvement of Average Breakdown capacity for various scenarios of traffic in the presence of MTFC-VSL (150/200) & MTFC-VSL-ISA (150/200) control with respect to absence of control.

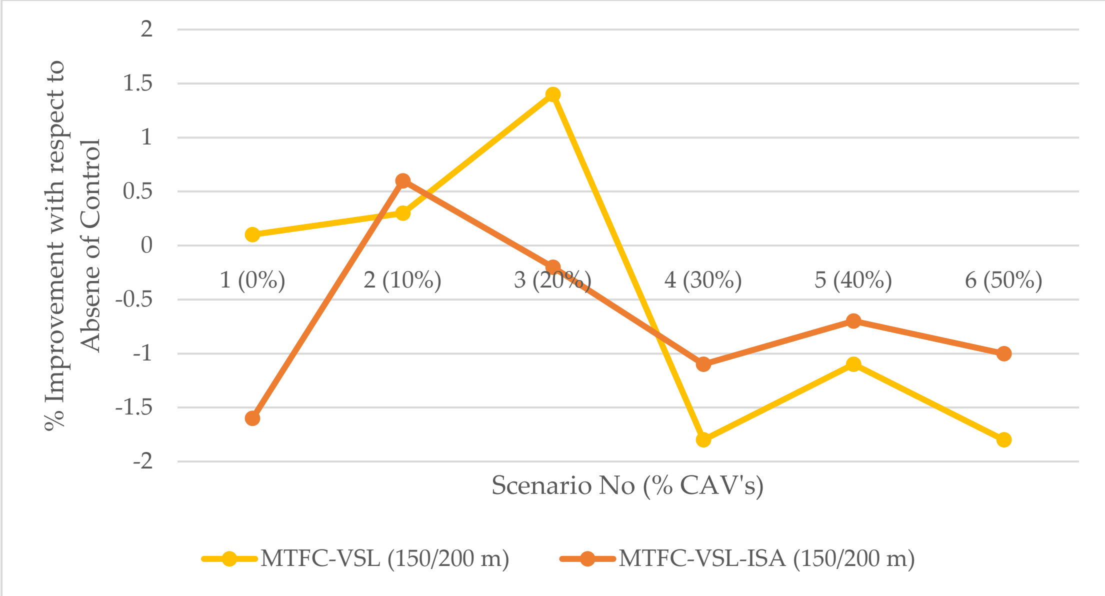


Figure 42: % improvement of Average Discharge capacity for various scenarios of traffic in the presence of MTFC-VSL (150/200) & MTFC-VSL-ISA (150/200) control with respect to absence of control.

Regarding Average Discharge capacity improvement under the presence of both the variants of Feedback MTFC-VSL control algorithms compared to the absence of control as shown in Figure 42, from Scenario 4 (30% CAV) onwards, the deterioration trend is similar for both variants of feedback MTFC-VSL control, with ISA variant better than the other. The lower values of Average Discharge Capacity in the presence of Feedback MTFC-VSL control *could* be attributed to the reason that, unless average occupancy of the bottleneck is less than critical occupancy, Feedback MTFC-VSL control remains activated, mostly displaying 50km/hr (the lowest allowable speed limit) at VSL sign b in Figure 25 when bottleneck is completely congested, indicating that vehicles in the application area and upstream of it drive according to the speed limits, unlike in the absence of control where in vehicles drive at nominal speed limit even when traffic breakdown occurs. Hence, there might be a possibility of lesser vehicle reaching the bottleneck and downstream of bottleneck in the presence of Feedback MTFC-VSL control, leading to lesser discharge rate.

Comparison between MTFC-VSL 150/200, MTFC-VSL-ISA 150/200, MTFC-VSL 150/175 and MTFC-VSL-ISA 150/175

Along with the two variants of Feedback MTFC-VSL control with 150/200 application/acceleration area combination which was the best performing combination for Scenario 1, the same two variants of Feedback MTFC-VSL control with changes of 150/175 application/acceleration area combination, which was the worst performing combination for Scenario 1, was also checked for other scenarios to see if the worst performing combination for Scenario 1 would perform the worst for other scenarios as well. With regards to Average of the total average TT of mainline and on-ramp vehicles and average network speed, its seen that overall, MTFC-VSL 150/175 and MTFC-VSL-ISA 150/175 perform worse compared to MTFC-VSL 150/200 and MTFC-VSL-ISA 150/200 respectively, indicating that the worse performing application/acceleration combination doesn't seem to improve for other scenarios of mixed traffic.

6.2.4. Further Analysis

In the previous section it was discussed that peculiarities related to *set-up of the Feedback MTFC-VSL control* and to that of the *setup of driving behavior of HDV's and CAV's (with ACC and CACC functionality)* could be the hypothesized as the reasons for the variants of feedback MTFC-VSL control not working effectively as penetration rate of *CAV's (with ACC and CACC functionality)* increases in mixed traffic. To get some insights into this reasoning, does changes in, *desired speed distribution* (a peculiarity of *simulation)* and *combination of application and acceleration area* (a peculiarity of the *Feedback MTFC-VSL control algorithm)* bring in improvements in some of the KPI's in mixed traffic will be discussed in this section.

As discussed in section 6.2.2, the presence of MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200) control increases the Average of the total average TT for certain scenarios of traffic compared to the absence of it. This might indicate that under the influence of Feedback MTFC-VSL control, the *desired speed heterogeneity*, where in CAV's exactly follow the speed limits and HDV's follow with ± 5 km/hr of the displayed speed limit in case of MTFC-VSL (150/200) and ≤ 5 km/hr in case of MTFC-VSL-ISA (150/200), might degrade the traffic performance. Thereby, it might be that having *different desired speed distribution* worsens the traffic in the presence of Feedback MTFC-VSL control. Hence, to check whether having same desired speed distribution, i.e., CAV's driving with the same desired speed distribution as that of HDV's, has an influence on the Feedback MTFC-VSL control effectiveness in mixed traffic, MTFC-VSL (150/200) is simulated with same desired speed distribution of ±5 km/hr of the nominal and displayed speed limits for both CAV's and HDV's. In other words, if Speed Limits display 50 km/hr, both CAV's and HDV's, get assigned desired speed based on linear distribution form 45km/hr to 55km/hr, instead of CAV's being assigned exact 50km/hr which would be the case during different desired speed distribution. Referring to Figure 43, with regards to the average of the total Average TT of mainline vehicles it was found that MTFC-VSL (150/200) with same desired speed distribution performs better than MTFC-VSL (150/200) with different desired speed for Scenario 2, 5 and 6, with scenario 2 and 6 better than absence of control. Furthermore, referring to Figure 44, with regards to the average of the total Average TT of on-ramp vehicles, MTFC-VSL (150/200) with same desired speed distribution performs better in all scenarios except Scenario 4 compared to MTFC-VSL (150/200) with different desired speed distribution and with scenario 2 and 6 performing better than the absence of control.

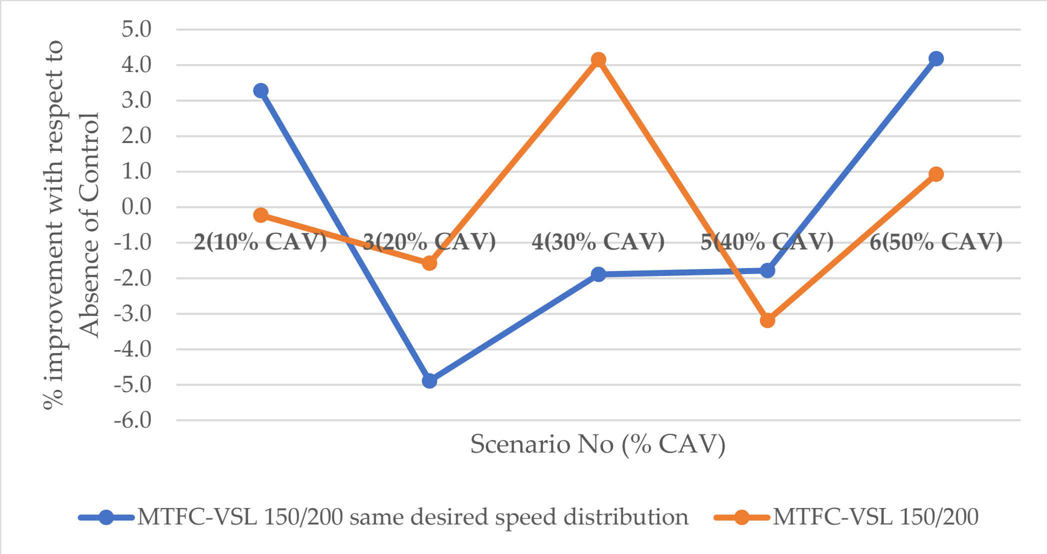


Figure 43: % improvement of Average of Total average TT of mainline vehicles for various scenarios of traffic in the presence of MTFC-VSL (150/200) control with same desired speed distribution & MTFC-VSL (150/200) control with respect to absence of control.

