Master Qualification Exam

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

Qualification Exam for Master Degree
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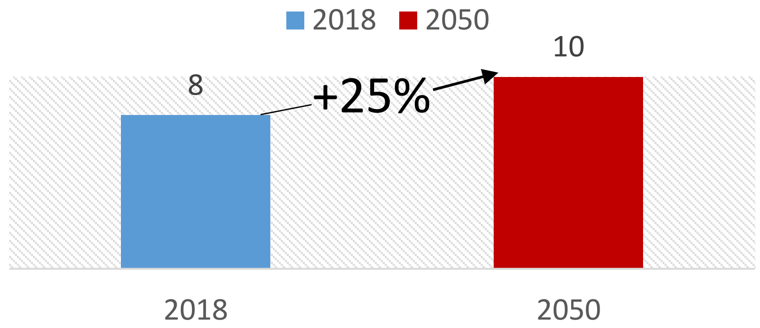
Supervisor: Prof. Dr. Leopoldo Rideki Yoshioka

1- Context: Urban Mobility

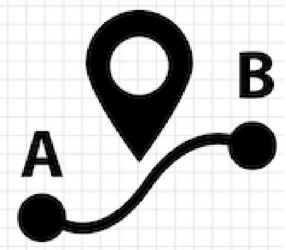
Population Increase



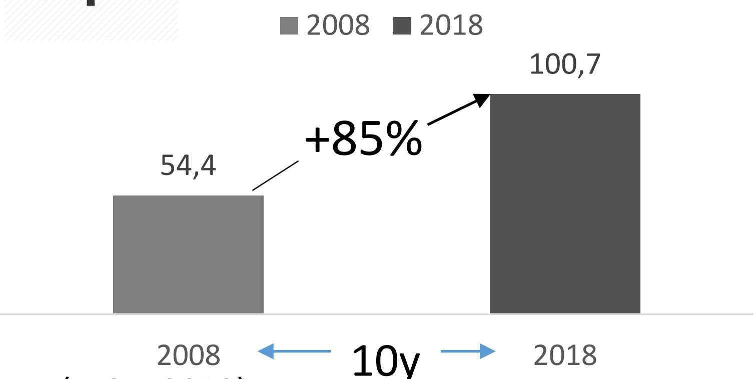
(UNITED NATIONS 1, 2018)

Urbanization

People need to MOVE



Vehicle Fleet in BR



(IBGE, 2019)

Road infrastructure remained at the same level

(ANT, 2018)

Decision Factors to choose a mean o transportation:

- **Time**
- Cost
- Safety
- Comfort

(MADHUWANTHI et al., 2015)

São Paulo

Home Work

≈ 45min

>1h (25% of population)

(PNAD, 2018)

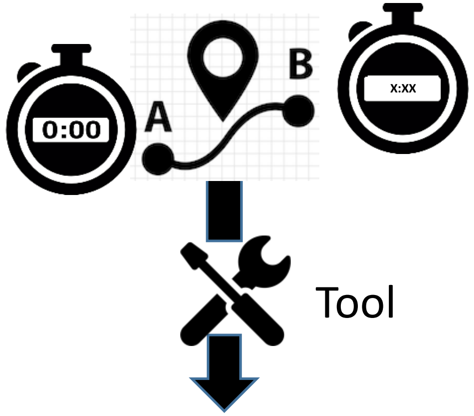
2- Research general objectives

To **measure the impacts** of Autonomous Vehicles **(AV)** and Connected and Autonomous Vehicles **(CAVs) on the traffic**

Considering road and traffic characteristics from **Brazilian metropolitan areas**

To **assess the transition phases:** mixed traffic/coexistence from HDVs, AVs and CAVs

Measure the traffic efficiency over Travel Time Measurement

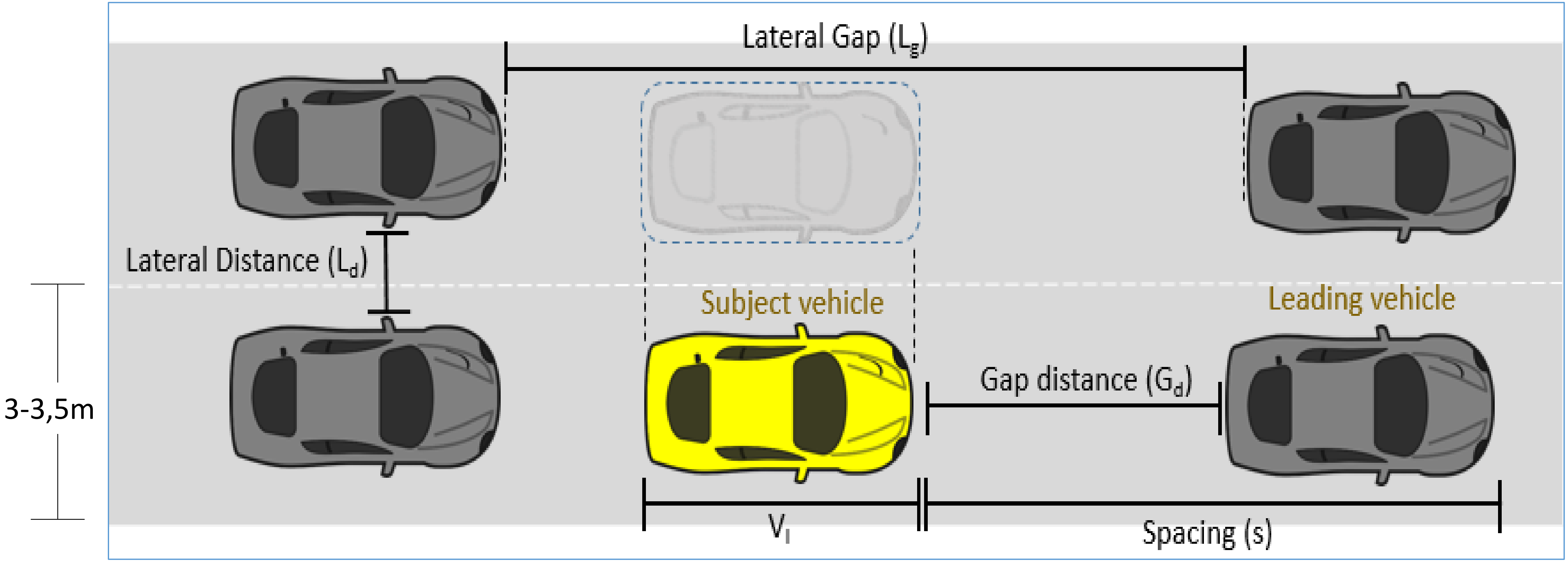


Microscopic Traffic Simulation

PTV VISSIM

Subtitles:
HDV: Human Driven Vehicles
AV: Autonomous Vehicles
CV: Connected Vehicles
CAV: Connected and Autonomous Vehicles

3.1 Key Concepts: Traffic Engineering



Source: Author

Width:
Passenger Car≈1,75m
Bus≈2,6m

3.2. Key Concepts: Vehicle Dynamics

Stopping Side Distance (SDD): the **distance** a vehicle needs to **full stop** (FHWA, 1997):

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

SSD (m)

V: Speed (km/h) → **90km/h**

***R_T* : Reaction Time (s)**

g: gravity → **9,8m/s²**

f: friction coefficient → **0,8**

G: grade (%) → **0% (flat)**

R_T (s)	SSD (m)
2	104,13
1	67,38
0,8	60,03
0,6	52,68
0,4	45,33
0,2	37,98
0	30,63

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

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

b: braking constant deceleration (m/s²) → **5m/s²**

***R_T* : Reaction Time (s)**

V_l : Leading vehicle speed (m/s) → **0 m/s**

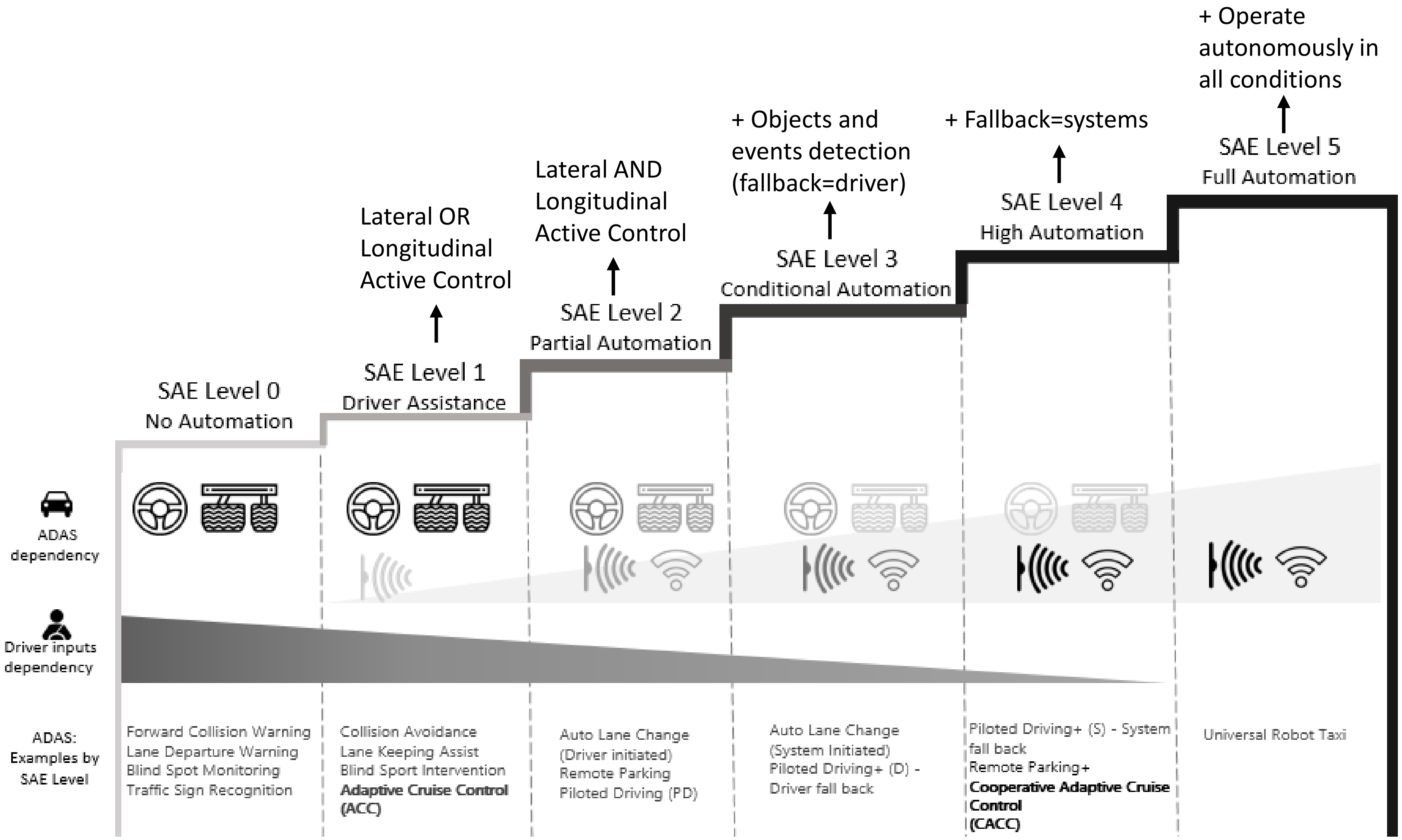
***(s-so): Gd* - gap distance (m)**

	Gd=100m	Gd= 10m
RT (s)	Safe Speed (km/h)	Safe Speed (km/h)
2	83,40	14,91
1	97,26	22,25
0,8	100,35	24,37
0,6	103,55	26,79
0,4	106,87	29,51
0,2	110,30	32,58
0	113,84	36,00

