Modeling and Impact Assessment Framework for Autonomous Vehicles in Multi-resolution Simulation Models

Workshop on Traffic Simulation and Connected and Automated Vehicle (CAV) Modeling, November 16-18 , 2020

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LEVITATE project

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Main solutions:

1. **Develop the Policy Support Tool (PST).**

2. **Framework to assess the impact of connected and automated transport (CAT)**

Develop an evaluation framework to assess the impact of connected and automated transport (CAT) on all aspects of transport and individual mobility as well as at societal level.

3. **Define methodology to scale-up the microscopic results at city level**

Upscaling of microscopic simulation results to a macroscopic level with respect to various AV impact indicators: traffic congestion, safety, emissions.

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Objective

- **Framework for assessing network-wide impacts of (C)AVs**
- **Model and quantify (C)AV impacts on network performance**
  - Derive network capacities (microscopic simulation)
  - Estimate effect on Passenger Car Unit (PCU) through a functional relationship
  - Forecast macroscopic impacts
- **Equivalence to other traffic flow resolutions**

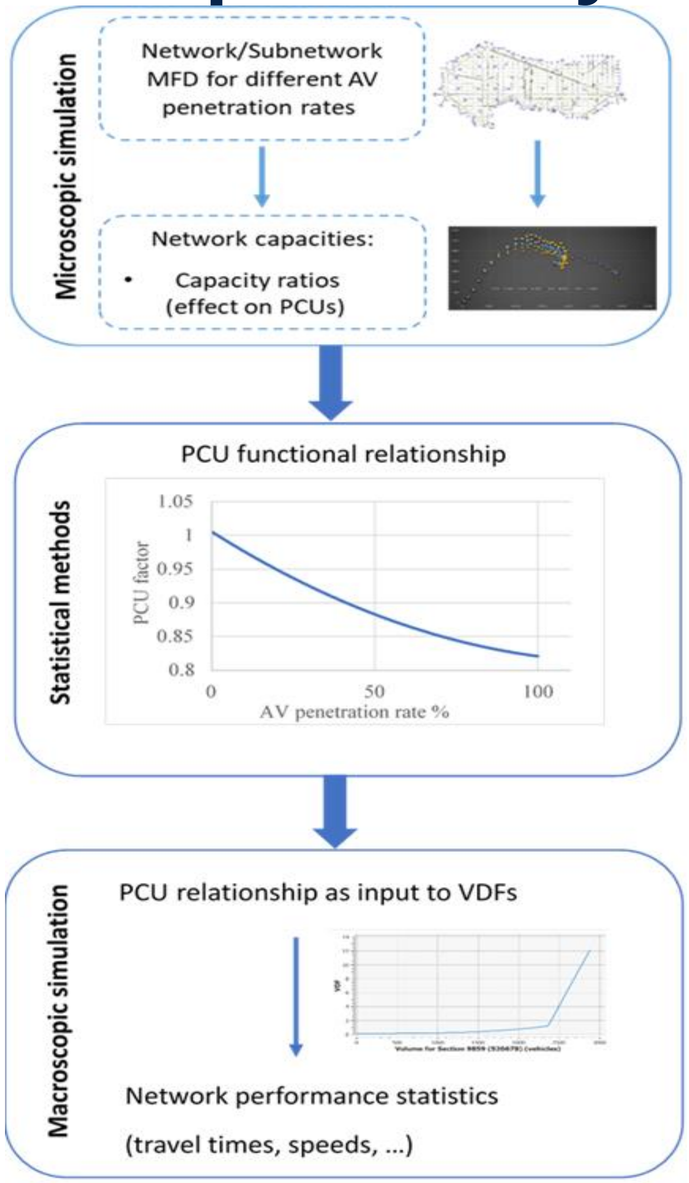
Motivation and expected contribution

- Recent study (CoEXist Horizon 2020: Friedrich et al., 2019) proposed a modeling framework to integrate AVs into existing macroscopic demand models. Extensive combinatorial analysis on disaggregated network elements (e.g. road type, intersection) and demand-supply interactions.
- Not feasible approach for the scope of this work due to the different AV implication aspects, up-scaling requirements, use-cases to be analyzed.
- Need for a **generic and transferable** methodology to derive AV network performance impacts.
- The network **Macroscopic Fundamental Diagram (MFD)** obtained from **microscopic simulations** is utilized to derived capacities:
  - Property of network infrastructure
  - Capacity is invariant when demand changes (in space and time)
- **Scalability:** The derived capacities can be used as aggregate upscaling indicators of microscopic/mesoscopic impacts to macroscopic level.
- **Transferability:** The estimated PCU functional relationship(s) can be used as input to strategic models to forecast the network performance impacts on any network of interest.

Framework for AV impact analysis

Scalability

Transferability



1. Microscopic simulation-based experiments to derive the network capacities through the network Macroscopic Fundamental Diagram (MFD).
2. Statistical analysis for the identification of the effects on the PCUs. Estimation of PCU functional relationship.
3. Use PCU functional relationship as input to the VDFs of macroscopic demand models to forecast impacts on network performance. Inform policy-making for optimal AV share.

1. Microscopic simulation-based analysis

- MFD approach

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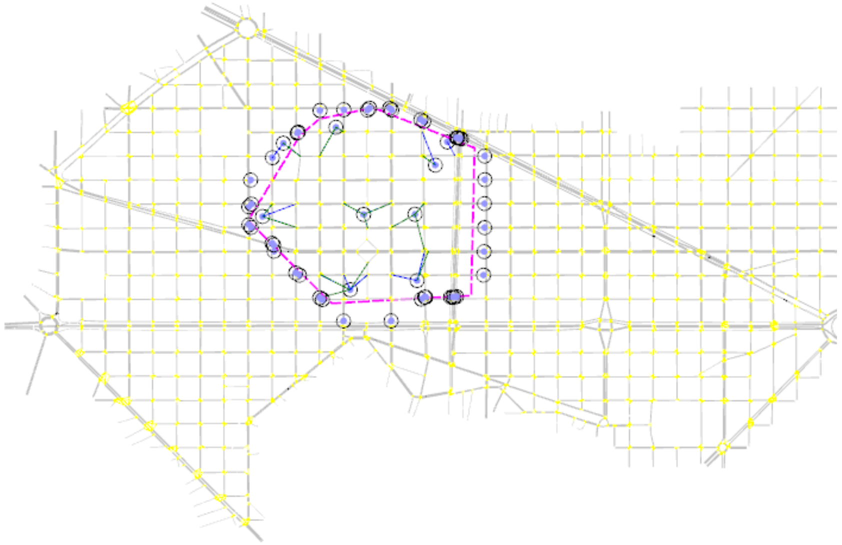
Simulation networks