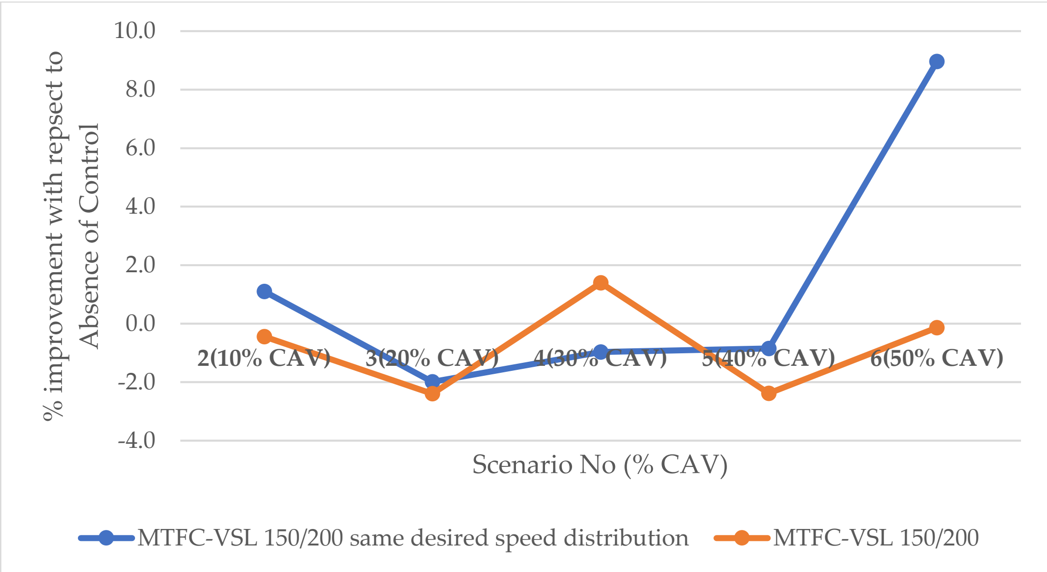


Figure 44: % improvement of Average of Total average TT of on-ramp vehicles for various scenarios of traffic in the presence of MTFC-VSL (150/200) control with same desired speed distribution & MTFC-VSL (150/200) control with respect to absence of control.

On the other hand, one of the peculiarities of the algorithm which influences the Feedback MTFC-VSL control effectiveness is the length of the VSL application and acceleration area as shown in Figure 25. Thereby, to investigate whether changes in the lengths of application/acceleration area incur changes in effectiveness of the Feedback MTFC-VSL control, Scenario 5 (40% CAV) which was the least effective with regards to Average of the total average TT of mainline and on-ramp vehicles and as well as average network speed, in the presence of MTFC-VSL (150/200) as discussed in section 6.2.2, the same variant of the MTFC-VSL control is simulated for other lengths of application and acceleration area. It's found that MTFC-VSL (200/175) effectiveness is better than MTFC-VSL (150/200) for Scenario 5 (40% CAV) with respect to Average of the total average TT of mainline and on-ramp vehicles and average network speed.

To conclude, comparing MTFC-VSL (150/200) control with same desired speed distribution for both CAV's (with ACC and CACC functionality) and HDV's with that of the MTFC-VSL (150/200) control with different desired speed distribution, the former shows improvements compared to the latter in average of the total average TT of mainline vehicles for 3 out of 5 scenarios analyzed and for 4 out of 5 scenarios concerning average of the total average TT of on-ramp vehicles. This gives some new insights that, letting CAV's follow the speed limit exactly in mixed traffic where HDV's follow with some distribution, *might* worsen the traffic, if the traffic is being controlled by Speed limits. However, this hypothesis needs to be further investigated. Concerning, different application/acceleration area length having influence on Feedback MTFC-VSL control effectiveness, for Scenario 5 (40% CAV's) it's found that it has an influence, this might indicate that Feedback MTFC-VSL control with certain lengths of VSL application /acceleration area which shows improvement for a scenario of traffic, cannot be expected to show improvements for other scenarios of traffic. However, this hypothesis needs to be further investigated as well.

6.3. Conclusions

In the previous sections 6.2.2, 6.2.3 and 6.2.4, the effectiveness of feedback MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200) control in addressing traffic breakdown, comparison between the aforementioned two Feedback MTFC-VSL control variants, and some insights into the reasoning of the ineffectiveness of Feedback MTFC-VSL control were investigated. Thereby, in this section the overall gained insights with respect to the effectiveness of the Feedback MTFC-VSL control in addressing traffic breakdown will be summarized thereby answering RQ3, *How effective is the traffic management measure in addressing the traffic flow phenomena for various scenarios of mixed traffic,* reframed after deciding upon the measure and phenomena as, *How effective is the Feedback MTFC-VSL control in addressing the traffic breakdown phenomena for various scenarios of mixed traffic?*

- The hypothesis that *"Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic"* **doesn't hold good** for the variants of Feedback MTFC-VSL control analyzed in this research.

Peculiarities related to set-up of the Feedback MTFC-VSL control and that of set-up of driving behavior of HDV's and CAV's (with ACC and CACC functionality) in simulations could be the reasons of the hypothesis not being valid. In addition, it might be that, based on the *specific* penetration rate of CAV's (with ACC and CACC functionality) in mixed traffic, having *same* desired speed heterogeneity for both HDV's and CAV's and/or *altering* the lengths of VSL application/acceleration area length might increase the effectiveness of Feedback MTFC-VSL control, rather than having *different* desired speed distribution and a *fixed* length of application/acceleration area *irrespective* of the penetration rate of CAV's in mixed traffic. Consequently, this might indicate that based on the penetration rate of CAV's in mixed traffic Feedback MTFC-VSL control needs to be tuned and tailored to increases its effectiveness. However, this reasoning needs to be further investigated.

- For approximately less than 20% CAV's (with ACC and CACC functionality) penetration rate (especially in case of traffic comprising of 100% HDV's), MTFC-VSL-ISA (150/200) shows good improvements in Average of the total average TT of mainline vehicles and average network speed, compared to MTFC-VSL (150/200) and the absence of control. This indicates that when penetration rate of CAV's (with ACC and CACC functionality) is less than 20%, especially in case of traffic comprising of 100% HDV's, it might be a good idea to have ISA installed as an OBU in HDV's. The installed ISA should be activated all the time where in it adjusts and limits (with automatic throttle/brake control) the driver exceeding the different speed limits displayed along the road by Feedback MTFC-VSL control.

- Both the variants of Feedback MTFC-VSL control studied, overall, increase the TT of on-ramp vehicles for most of the scenarios of mixed traffic studied. Hence, in mixed traffic, the on-ramp vehicles are better off in during the absence of control than during the Feedback MTFC-VSL control.

- Overall, both the variants of Feedback MTFC-VSL control for various scenarios of mixed traffic studied either increase Average Breakdown Capacity or have no effect. However, from Scenario 3 (20% CAV's) onwards a degradation in Average Discharge Capacity in the presence of both the variants of Feedback MTFC-VSL control is evident compared to the absence of control. This could be due to the reason that after breakdown speed limits by Feedback MTFC-VSL control might limit the discharge rate compared to no speed limits in the absence of control after breakdown. Consequently, this indicates that in mixed traffic Feedback MTFC-VSL control doesn't effectively address the capacity drop phenomenon, might rather increase it compared to the absence of control.

- MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200) control both influence the FD's for all the scenarios of traffic derived at the merging bottleneck section, specially the congested states, as in most of the free flow states, the control isn't activated. The congested states of FD's are more spread out in case both the variants of Feedback MTFC-VSL control compared to the absence of them, however, the states become streamlined as penetration rate of CAV's (with ACC and CACC functionality) penetration increases in case of MTFC-VSL (150/200).

- *It is important to mention that the insights gained which are discussed in the aforementioned points with respect to the effectiveness of the Feedback MTFC-VSL control in addressing traffic breakdown, irrespective of the driving behavior set up of HDV's and CAV's in simulation, are expected to be dependent on the way Feedback MTFC-VSL control algorithm is set-up in simulation to analyze its effectiveness. In this research, this specifically relates to the* ***practical considerations*** *of implementing Feedback MTFC-VSL control algorithm in real life (as discussed in section 6.2.1) which is used to set up Feedback MTFC-VSL control algorithm.*

- It is to be noted that in this research, in mixed traffic, when CAV's followed preceding CAV's *which were driving with CC1 (desired time gap in W99) value of 0.6s (or 1.0s if the preceding CAV follows HDV),* the follower CAV irrespective of its CC1 value accelerated with extra 10% acceleration if preceding CAV accelerated, *to* mimic the simultaneous acceleration observed empirically when CACC functionality was active. However, had the case been that CAV's accelerated with extra 10% acceleration if the preceding CAV's (*irrespective of preceding CC1 value)* accelerated then the improvements in the simulation results of KPI's studied in this research could be expected to be higher as penetration rate of CAV's (with ACC and CACC functionality) increases. Because, as penetration rate of CAV's (with ACC and CACC functionality) increases in mixed traffic, probability of CAV's following CAV's increases and for instance if breakdown occurs, then *all* CAV's when following other CAV's accelerate with higher (10% extra) leading to better improvements in the KPI's than given in this research.