3.3. Key concepts: SAE J3016 - Automation Levels

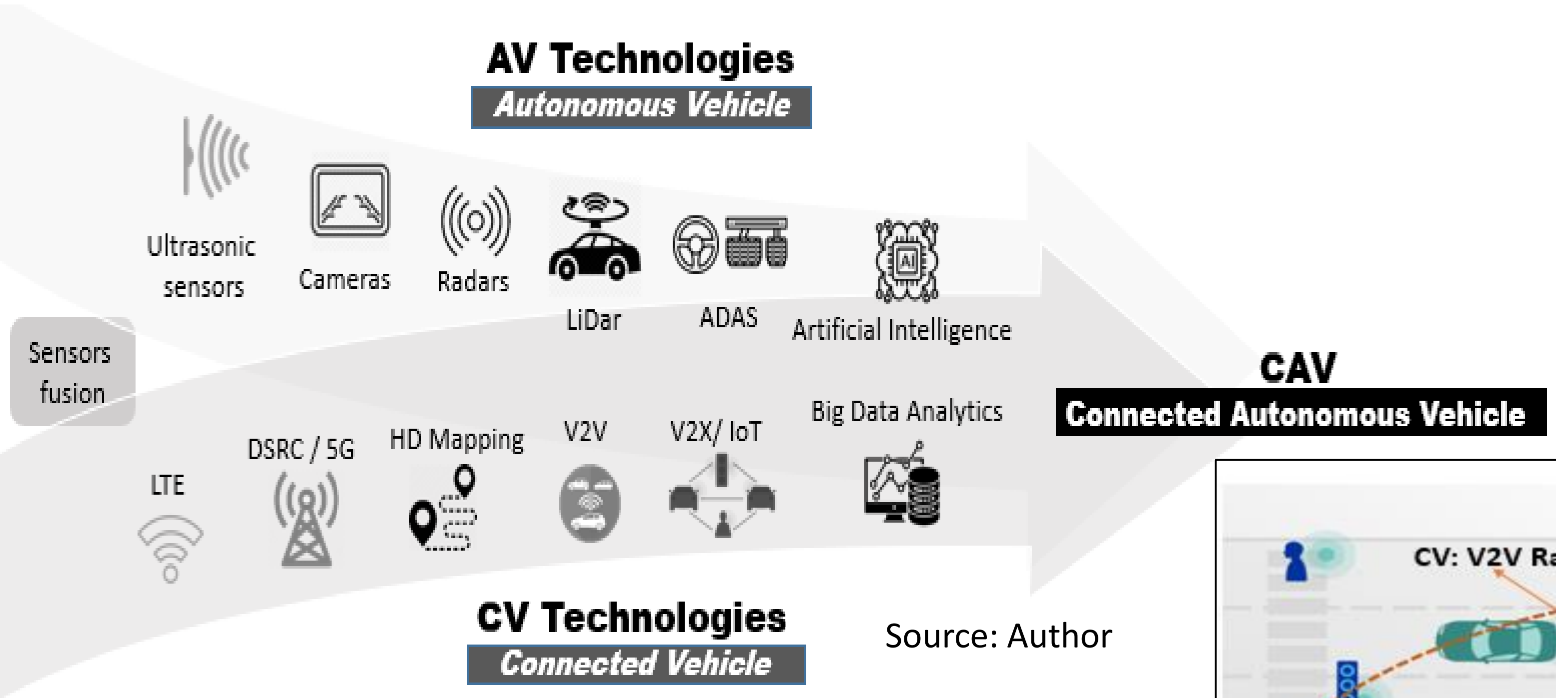
SAE J3016

Taxonomy for Vehicles Driving Automation



Source: Author

3.4. Key concepts: AV ≠ CV ≠ CAV



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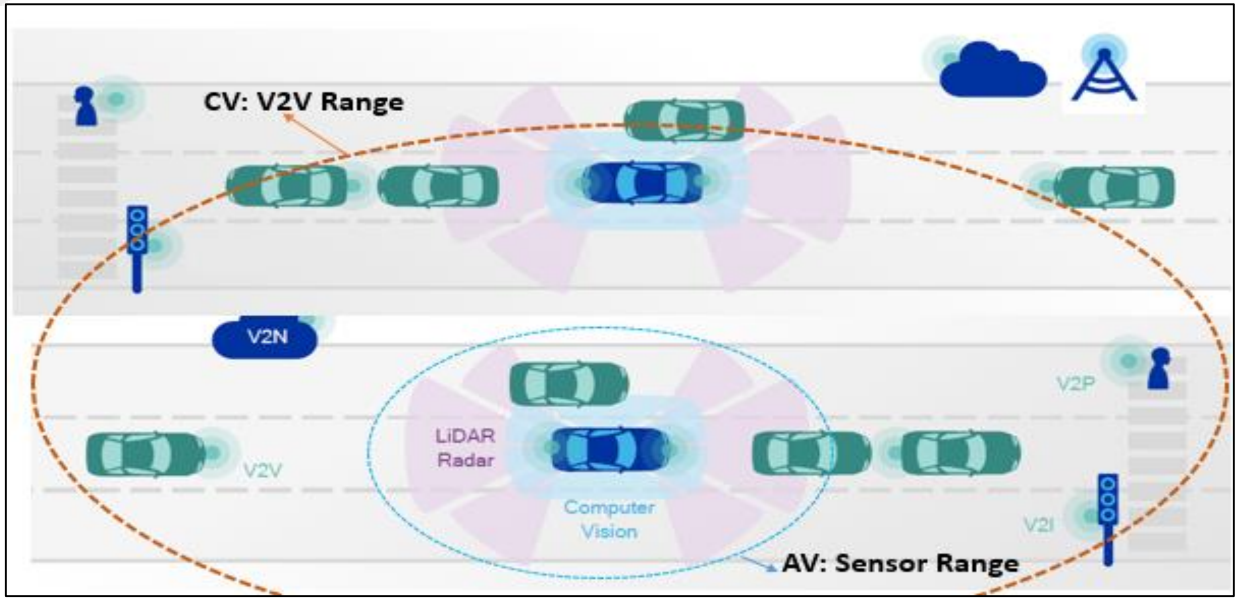
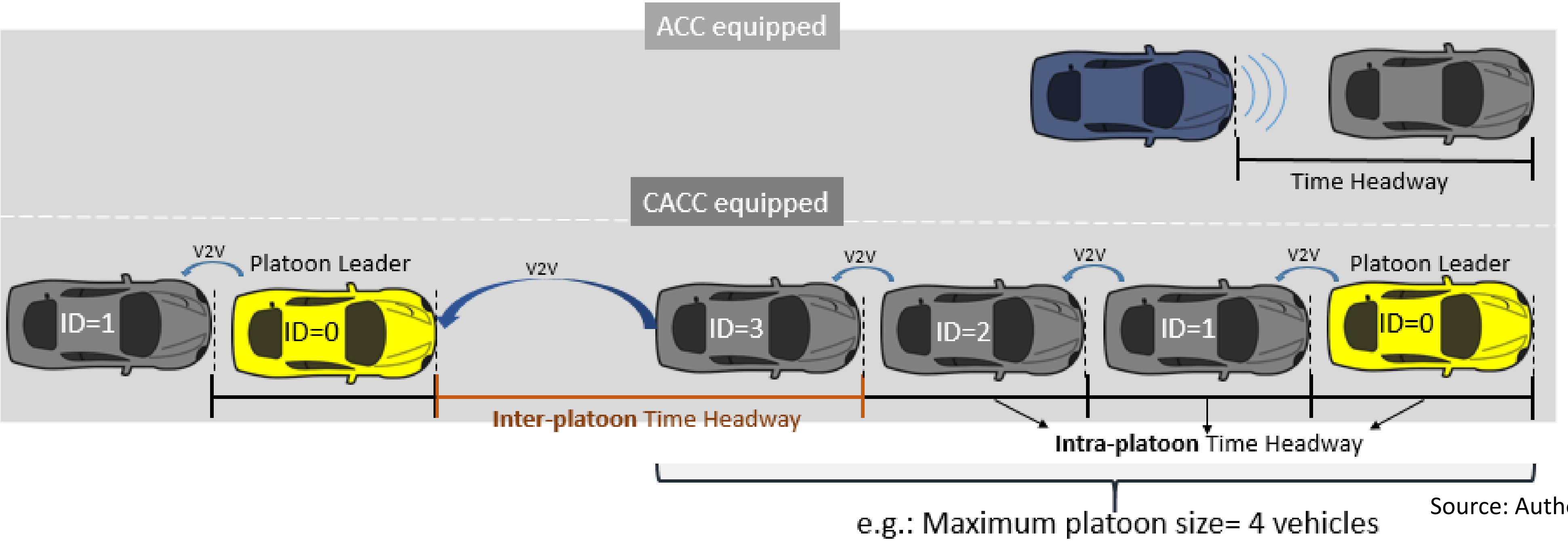


Source: adapted from Qualcomm (2016)

Subtitles:
LiDar: Light Detection and Ranging
ADAS: Advanced Driver Assistance Systems
DSRC: Dedicated Short Range Communication
HD: High Definition
LTE: Long Term Ethernet
V2V: Vehicle to Vehicle
V2X: Vehicle to Everything
V2N: Vehicle to Network
V2P: Vehicle to Person
IoT: Internet of Things

3.5. Key Concepts: CACC / Platooning / Automated Convoys

CACC: Cooperative Adaptive Cruise Control



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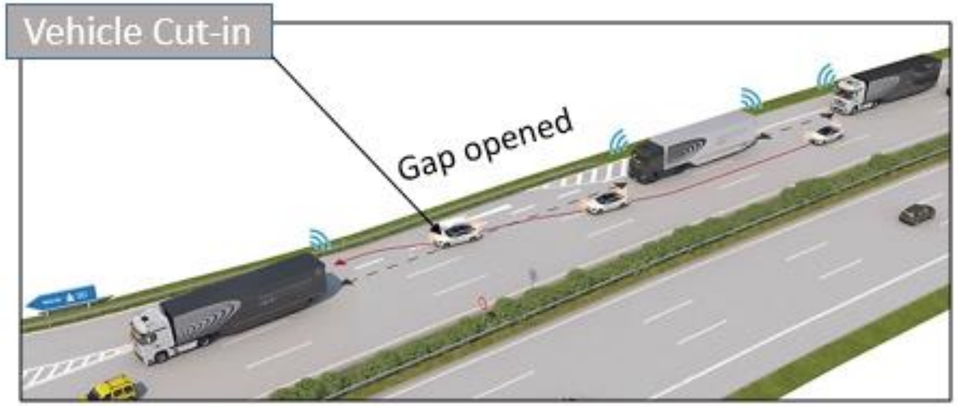
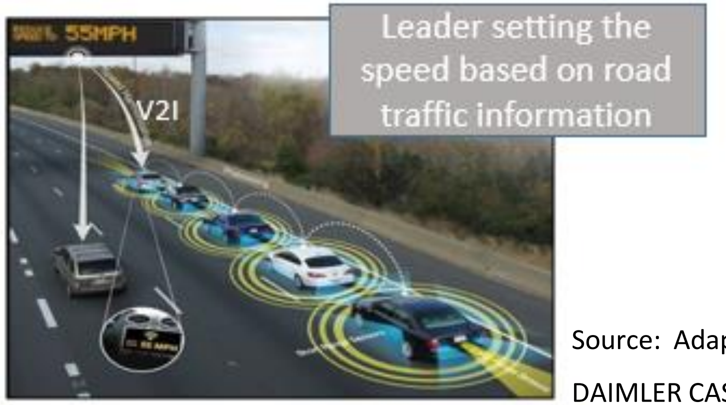




Source: Adapted from DIRT (2019) and DAIMLER CASE (2019).