Barcelona sub-network



- 1570 sections
- 565 signalized intersections.
- 261 x 261 OD matrix
- Demand
  - Duration: 1 hour
  - Trips: 115,151

Bilbao city network

- 1264 sections
- 63 signalized intersections.
- 37 x 37 OD matrix
- Demand
  - Duration: 1,5 hours
  - Trips: 44,068

Experimental design and assumptions

For the scope of this analysis the following assumptions are made:

- Homogeneous demand fleet consisting only of cars in order to identify the capacities for conventional vehicles and AVs
- Mixed-traffic flow is considered with conventional vehicles and various AV penetration rates
- For each scenario, 10 simulation replications with different random seed are conducted

Simulation Scenarios								
Type of Vehicle	1	2	3	4	5	6	7	8
Conventional	100%	80%	60%	50%	40%	20%	10%	0%
Autonomous	0%	20%	40%	50%	60%	80%	90%	100%

Overview of AV parameter assumptions

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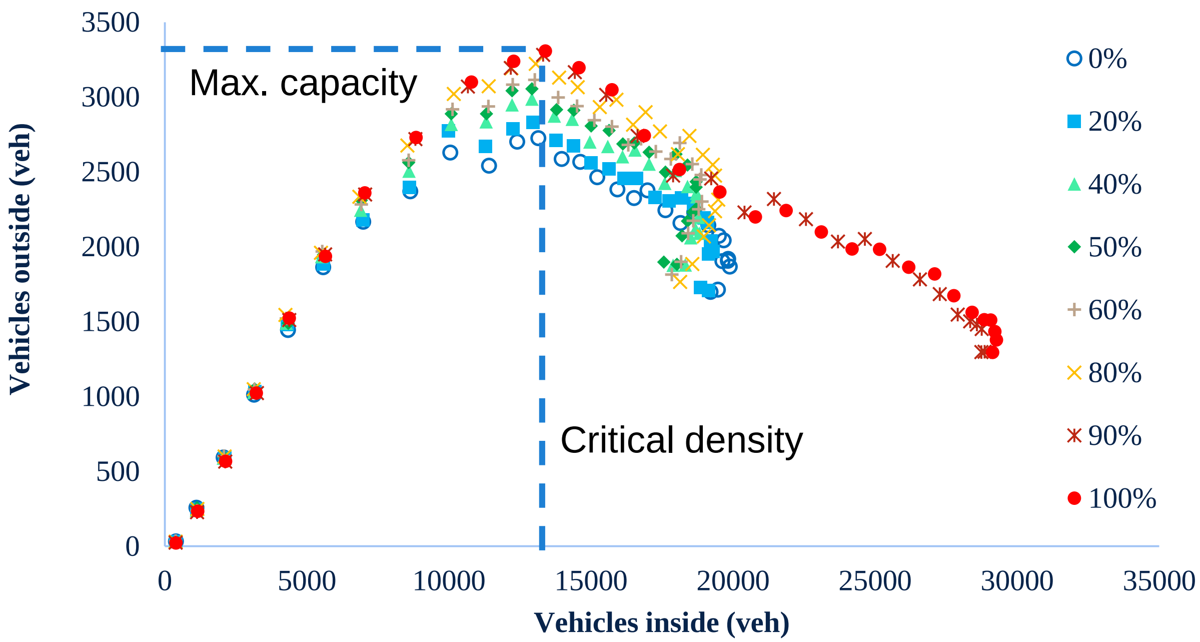
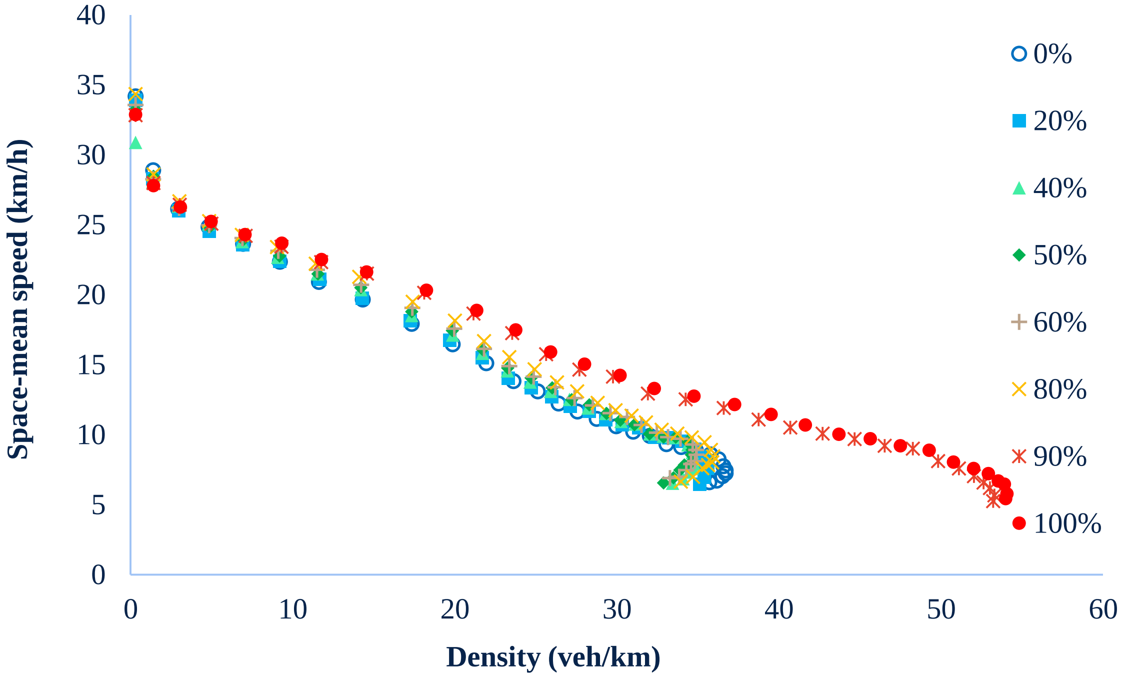
- One AV type is assumed with aggressive behavior compared to conventional vehicles
- No vehicle connectivity is assumed
- Due to the enhanced technological capabilities of AVs the AV impacts are assessed with respect to modified parameter values in the **car-following**, **lane-changing** and **gap acceptance models** in Aimsun Next, which in turn is expected to increase the capacity.

