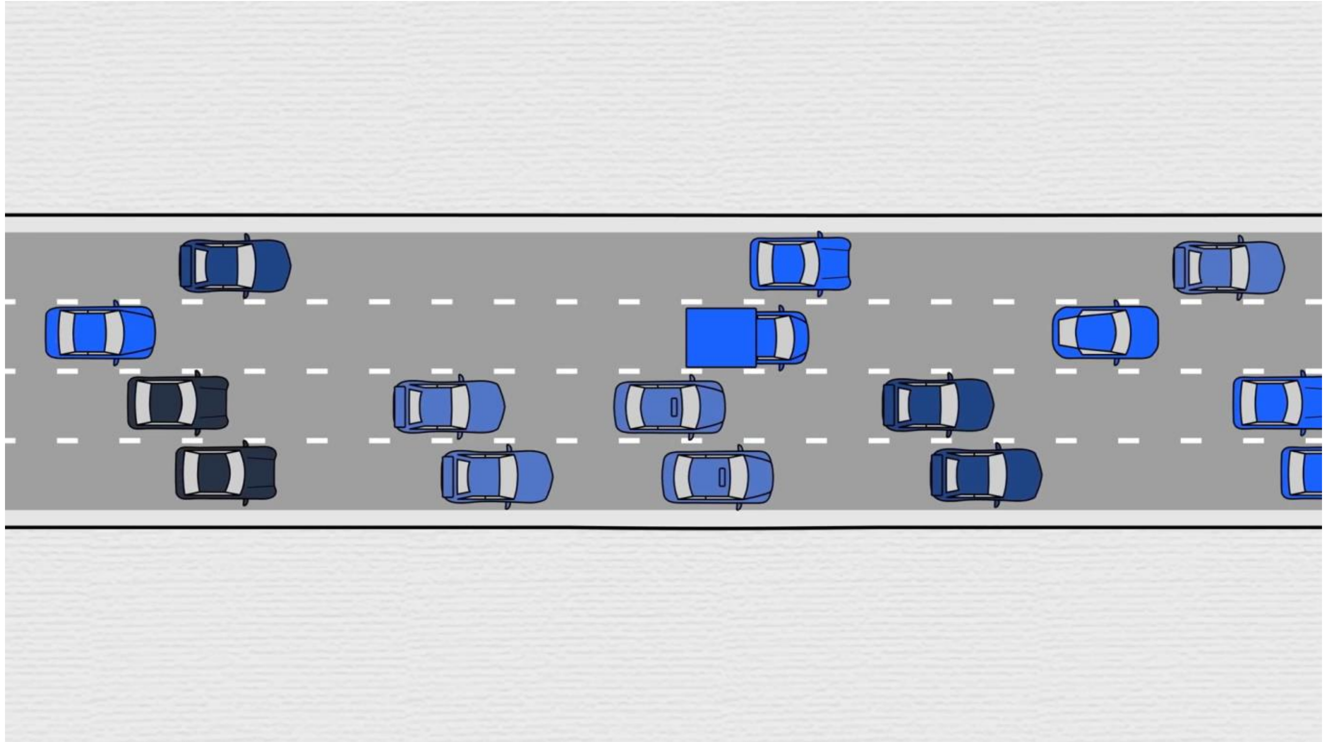
Macroscopic Modelling and Control of Mixed Traffic



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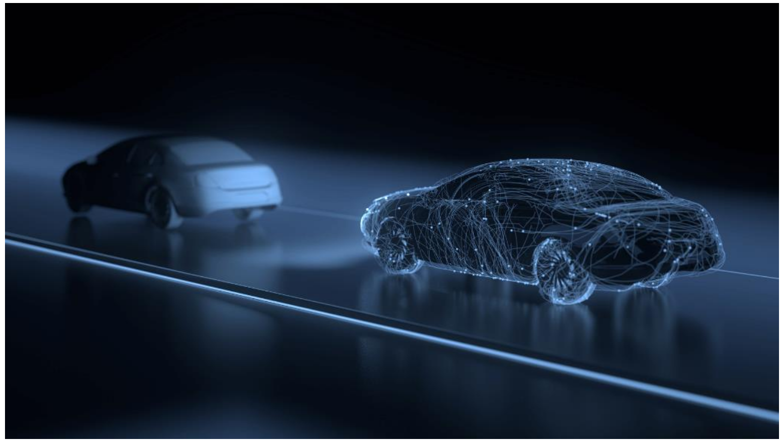
Generalization of the problem

- Traffic flow dynamics
- Macroscopic models
- Connected and Autonomous Vehicles (CAVs).



- Existing models and challenges.

Objectives

The objectives of this study are to formulate Second Order Traffic Model (SOTFM) for Mixed-Traffic, can be used to:

- Describe the dynamics of Mixed-Traffic in the presence of CAVs and Human-Driven Vehicles (HDVs).

Consequently:

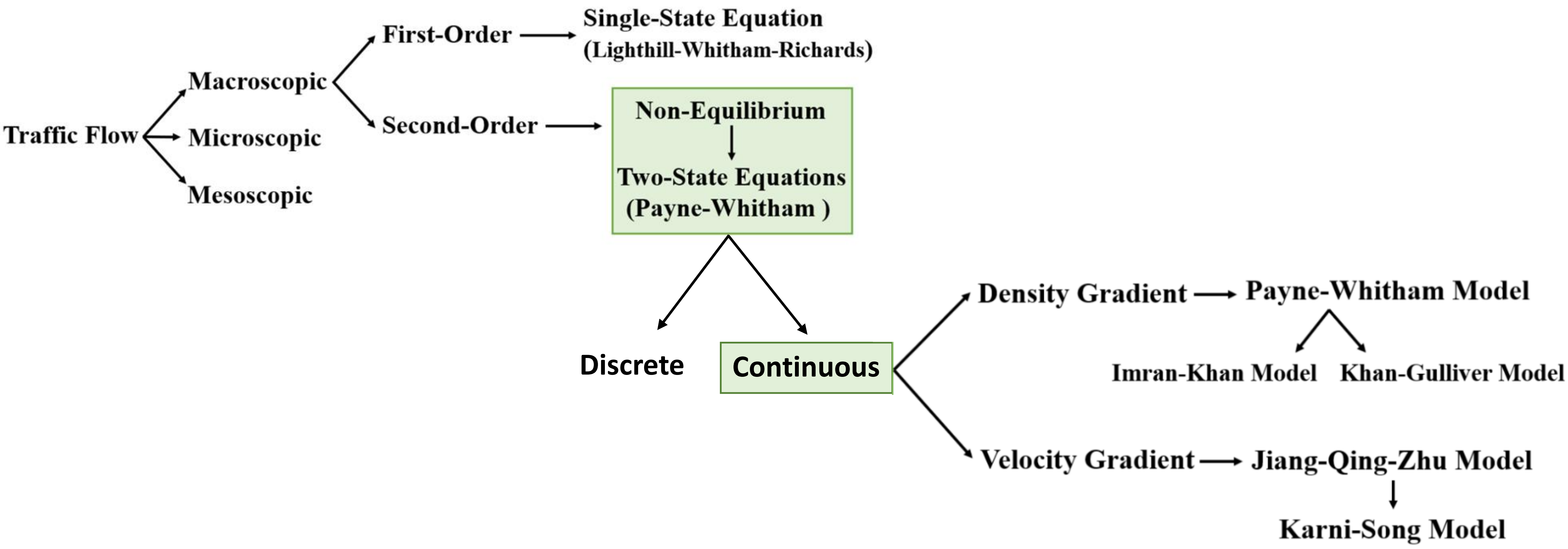
- Analysis of traffic flow.
- Traffic control applications.

Understanding of the existing macroscopic models

Aims:

- Expansion of model tree
- Performance assessment
- Computational efficiency

Model Tree



- **Density gradient:** Presumption of forward condition is based on spatial changes in density
- **Velocity gradient:** Presumption of forward condition is based on spatial changes in velocity

The second-order macroscopic models

- $$\begin{cases} \frac{\partial\rho(x,t)}{\partial t} + \frac{\partial(v(x,t).\rho(x,t))}{\partial x} = 0, & \dots (1) \\ \frac{\partial v(x,t)}{\partial t} + (v(x,t) - c_0)\frac{\partial v(x,t)}{\partial t} = \frac{V(\rho(x,t)) - v(x,t)}{T}. & \dots (2) \end{cases}$$

- JQZ model
- Uniform characterization

$\boldsymbol{v(x,t)}$: velocity; $\boldsymbol{\rho(x,t)}$**:** density; $\boldsymbol{c_0}$**:** velocity constant; $\boldsymbol{V(\rho(x,t))}$: Velocity-Density relationship; $\boldsymbol{T}$: Relaxation time;

JQZ: Jiang, Qing and Zhu.