4. Mathematical Models **(AV)**

ACC is frequently used to model AVs → Intelligent Driver Model (IDM)

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

α_{IDM}: Vehicle Acceleration (m/s²)
a: comfortable acceleration rate;
v: subject current vehicle speed (m/s);
v_0 : is the desired (safety) speed (m/s);
Δv : speed difference between the subject vehicle and the leading vehicle (m/s);
s : distance from subject to leading vehicle (m);
δ: magnitude of acceleration decrease parameter depending on the vehicle speed;
s*: desired distance (safety gap) described as:

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

s_0 : minimum gap (m);
T: desired gap (m);
a: comfortable acceleration rate
b: deceleration rate.

(TREIBER & KESTING, 2013)

4. Mathematical Models **(CV/CAV)-** CACC is frequently used to model CAVs

MIXIC: Microscopic Model for simulation of Intelligent Cruise Control

Safe following distance

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

v: current vehicle speed,
d: deceleration capability subject vehicles
d_p: deceleration capability of the leading

Following distance

$$r_f = t_{system} \cdot v \quad (13)$$

v: subject vehicle speed
t_{system} : time headway →
e.g.: 0,5 seconds if the leading vehicle has CACC function and 1,4 seconds, otherwise.

Van AREM et al., (2006)

4. Mathematical Models **(CV/CAV)-** CACC is frequently used to model CAVs

CACC:
Accelerations of Vehicles

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

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

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

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

a: acceleration in next step of subject vehicle,
$\boldsymbol{a_l}$: acceleration of the leading vehicle
v_s: vehicle speed of subject vehicles
v_l : vehicle speed of leading vehicles
a_{max}: maximum allowed acceleration
a_{min}: maximum allowed deceleration
k_v and k_s: constant gain greater than zero

ZHAO & SUN, (2013)

4. Mathematical Models **(CV/CAV)-** CACC is frequently used to model CAVs

MIXIC: Microscopic Model for simulation of Intelligent Cruise Control

Safe speed

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

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

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

n : subject vehicle; $n\text{-}1$:leading vehicle;
X_n: position, l_n:length, v_n: vehicle speed, **τ: reaction time,**
a_n^{decc}: maximum deceleration of the subject vehicle vehicle

TELEBPOUR & MAHMASSANI (2016)

4. Mathematical Models **(CAV)**

Anticipation distance: based on the premise that CAVs can obtain the exact value of space gap

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

d : distance gap between subject and leading vehicle;
v_{anti} is the expected speed of leading vehicle;
$b_{defense}$: randomization-deceleration rate under the defensive state

This equation is based on the worst case where a **CAV is following a HDV**. As a **HDV driving** behavior **is unpredictable** the **CAV needs always to drive on the defensive.**

Safe Speed: connectivity characteristics of V2V

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

v_{li} : average speed of leading **CV within the communication distance range**;
v_l : leading vehicle speed;
d_l : gap distance from leading vehicle

YE & YAMAMOTO (2017)

4. Mathematical Models **(AV/CV/CAV)-** Evolution

AVs

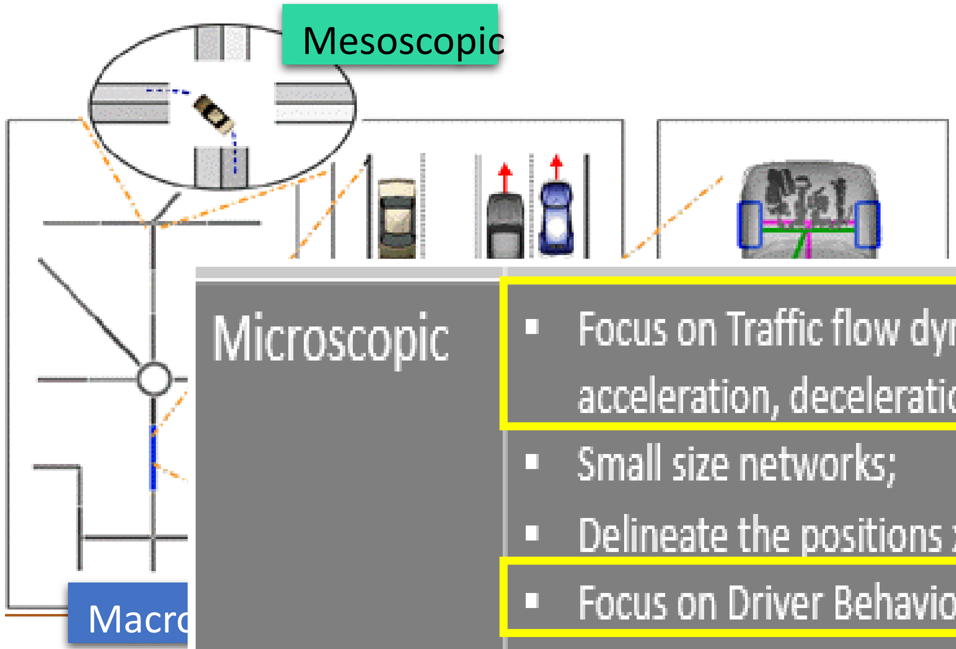
- ACC / IDM
  (TREIBER & KESTING, 2013)

CVs/ CAVs

- MIXIC
  Van AREM et al., (2006)
- CACC
  ZHAO & SUN, (2013)
- MIXIC + Sensor Features
  TELEBPOUR & MAHMASSANI (2016)
- CACC + Mixed Scenarios + Communication Technologies (CV)
  YE & YAMAMOTO (2017)

Subtitles:
AV: Autonomous Vehicles
CAV: Connected and Autonomous Vehicles
IDM: Intelligent Driver Model
ACC: Adaptive Cruise Control
CACC: Cooperative Adaptive Cruise Control
MIXIC: Microscopic Model for simulation of Intelligent Cruise Control

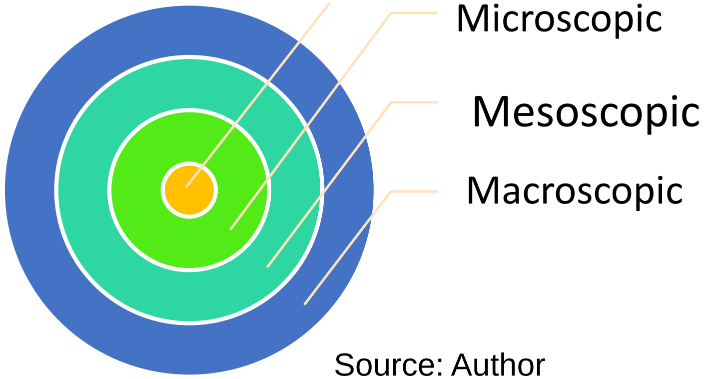
5. Traffic Simulation - Why to use microscopic Simulation?



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	CARLA PRESCAN
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
	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

Level o details

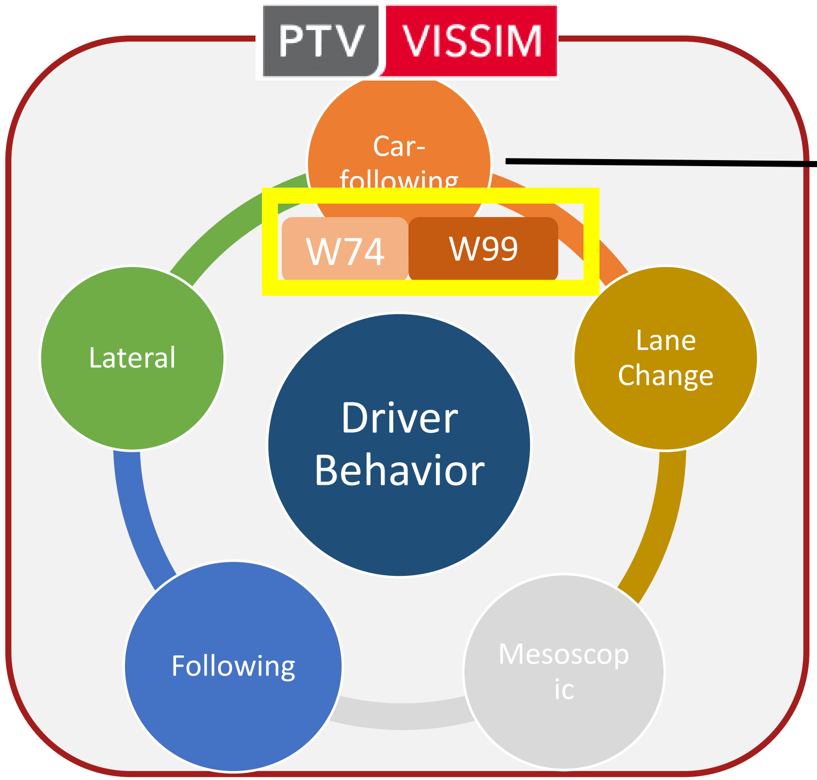
Source: Author



Source: Author

5. VISSIM input Data: Microscopic Driving Behavior

Driving Behavior: "underlying logic" of a traffic simulation model (Gao; 2008)



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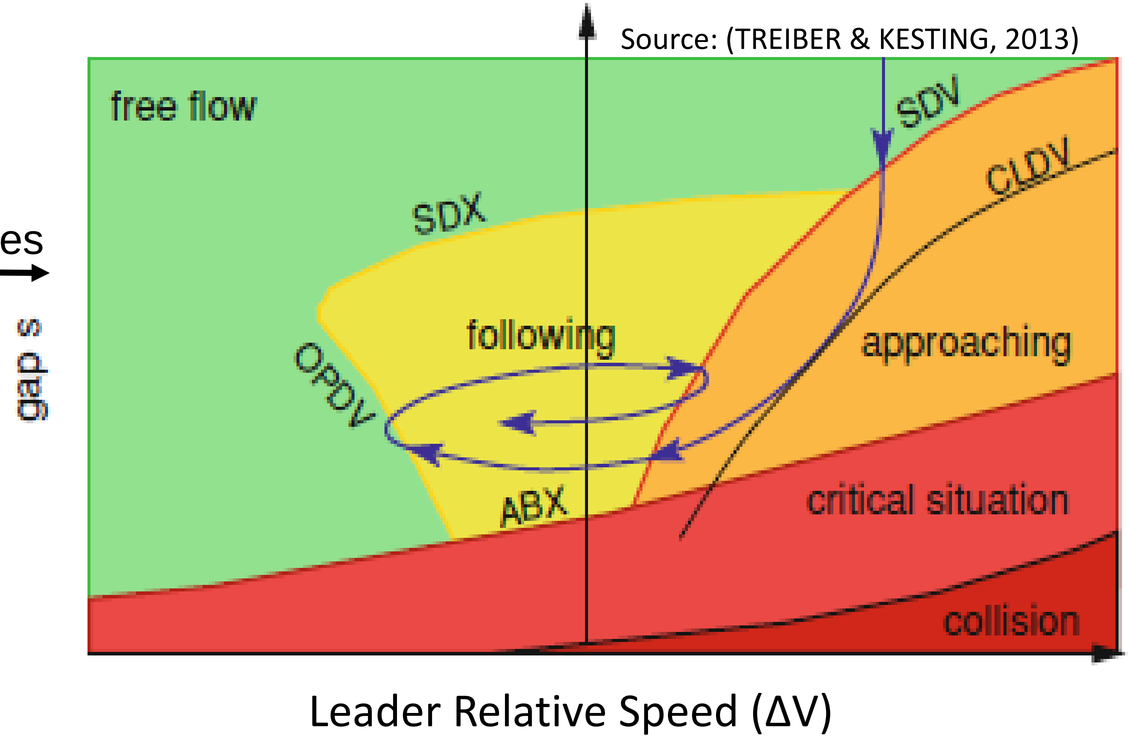
Driving regimes

Source: (TREIBER & KESTING, 2013)



SDV: the points at **long distances** where **drivers perceive speed differences** when they are approaching **slower vehicles**

CLDV: the points at **short distances** where drivers **perceive that their speeds are higher** than their lead vehicle speeds

OPDV: the points at short distances where **drivers perceive** that they are **travelling at a lower speed than their leader**

SDX: The **maximum following distance** indicating the upper limit of car-following process

ABX: the **minimum following distance** which is considered as a **safe distance by drivers**

5. VISSIM input Data: Wiedemann Models

Wiedemann 74 (W74)

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

$u_n(t+\Delta t)$ is the minimum between two speeds.

