BRUNO SCARANO PATERLINI

Assessment of Connected and Autonomous Vehicles impacts on traffic flow through microsimulation

São Paulo

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I dedicate this work at first place to God.

To my wife Amanda, my daughter Lívia, my parents Ednei and Marcia and to all who gave me support from different perspectives during this journey.

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RESUMO

AVALIAÇÃO DO IMPACTO DO VEÍCULO AUTÔNOMO E CONECTADO NO FUXO DE TRÁFEGO ATRAVÉS DA MICROSSIMULAÇÃO

Veículos Autônomos e Conectado (CAVs) são tidos como parte do futuro das vias inteligentes ao redor mundo. Eles são objeto de interesse dos órgãos mundiais de trânsito e da sociedade por apresentarem um grande potencial para melhoria no fluxo de tráfego, redução no número de acidentes, aumento da eficiência enérgica e redução dos níveis de emissão que os veículos com controle autônomo podem apresentar.

A indústria e a academia vêm aumentado seus esforços e investimentos para desenvolver as várias tecnologias que irão integrar o CAV assim como avaliar o seu impacto nas vias. As fases de transição apresentam maior complexidade devido a coexistência de veículos autônomos e não autônomos na mesma via, e assim necessitam ser cuidadosamente avaliadas.

Este trabalho tem por objetivo avaliar o impacto que dos CAVs no fluxo de tráfego em vias urbanas de regiões metropolitanas. Como características em países como o Brasil estas regiões apresentam grande fluxo em horários de pico com uma alta porcentagem de motos, ônibus e caminhões compartilhando a mesma via com os veículos de passeio. As fases de transição que incluem o tráfego misto dos veículos dirigidos por humanos (HDVs), veículos autônomos (AVs) e veículos autônomos e conectados são também foco do estudo.

O estudo está sendo realizado através da microsimulação de tráfego com o software PTV VISSIM, onde os modelos de *car-following* são desenvolvidos e calibrados. Até esta etapa da pesquisa o cenário base que reproduz as condições de tráfego atuais além do modelo para AVs foram desenvolvidos. Resultados parciais mostraram uma redução e 5% no tempo de viagem para cenários mistos com taxa de penetração de 50% de AVs, e redução de 34% para os cenários com 100% de AVs quando comparados com o cenário base. Além disso, foram criados sub-cenários onde um distúrbio no trânsito foi provocado, como a quebra de um veículo. Nestas situações os tempos de viagem foram reduzidos em 11% e 30% para os cenários misto (50% AVs) e 100% AVs, respectivamente, em relação ao cenário base.

Os cenários para CAVs serão explorados através da alteração de parâmetros no micosimulador assim como com funções embutidas no software, como o comboio autônomo ou controle de cruzeiro cooperativo adaptativo (CACC), onde a comunicação entre os veículos é uma tecnologia mandatória. O software PTV VISSIM lançou em agosto de 2019 uma nova versão onde esta função foi embarcada e que será utilizada neste estudo para avaliar o impacto dos comboios autônomos em vias urbanas. Este é o foco da próxima etapa da pesquisa para dissertação final.

Descritores: Veículos autônomos e conectados (CAV), Microssimulação de tráfego, comboios, VISSIM.

ABSTRACT

ASSESSMENT OF CONNECTED AND AUTONOMOUS VEHICLES IMPACTS ON TRAFFIC FLOW THROUGH MICROSIMULATION

Autonomous and Connected Vehicles (CAVs) will be part of the future smart roads around the world. They are the object of interests of the world traffic agencies and society in general due to several factors such as improvements in traffic flow, potential reduction on road accidents, and higher fuel efficiency that autonomously controlled vehicles enable.

Both industry and academy have increased their efforts and investments to develop a package of technologies that will integrate the CAV, as well as assess their impacts and on the roads. In particular, the transition phases need to be deeply assessed due to the high complexity autonomous and non-autonomous vehicles coexistence driving at the same road will cause.

This research aims to evaluate the traffic flow impact of CAVs on urban roads in metropolitan areas. As characteristics in countries such as Brazil, these regions have high traffic flow at rush times including a high relative flow of motorcycles, buses, and trucks traveling on the same road together with passenger cars. The transition phases that include mixed traffic with human-driven vehicles (HDVs), autonomous vehicles (AVs), and connected autonomous vehicles (CAVs) also focus on the study.

The study is based on a traffic microsimulation tool called PTV VISSIM software, where car-following models are developed and calibrated. Until this stage of the research, the baseline scenario that reproduces how current traffic conditions are and the AV model has been developed. Partial results showed a 5% reduction in travel time for mixed scenarios with 50% AVs and 34% for scenarios with 100% AVs, compared to the baseline scenario. Also, sub-scenarios were created where a traffic disturbance was caused, such as a vehicle breakdown. At these sub-scenarios, the travel times were reduced by 11% and 30% for 50% AVs and 100% AVs, respectively, relative to the baseline scenario.

Scenarios for CAVs will be explored through microsimulation parameter changes and software-embedded functions such as platooning or Adaptive Cooperative Cruise Control (CACC), where communication between vehicles is the framework technology. PTV launched a new VISSIM software version in August 2019 that presents this feature embedded. It will be used to assess the impact of autonomous trains on urban roads. That is the focus of the next step of the research, aiming for the final dissertation.

Keywords: *Connected and Autonomous Vehicles (CAV), Traffic Microsimulation, VISSIM, Platooning.*

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LIST OF ABBREVIATIONS

ABS - Anti-lock Brake System)
AV – Autonomous Vehicles
ACC – Adaptive Cruise Control
ADAS- Advanced Driver Assistant Systems
CACC – Cooperative Adaptive Cruise Control
CAH - Constant Acceleration Heuristics
COM - Component Object Model
CASE – Connected, Autonomous, Shared, Electric
CAV – Connected Autonomous Vehicles
C2C – Car to Car
C2X – Car to “X” (anything)
ESP - Electronic Stability Program
EIDM – Enhanced Intelligent Driver Model
IBGE - Brazilian Institute of Geography and Statistics
IDM – Intelligent Driver Model
IoT – Internet of Things
ITS - Intelligent Transportation Systems
NCAP - New Car Assessment Programs
OEM - Original Equipment Manufacturer
PNAD - National Household Sample Survey
RSU (Road-Side Units),
SPTRANS – São Paulo Transportation
SAE - Society of Automotive Engineers
SAE – Society of Automotive Engineers
UMTRI - University of Michigan Transportation Research institute
USDOT – United States Department of Transportation
VANETs- Vehicular Ad Hoc Networks
VDOT- Virginia Department of Transportation
V2V – Vehicle to Vehicle
V2X –- Vehicle to Everything
WAVE - Wireless Acess in Vehicular Environments
W74 – Wiedmann 74
W99 - Wiedmann 99
WHO - World Health Organization

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1 INTRODUCTION

1.1 CONTEXT

Humans are almost 8 billion people in the world, and United Nations estimates that this number will be near to 10 billion in 2050 (UNITED NATIONS 1, 2018). Also, the world urbanization prospects from the United Nations show that despite the pace is reducing, anyhow, the number of big cities will continue to rise (UNITED NATIONS 2, 2019). At the same time, the vehicle fleet in Brazil almost doubled in the last ten years, from 54,5 million in 2008 to 100,7 million in 2018 (IBGE, 2019). In the same period, the road infrastructure remained at the same level (ANT, 2018). These prospects reinforce the relevance of studies on Smart Cities and Intelligent Transportation Systems (ITS) context to keep the cities sustainable.

Mobility is a basic human need, and the demand is growing mainly in metropolitan areas (MEYER and SHAHEEN 2017). The decisions on how to go from “a” to “b” when you have several mobility options involve four main factors: distance and time to achieve the destination, cost, safety and comfort (MADHUWANTHI et al., 2015). To match all those factors including the environment, European Commission, in 2018, delivered a communication with the directives to the sustainable mobility for Europe, which they are: safe, connected, and clean (EUROPEAN COMISSION, 2018). This directive drives the main topics for overcoming current transportation challenges of reducing traffic jams and air pollution, improve energy efficiency and accessibility for all citizens (including elderly and disabled).

At the same time, changes in lifestyle, demographic changes, and the rise of the “Mobility-as-a-Service” (MaaS) concept are paving the way for a new mobility ecosystem in urban multimodal planning (MEYER & SHAHEEN, 2017).

Following this path, the traditional Original Equipment Manufacturers (OEMs) as Audi and Daimler group in the last years have set a vision for the future of the mobility based on four technology pillars: connected, autonomous, shared and electric. (AUDI, 2019; DAIMLER, 2019). The automotive business will change drastically, mainly for passenger cars. Owning a Connected and Autonomous Vehicle (CAV) as a personal car will not be possible for most of the population due to its cost (BANSAL & KOCKELMAN, 2017). Buying a car will be much more related to an investment where during the time one is not using it, one could offer this availability as part of the mobility service. The most interested in being large fleet owners will be experts in some core aspects of vehicles or transportation as specialists on high tech cars maintenance or logistics, energy supply/storage companies, owners of parking places, multimodal transportations companies, etc (JIA & NGODUY, 2016).

The beginning of the transition phase from current to future mobility has begun. The traditional OEMs, as well as new high tech players as Uber, Tesla, and Google, are frequently announcing their progress on public roadside testing on autonomous vehicles. In this situation, it is clear that mixed traffic will provoke a complex interaction between Human Driven Vehicles (HDV) and CAVs from different automakers (including different systems providers), merging on the same road (GE, et al., 2018).

CAVs will bring the Advanced Driver Auxiliary Systems (ADAS) and communication technologies together. They enable the data sharing from vehicle sensors and actuators, positioning, and routes with other vehicles, infrastructure, pedestrians, or any relevant elements. It leads to the so-called Vehicle-to-Everything communication (V2X), in close relationship with the Internet-of-Things (IoT) concept (SBD, 2018; FROST & SULLIVAN,2017; BAILEY, 2016; AISSIOUI et al., 2018).

Vehicle-to-vehicle communication (V2V) enables the development of new features as the Cooperative Cruise Control (also called platooning or automatic convoy). It brings new possibilities to improve traffic flow. The communication between is possible due to development of Vehicular Ad Hoc Networks (VANETs) and 5G complying with low latencies, high reliability, and data security requirements (FROST & SULLIVAN, 2017; CHAI et al., 2017; AISSIOUI et al., 2018; 5G Automotive Association, 2019)

The communication from the vehicle to the infrastructure (V2I) brings additional possibilities for merging much real-time relevant information for improving traffic efficiency. Traffic lights timing, road signs, traffic jams, road accidents, bus lines management, modals integration, and weather forecast as well as historical data, are examples of relevant traffic-related data. These are the critical interfaces between the ITS and the Smart Cities (NETO et al., 2016; C-ITS, 2017).

This highly complex combination of technologies raises many questions about validation and homologation aspects as well as data security robustness. Either way, vehicular field testing is essential in this process, but it is important to note that it is time-consuming and expensive. To support this development, a wide variety of traffic simulators are available, playing an essential role in technology assessment, either individually or in the combination of them (SONGCHITRUKSA et al., 2016).

The traffic simulators bring relevant outputs that can clarify different actors such as the government, industries, legal entities, and the population the real benefits that CAVs can bring to the mobility ecosystem. Therefore, traffic simulation can help to provide a more accurate estimation of the impact of these technologies on traffic flow, allowing to test varied scenarios and evaluate the most appropriate traffic behaviors to achieve the proposed goals (ZHANG et al., 2018).

The context of this research is summarized in FIGURE 1.

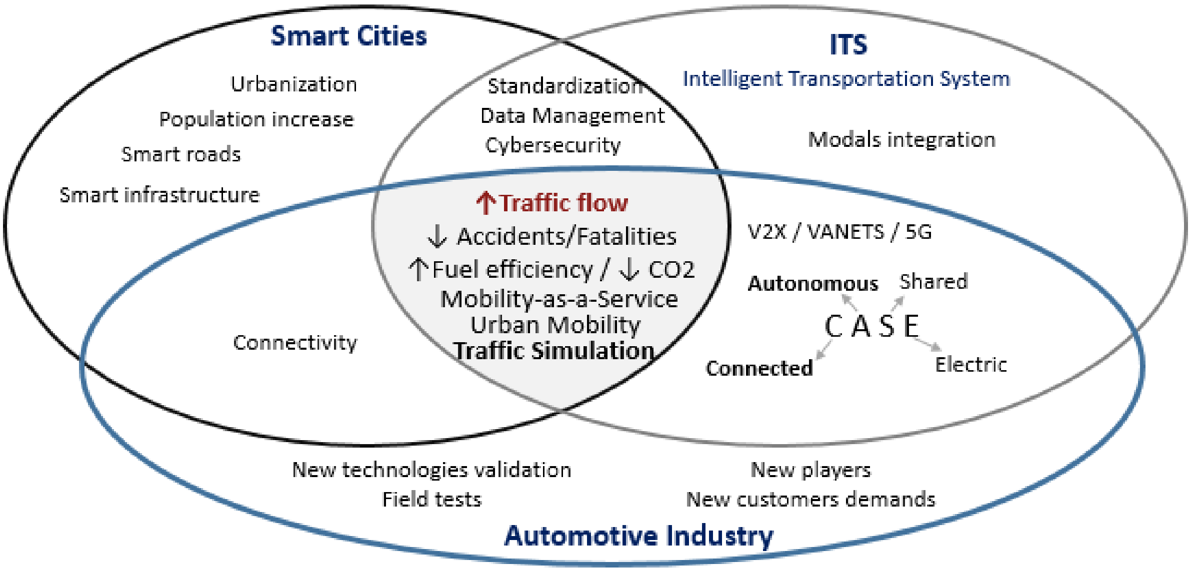


FIGURE 1 – Context and fields in which the research localizes.

Source: Author.

1.2 MOTIVATION

According to IBGE (abbreviation for Brazilian Institute of Geography and Statistics) over PNAD (abbreviation for National Household Sample Survey) data from 2018 (PNAD, 2018) the average time spent from home to work in São Paulo city is around 45 minutes. More than 25% of the population spend more than 1 hour on this route. It directly affects the population's health and the economy.

CAVs bring new possibilities to reduce these numbers exponentially. Delivering reliable data from CAVs benefits to the context of Brazilian cities can support the deployment of these technologies and speed up the introduction of them on the roads.

The key topic of this study is to evaluate one attention point from CAVs introduction: the transitions phase. Many different aspects will in place when roads have human-driven vehicles (HDV) and vehicles with different automation levels. The traffic behavior and new possibilities that vehicles communication technologies will bring are the most relevant contributions. The focus is on the different dynamic behaviors and traffic characteristics of big cities.

This research can be part of a set of studies that support Brazilian government decisions to accelerate the current path on approving regulations to make safety features mandatory, as airbag and ABS (Anti-lock Brake System) in 2014 and ESP (Electronic Stability Program) that will start in 2020. It can also support the approval of regulations to allow autonomous vehicles testing on a public road. Another relevant aspect in supporting on forming consumer market and investors opinion influencing the decision to buy vehicles equipped with those features.

One important topic to mention is that measuring the benefits of CAVs on traffic conditions in Brazil is a topic still underrated. A few researchers were released with a focus on traffic performance on national universities.

The overall motivation comes from the possibility to contribute to an emerging and trend topic that can play a critical transformation role in society.

1.3 OBJECTIVES

General objective: to analyze, identify, and quantify the benefits for traffic flow on high-density traffic roads of CAVs. The analysis will also be extended to the heterogeneous environment where autonomous and human-driven vehicles will coexist.

Specific objectives:

- To understand the characteristics of traffic microsimulation and choose one that suits the model and objectives proposed in the research.
- To use a traffic microsimulation to build a model with the following characteristics: high density flow roads in a big city in Brazil including bus stops and the high number of motorcycles and measure the impacts of disturbances such as road accidents on traffic flow on that ecosystem;
- To assess models that describe driver behaviors: the software object of the study uses the Wiedemann models;
- To understand which features of autonomous vehicles distinguish from those human-driven and how these characteristics interfere with traffic microsimulation models;
- To assess the impact of autonomous vehicles on traffic flow.

1.4 DOCUMENT ORGANIZATION

The main text of this document is ordered as follows.

Chapter 1 is an introduction that shows an overview of the research context, motivation, objectives, and organization of this document.

Chapter 2 gives an overview of the key concepts from the future of the automotive industry that drives this research, including the concept of CAVs and the tool used to develop this research: traffic microsimulation.

Chapter 3 describes and discusses the literature review from CAVs traffic simulation and the measured benefits on traffic flow.

Chapter 4 formally states the problem and the methodology to study the problem.

Chapter 5 describes the methods, materials, scenarios evaluated, and software setups to validate the study.

Chapter 6 presents partial experimental results, the comparison between scenarios, and the discussions.

Chapter 7 describes the timeline and next steps to the final dissertation.

Finally, chapter 8 describes the conclusions of this research and suggestions for further researches.

2 KEY CONCEPTS OF CONNECTED AND AUTONOMOUS VEHICLES AND TRAFFIC SIMULATION

Connected and autonomous vehicle researches and developments are mainly focused on the following aspects: to reduce accidents, to increase fuel efficiency, to reduce emissions, and to improve traffic flow. To achieve that, targets the vehicles need to be equipped with proper systems and technologies (PENDLETON, et al., 2017).

The most critical concept when it comes to autonomous vehicles is to understand its classification. After many years of divergence, SAE International (Society of Automotive Engineers) released the first worldwide-adopted taxonomy and definitions for terms related to driving automation. It is the standard J3016 first released in 2014 with two additional revisions in 2016 and 2018 (SAE, 2018). FIGURE 2 shows a timeline with the evolution of this definition.

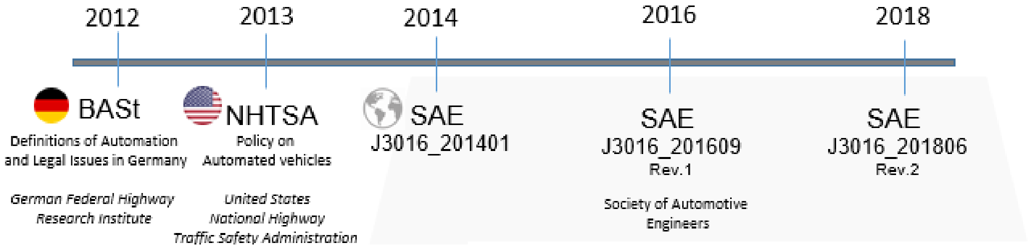


FIGURE 2 – Taxonomy timeline of vehicle automation level standardization
Source: Author.

The standard classifies six different levels, from no automation to full automation. The higher the automation level is, the lower is the driver inputs dependency. Nevertheless, the higher the automation is the Advanced Driver Assistance Systems (ADAS) dependency that requires an incremental combination of sensors (ultrasonic, cameras, LiDars), the control of active driveability systems as well vehicle communication features. On SAE Level 5, the vehicles will not need physical acceleration and brake pedals; the driver will become a passenger (SAGIR & UKKUSURI, 2018).

FIGURE 3 shows the definition of each automation level and ADAS examples.

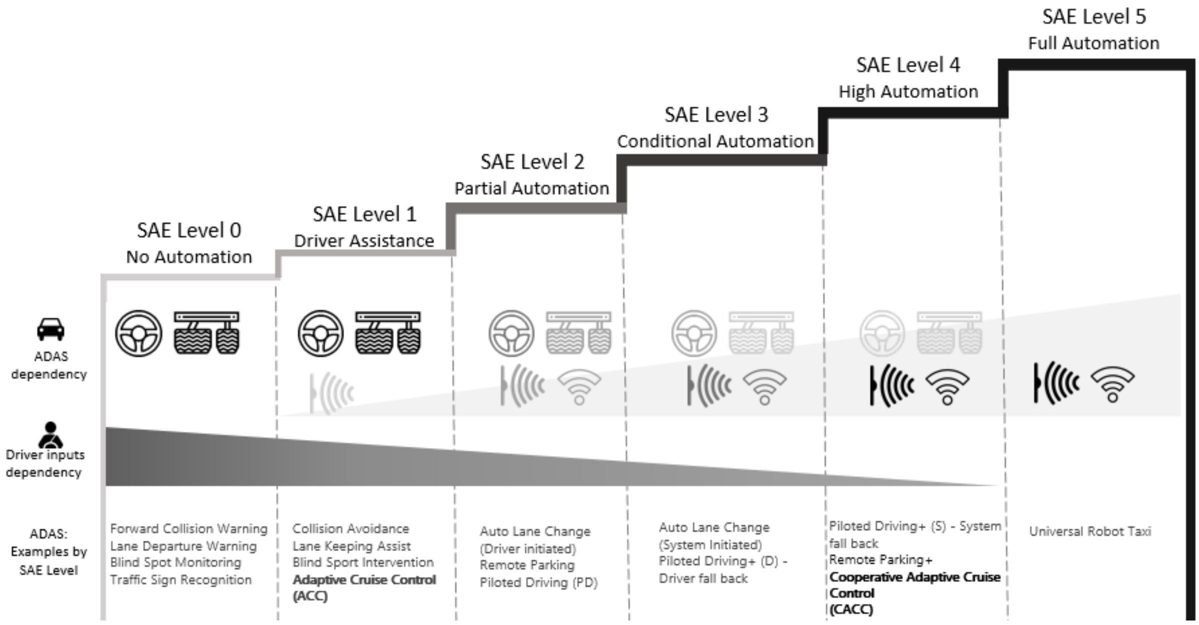


FIGURE 3 – SAE automation levels

To illustrate the path of automation levels development, Audi A8 was the world’s first production car to have achieved Level 3 (IEEE Spectrum, 2017). Mercedes-Benz, in partnership with Torq Robotics, announced the first public road test of an autonomous truck level 4 in September 2019 in Virginia, USA (DAIMLER AG, 2019).

2.1 TRAFFIC ENGINEERING AND VEHICLE DYNAMICS RELEVANT ASPECTS

ADAS development framework was to perform human drivers' capabilities with higher performance and reliability. In order to understand in more in-depth, it is crucial to explore some concepts from vehicle dynamics, traffic engineering, and the concepts of driver behavior, further explored on 2.6: Let consider the FIGURE 4 to illustrate traffic engineering parameters.

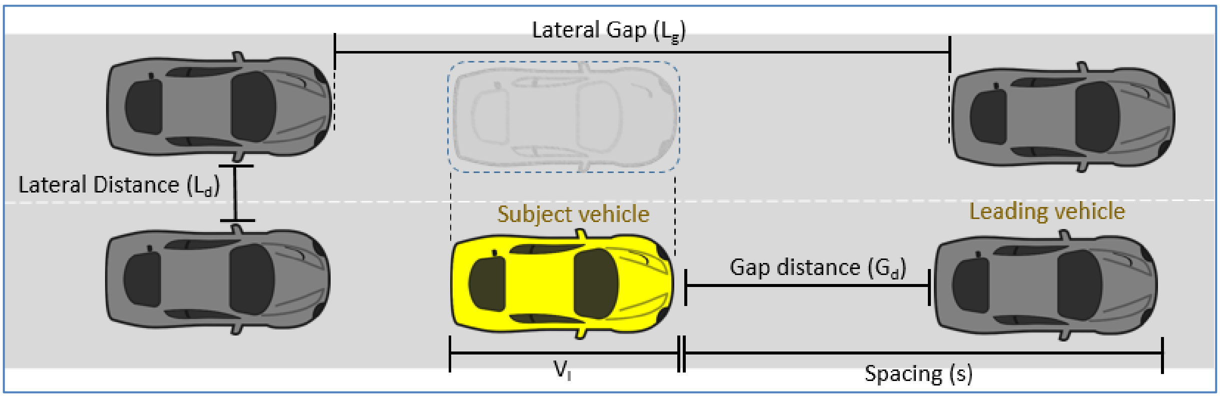


FIGURE 4 – Traffic engineering parameters illustration.

Source: Author

- **Spacing (s)**: is the distance between the front bumper of two consecutive vehicles.
- **Gap distance (G_d)**: is the distance between the rear bumper of the subject vehicle and the front bumper of the leading vehicle, where headway focuses on front-to-front distances.
- **Headway (h)**: a measure of the temporal space between two vehicles. The front bumpers of successive vehicles are used as a reference.
- **Time Gap (Tg)**: also a measure of the temporal space between two vehicles. Anyhow the references now are the rear bumper and front bumper of successive vehicles. The time gap is the ratio between spacing and speed. This concept is linked to a driver behavior so-called safety distance. The higher the speed is the higher is the time distance a human driver maintains from the vehicle forward. It is essential to mention that for human drivers, this safety distance is not proportional to the vehicle brake performance. It means that independent from the brake performance one individual in a determined vehicle speed will keep the same time distance.
- **Lateral Gap (Lg)**: is front to rear bump distance between two vehicles placed at the side lane of the subject vehicle. This distance affects the driver's behavior decision of lane changing. It also affects the possibility of traveling with a higher speed if the driving condition in the target lane is better than that in the current lane (YE & YAMAMOTO, 2017). The perception of a proper lateral gap to perform the maneuver is also dependant on the speed.
- **Lateral distance (Ld)**: is the distance between side-by-side vehicles. The lateral mirrors or cameras are used as a reference. This concept is especially relevant for traffic jams.
- **Driver reaction time (RT)**: usually defined on simulations as the time lag that the follower uses to react to the change in the leader driving behavior during a car-following. On real traffic, it corresponds to the time delay between the lit of the brake lights from the leading vehicle and the touch of the brake pedal in the pursuing car. On a human-driven vehicle, it is affected by several factors from the driver distraction to the driver experience (ZHANG & BHAM, 2007).
- **Stopping Side Distance (SDD)**: is the distance a vehicle needs to full stop. It is a consolidated formula used on transportation engineering field (FHWA, 1997) which the mathematical model is described as:

$$SSD = 1{,}47V(R_T) + \frac{V^2}{2g\left[f \pm \left(\frac{G}{100}\right)\right]} \tag{1}$$

Where: *SSD* is the Stopping Side Distance (m), *V* is the Speed (km/h), R_T is the Reaction Time (s), *g* is the gravity, *f* is the friction coefficient, and *G* the grade (%).

