Coordinated Traffic Control for Highway Systems

Doctoral exam presentation

Coordinated Traffic Control for Highway Systems

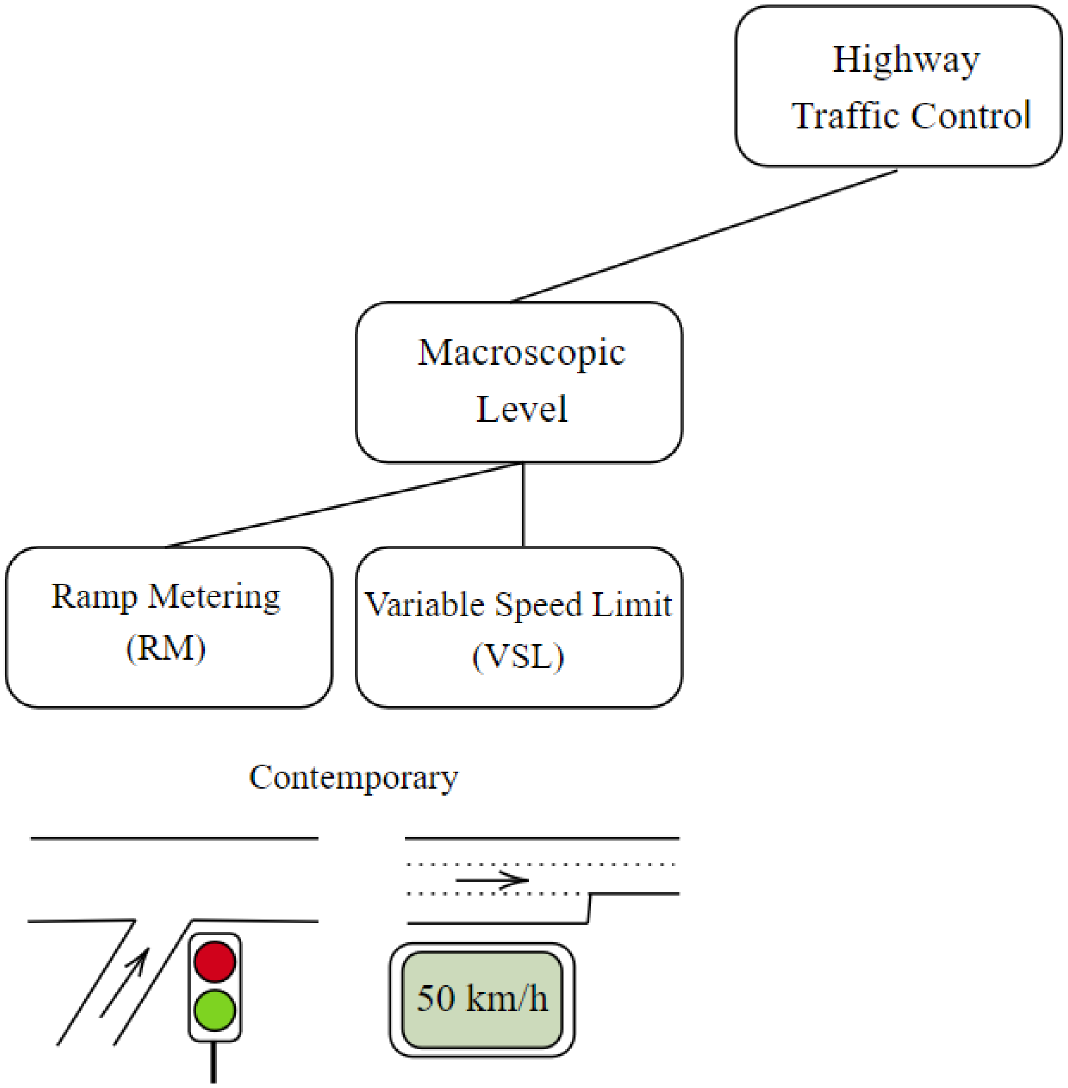
Kimia Chavoshi
Doctoral exam presentation
October 18th 2024, Zurich