AX and BX are adjustable parameters expressed a

$$d = AX + BX$$

AX is the standstill distance (m). BX is the safe **(m)** given by

$$BX = (BX_{add} + BX_{mult} \cdot z) \cdot \sqrt{v}$$

v :vehicle speed (m/s),
BX_{add} : **additive part of the safety distance**
BX_{mult} : **multiplicative part of the safety distance** and
z is a value from 0-1

(GAO, 2008)

Wiedemann 99 (W99)

$$min \begin{cases} u_n(t) + 3.6 \cdot \left(\boldsymbol{CC8} + \frac{CC8 - CC9}{80} \dot{u}_n(t)\right)\Delta t \\ 3.6 \cdot \left(\frac{s_n(t) - CC0 - L_{n-1}}{u_n(t)}\right)^2 \end{cases}, u_f \quad (25)$$

$$CLDV = \frac{CC6}{17000} \times (\Delta x - L)^2 - CC4 \quad (26)$$

$$OPDV = -\frac{CC6}{17000} \times (\Delta x - L)^2 - \delta.CC5 \quad (27)$$

...istance (m),
...llowing threshold (m/s)
...lowing threshold (m/s)
CC6: Speed dependency of oscillation (10^-4 rad/s)
CC8 : standstill acceleration (m/s²) and
...peed of 80 km/h
...hicles (m)

	model	parameter**
following behavior	Wiedemann 99	CC0
		CC1
		CC2
		CC3
		CC4
		CC5
		CC6
		CC7
		CC8
		CC9
	W74	ax
		bxadd
		bxmult

VISSIM user manual recommendation:

- **Wiedemann 74 (W74):** urban traffic and merging areas
- **Wiedemann 99 (W99):** freeways interactions

5. VISSIM and CoEXist: Project partnership supported PTV on developing features for AVs traffic simulation

CoEXist is a European project (May 2017 – April 2020) which aims at preparing the transition phase

CoEXist · PTV GROUP the mind of movement · Universität Stuttgart Germany · GROUPE RENAULT · tass international

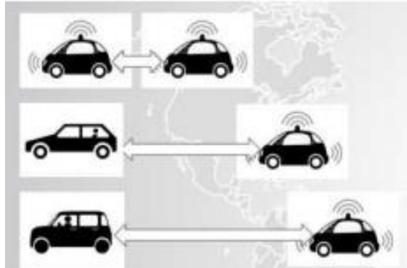
→ 4 different Driving Logic models were developed

Definition under CoExist project:

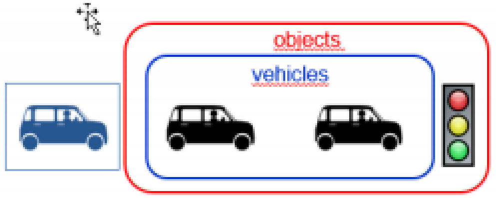
Rail safe | Cautious | Normal | „all knowing“

Project supported the development of new features applied at VISSIM 11

- Class dependent safety distance in following behavior



- Number of interaction: objects & vehicles



- Use implicit stochastics behavior for human drivers

(Coexist D2.4, 2018)

5. Vissim and CoExist (Field Operational Trial): recommended of parameters for each Driving Logic

CoEXist

model		parameter**	driving logic: rail safe	cautious	normal	all knowing	def
following behaviour	Wiedemann 99	CC0 – Standstill distance (m)	1.5	1.5	1.5	1	1.5
		CC1 – Spacing time (s)	1.5*	1.5*	0.9	0.6	0.9
		CC2 – Following variation (m)	0	0	0	0	4
		CC3 – Threshold for entering "following" (s)	-10	-10	-8	-6	-8
		CC4 – Negative „following" threshold (m/s)	-0.1	-0.1	-0.1	-0.1	-0.35
		CC5 – Positive „following" threshold (m/s)	0.1	0.1	0.1	0.1	0.35
		CC6 – Speed dependency of oscillation (10^{-4} rad/s)	0	0	0	0	11.44
		CC7 – Oscillation acceleration (m/s^2)	0.1	0.1	0.1	0.1	0.25
		CC8 – Standstill acceleration (m/s^2)	2	3	3.5	4	3.5
		CC9 – Acceleration at 80 km/h (m/s^2)	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

* if EABK[1] is on, brick wall stop distance is guaranteed

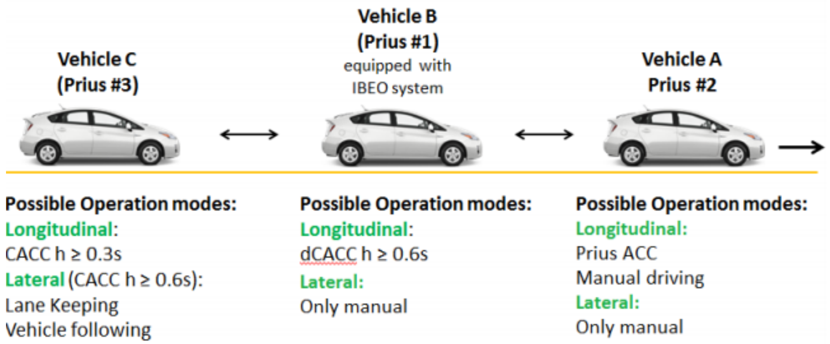
** see PTV Vissim manual for detailed description

*** might be used for very simple models only

(Coexist D2.3, 2018)

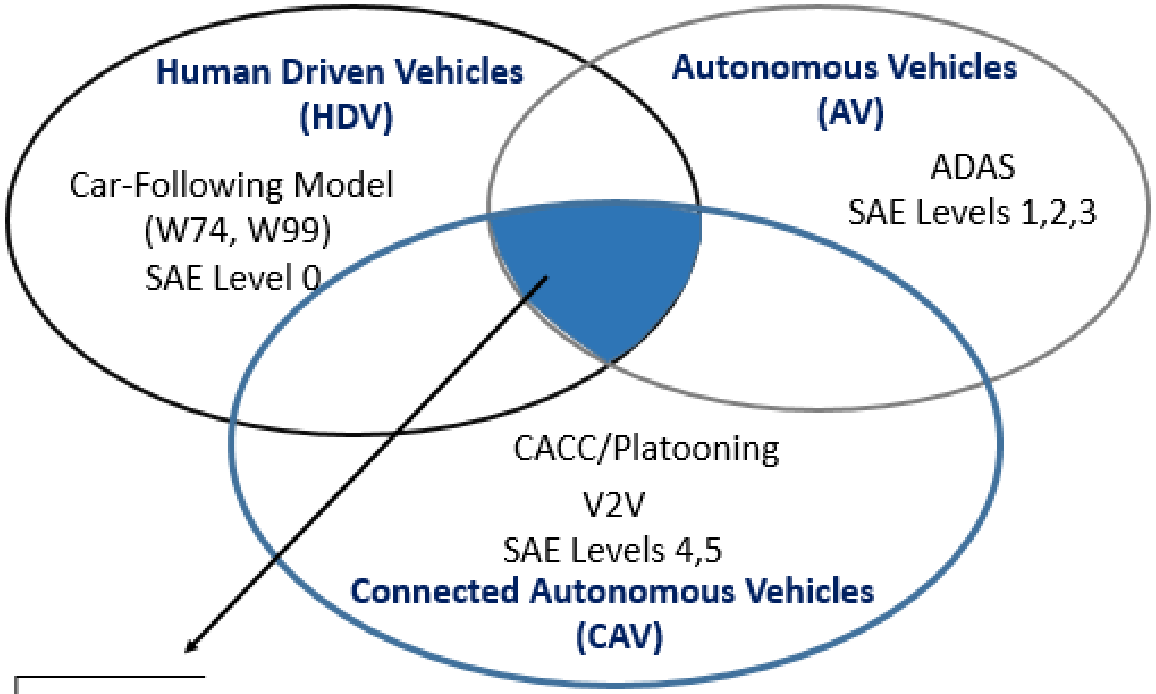
Recommendations are based on:

- Analysis of **empirical data collected in TASS test track in Helmond – Netherlands** + Co-simulations (PreScan + VEDECOM) + simulation VISSIM (Coexist D2.6, 2018):



Recommendation to use W99 to simulate AVs because of more options to control the behavior through driving parameters (Coexist D2.6, 2018)

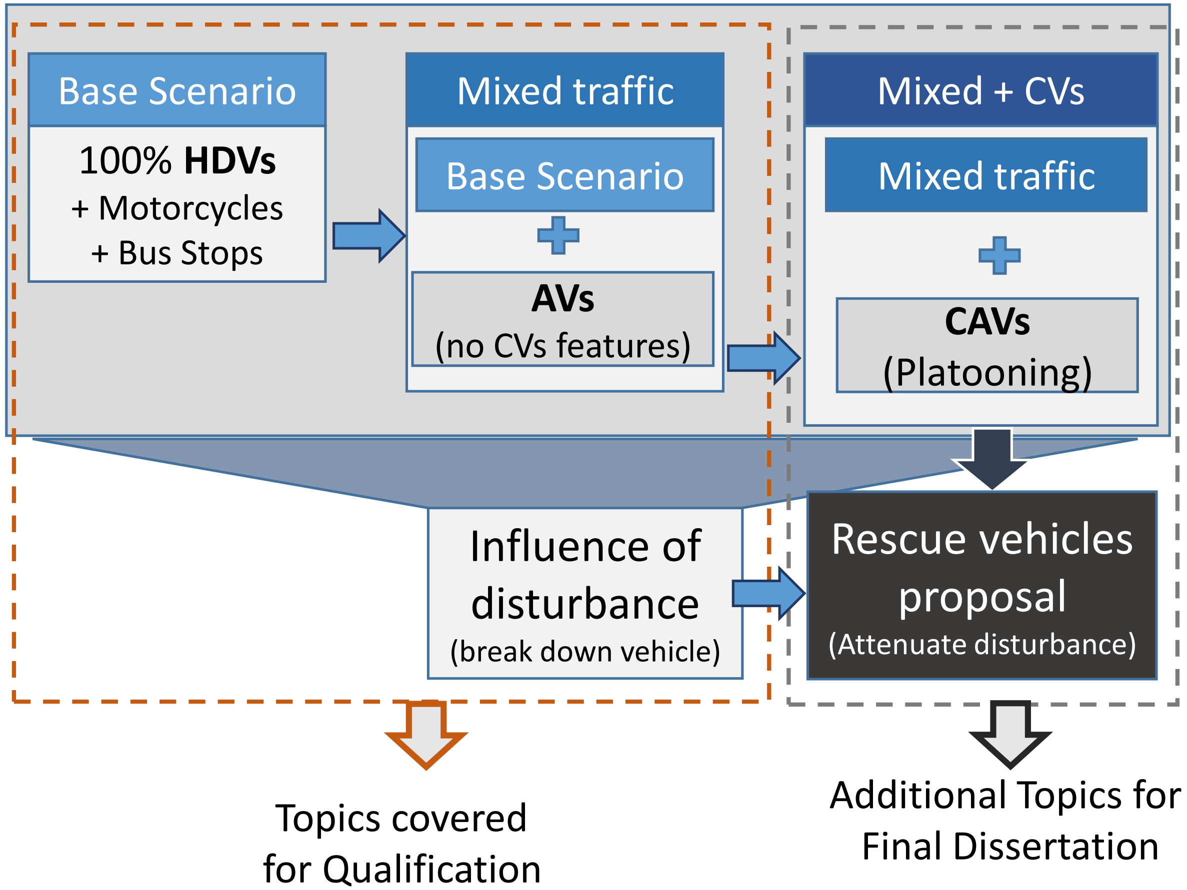
6. Research Proposal



Source: Author

Traffic behavior for
Mixed/Heterogeneous roads:

- **+ Urban heavy traffic (Brazilian characteristics)**
- **+ Motorcycles**
- **+ Bus Stops**
- **+ Disturbances (vehicles break-down)**
- + Platooning new feature (Vissim 2020)
- + rescue vehicles shared model proposal



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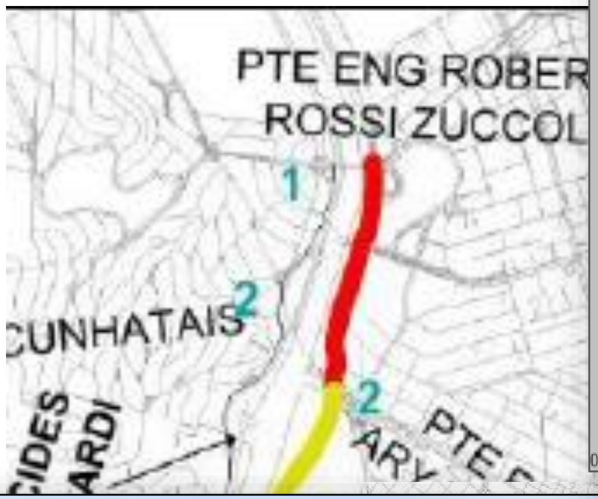
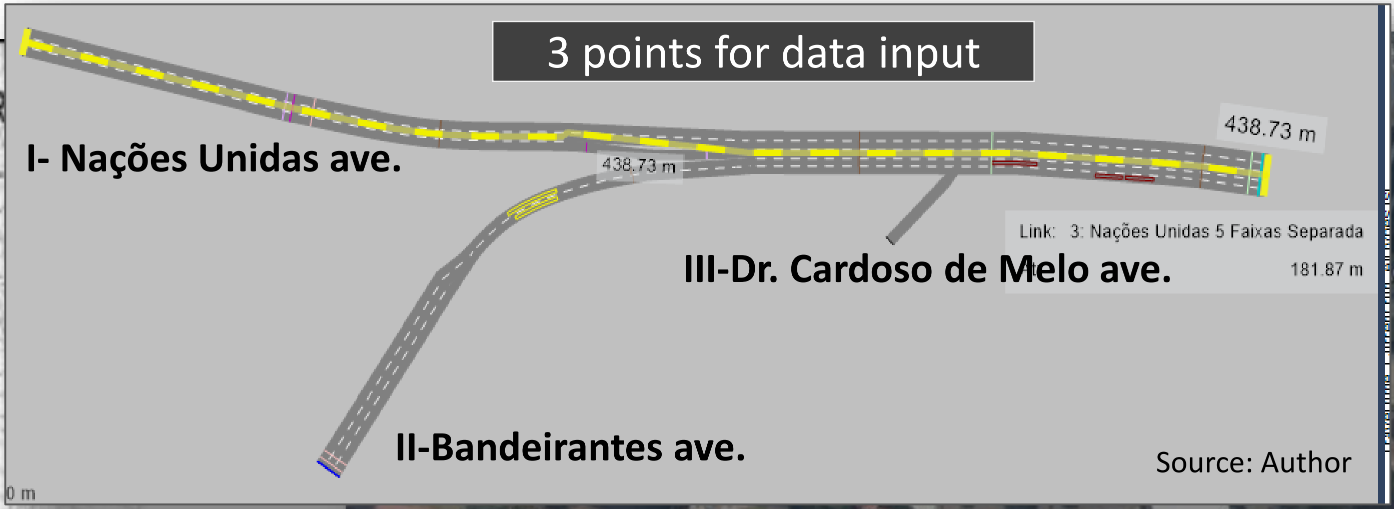
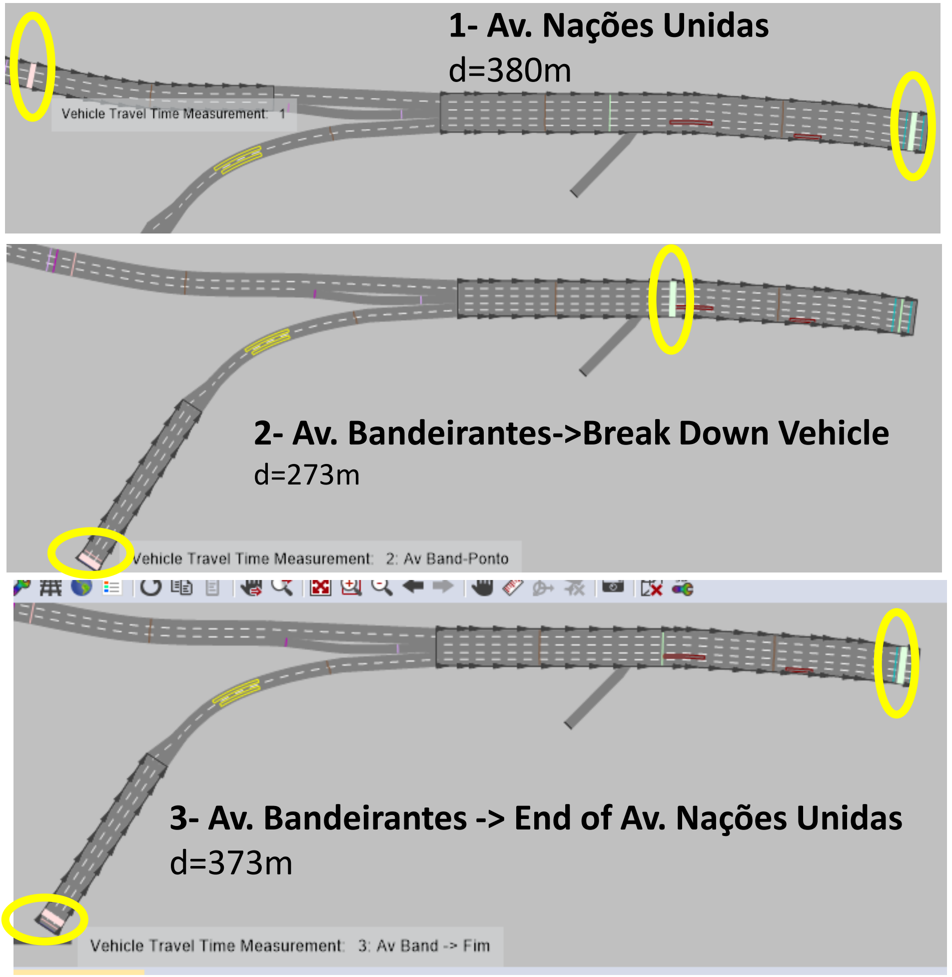
6.1. Characteristics from base model: why this segment was chosen?



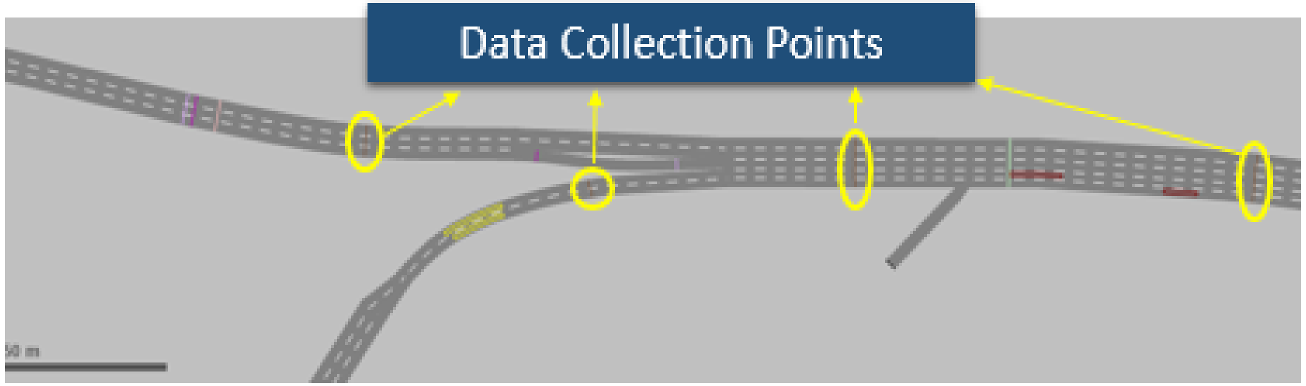


6. VISSIM data outputs

Travel Time Measurement



Source: Author



Source: Author

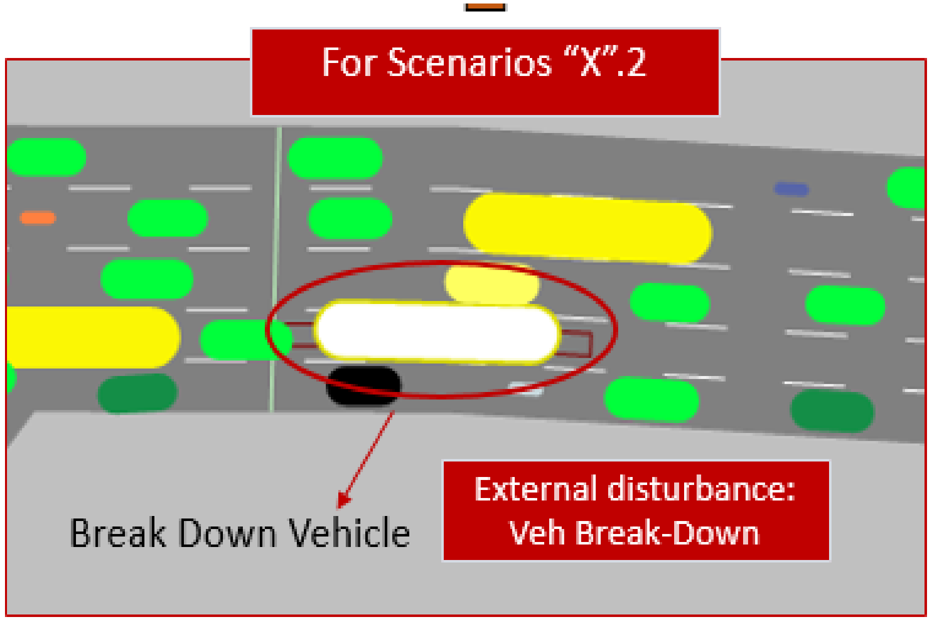
- Each lane has its own Data Collection Point
- VISSIM gives many different outputs. The key output element for this study is:
  - Average vehicles speed
  - Queue delay
  - Occupation Rate