- **Safe Speed**: according to the Gipps model, the highest speed a vehicle can drive on an accident-free model where the subject vehicle can stop even on a sudden break from the leading vehicle (TREIBER & KESTING, 2013).

$$v_{Safe} = -bR_T + \sqrt{b^2 R_T^2 + V_l^2 + 2b\,(s - s_0)} \qquad (2)$$

Where R_T is the driver reaction time (s), *b* is the constant braking deceleration (m/s²), V_l is the vehicle length (m), and *(s-so) = Gd* as gap distance (m).

This group of concepts presents the aspects involved in traffic, vehicle dynamics, and driver behaviors that characterize the human-driven vehicles. They are the basis to discuss how CAVs technologies will affect traffic conditions.

2.2 AUTONOMOUS VEHICLES (AV)

AVs are a composition of different ADAS systems that will perform the core vehicle dynamics behaviors independent from the driver (RAJESH, 2006). It means the ability to accelerate, brake autonomously, and to execute longitudinal and lateral movements as well as maneuvers. These activities are under development based on the way that humans perceive, plan and act over the environment during driving, replacing it with an extensive range of sensors, actuators and artificial intelligence (PENDLETON et al., 2017; FROST & SULLIVAN, 2017; HE et al. 2019).

It brings the ability to continually monitor vehicles surrounding, leading to deterministic behavior when compared to human drivers and almost instantaneous reaction time when relevant changes in the driving environment are assessed (MAHMASSANI, 2016). AVs are in continuous development to broad scope and limits of driving domains where humans' capabilities are limited due to environmental, geographical, and time-of-day restrictions and the requisite presence or absence of specific traffic or roadway characteristics. It is defined as Operational Design Domains (ODD) (SAGIR & UKKUSURI, 2018).

The Adaptive Cruise Control (ACC) was the first ADAS with capabilities to control longitudinal vehicle motion, also referred to as the first step on AVs roadmap (RAJESH, 2006). The Intelligent Driver Model (IDM) has been developed and enhanced for several researches along the years to model ACC and other aspects from AV and CAVs (TREIBER et al., 2000; KESTING et al., 2010; SCHAKEL et al., 2010; SHLADOVER et al., 2012; TREIBER & KESTING, 2013; DERBEL et al., 2013; MAHMASSANI, 2016; ZHOU et al.,2017; XIE et al., 2019). IDM considers some aspects as no exact reaction time or destabilizing effects on acceleration and braking caused by human imperfections (DO et al., 2019).

IDM specifies a subject vehicle acceleration as a continuous function of its current speed, the ratio between the current spacing to the desired spacing, and the vehicle speed difference between the leading and the subject vehicle

$$\alpha_{IDM} = a\left[1 - \left(\frac{v}{v_o}\right)^{\delta} - \left(\frac{s^*(v,\Delta v)}{s}\right)^2\right] \tag{3}$$

where s is the distance from subject and leading vehicle, v is the subject current vehicle speed, v_0 is the desired (safety) speed, Δv is speed difference between the subject vehicle and the leading vehicle, δ is the parameter that decides the magnitude of acceleration decrease depending on the vehicle speed, s^* is the desired distance (safety gap) described as

$$s^*(v,\Delta v) = s_o + max\left[0, vT + \left(\frac{v,\Delta v}{2\sqrt{ab}}\right)^2\right] \tag{4}$$

where s_0 is the minimum gap, T is a constant value representing the desired gap, a is the comfortable acceleration rate, and b is the deceleration rate (TREIBER & KESTING, 2013; DO et al., 2019).

As IDM acceleration and deceleration rates are plausible for most of the situation other than when the gap between the subject vehicle and the leading vehicle is significantly lower than the desired gap, TREIBER & KESTING (2013) combined the IDM and the Constant Acceleration Heuristics (CAH) to avoid the unrealistic deceleration rates. The frameworks of CAH matches with some assumptions assumed for CVs, as:

i. The leading vehicle will not change its acceleration suddenly on following seconds;

ii. Safe time headway or minimum distance do not need to be considered;

iii. Drivers reaction time is zero (no delays);

Considering the gap s, the subject vehicle speed v, the leading vehicle speed v_l, and constant acceleration of both vehicles $\dot{v}$ and $\dot{v}_l$, the maximum acceleration max ($\dot{v}$) = α_{CAH} that prevents accidents is described as:

$$\alpha_{CAH}\,(s, v, v_l, \dot{v}_l) = \begin{cases} \frac{v^2\bar{a}_l}{v_l - 2s\bar{a}_l}, & if\ v_l(v - v_l) \leq -2s\bar{a}_l \\ \bar{a}_l - \frac{(v-v_l)^2\theta(v-v_l)}{2s}, & otherwise \end{cases} \tag{5}$$

Where $\bar{a}_l(\dot{v}_l)$=min $(\dot{v}_l, a)$ is the adequate acceleration used to outline the situation where the leading vehicle acceleration capability is higher than the subject vehicle acceleration. The condition $v_l(v - v_l) \leq \; -2s\bar{a}_l$ is valid if the vehicles stop until the minimum gap $s = 0$ is achieved. It means that negative approaching rates makes no sense and it is handled by Heaviside step function $\theta(x)$ (with $\theta(x) = 1$ if $x \geq 0$ and zero, otherwise).

IDM and the CAH acceleration models combined lead to the ACC model formulated as (TREIBER & KESTING, 2013):

$$\alpha_{ACC} = \begin{cases} \alpha_{IDM}, & if\ \alpha_{IDM} > \alpha_{CAH} \\ (1-c)\alpha_{IDM} + c\ _l[\alpha_{CAH} + b\ \tanh\left(\frac{\alpha_{IDM}-\alpha_{CAH}}{b}\right) & ,\ otherwise \end{cases} \qquad (6)$$

Where c is the coolness factor, for c=0, the ACC model comes to IDM, while c=1, means no speed difference exists. TREIBER & KESTING, 2013, have assumed c =0.99.

2.3 CONNECTED VEHICLES (CV)

Connected Vehicles will bring additional capabilities that humans are not able to. It will bring a complete assessment to perceive beyond the 360º surrounding area directly and instantly, as illustrated in FIGURE 5. It will be enabled mainly by vehicle to everything communication (V2X) together with high definition online mapping, analytics and stored big data (JIA & NGODUY, 2016; FROST & SULLIVAN, 2017; UHLEMANN, 2016; SBD, 2018). CVs will be the basis of Cooperative ITS (C-ITS) features (C-ITS, 2017; SINGH et al., 2019).

The framework from connected vehicles is the ability to exchange information. For that V2X capabilities includes (for additional applications see Anexx 2):

- **Vehicle-to-Vehicle (V2V):** this technology enables each vehicle to be a gateway from its information and the whole ecosystem connected to it. It will enable features as Cooperative Adaptive Cruise Control (C-ACC) or platooning (MAHMASSANI, 2016; DOLLAR & VAHIDI, 2017)
- **Vehicle-to-Infrastructure (V2I)**: this technology enables the vehicle to broadcast information with infrastructure over the Road Side Units (RSU), telecom infrastructure, radars, or traffic signs. It will allow access and share to real-time data from the weather forecast, road conditions, online traffic information and historical data as well as traffic signals timing (GUO & BAN, 2019; SINGH et al., 2019).

- **Other V2X technologies:** Vehicle-to-Pedestrian (V2P), Vehicle-to-Network (V2N), Vehicle-to-Home (V2H), and additional connectivity that matches with the Internet of Thing (IoT) concepts (MIR & FITALI, 2016).

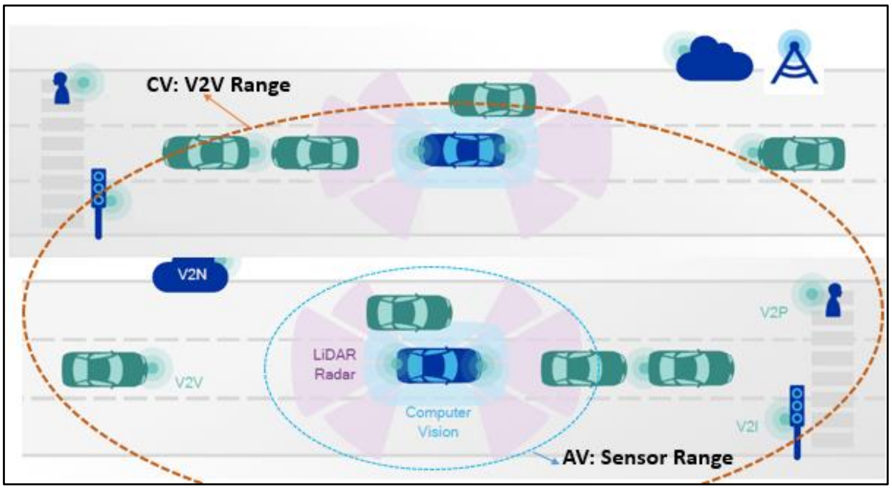


FIGURE 5 – V2V allows CAV vehicles to scan a broader vehicle ecosystem beyond the sensors range

Source: adapted from Qualcomm (2016).

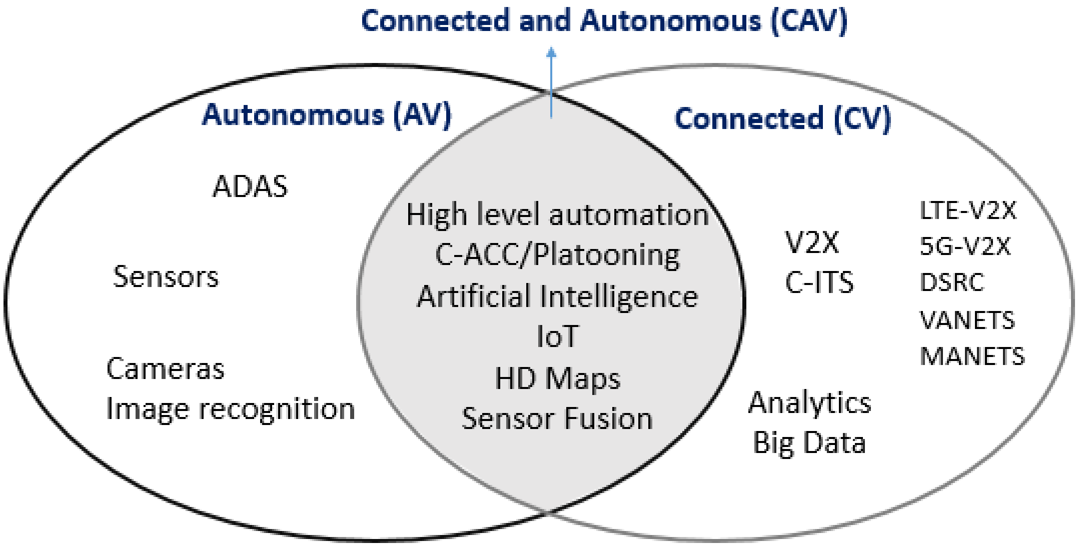


FIGURE 6 – CAVs convergent topics

Source: Author.

V2X network infrastructure and requirements to allow the data exchange with the characteristics of Wireless Acess in Vehicular Environments (WAVE) were standardized over IEEE.802.11p/DSRC (IEEE, 2010). It includes characteristics as multiple propagation paths, high nodes dynamism, high bandwidth, and low latency (PENDLETON et al., 2017; VUKADINOVIC et al., 2018; HE et al., 2019).

However, in the last five years, the development of 5G brought new discussions opportunities, as it was conceived to fulfill V2X requirements (Trafic Technology International, 2017; 5G Automotive Association, 2019; LUCERO, 2016; AISSIOUI et al., 2018; HUSSAIN, HUSSAIN, & ZEADALLY, 2019; SINGH et al., 2019).

The current picture is that there is no convergent decision about adopting DSRC or 5G. Pros and cons of technologies application, time to market, and costs are under discussion (AISSIOUI et al., 2018; LUCERO, 2016; SBD, 2018).

2.4 CONNECTED AND AUTONOMOUS VEHICLES (CAV)

To achieve high reliability for higher automation levels, the interface between a connected and autonomous vehicle will merge. CAV is a terminology adopted in the last few years to vehicle clustering features as CACC/platooning that will require the full integration between sensors and communication technologies to control the vehicle's dynamics, considering overall predictability from the road environment. CAVs will merge the technologies to enable the broad application of Artificial Intelligence (AI), including being adaptive, self–learning and foresight of future events on the road (uptime) as well as make a historical analysis based on big data analytics.

FIGURE 7 shows the convergent point between the technologies.

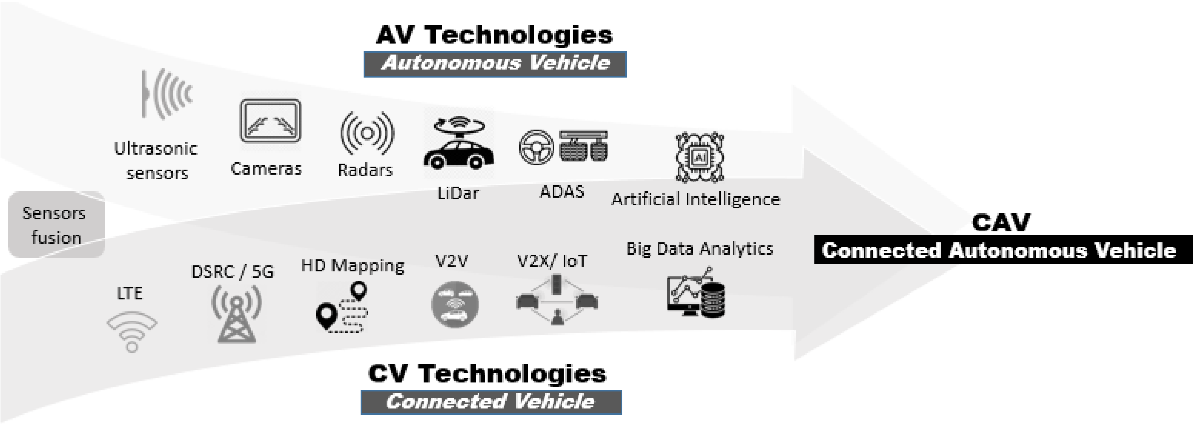


FIGURE 7 – CAV technologies roadmap

Source: Author.

CAVs will enable cooperative driving features that allow lower gap distances, lower lateral distances, and optimized merging conditions. A fully SAE 5 level road will have 100% of CAVs, which will also be able to process a considerable amount of real-time data from vehicles around that simultaneously will make useless the former mandatory components on the human driver environment (e.g., brake lights, turn indicators and horns). On the other hand, AI algorithm together with big data analytics will be essential players to replace distinctive human capabilities as context-sensitivity (memory effect of present and past overall traffic conditions), courtesy and cooperation (particularly relevant for merging and lane changes situation) (TREIBER et al., 2000; DO et al., 2019, HE, et al. 2019).

Also, the EU recently introduced legislation that requires OEMs to fit eCall as standard on all new vehicles. eCall regulation could mean that all OEMs in the EU will have embedded SIM in the future. It is expected that around 60% of new cars sale in the EU and the US will be equipped with embedded connectivity by 2020 (SBD, 2018). MEYER & SHAHEEN (2017) states that Fully CAVs, where a driver no longer has to steer or adjust speed, could be commercially available within the next 10–20 years.

Coming to the relevant concepts of CAVs, the CACC that incorporates communication technologies to ACC is frequently used to model it (JIA & NGODUY, 2016; MAHMASSANI, 2016; ZHOU et al., 2017; GE et al., 2018; DO et al., 2019). DO, et al. (2019) presents a survey of studies of CACC that highlight benefits on traffic flow considering shorter time headway (i.e., 0,5 seconds) compared to the ACC (i.e., 1,4 seconds), mainly due to V2V technologies that bring a different approach to minimum safety distance. Field tests showed the same tendency to shorten time gaps due to faster response on changing behavior from the leading vehicle (SCHLADOVER et al., 2010).

ZHAO & SUN (2013), based on previous studies by KESTIN et al. (2008), proposed acceleration equations for ACC and CACC acceleration. The model of acceleration is a linear function between the subject vehicle and the leading vehicle and the current speed. The accelerations of vehicles are described by equations (7) and (8) for ACC vehicle and (9) and (10) for CACC (PARK et al., 2017).

$$a_{c\,ACC} = k_v \cdot (v_l - v_s) + k_s \cdot (s - v \cdot t_d) \tag{7}$$

$$a = \max\,[a_{min}, min(a_c, a_{max})] \tag{8}$$

$$a_{c\,CACC} = \boldsymbol{a_l} + k_v(v_l - v_s) + k_s \cdot (s - v \cdot t_d) \tag{9}$$

$$a = \max\,[a_{min}, min(a_c, a_{max})] \tag{10}$$

Where a is the acceleration in the next step of the subject vehicle, $\boldsymbol{a_l}$ is the acceleration of the leading vehicle (the only additive variable added at CACC), v_s and v_l are the vehicle speed of the subject and leading vehicles, respectively, a_{max} is the maximum allowed acceleration, a_{min} is the maximum allowed deceleration, k_v and k_s is constant gain greater than zero.

On the other hand, Van AREM et al. (2006) developed the Microscopic Model for Simulation of Intelligent Cruise Control (MIXIC), which is compatible with CACC. The first focus of the study was to enable the assessment of the throughput and stability impacts of the system. Results showed better stability and average speed increase on a freeway lane drop with increasing penetration of CACC. The model is capable of incorporating V2V by sharing relevant information from leading vehicles to subject one, like vehicle speed, acceleration and braking, assuming that the delay is zero (SHLADOVER et al., 2012; DO et al., 2019).

. On MIXIC basic model the safe following distance is given by

$$r_{safe} = \frac{v^2}{2} \cdot \left(\frac{1}{d_p} - \frac{1}{d}\right) \tag{11}$$

Where v is the subject vehicle speed, d_p and d are the deceleration capability of the leading and subject vehicles, respectively.

The following distance is given by

$$r_{safe} = t_{system} \cdot v \tag{13}$$

Where v is the current vehicle speed, and t_{system} is the time headway (0,5 seconds if the leading vehicle has CACC function and 1,4 seconds, otherwise). It means that for CACC equipped vehicles, the safe distance can be almost three times lower. SONGCHITRUKSA et al. (2016) stated that a proper time headway for CACC could be as small as 0,6 seconds. FIGURE 8 illustrates it.

TELEBPOUR & MAHMASSANI (2016) developed important concepts for CAVs based on MIXIC. The framework is that the speed of the CAV enables it to stop at the sensor detection range. The model that calculates safe speed considering it is

$$\Delta X_n = (X_{n-1} - X_n - l_{n-1})\, v_n \tau + \frac{v_{n-1}^2}{a_{an-1}^{decc}} \tag{13}$$

$$\Delta X_n = min(SensorDetectionRange, \Delta X_n) \tag{14}$$

$$v_{max} = \sqrt{-2 a_i^{decc} \Delta X} \tag{15}$$

where n and $n-1$ are the subject and the leading vehicles, respectively. X_n, l_n , v_n ,τ, and a_n^{decc} denotes the position, the length, the vehicle speed, the reaction time and the maximum deceleration of the subject vehicle n, respectively.

The researches defined the safe following distance (s_{safe}) and the following distance based on the reaction time (s_{system}) as

$$S_{safe} = \frac{v_{n-1}^2}{2} \cdot \left(\frac{1}{a_n^{decc}} - \frac{1}{a_{n-1}^{decc}}\right) \tag{16}$$

$$S_{system} = \quad v_n \tau \tag{17}$$

It leads to the acceleration of CAV given by

$$a_n(t) = \min\,[a_n^d(t), k(v_{max} - v_n(t)] \tag{18}$$

where k is a model parameter which is the same as the basic MIXIC (TELEBPOUR & MAHMASSANI, 2016; DO, et al., 2019).

YE & YAMAMOTO (2017) denotes the anticipation distance as (based on the premise that CAVs can obtain the exact value of space gap). The equation 19 shows clearly the driver behavior difference when the leading vehicle is a CAV or an HDV, given by

$$d_{anti}^{CAV} = \begin{cases} d + v_{anti}, & if\ v_l\ is\ a\ CAV \\ d + v_{anti} - b_{defense}\ , & otherwise \end{cases} \tag{19}$$

where d is the distance gap between subject and leading vehicle, v_{anti} is the expected speed of the leading vehicle, and $b_{defense}$ is the randomization-deceleration rate under the defensive state. This equation is based on the worst-case where a CAV is following an HDV. As an HDV driving behavior is unpredictable, the CAV always needs to drive on the defensive.

YE & YAMAMOTO (2017) incorporate the connectivity characteristics of V2V on the safe speed of a CAV as

$$v_{anti}^{CAV} = \min\,(d_l\,, v_l + a\,, v_{max}\,, v_{li}\ ) \tag{20}$$

where v_{li} is the average speed of leading CV within the communication distance range, v_l and d_l are the speed and gap distance from the leading vehicle, respectively.

2.4.1 Deep dive on CACC/Platooning

A sophisticated feature that CAVs enable is the platooning, also called an automated convoy. The first public assessment of the technology dates from more than 20 years ago, in 1997, where the National Automated Highway Systems Consortium (NAHSC) conducted a public demonstration of eight fully automated cars driving in convoy in San Diego, California. To enable it the road was equipped with reference magnets for steering maneuvers and the communication between vehicles was based on radio technologies (RAJESH, 2006).

The current approach for platooning is to use CACC as a framework. Its sensors and V2V communication technologies make it possible to create a group of vehicles electronic engaged. The first vehicle has responsibility for leading the convoy setting the speed, lane, and directions. The other vehicles act as slaves or followers (RAHMAN & ABDEL-ATY, 2017).

The vehicles at the platoons use an Identification number (ID) to represents their sequential position on the convoy. The leader ID is zero, and the other vehicles have the ID number increased one unit (1,2,3…) sequentially until the maximum allowed platoon size. If a vehicle is approaching the platoon and the maximum platoon size is already achieved, this vehicle will start a new platoon where the inter platoon time headway should be considered. The maximum platoon size can be dependant on many different factors like the road type, maximum allowed road vehicle speed andvehicles model (SERAJ et al., 2018; GONG & DU, 2018).

The relevant variables that will determine the performance of the platoon are the number of vehicles and the distance between them. One additional primary feature that affects its performance is the capability to open gaps, to accept new vehicles or allow vehicles cut-in, and close gaps from vehicles that left the convoy (HU et al., 2017). FIGURE 8 shows examples.

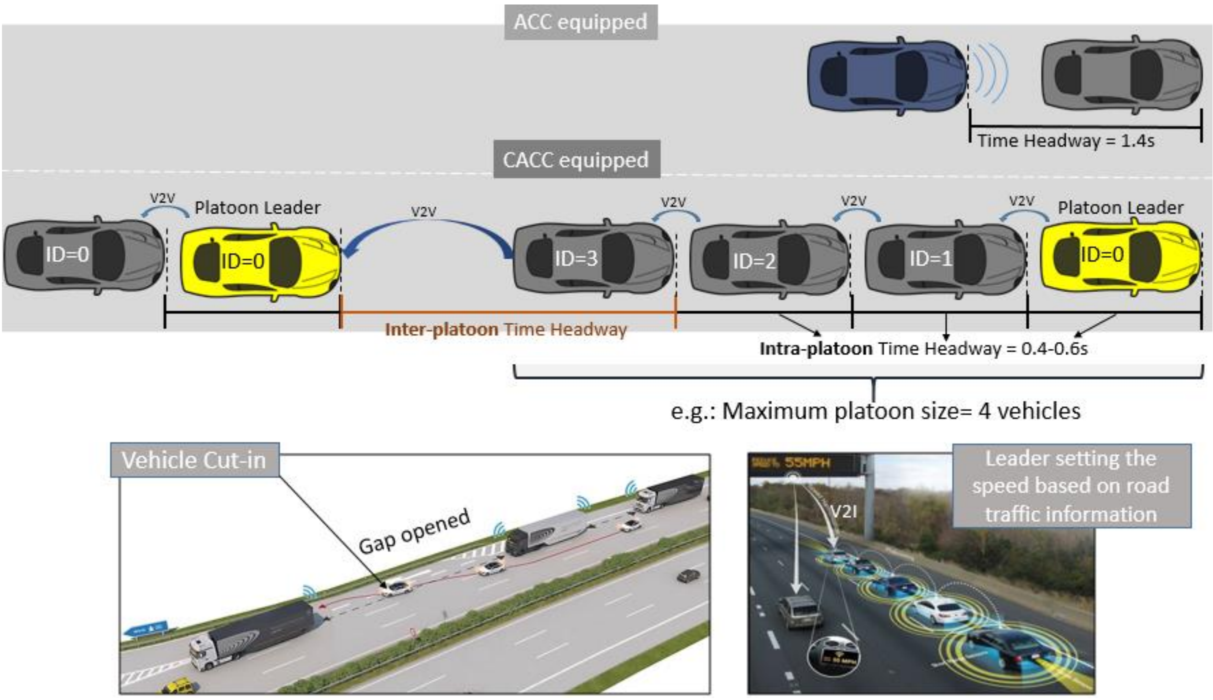


FIGURE 8 - Platooning/CACC key concepts

Source: Author and adaptation from DIRT (2019) and DAIMLER CASE (2019).

SERAJ et al. (2018) bring the modeling of acceleration of the subject vehicle in a CACC system, similar to proposed by ZHAO & SUN, (2013) on equation 8 as

$$v(t+\Delta t) = k_1(d(t) - \dot{v}(t) \cdot T - s_0) + k_2 \Delta v(t) \qquad (21)$$

where k_1, k_2 are control constants for relative distance and speed, respectively, higher than zero, d is the distance gap between leading and subject vehicle and T is the reaction time.

The researchers simulated numerous scenarios with a stream of 20 vehicles following a platoon leader vehicle. The first analysis showed that creating platoons along with HDV on mixed traffic configurations brought positive impacts on the overall traffic flow. The best platoon configuration that gives the maximum benefits to the traffic was: intra-platoon headway = 0,5 sec, inter-platoon headway = 2 sec, and maximum platoon size = 5/6 vehicles (SERAJ, LI, & QIU, 2018).