I. Introduction

The story of every big city

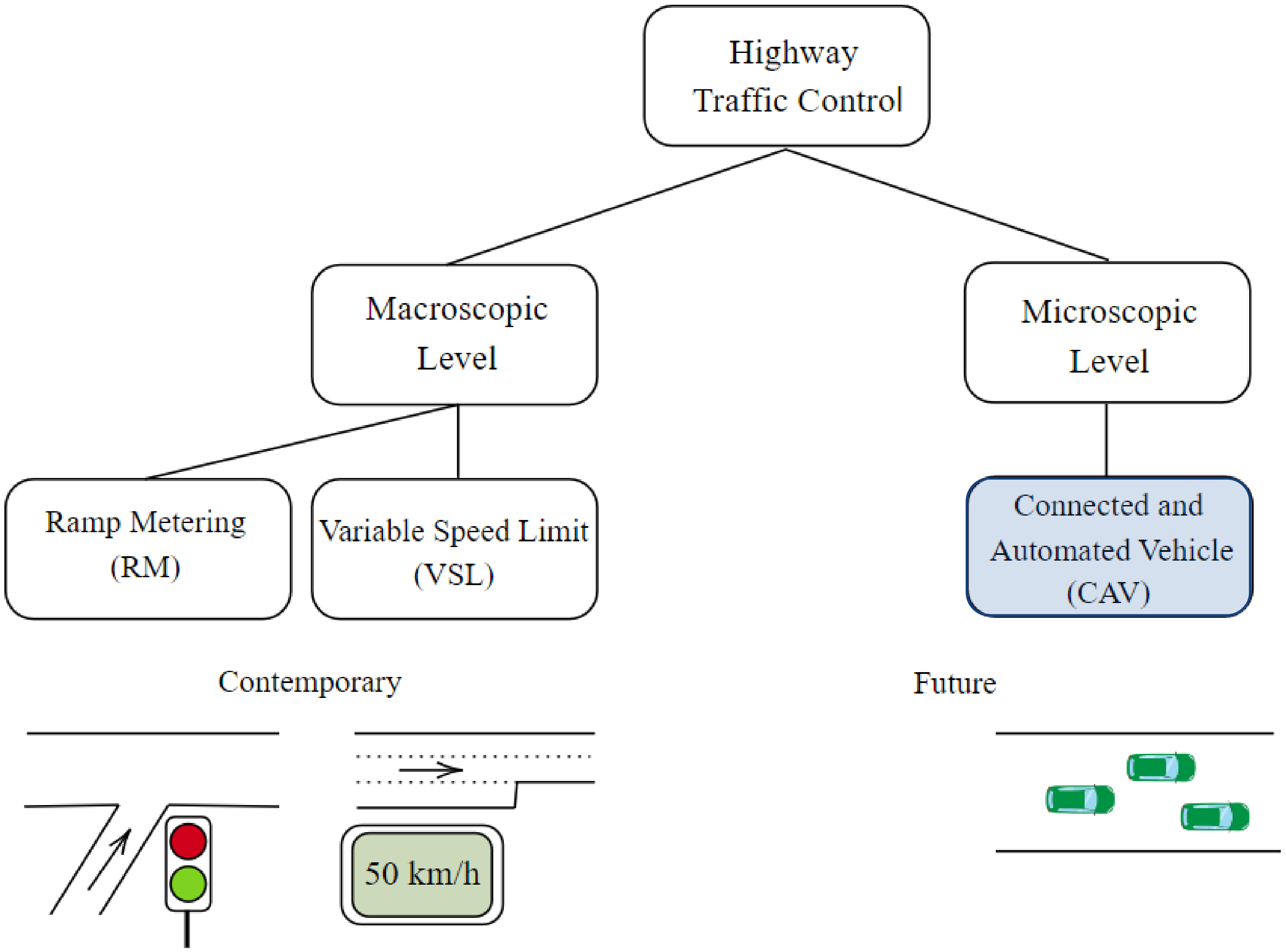
Are we utilizing the full potential of current highways?

What are the tools for traffic control on contemporary highways?



We can improve traffic on highways, but we are limited to the framework designed for human-driven vehicles.