7. Methodology: Scenarios description

	Driver Behavior	Pen Rate
Scenario 1.1 / 1.2 (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%

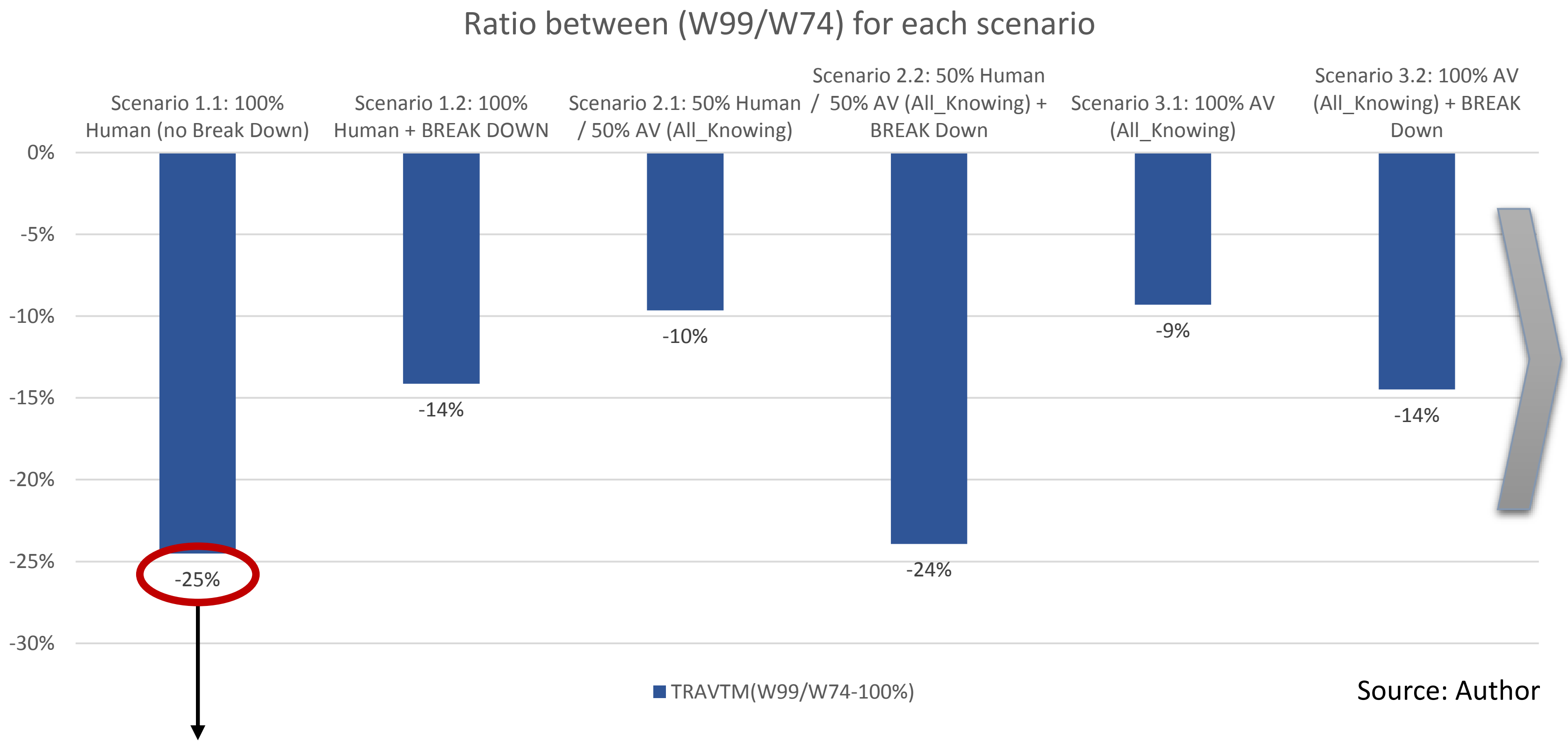
Source: Author

Illustration of “Break Down” Scenarios



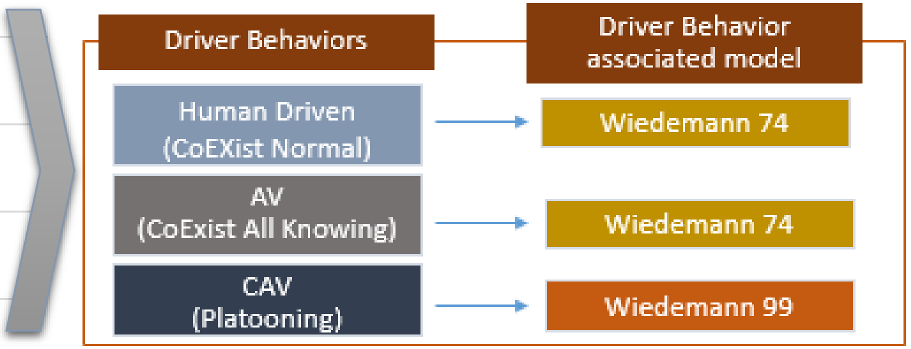
Source: Author

7. Partial Results: Comparison between W74 and W99



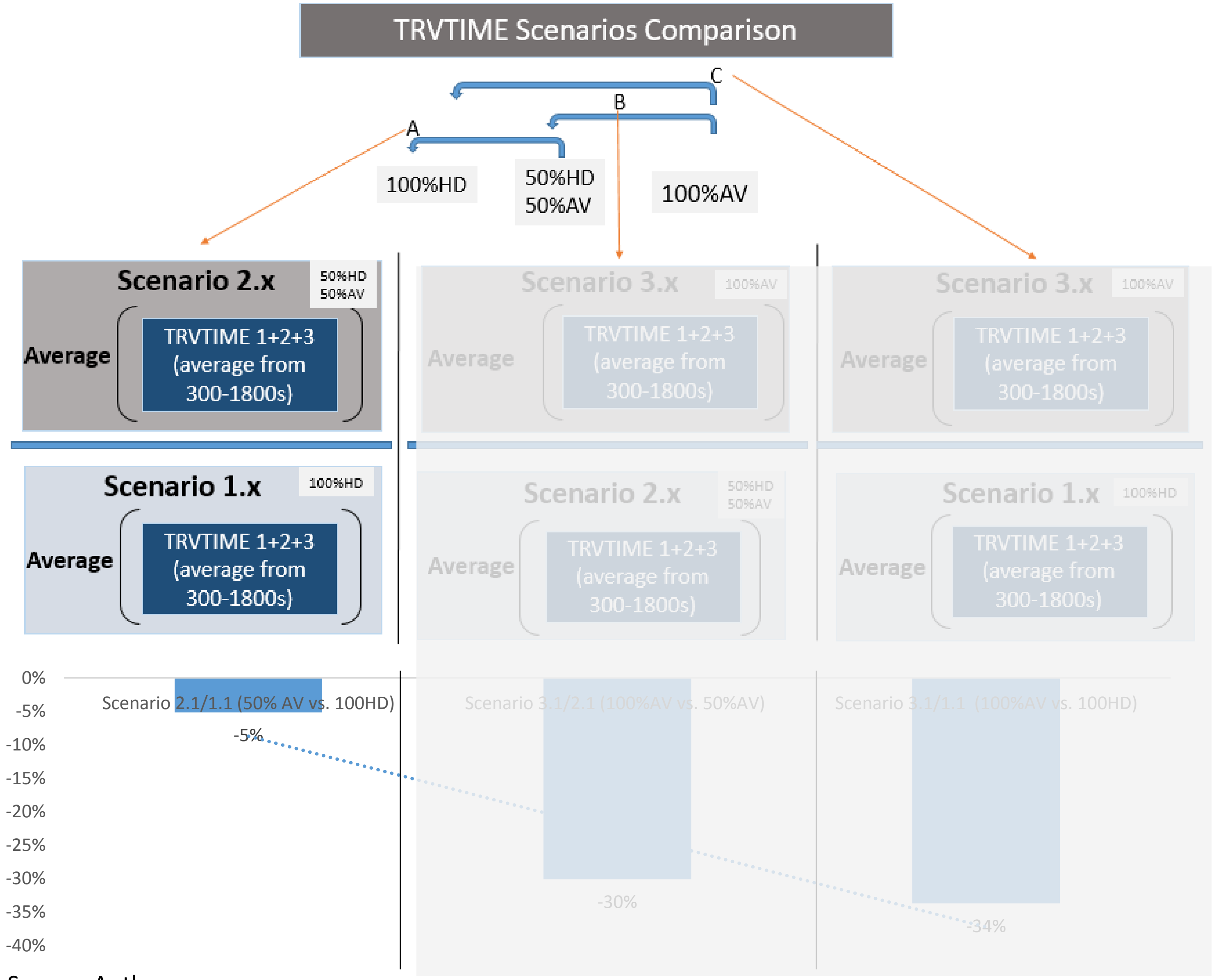
Source: Author

Travel Time for W99 is 25% faster than W74



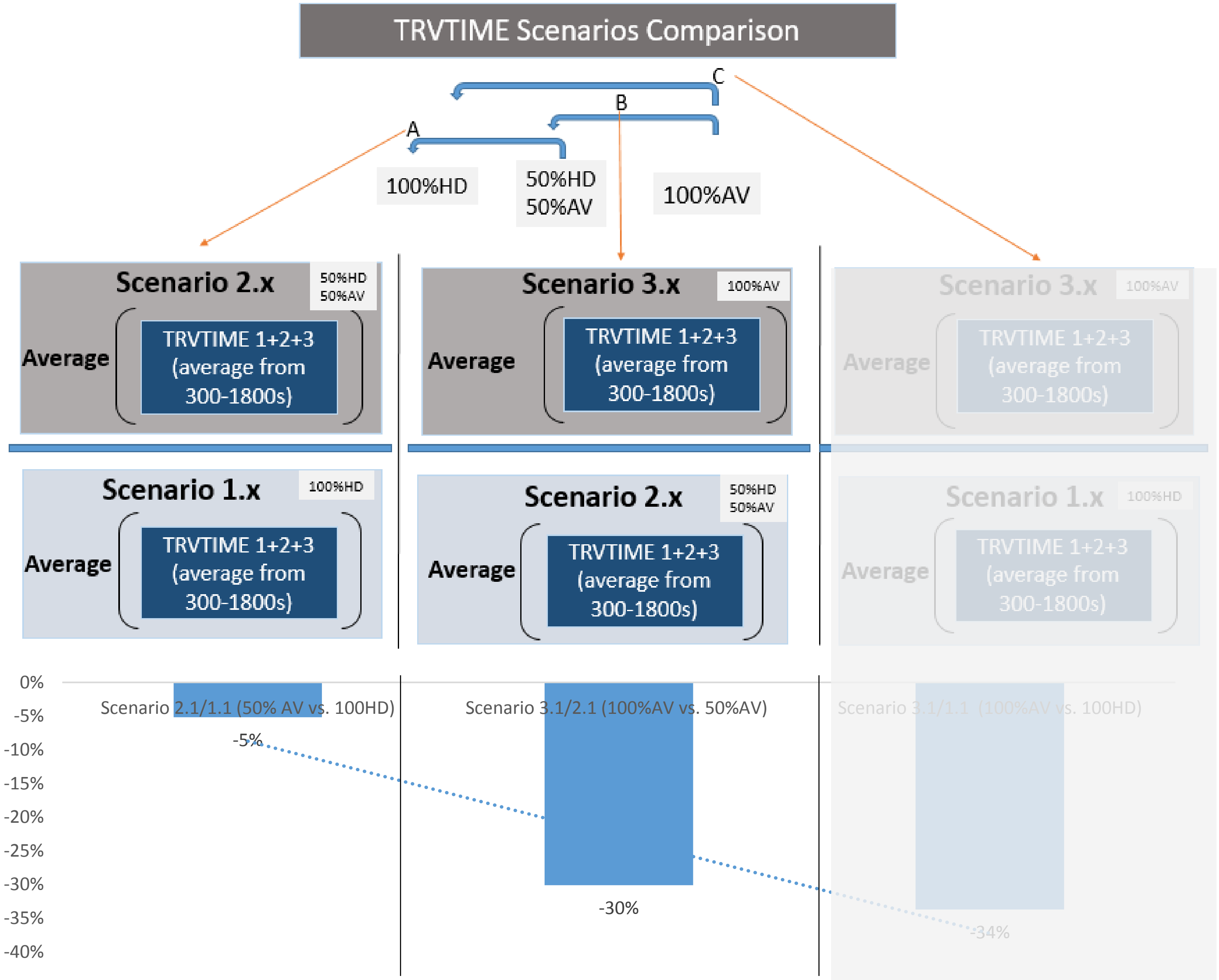
Source: Author

8. Partial Results: Comparison between Scenarios



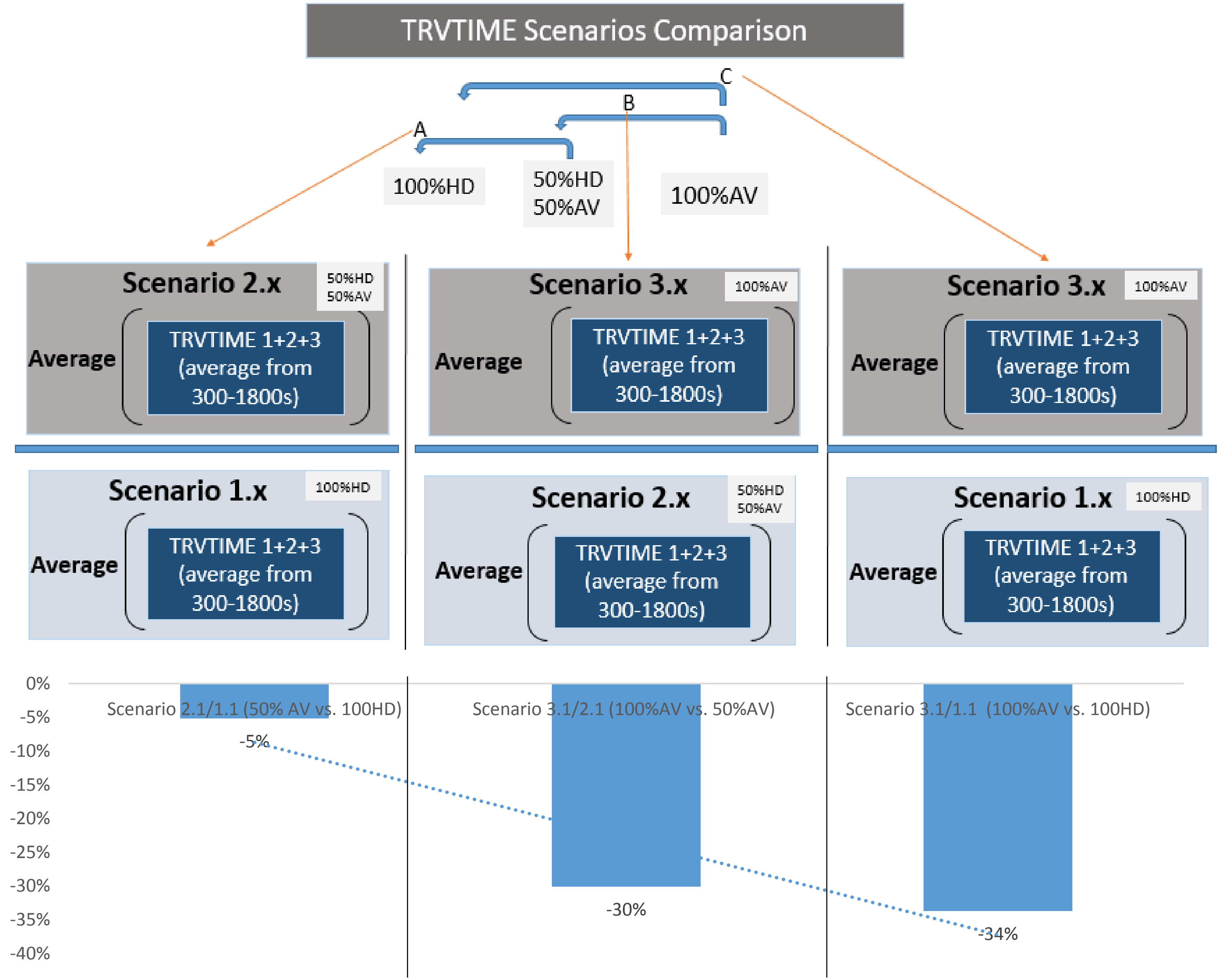
Source: Author

8. Partial Results: Comparison between Scenarios



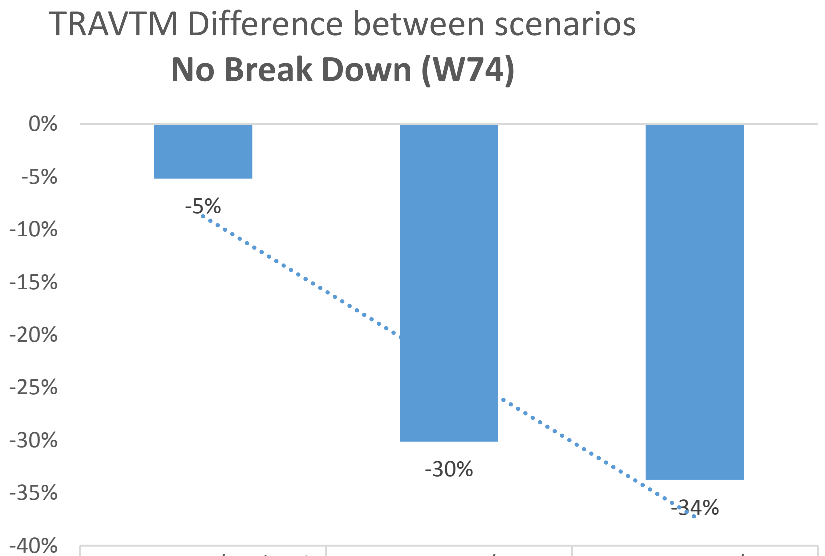
Source: Author