7. Design of new traffic control measure: Phase 3

In section 6.2, effectiveness of Feedback MTFC-VSL control in addressing traffic breakdown was studied and it was found that overall, Feedback MTFC-VSL control isn't effective enough to address traffic breakdown as penetration rate of CAV's increases in mixed traffic. In other words, the hypothesis framed earlier before simulation and analysis doesn't hold good as shown in Figure 45. This indicates that, in the future, the Feedback MTFC-VSL control alone with all the practical considerations of implementing it, won't be sufficient to influence traffic breakdown phenomenon. Thereby, following from Figure 45 to explore the possibilities of better addressing traffic breakdown in the future together with Feedback MTFC-VSL control, three things need to be considered.

- Address causes of traffic breakdown not being addressed by Feedback MTFC-VSL control, green arrow in Figure 45.
- Better utilize the driving behavior characteristics of AV's (ACC) and CAV's (CACC), yellow arrow in Figure 45.
- Insights gained from the simulation and analysis of MTFC-VSL control in addressing traffic breakdown in mixed traffic, orange arrow in Figure 45.

Hence, in this chapter, Section 7.1 first discusses different possibilities of better addressing traffic breakdown in conjunction with MTFC-VSL control in mixed traffic in the future by focusing on first and last of the aforementioned bullet points. Later, based on the analysis of section 7.1 and focusing on the second bullet point, a new control measure is proposed and discussed in section 7.2. Lastly, given the time limit of this research, the proposed measure won't be simulated and analyzed, however, expected effectiveness of the proposed measures are shortly elaborated in section 7.3 and to demonstrate how this proposed measure might work, a numerical example is discussed in section 7.4.

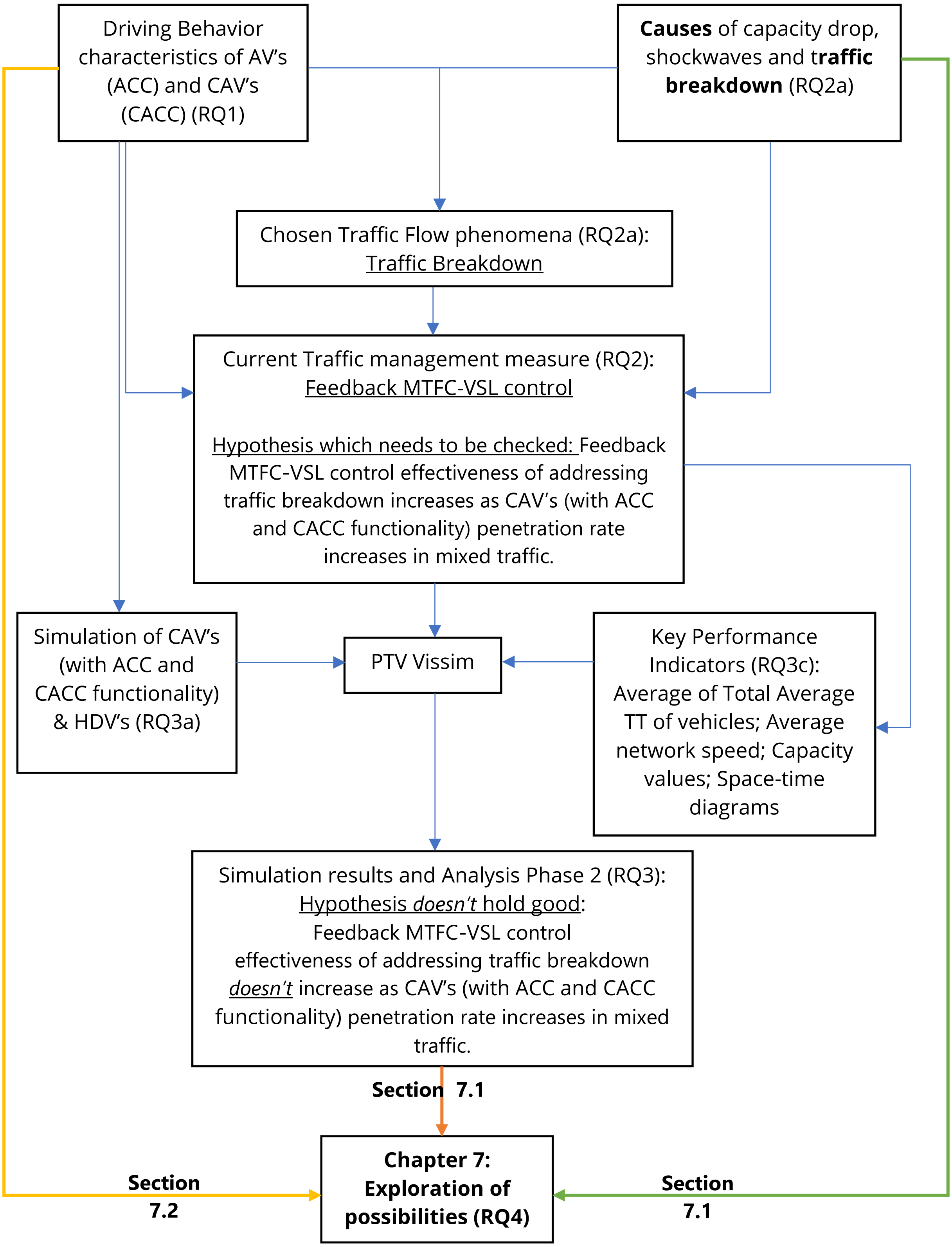


Figure 45: Part of the flow chart of research methodology

7.1.Problem Description

Table 36 derived from chapter 4, lists the microscopic influencing factors of traffic breakdown and various traffic management measure which are expected to address them. From the table, in general, VSL addresses three factors of traffic breakdown, which are, *Actual time headways between mainline vehicles (which influences Mainline flow rate), Desired speed on the mainline and Desired speed heterogeneity*. Specifically, MTFC-VSL control algorithm used in this research directly influences *Actual time headways between mainline vehicles (which influences Mainline flow rate)* by controlling the *Desired speed of vehicles on the mainline.* This indicates that for better addressing traffic breakdown, the new measures should focus on the influencing factors which aren't addressed by VSL and also MTFC-VSL, which are highlighted in grey in Table 36.

During simulations, it has been observed that the main trigger of traffic breakdown, occurs at high traffic flow on the mainline, due to which on-ramp vehicles cannot find a safe gap to merge onto the mainline. Thereby, the on-ramp vehicles wait at the end of the acceleration lane to find safe gaps to merge. Later, when a safe gap is available, the on-ramp vehicle makes a lane change from acceleration lane to the mainline at very lower speeds. *This lane change of on-ramp vehicle executed at such a low speed, referred to as trigger hereafter*, causes upstream mainline vehicles to decelerate, leading to shockwaves and thereby traffic breakdown. It could also be argued that this trigger observed in simulation, might also exist empirically. Because, if the mainline traffic flow is high, where in its hard for on-ramp vehicles to find a safe gap to merge, the on-ramp vehicle no option but to wait (standstill) for a safe gap and then merge when a suitable one is found. Additionally, this trigger relates to the *Duration and Magnitude of the disturbance (merging vehicle)* & *Merging position of the merging vehicle* which are listed as the microscopic influencing factors of traffic breakdown in Table 36, indicating that the authors and the relevant scientific papers from which these factors have been derived from as shown in Table 9, further enhances that the trigger is indeed one of the hypothesized causes of traffic breakdown.

This trigger, relating to *Duration and Magnitude of the disturbance (merging vehicle)* & *Merging position of the merging vehicle* in Table 36 isn't address by MTFC-VSL control. Once this trigger is activated and mainline vehicles react (decelerate) to this trigger, that is when occupancy of the bottleneck exceeds critical occupancy and then Feedback MTFC-VSL control algorithm activates. Thereby, it can be hypothesized that if this trigger is avoided or its effect is lessened then traffic breakdown can be postponed and thereby better addressed.

Table 36: Various traffic management measures and the expected microscopic influencing factors of traffic breakdown they address.