Simulation setting

- **Ground truth:** Simulation of Urban Mobility (SUMO)
- **Study Area:** A 20,000 m highway with closed boundary conditions
- **Initial traffic conditions (SUMO and SOTFMs):**

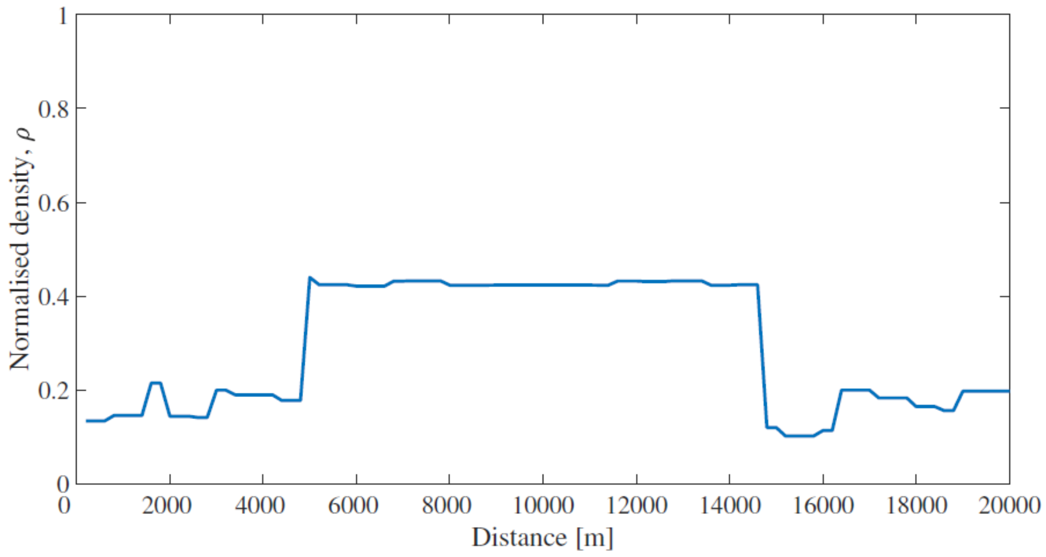


Figure 1: Initial density distribution – scenario I

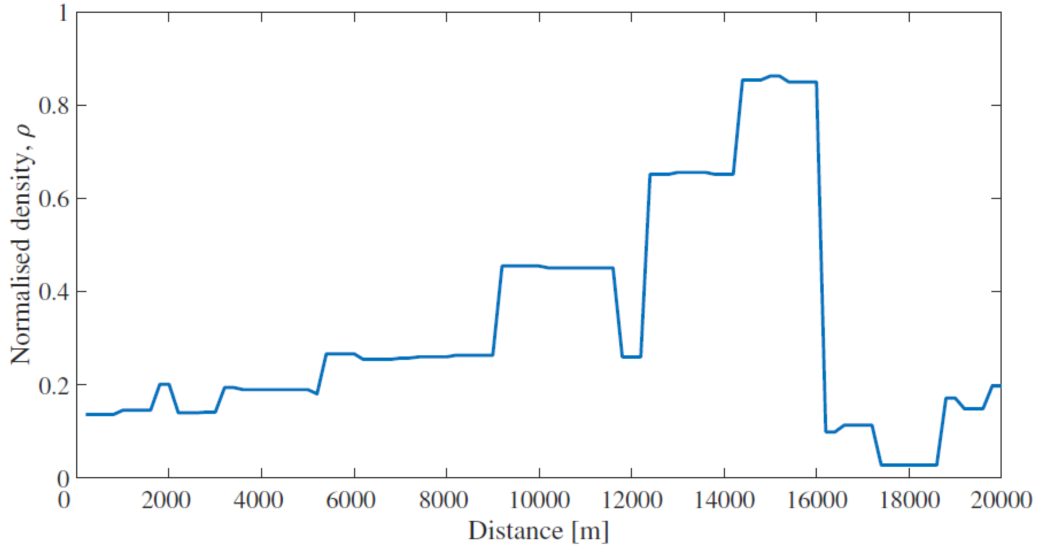


Figure 2: Initial density distribution - scenario II

- **Discretization methods for SOTFMs:**
  - Density gradient models: First-Order Centered (FORCE) scheme
  - Velocity gradient models: Finite difference (conserved) scheme

Performance Assessment

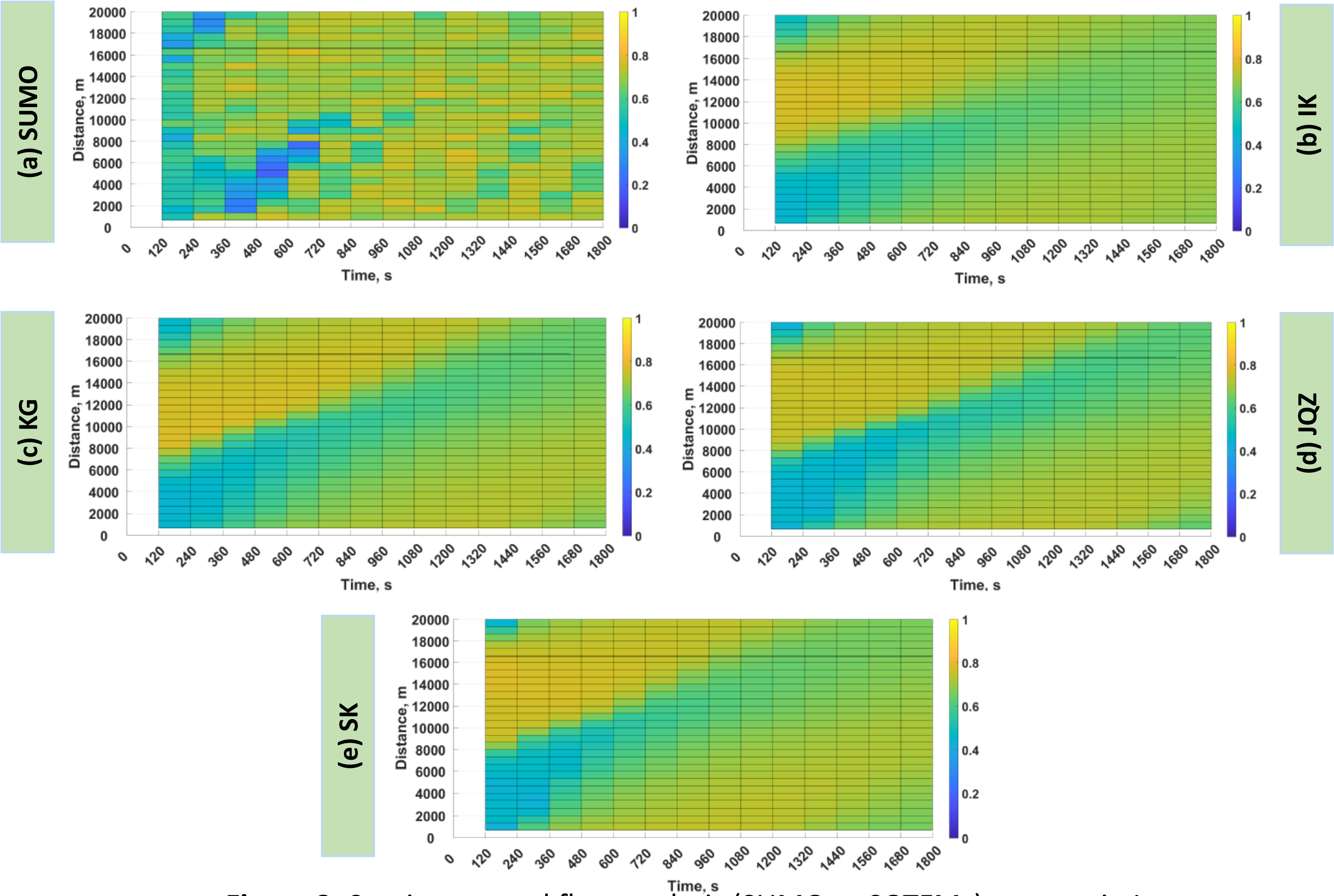


Figure 3: Spatiotemporal flow analysis (SUMO vs SOTFMs) – scenario I.