	Car-Following	Lane Selection	Gap-Acceptance in Lane changing	Overtaking	Gap-Acceptance in Giveway
Autonomous Vehicles	Short clearance (shorter headways)	Long clearance	Longer clearance with the leader during lane changing, compared to conventional cars.	Lower percentage of the desired speed of a vehicle below which the vehicle may decide to overtake	Lower safety gap that determines the time spent by a vehicle waiting for a gap to move at a priority junction.

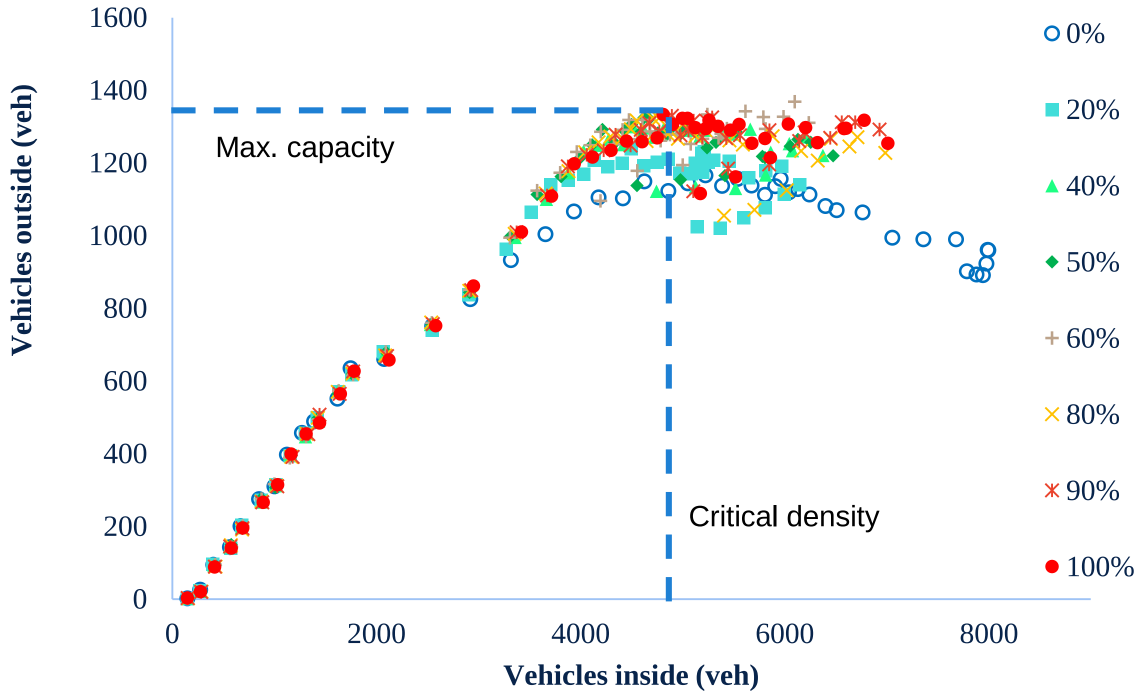
Barcelona results (average for 10 replications)

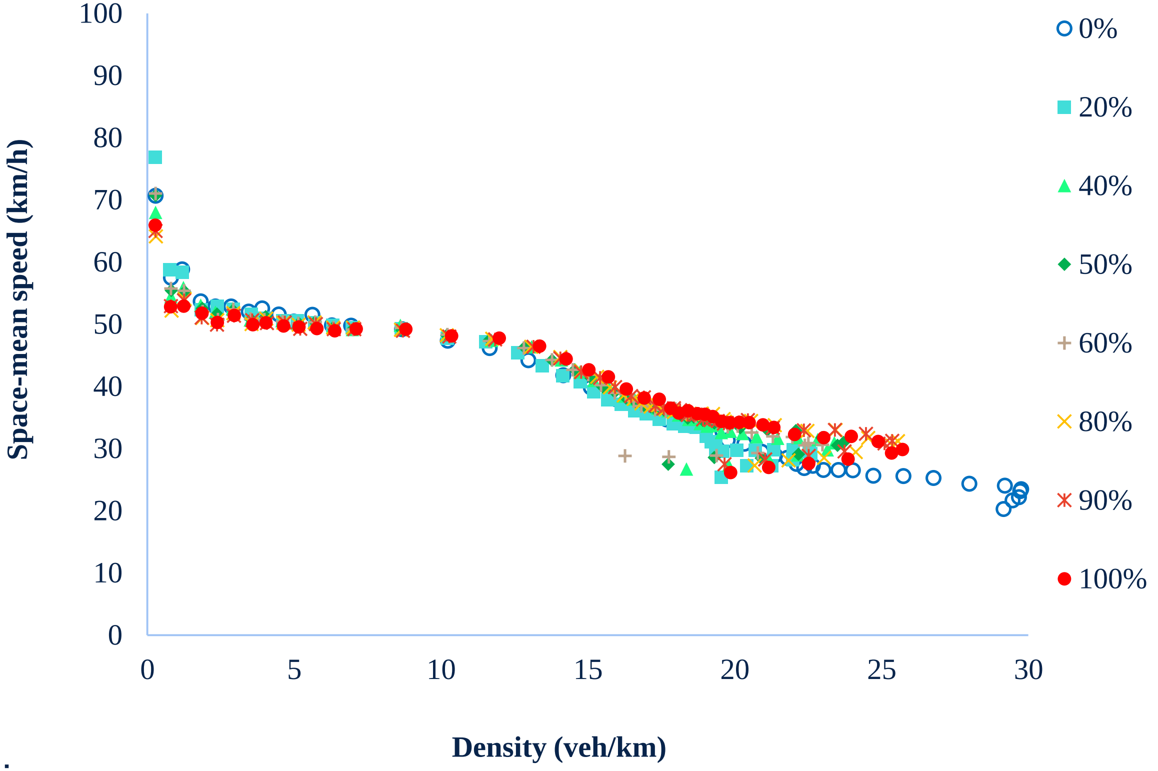




- Network throughput increases as AV penetration rate increases
- Capacity increase almost invariant above 80% AV penetration rate
- Average network densities increase for high AV penetration rates
- Space-mean speeds remain on average higher for AVs for the same density values