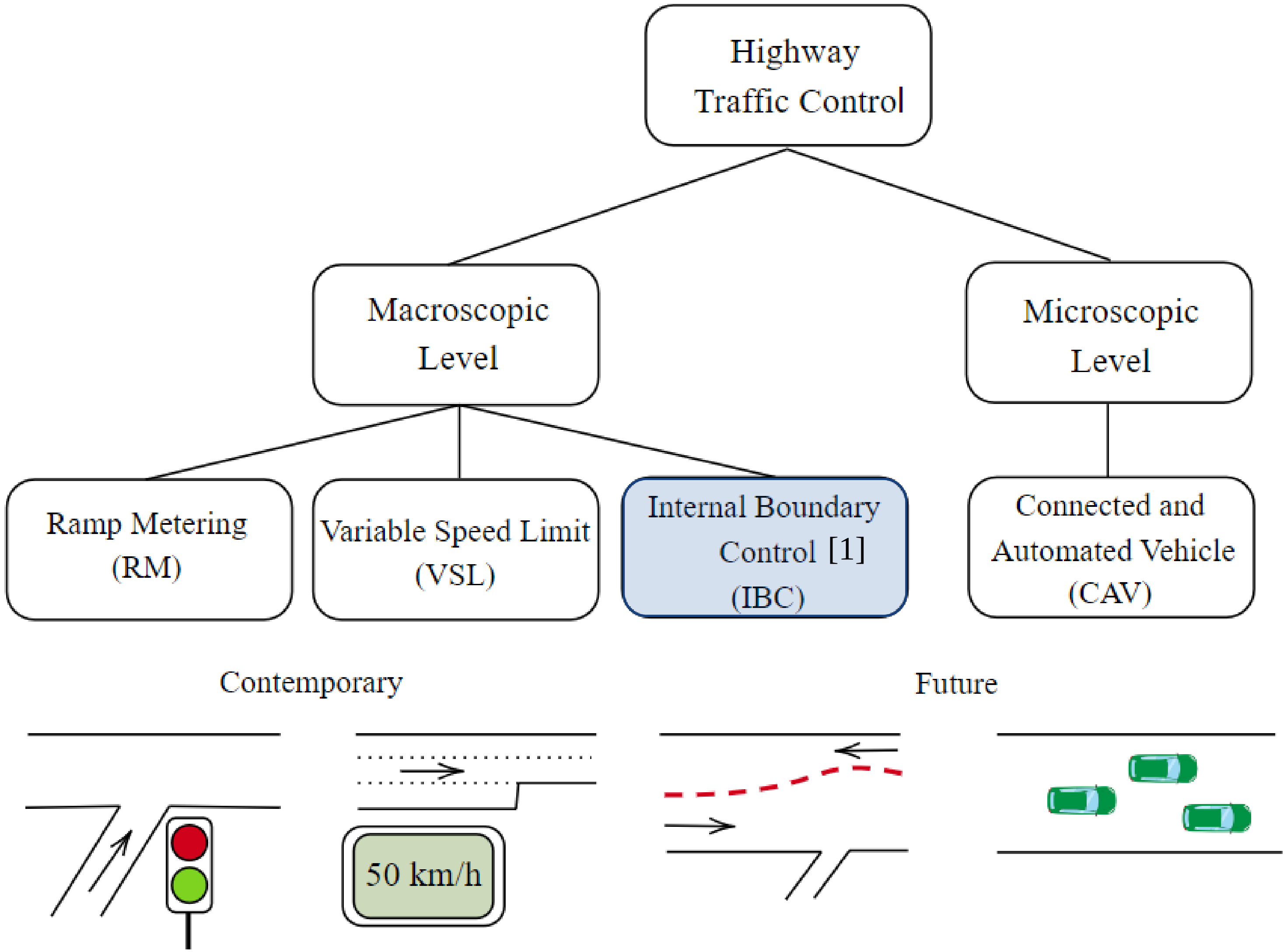
What are the tools for traffic control on future highways?