Performance Assessment

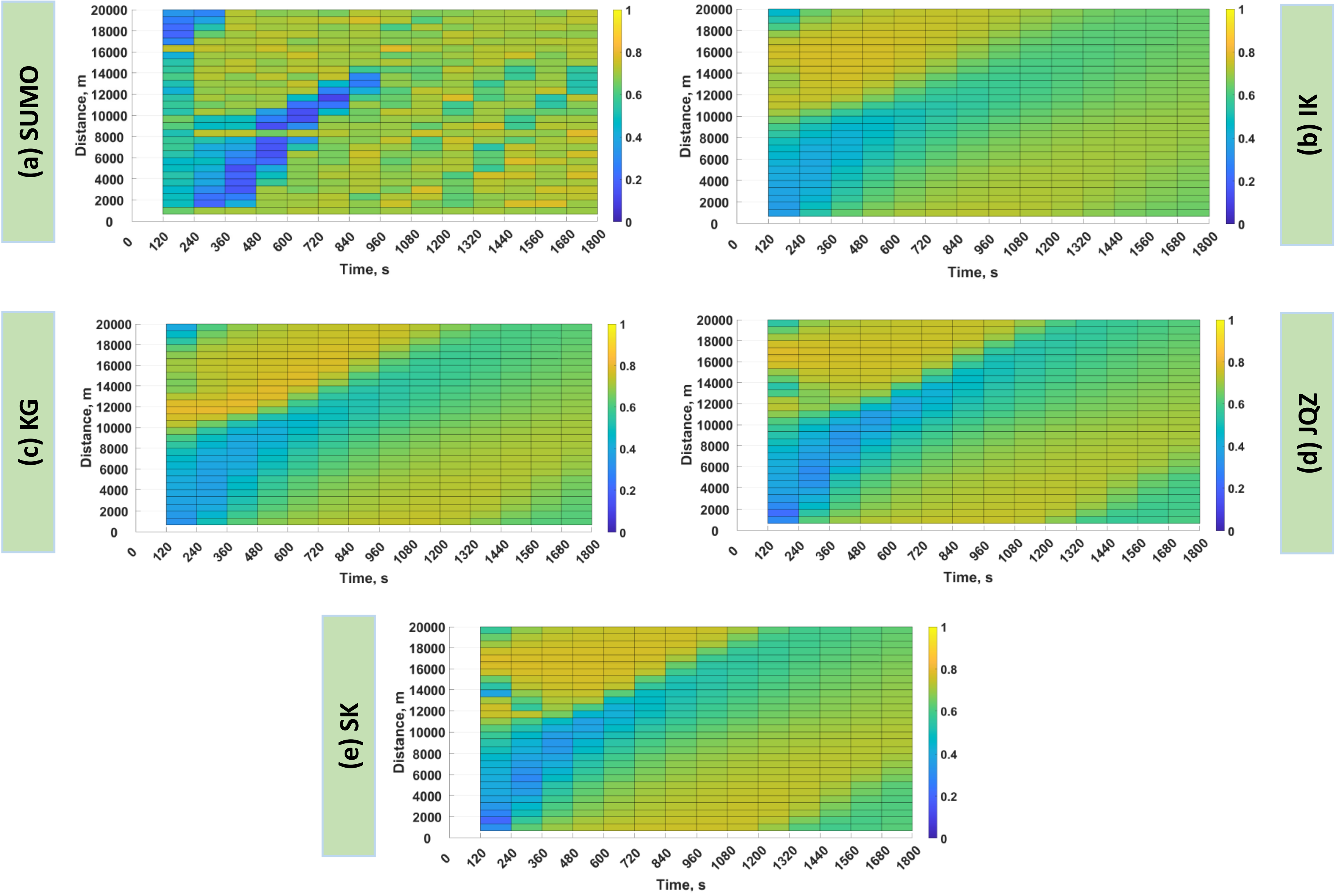


Figure 4: Spatiotemporal flow analysis (SUMO vs SOTFMs) – Scenario II.

Performance Assessment

Density gradient (IK, KG)

Velocity gradient (JQZ, SK)

Table 1: Summary

Model	PI (I/II)	Parameter	Admissible Range	Calibrated Value (I/II)	Unit
IK	0.078 / 0.10	b	0.1 – 1	0.75 / 0.95	[]
		v_f	28 - 32	30.72 / 30.78	m/s
		τ	5 – 20	5.28 / 19.62	s
		τ_h	1 – 20	17.23 / 13.87	s
KG	0.083 / 0.10	τ_r	0.7 – 1.7	0.78 / 0.73	s
		v_f	28 - 32	30.70 / 30.68	m/s
		τ	5 – 20	5.12 / 19.42	s
		s_{st}	1 – 5	3.15 / 4.42	m
JQZ	0.091 / 0.125	c_0	5 - 25	24.81 / 15.56	m/s
		v_f	28 – 32	30.09 / 30.21	m/s
		τ	5 – 20	19.65 / 19.95	s
SK	0.089 / 0.12	s_{min}	1 – 6	5.51 / 4.51	m
		v_f	28 – 32	30.09 / 30.27	m/s
		τ	5 – 20	19.66 /19.48	s
		τ_r	0.7 – 1.7	0.78/0.99	s
		L_c	7 – 10	9.18 / 7.40	m

PI: Performance Index; **IK:** Imran and Khan; **KG:** Khan and Gulliver; **JQZ:** Jiang, Qing and Zhu; **SK:** Song and Karni

Computational Efficiency

Table 2: Computational efficiency

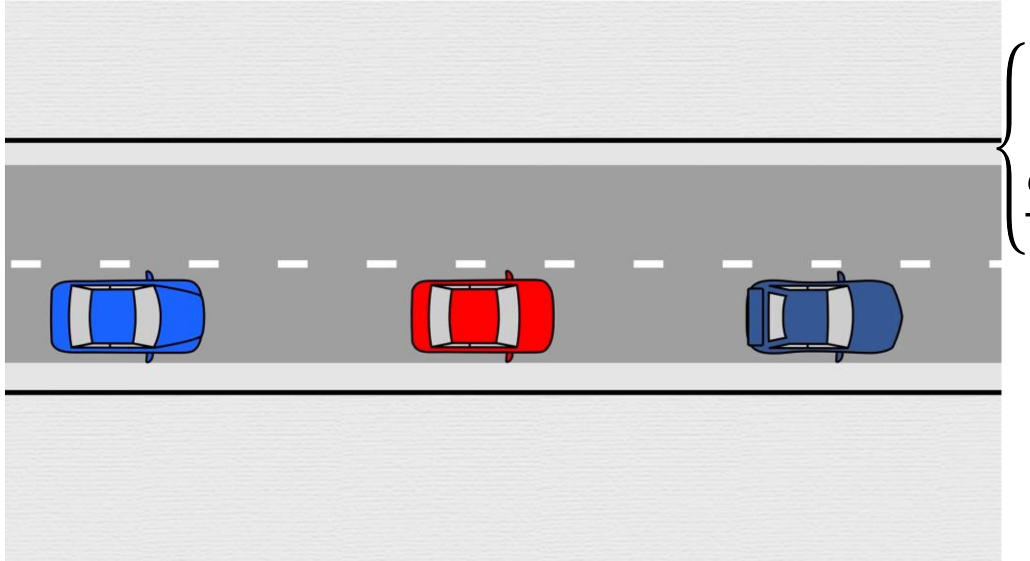
Model	Average Simulation Time [s] (I/II)	Std [s] (I/II)	Coefficient of Variation (I/II)
IK	0.4376 / 0.5773	0.1553 / 0.2732	0.3548 / 0.3548
KG	0.3998 / 0.4121	0.0712 / 0.0744	0.1780 / 0.1780
JQZ	0.0013 / 0.0013	$2.70 \cdot 10^{-4}$ / $2.76 \cdot 10^{-4}$	0.2125 / 0.2125
SK	0.0014 / 0.0015	$3.08 \cdot 10^{-4}$ / $3.17 \cdot 10^{-4}$	0.2126 / 0.2126

Characterization of Mixed Traffic

Aims:

- New model for mixed traffic.
- Calibration and validation
- Practical utility in traffic analysis
- Application in traffic control

Characterization of Mixed-Traffic



$$\begin{cases} \dfrac{\partial \rho(x,t)}{\partial t} + \dfrac{\partial (v(x,t).\rho(x,t))}{\partial x} = 0, \\ \dfrac{\partial v(x,t)}{\partial t} + (v(x,t) - [\zeta_* + \varphi_*])\dfrac{\partial v(x,t)}{\partial x} = \dfrac{V(\rho(x,t)) - v(x,t)}{T}. \end{cases} \quad ..(7)$$

Table 3: Model parameters

v	Velocity
ρ	Density
$V(\rho(x,t))$	Equilibrium Velocity
T	Relaxation Time of each class
H_a	Headway of HDVs
H_b	Headway of CAVs
ζ_*	Reaction Velocity of HDVs
φ_*	Reaction Velocity of CAVs
τ_r	Reaction time
τ_h	Harmonization time
d_m	Maximum deceleration

$$H_a = L + \frac{v(x,t)^2}{2d_m(HDV)} + (v(x,t).(\tau_r + \tau_h)_{HDV}). \dots (3)$$

$$\zeta_* = (1-\sigma)\frac{H_a}{\tau_a}, \dots (4)$$

$$H_b = L + \frac{v(x,t)^2}{2d_m(HDV)} + (v(x,t).(\tau_r + \tau_h)_{CAV}). \dots (5)$$

$$\varphi_* = (\sigma)\frac{H_b}{\tau_b}, \dots (6)$$

Simulation settings

- **Ground truth:** SUMO
- **Study area:** Dublin motorway (M-50), IE [1].
- **Data:** Historical traffic data (Transport infrastructure Ireland) based on conventional traffic [2].
- **Corridor length:** 11 kms

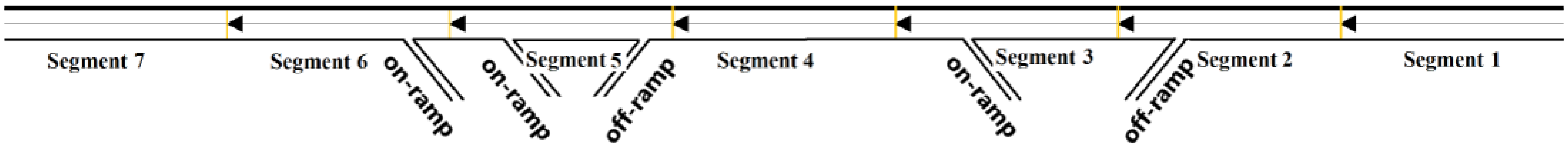


Figure 5: Representation of the motorway corridor

- **Discretized model:**

$$\begin{cases} \rho_i^{n+1} = \rho_i^n + \frac{\Delta t}{\Delta x}\left(\rho_i^n(v_i^n - v_{i+1}^n)\right) + \frac{\Delta t}{\Delta x}(v_i^n(\rho_{i-1}^n)), \dots (8) \\ \text{if } v_i^n \leq [\zeta_* + \varphi_*]:\ v_i^{n+1} = v_i^n + \frac{\Delta t}{\Delta x}([\zeta_* + \varphi_*] - v_i^n)(v_{i+1}^n - v_i^n) + \frac{\Delta t}{T}(V(\rho_i^n) - v_i^n), \dots (9) \\ \text{else: } v_i^{n+1} = v_i^n + \frac{\Delta t}{\Delta x}([\zeta_* + \varphi_*] - v_i^n)(v_i^n - v_{i-1}^n) + \frac{\Delta t}{T}(V(\rho_i^n) - v_i^n). \dots (10) \end{cases}$$