	Traffic Management Measures			
Expected Microscopic influencing factors of Traffic Breakdown	VSL	RM	RM+VSL	RGIS
Actual time headways between mainline vehicles (which influences Mainline flow rate)	+		+	+
Duration and Magnitude of the disturbance				
Merging position of the merging vehicle				
Reaction time of the mainline vehicles to the disturbance				
Reaction time of the vehicles moving out of the disturbance				
Actual time headways between on-ramp vehicles (which influences merge flow rate)		+	+	+
Secondary Lane changes				
Desired speed on the mainline	+		+	
Desired speed heterogeneity	+		+	

7.2. Traffic control concept

Having discussed the problem which needs to be addressed, the next step is to see how to address it. As penetration rate of CAV's (with ACC and CACC functionality) increases, often C-ITS measures are mentioned to control traffic to better utilize the connectivity feature of CAV's. However, in the near future, it's safe to presume that HDV's still comprise majority share of the traffic, indicating that new traffic control measures should also be designed to cater for HDV's. Hence, to better address traffic breakdown in mixed traffic, i.e., for Scenario 2 to 5, as for scenario 1 (0% CAV's) major improvements are observed in the presence of Feedback MTFC-VSL control than absence of it, a combination of C-ITS measure in combination with feedback MTFC-VSL control is proposed, where in the C-ITS measure needs to address the trigger discussed before. In this research its assumed that irrespective of preceding vehicle type, CAV's (with ACC and CACC functionality) are presumed to have connectivity feature which can be used for Infrastructure to Vehicle or Vehicle to Infrastructure (I2V/V2I) communication if there is any.

<u>C-ITS measure (Merging Assistant)</u>

The main premise in addressing the trigger discussed before is by providing merging assistance for on-ramp vehicle during high mainline traffic flow at the bottleneck section, rather than letting the on-ramp vehicle find gaps, which most of time they won't, and they end up decelerating and waiting standstill at the end of the acceleration lane.

In scientific literature, among others, (Pueboobpaphan, Liu, & Van Arem, 2010), (Zhou, 2019) and (Ding, Peng, Zhang, & Li, 2019) have specifically looked into Cooperative merging i.e. merging assistant of onramp vehicles using C-ITS measures in mixed traffic comprising of CAV's. Considering simplicity of the measure and its ease of set-up in simulation, the merging assistant strategy by (Pueboobpaphan et al., 2010) is proposed as a C-ITS measure to address the trigger discussed before.

In the following points, the merging assistant strategy proposed by (Pueboobpaphan et al., 2010) with some adjustments relevant to this research will be elaborated.

- The algorithm of the merging assistant *only* controls CAV's on the mainline to create gaps for efficient and smoother merge of *all* on-ramp vehicles in mixed traffic.
- The algorithm was proposed for one-lane mainline, thereby the control of CAV's is either to accelerate or decelerate to create gaps. However, in this research there are two mainline lanes as shown in Figure 25. To align with this algorithm, the CAV's on the right-most lane once they enter the Communication range as shown in Figure 46, they will be communicated not to execute lane changes.
- A Roadside Unit (RSU) is assumed to detect the on-ramp vehicle at t_0 and predict its expected arrival at the start of the merging section at t_1 as shown in Figure 46. RSU is assumed to have communication range of 400m upstream from the start of the merge on the mainline and it can detect on-ramp vehicles at a distance around 8s before the vehicle arrives at the start of the merging section.
- Once RSU has estimated the expected arrival time of on-ramp vehicle, t_1, RSU sends information about the expected arrival time to all the CAV's (for instance Vehicle A in Figure 46) on the mainline within the RSU communication range so that CAV's can predict their position at t_1 based on their current position and speed at time t, as they travel along the communication range, using the equation below.

$$\hat{x}_A(t_1) = x_A(t) + v_A(t) * (t_1 - t)$$

Where,

$\hat{x}_A(t_1)$ = Predicted position of mainline CAV vehicle A at time t_1

$v_A(t)$ = Speed of vehicle A at time t
$x_A(t)$ = Position of vehicle A at time t
$t \in [t_0, t_1]$

- If at any time instant, t, the predicted position of CAV lies within the safety zone of the merging vehicle as shown in Figure 46, then CAV will calculate the required acceleration rate for merging assistance using the equation below.

$$a_{merge\ asst}(t) = \frac{\hat{x}_M(t_1) - \hat{x}_A(t_1) - v_A(t) * h}{0.5(t_1 - t)^2 + h * (t_1 - t)}$$

Where,
$\hat{x}_M(t_1)$ = Predicted position of merging vehicle M, at time t_1

Later, $a_{merge\ asst}(t)$, is compared with the comfortable deceleration rate $d_{comfort}$, which in this research will be set equal to -1.0 m/s2, and the normal acceleration rate obtained from the driving rule, $a_{normal}(t)$. In this research, $a_{normal}(t)$ will be obtained by W99 car following behavior. Finally, the most restricted acceleration rate is chosen as the acceleration rate of CAV (vehicle A in Figure 46), using the following condition.

$$a(t) = \min\{\max[a_{merge\ asst}(t), d_{comfort}], a_{normal}(t)\}$$

If at any time instant, t, the predicted position of CAV *doesn't* lie within the safety zone of the merging vehicle as shown in Figure 46, then $a_{normal}(t)$ prevails.

- The safety zone of the merging vehicle M, with respect to vehicle A at t_1 is assumed to be dependent on the speed of A and the boundaries of the safety zone are calculated using the following equations.

$$x_{MA\_up}(t_1) = \hat{x}_M(t_1) - v_A(t) * h_{safe}$$
$$x_{MA\_down}(t_1) = \hat{x}_M(t_1) + v_A(t) * h_{safe}$$

where,
$x_{MA\_up}(t_1)$ = upstream boundary of safety zone of vehicle M with respect to vehicle A
$x_{MA\_down}(t_1)$ = downstream boundary of safety zone of vehicle M with respect to vehicle A
h_{safe} = safety time gap, in this research will set equal to 2.0 s.

- One of the limitations of the merging assistant algorithm is that errors may occur on the prediction of the arrival of on-ramp vehicles.

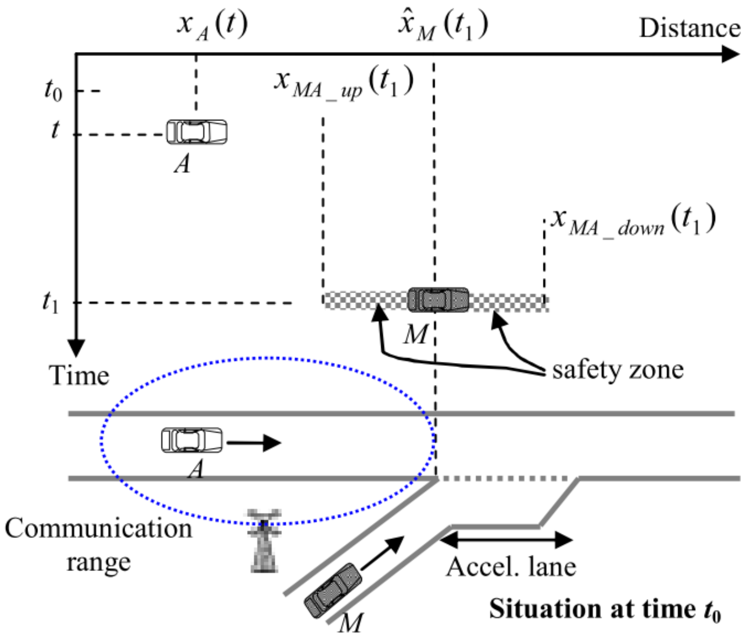


Figure 46: Merging Assistant Logic. Source:(Pueboobpaphan et al., 2010)

<u>C-ITS measure (Merging Assistant) + Feedback MTFC-VSL control</u>

Previously, the logic and working principle of the C-ITS measure, i.e., merging assistant strategy to address the trigger of traffic breakdown was discussed. The next step is to investigate how the C-ITS measure can be combined with MTFC-VSL control which caters for HDV's on mainline vehicles. The main reason of combining the merging assistant strategy with the MTFC-VSL control, is that in the initial scenarios of traffic with smaller penetration rate of CAV's, for instance, Scenario 2 (10% CAV) and Scenario 3 (20% CAV), CAV's will less frequently be present in the RSU communication range to provide merging assistance. Thereby, merging assistant strategy alone wouldn't fully be able to address traffic breakdown in mixed traffic. Hence, combining it with that of the MTFC-VSL control will increase its effectiveness.

To efficiently combine the two control measures, certain conditions need to be established based on which the measures will be activated. MTFC-VSL control as discussed in Section 4.3, regulates occupancy rate (%) at the bottleneck with respect to critical occupancy rate (%) of the bottleneck (merging section). Thereby, MTFC-VSL control gets activated based on the occupancy rate of the bottleneck. On the other hand, the merging assistant addresses trigger, which as discussed before, only prevails at higher mainline flow at the bottleneck. Because, at lower mainline flows, the gaps are easily available for the on-ramp vehicle to merge, thereby no assistance might be required. Thereby, the merging assistant needs to be activated only when high mainline flow is detected at the bottleneck. Thereby, a condition needs to be set which can indicate the presence of higher flows at the mainline. The detectors shown in Figure 25 which are used to measure occupancy required by MTFC-VSL control, can be used to measure flow values required by the merging assistant control. Similar to the feedback MTFC-VSL control, instead of occupancy rates (%), flow values will be regulated with respect to critical flow value. This critical flow value needs to set based on simulation results.