Platooning is expected to bring benefits for traffic as well as improvements in the fuel efficiency of the group by reducing the overall air drag (ALAM et al., 2015). TSUGAWA (2014) delivered the results from the field test project that tested a platoon of 3 fully-automated trucks, driving along an expressway at 80 km/h with the preset distance of 10m between them. The fuel consumption measurement showed a reduction of about 14%. WANG et al. (2017) assessed an eco-friendly CACC system with passenger's car and got 2% higher fuel efficiency with 17% emission reductions.

Finally, considering that CAVs will enable a shorter gap and lateral distance between the vehicles, one additional relevant aspects that these technologies will bring to the society comes up: the throughput capability increase using the same road area or keeping the throughput decreasing the number of lanes. Adding it to the new approach that V2X can give to sharing mobility and multi-modal transportation, it can dramatically change the cities architecture, avoiding the continuous necessity of roads area increase as well as opening spaces for sidewalks, bicycles lanes, parks, etc (NTOUSAKIS et al., 2015; ARIA et al., 2016; HAO et al., 2017).

Platooning technology will be assessed on the final dissertation of this research. It will enable the simulation of CAVs behaviors to evaluate the traffic flow impacts of its application in an urban environment.

2.5 VEHICLE AUTOMATION FIEL OPERATIONAL TRIALS (FOT)

A Field Operational Trial (FOT), in terms of CAVs, is a private or government-funded project in which autonomous technologies are tested in a real-world environment. A key benefit of real-world trials is that the technology can be observed and monitored to evaluate how it reacts to random scenarios. The possibility to expose the technology to public interaction is another positive aspect of making people aware and more comfortable with innovations (SBD, 2018).

These CAVs field tests have many different targets as the assessment of operational systems, artificial intelligence, sensing, DSRC, 5G, communication, mobility, mapping, software and hardware development, simulation, transition phases, and coexistence between human-driven and CAVs as well as government certification and legislation relevant topics.

2.5.1 CoEXist project

Inside the FOT context, the CoEXist project has to be highlighted and further explained as some of its deliverables were used as core references for the traffic microsimulation phase developed inside this research. CoEXist is a European project (May 2017 – April 2020) which aims at preparing the transition phase where automated and conventional vehicles will co-exist on the roads. The mentioned deliverables were related to field tests in cooperation with PTV are described below:

- (Coexist D2.3, 2018) - Default behavioral parameter sets for Autonomous vehicles (AV): set of new features to make AV vehicles simulation more accurate (available from VISSIM 11), the numerical recommendation for the Wiedemann 74, and Wiedemann 99 following behavior, lane changing behavior and signal control behavior.
- (Coexist D2.4, 2018) - PTV VISSIM extension new features and improvements: show the results of data evaluation in combination with the proposed concept of four different driving logics which characteristics are:
    i. Rail Safe: suggested parameters characterize a mostly closed environment (e.g., no lane changes allowed), similar to driver behavior on public transportation dedicated lanes;
    ii. Cautious: driver that follows all rule straightly, keep a safe distance from the vehicle ahead and change lanes when significant gaps are opened at the lateral lane;
    iii. Normal: suggested parameters mostly based on PTV VISSIM users manual. This will represent the driver's behavior that reproduces with more accuracy the real human-driven vehicle.
    iv. All-knowing: based on driver behavior and dynamic characteristics of CAV, as smaller front-rear gaps between vehicles, cooperative lane changes (vehicles at the lateral lane create the gaps), and slower reaction time. Anyhow just setting this behavior at VISSIM does not mean that any connected technology can be assessed. For this research, it was considered as a CV on SAE levels 3 to 4. CAV on level 5 is considered when technologies as platooning/CACC can be directly configured and evaluated.
- (Coexist D2.5, 2018) - Micro-simulation guide for automated vehicles: deep dive explanation on how to use the new features available at VISSIM 11 including “enforce absolute braking distance,” “use implicitly stochastic,” “number of interaction vehicles” and “increased desired acceleration.”

- (Coexist D2.6, 2018) – Technical report on data collection and validation process: details the validation process with the data collection process done in TASS international test track in Helmond Netherlands. The tests were performed using three vehicles equipped with CAVs Level 3 systems.

The project results proved that using new features and adapted driver behaviors parameters, and it is possible to simulate CAVs behavior with a satisfactory level of accuracy.

2.6 TRAFFIC SIMULATION

The study of traffic for roads and urban environments is a complex science. It presents a vast number of variables and interactions that make it a challenge to find a formal general description. Researchers recognized the need to represent traffic flow in analytical terms and developed formulations, which could be used by simulation modelers.

That context triggered the traffic simulators that dates from the 1950s (Transportation Research Circular, 2015) . In Annex 4, a genealogy of traffic simulators is presented. They are software tools that support traffic engineers, transportation planners, system designers, authorities, and researches to assess diverse traffic ecosystems and relevant topics with agility and low cost. They are used for many different purposes from the design of sensors and algorithms to control driverless cars individually (DOSOVITSKIY et al., 2017) as well as to evaluate the impacts at the overall traffic condition, supporting to find optimization opportunities during the design phase of new highways and urban pathways. They also can assess the effect of public transportation and pedestrian interactions (HELBING, 2002; SAIDALLAH et al., 2016). One more capability of traffic simulators was used in this research: to evaluate the impact of new technologies as V2X and CAVs vehicles on different aspects of the traffic.

As mentioned, the complexity of the traffic made it necessary to split the traffic simulators into four categories, from nanoscopic to macroscopic. The category choice depends on the focus of the study. FIGURE 9 and TABLE 1 describes the differences between these levels of simulations.

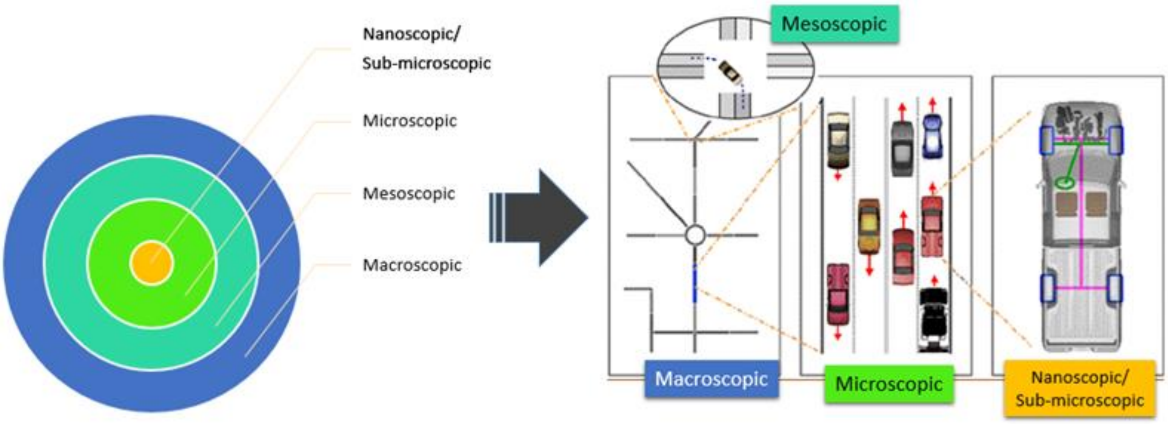
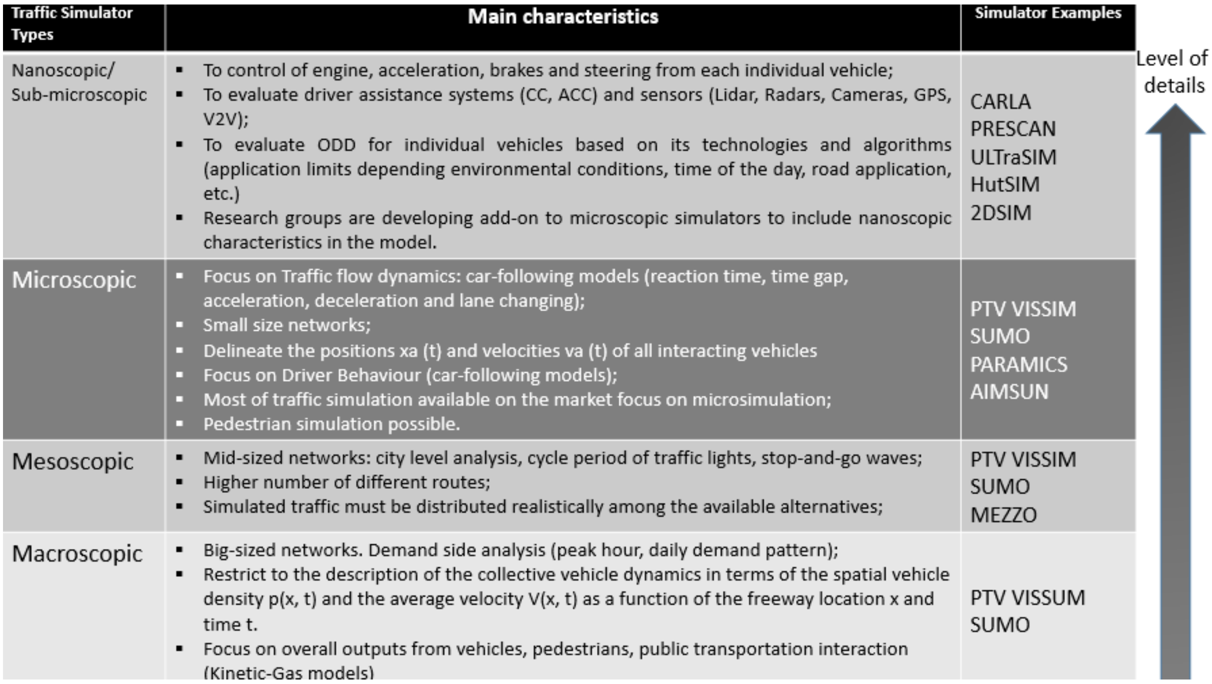


FIGURE 9 – Traffic simulation categories

Source: Author.

TABLE 1 – Characteristics of traffic simulators



Traffic Simulator Types	Main characteristics	Simulator Examples
Nanoscopic/ Sub-microscopic	▪ To control of engine, acceleration, brakes and steering from each individual vehicle; ▪ To evaluate driver assistance systems (CC, ACC) and sensors (Lidar, Radars, Cameras, GPS, V2V); ▪ To evaluate ODD for individual vehicles based on its technologies and algorithms (application limits depending environmental conditions, time of the day, road application, etc.) ▪ Research groups are developing add-on to microscopic simulators to include nanoscopic characteristics in the model.	CARLA PRESCAN ULTraSIM HutSIM 2DSIM
Microscopic	▪ Focus on Traffic flow dynamics: car-following models (reaction time, time gap, acceleration, deceleration and lane changing); ▪ Small size networks; ▪ Delineate the positions xa (t) and velocities va (t) of all interacting vehicles ▪ Focus on Driver Behaviour (car-following models); ▪ Most of traffic simulation available on the market focus on microsimulation; ▪ Pedestrian simulation possible.	PTV VISSIM SUMO PARAMICS AIMSUN
Mesoscopic	▪ Mid-sized networks: city level analysis, cycle period of traffic lights, stop-and-go waves; ▪ Higher number of different routes; ▪ Simulated traffic must be distributed realistically among the available alternatives;	PTV VISSIM SUMO MEZZO
Macroscopic	▪ Big-sized networks. Demand side analysis (peak hour, daily demand pattern); ▪ Restrict to the description of the collective vehicle dynamics in terms of the spatial vehicle density p(x, t) and the average velocity V(x, t) as a function of the freeway location x and time t. ▪ Focus on overall outputs from vehicles, pedestrians, public transportation interaction (Kinetic-Gas models)	PTV VISSUM SUMO

Source: Author.

Due to the characteristics of this research, the microscopic model was chosen. The delta on driving behavior between HDV and CAVs can be better explored in the microscopic environment.

2.6.1 Microscopic Traffic simulators

Microscopic traffic simulation models consist of several sub-models that are used to describe driving behavior. These sub-models are referred to by (GAO, 2008) as the "underlying logic” of a traffic simulation model. This logic consists of car-following, lane-changing, and gap-acceptance logics, which are all highly relevant in driver behavior modeling.

A wide range of micro simulators is available for commercial and research applications (SAIDALLAH, at al., 2016). On TABLE 2, an overview of them is presented.

TABLE 2 – Overview of most used traffic microstimulators.

Traffic Micro simulator	Car-following model	Application
PTV VISSIM	Wiedemann (1974–W74 and 1999–W99)	Comercial Developed by PTV (Planung Transport Verkehr AG) in Karlsruhe, Germany.
SUMO	Krauss (1997)	Open-source Developed by the German Aerospace Center (DLR), Germany.
AIMSUN	Gipps (1981)	Comercial Develop by Transport Simulation Systems (TSS), Spain.
CORSIM	Pipes or GM (1953)	Comercial Developed by The Federal Highway Administration (FHWA), USA.
PARAMICS	Fritzsche (1994)	Comercial Developed by Quadstone Paramics, UK.

Source: Author.

Among them, VISSIM and SUMO are the simulators more mentioned on traffic planners' studies as well as for traffic planners researchers. Many different studies worldwide were done based on those two software, and they are described in chapter 3. Due to the characteristics of this research, VISSIM was the option chose.

The PTV group headed by Rainer Wiedemann at Karlsruhe University in Germany developed the traffic microsimulation software called VISSIM. The backbone of the micro simulator is driving behavior (OLSTAM & TAPANI, 2004). FIGURE 10 shows the main components of VISSIM.

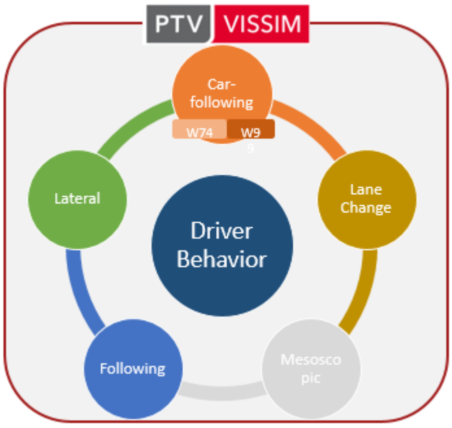


FIGURE 10 – Driver behavior components of VISSIM.

Source: Author.

The car-following behavior in VISSIM is based on a so-called psychophysical model. It combines human physiological restrictions as reaction times, estimation errors, and perception thresholds (HIGGS, ABBAS, & MEDINA, 2011) as well as psychological aspects as anticipation, context-sensitivity and driving strategy. Wiedemann suggested this model in 1974 (WIEDEMANN, 1974) and 1999. This characteristic is the reason why the distance a human driver keeps from the leading oscillates around a target time headway. This human behavior shall be adjusted to modeling the deterministic behavior of the test vehicles (TREIBER & KESTING, 2013).

GAO (2008) and HIGGS et al. (2011), the Wiedemann model assumes that a driver can be in four different driving regimes:

- Free driving: no obstacles or vehicles in front of the vehicle. The driver can proceed with its desired current speed;
- Approaching: the driver identify the leading vehicle in lower vehicle speed and brakes until it achieves the desired gap;
- Following: the driver tries to keep the desired gap from the leading vehicle. For human drivers the distance oscillates due to acceleration and brake patterns;
- Braking: the leading vehicle applies the harsh brake, and the subject vehicle must also brake.

Transition points that represent the points at which a driver changes his driving behavior define these regimes. FIGURE 11 shows a simplified representation of these transitions in the three-dimensional state space spanned by a gap (s), speed (v), and approaching rate Δv. The line in blue shows the trajectory of a vehicle coming from a free driving, coming to approaching and starting to follow the leading vehicle.

The thresholds are SDV (point, where the driver recognizes he is driving, is a higher speed than the leading vehicle and starts approaching), CLDV (the point where a driver recognizes minor differences in speed, decreasing distances), OPDV (point, where the driver recognizes he is driving, is a lower speed than the leading vehicle and starts to accelerate to keep following), ABX (minimum following distance) and SDX (maximum following distance during the same speed conditions as ABX) (TREIBER & KESTING, 2013; FRANSSON, 2018).

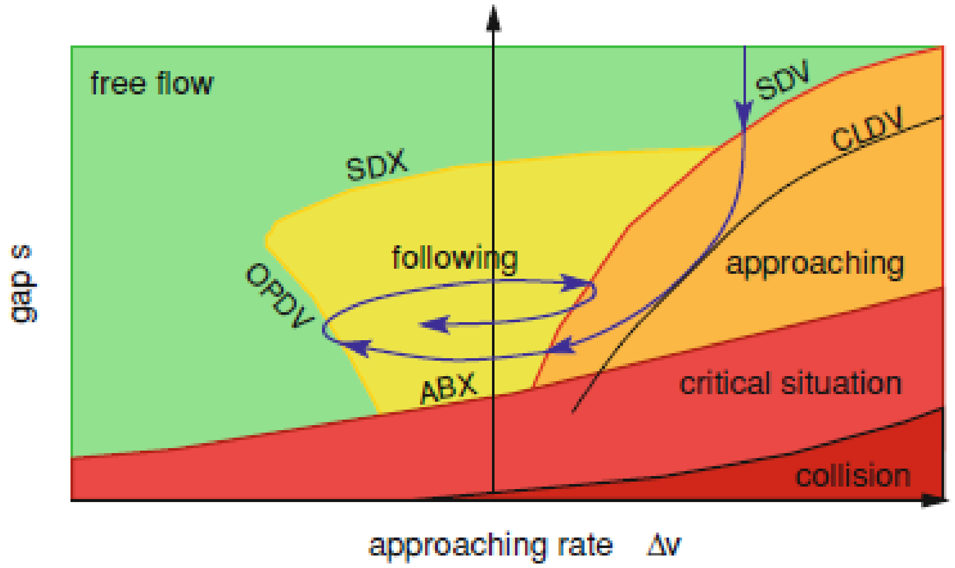


FIGURE 11 – Wiedemann model regimes

Source: (TREIBER & KESTING, 2013)

According to GAO (2008) Wiedemann 74 (W74) model used in VISSIM is formulated as

$$u_n(t+\Delta t) = \min \begin{cases} 3.6 \cdot \left(\frac{\dot{s}_{n}(t)-AX}{BX}\right)^2 \\ 3.6 \cdot \left(\frac{s_{n}(t)-AX}{BX \cdot EX}\right)^2 \end{cases} , u_f \tag{22}$$

where, $u_n(t+\Delta t)$ is the speed update. AX and BX are adjustable parameters expressed at

$$d = AX + BX \tag{23}$$

where, AX is the standstill distance (m) and BX the safety distance (m) given by

$$BX = BX_{add} + BX_{mult} \cdot z\,) \cdot \sqrt{v} \tag{24}$$

where v is the vehicle speed (m/s), BX_{add} is the additive part of the safety distance, BX_{mult} the multiplicative part of the safety distance and z is a value from 0-1, usually distributed around 0,5 with a standard deviation of 0,15.

While Wiedemann 74 is usually applied for urban traffic interactions and merging areas, Wiedemann 99 (W99) is a refined and modified version in order to model the freeway traffic conditions (PARK et al., 2017; Vissim User Manual, 2019; LACERDA & NETO, 2014; SONGCHITRUKSA et al., 2016). According to GAO (2008) W99 model used in VISSIM is formulated as:

$$u_n(t+\Delta t) = m\imath n \quad \begin{cases} u_n(t) + 3.6 \cdot \left(CC8 + \frac{CC8-CC9}{80}\, u_n(t) \right) \Delta t \\ 3.6 \cdot \left(\frac{s_n(t) - CC0 - L_{n-1}}{u_n(t)} \right)^2 \end{cases} , u_f \tag{25}$$

where CC0 is the standstill distance (m), CC8 is the standstill acceleration (m/s) and CC9 is the desired acceleration (m/s) at a speed of 80 km/h. Besides CC0, CC8, and CC9 there are still additional adjustable parameters from W99 described on Annex 5 (FRANSSON, 2018).

When it comes to CAVs simulation, a recommendation from the CoExist project is to use W99 even on freeway traffic conditions (Coexist D2.6, 2018). It is recommended mainly due to the availability of more parameters to control the behaviors. Also, on the W74 model, the vehicles keep their exact desired speed on the free driving mode when W99 allows for changing many of the parameters used and assumes a linear relationship between speed and following distance (i.e., a constant time headway plus standstill distance). In conclusion, W99 demonstrates to be more suitable for simulating CAVs independent of road characteristics.

Finally, apart from car-following parameters, more than forty-seven other parameters are available to define the driver behavior. The table shows manuals and researchers with reference values for each of those parameters.

TABLE 3 – References for VISSIM parameters set

Reference	Weblink
VISSIM 11 Manual	Available inside the installation folders
Advanced Transportation Leadership and Safety Center (ATLAS Center) from the University of Michigan and Texas A&M Transportation Institute: *Incorporating Driver Behaviors into Connected and Automated Vehicle Simulation (2016)*	https://www.atlas-center.org/wp-content/uploads/2014/10/ATLAS-Research-Report-Songchitruksa-ATLAS-2016-13.pdf Access: September 2019
Oregon Department of Transportation (ODT): Protocol for VISSIM Calibration (2011)	https://www.oregon.gov/ODOT/Planning/Documents/APMv2_Add15A.pdf Access: September, 2019
Wisconsin Department of Transportation (WSDOT): *Protocol for VISSIM simulation (2014)*	https://www.wsdot.wa.gov/NR/rdonlyres/378BEAC9-FE26-4EDA-AA1F-B3A55F9C532F/0/VISSIMProtocol.pdf Access: September 2019
Wisconsin Department of Transportation (WSDOT): *VISSIM Calibration Settings (2018)*	https://wisconsindot.gov/dtsdManuals/traffic-ops/manuals-and-standards/teops/16-20att6.3.pdf Access: September, 2019
Deliverable 2.3 CoEXISt: *Default bahavioural parameter sets (2018)*	https://www.h2020-coexist.eu/wp-content/uploads/2018/10/D2.3-default-behavioural-parameter-sets_final.pdf Access: September, 2019

Source: Author.

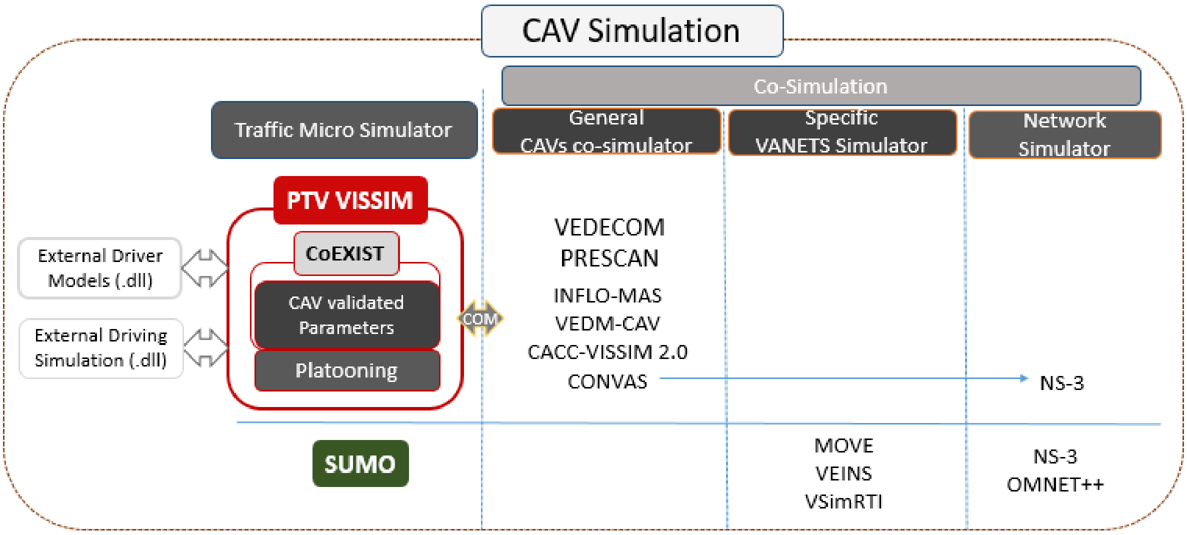
2.6.2 CAVs simulation

In order to simulate CAVs, it is demanded to gather expertise in many different fields of knowledge. Including road traffic simulation, network simulation, and V2X application. According to (GOEBEL, 2017) simulating it in a single simulator would have many disadvantages consuming a significant amount of time for planning, programming and verification of the combined simulator. He states that the approach to couple well-established simulators of the different domains is much more promising. At least three sets of simulators are necessary to allow realistic simulations of V2X applications communicating via cellular networks:

i. Well-established road traffic simulator to simulate the traversal of vehicles on the road network appropriately;
ii. Network simulator with cellular network simulation capabilities (MUSSA et al., 2016);

iii. The simulator for the V2X application

FIGURE 12 shows an overview of possible settings for CAVs simulation with SUMO and VISSIM. (GÁLVAN, 2016). Moreover, (GOEBEL, 2017) describes in detail the co-simulators compatible with SUMO. At the website from Open Source Application Development Portal (OSADP) from USDOT, it is available some co-simulators developed to be compatible with VISSIM (e.g., for CACC feature) (itsforge.net, 2019). It is essential to mention that some tries on using OSADP co-simulators were performed unsuccessfully due to a lack of documentation.



.FIGURE 12 – Overview of combined simulators for CAVs.

Source: Author.

On the VISSIM, version 11, new features were added in order to support CAVs characteristics and mixed traffic situations, as described in Table 4.