[1] https://github.com/maxime-gueriau/ITSC2020_CAV_impact
[2] https://traffic.tii.ie/

Calibration of the Fundamental Diagram

$$v(\rho(x,t)) = v_f . \exp[\frac{-1}{c}(\frac{\rho(x,t)}{\rho_{cr}})^c] \quad \text{... (11)}$$

v_f: free flow velocity; ρ_{cr}: critical density; c: shape factor

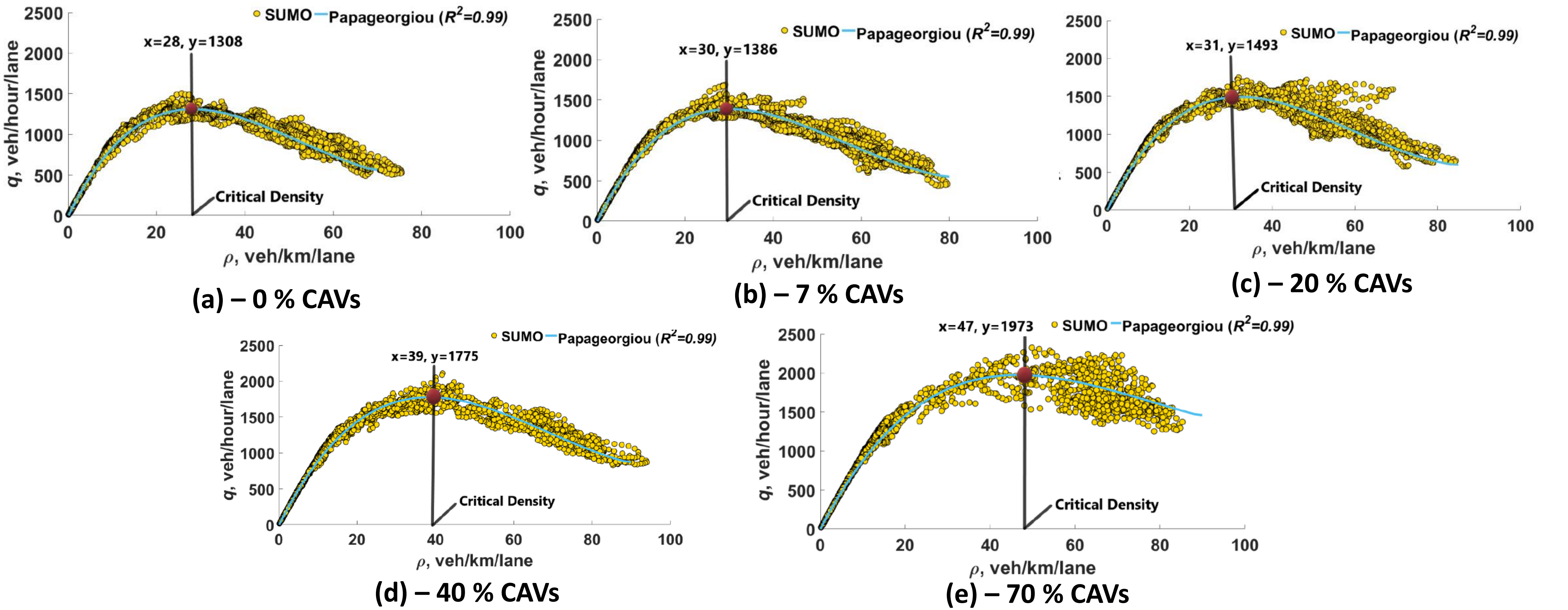


Figure 5: SUMO vs Papageorgiou model.

Papageorgiou, M., Blosseville, J.-M., & Hadj-Salem, H. (1989). Macroscopic modelling of traffic flow on the Boulevard Périphérique in Paris. *Transportation Research Part B: Methodological*, *23*(1), 29–47. https://doi.org/10.1016/0191-2615(89)90021-0

Validation against SUMO

Table 3: Comparison of the proposed SOTFM and the JQZ model.

	RMSPE of the proposed model		RMSPE of the JQZ model	
PR (%) of CAVs	Density	Velocity	Density	Velocity
0	1.24	1.80	3.75	5.33
7	1.22	1.69	3.71	5.24
20	1.19	1.60	3.65	5.21
40	1.12	1.35	3.43	5.05
70	0.91	1.07	1.90	3.01

RMSPE: Root Mean Square Percentage Error; **PR:** Penetration Rate

Utility in Traffic Analysis

Practical utility of the proposed model

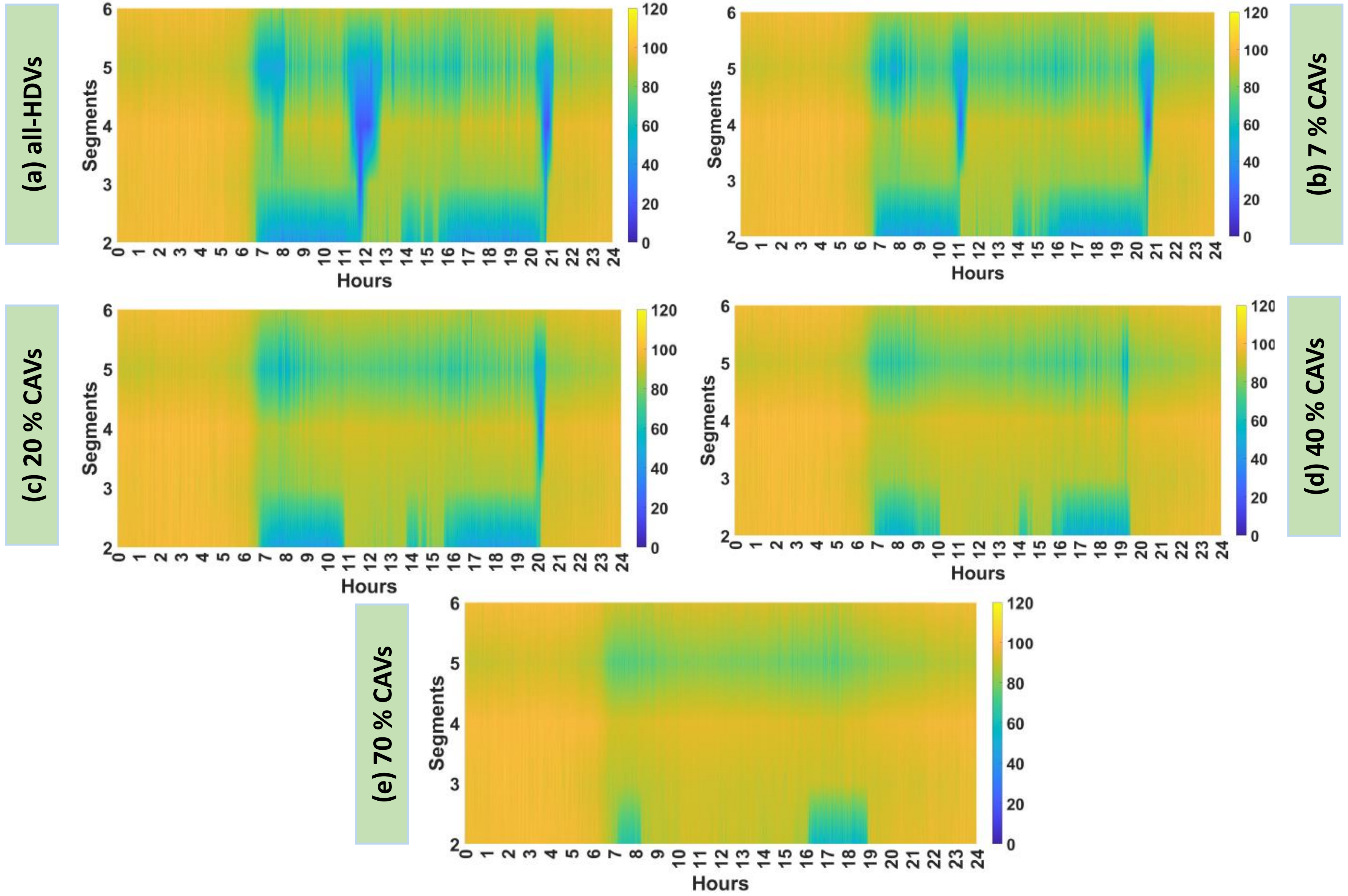


Figure 6: Spatiotemporal velocity evolution over the Dublin motorway corridor.