Having discussed the conditions of activation for both the measures, the steps on how the combination of C-ITS measure (Merging Assistant) + MTFC-VSL control works, will be elaborated as follows:

1. Regulate occupancy and flow values at the bottleneck section using the following equations:

   $$e_o(k) = \hat{o}_{out} - o_{out}(k)$$
   $$e_f(k) = \hat{f}_{out} - f_{out}(k)$$

   Where,
   $e_o(k)$ and $e_f(k)$ represent occupancy and flow control error respectively
   $\hat{o}_{out}$ and $\hat{f}_{out}$ represent critical occupancy and flow values respectively

   $o_{out}(k)$ represents average occupancy rate (%) on the mainline at the merging bottleneck at time instant k, which is obtained by taking the *maximum* average occupancy rate among the average occupancy rates measured by each of the four pair of detectors as discussed earlier in section 6.2.1.

   $f_{out}(k)$ represents the total flow (veh/hr) on the mainline at the merging bottleneck at time instant k, which is obtained by taking the *maximum* total flow value among the total flow measured by each of the four pair of detectors on the mainline as shown in Figure 14.

2. If $e_f(k)$ is positive ***and*** $e_o(k)$ is positive, then neither of the measures are activated.
3. If $e_f(k)$ is negative ***and*** $e_o(k)$ is positive, then merging assistant control algorithm is activated.
4. If $e_f(k)$ is negative ***and*** $e_o(k)$ is negative, then merging assistant control is deactivated and MTFC-VSL control is activated

Consequently, the above steps will help to check the hypothesis that "*Merging Assistant Strategy + Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic compared to MTFC-VSL alone*"

7.3. Expected results

Given the time limit, the proposed Merging Assistant Strategy + feedback MTFC-VSL control will not be simulated to check if the proposed hypothesis holds good. However, it can be expected that for Scenario 2 (10% CAV) and 3 (20% CAV), merging assistant might be activated less given the lesser occurrence of CAV's in the communication range when assistance is required, thereby, minor improvement of the KPI's could be expected compared to the MTFC-VSL control alone. For scenario 4 (30% CAV), 5 (40% CAV) and 6 (50% CAV), it can be expected that merging assistant strategy will be effective in addressing the traffic breakdown, at the very least it might postpone traffic breakdown by certain time, before MTFC-VSL control gets activated.

It can be argued that the merging assistant strategy activation might cause shockwaves on the mainline due to deceleration of CAV's while creating a gap and providing assistance for merging vehicles, and thereby the aforementioned hypothesis might not hold good. However, the author believes that the shockwaves caused by deceleration of CAV's and the vehicles upstream of it on the mainline, are better to have, rather than the shockwaves caused by the deceleration of mainline vehicles in the absence of merging assistant, when on-ramp vehicles make a lane change at really low speeds at the end of acceleration lane.

7.4. Numerical Example

In this section a numerical example to get an insight into how this proposed strategy might work in simulation is illustrated. *The network shown in Figure 14 and the demand shown in Figure 20 are assumed to hold good for this example.*

The first step in the new proposed measure, irrespective of the scenario of mixed traffic under study, is to regulate critical occupancy and critical flow at the merging bottleneck all the time as discussed in section 7.2, using the equation:

$$e_o(k) = \hat{o}_{out} - o_{out}(k)$$
$$e_f(k) = \hat{f}_{out} - f_{out}(k)$$

where,
$e_o(k)$ and $e_f(k)$ represent occupancy and flow control error respectively
$\hat{o}_{out}$ and $\hat{f}_{out}$ represent critical occupancy and flow values respectively
$o_{out}(k)$ and $f_{out}(k)$ represent average occupancy rates and total flow values measured at the merging bottleneck at time instant k respectively

$\hat{o}_{out}$ = 20% for all scenarios as obtained from analysis in section 6.2.1.
Thereby, $e_o(k)$ = 20 - $o_{out}(k)$

$\hat{f}_{out}$ = the critical flow values, which should be indicative of higher mainline flow so that when flow measured at time instant k, $f_{out}(k)$, is higher than this critical flow value, $e_f(k)$ is negative and given that $e_o(k)$ is positive, merging assistant strategy can be activated. $\hat{f}_{out}$ varies for different scenarios of mixed traffic, because as penetration rate of CAV's (with ACC and CACC functionality) increases in mixed traffic, the average breakdown capacity values increase as seen in Table 22. Thereby, this indicates that $\hat{f}_{out}$ value should increase as penetration rate of CAV's (with ACC and CACC functionality) increases in mixed traffic to be indicative of higher mainline flow for that particular penetration rate. Following from average breakdown capacity values in Table 22, Table 37 indicates fictive reasonable values of $\hat{f}_{out}$ for respective scenarios of mixed traffic. The $\hat{f}_{out}$ values in Table 37 are quite *less* than average breakdown capacity values shown in Table 22, owing to two reasons:

- Average Breakdown capacity values are measured across three lanes (two mainline and an acceleration lane) whereas critical flow rate concerns only with respect to two mainline lanes
- $\hat{f}_{out}$ values should be such that they are indicative of the start of higher mainline flow rather than breakdown capacity values

Table 37: Various scenarios of mixed traffic and the relevant fictive reasonable values of critical flow rate($\hat{f}_{out}$) and thereby the flow control error [$e_f(k)$].

Scenario No (% CAV's)	**$\hat{f}_{out}$ values (veh/hr)**	**$e_f(k) = \hat{f}_{out} - f_{out}(k)$**
2 (10%)	2030	$e_f(k) = 2030 - f_{out}(k)$
3 (20%)	2096	$e_f(k) = 2096 - f_{out}(k)$
4 (30%)	2132	$e_f(k) = 2132 - f_{out}(k)$
5 (40%)	2180	$e_f(k) = 2180 - f_{out}(k)$
6 (50%)	2224	$e_f(k) = 2224 - f_{out}(k)$

Having set the conditions to regulate the critical flow and occupancy at the merging bottleneck for various scenarios of mixed traffic, *let's consider Scenario 5 (40% CAV) for further analytical analysis.*

A. The proposed controller measures average occupancy rates and total flow values across the two mainline lanes at the merging bottleneck i.e., $o_{out}(k)$ and $f_{out}(k)$ every minute as described in section 7.2 and is inserted in equations below to obtain the occupancy $e_o(k)$ and flow $e_f(k)$ error values every minute.

$$e_o(k) = 20 - o_{out}(k)$$
$$e_f(k) = 2180 - f_{out}(k)$$

B. The next step is based on the values of $e_o(k)$ and $e_f(k)$, further actions need to be taken depending on the following conditions derived from section 7.2,
   a. If $e_f(k)$ is positive ***and*** $e_o(k)$ is positive, then neither of the measures are activated.
   b. If $e_f(k)$ is negative ***and*** $e_o(k)$ is positive, then merging assistant control algorithm is activated.
   c. If $e_f(k)$ is negative ***and*** $e_o(k)$ is negative, then merging assistant control is deactivated and MTFC-VSL control is activated

C. For most of the times it can be hypothesized that condition b will hold good before c. Based on this hypothesis, let's consider for further analysis *that condition b holds good and merging assistant is activated.*

Merging Assistant Strategy Activation

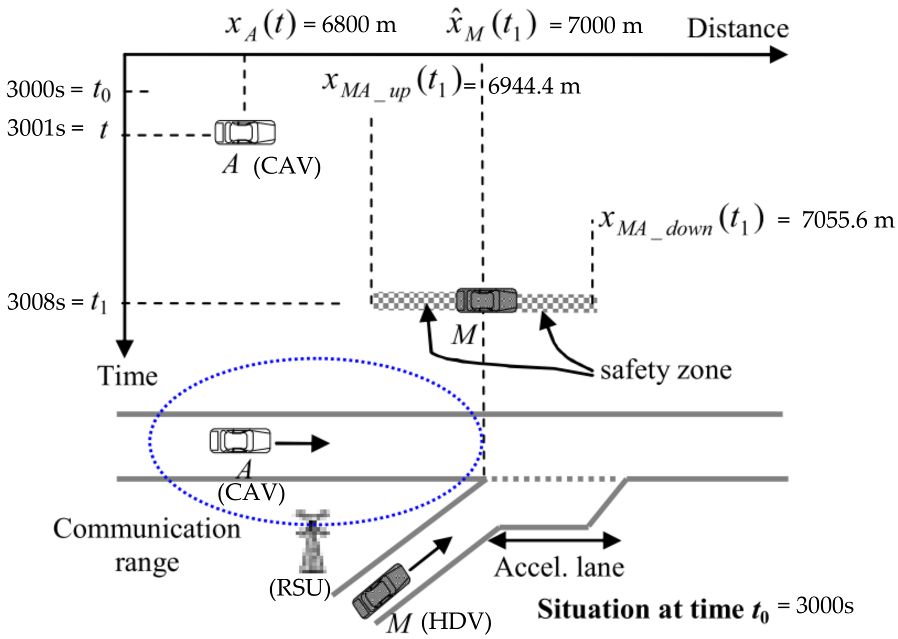


Figure 47: Merging Assistant example. Source: (Pueboobpaphan et al., 2010)

1. Given that the merging assistant is activated, let's assume the situation as shown in Figure 47 at t_0 = 3000 simulation second. For the sake of better understanding of the numerical example, lets presume that Figure 47 is the zoomed version of the shoulder lane of the two mainlines as shown in Figure 14. Following from Figure 47,
   a. RSU detects an on-ramp HDV travelling at desired speed of 98 km/hr at t_0 = 3000 simulation second. Presuming that it maintains the same desired speed, RSU predicts its arrival at the start of the merging section at t_1 = 3008 simulation second

b. Right from t_0 until t_1, RSU communicates messages to CAV's on the mainline within 400m of the communication range about the arrival time t_1 of the HDV at the merge section.