8. Partial Results: Comparison between Scenarios



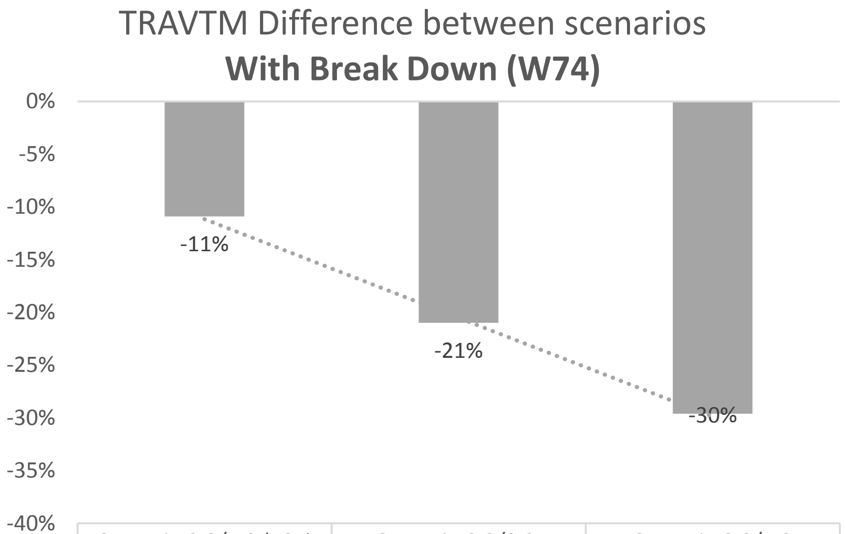
Source: Author

8. Partial Results: Comparison between Scenarios



	Scenario 2.1/1.1 (50% AV vs. 100HD)	Scenario 3.1/2.1 (100%AV vs. 50%AV)	Scenario 3.1/1.1 (100%AV vs. 100HD)
TRAVTM Diference	-5%	-30%	-34%

Source: Author



	Scenario 2.2/1.2 (50% AV vs. 100HD)	Scenario 3.2/2.2 (100%AV vs. 50%AV)	Scenario 3.2/1.2 (100%AV vs. 100HD)
TRAVTM Diference	-11%	-21%	-30%

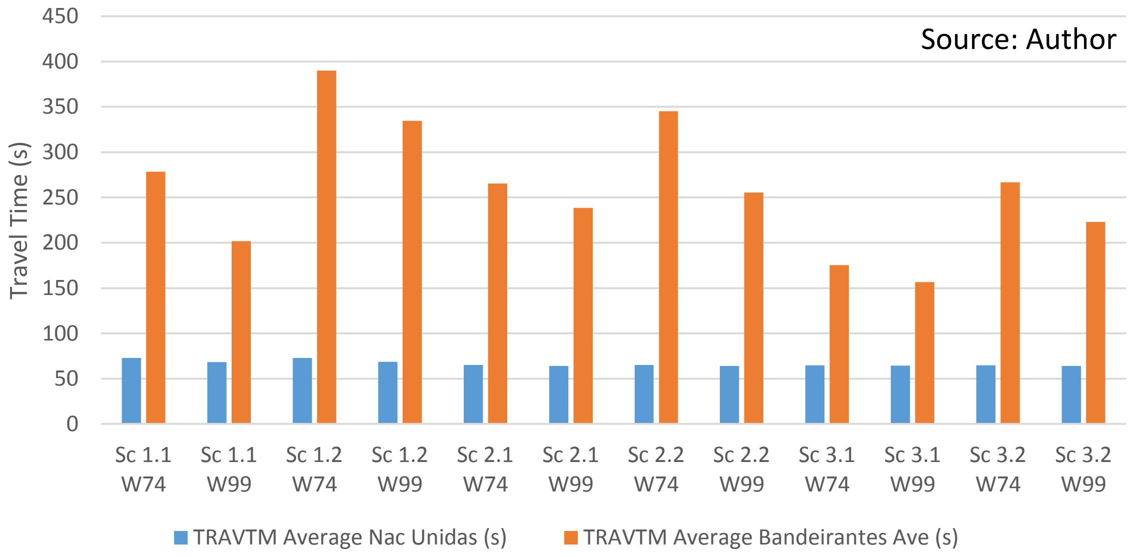
Source: Author

- AVs even mixed with HDVs shows a small improvement on traffic flow. For 50% AV/50% HDV the travel time reduced just 5%
- The higher introduction of AVs brings much higher benefits to the traffic flow.