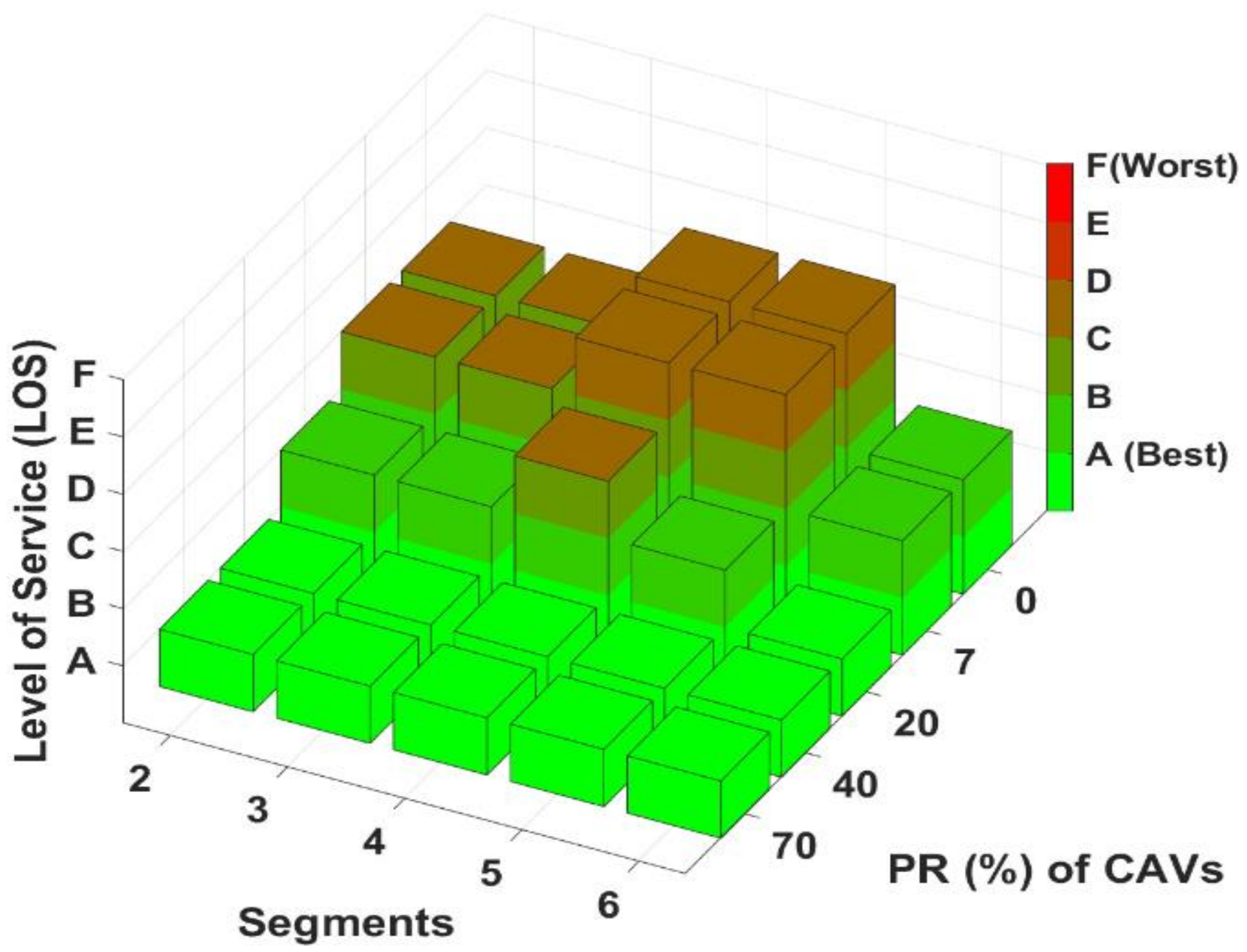


Figure 7: Level of Service (LOS) demonstration over the Dublin motorway during the evening peak hour evaluated with the proposed SOTFM.

Applications in Traffic Control

Model Predictive Control (MPC)

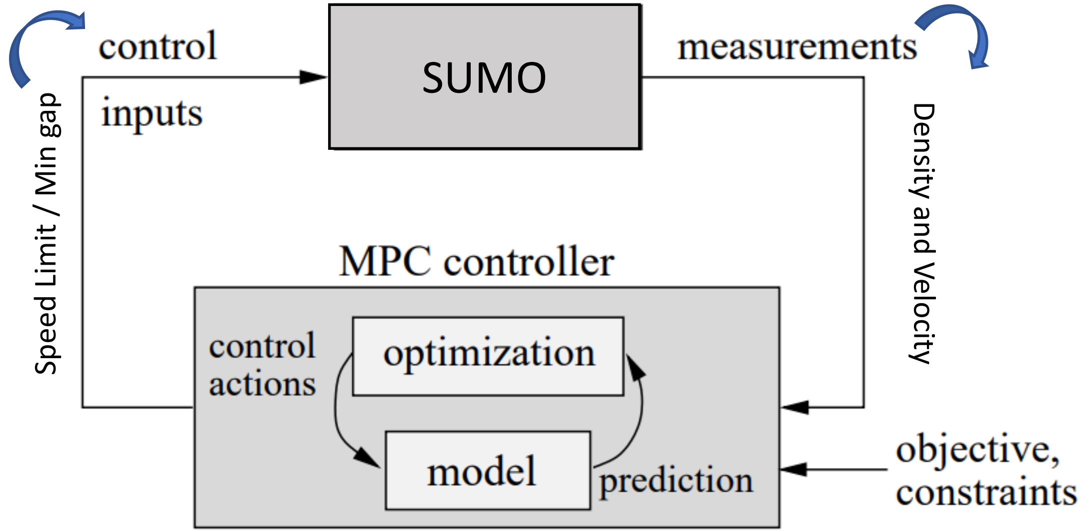


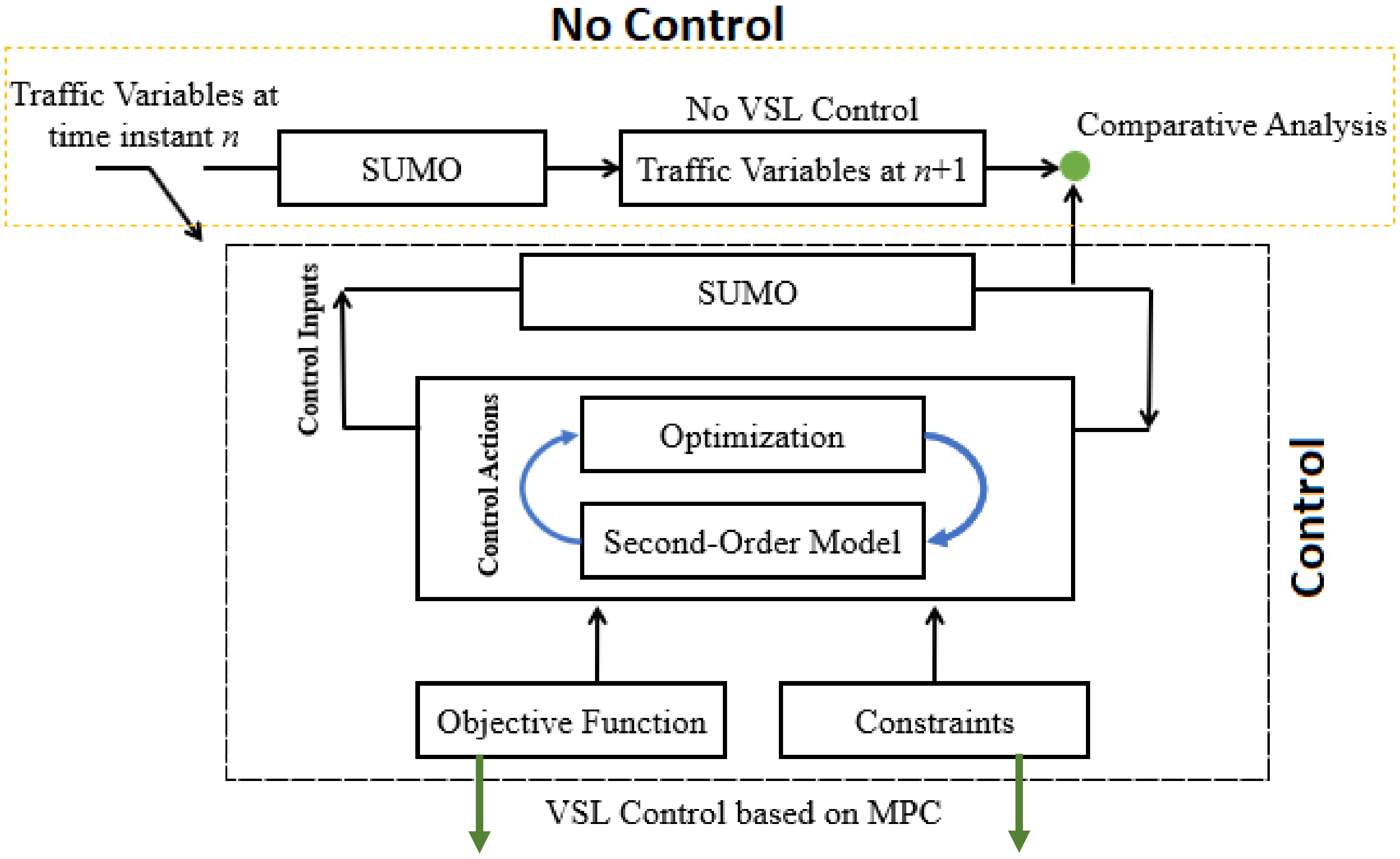
Figure 8: MPC framework.

- SUMO (TraCi4MATLAB, MATLAB)
- Prediction Model (SOTFM)

NEXT?