Bilbao results (average for 10 replications)





- Network throughput increases as AV penetration rate increases
- Capacity increase stabilizes above 60% AV penetration rate
- Network not severely congested
- No significant variation in average space-mean speeds and densities

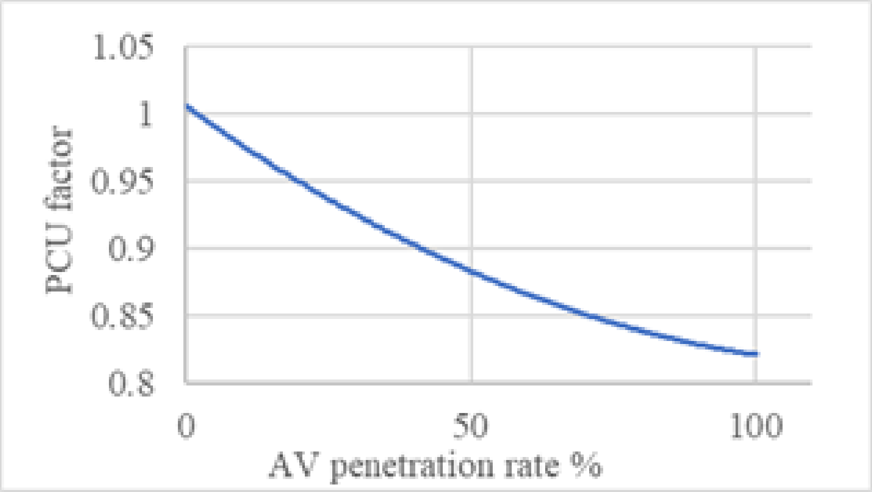
2. Statistical analysis

- Estimate PCU functional relationship

Effects on PCU on VDFs

- A polynomial function is used as an example to derive the effect on PCU factors based on the capacities:

$$PCU = \beta_0 + \beta_1 p_{AV} + \beta_2 p_{AV}^2$$



Where

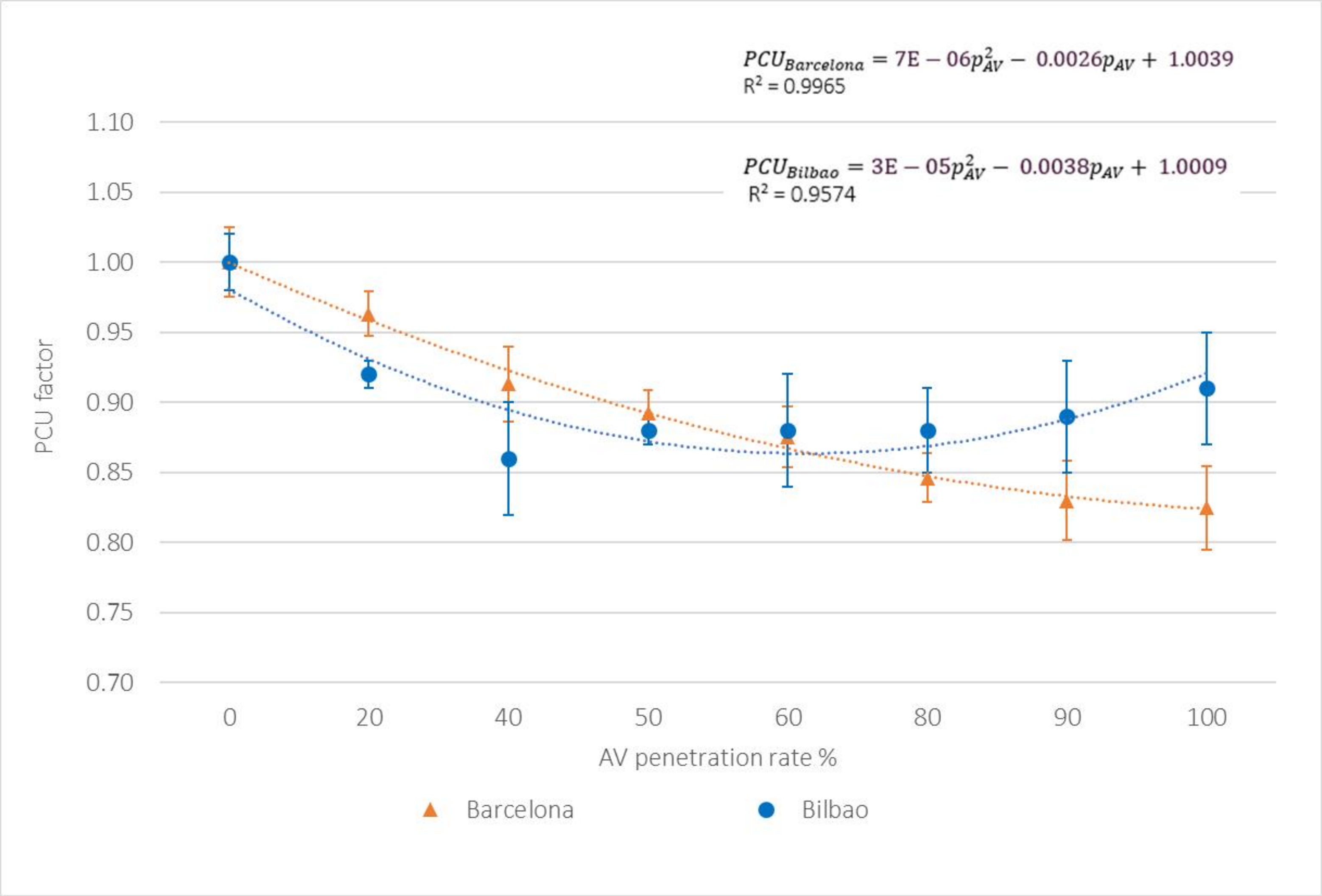
- p_{AV} is the AV penetration rate
- The estimated PCU factors derived as follows:

$$PCU = PCU_{CV} \frac{capacity_{human}}{capacity_{AV}}$$

- PCU_{CV} is the PCU factor for conventional vehicles and is assumed to be equal to 1.0
- US Bureau Public Roads (BRP) function: $t = t_{ff}\left(1 + \alpha \cdot \left(\frac{v \cdot f_{PCU}(p_{AV})}{c}\right)^b\right)$