2. Given that the considered scenario for analysis is Scenario 5 with 40% CAV's (with ACC and CACC functionality) penetration rate in mixed traffic, the probability of finding a CAV on the mainline within the 400m detection range during $t \in [t_0, t_1]$ i.e., $t \in$ [3000, 3008] to provide merging assistant for the HDV can be presumed to be good.
3. Let's assume for the sake of analysis that a CAV is found at t = 3001 simulation second at position 6800m on the mainline as shown in Figure 47. RSU communicates the arrival time t_1 of the HDV at the merge section to this CAV. Presuming that the CAV is driving at its desired speed which is 100km/hr, its calculated predicted position at t_1, $\hat{x}_A(t_1)$ is:

$$\hat{x}_A(t_1) = x_A(t) + v_A(t) * (t_1 - t)$$
$$\hat{x}_A(3008) = 6800 + [100 * 0.278 * (3008 - 3001)]$$
$$\hat{x}_A(3008) = 6994.44\text{m}$$

4. The next step is that the CAV checks whether its predicted position, $\hat{x}_A(3008)$ is within the safety zone of the HDV (merging vehicle) as shown in Figure 47, which is calculated using the equation,

$$x_{MA\_up}(t_1) = \hat{x}_M(t_1) - v_A(t) * h_{safe}$$
$$x_{MA\_up}(3008) = 7000 - 100 * 0.278 * 2$$
$$x_{MA\_up}(3008) = 6944.4\text{m}$$

Similarly,

$$x_{MA\_down}(t_1) = \hat{x}_M(t_1) + v_A(t) * h_{safe}$$
$$x_{MA\_down}(3008) = 7055.6\text{m}$$

$\hat{x}_M(t_1)$ = 7000m, following from Figure 25
h_{safe} = assumed to be equal to 2.0s

5. As $\hat{x}_A(3008)$ lies within the safety zone of the merging vehicle, [6944.4m, 7055.6m] then the acceleration rate of the CAV at t = 3001 simulation second is determined by

$$a(3001) = \min\{\max[a_{merge\ asst}(3001), d_{comfort}], a_{normal}(3001)\}$$

$a_{merge\ asst}(3001)$ calculated from equation mentioned in section 7.2 yields -1.3m/s2 using the values obtained before and assuming h = 2.0 s.
$d_{comfort}$ is assumed to be -1.0 m/s2
$a_{normal}(3001)$ is assumed to be 0 m/s2 as the CAV is assumed to be driving at its desired speed of 100 km/hr

Consequently, $a(3001)$ = -1.0 m/s2

6. Hence, due to the acceleration rate calculated by the merging assistant, the CAV on the mainline decelerates with -1.0 m/s2 instead of travelling at desired speed with zero acceleration. Thereby it can be expected that due to the deceleration of the CAV, the HDV (merging vehicle) finds suitable gap to merge, instead of decelerating and waiting at the end of the acceleration lane to find suitable gaps, which causes the trigger as described in section 7.2.
7. Steps 3, 4 and 5 described before referred to t = 3001 simulation second. The same steps are repeated to calculate the new acceleration rate for the CAV for the subsequent simulation seconds until $t \in$ [3000, 3008].
8. Hence, it can be presumed that the HDV merged successfully with the gap created by the CAV on the mainline. With this presumption, it can be said that the merging assistant activation lessened overall TT of both mainline and on-ramp vehicles *(say around 2 minutes),* because if it didn't merge and waited at the end of the acceleration lane to merge then it would have acted as trigger for breakdown and congestion would occur increasing the overall TT of vehicles. In other words, it can be expected that the merging assistant fostered in postponing the traffic breakdown.

Merging Assistant Strategy Deactivation

D. So far, the activation of merging assistant strategy as elaborated in steps 1 to 8 before lead to saving of 2 minutes of overall TT. After that, lets presume that even though the assistant strategy was active it couldn't find CAV's to provide merging assistant for the on-ramp vehicles. Furthermore, for the next minute when $e_o(k)$ and $e_f(k)$ were checked it can be presumed that condition **c** as highlighted in bullet point **B** earlier holds good i.e., both $e_f(k)$ ***and*** $e_o(k)$ are negative, which indicates that the merging assistant control is deactivated and MTFC-VSL control is activated. Thereby MTFC-VSL control takes over the control.

To conclude, from this numerical example we can see that the merging assistant strategy activation before the MTFC-VSL activation, fostered in decreasing the overall TT by addressing the trigger which otherwise could have increased the overall TT. Thereby, the merging assistant strategy + MTFC-VSL control can be expected to bring positive improvements rather than MTFC-VSL alone. However, this needs to be confirmed through detailed simulation analysis as the reasoning of this numerical example depends on assumptions which were mentioned in the relevant context.

8. Conclusions

The main objective of this research was to study how effectively a current traffic management measure i.e., feedback MTFC-VSL control, addresses its control objective i.e., traffic breakdown, in mixed traffic, where in CAV's (with ACC and CACC functionality) and HDV's interact and drive together. Later, based on the analysis of the effectiveness of MTFC-VSL, new possibilities were to be explored from a C-ITS or vehicle-based control perspective which can better address the traffic breakdown in mixed traffic in conjunction with MTFC-VSL control than MTFC-VSL alone. Thereby, the main research question which this research has answered is:

What are the possibilities of <u>better</u> addressing traffic breakdown phenomena from a C-ITS or vehicle-based control perspective in mixed traffic than feedback MTFC-VSL control which addresses the same phenomena?

This chapter summarizes the main findings of this research which helps to answer the main research question. First the findings related to the effectiveness of feedback MTFC-VSL control in addressing traffic breakdown in mixed traffic will be summarized. Later, the possibilities of better addressing traffic breakdown in mixed traffic will be summarized.

<u>Findings related to the Effectiveness of feedback MTFC-VSL control in addressing traffic breakdown</u>

Before checking the effectiveness of feedback MTFC-VSL control in addressing traffic breakdown at a hypothetical merge section in mixed traffic through simulation, it was hypothesized that "*<u>Feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic</u>*", because CAV's are expected to precisely follow the speed limits. However, simulation results and analysis revealed that, the earlier framed hypothesis **doesn't hold good** for the both the variants of feedback MTFC-VSL control i.e., MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200).

Peculiarities related *to the set-up of the Feedback MTFC-VSL control* and *to the set-up of that of the driving behavior of HDV's and CAV's (with ACC and CACC functionality) in simulation* could be the reasons of the hypothesis not being valid. Specifically, it could be that, *based on the <u>specific</u> penetration rate of CAV's (with ACC and CACC functionality) in mixed traffic,*

- Having *<u>same</u>* desired speed distribution for both HDV's and CAV's while following the speed limits might increase the effectiveness of the

feedback MTFC-VSL control, instead of having *different* desired speed distribution wherein CAV's exactly following the speed limits and HDV's with some desired speed distribution.
- *Altering* the lengths of VSL application/acceleration area length might increase the effectiveness of the feedback MTFC-VSL control, rather than having a *fixed* length of VSL application/acceleration area irrespective of the penetration rate of CAV's (with ACC and CACC functionality) in mixed traffic.

Consequently, this might indicate that based on the *specific* penetration rate of CAV's (with ACC and CACC functionality) in mixed traffic Feedback MTFC-VSL control needs to be tuned and tailored to increases its effectiveness. *However, these are just probable reasonings which needs to be further investigated to be considered valid.* Lastly, it is important to mention that for both the variants of feedback MTFC-VSL control i.e., MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200), the feedback MTFC-VSL control was set-up in simulation with all the relevant practical considerations of implementing it real-life, such as:
- Translation of the speed limit values obtained from the feedback MTFC-VSL control law into *Discrete values* to be displayed as VSL
- *Spatial and temporal constraint* which ensure safety through smooth transition of vehicle speeds spatially and temporally
- *Mandatory compliance to the* speed limit by HDV's and CAV's, where in HDV's follow the speed limit with a certain distribution, whereas CAV's exactly follow the speed limits.