- The higher penetration of AVs improve the traffic flow for this disturbance application
- For 50% of AVs the improvement was up to 11%: AVs perform better on disturbance scenarios

8. Partial Results: Deep dive on simulated segments – Bandeirantes Ave. is the bottleneck

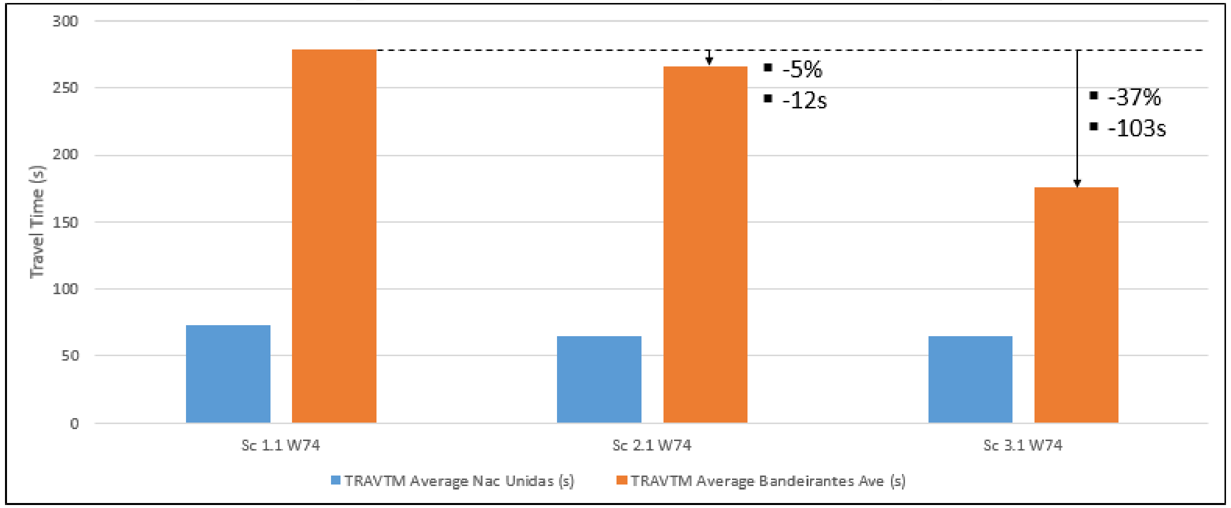
Travel time difference between Nac Unidas and Bandeirantes avenues for all scenarios and driver behavior types



- The travel time for Nac. Unidas Ave has a much lower variation when compared to Bandeirantes Ave.
- Bandeirantes Ave. is the bottleneck

- Comparing the scenarios without break-down there is a variation of -37% on travel time from base scenario to 100% AV

Source: Author



Travel time comparison between Nacões Unidas and Bandeirantes avenue

8. Partial Results: Comparison with literature

Reference	Simulator	Application	Results
BAILEY (2016) Modified IDM	AIMSUM	Urban	**20% AVs → ↓ 53% travel time** **100% AVs → ↓ 80% travel time**
RIOS-TORRES et al. (2017): Optimal Control	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
TILG et al. (2018)	MATLAB + Not mentioned	Highway	100% AVs → ↑ 15% traffic capacity
EVANSON (2017)	VISSIM + Platooning (external)	Highway	100% CAVs → ↓ 11% travel time
ZHOU et al. (2019)	Not mentioned	Highway	100% CACC → ↑ 95% lane capacity

Source: Author

Simulator	Application	Results
VISSIM+ Platooning (VISSIM integrated)	Urban	50% AVs → ↓ 5% travel time 100% AVs → ↓ 34% travel time

- It was not found at the literature a similar research using CoExist project outputs to measure traffic flow impacts on metropolitan areas

CAVs (CACC) shows promising results

9. Partial Conclusions

- AVs and CAVs allows lower standstill and safety distance due to its sensors and reaction time
- AVs shows benefits to the traffic flow mainly for higher penetration rates
- AVs show better traffic performance on disturbances (e.g. vehicle breakdown) even for mixed scenarios
- Results can have a high correlation for other big cities in Brazil and worldwide

10. Next Steps

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

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BACKUP

4. Mathematical Models **(CV/CAV)-** CACC is frequently used to model CAVs

CACC: Accelerations of Vehicles

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

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

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

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

a: acceleration in next step of subject vehicle,
$\boldsymbol{a_l}$: acceleration of the leading vehicle
v_s: vehicle speed of subject vehicles
v_l : vehicle speed of leading vehicles
a_{max}: maximum allowed acceleration
a_{min}: maximum allowed deceleration,
k_v and k_s: constant gain greater than zero.

ZHAO & SUN, (2013)

MIXIC: Microscopic Model for simulation of Intelligent Cruise Control

Safe following distance

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

v: current vehicle speed,
d: deceleration capability subject vehicles
d_p: deceleration capability of the leading

Following distance

$$r_{safe} = t_{system} \cdot v \qquad (13)$$

v: subject vehicle speed
t_{system} : time headway → 0,5 seconds if the leading vehicle has CACC function and 1,4 seconds, otherwise.

Van AREM et al., (2006)

MIXIC: Microscopic Model for simulation of Intelligent Cruise Control

Safe speed

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

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

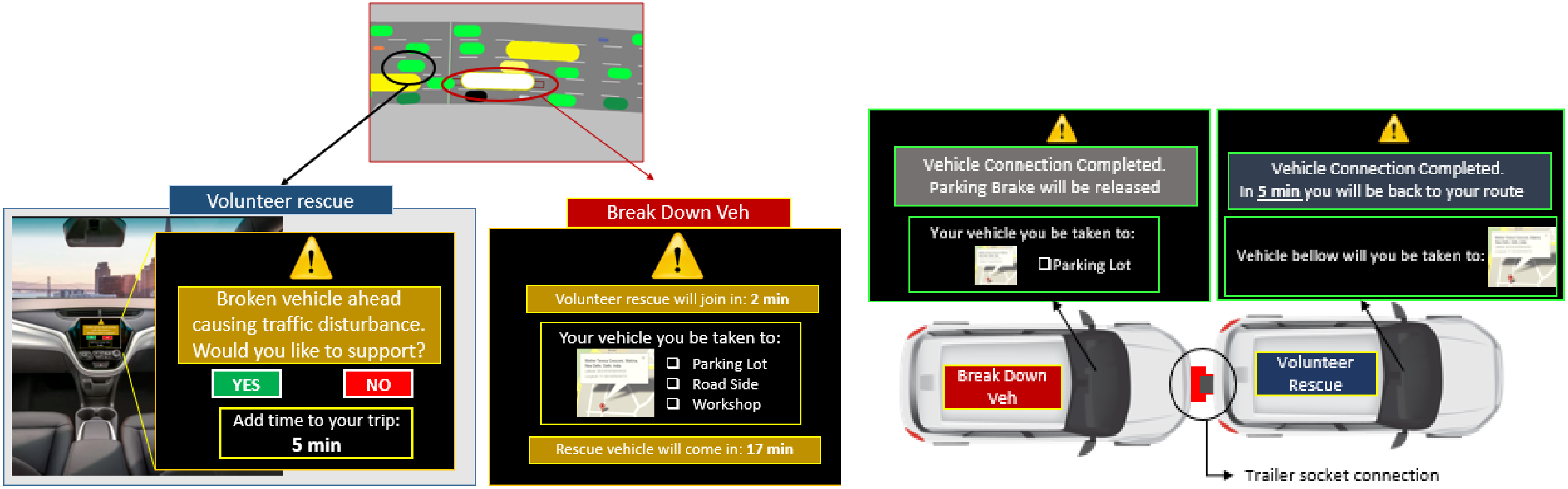
$$v_{max} = \sqrt{-2a_i^{decc}\Delta X} \qquad (15)$$

n : subject vehicle; n-1:leading vehicle;
X_n: position, l_n:length, v_n: vehicle speed, τ: reaction time, a_n^{decc}: maximum deceleration of the subject vehicle vehicle

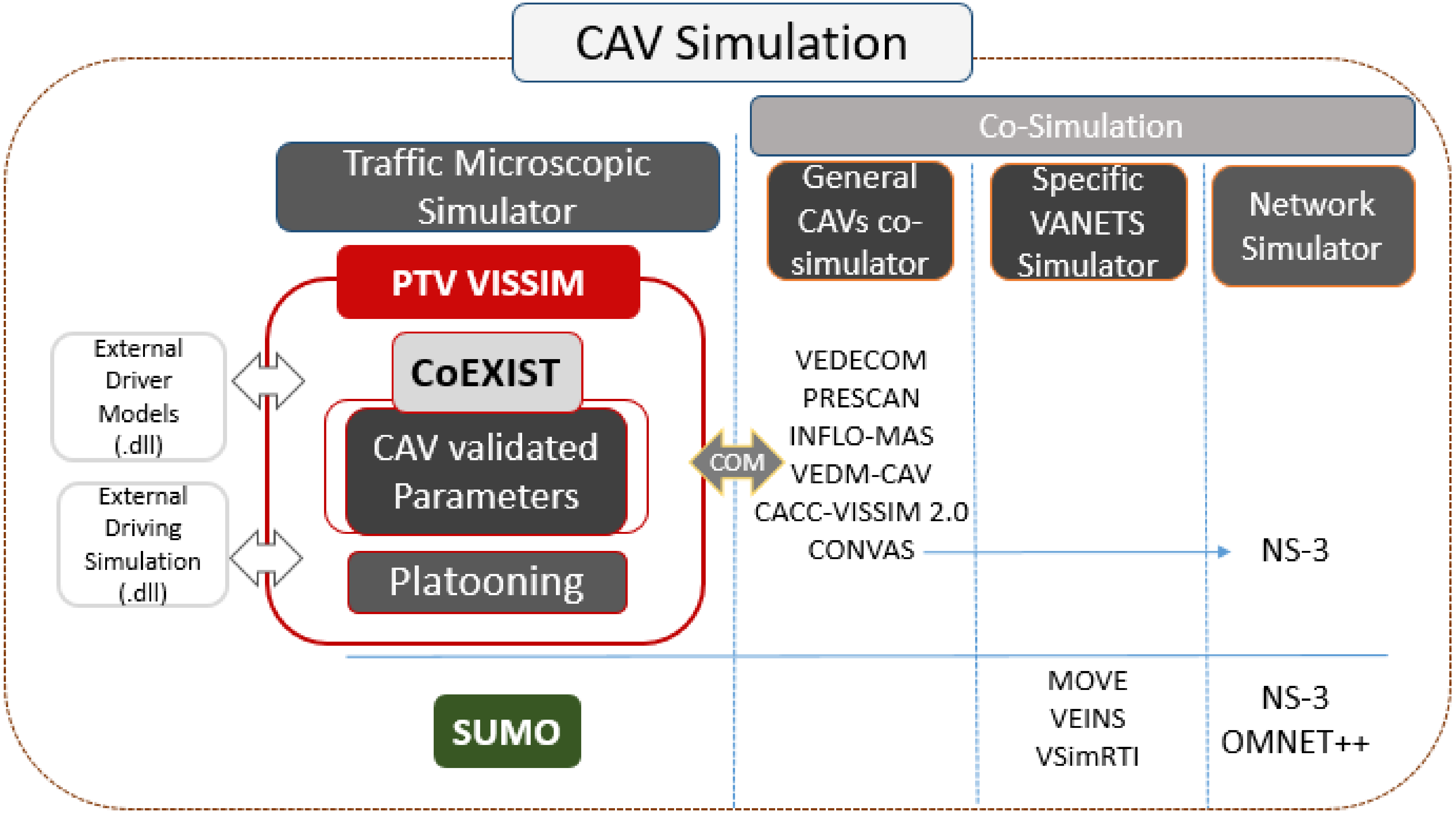
TELEBPOUR & MAHMASSANI (2016)

8.1. Scenarios X.3: Faster disturbance using V2V technologies – to be assessed for final dissertation

Based on V2V technologies for 100% CAVs scenarios: “driver” will be asked for acceptance



5. How to simulate CAVs



Source: Author