Table 4 – New features released at VISSIM to enable AVs and CAVs traffic simulation

Feature	100% HDV environment	CAV/ mixed environment
Enforce absolute braking distance		
Use implicit stochastics	Stochastic: the imperfection of human driving	Deterministic machines & computers
Class dependent safety distance in the following behavior	Headway is fixed for all vehicle classes	Headway dependant on followed vehicle class: possible to set different following distances to conventional vehicles, automated vehicles, connected and automated vehicles, cyclists, etc
Number of interaction objects & vehicles	Humans can see many vehicles ahead independent of sensors but have limited capacity to interact with many objects	AVs can detect objects and interpret visual information inside the sensors range. CAVs can interact with more objects due to communication capabilities.
Increased acceleration in following possible	Humans have limited capacity to keep close following to the leading vehicle. During the following behavior, the acceleration rates are not highly increased to keep the distance.	For CAVs, mainly in a platoon, higher acceleration rates are demanded to keep the headway even if the speed of the leading vehicle increases significantly. To mimic such behavior this parameter can be set above 100%.
Zero passengers	It will be every time at least the driver inside the vehicle	It allows setting vehicles with zero passengers (for SAE Level 4 and 5)

Source: Adapted from PTV (2019) and Coexist D2.6 (2018).

VISSIM did the first try on having a connected vehicles integrated tool in August 2019. VISSIM 2020.00-0 beta version released the feature platooning (PTV, 2019).

Before launching platooning, all the material that the PTV released for testing CAVs was done using external coding. Inside the *“Examples Training”* folder from version 11, it is available some base examples for the users that aimed to simulate CAVs scenarios. See below two of those examples with possible interfaces including the first platooning implementation before it comes to be part of the software:

I. Example “Platooning”: a python script and COM interface is used to generate of platoons at the edge of the network as well as platoon operations such as vehicles closing the gap if a vehicle leaves the platoon and vehicles opening a gap to allow another vehicle to enter the platoon. This implementation is limited to specific driving behavior.

II. Example “Speed at signals C2X (Car to Everything)”: a python script runs in parallel with the simulation, taking the information about the upcoming signal and adjust their speed to arrive at green without stopping. This example brings the interface between the vehicle and the infrastructure.

As platooning is a new feature with a focus on V2V, and there are no researches worldwide that delivered results using that software capability, it will be used in that research on scenarios with CAVs.

3 LITERATURE REVIEW

This chapter presents different aspects of CAVs concept evolution along the years with the focus on microscopic simulation. The review is presented chronologically with the most relevant studies related to the topic aiming to explore the state of the art in that research field. This review aims to answer four central questions: (i) How will CAVs impact the traffic performance of the cities and roads, (ii) How will be the traffic performance and which are the most relevant aspects to be evaluated during transition phases where different vehicle automation levels will share the same road? (iii) Any of those studies cover Brazilian city traffic situations? (iv) Which technologies are more relevant?. Bearing those questions in mind, the gaps that this research assesses and its relevance can be further comprehended.

The literature about traffic microsimulation for CAVs is mostly condensed in the last four years due to the increasing prominence of the topic. At the same time, the capabilities of the simulator to model the characteristics of this environment have ben improved. RIOS-TORRES & MALIKOPOULOS (2017) brings a collection of studies starting from the end of the 1960s with different approaches to achieve safe and efficient coordination of vehicles to improve the traffic flow. TIAN et al. (2018) and DO et al. (2019) published surveys with many different types of research related to simulation of CAVs. Those surveys and a further active literature search on leading journals, books, and congress proceedings are presented in the following.

Along with the 90s, the first system on the roadmap to the AV's most used terminology was Autonomous Intelligent Cruise Control (AICC). It was defined as a vehicle-installed system that aims to automatically adapt the speed to keep a safe distance from the vehicle ahead. The vehicle's communication technologies were still not part of those researches. KING et al. (1993) and BJORNBERG (1994) presented the control algorithms description to define the system that years later would be so-called ACC. CHIEN & IOANNOU (1993) showed that the AICC system outperformed the human driver model due to its faster and better transient response, resulting in smoother traffic and faster traffic flow. CARREA & SAROLDI (1993) explored in a testing vehicle the integration between AICC and anti-collision systems. Other studies as ERIKSSON & AS (1995) and AOYAGI, et al. (1997), had the focus on radar development for AICC systems.

After the 2000s, the terminology ACC and CACC become more used. WERF et al. (2002) developed a simulation based on Monte Carlo to estimate the impacts of ACC in different proportions along with HDVs. AREM et al. (2006) developed a microsimulation model dedicated to studying the impact of CACC on traffic flow. The authors evaluated its impacts on a highway scenario with a focus on merging spots comparing to non equipped vehicles. They reported an improvement in traffic flow stability anyhow it was not found relevant improvements on travel times. On the other hand, KESTING et al. (2008) developed a microscopic traffic simulator and used the IDM to propose an ACC with the active jam-avoidance system. They noticed that a proportion of 5% of ACC vehicles already improved the traffic flow, and 25% of ACC reduced the cumulated travel time by approximately 75%, mainly because ACC avoided the breakdown of traffic flow in the model.

In the current decade, many types of research had a focus on ACC, IDM models, and CACC impact on traffic performance. SCHAKEL et al. (2010) used a modified version of IDM so-called IDM+ and CACC algorithms to evaluate traffic flow stability on field tests with 50 vehicles (FOT). In mixed traffic scenarios with 50% of CACC equipped vehicles, the shockwave duration was five times lower than with 100% HDVs. KESTING et al. (2010) proposed an Extended IDM (EIDM) using constant-acceleration heuristic (CAH) as a performance index and found a direct relation between ACC penetration rate on traffic performance: each 1% more ACCs increased road capacity by about 0.3%. (LIU, et al., 2018) also developed a variation of Extended IDM that considers V2V technologies. A stability analysis is performed where EIDM shows a broader stability region when compared to IDM. LU et al. (2019) proposed a model for CAVs in a platoon based on an ecological control strategy so-called Ecological Smart Driver Model (EcoSDM), considering IDM as the base model (100% HDVs). The results in the simulation show that the model is superior in fuel efficiency (at fully CAVs scenarios, EcoSDM was 10% better for the platoon when compared to EIDM) and stabilization effects when compared to SDM and EIDM. A topic to highlight in this study is that the position of the platoon has interference on the fuel consumption as expected, anyhow a non-trivial output was that the leader of the platoon was almost 2% better fuel efficiency when compared to base scenario and the vehicle on position 16 of the platoon was near to 0%.

In parallel, several researchers used microsimulation tools to assess their studies in the same fields. PLOEG et al. (2011) simulated CACC systems and showed pieces of evidence that the smaller gaps achieved with the platoon of vehicles increased the road throughput. PARK et al. (2011) used VISSIM to explore a lane change advisory algorithm for CAVs on-road merge conflicts, considering V2V capabilities. As the vehicles on the road open gaps for vehicles entering the merging areas, they measured a 6,4% higher average vehicle speed in the freeway and 5,2% reduction in emissions with 100% of CAVs when compared to the merging area with 100% HDVs. On the other hand, SHLADOVER et Al. (2012) simulated ACC and CACC with AIMSUM traffic simulation. They tested different market penetrations and results showed that ACC has low impacts on increasing road capacity (veh/h), even in higher penetration rates. Although, CACC showed since a low penetration of 20% already increased the capacity by 7%, achieving the double of the lane capacity for 100% of CACC. It is essential to mention that the better results came with CACC penetration rates above 80%. (ZHAO & SUN, 2013) used VISSIM to simulated a mixed freeway with vehicles with no ADAS together with vehicles equipped with ACC and CACC (platoon mode). ACC and CACC were simulated using the External Driver Behavior Model (EDBM) coded in C/C++ coding. Results showed that traffic capacity almost doubled from 0% CACC market to 100%. One relevant outcome was that the size of the platoon (from 2 to 6 vehicles) did not have a significant impact on traffic capacity.

Other researches had focus on the interface between vehicle and infrastructure. Their studies were assessed on micro simulators. LEE & PARK (2012) developed a V2I system for Cooperative Vehicle Intersection Control (CVIC), and simulation results revealed a reduction of 99% of stop delays and travel time which impacted on 44% reduction of fuel consumption when compared to the same intersection with 0% vehicles equipped with V2I technology. KATSAROS et al. (2011) reported a 7% reduction in fuel consumption in a scenario with 100% of vehicles equipped with Green Light Optimized Advisory (GLOSA) when compared to standard vehicles. STEFANOVIC et Al. (2013) also evaluated GLOSA with high penetration rates that presented a reduction of 52% vehicle stop delay, a 46% reduction on vehicles stop, although just 0,5% higher fuel efficiency. A few years later, GLOSA was the focus of CHOUDHURY et al. (2016) that developed a simulation setup with VISSIM, MATLAB and NS-3 (network simulator) to test this application. In the scenario with GLOSA applied to 100% of the vehicles, it was found a 7,4% decrease in fuel consumption and a 20% higher network throughput when compared to the scenario without it. An extensive report from FROST & SULLIVAN, (2017) shows that intelligent traffic system applications can reduce travel time by 23% for emergency vehicles (hospital ambulances, fire engines), and by 27% for other vehicles.

During the last few years, studies with mixed or heterogenous traffic topics got more attention from the researchers. The aspect when human-driven AVs and CAVs coexist at the same road is further explored by YANG et al. (2016) simulations resulted in an evident decrease in the total number of stops and delayed when using an algorithm for CVs relative flows above 50%. BAILEY (2016) modeled a mixed flow with autonomous, based on modifications on IDM (presented in chapter 2 so-called Enhanced Intelligent Driver Model (EIDM). ZHOU et al. (2017) also proposed modifications on IDM so-called Cooperative IDM (CIDM) and evaluated the average travel time for AVs percentage from 0-25%. Results showed that for safe time gaps between 0.4s to 0.8s, the average travel was reduced by 15% when a 25% percentage of AVs was achieved. It was also concluded that an increase in urban traffic network capacity and a decrease in average delay as CVs penetration rate is increased (on 100% and 20% CVs penetration a reduction in travel time of 80% and 53%, respectively, was achieved). RIOS-TORRES & MALIKOPOULOS (2017) made a comparison with an optimal control scenario considering 100% of CAVs penetration and reached 60% of time reduction for heavy traffic.

ARIA et al. (2016) used VISSIM (W99 model) to simulate AVs based on parameter adjustments. At the simulated autobahn with 100% of AVs, the authors reported improvement by 9% on travel times and 8,48% higher average vehicle speed when compared to the base scenario (0% AVs). PARK et al. (2016) used VISSIM running with the COM (Component Object Model) interface that makes it possible to anticipate the information from the next step of the simulation. They concluded that the CV environment reduces the congestion in proper traffic volume because of the elimination of the perception-reaction time gap. YE & YAMAMOTO (2017) focus was also on heterogeneous traffic flows showing more significant improvement when the penetration rate o CAVs is above 30%. DOLLAR and VAHIDI (2017) show different algorithms to compare platooning performance and reports a potentially significant fuel efficiency benefit when the proposed Model Predictive Control (MPC) algorithms are used. HAAS & FRIEDRICH (2017) developed a microscopic simulation with SUMO and Plexe (extension for SUMO to implement platoon functionality) for CAVs platoons, used in city logistics with the focus on the travel time issue. The main results show that an increase in the number of vehicles per platoon (from 2 to 6) decreases the travel time. This result was achieved mainly during peak hours (network crowded).

The pace of studies on the related kept increasing in the last two years. RIOS-TORRES & MALIKOPOULOS (2018) simulated based on Gipps car-following model and optimal control, including V2V and V2I, to evaluate the impacts of CAVs on fuel consumption and a traffic flow from 0% to 100% penetration. The results for low traffic volumes were the fuel-saving achieved 55% increasing proportionally from 0 to 100% CAVs. One conclusion was that for medium and high traffic demand, a significant fuel saving was achieved just near to 100% CAVs penetration. BAZ (2018) used VISSIM and concepts from game theory to propose a method to improve delay times on roundabouts and intersections. The results show that the proposed system reduces the total delay by more than 65% on the roundabout and about 85% percent on a signalized intersection. TILG et al. (2018) developed a variation of the multi-class hybrid model (MHT) based on multiple vehicle classes for CAVs at mixing traffic in weaving sections. The model was developed using MATLAB and calibrated with field data from the city of Basel, Switzerland. Results show that growing shares of CAVs can increase up to 15% traffic flow capacity by optimizing the spatial lane change distribution when compared to scenarios with no CAVs. OLIA et al. (2018) simulated the CAVs under mixed-traffic conditions with the assumption of increasing a 10% gap of CAVs. The result shows that a 100% penetration rate of CAVs could increase road capacity from 2,046 to 6,450 vehicles/hour/lane. LIU et al. (2018)

simulated the impacts of a CACC multi-lane freeway with mixed traffic highway simulations by increasing CACCs' gap by 20%. The results show that the freeway capacity could be approximately 90% higher with a 100% CACC penetration rate, compared to 0%.

CHEN, et al. (2019) simulated with VISSIM to assess the impact of ACC and CACC increasing penetration rates among HDVs. For both ACC and CACC increasing penetration rates, the most significant impacts were found on travel time. For a 90% penetration rate, there was 9% and 11% reduction of travel time ACC and CACC, respectively. XIE et al. (2019) propose a generic car-following model for HDVs and CAVs. Results shoes that increasing penetration of CAVs can suppress traffic waves (using information from ADAS for penetration above 80% the variation on vehicle speed could be almost neglected) stabilize traffic, therefore, increasing the traffic flow. ZHOU et al. (2019) modeled a four-lane cellular automata traffic on mixed traffic with ACC/CACC and manual vehicles. The numerical results indicated that the CACC strings presented considerable stability while the ACC strings show instability. The evaluation of the CACC penetration rate showed that the capacity per lane almost doubled from 2000 veh/hr (0% CACC) to approximately 3900 veh/hr (100% CACC), where the higher impacts came from penetration rates above 60%. GHIASI (2019) presented a speed harmonization algorithm to harmonize traffic for HDVs and CAVs in mixed traffic situations. The numerical experiment results indicate that the algorithm was capable of smoothing CAV movements but also harmonizing the following human-driven traffic.

TABLE 5 shows a summary table with the central studies on CAVs microscopic simulation researches that presented numerical results related to its impacts on traffic flow, fuel efficiency, and emissions. As the impacts on traffic flow are the focus of this research, those results are used to assess the results found during the simulation scenarios proposed.

TABLE 5 – Summary table with results comparison between references and author

Reference	Simulator	Application	Results
H. PARK et al. (2011)	VISSIM	Merging Highway	↑ 6,4% average vehicle speed ↓ 5,2% emissions
KATSAROS et al. (2011)	SUMO	Urban	100% GLOSA equipped vehicles → ↓ 7% fuel consumption
STEVANOVIK et al. (2011)	VISSIM	Urban	100% GLOSA equipped vehicles → ↓ 50% stop delays
SHALODER et al. (2012)	AIMSUM	Highway	100% CACC → 2x lane capacity
ZHAO & SUN (2013)	VISSIM + C++ DLL	Highway	100% CACC → ↑ 95% traffic capacity
ARIA et al. (2016)	VISSIM	Highway	↑ 8.48%: average vehicle speed ↓9.00%: travel time
CHOUDHURY et al. (2016)	VISSIM NS-3 Matlab	Urban	100% CACC → ↓ 7,4% fuel consumption 100% CACC → ↓ 7% emissions
BAILEY (2016)	AIMSUM	Urban	20% AVs → ↓ 53% travel time 100% AVs → ↓ 80% travel time
RIOS-TORRES et al. (2017)	AIMSUM	Urban	100% AVs → ↓ 60% travel time
EVANSON (2017)	VISSIM + Platooning (external)	Highway	100% CAVs → ↓ 11% travel time
BAZ (2018)	VISSIM	Urban	↓ 65% total delays in roundabouts ↓ 85% total delays on signalized intersections
OLIA et al. (2018)	Not mentioned	Higway	100% CAVs → ↑ 315% veh/hr/lane capacity
TILG et al. (2018)	MATLAB + Not mentioned	Highway	100% AVs → ↑ 15% traffic capacity
LU et al. (2019)	Not mentioned	Highway	100% AVs → ↓ 16% fuel consumption
ZHOU et al. (2019)	Not mentioned	Highway	100% CACC → ↑ 95% lane capacity
CHEN et al. (2019)	VISSIM	HIghway	90% ACC → ↓ 9% travel time 90% CACC → ↓ 11% travel time.

Source: Author.

Besides the mentioned CAVs impacts, it worths to mention additional studies on road safety focus. VALIDI et al. (2017) use SUMO and “Scene Suit” to show the impact of CAVs on road safety. For the scenarios evaluated, the overall results show that even the lowest penetration rate (40%) of V2V resulted in a dramatic improvement in the level of road safety by preventing all types of accidents. One additional valuable reference from GE et al. (2018) shows an experimental validation done with retrofitted vehicles equipped with V2X devices at the University of Michigan Mobility Transformation Center. The experiments demonstrate that both safety and fuel efficiency can be significantly improved for CAVs as well as for nearby human-driven vehicles, and they conclude that CAV may bring additional societal benefits by mitigating traffic waves.

Other crucial aspects for CAVs evaluated by FERNANDES & NUNES, (2012); OSMAN & ISHAK (2015), BIDÓIA (2015), MIR & FITALI (2016), CHAI et al. (2017), HE, et al. (2017), NANAJI et al. (2017) and TAKAHASHI, (2018), NAUFAL et al. (2018) and (HUSSAIN et al., 2019), are the connectivity robustness, cyber/data security, network performance and functional safety (ISO 26262). They discuss topics related to the effects of the position error, communication delay, received signal strength, packet delivery ratio, number of nodes, and reliable communication range for the given data rate settings.

Besides, apart from the already mentioned Bidoia (2015), it is important to highlight other researches done in Brazil related to CAVs. It was not found studies related explicitly to CAVs traffic microsimulation impacts on traffic flow, anyhow other essential topics from their ecosystems were on the scope. MATEUS (2010) provided new directions to design efficient routing protocols performance for vehicular networks. CARIANHA (2011) also focused on vehicle networks assessing a model of cryptographic “mix-zones” to improve location privacy information. GÁLVAN (2016) used the combination of SUMO and OMNET++ to study the vehicle's wave propagation modes from VANETs on the urban environment.

In conclusion, a wide range of researches in CAVs from simulation to field tests shows that these technologies have positive impacts on highway traffic flow, lane capacity, and as a consequence of fuel efficiency and emissions. On many different studies based on microscopic traffic simulation among different assumptions about car-following behavior, lane changing behavior, and connectivity, there is a common trend showing that increased penetration of autonomous vehicles leads to increased capacity and flow. On the challenging mixed traffic conditions, the increasing penetration of technologies enabled by CAVs (as CACC/platooning, GLOSA and modified version of IDM) impacted on better results from all the aspects evaluated. It shows that the technologies should continue to be developed and the implementation path accelerated.

The gaps found to be explored at this research are: The simulation researches explores highways or city conditions with aspects that do not cover Brazilian metropolitan areas roads and streets reality as the high number of motorcycles, buses, and trucks, non-dedicated public transportation lanes. Another topic that is not explored in many types of research is to add disturbance as vehicle breakdown and how to recover the normal traffic conditions in less time. Also, the performance of CACC/platoons on city traffic where many merging and a possible destination for the vehicles is still a point to be explored. Finally, there are not released studies using VISSIM 2020 version including an in-software platooning feature. This version was recently launched (the beta version in August 2019).

Considering the aspects that have been addressed so far, in chapter 4, we will present the research proposal

4 RESEARCH PROPOSAL

Connected and autonomous vehicles will be part of daily traffic along the next decades. The motivations are clear, and they are related mainly to sustainable mobility, reduction in road accidents, and new mobility needs for an increasing world population. Many studies mentioned in chapters 2 and 3 demonstrates that CAVs benefits merge with the motivation behind the mobility of the future.

Besides that, there is still a challenging pathway ongoing. Much more than the continuous improvement from products done individually for each OEM, it will demand standardization and the parallel development of compatible technologies to get connected traffic. The Unique Selling Points (USP) that drove the development of vehicles during the last century will follow a new logic. The car owners will follow a new logic as well, so the decision on which vehicle to purchase will be based on different aspects.

This ecosystem will make our roads a mix of different car technologies for many years. For traffic agencies, this heterogeneous environment brings new challenges widely discussed on the legislation, legal responsibilities, cybersecurity, infrastructure and road construction (dedicated lanes, ITS corridors) aspects.

This new ecosystem gets even more complicated for large cities and metropolitan areas where the driver behavior on heavy traffic changes. In countries like Brazil, two more characteristics play an essential role in traffic behavior: the high relative flow of motorcycles driven between the cars and the bus stops that are not placed on dedicated lanes.

Studies from YANG et Al. (2016), BAILEY (2016), and RIOS-TORRES and MALIKOPOULOS (2017) show that from 40% to 50% AVs or CAVs relative flow there is a significant improvement on travel times and road capacity.

4.1 RESEARCH GAP

This research looks for measuring the impacts of AVs and CAVs on the travel time for the mentioned mixed traffic environment considering big Brazilian cities' traffic characteristics. In order to bring new contributions, this research will evaluate for different scenarios how a disturbance (e.g., break down vehicle) affects traffic performance and proposes a rescue vehicle shared model to fasten attenuate the disturbance effects. Moreover, on the next steps of this research platooning which is a new integrated feature released for PTV VISSIM in August 2019, will be evaluated to simulate CAVs characteristics. FIGURE 13 illustrates the research gap.

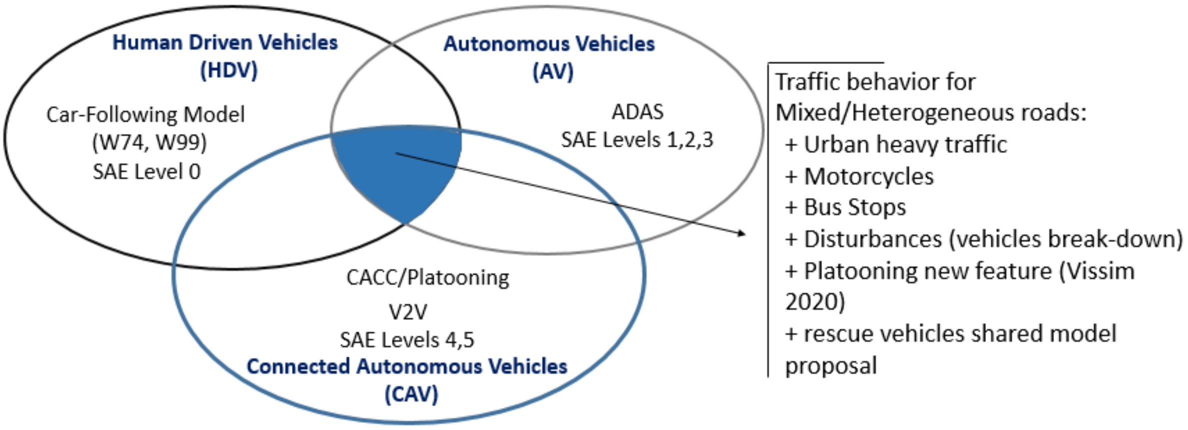


FIGURE 13 – The research gap

Souce: Author.

FIGURE 14 shows how the topics will be covered and how the simulation models and scenarios will be built in order to cover the research gap

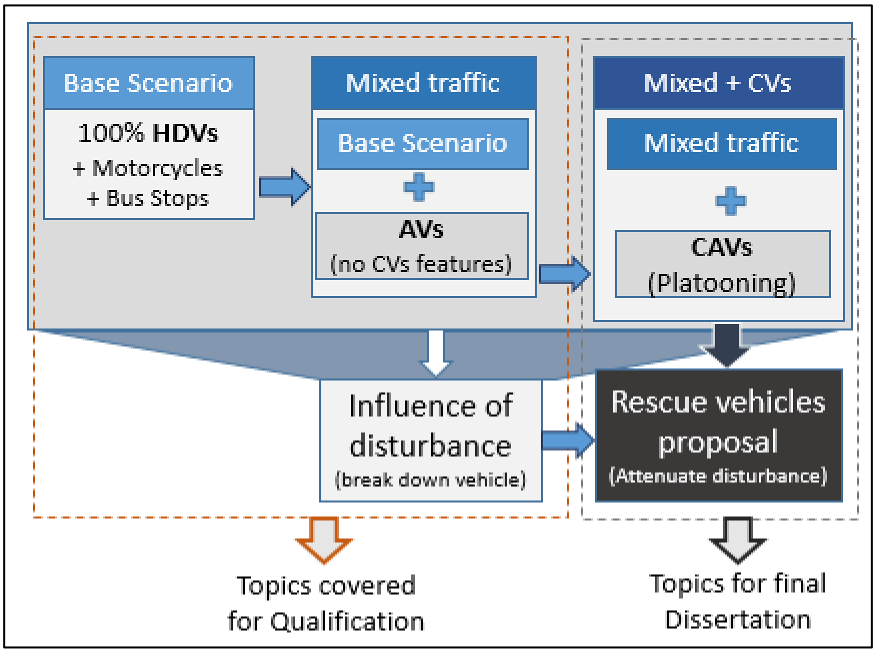


FIGURE 14 - Topics evaluated to cover the research gap.

Source: Author.

Considering this research gap and topics that will be handled, this research aims to answer the following question:

- How will the CAVs influence the traffic travel times for big cities scenarios including the transition phases?

5 METHODS AND MATERIALS

In this chapter, it is presented the methods and materials used during the research development. The input data and simulator calibrations performed during the simulations are described as soon as the description and background of the scenarios that are the framework to get the results.

5.1 MATERIAL

As this research was done based on computer simulations, the details of the materials used are described in TABLE 6:

TABLE 6 – List of materials

Item	List of materials	Details
1	Ultrabook LG	Model U46 Processor: Core i5 RAM: 4GB HD: 512 GB Dedicated graphics board: no
2	Desktop Computer	Intel i7 Processor 3.2GHz SSD 480GB DATA 6GB Memory DDR$ 16GB 2400MHz Video card (GPU) Geforce RTX2070 HD 2TB
3	PTV VISSIM Software	Thesis license Versions: 11.00 -06 to -10 2020.00-00 Beta Version

Source: Author.