These practical considerations could be expected to have significant effect on the hypothesis not being valid.

For approximately less than 20% CAV's (with ACC and CACC functionality) penetration rate (especially in case of traffic comprising of 100% HDV's), MTFC-VSL-ISA (150/200) shows good improvements in the average of the total average TT of mainline vehicles and average network speed, compared to MTFC-VSL (150/200) and the absence of control. *This indicates that when penetration rate of CAV's (with ACC and CACC functionality) is less than 20%, especially in case of traffic comprising of 100% HDV's, it might be a good idea to have ISA installed as an OBU in HDV's. The installed ISA should be activated all the time where in it adjusts and limits (with automatic throttle/brake control) the driver exceeding the different speed limits displayed along the road by Feedback MTFC-VSL control.*

Both the variants of Feedback MTFC-VSL control studied, overall, increase the average of the total average TT of on-ramp vehicles for most of the scenarios of mixed traffic studied. *Hence, in mixed traffic, the on-ramp vehicles are better off during the absence of control than during the presence of Feedback MTFC-VSL control.*

Overall, both the variants of Feedback MTFC-VSL control for various scenarios of mixed traffic studied either increase Average Breakdown Capacity or have no effect. However, Average Discharge Capacity from Scenario 3 (20% CAV's) onwards a degradation is evident in the presence of both the variants compared to the absence of control. This could be due to the reason that after breakdown, speed limits by the Feedback MTFC-VSL control might limit the discharge rate compared to no speed limits in the absence of control after breakdown. *Consequently, this indicates that in mixed traffic, Feedback MTFC-VSL control doesn't effectively address the capacity drop phenomenon, might rather increase it compared to the absence of control.*

MTFC-VSL (150/200) and MTFC-VSL-ISA (150/200) control both influence the FD's derived at the merging bottleneck section for all the scenarios of traffic, *especially the congested states*, as in most of the free flow states, the control isn't activated. The congested states of FD's are more spread out in case of both the variants of the control compared to the absence of them, however, the congested states become streamlined as penetration rate of CAV's (with ACC and CACC functionality) penetration increases in case of MTFC-VSL (150/200).

Findings related to the Possibilities of better addressing traffic breakdown in mixed traffic

As Feedback MTFC-VSL control wasn't found to be effective enough in addressing traffic breakdown for various scenarios of mixed traffic, then the possibilities of better addressing traffic breakdown phenomena in conjunction with MTFC-VSL from a C-ITS or vehicle-based control perspective in mixed traffic should focus on the influencing factors of traffic breakdown (causes) which aren't addressed by VSL in general and as well as MTFC-VSL control, which are highlighted in grey in Table 38. One of the several possibilities which was further looked into and proposed in this research relates to *Duration and Magnitude of the disturbance (merging vehicle) & Merging position of the merging vehicle* factors of traffic breakdown.

It is reasoned that in simulations, at high flow on the mainline, it's hard for an on-ramp merging vehicle to find safe gaps to merge, thereby, they end up waiting at the end of the acceleration lane and then when a safe gap is found, the merging vehicle merges at very low speed, which creates a *trigger* for traffic breakdown. This creates a trigger because, following from section 3.1, when vehicle merges at *lower speeds (magnitude)* they need more *time (duration)* to accelerate and reach their desired speed. As the *duration* of the *lower speed* of merging vehicle is higher, the merging vehicles acts as a *disturbance* to the mainline vehicles travelling upstream of the disturbance at higher speeds. The impact of this disturbance is significant if the *position* of the lane change of the merging vehicle (disturbance), causes the immediate followers on the mainline travelling at higher speeds to react to the disturbance and decelerate more than necessary to avoid collision. At high mainline flow, this deceleration causes shockwaves which travel upstream faster causing slowing down of vehicles and thereby traffic breakdown. Consequently, this trigger relates to the *Duration and Magnitude of the disturbance (merging vehicle) & Merging position of the merging vehicle* factors of traffic breakdown as mentioned in Table 38 which isn't addressed by the feedback MTFC-VSL control. Thereby, the proposed possibility in this research of better addressing traffic breakdown was, a C-ITS measure (merging assistant strategy by (Pueboobpaphan et al., 2010)) which tries to address the trigger described before in conjunction with feedback MTFC-VSL control, with MTFC-VSL control remaining deactivated unless critical occupancy is reached at the bottleneck. This leads to the hypothesis that "*Merging Assistant Strategy + feedback MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic compared to MTFC-VSL alone*". However, given the time limit, this hypothesis wasn't checked in this research and is recommended for future research.

Table 38: Various traffic management measures and the expected microscopic influencing factors of traffic breakdown they address.

	Traffic Management Measures			
Expected Microscopic influencing factors of Traffic Breakdown	VSL	RM	RM+VSL	RGIS
Actual time headways between mainline vehicles (which influences Mainline flow rate)	+		+	+
Duration and Magnitude of the disturbance				
Merging position of the merging vehicle				
Reaction time of the mainline vehicles to the disturbance				
Reaction time of the vehicles moving out of the disturbance				
Actual time headways between on-ramp vehicles (which influences merge flow rate)		+	+	+
Secondary Lane changes				
Desired speed on the mainline	+		+	
Desired speed heterogeneity	+		+	

9. Recommendations and Limitations

In this chapter the limitations of this research and the recommendations for further research will be discussed in section 9.1 and 9.2 respectively.

9.1. Limitations

In this section the limitations of this research will be discussed. Section 9.1.1 discusses limitations with regards to simulation of mixed traffic which might influence the simulation results. Section 9.1.2 discusses the limitations with regards to the set-up and execution of the feedback MTFC-VSL control which might have an effect on the effectiveness of it in addressing traffic breakdown.

9.1.1. Limitations in simulation of mixed traffic

The following points summarize the assumptions considered while simulating mixed traffic in this research which have limited to capture the better picture of mixed traffic.

- Owing to the lesser gained insights of empirical lane change driving behavior of AV's and CAV's with ACC and CACC functionality and also incomplete information on the calibrated and validated lane change parameters of HDV's which can be used in Vissim, the *default lane change parameters* were used for both CAV's (with ACC and CACC functionality) and HDV's. Thereby, simulation results and thereby the analysis might vary if different lane change parameters are used.

- CAV's with CACC functionality can be expected to react faster to the changes of preceding vehicle when in car following mode, than CAV's with ACC functionality. Furthermore, CAV's with ACC functionality can be expected to react faster (in the range of 0.4-0.5s) than HDV's as concluded in section 2.1.6. In this research, this difference of reaction times isn't considered, owing to the reason that in this research built-in driving behavior models of Vissim are used, where in there is no reaction time variable which can be changed based on the vehicle type. Thereby, in this research, all the vehicles, i.e., CAV's (with ACC and CACC functionality) and HDV's are simulated with simulation resolution of 10-time steps/simulation second, i.e., 0.1s. Considering different reaction times, larger than 0.1s, can be hypothesized to have slightly negative effect on the simulation results.

- Owing to the lesser-known information of acceleration behavior of CAV's (with ACC and CACC functionality) at standstill and at 80km/hr, i.e., relevant to CC8 and CC9 parameters of W99, the CC8 and CC9 of CAV's with ACC and CACC functionality were assumed to be same as that of HDV's. However, in simulation, acceleration of *certain* CAV's, i.e., if CAV's *only* follow preceding CAV's driving with 0.6s time gaps (or 1s if the preceding CAV follows an HDV), then the following CAV's acceleration is increased by 10%. Thereby, this increased acceleration of 10% wasn't applied to all CAV's, where in CAV's following preceding CAV's of any time gaps would accelerate with 10% increase in its acceleration. Hence, if 10% increased acceleration was applied to all CAV's, the simulation results of KPI's of mixed traffic obtained in this research might be expected to improve better than currently obtained values as penetration rate of CAV's increases, owing to the reason that CAV's accelerate 10% higher when following another CAV's, especially when accelerating out of congestion.

- It's assumed that in mixed traffic, HDV's driving behavior is same irrespective of the type of surrounding vehicles. In other words, HDV's drive the same when driving around HDV's and/or CAV's in simulation considered in this research. Considering driving behavioral adaptation of HDV's when driving in mixed traffic might effect the simulation results and analysis.

- It's assumed that CAV's drive with W99 car following parameters relevant to ACC/CACC functionality depending on the preceding vehicle type *all the time i.e., for all the speeds*. However, in reality, the functionality might be activated by the drivers after reaching certain vehicle speed or according to the speed range of the functionality activation specified by the vehicle manufacturing company. Thereby, presuming that ACC or CACC functionality is activated all the time as in this research might slightly exaggerate the results as penetration rate of CAV's increases in mixed traffic.