Where t is the section travel time, t_{ff} the free-flow travel time, volume-to-capacity ratio $\frac{v}{c}$ $f_{PCU}(p_{AV})$ the PCU function depending on the AV penetration rate p_{AV}, and two parameters α and b

Estimated regression functions



- Similar trend of PCU factors across the two networks

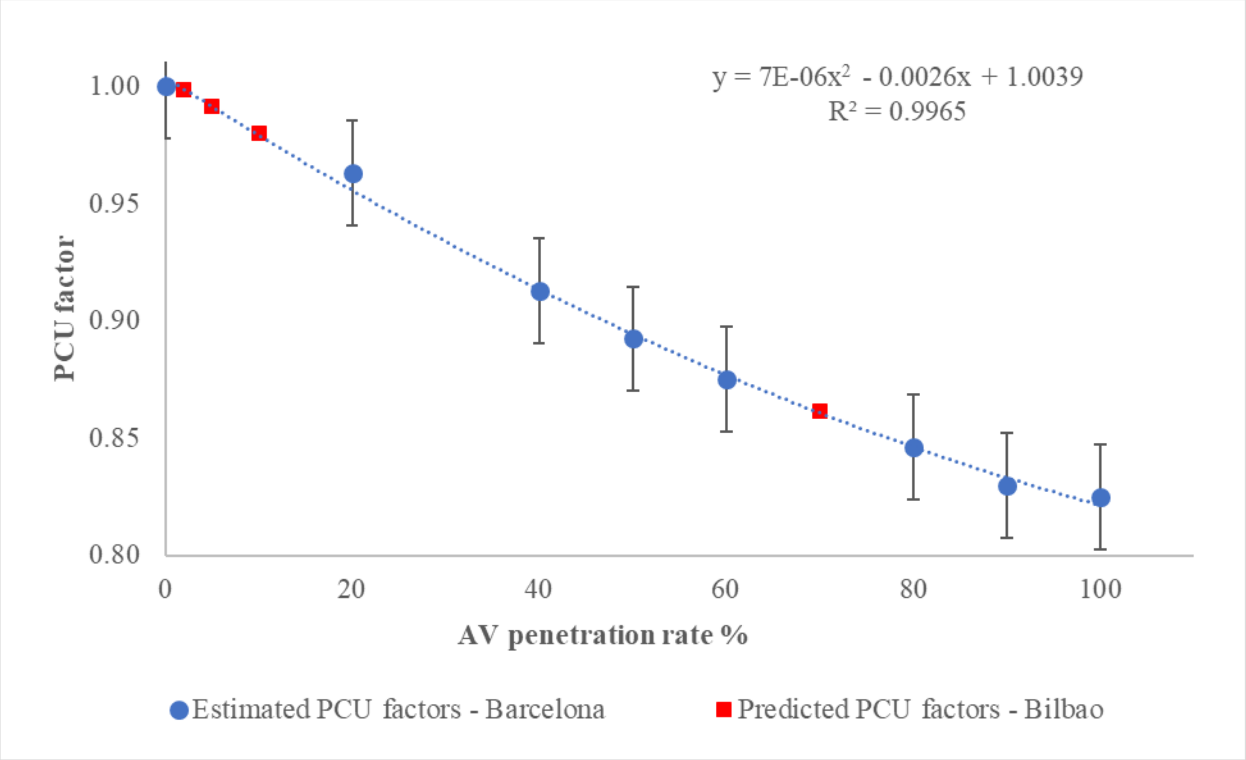
Regression models

	Coefficients		Standard Error		tStat		P-value		Lower 95%	Upper 95%	Lower 95%	Upper 95%
	Barcelona	Bilbao	Barcelona	Bilbao	Barcelona	Bilbao	Barcelona	Bilbao	Barcelona		Bilbao	
Intercept	1.004	1.001	0.00	0.01	250.71	94.64	0.00	0.00	0.987	1.023	0.97	1.03
p_{AV}	-0.003	-0.004	0.00	0.00	-14.70	-8.32	0.00	0.00	-0.004	-0.002	-0.01	0.00
p_{AV}^2	0.000	0.000	0.00	0.00	4.50	6.17	0.01	0.00	0.000	0.000	0.00	0.00

- Statistically significant regression coefficients for 95% confidence level for both networks