It is important to remark that for this simulated track, it was possible to run VISSIM properly even with a medium performance computer without a dedicated graphics board (TABLE 6 – List of materials item 1).

5.1.1 Traffic simulator used during the research

All the results presented at this research are based on PTV VISSIM microscopic traffic simulator. All the characteristics of this software and the comparison with other off-the-shelf simulators are described inside section 2.2.

The main reasons for choosing PTV VISSIM were the following:

- Software widely used for traffic management entities from the government in many cities as São Paulo (target of this research);

- Software widely used on traffic research groups inside and outside universities on many different locations around the world, as described in section 2.3: accessible high quality and up to date information from the literature;
- Friendly user interface when compared to open source software: it enabled a faster model set up to keep the focus on the benefits of vehicles automation and communication;
- User guide detailed information and very well documentation when related to other software;
- The same software used for colleagues from research group: significant synergy on sharing experiences;
- Local support in Brazil from PTV.

The simulations run in two different versions:

- VISSIM11.00 from -06 to -10: PTV released update packages regularly with corrections or new features.
- 2020.00-00 (beta) released in August 2020: this version was the first one with Plattoning feature available to make connected vehicles simulations more realistic

Even though it is commercial software, PTV Group offers a thesis license to students. This license was offered for ten months and it was installed on a personal computer and. It is also available at the university labs.

5.2 DRIVER BEVAHIORS SIMULATED MODELS

The main goal of the research was to investigate the benefits of vehicle automation on different levels for high-density city traffic applications.

To achieve the goal, some scenarios were built based on three different driver behaviors described on FIGURE 15 –. Mind that two of them (HDV and AV) were based on the CoEXist project model validated in partnership with PTV, mentioned on chapter 2.5.1. CAV driver behavior will be modeled over AV adding platooning feature.

The decision for using W74 and W99 at the same simulation track is explained in section 4.2.

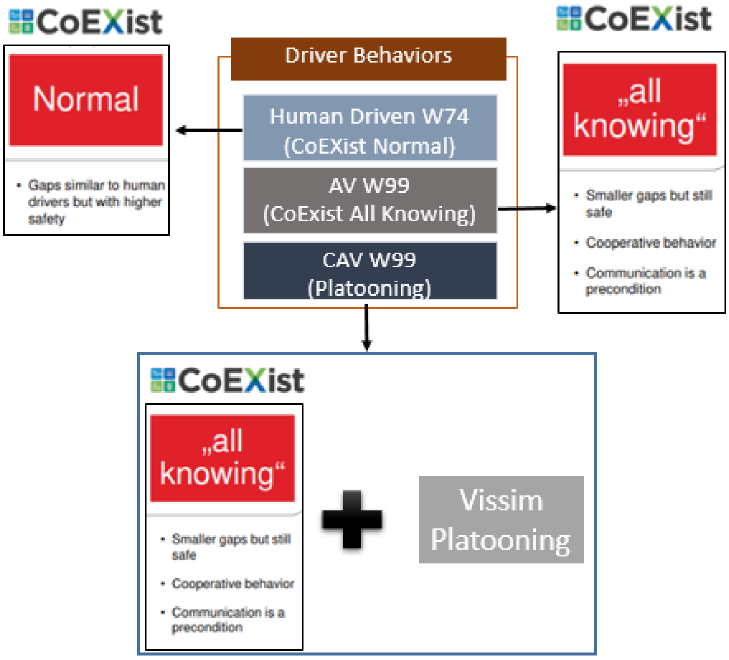
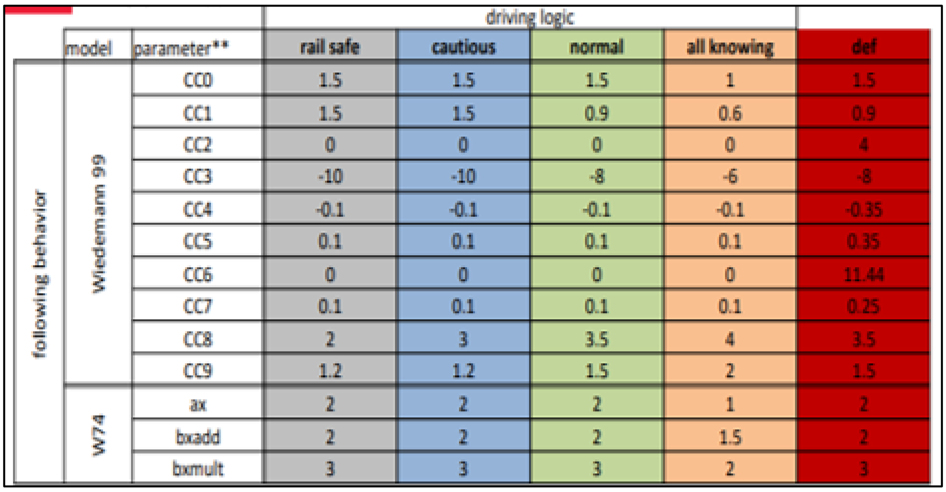


FIGURE 15 – Driver behaviors description
Source: adapted from (Coexist D2.4, 2018).

The parameters validated for simulation of each driver behavior during the CoEXist project are presented at FIGURE 16, where the list column denominated "def" shows the default parameters recommended at the VISSIM user manual (Vissim User Manual, 2019).



			driving logic				
	model	parameter**	rail safe	cautious	normal	all knowing	def
following behavior	Wiedemann 99	CC0	1.5	1.5	1.5	1	1.5
		CC1	1.5	1.5	0.9	0.6	0.9
		CC2	0	0	0	0	4
		CC3	-10	-10	-8	-6	-8
		CC4	-0.1	-0.1	-0.1	-0.1	-0.35
		CC5	0.1	0.1	0.1	0.1	0.35
		CC6	0	0	0	0	11.44
		CC7	0.1	0.1	0.1	0.1	0.25
		CC8	2	3	3.5	4	3.5
		CC9	1.2	1.2	1.5	2	1.5
	W74	ax	2	2	2	1	2
		bxadd	2	2	2	1.5	2
		bxmult	3	3	3	2	3

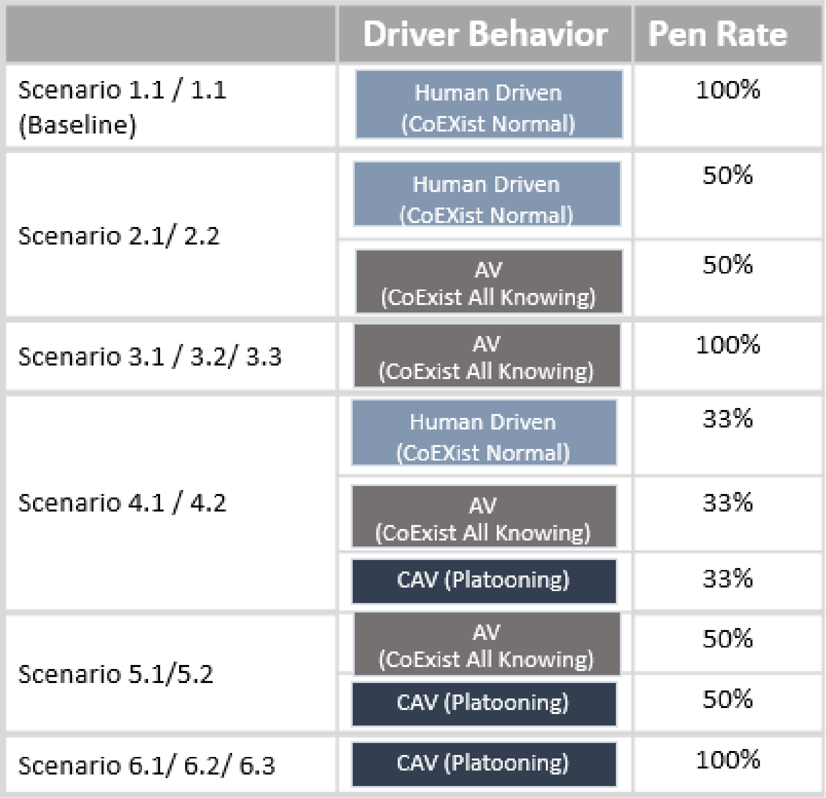
FIGURE 16 – Parameters for Following Behaviour validated inside CoEXist project.

Source: (Coexist D2.3, 2018).

5.2.1 Evaluated scenarios

A total of 14 scenarios were built combining different elements as driver behaviors, external disturbance and an additional new proposal. For every scenario, the penetration rate of each driver's behavior was predefined to make it possible to measure the benefits of the incremental introduction of the autonomous and connected vehicles. TABLE 7 **Erro! Fonte de referência não encontrada.**shows the overview.

TABLE 7 - Evaluated scenarios overview



	Driver Behavior	Pen Rate
Scenario 1.1 / 1.1 (Baseline)	Human Driven (CoEXist Normal)	100%
Scenario 2.1/ 2.2	Human Driven (CoEXist Normal)	50%
	AV (CoExist All Knowing)	50%
Scenario 3.1 / 3.2/ 3.3	AV (CoExist All Knowing)	100%
Scenario 4.1 / 4.2	Human Driven (CoEXist Normal)	33%
	AV (CoExist All Knowing)	33%
	CAV (Platooning)	33%
Scenario 5.1/5.2	AV (CoExist All Knowing)	50%
	CAV (Platooning)	50%
Scenario 6.1/ 6.2/ 6.3	CAV (Platooning)	100%

Source: Author.

Details from scenarios composition:

- **Scenarios X.1:** base scenarios without disturbances.
- **Scenarios X.2 –> adding a disturbance:** same as X.1, including an external disturbance. The disturbance is a vehicle break down always at the same position on the track and starting at the same simulation time step.

  In order to simulate a broken vehicle, it was inserted a bus stop and the open door time was defined with a value higher than the total simulation time.FIGURE 17 shows how the disturbance was added to the simulation.

FIGURE 17 – Disturbance added to the model on scenarios X.2.

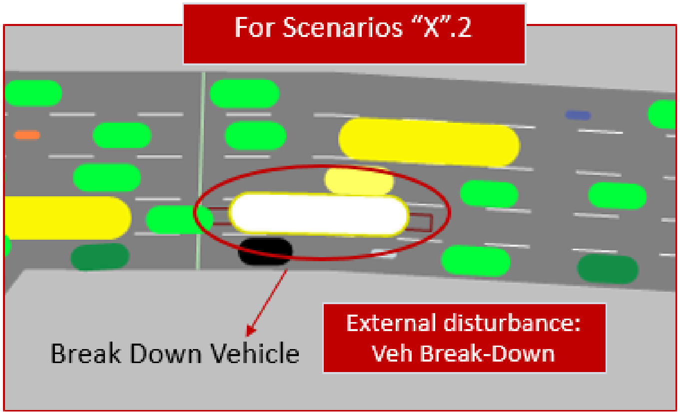


FIGURE 18 – Disturbance added to the model on scenarios X.2.

Source: Author.

- **Scenarios X.3 -> rescue vehicles shared model proposal:** a new proposition is presented with these scenarios. It is based on X.2 scenarios and on the premise that the faster a disturbance is overcome the faster the traffic flow normal conditions are recovered.

It is composed of two elements: a broke down the vehicle and a rescue vehicle.

A mandatory requirement is that both elements should be equipped with the V2X communication feature. Then it makes possible that when a break down happens, an emergency condition is triggered, and this status is sent to surrounding vehicles and infrastructure.

If one of the surround vehicles can act as a rescue car supporting the breakdown vehicle, it will receive a message on display. The rescue vehicle should be able to move the other one out of the track to a safe point. The message on display should have the following content:

- Information of broke down vehicle ahead;
- Question asking permission to support;
- Additional travel time: to make it transparent how long it will take and motivate rescue vehicles to accept the request.

FIGURE 19 – and FIGURE 20 - describes the proposal from scenarios "X.3".

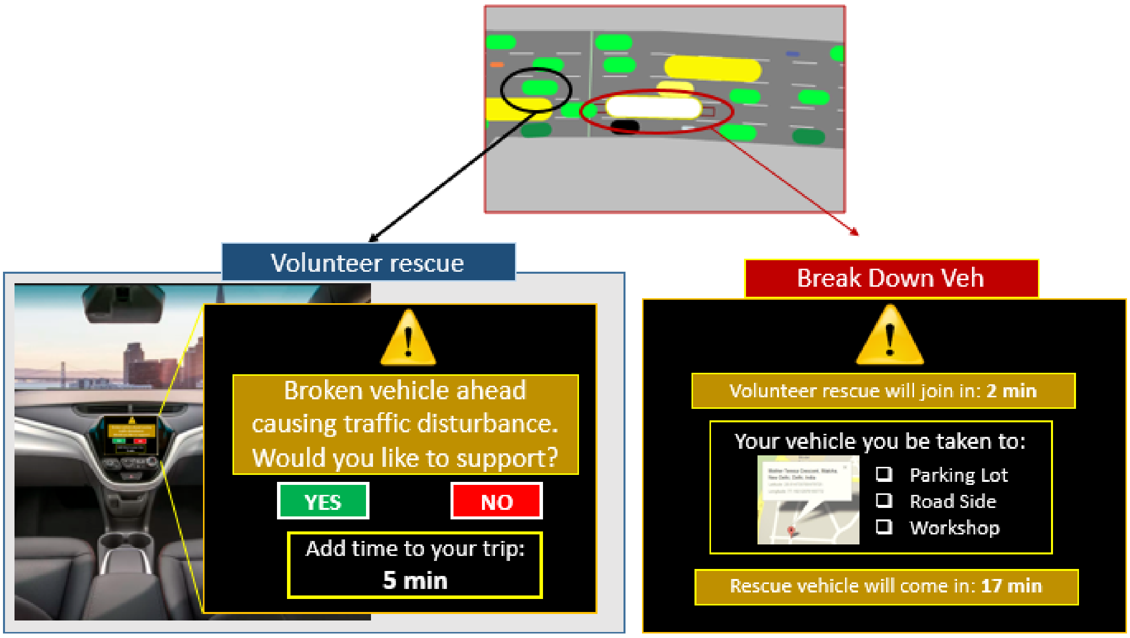


FIGURE 19 – Proposal for scenario “X.3’ (step 1).

Source: Author.

Also, to making an automatic trailer connection between the vehicles, both should be equipped with trailer sockets, as described in Figure 19.

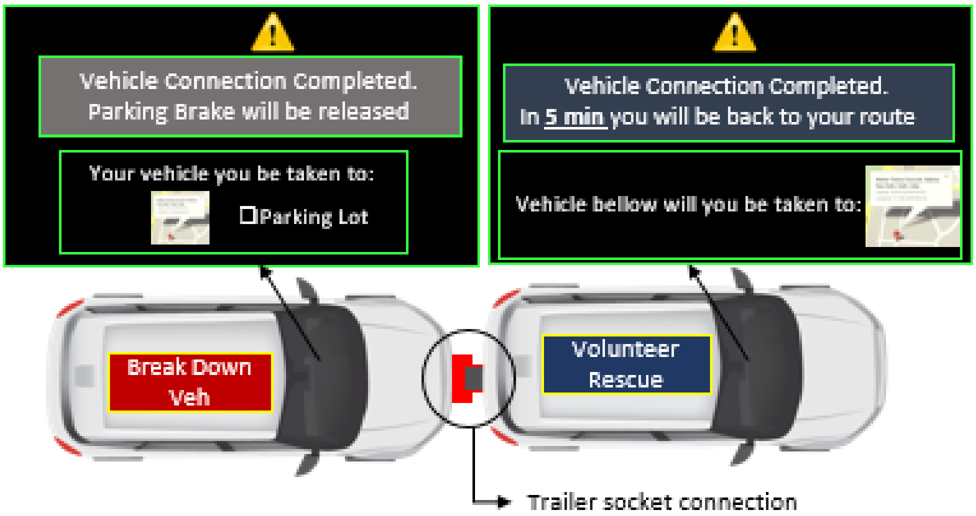


FIGURE 20 - Proposal for scenario ‘X.3 (step 2)’.

Source: Author.

To motivate even more the vehicles around to accept the request a reward can be offered. The reward can be offered in a different way: cashback, credit card reward programs logic, points for ranking (e.g., as used on Waze app), among others.

The mix of the three driver behaviors and scenario setups makes it possible to evaluate the impacts of the introduction of the autonomous and connected vehicle.

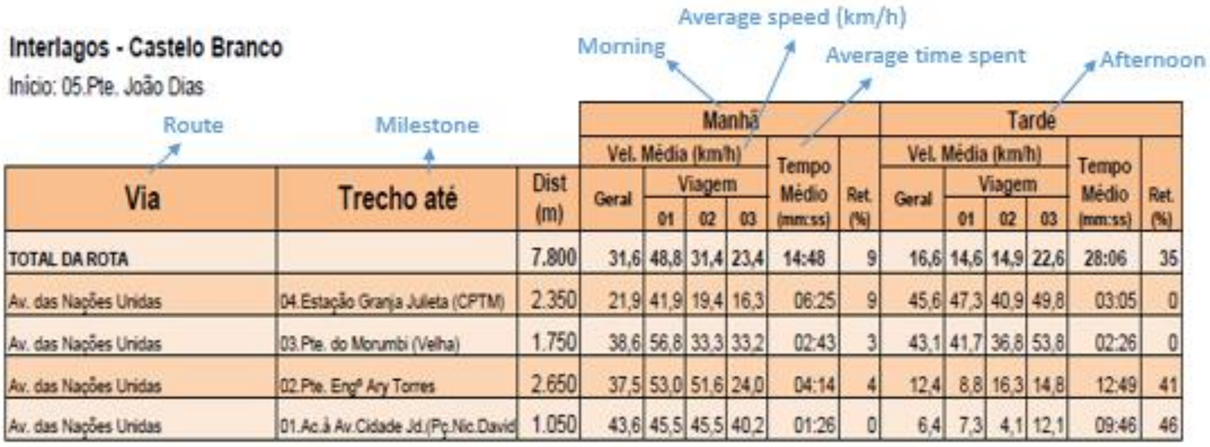
5.3 CITY TRACK USED FOR SIMULATION

The following section will detail the simulated track model, data input, data output, and calibration.

In order to select a proper track to the simulation, extensive research was performed. The target city was São Paulo in Brazil due to the well-known traffic jam issues as well as to the proximity to the university and the possibility to do evaluations "*in loco.*"

The starting point was to find trustworthy and scientific information from the traffic situation to be a robust framework. Then it was found the annual Mobility Road System report released for CET (abbreviation in Portuguese to Traffic Engineer Company) (CET, 2018). This report delivers information from traffic volumes and average vehicle speed from distinct main roads in the city. It is a reference used by public and private traffic management entities to report the improvements at the tracks and critical points that demand further attention.

This report presents a very robust statistics and measurement methodology to acquire data as well as a complete set of detailed results. FIGURE 21 shows an example of data delivered on that report.



Interlagos - Castelo Branco
Início: 05.Pte. João Dias

			Manhã						Tarde					
Via	Trecho até	Dist (m)	Vel. Média (km/h)				Tempo Médio (mm:ss)	Ret. (%)	Vel. Média (km/h)				Tempo Médio (mm:ss)	Ret. (%)
			Geral	Viagem					Geral	Viagem				
				01	02	03				01	02	03		
TOTAL DA ROTA		7.800	31,6	48,8	31,4	23,4	14:48	9	16,6	14,6	14,9	22,6	28:06	35
Av. das Nações Unidas	04.Estação Granja Julieta (CPTM)	2.350	21,9	41,9	19,4	16,3	06:25	9	45,6	47,3	40,9	49,8	03:05	0
Av. das Nações Unidas	03.Pte. do Morumbi (Velha)	1.750	38,6	56,8	33,3	33,2	02:43	3	43,1	41,7	36,8	53,8	02:26	0
Av. das Nações Unidas	02.Pte. Engº Ary Torres	2.650	37,5	53,0	51,6	24,0	04:14	4	12,4	8,8	16,3	14,8	12:49	41
Av. das Nações Unidas	01.Ac.à Av.Cidade Jd.(Pç.Nic.David	1.050	43,6	45,5	45,5	40,2	01:26	0	6,4	7,3	4,1	12,1	09:46	46

FIGURE 21 – Example of data delivered at CET Mobility Road System report
Source: Adapted from CET (2018).

From the CET's report, a particular track was chosen. It is the intersection between Bandeirantes Avenue and Nações Unidas Avenue. See on FIGURE 22.

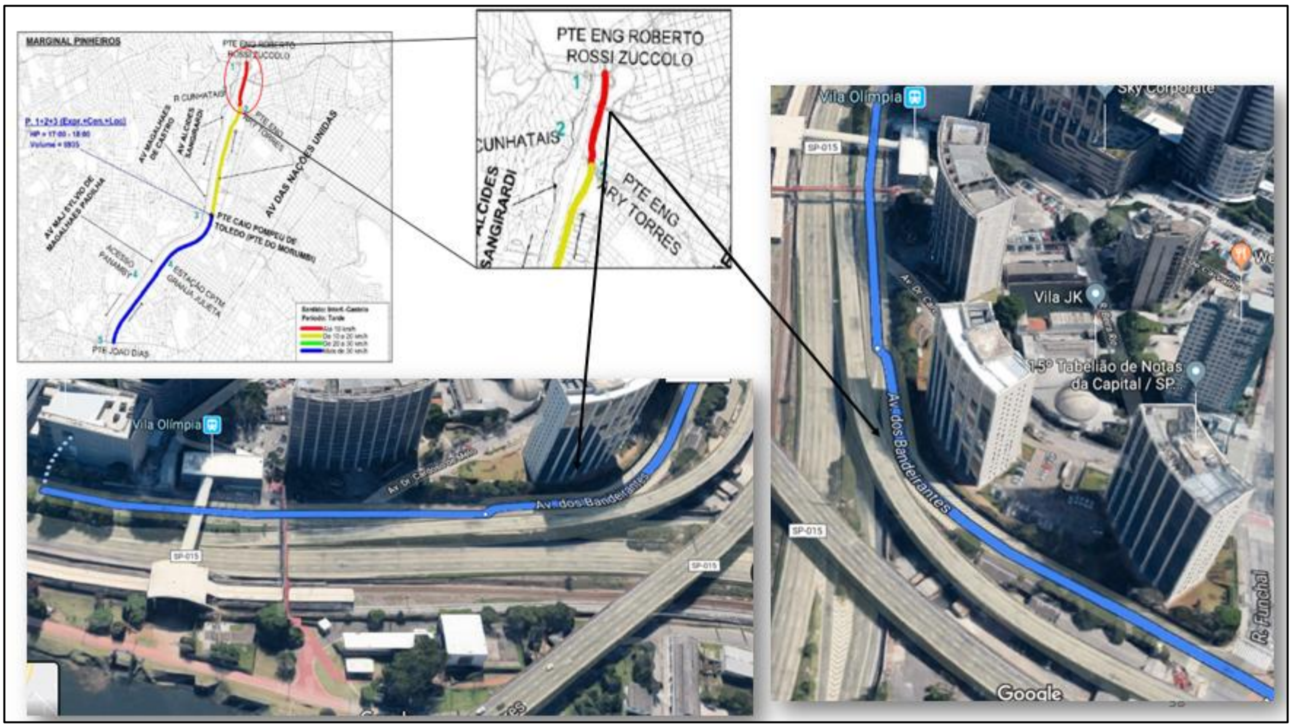


FIGURE 22 – Top view of the simulated track

Source: Adapted from CET (2018) and Google Maps.

This track was chosen between the options due to the following reasons:

- The highly congested area on rush time: <10km/h average speed;
- Intersection from two large traffic flow roads (pointed as I and II on FIGURE 22);
- Intersection from I and III: approx. 60° without speed increase area
- The bus stop with several lines: two busses together at the bus stop most of the time leading almost to a lane blocking;
- >10% motorcycles relative flow: typical from São Paulo city.

After choosing the tracks, the first step was to reproduce the streets inside PTV VISSIM software. It offers many resources to make the track as near a possible to reality. The min resources are listed below and the ones used at the model in this research are in italic:

- *Number of lanes and the total length;*
- *Intersections;*
- *Reduced speed areas;*
- *Bus Stops;*
- *Priority rules;*
- *Sidewalks and crosswalks;*
- *Lane marks and road signs;*

- *Traffic sign;*

It is important to remark that there is an auxiliary resource to make it easier to draw the track is to use a background map from the HERE® mapping source company. On FIGURE 232, it is shown the simulation test track built inside PTV VISSIM.

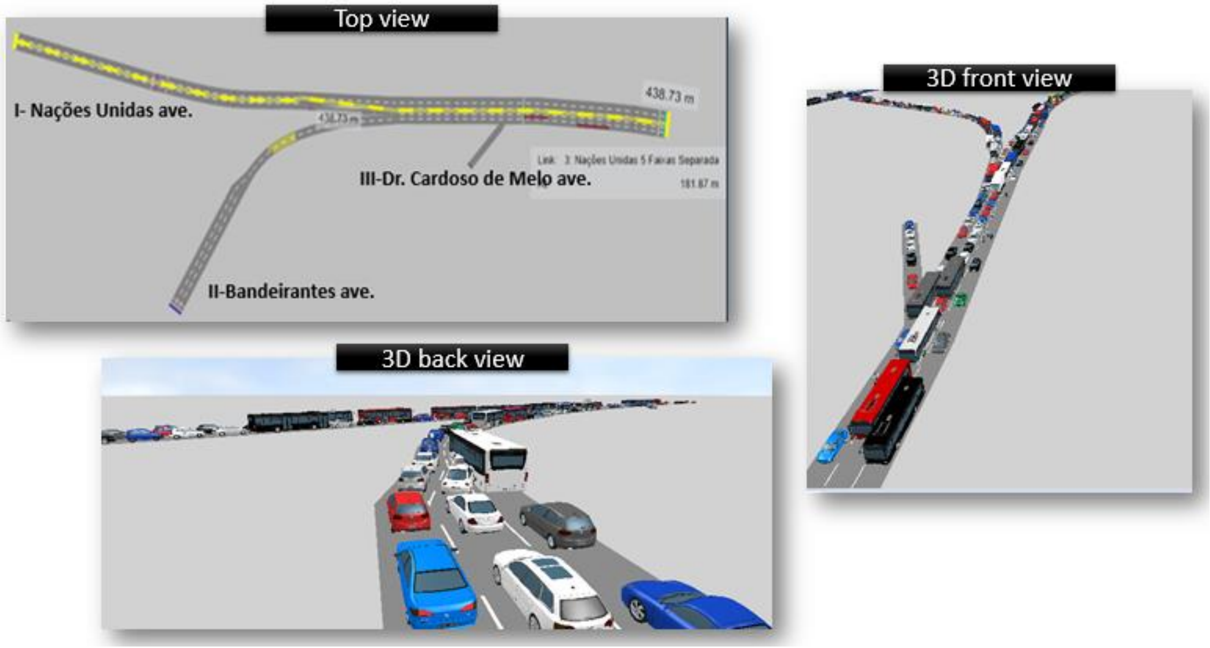


FIGURE 23 – Simulation track on PTV VISSIM

Source: Author.