- In this research, when a CAV follows a CAV with CACC W99 parameters, connectivity is not modelled between those two CAV's and is presumed to exist. However, consideration of connectivity and data loss during following behavior might slightly negatively effect the improvements in KPI's observed in this research as penetration rate of CAV's increases in mixed traffic.

- Following from section 2.1.6, vehicles with ACC functionality can be expected to have *smoother acceleration and deceleration* behavior.

However, this smoother acceleration and deceleration behavior of CAV's with ACC functionality was not adopted in simulation owing to lesser-known empirical quantitative information of acceleration and deceleration values for various vehicle speeds of vehicles with ACC functionality, because, in Vissim, acceleration and deceleration functions are defined with respect to various vehicle speeds.

9.1.2. Limitations in the setup of the Feedback MTFC-VSL control

The following points summarize the decisions taken while setting up the Feedback MTFC-VSL control in simulation of this research which might have limited to capture its effectiveness.

- The value of integral gain, K_I, which was set equal to 0.08 in the feedback MTFC-VSL control law used in this research, was obtained by testing for *certain reasonable values* for a specific length of application/acceleration area (150/200m). The value of integral gain might have been different if it was tuned for different lengths of application/acceleration area, and thereby might effect the results. Furthermore, obtaining the value of the integral gain by the method specified by (Müller et al., 2015) instead of trying out reasonable values as in this research might yield different values of integral gain and thereby might influence the effectiveness.

- The *linearity check* of the relationship between capacity flow induced by the speed limits before obtaining the integral gain K_I as shown in Figure 26, was carried out with VSL application area of 150m and for Scenario 1. Different application area and scenario might slightly change the linear relationship obtained in Figure 26 and thereby the integral gain.

9.2. Recommendations

In this section the recommendations based on the insights gained on several aspects while carrying out this research will be discussed. Section 9.2.1 discusses recommendations for better simulation of mixed traffic. Section 9.2.2 discusses the recommendations for future traffic management addressing traffic breakdown. Section 9.2.3 discusses the recommendations while carrying out FOT's and lastly section 9.2.4 provides recommendations for future research.

9.2.1. Recommendations on simulation of mixed traffic

The following points summarize the recommendations for better simulation of mixed traffic comprising of HDV's and CAV's.

- Different *reaction times* of CAV's with ACC functionality, CAV's with CACC functionality and HDV's to the preceding vehicle, needs to be considered for better simulation of mixed traffic. If this option of having different reactions times based on vehicle type is incorporated in Vissim, then simulation of mixed traffic can be better mimicked using the built-in driving behavior models of Vissim.

- It might be better to consider and simulate driving behavior adaptation of HDV's when driving around CAV's for better representation of mixed traffic.

- Deactivation of CAV's driving with ACC or CACC functionality in mixed traffic might be better to be considered at certain speed conditions, during which CAV's drive with the driving behavior of HDV's.

- Effectiveness of traffic management measure when CAV's drive in platoons isn't considered in this research as it was out of the scope of the objective of this research. It might be better if CACC platoon string stability are considered in simulation which becomes prominent as penetration rate of CAV's increases, as CACC platoons *can be expected to be string stable* at time gaps less than 1.0s. The analysis of how the effectiveness of measures varies with/without consideration of CACC platoon string stability in mixed traffic might be interesting to research. Vissim already has an in-built platooning possibility option. This option needs to be checked if it includes string stability feature (even during cut-in/cut-outs) which is important for CACC platoons. If that option is adapted to capture string stability of CACC platoons, then mixed traffic in the context of CACC platooning can be better captured using Vissim in-built features and models.

9.2.2. Recommendations on the traffic management measures

In this section suggestions are discussed with regards to future traffic management measures focusing on addressing traffic breakdown.

From Table 39 its evident that the current traffic management measures, which are VSL, RM, RM+VSL & RGIS, all of them, cannot be expected to address five influencing factors of traffic breakdown, highlighted in grey in Table 39, which are *duration and magnitude of disturbance, merging position of the merging vehicle, reaction time of the mainline vehicles to the disturbance, reaction time of the vehicles moving out of the disturbance and Secondary lane changes.* Thereby, its suggested that the future traffic management measures should focus on those five factors, so that the future measures in combination with the current measures, can together be expected to address traffic breakdown better than the current measures.

Table 39: Various traffic management measures and the expected microscopic influencing factors of traffic breakdown they address.

	Traffic Management Measures			
Expected Microscopic influencing factors of Traffic Breakdown	VSL	RM	RM+VSL	RGIS
Actual time headways between mainline vehicles (which influences Mainline flow rate)	+		+	+
Duration and Magnitude of the disturbance				
Merging position of the merging vehicle				
Reaction time of the mainline vehicles to the disturbance				
Reaction time of the vehicles moving out of the disturbance				
Actual time headways between on-ramp vehicles (which influences merge flow rate)		+	+	+
Secondary Lane changes				
Desired speed on the mainline	+		+	
Desired speed heterogeneity	+		+	

In mixed traffic, the expected driving behavior of CAV's with ACC and CACC functionality can be expected to address certain of the grey highlighted factors in Table 39. From Table 40 obtained by the combination of Table 10 and Table 39, it can be expected that in mixed traffic the faster reaction times of CAV's (with ACC and CACC functionality) might be expected to address two of the five influencing factors of traffic breakdown, which are *Reaction time of the mainline vehicles to the disturbance and Reaction time of the vehicles moving out of the disturbance*. However, this depends on the penetration rate of CAV's and also *that ACC and CACC functionality of CAV's are enabled* when moving out of congestion. But there are still three factors which aren't influenced by neither the current measures nor the driving behavior of CAV's (ACC & CACC), which are *Duration and Magnitude of the disturbance, Merging position of the merging vehicle and Secondary Lane changes*. CAV's (ACC & CACC) in Table 40 refers to CAV's (with ACC and CACC functionality). Hence, its recommended that the future traffic management measure for mixed traffic should focus on those three factors, so that in combination with the current measures and expected driving behavior of CAV's (ACC & CACC), its high probable that traffic breakdown can be better addressed.

Table 40: Overview of various traffic management measures and CAV's (ACC & CACC) driving behavior which address/ influence the expected microscopic influencing factors of traffic breakdown

	Traffic Management Measures				**CAV's (ACC & CACC) driving behavior**
Expected Microscopic influencing factors of Traffic Breakdown	VSL	RM	RM+ VSL	RGIS	
Actual time headways between mainline vehicles (which influences Mainline flow rate)	+		+	+	
Duration and Magnitude of the disturbance					
Merging position of the merging vehicle					
Reaction time of the mainline vehicles to the disturbance					Faster Reaction time
Reaction time of the vehicles moving out of the disturbance					Faster Reaction time
Actual time headways between on-ramp vehicles (which influences merge flow rate)		+	+	+	
Secondary Lane changes					
Desired speed on the mainline	+		+		
Desired speed heterogeneity	+		+		

9.2.3. Recommendations for FOT's

In this section recommendations are discussed with regards to future FOT's carried out on AV's and CAV's. Lot of the previously conducted FOT's are carried out on ACC and CACC functionality of AV's and CAV's respectively. However, there is insufficient empirical information on lane change behavior of AV's and CAV's (even to a certain extent of HDV's as well), due to which simulating the lane change behavior of AV's and CAV's is challenging. It's recommended that FOT's should be conducted on lane change behavior of AV's and CAV's so that the empirical information can be used to calibrate and validate the lane change parameters of AV's and CAV's in simulation, which will further help to get better simulation results.

9.2.4. Recommendations for further research

In this section recommendations for further research based on this research is discussed.

The following points highlight the important differences/peculiarities of driving behavior of HDV's and CAV's incorporated in this research using in-built functions and driving behavior models of Vissim.

- In mixed traffic, CAV's and HDV's drive with the ***same*** car following model, i.e., W99, with reasonable changes in the W99 parameters values to differentiate between HDV car following behavior and CAV's with ACC and CACC car following behavior.
- Implicit stochastics component is switched off for CAV's to account for homogeneity in certain aspects of driving behavior and switched on for HDV's to account for heterogeneity.
- With regards to acceleration of CAV's, they accelerate with 10% higher when following *certain* CAV's.

The simulation results, analysis and conclusions of this research depend on (among others) the differences/similarities discussed before. Further research needs to be carried out on mixed traffic with other external controllers for car-following behavior of ACC and CACC to check whether still the hypothesis that "*Feedback MTFC-VSL control (with all the practical considerations) effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic"* doesn't hold good.

Lastly, given the time limit of this research, the hypothesis "*Merging Assistant Strategy (C-ITS measure) + MTFC-VSL control effectiveness of addressing traffic breakdown increases as CAV's (with ACC and CACC functionality) penetration rate increases in mixed traffic compared to MTFC-VSL alone"* wasn't checked. Thereby, future research can focus on this hypothesis.

10. Bibliography

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