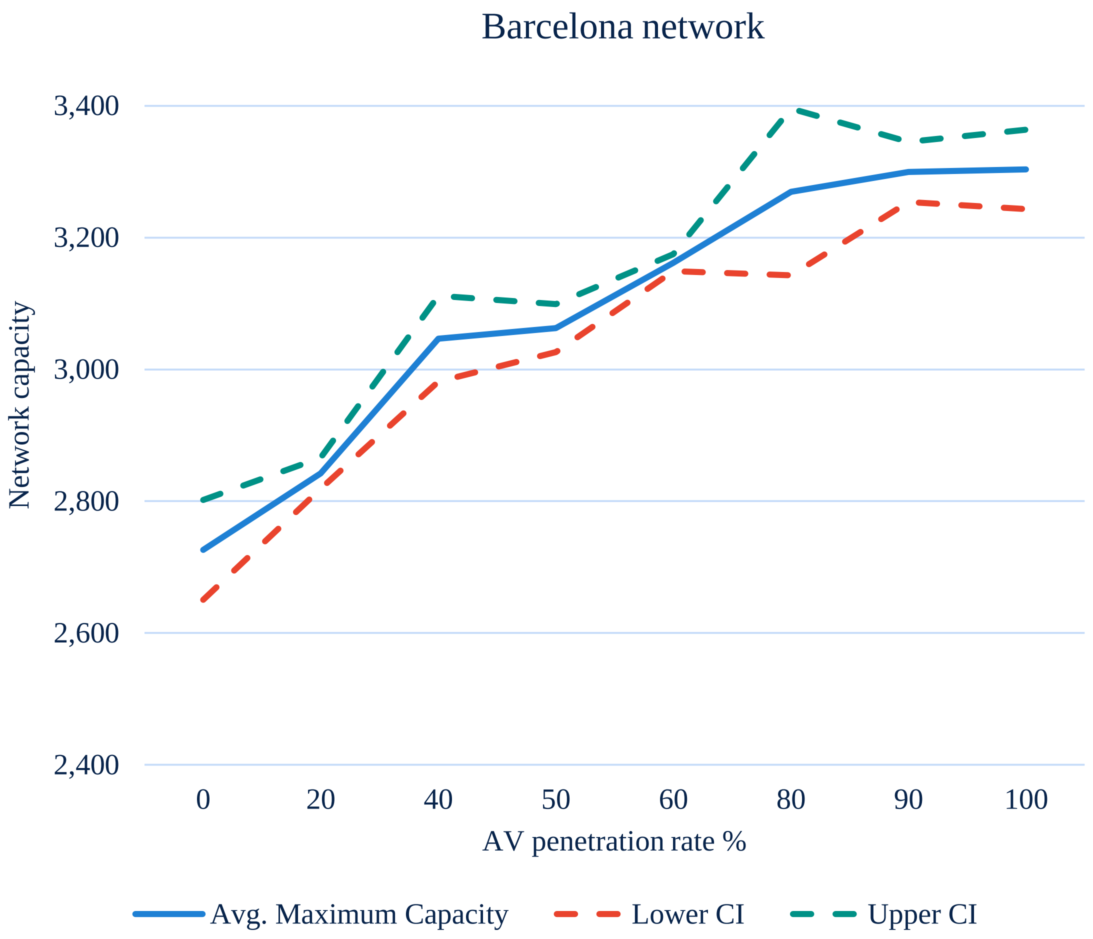
External validation of PCU function

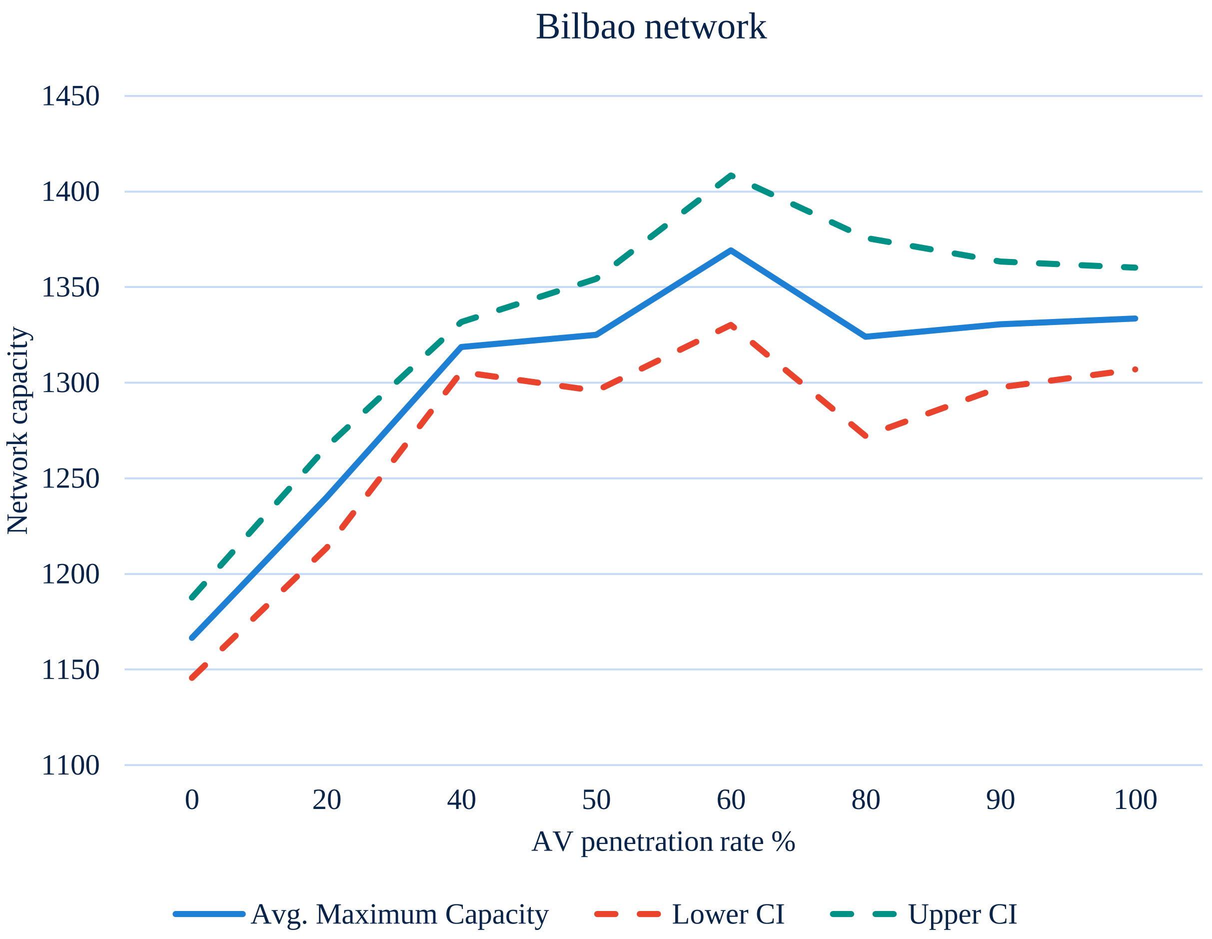
- The Barcelona PCU function is validated using the Bilbao network
- PCUs are estimated using the functional relationship for new penetration rates not included in the original data set
- The PCUs for the new AV penetration rates of another network (Bilbao) are calculated through simulation (via capacities) and compared against the estimated ones



New AV share % points	Estimated PCU	Simulation results PCU (st. dev.)
2	1.00	1.00 (0.04)
5	0.99	0.99 (0.02)
10	0.98	0.97 (0.03)
70	0.86	0.87 (0.02)

Confidence intervals (95% level)