Lane-free traffic of CAVs
a new paradigm for future highways. [1]

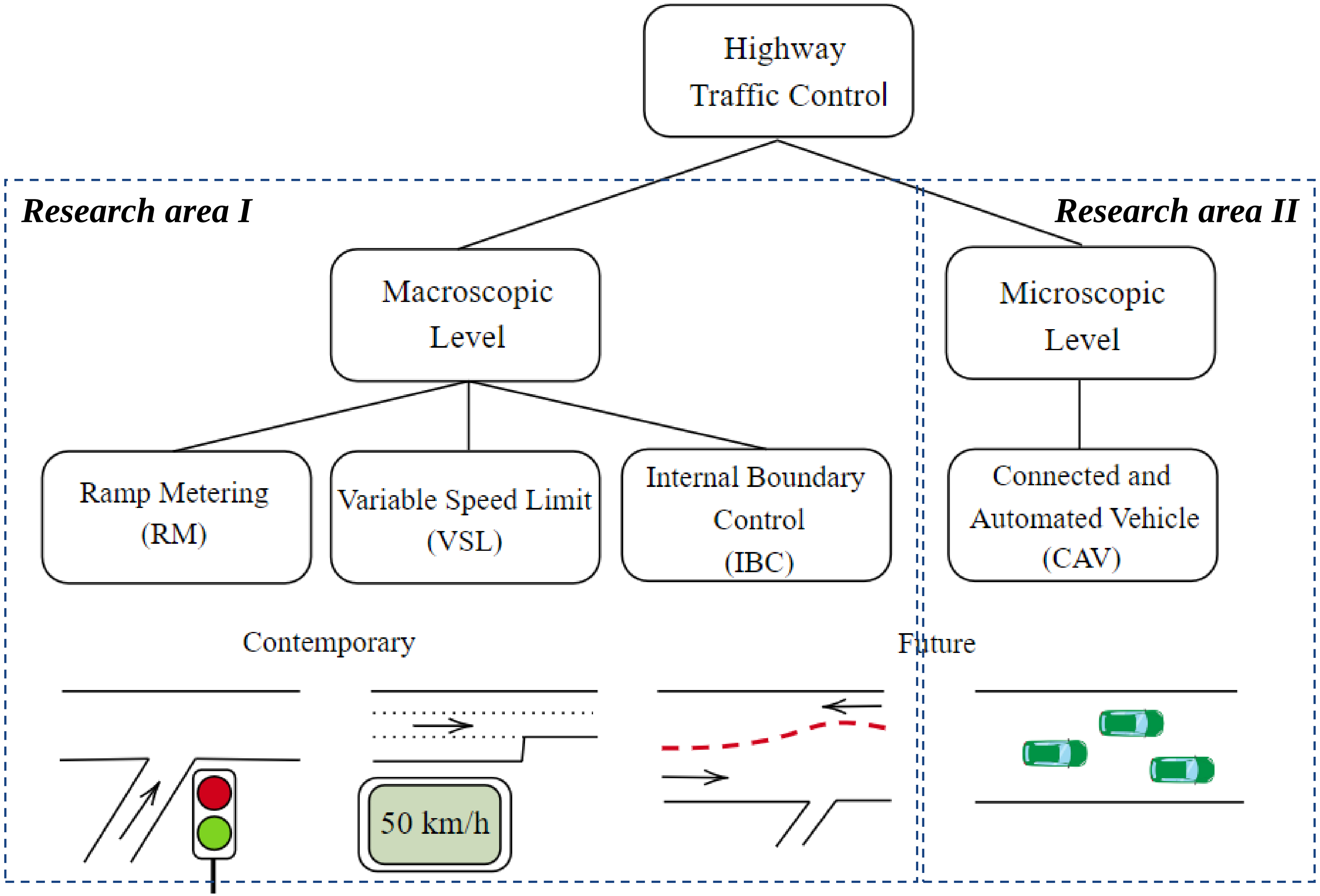
[1] Papageorgiou, M., Mountakis, K. S., Karafyllis, I., Papamichail, I., & Wang, Y. (2021). Lane-free artificial-fluid concept for vehicular traffic. *Proceedings of the IEEE*, *109*(2), 114-121.

What are the tools for traffic control on future highways?



[1] Malekzadeh, M., Papamichail, I., & Papageorgiou, M. (2021). Internal Boundary Control of Lane-Free Automated Vehicle Traffic using a Model-Free Adaptive Controller. *IFAC-PapersOnLine*, *54*(2), 99-106.