5.3.1 Data input

In order to have a robust simulation, many different data are required to input in traffic micro simulator software. The most important are:

i. Vehicle volume by time interval: number of vehicles in volume/hour for each avenue/street;
ii. Vehicles relative flow by model: percentage split between passengers cars, trucks (HGV), buses, bikes/motorcycles a train;
iii. Desired vehicle speed for each vehicle model;
iv. Driver behavior parameters;
v. Bus stops: bus lines, volumes, number of passenger and parameters related to the time the bus stay in a standstill at the bus stop;

In the following sections, it is described how these data were obtained.

5.3.1.1 Vehicle volume and Relative flows

There are at least three possible ways:

a. *Official data from the CET Report* (CET, 2018)*:* as this report presents a clear and robust data collection methodology, its information was used as the primary source for the research.

b. *Real-time buses with tracking system data available on a public API from the government*: the government traffic entity in São Paulo city (SPTRANS) lets it available public documentation on the developers portal that makes it possible to extract a KMZ file. This file contains a city flow map with average vehicle speed for each track. These data come from the city bus fleet (around 15000 busses) that is equipped with a tracking system. As the bus fleet population is considerable, the data available are valuable information in real-time (SPTrans, 2019).

c. *Google traffic:* using the "Typical Traffic" tool it is possible to search the usual traffic conditions from a route based on historical information stored. It is based on weekday and day time, as illustrated in FIGURE 24 – Google Traffic information. Anyhow this tool presents just a color scale reference for the traffic condition that makes this information just a visual reference. So this cannot be used for this research proposal.

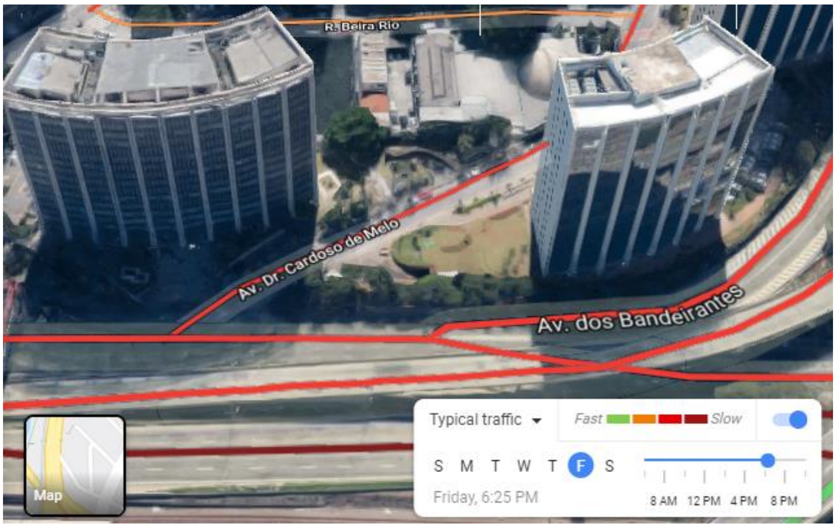


FIGURE 24 – Google Traffic information

Source: Google Traffic.

At the simulation model, there are three avenues. For each one, a vehicle input (vehicle volume by time interval) point was added as illustrated in FIGURE 25 – Vehicles data input.

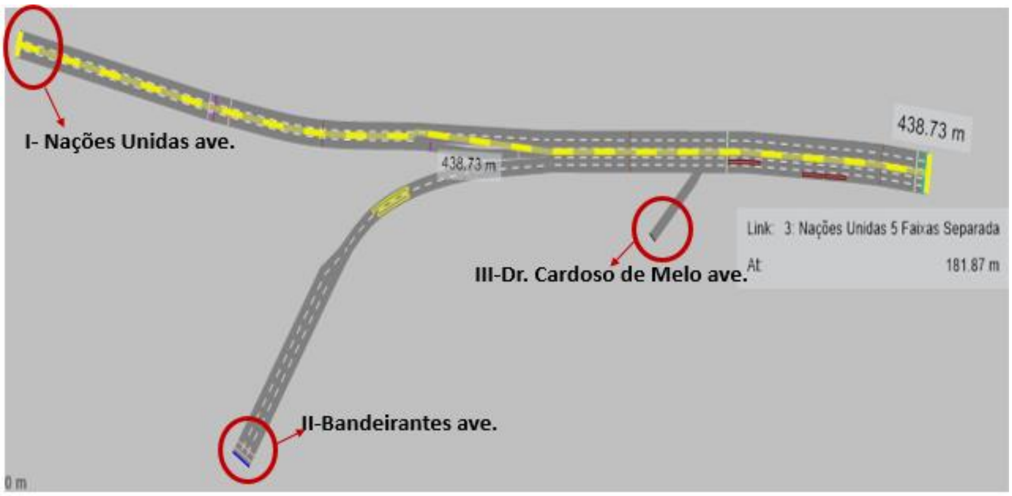
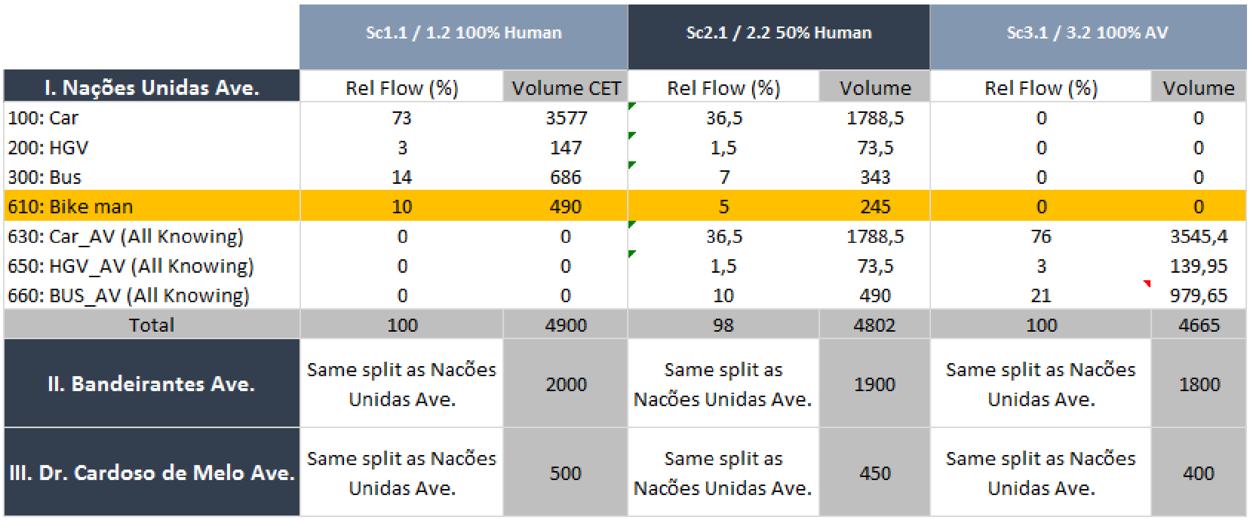


FIGURE 25 – Vehicles data input

Source: Author.

On TABLE 8 – Vehicle inputs and relative flow for each avenue and scenario, the volumes and relative flow for each scenario are presented.

TABLE 8 – Vehicle inputs and relative flow for each avenue and scenario



	Sc1.1 / 1.2 100% Human		Sc2.1 / 2.2 50% Human		Sc3.1 / 3.2 100% AV	
I. Nações Unidas Ave.	Rel Flow (%)	Volume CET	Rel Flow (%)	Volume	Rel Flow (%)	Volume
100: Car	73	3577	36,5	1788,5	0	0
200: HGV	3	147	1,5	73,5	0	0
300: Bus	14	686	7	343	0	0
610: Bike man	10	490	5	245	0	0
630: Car_AV (All Knowing)	0	0	36,5	1788,5	76	3545,4
650: HGV_AV (All Knowing)	0	0	1,5	73,5	3	139,95
660: BUS_AV (All Knowing)	0	0	10	490	21	979,65
Total	100	4900	98	4802	100	4665
II. Bandeirantes Ave.	Same split as Nacões Unidas Ave.	2000	Same split as Nacões Unidas Ave.	1900	Same split as Nacões Unidas Ave.	1800
III. Dr. Cardoso de Melo Ave.	Same split as Nacões Unidas Ave.	500	Same split as Nacões Unidas Ave.	450	Same split as Nacões Unidas Ave.	400

Source: Author.

The content of TABLE 8 – Vehicle inputs and relative flow for each avenue and scenarioand its relations to the model is as follows:

- The overall relative flow between the avenues was considered the same:
    - Buses are allowed for all avenues: for Bandeirantes and Nações Unidas avenues, there are restrictions on the lanes they are allowed to drive. For that specific lanes they were blocked;

    - At avenue, Dr. Cardoso de Melo the trucks (HGV) are not allowed, so they were blocked. As the volume of the truck at the overall traffic system is low it did not affect the results;
- The relative flow along the scenarios was done based on TABLE 7. It was assumed that the more autonomous vehicles on the streets the fewer motorcycles would be present. So the relative flow from motorcycles was mainly distributed among the buses.
- A premise assumed is that the higher is the percentage of autonomous vehicles on the streets, the lower will be the total volume of vehicles: shared vehicles models will be more present as well as other transportation modal. That is why the total number of vehicles is reduced along with the scenarios.

5.3.1.2 Desired vehicle speed

It is the critical factor in the model calibration. The value considered for calibration was taken from the worst case at the CET report. The details of the calibration process are present in section 5.4.

5.3.1.3 Driver Behavior parameters

Regarding Driver Behavior, it is described in more detail in section **Erro! Fonte de referência não encontrada.** the most relevant parameters that make a significant influence in the models as well as recommended parameter values according to different references.

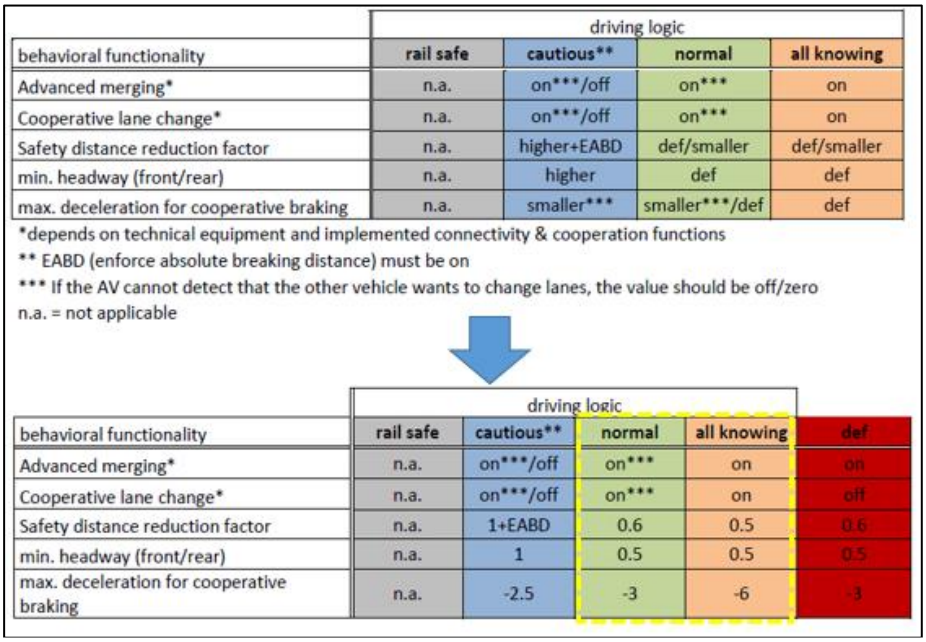
At this research, Wiedemann parameters for driver behaviors are in FIGURE 15 and FIGURE 16. Besides that, lane change related parameters are described in FIGURE 26 and FIGURE 27 following CoEXist references.

	driving logic							
	rail safe		**cautious****		**normal**		**all knowing**	
parameter for necessary lane change*	own	trailing vehicle	own	trailing vehicle	own	trailing vehicle	own	trailing vehicle
maximum deceleration	n.a.	n.a.	smaller/ def	smaller/ def	def	smaller/ def	def	higher/ def
- 1 m/s per distance	n.a.	n.a.	smaller/ def	smaller/ def	def	def	def	smaller/ def
accepted deceleration	n.a.	n.a.	smaller/ def	smaller/ def	def	def	def	higher/ def

*necessary lane change means a lane change which is necessary in order to follow a defined route (it is not overtaking because of higher own desired speed)
** EABD (enforce absolute breaking distance) must be on
n.a. = not applicable

	driving logic									
	rail safe		**cautious****		**normal**		**all knowing**		**def**	
parameter for necessary lane change*	own	trailing vehicle	own	trailing vehicle	own	trailing vehicle	own	trailing vehicle	own	trailing vehicle
maximum deceleration	n.a.	n.a.	-3.5	-2.5	-4	-3	-4	-4	-4	-3
- 1 m/s per distance	n.a.	n.a.	80	80	100	100	100	100	100	100
accepted deceleration	n.a.	n.a.	-1	-1	-1	-1	-1	-1.5	-1	-1

FIGURE 26 – Recommended parameters related to lane change behavior
Source: adapted from (Coexist D2.3, 2018)



	driving logic			
behavioral functionality	**rail safe**	**cautious****	**normal**	**all knowing**
Advanced merging*	n.a.	on***/off	on***	on
Cooperative lane change*	n.a.	on***/off	on***	on
Safety distance reduction factor	n.a.	higher+EABD	def/smaller	def/smaller
min. headway (front/rear)	n.a.	higher	def	def
max. deceleration for cooperative braking	n.a.	smaller***	smaller***/def	def

*depends on technical equipment and implemented connectivity & cooperation functions
** EABD (enforce absolute breaking distance) must be on
*** If the AV cannot detect that the other vehicle wants to change lanes, the value should be off/zero
n.a. = not applicable

	driving logic				
behavioral functionality	**rail safe**	**cautious****	**normal**	**all knowing**	**def**
Advanced merging*	n.a.	on***/off	on***	on	on
Cooperative lane change*	n.a.	on***/off	on***	on	off
Safety distance reduction factor	n.a.	1+EABD	0.6	0.5	0.6
min. headway (front/rear)	n.a.	1	0.5	0.5	0.5
max. deceleration for cooperative braking	n.a.	-2.5	-3	-6	-3

FIGURE 27 - Recommended parameters related to lane change functionalities
Source: adapted from Coexist D2.3 (2018).

5.3.1.4 Bus Stops

At the model, there is one bus stop on the track, as shown in FIGURE 28. The first topic to highlight is that the many different bus lines are present on the same bus stop. It matches with SPTRANS itinerary plan (SPTans 2, 2019).

Additionally, It was performed an observation field research nearby to that bus stop on a rush hour. The main observed results are:

- Mainly articulated buses are present on those lines. PTV VISSIM does not have this bus model at the list of default vehicle models. As the average vehicle speed is low on rush time, the difference in the dynamics behavior between articulated and non-articulated buses was considered as not relevant, Anyhow the passenger capacity between them is considerably different. To overcome that, it was considered non-articulated buses were considered with a higher time of doors opened (due to the higher number of passengers).
- Due to the high number of bus lines the most of the time there are two buses stopped waiting for passengers to go onboard or offboard. Frequently the bus that is behind needed to wait until the bus at the front to leave. This characteristic leads almost to a lane block.

One more bus stop was added to simulate the scenarios with vehicle break down as described in section 5.2.1.

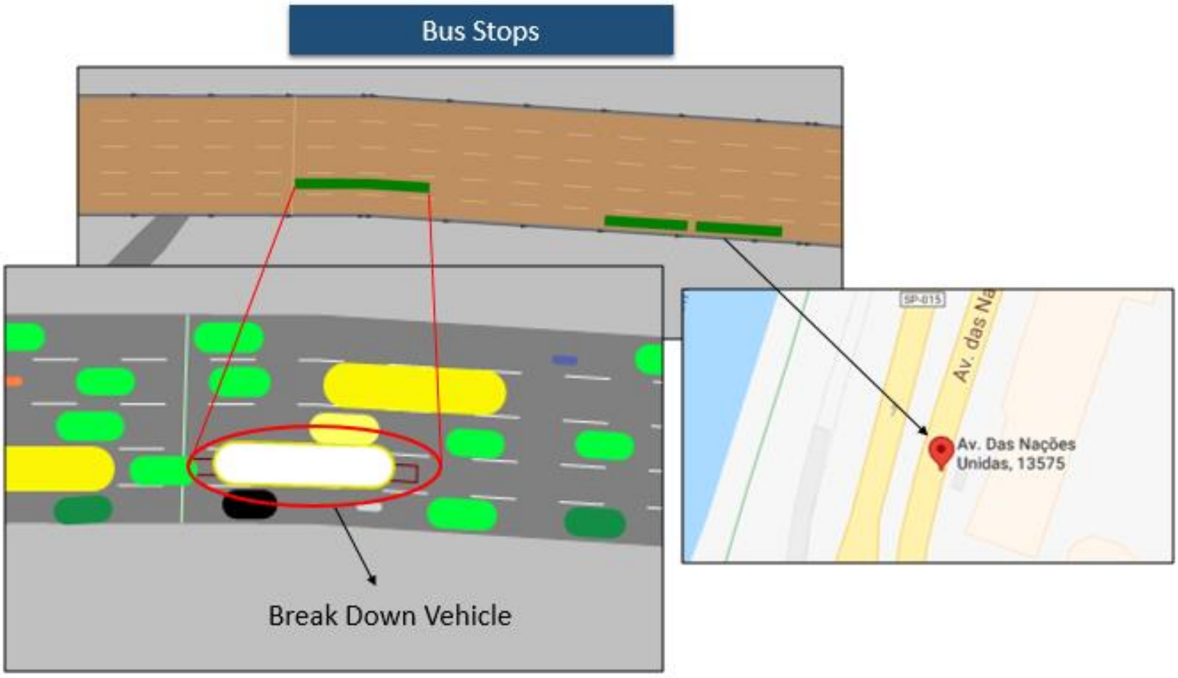


FIGURE 28 – Bus stops on the simulation model.

Source: Author.

5.3.1.5 Adding autonomous and Connected characteristics (CoEXist model)

As shown in FIGURE 15, the characteristics of the autonomous vehicle were done based on CoEXist validated driver behavior parameters so-called “All-Knowing.”

It is recommended that these parameters are used with a cooperative behavior similar to connected vehicles. It is a precious contribution but in fact, as any tool to accurately simulate connected vehicles is used. It was considered that simulate connected vehicles based just on a set of parameters would bring a very limited contribution. As described on 2.6.2 to fulfill this gap of CAVs vehicles, different tolls can be used.

Connected vehicles are still a topic to be embroidered at the next step of the research. At this moment, PTV has just launched the Beta Version of VISSIM Version 2020, the first version with a platooning feature as an internal tool.

5.3.2 Data Output

PTV VISSIM delivers many kinds of output data based on three main tools:

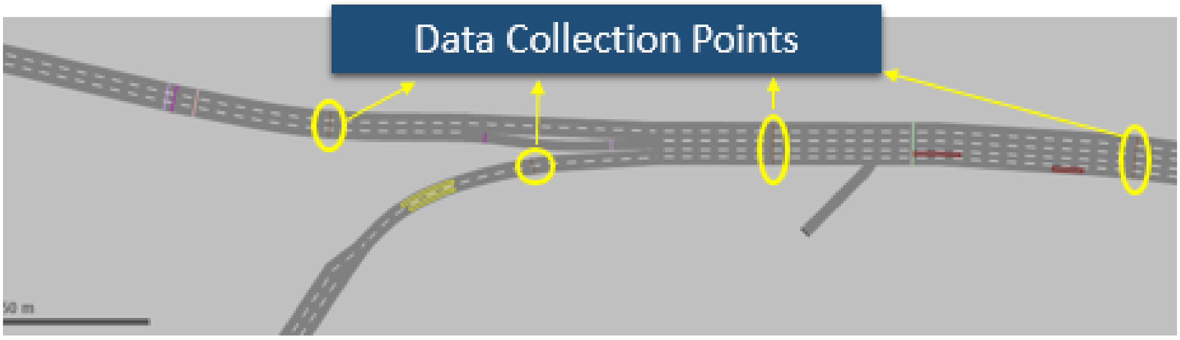
I. Data Collection Points
II. Vehicle Travel Times
III. Queue Counters

At this research I. and II. were used as described below.

5.3.2.1 Data Collection points

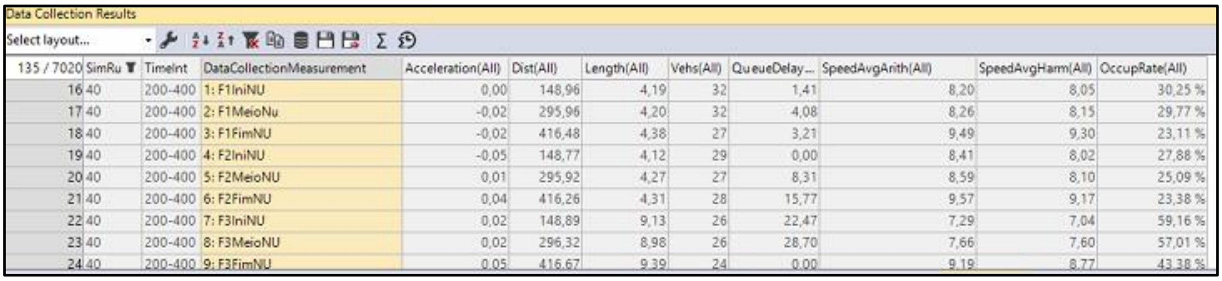
The data collection points can be distributed at any position of the track. At this research simulated model, four collection points were added as illustrated in FIGURE 29. The position from each of them was chosen to bring more meaningful results to be analysed.

FIGURE 29 - Data collection points



Source: Author.

This tool takes much information from each lane as FIGURE 30 shows. The critical output element for this research are harmonic average vehicle speed, queue delay and occupation rate.

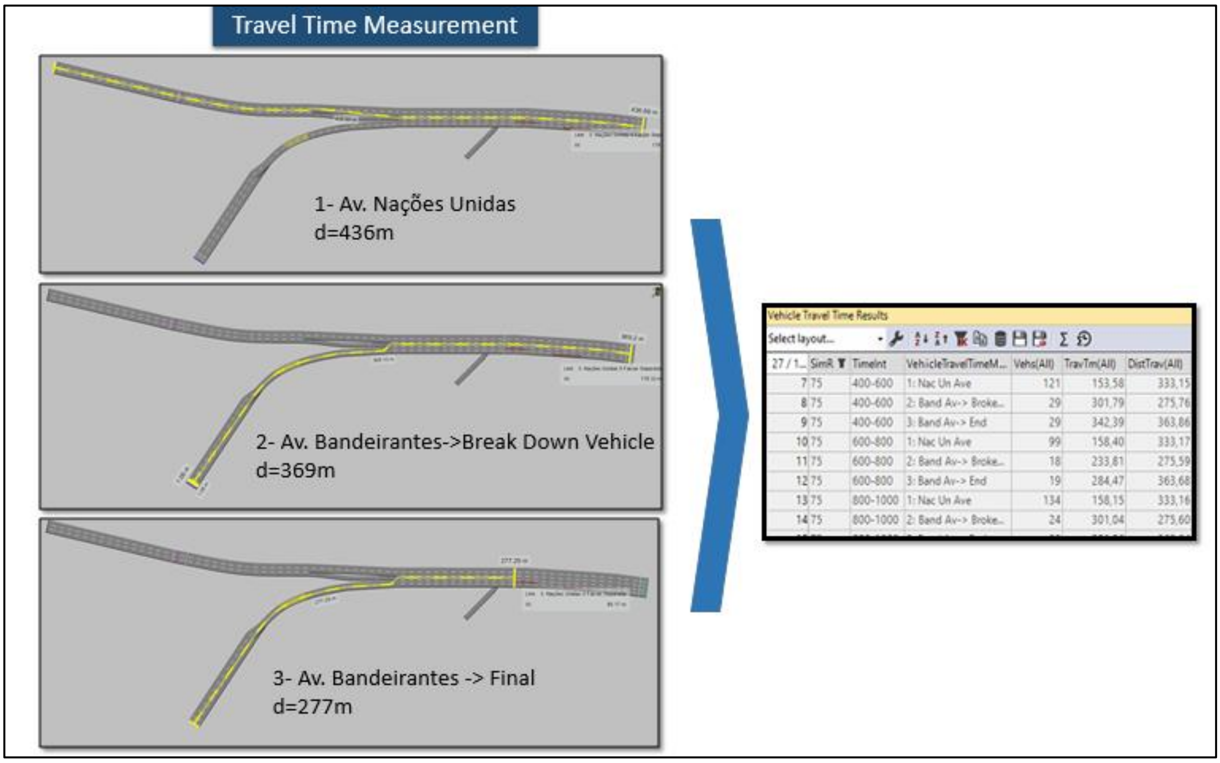


135 / 7020	SimRu	TimeInt	DataCollectionMeasurement	Acceleration(All)	Dist(All)	Length(All)	Vehs(All)	QueueDelay...	SpeedAvgArith(All)	SpeedAvgHarm(All)	OccupRate(All)
16	40	200-400	1: F1IniNU	0,00	148,96	4,19	32	1,41	8,20	8,05	30,25 %
17	40	200-400	2: F1MeioNu	-0,02	295,96	4,20	32	4,08	8,26	8,15	29,77 %
18	40	200-400	3: F1FimNU	-0,02	416,48	4,38	27	3,21	9,49	9,30	23,11 %
19	40	200-400	4: F2IniNU	-0,05	148,77	4,12	29	0,00	8,41	8,02	27,88 %
20	40	200-400	5: F2MeioNU	0,01	295,92	4,27	27	8,31	8,59	8,10	25,09 %
21	40	200-400	6: F2FimNU	0,04	416,26	4,31	28	15,77	9,57	9,17	23,38 %
22	40	200-400	7: F3IniNU	0,02	148,89	9,13	26	22,47	7,29	7,04	59,16 %
23	40	200-400	8: F3MeioNU	0,02	296,32	8,98	26	28,70	7,66	7,60	57,01 %
24	40	200-400	9: F3FimNU	0,05	416,67	9,39	24	0,00	9,19	8,77	43,38 %

FIGURE 30 – Data collection results example at PTV VISSIM
Source: Author.