- Conventional Control with Variable Speed Limit (VSL)
- A Novel Regulation of Motorway Traffic with CAVs

Conventional Control with VSL employing a Continuum Model as a Prediction Model



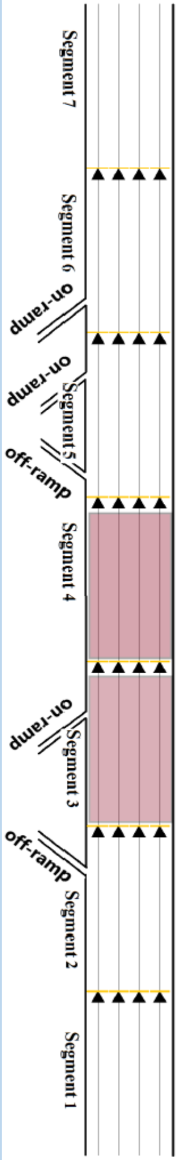
min(Total Travel Time)

SOTFM

$$\min_{SL_i^n}(TTT(\rho(n)))$$

***SL*:** Speed Limit; ***n*:** Time instant

MPC Driven VSL Control of Traffic



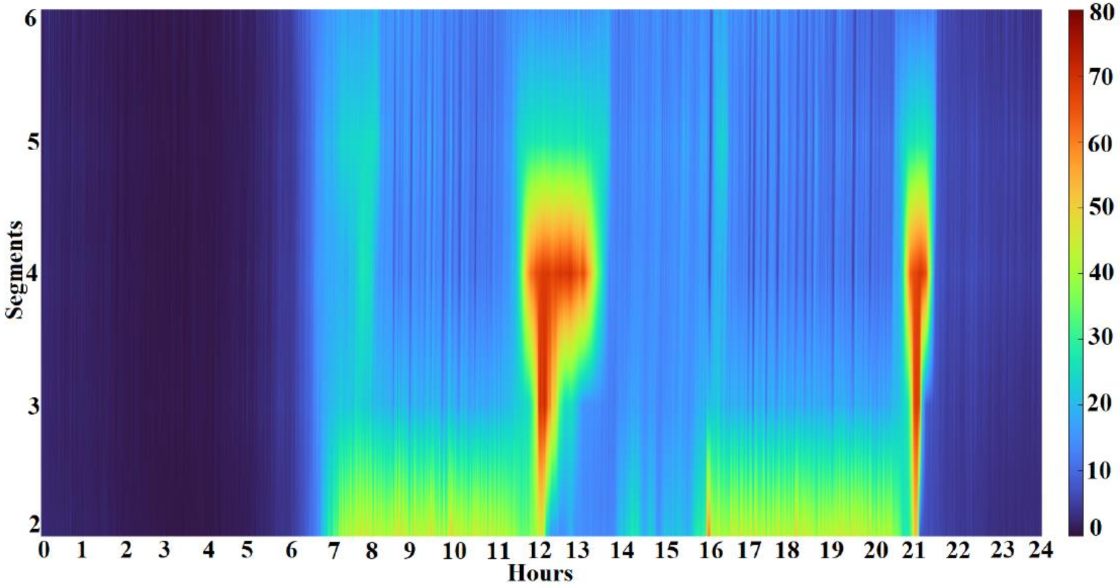


Figure 9: No-VSL-control scenario (density evolution)

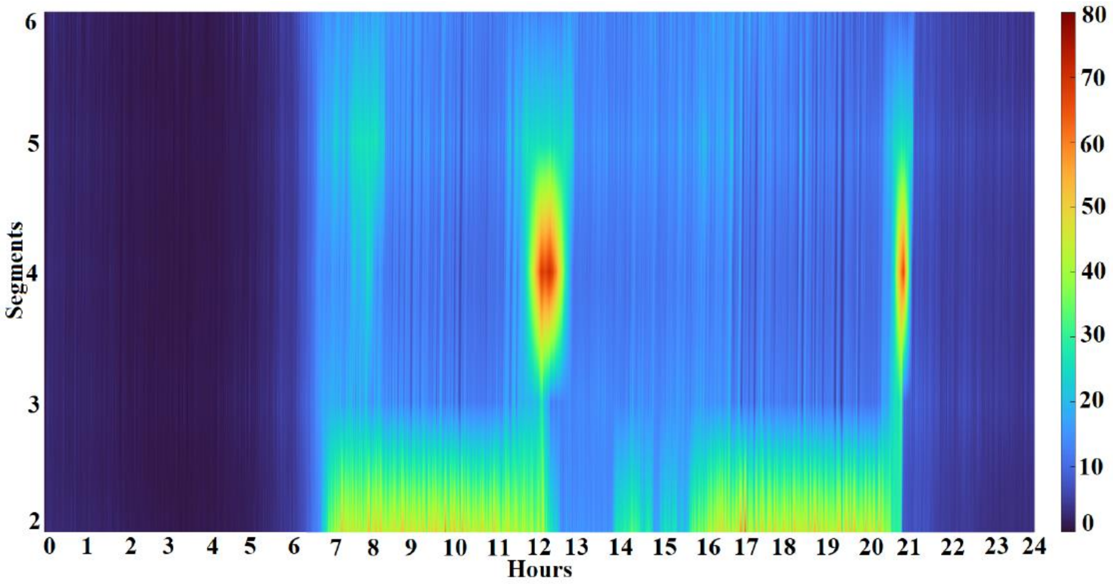
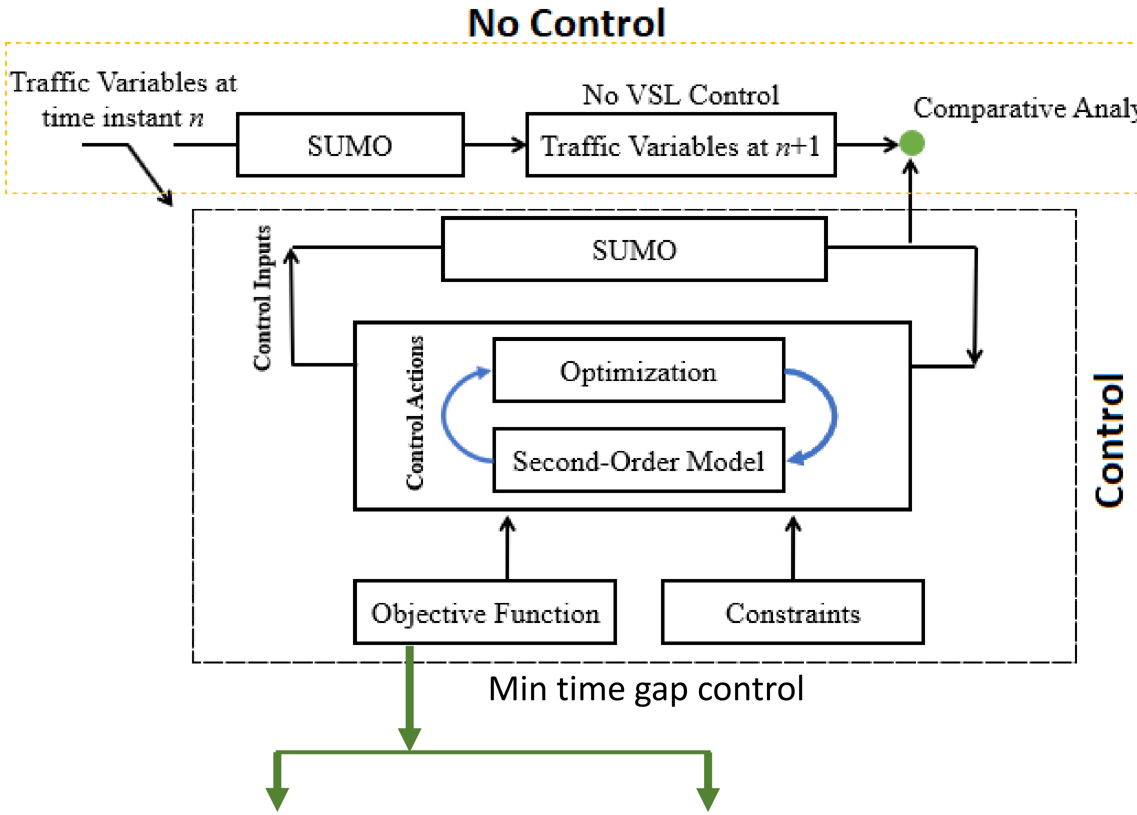


Figure 10: VSL-control scenario (density evolution)

A Novel regulation of Motorway Traffic with CAVs (CAVs penetration rate 40 %)



- Minimize Standard deviation in velocity (safety)
- Maximize mean velocity (efficiency)

$$\theta = (\theta_1 - \theta_2) : \min_{\tau}(\theta)$$

$$\theta_1 = \sum_i \frac{v_i(\tau) - \bar{v}_i}{N-1}, \text{ minimize}$$

$$\theta_2 = \sum_i \frac{v_i(\tau)}{N}, \text{ maximize}$$

$$\theta = \frac{\theta_1}{\theta_{1,max}} - \frac{\theta_2}{\theta_{2,max}}$$

$\bar{v}_i$: mean velocity (segment)

A Novel regulation of Motorway Traffic with CAVs (CAVs penetration rate 40 %)