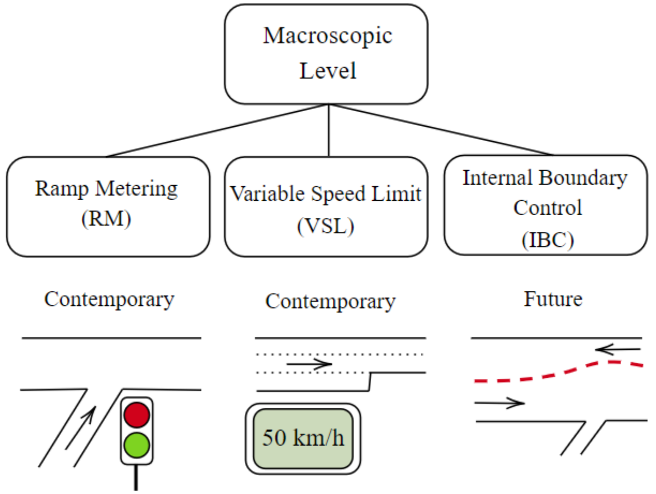
What are the focus areas of our research?



What are the research objectives and contributions?

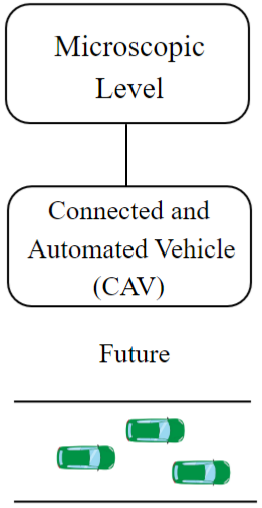
Research area I: Macroscopic level

- **Research objective:** Real-time coordinated traffic control
- **Contribution:** Combined feedback linearization and model predictive control



Research area II: Microscopic level

- **Research objective:** Fair, safe, and efficient lane-free traffic of CAVs
- **Contribution:** Bi-level collaborative control for threatening vehicle clusters



II. Macroscopic level

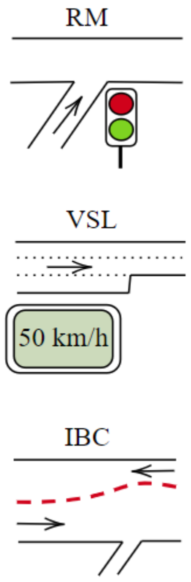
Research objective: Real-time coordinated traffic control
Contribution: Combined feedback linearization and model predictive control