5.3.2.2 Travel time measurement

Travel time measurement is a tool that makes it possible to measure delta values between two points in the track. Among the output, values are vehicle travel time, number of vehicles and travel distance. FIGURE 31 shows the three travel time measurements and examples of output data.



27 / 1...	SimR	TimeInt	VehicleTravelTimeM...	Vehs(All)	TravTm(All)	DistTrav(All)
7	75	400-600	1: Nac Un Ave	121	153,58	333,15
8	75	400-600	2: Band Av-> Broke...	29	301,79	275,76
9	75	400-600	3: Band Av-> End	29	342,39	363,86
10	75	600-800	1: Nac Un Ave	99	158,40	333,17
11	75	600-800	2: Band Av-> Broke...	18	233,81	275,59
12	75	600-800	3: Band Av-> End	19	284,47	363,68
13	75	800-1000	1: Nac Un Ave	134	158,15	333,16
14	75	800-1000	2: Band Av-> Broke...	24	301,04	275,60

FIGURE 31 – Travel time measurements at PTV VISSIM.
Source: Author.

5.4 MODEL CALIBRATION

The model calibration is a very crucial point to establish a reliable framework that makes the data assessment scientifically valid. The theory of traffic model calibration is addressed in section **Erro! Fonte de referência não encontrada.Erro! Fonte de referência não encontrada.**. The main characteristics used to the calibration at this research are listed below:

- The base scenario 1.1 was used to calibrate the simulation model;
- Simulation time 1800s (30 minutes);
- Starting of valid data from 300s simulation time on: recommended waiting time for simulation traffic loading;
- All the parameters described in section 5.3.1 were fixed: based on CoExist's "Normal" driving logic.

The primary output data used as reference was the average vehicle speed. It is the only scientifically validated data found on that specific track. FIGURE 32 shows a flow chart with the calibration process.

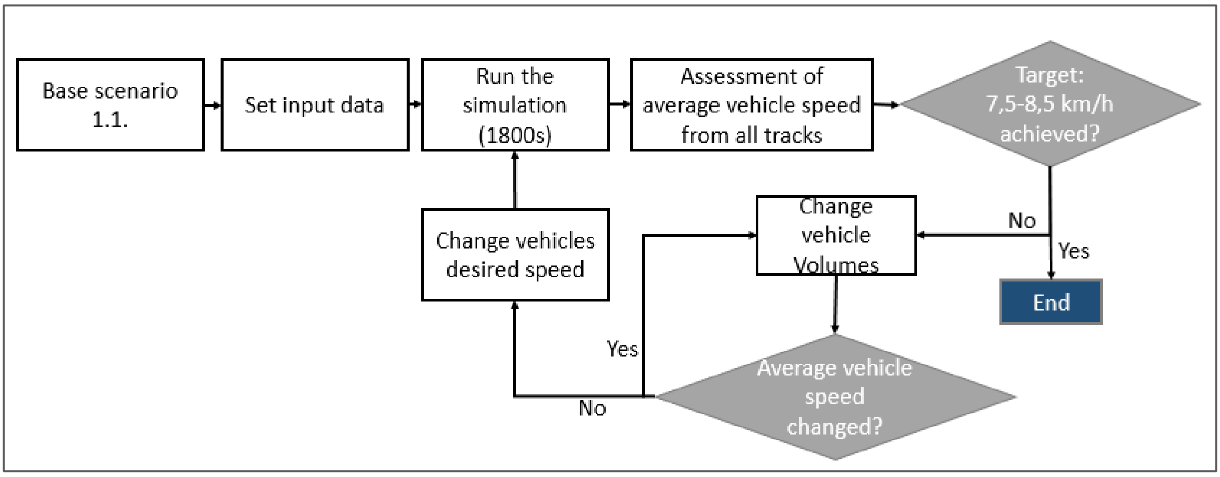
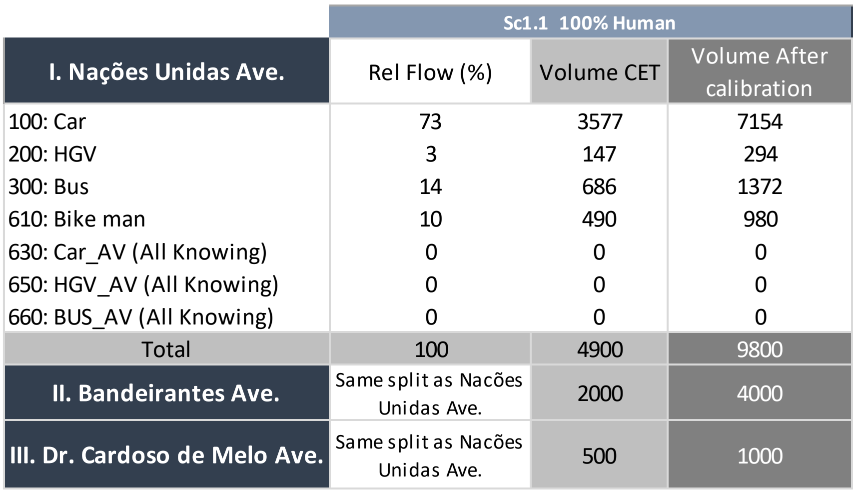


FIGURE 32 – Flow chart from the calibration process

Source: Author.

During the calibration process, it was concluded that until the double of CET report volumes described in TABLE 8, the average vehicle speed was affected. For higher volumes, It was not observed the same behavior. Then the final volumes after calibration are described on TABLE 9.

TABLE 9 –Vehicles volumes after calibration



	Sc1.1 100% Human		
I. Nações Unidas Ave.	Rel Flow (%)	Volume CET	Volume After calibration
100: Car	73	3577	7154
200: HGV	3	147	294
300: Bus	14	686	1372
610: Bike man	10	490	980
630: Car_AV (All Knowing)	0	0	0
650: HGV_AV (All Knowing)	0	0	0
660: BUS_AV (All Knowing)	0	0	0
Total	100	4900	9800
II. Bandeirantes Ave.	Same split as Nacões Unidas Ave.	2000	4000
III. Dr. Cardoso de Melo Ave.	Same split as Nacões Unidas Ave.	500	1000

Then when each model fixed the volumes, the final desired vehicle speed is described on TABLE 10.

TABLE 10 – Desired vehicles speed after calibration

Vehicle model	Desired vehicles speed after calibration:
Car	20km/h
Trucks (HGV)	12 km/h
Bus	15 km/h
Bikes	30 km/h

Source: Author.

5.5 PTV VISSIM ADDITIONAL MODEL ELEMENT: VEHICLE BREAK DOWN

As described in TABLE 7, all the scenarios have a variation “x.2”. This variation is a disturbance added to evaluate how the traffic is affected when a vehicle break down occurs. To simulate that a bus stop was added to the model on a specific position where the traffic performance was most affected as FIGURE 33 shows. To keep the bus in a standstill for the complete simulation the time that the doors remain opened was increased to a value higher than the total simulation time.

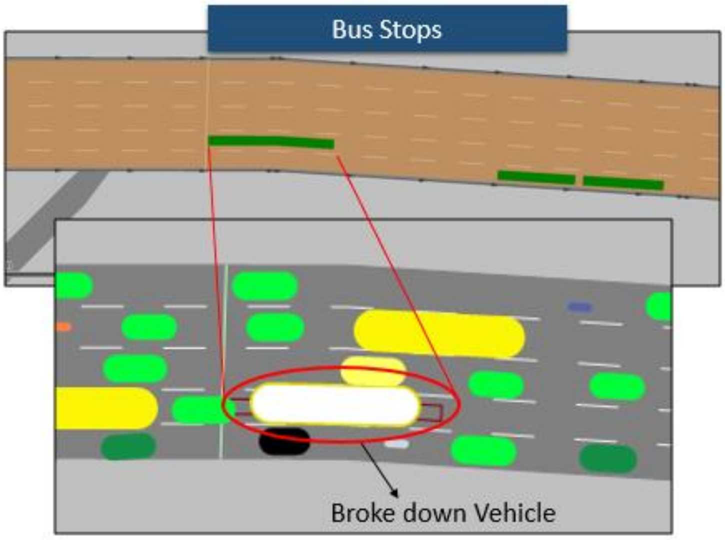


FIGURE 33 – Simulation of a broke down vehicle on track

Source: Author.

6 PARTIAL RESULTS AND DISCUSSION

Preliminary results from this study consider scenarios from 1.1 to 3.2, as described in table TABLE 7. It means scenarios from 100% human-driven vehicles to 100% autonomous without communication technologies as V2X and CACC included. In parallel, the effects a disturbance (as vehicle break down) for each scenario is presented.

At first, the comparison between W74 and W99 is evaluated to bring tangible results to the statements presented in chapter 6.1.

Then a comparison between the scenarios for W74 is detailed including the effects at the complete evaluated track environment as soon as the effects on specific points.

6.1 WIEDMANN 74 X WIEDMANN 99 COMPARISON

As described on 2.6.1 PTV VISSIM software manual as other references recommend to use to W74 model for the simulation that has interactions between vehicles with urban areas characteristic. However, the primary reference used in this study for automation vehicles simulation recommends using the W99 model due to the higher number of driver behavior parameters which could make it more precise.

For a better understanding of the differences between those two driver behaviors models, it was evaluated scenarios from 1.1 to 3.2. On GRAPHIC 1, it is presented the results comparing the travel time average ratio between W99 and W74 according to the calculation presented in FIGURE 34. Travel time measurements were considered just above 300s time simulation to guarantee that the interactions and inputs were already stable.

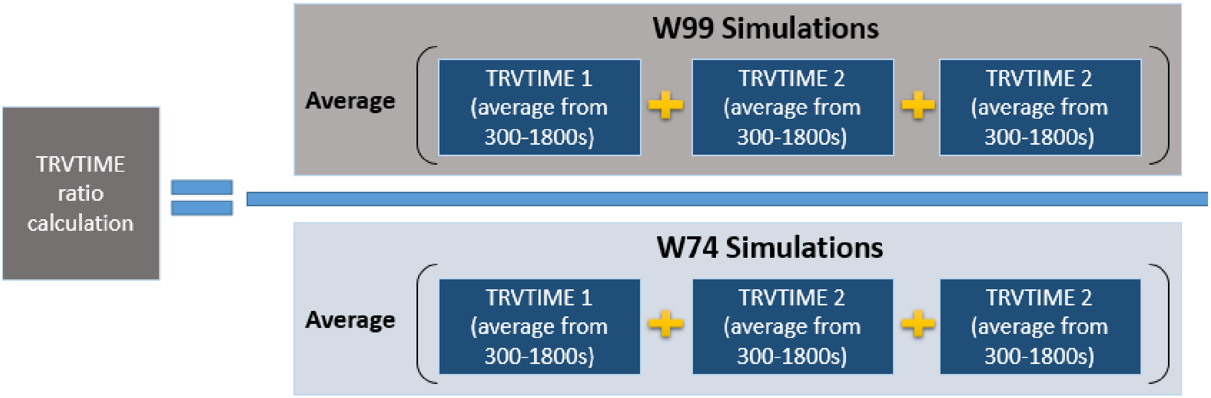
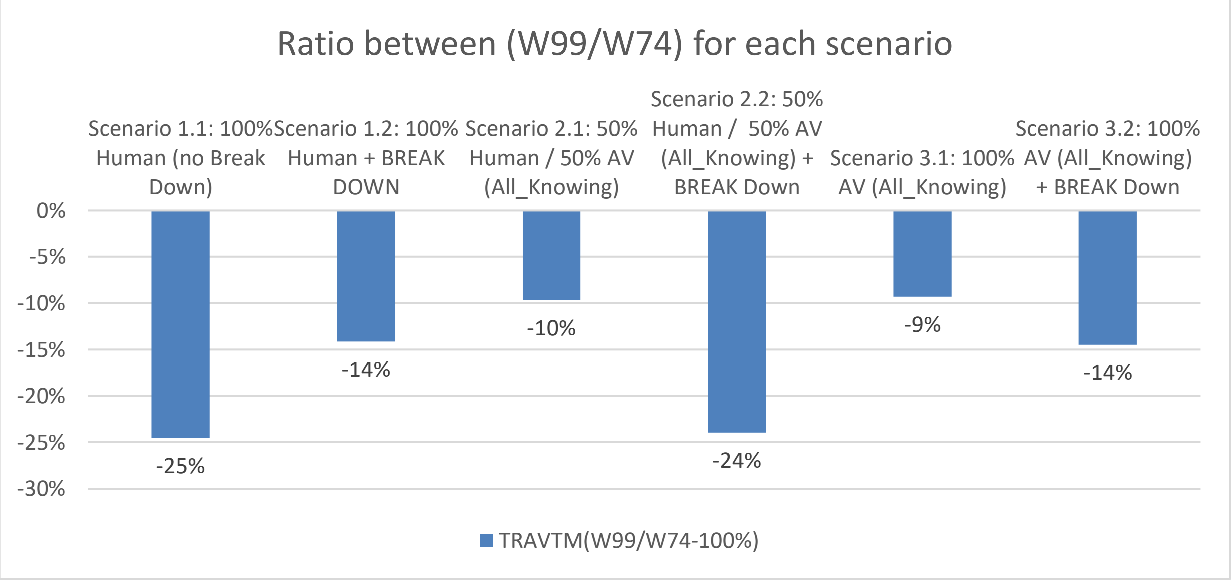


FIGURE 34 – Travel Time ratio calculation between W99 and W74
Source: Author.

It is important to remark that driver behavior parameters for each scenario are described in item 2.5.1 based on COEXIST project reference. The base scenario (1.1) calibration description was done first for W74.

GRAPHIC 1 - Relation between W99 and W74 simulations



Source: Author.

Analyzing the above result, it is evident that for the same scenario, the W99 driver behavior type presents lower travel time when compared to W74. For scenarios with no vehicle brake down as a disturbance (1.1, 2.1 and 3.1) scenario 1.1 is has a much more significant difference between W99 and W74 when compared to scenarios partially or fully automated. For scenarios with vehicle break down, there is no clear tendency comparing human-driven to fully autonomous vehicles.

Anyhow the general conclusion is that for urban areas, W99 driver behavior presents interactions that result in general higher vehicle speed and as a consequence a lower travel time.

Considering the results obtained and the references described in chapter 2.6 the following conclusions were taken:

I. As the track model is defined as an urban area, W74 should be the most appropriate for human-driven vehicles. As a consequence base scenarios, 1.1 and 1.2, should be simulated based on W74.
II. COEXIST project recommends based on several evaluations including field validation. For this research, the W99 model will be used just for CAVs simulation.

On FIGURE 35 –it is presented the driver behavior associated models that will be a framework for the following analysis.

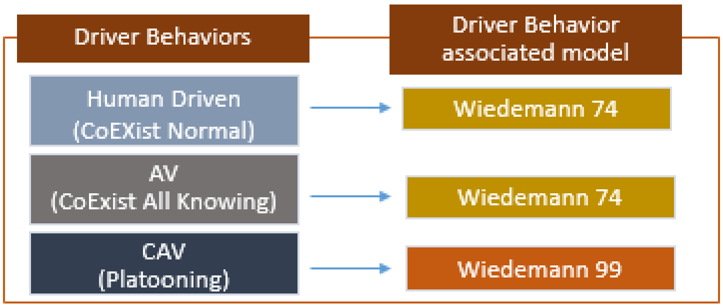


FIGURE 35 – Driver behavior associated models
Source: Author.

6.2 COMPARISON BETWEEN SCENARIOS

Once that the base scenario 1.1 was calibrated all the other scenarios were simulated based on driver behavior models described in FIGURE 35 and all the other demanded parameters described in section 3.2.1.1.

To better understand the possible gains that the vehicle's automation can have on traffic conditions, a comparison method is described in FIGURE 36. This is the basis for analyzing the following graphics.

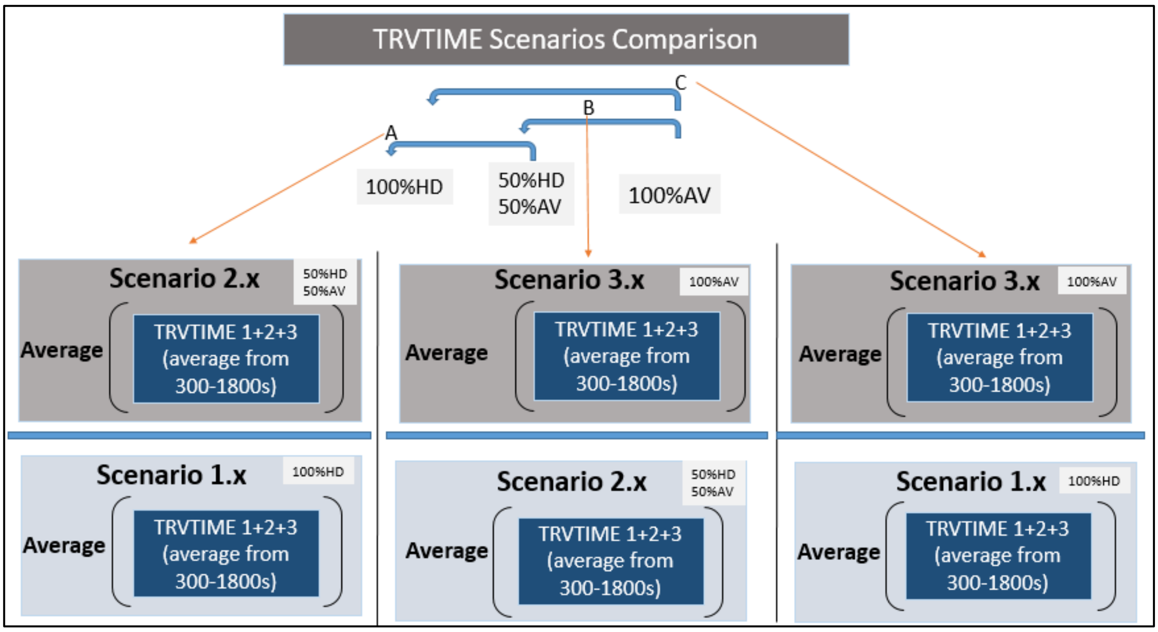
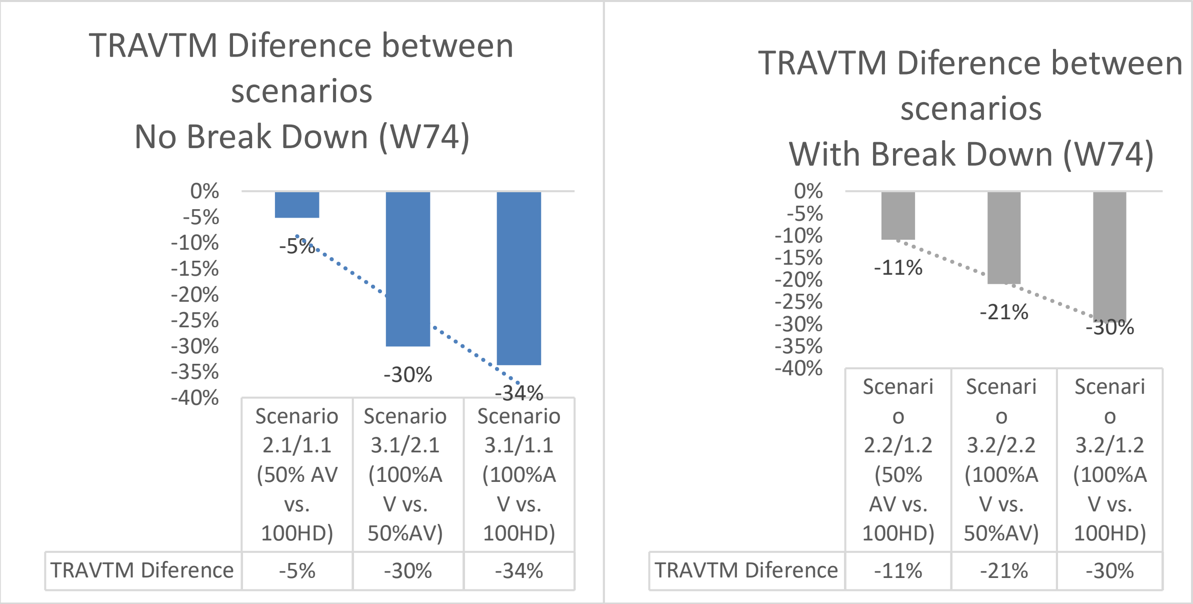


FIGURE 36 – Travel Time Scenarios Comparison method
Source: Author.

Graphic 2 presents the results for scenarios with and without breakdowns.

GRAPHIC 2 - Travel Time Scenarios Comparison



Source: Author.

The first general conclusion expressed in both graphics is that the travel time reduces significantly when it is compared 100% human-driven vehicles, hybrid and fully autonomous vehicles scenarios. It is important to remark that the base scenario was built to simulate a highly congested area in São Paulo city at rush time. This means a critical scenario in terms of traffic, where the average vehicle speed is from 7km/h to 10km/h. This low average vehicle speed is one reason why the gain in percentage comes to a high value: 34% lower travel time between fully autonomous (3.1) and 100% human-driven (1.1) as displayed at the third blue bar on GRAPHIC 2 - Travel Time Scenarios Comparison.

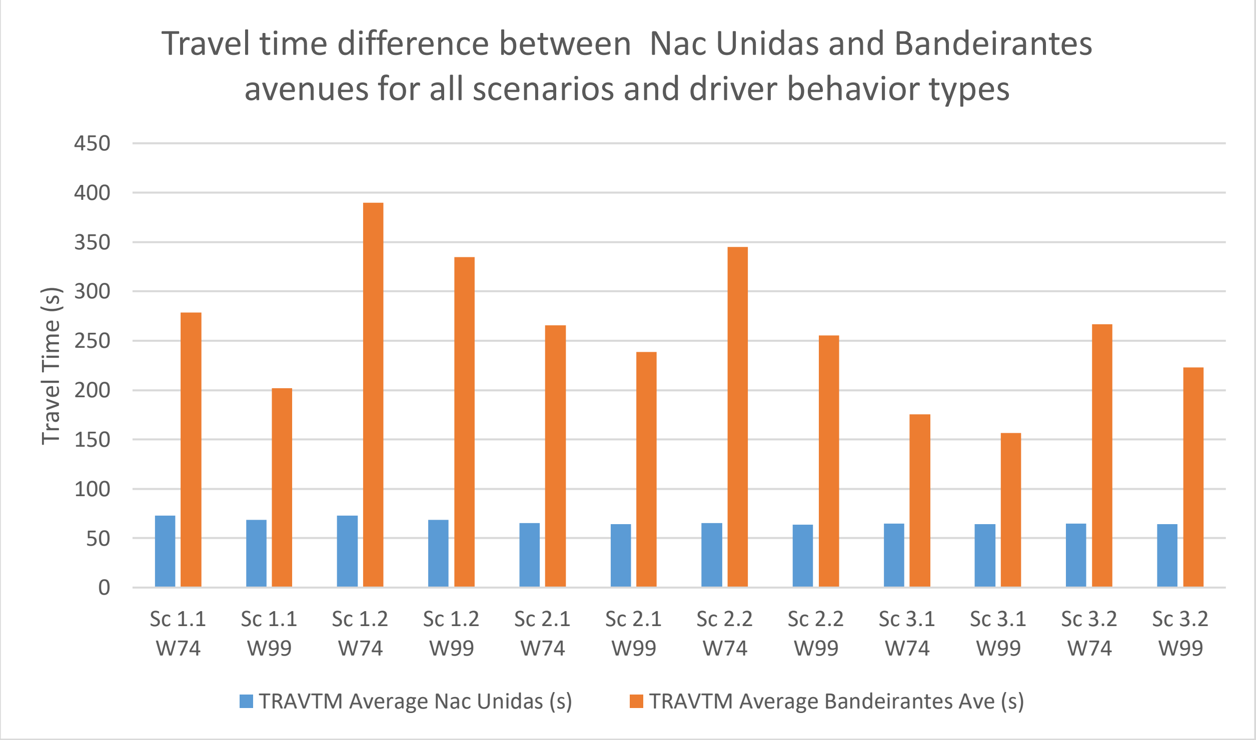
A hybrid scenario without a break (2.1) down presented a small benefit on travel time when compared to the base scenario (-5%). However, full autonomy shows a much more significant reduction (-34%). When it comes to scenarios with break down (X.2), the hybrid scenario (2.2) brings higher benefits (-11% travel time).

Comparing the left and right graphics when a disturbance is added the tendency remains the same although the higher vehicle automation level brings a slightly lower travel time performance gain. It is is a reason why as more the disturbances are avoided or fastly corrected (as a vehicle break down moved out of the track) the more vehicles automation will bring better contribution to travel time. This paragraph's conclusion will be the basis for the propositions in section 4.2.1.