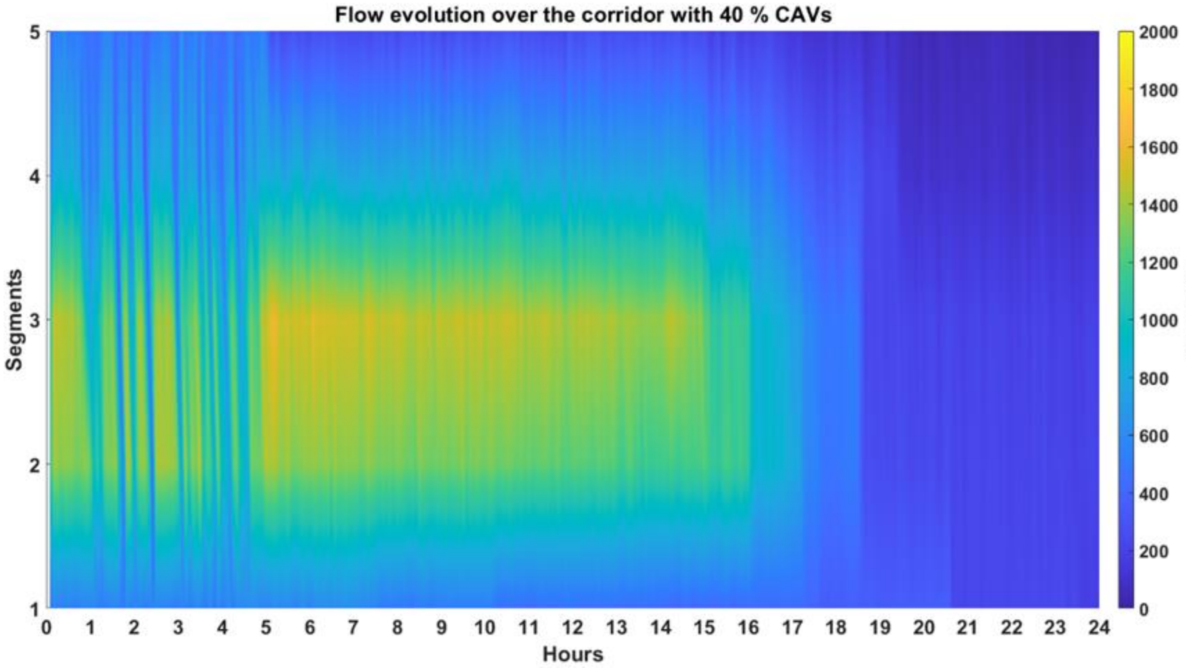


Figure 12: No-control scenario
(flow evolution)

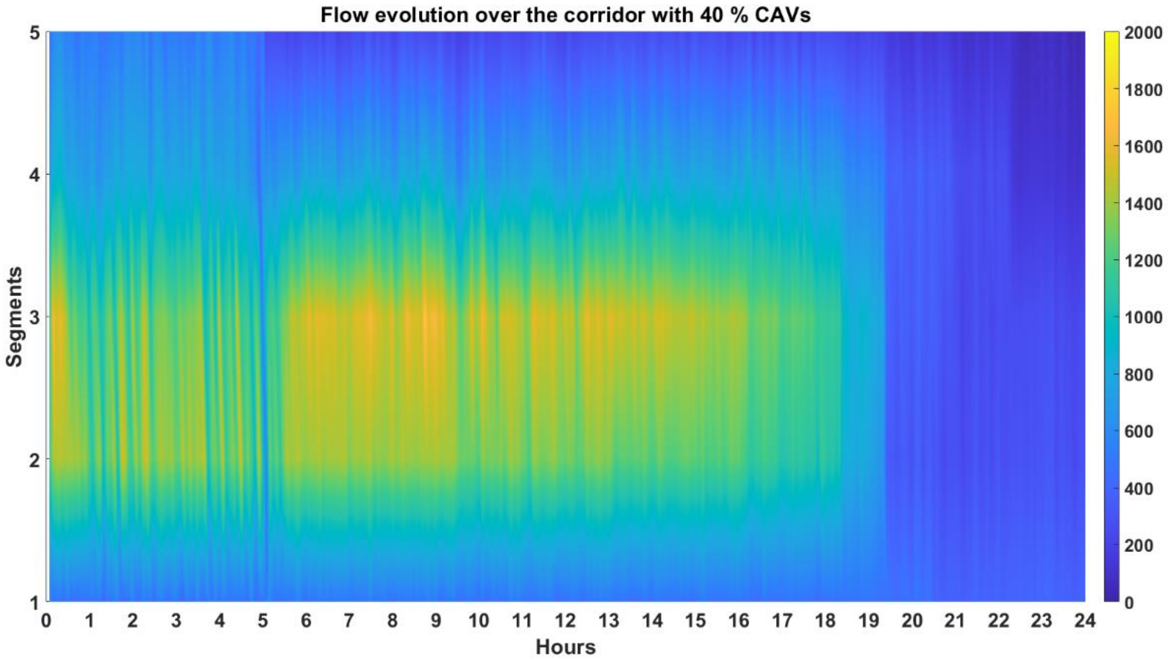


Figure 13: Control scenario
(flow evolution)

More?

- ✓ Characterization of self-organizing behavior of traffic flow with CAVs
- ✓ Traffic flow and emissions profiling driven on the fundamental diagram of mixed traffic

Outcomes

Research Articles		
Title	**Status**	**Journal**
1. Macroscopic evaluation of traffic flow in view of connected and autonomous vehicles: A simulation-based approach	Published	Alexandria Engineering Journal
2. Macroscopic modeling of connected, autonomous and human-driven vehicles: A pragmatic perspective	Published	Transportation Research Interdisciplinary Perspectives
3. Appraisal of the second-order traffic systems employing sensitivity analysis and numerical simulation	Submitted	Transportation Research Interdisciplinary Perspectives
4. Traffic flow and emissions profiling driven on the fundamental diagram of mixed traffic	Ready	To be decided
5. An MPC-driven VSL control of motorway traffic	Submitted	Transportation Engineering
6. A novel MPC-driven regulation of traffic flow with connected and autonomous vehicles	Under-prep	To be decided

Recommendations

- Characterization of mixed traffic employing other macroscopic models, such as METANET and Cell Transmission Model (CTM), others.
- Practical utilization of the proposed models in weather based adaptive control and pavement conditions based adaptive control.
- Use of the proposed model in Hybrid simulation approach
- Safety evaluation of traffic employing surrogate measures in the framework of SOTFMs.
- Business modules, product development for vehicles based on macroscopic systems for advanced decision making.
- Comparison of conventional control strategies with the proposed novel control strategy in a more complex traffic scenarios.

Profile

Related to Ph.D:

1. **W. Imran,** T. Tettamanti, B. Varga, G. N. Bifulco, and L. Pariota, “Macroscopic modeling of connected, autonomous and human-driven vehicles: A pragmatic perspective,” Transp. Res. Interdiscip. Perspect., vol. 24, p. 101058, Mar. 2024

2. **W. Imran** and L. Pariota, “Macroscopic evaluation of traffic flow in view of connected and autonomous vehicles: A simulation-based approach,” *Alexandria Engineering Journal*, vol. 79, pp. 581–590, 2023.

3. **W. Imran**, Z. H. Khan, T. A. Gulliver, M. Alam, and K. S. Khattak, “Non-homogeneous traffic characterization based on driver reaction and stimuli,” *Transportation Research Interdisciplinary Perspectives*, vol. 21, p. 100858, 2023.

4. Z. H. Khan, **W. Imran** et al., “Macroscopic traffic characterization based on driver memory and traffic stimuli,” *Transportation Engineering*, vol. 14, p. 100208, 2023.

5. Z. H. Khan, T. A. Gulliver, **W. Imran**, K. S. Khattak, A. B. Altamimi, and A. Qazi, “A macroscopic traffic model based on relaxation time,” *Alexandria Engineering Journal*, vol. 61, no. 1, pp. 585–596, **2021.**

General:

1. Z. H. Khan, A. B. Altamimi, **W. Imran**, M. Alsaffar, K. S. Khattak, and F. F. Alfaisal, “Macroscopic Traffic Modelling on the Impact of Road Surface Potholes: Development and Numerical Solution,” IEEE Access, vol. 12, pp. 81718–81735, 2024

2. D. Khan, Z.H. Khan, **W. Imran**, K.S. Khattak, T. A. Gulliver, “Macroscopic Flow Characterization at T-Junctions”, *Transportation Research Interdisciplinary Perspectives*, vol. 14, 2022.

3. S. Islam, Z. H. Khan, T. A. Gulliver, K. S. Khattak, and **W. Imran**, “Pedestrian traffic characterization based on pedestrian response,” *IEEE Access*, vol. 10, pp. 118397–118408, 2022.

4. **W. Imran**, Z. H. Khan, T. A. Gulliver, K. S. Khattak, S. Saeed, and M. S. Aslam, “Macroscopic Traffic Flow Characterization for Stimuli Based on Driver Reaction,” *Civil Engineering Journal*, vol. 7, no. 1, pp. 1–13, **2021**.

5. Z. H. Khan, T. A. Gulliver, and **W. Imran**, “A Macroscopic Traffic Model Based on the Safe Velocity at Transitions,” *Civil Engineering Journal*, vol. 7, no. 6, pp. 1060–1069, **2021**.

6. A. Khan, K. Khattak, Z. Khan, T. Gulliver, **W. Imran**, and N. Minallah, “Internet-of-Video Things Based Real-Time Traffic Flow Characterization,” ICST Transactions on Scalable Information Systems, vol. 8, no. 33, p. 171596, **2021**.

7. M. Sarir, R. Khan, M. Alam, M. T. Khan, and **W. Imran**, “Performance Evaluation of Asphalt Concrete Mixtures Using Bagasse Ash as Filler,” *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, **2021**.

8. **W. Imran**, Z. H. Khan, T. A. Gulliver, K. S. Khattak, and H. Nasir, “A macroscopic traffic model for heterogeneous flow,” *Chinese Journal of Physics*, vol. 63, pp. 419–435, **2020**.