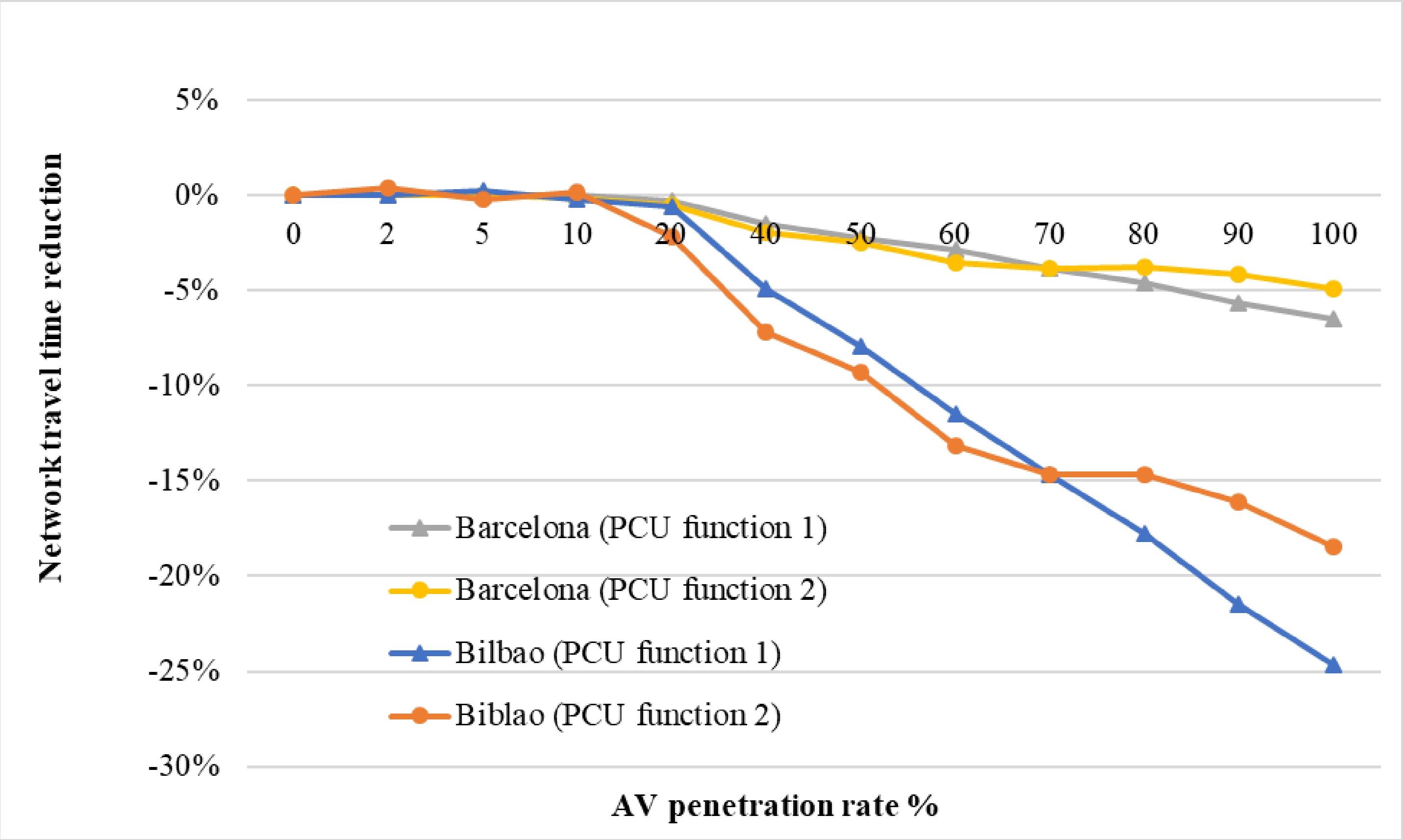


3. Macroscopic network performance impacts

- Forecast impacts using PCU functional relationship in VDFs

Macroscopic network performance impacts

Forecasting macroscopic network performance impacts is conducted using VDFs as a function of the PCU factors and AV penetration rates.



- Static traffic assignment conducted for Barcelona and Bilbao using VDFs as a function of PCU factors and for two relationships
  - function 1: Barcelona regression line
  - function 2: Bilbao regression line
- Consistent trend in terms of total network cost reduction for both networks
- Non-parametric Mann-Whitney U indicated no significant difference between the functions for 95% confidence level (H_0: $equal\ effect\ of\ PCU\ functions$)
- Absolute cost reduction depends on the network itself (route choice options, demand, etc.)

Equivalence to multi-resolution simulation models

- Identification of equivalent parameter relationships that affect the MFD in mesoscopic models

Equivalence to other traffic flow resolutions

Fundamental Diagrams from Gipps car-following model

Previous sensitivity analysis based on conventional vehicles showed that the equivalence between microscopic models, at equilibrium, and mesoscopic models is reached when the **reaction time (RT)** of the mesoscopic model is **1.5 times** the RT of microscopic model:

$$Headway(s) = \Delta X / V = 1.5 \cdot RT + L$$

Where ΔX the distance of the vehicle's front bumper and the preceding vehicle's front bumper, V the vehicle speed, L the effective length of the vehicle

- Flow (veh/hr) = 3600/Headway = $\frac{3600}{\Delta X/V} = \frac{3600}{1.5\,\tau + L/V}$
- Density (veh/km) = Flow/(3.6*V) = $\frac{1000}{\Delta X} = \frac{1000}{1.5\,V\tau + L}$
- At V = 0 : Density = Jam Density = 1000/L
  Flow = 0
- At V = Vfree flow : Flow = Capacity = $\frac{3600}{1.5\,\tau + \frac{L}{Vff}}$
  Density = Critical Density = $\frac{1000}{1.5\,Vff\tau + L}$