Looking more specifically to segments of the simulated track model for all scenarios and driver behavior type described on GRAPHIC 3 – Travel time comparison between Nacões Unidas and Bandeirantes avenuetwo behaviors are clear:

i. Bandeirantes Avenue presents the worst traffic conditions;
ii. Nações Unidas avenue presents much lower travel time variation between the scenarios when compared to Bandeirantes Avenue. An additional conclusion is that the simulation with break down affected more Bandeirantes avenue than Nacoes Unidas Avenue due to the position of the breakdown vehicle at lane 2 (as described in FIGURE 33).

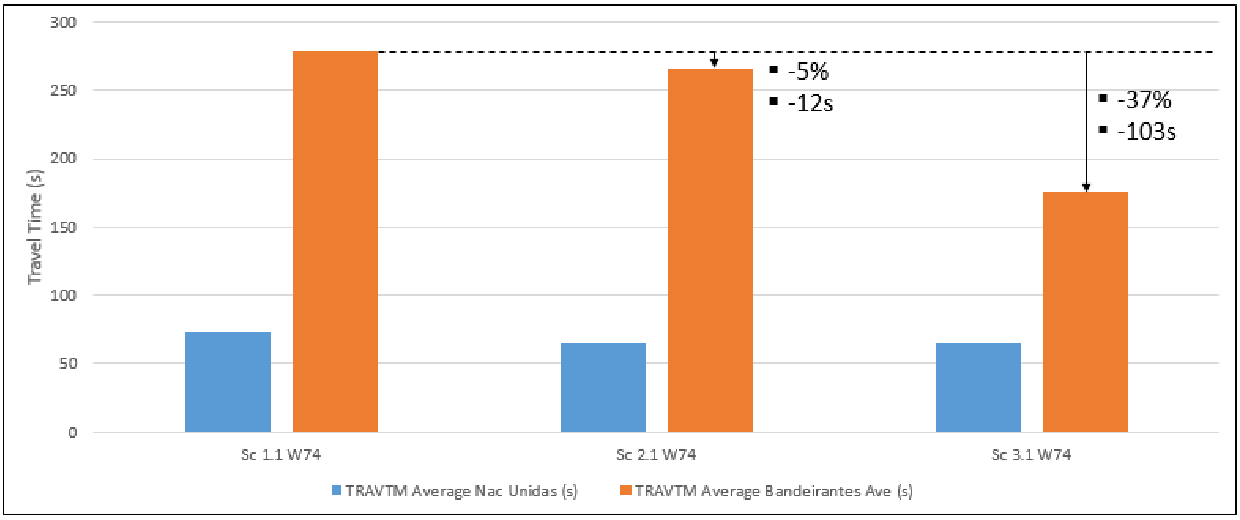
GRAPHIC 3 – Travel time comparison between Nacões Unidas and Bandeirantes avenue



Source: Author.

One important topic to point out is the absolute values, as described in Graph 3. On the base scenario (1.1), it takes 278s to run 369m from the beginning of Bandeirantes Avenue to the end of Nações Unidas avenue simulated segment. It comes to an average vehicle speed of 4,77 km/h. Comparing to full autonomous scenario 3.1 the absolute travel time reduction is minus 103s (-37%), leading to an average vehicle speed of 7,59 km/h (+37%).

GRAPHIC 4 - Travel time comparison between Nacões Unidas and Bandeirantes avenue



Source: Author.

General conclusions are:

- The higher the vehicle automation level is the lower is the travel time. It was an expected result.
- A hybrid scenario without a break down (2.1) presented much lower benefits on travel time when compared to base scenario (1.1) than full autonomous (3.1) compared to the same scenario.
- When a disturbance as a breakdown vehicle is added, the introduction of automated vehicles brings significant benefits on travel time, even when mixed up with human-driven vehicles.

On TABLE 11, it is presented a summary of the results found until this stage of the research.

TABLE 11 – Summary of partial research results.

Author: PATERLINI (2019)	VISSIM+ Platooning (VISSIM integrated)	Urban	50% AVs → ↓ 5% travel time 100% AVs → ↓ 34% travel time 33% HD + 33% AVs + 33% CAVs → (?) next simulations 50% AVs+ 50% CAVs → (?) next simulations 100% CAVs → (?) next simulations

Source: Author.

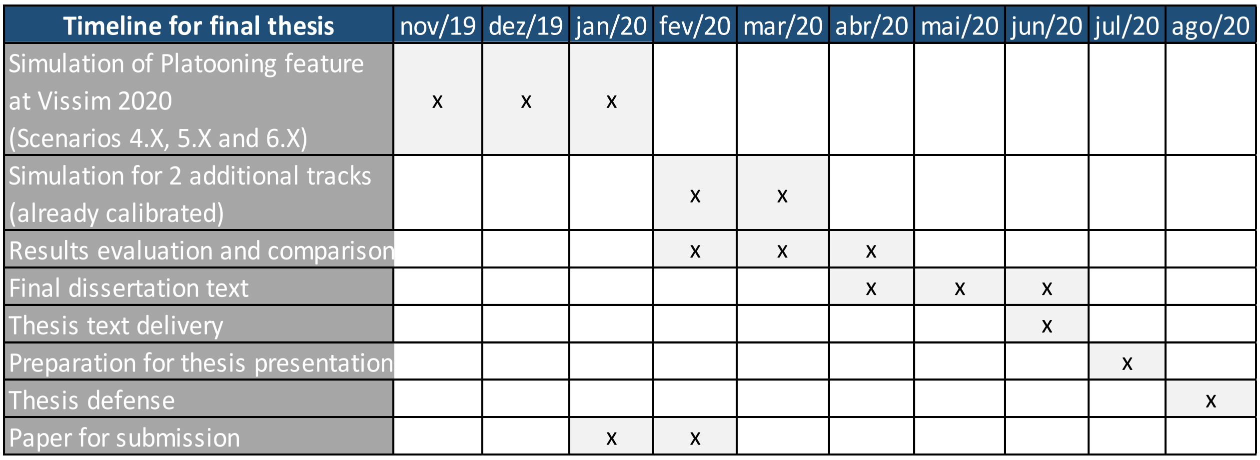
6.2.1 Scenarios with faster disturbance release (3.3 and 6.3) - Automatic Trailer Connection

Two additional scenarios are proposed as an additional collaboration from this thesis.

7 NEXT STEPS FOR MASTER FINAL DISSERTATION

The next steps and timeline for the final dissertation are presented in TABLE 12.

TABLE 12 – Timeline for final dissertation



Timeline for final thesis	nov/19	dez/19	jan/20	fev/20	mar/20	abr/20	mai/20	jun/20	jul/20	ago/20
Simulation of Platooning feature at Vissim 2020 (Scenarios 4.X, 5.X and 6.X)	x	x	x							
Simulation for 2 additional tracks (already calibrated)				x	x					
Results evaluation and comparison				x	x	x				
Final dissertation text						x	x	x		
Thesis text delivery								x		
Preparation for thesis presentation									x	
Thesis defense										x
Paper for submission			x	x						

8 CONCLUSIONS

To be presented in the final dissertation version.

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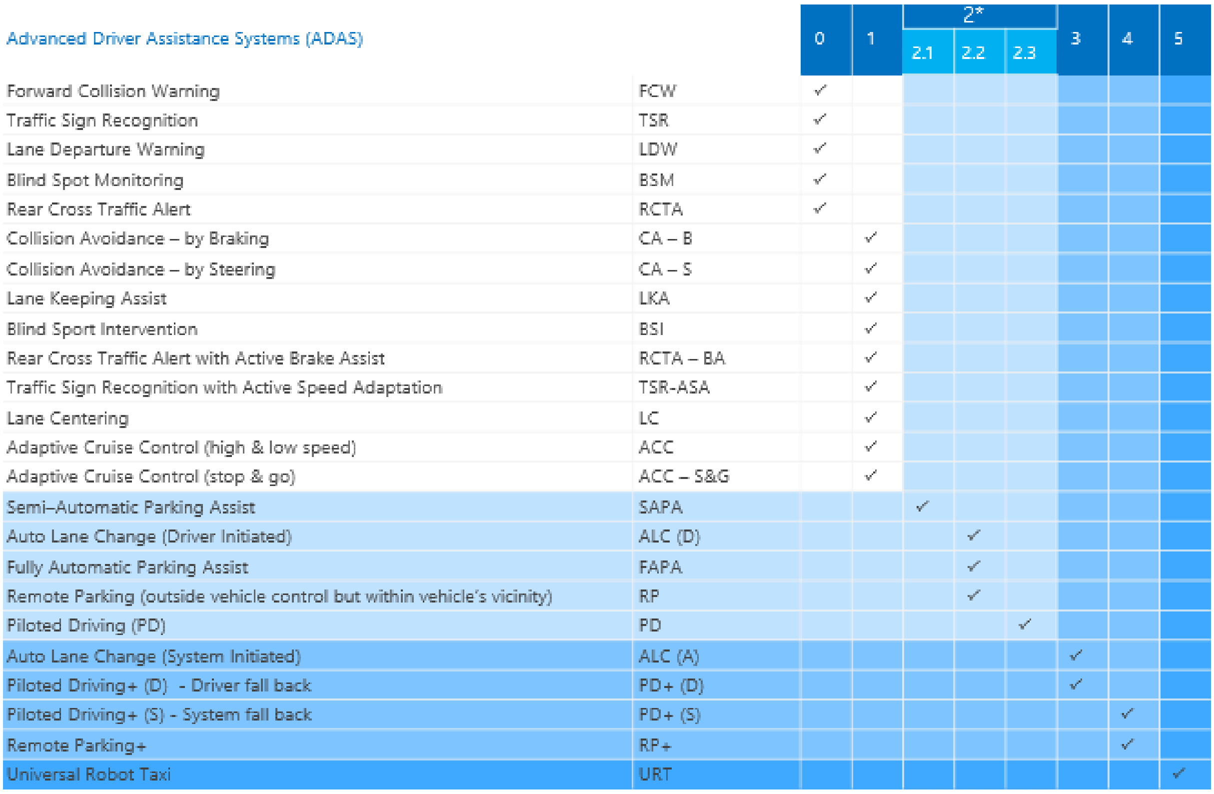
ANNEX 1 – ADAS SYSTEM CLASSIFICATION

Baseon d SAE automation level definition, a number of ADAS being made available qualify to be classified as Level 2 system. However, the level of functionality and system delivery varies between the different systems as well as their implementation by different OEMs. Therefore to make a more clearer distinction, SBD classifies system into 2.1, 2.2 and 2.3. See table below for distinction:

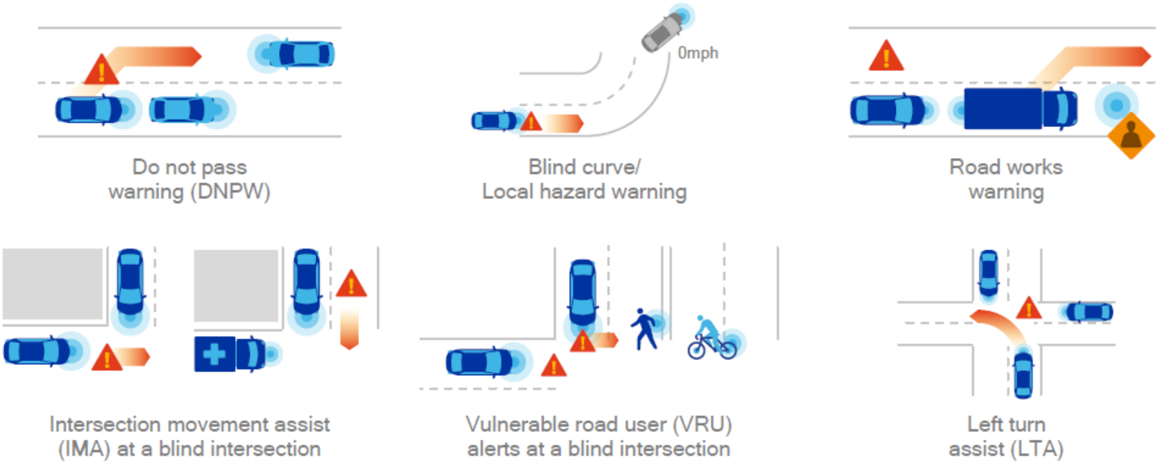


Advanced Driver Assistance Systems (ADAS)		0	1	2*			3	4	5
				2.1	2.2	2.3			
Forward Collision Warning	FCW	✓							
Traffic Sign Recognition	TSR	✓							
Lane Departure Warning	LDW	✓							
Blind Spot Monitoring	BSM	✓							
Rear Cross Traffic Alert	RCTA	✓							
Collision Avoidance – by Braking	CA – B		✓						
Collision Avoidance – by Steering	CA – S		✓						
Lane Keeping Assist	LKA		✓						
Blind Sport Intervention	BSI		✓						
Rear Cross Traffic Alert with Active Brake Assist	RCTA – BA		✓						
Traffic Sign Recognition with Active Speed Adaptation	TSR-ASA		✓						
Lane Centering	LC		✓						
Adaptive Cruise Control (high & low speed)	ACC		✓						
Adaptive Cruise Control (stop & go)	ACC – S&G		✓						
Semi–Automatic Parking Assist	SAPA			✓					
Auto Lane Change (Driver Initiated)	ALC (D)				✓				
Fully Automatic Parking Assist	FAPA				✓				
Remote Parking (outside vehicle control but within vehicle's vicinity)	RP				✓				
Piloted Driving (PD)	PD					✓			
Auto Lane Change (System Initiated)	ALC (A)						✓		
Piloted Driving+ (D) - Driver fall back	PD+ (D)						✓		
Piloted Driving+ (S) - System fall back	PD+ (S)							✓	
Remote Parking+	RP+							✓	
Universal Robot Taxi	URT								✓

Source: (SBD, 2018).

ANNEX 2 – LIST OF C-ITS PRIORITY SERVICES

Vehicle-to-vehicle services		
Traffic jam	Dangerous end of queue	Already deployed using LTE-V2X long-range mode when considered as "hazard information" (otherwise similar service as "electronic emergency brake light")
	Traffic jam ahead	Already deployed using LTE-V2X long-range mode
Stationary vehicle warning	Stopped vehicle	
	Broken-down vehicle	
	Post-crash	
Special vehicle warning	Emergency vehicle in operation	Already deployed using LTE-V2X long-range mode
	Stationary safeguarding emergency vehicle	
	Stationary recovery service warning	
Exchange of IRCs	Request IRC	
	Response IRC	
Dangerous situation	Electronic emergency brake light	
	Automatic brake intervention	
	Reversible occupant restraint system intervention	
	Fog	Already deployed using LTE-V2X long-range mode
	Precipitation	
	Traction loss	



Source: (5G Automotive Association, 2019)

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ANNEX 3 – LIST OF CAVS PROJECTS AND FOT

6.5.8.5 EU Funded Projects: Automation in Urban Ares

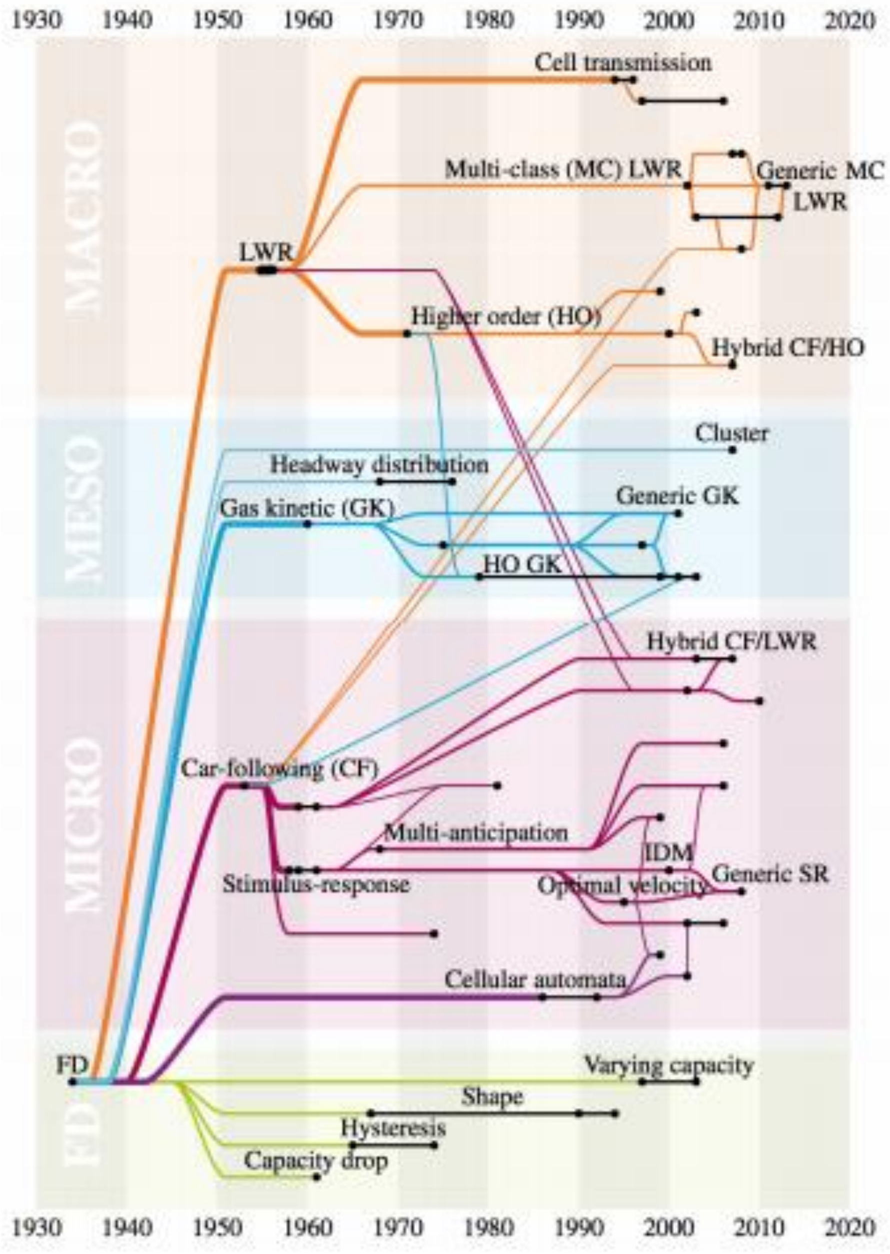
Project	Useful Urban Project Results	Status
AUTOPILOT http://autopilot-project.eu/	Enhance the driving environment perception with IoT sensors enabling safer highly automated driving; Foster innovation in automotive, IoT and mobility services; Use and evaluate advanced vehicle-to-everything (V2X) connectivity technologies, Involve Users, Public Services, Business Players to assess the IoT socio-economic benefits; Contribute to the IoT Standardisation and eco-system.	On-going
CO-EXIST https://www.h2020-coexist.eu/	Analysis on the effects of automated vehicles on urban road infrastructure and the co-existence between automated and conventional vehicles in mixed traffic.	On-going
CARTRE https://connectedautomateddriving.eu/about-us/cartre/	Its objectives include the creation of a knowledgebase of all European activities; to setup a platform for sharing and re-using data and experiences from different automated road transport systems; to actively support Field Operational Tests (FOTs) and pilots carried out at National and European levels; and to work on future visions, potential impacts and research gaps in the deployment of automated road transport.	On-going
HEIGHTS http://hights.eu	Pilot testing of location precision, robustness and latency - automated driving, platooning and safety of vulnerable road users.	On-going
MAVEN http://connectedautomateddriving.eu/project/maven	Infrastructure assisted algorithms for the management of automated vehicles, which connect and extend vehicle systems for trajectory and maneuver planning.	On-going

EU Project	Useful Urban Project Results	Status
CIMEC http://cimec-project.eu	C-ITS use cases, standardisation gaps and requirements, deployment roadmap	Completed
Compass4D www.compass4d.eu	Pilot results of Energy Efficient Intersection Service, Road Hazard Warning, and Red Light Violation Warning in different tests sites based on ITS-G5 and 3G/LTE.	Completed [19]
DRIVE C2X www.drive-c2x.eu	Impacts of several C-ITS services on driver behaviour, traffic safety, efficiency, environment and user acceptance based on field studies in urban environment in several European cities.	Completed
FOTNET http://fot-net.eu/	Data management and data sharing in field operational tests.	Completed
FREILOT http://www.ecomove-project.eu/links/freilot/	Project aiming at energy efficiency in urban areas. Showed clear savings fuel and CO2 by combination of GLOSA and priority for dedicated vehicles	Completed
OPTICITIES http://www.opticities.com/	A contractual framework on data access and exchange policy allowing enlarged access to high quality data	Completed
TEAM http://www.collaborative-team.eu/	TEAM Tomorrow's Elastic Adaptive Mobility developing collaborative ITS for city environment	Completed
VRUITS www.vruits.eu	ITS VRU Implementation Scenarios and ITS Assessment, VRU Integration Architecture and	Completed

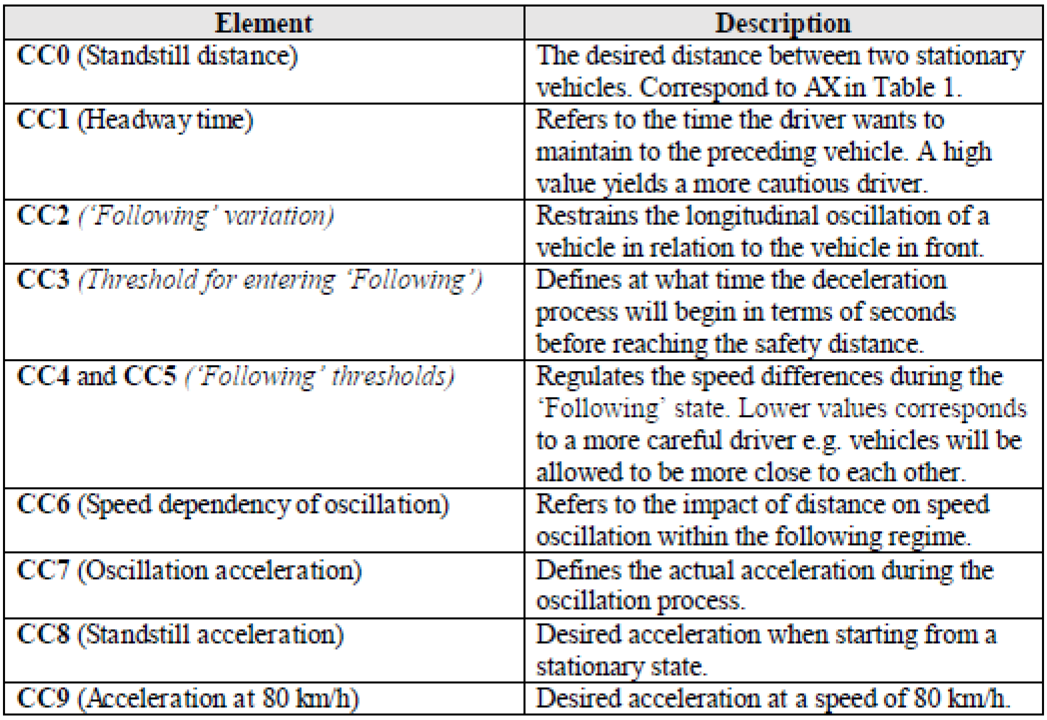
EU Project	Useful Urban Project Results	Status
	Recommendations, Exploitation Plan	
AUTOCITS www.autocits.eu	Pilot testing of C-ITS services for automated vehicles on outer-ring roads entering cities in Paris, Madrid, Lisbon	On-going
CAPITAL http://capital-project.its-elearning.eu	Preparation of C-ITS training and educational resources for local authorities	On-going
C-MOBILE http://c-mobile-project.eu/	Large-scale deployment of bundled C-ITS services in complex urban and extra-urban areas in 8 cities across 6 MS. incl. interactions with VRUs. On a small scale the extension towards automated driving is piloted.	On-going
CODECS www.codecs-project.eu	Common technical specifications for interfacing the vehicle and urban traffic management system & urban transport authority C-ITS requirements	On-going
CO-GISTICS http://cogistics.eu	Pilot results of C-ITS for logistics - Intelligent Truck Parking and Delivery Areas Management, Cargo Transport Optimisation, CO2 Footprint Monitoring and Estimation, Priority and Speed Advice and Eco-Drive Support.	On-going
C-ROADS https://www.c-roads.eu/	Pilot testing of C-ITS services (CZ, FR in particular useful for inner-city testing)	On-going
C-THE-DIFFERENCE www.c-thedifference.eu	Pilot testing of different C-ITS services in Helmond and Bordeaux based on ITS-G5 and 3G/LTE.[20]	On-going
SPICE http://spice-project.eu	Preparation of ITS Procurement Guidelines	On-going

ANNEX 4 – TRAFFIC SIMULATION GENEALOGY

Transportation Research Circular E-C195: Traffic and Transportation Simulation



ANNEX 5– WIEDEMANN 99 ADJUSTABLE PARAMETERS



Element	Description
CC0 (Standstill distance)	The desired distance between two stationary vehicles. Correspond to AX in Table 1.
CC1 (Headway time)	Refers to the time the driver wants to maintain to the preceding vehicle. A high value yields a more cautious driver.
CC2 *('Following' variation)*	Restrains the longitudinal oscillation of a vehicle in relation to the vehicle in front.
CC3 *(Threshold for entering 'Following')*	Defines at what time the deceleration process will begin in terms of seconds before reaching the safety distance.
CC4 and **CC5** *('Following' thresholds)*	Regulates the speed differences during the 'Following' state. Lower values corresponds to a more careful driver e.g. vehicles will be allowed to be more close to each other.
CC6 (Speed dependency of oscillation)	Refers to the impact of distance on speed oscillation within the following regime.
CC7 (Oscillation acceleration)	Defines the actual acceleration during the oscillation process.
CC8 (Standstill acceleration)	Desired acceleration when starting from a stationary state.
CC9 (Acceleration at 80 km/h)	Desired acceleration at a speed of 80 km/h.