9. Z. H. Khan, **W. Imran**, T. A. Gulliver, K. S. Khattak, Z. Wadud, and A. N. Khan, “An Anisotropic Traffic Model Based on Driver Interaction,” *IEEE Access*, vol. 8, pp. 66799–66812, **2020**.

10. Z. H. Khan, **W. Imran**, S. Azeem, K. S. Khattak, T. A. Gulliver, and M. S. Aslam, “A Macroscopic Traffic Model based on Driver Reaction and Traffic Stimuli,” *Applied Sciences*, vol. 9, no. 14, p. 2848, **2019**.

Q & A

Thank You!

Characterization of Self-Organizing Behavior of Traffic Flow with CAVs

Aims:

- Modeling the anticipative behavior of CAVs
- Spatiotemporal analysis of traffic variables

A macroscopic model driven on self-anticipative behavior

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \dfrac{\partial (v(x,t).\rho(x,t))}{\partial x} = 0, \\ \dfrac{\partial v(x,t)}{\partial t} + \left(v(x,t) - \dfrac{l_g + \tau_r(\rho).v(x,t)}{\tau_r(\rho)} \right) \dfrac{\partial v(x,t)}{\partial x} = \dfrac{V(\rho(x,t)) - v(x,t)}{T}. \end{cases} \quad \dots (15)$$

$$\tau_r(\rho) = \frac{\tau_{r(min)}}{\frac{\rho(x,t)}{\rho_m}}$$

Table 4: Parameters

Parameters	Description
$\tau_r(\rho)$	Reaction time as function of density
$\tau_{r(min)}$	Min reaction time
l_g	Lengthways gap

* W. Imran and L. Pariota, “Macroscopic evaluation of traffic flow in view of connected and autonomous vehicles: A simulation-based approach,” Alexandria Engineering Journal, vol. 79, pp. 581–590, 2023.

A macroscopic model driven on self-anticipative behavior

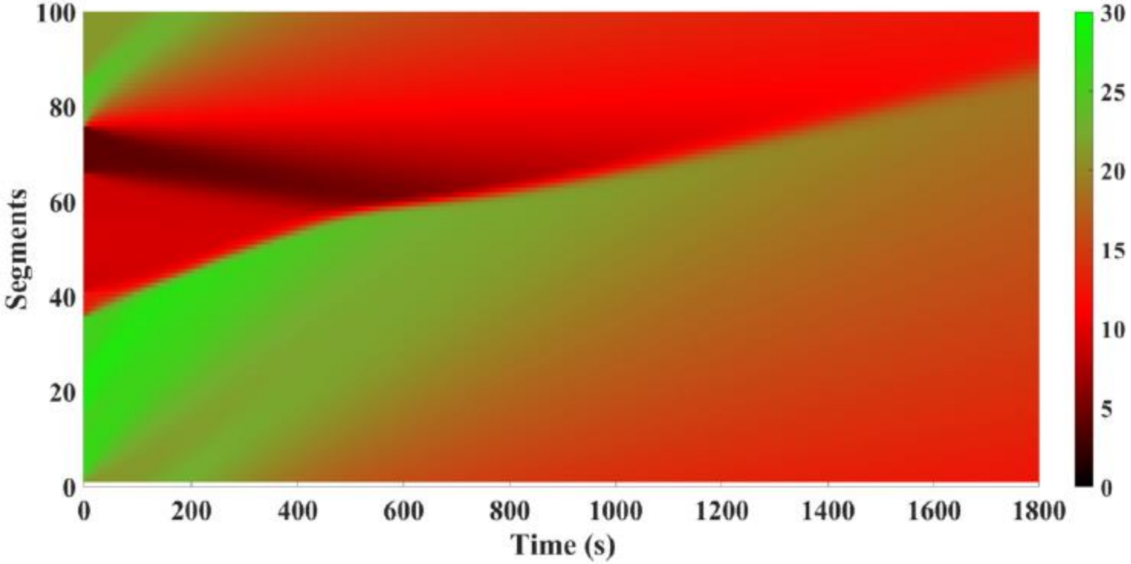


Figure 14: Velocity evolution with HDVs

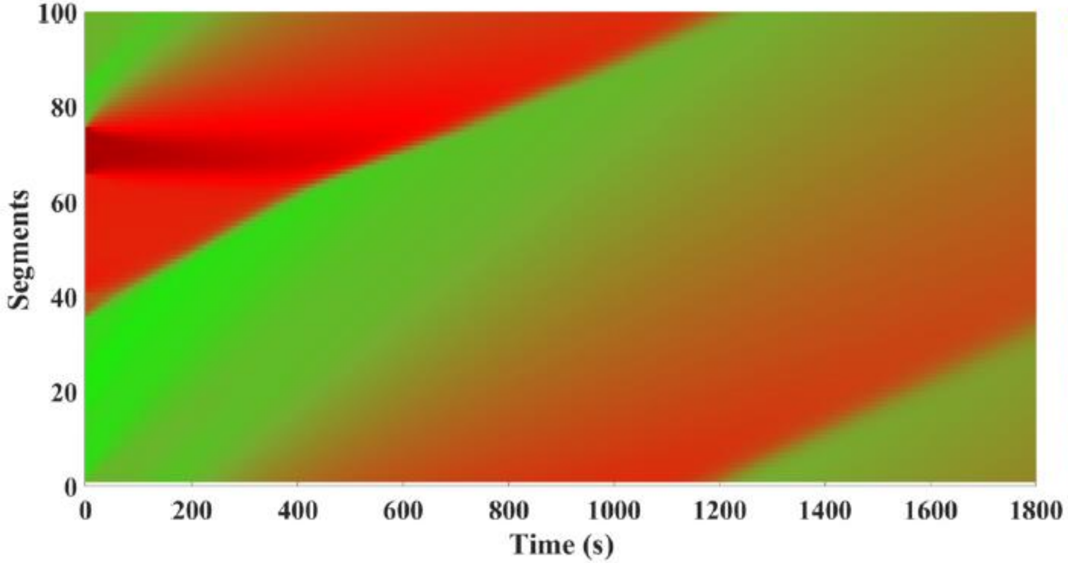


Figure 15: Velocity evolution with CAVs and HDVs (50 % each)

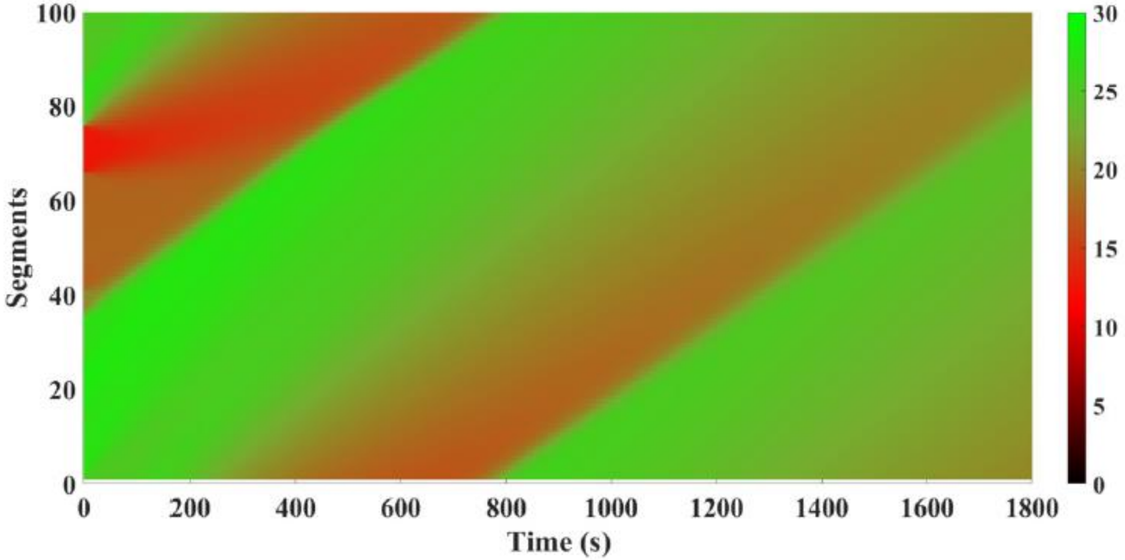


Figure 16: Velocity evolution with CAVs

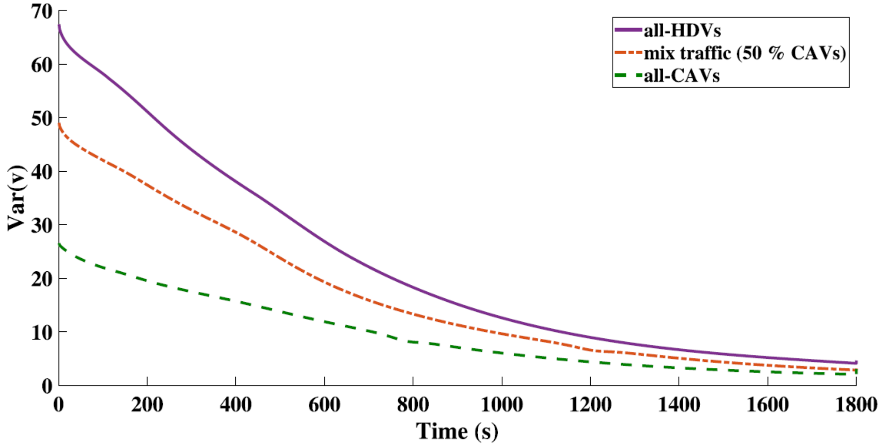


Figure 17: Variance of velocity