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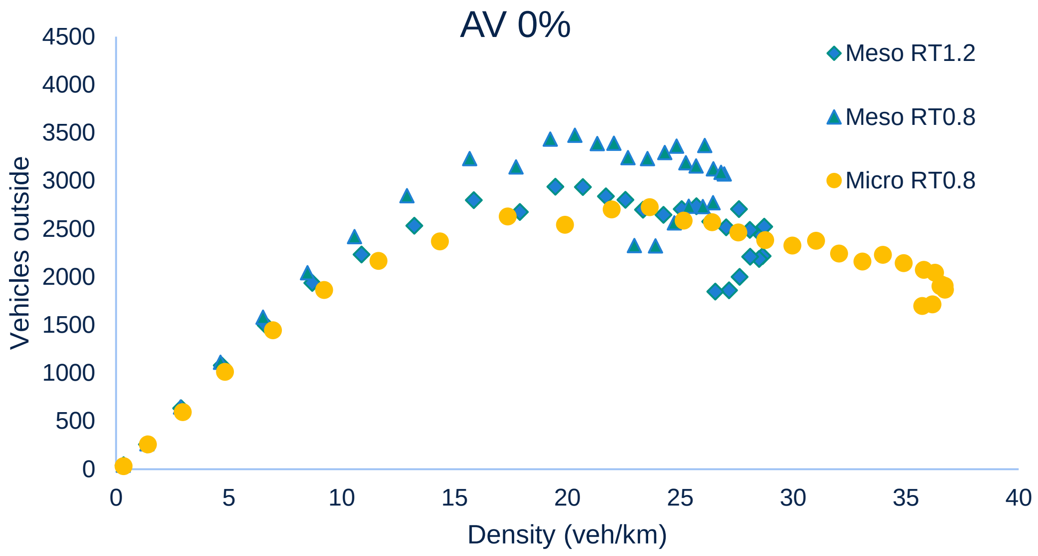
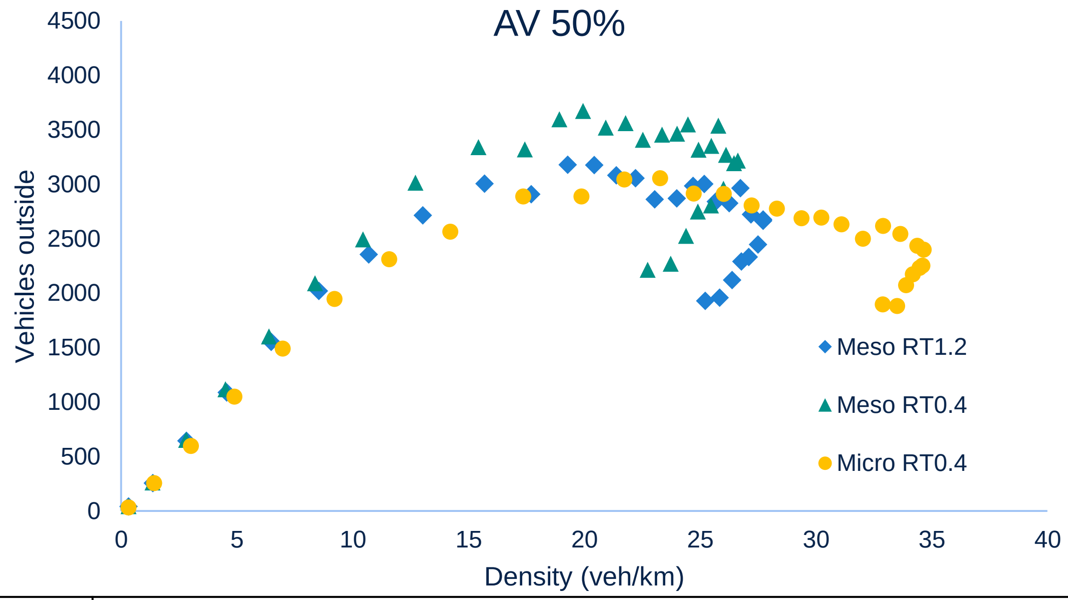
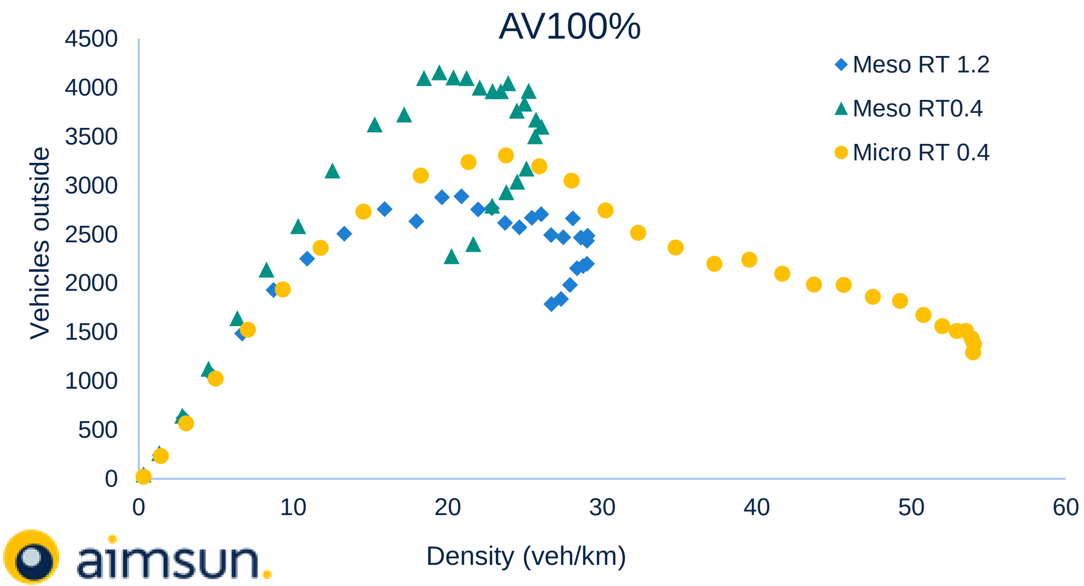
Preliminary analysis







	Maximum capacity (Meso equivalence to micro)		
AV share %	Micro ($RT_{AV} = 0.4, RT_{CV} = 0.8$)	Meso ($RT_{AV} = 1.2, RT_{CV} = 1.2$)	Meso ($RT_{AV} = 0.4, RT_{CV} = 0.8$)
0	2726	2939 (1.1)	3473 (1.3)
50	3055	3180 (1.0)	3672 (1.2)
100	2887	3306 (1.1)	4158 (1.4)

Conclusion

- A **general framework** is proposed to evaluate the network performance implications of (C)AV in urban transport networks.
- Preliminary **PCU functional relationships** are estimated → input to macroscopic demand models for the upscaling of the AV impacts
- **Positive effects of AVs** on the traffic characteristics, specifically, the network capacity increase as the AV penetration rate increases (attributed to lower reaction times).
- Consistency in the trend of the **effect of AVs on the PCU factors** as a function of the AV penetration rates
- Consistency in terms of **total network cost reduction** with the PCU functional relationships
- Current work continues the determination of the set of parameters to model AVs and derive systematically the **equivalent relationships** for the integration **to multi-resolution models**

Thank you!

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