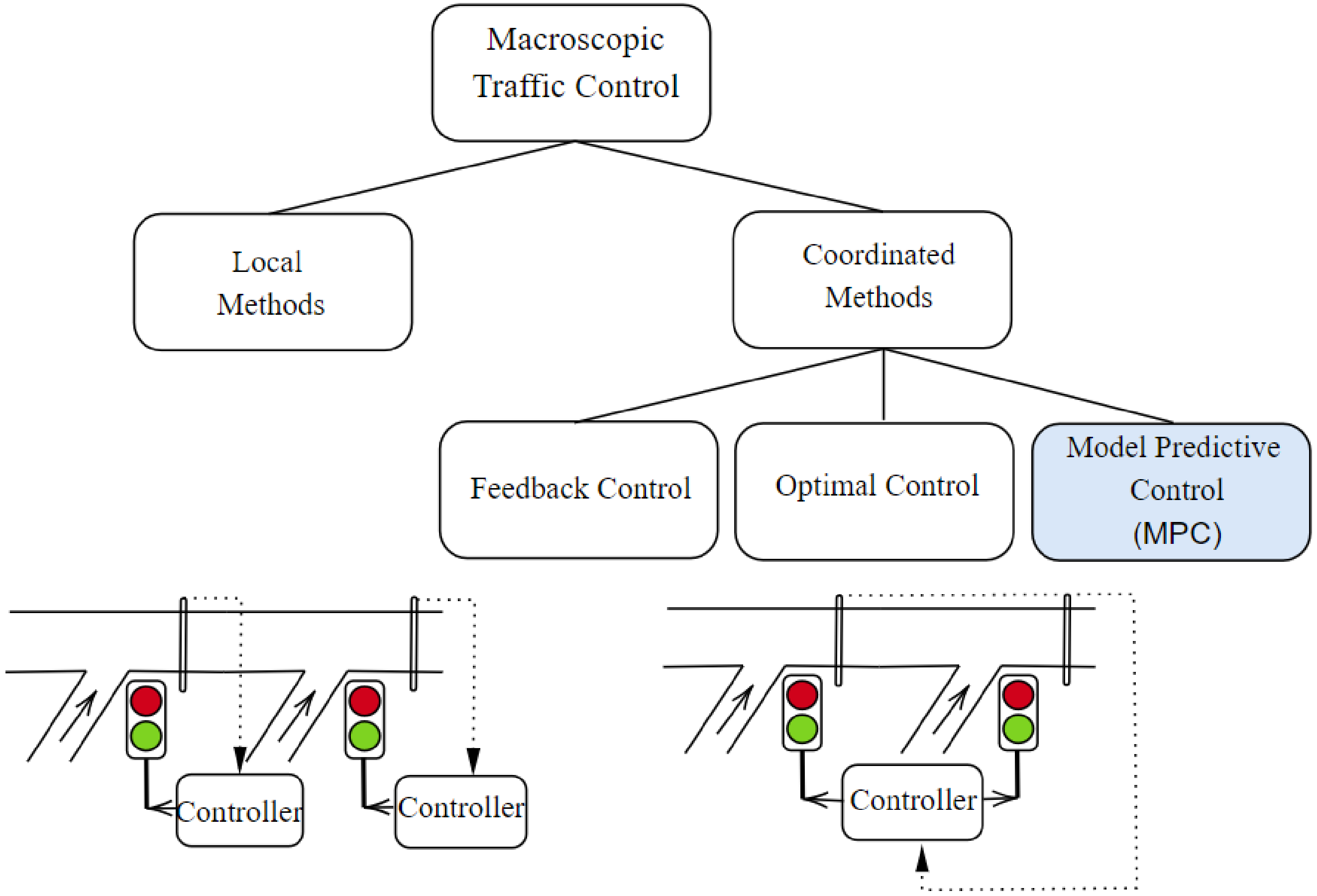
Application I: Contemporary highways [1]
Application II: Future highways [2]

[1] Chavoshi, K., Ferrara, A., & Kouvelas, A. (2023). A feedback linearization approach for coordinated traffic flow management in highway systems. *Control Engineering Practice*, *139*, 105615.
[2] Chavoshi, K., Malekzadeh, M., Papageorgiou, M., Ferrara, A., & Kouvelas, A. (2024). Integrated internal boundary control and ramp metering in lane-free highway systems: A combined feedback linearization and mpc approach. *TechRxiv*.

Current status of macroscopic traffic control for highway systems

Actuators:





Ferrara, A., Sacone, S., & Siri, S. (2018). An overview of traffic control schemes for freeway systems. In *Freeway traffic modelling and control* (pp. 193–234). Springer International Publishing.

General approaches to tackle the high computational cost of MPC for highway traffic control

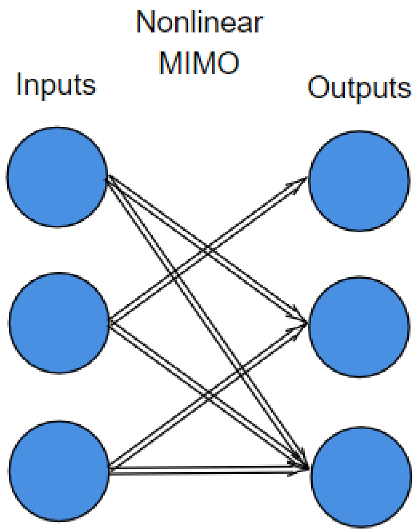
1. Decomposing control problem into smaller sub-problems
2. Controlling only when and where necessary
3. Simplifying the problem by reformulation and approximation

Ferrara, A., Sacone, S., & Siri, S. (2018). An overview of traffic control schemes for freeway systems. In *Freeway traffic modelling and control* (pp. 193–234). Springer International Publishing.

What is the source of complexity?

Macroscopic traffic flow models

- Nonlinear systems
- Multiple inputs and multiple outputs
- Disturbances



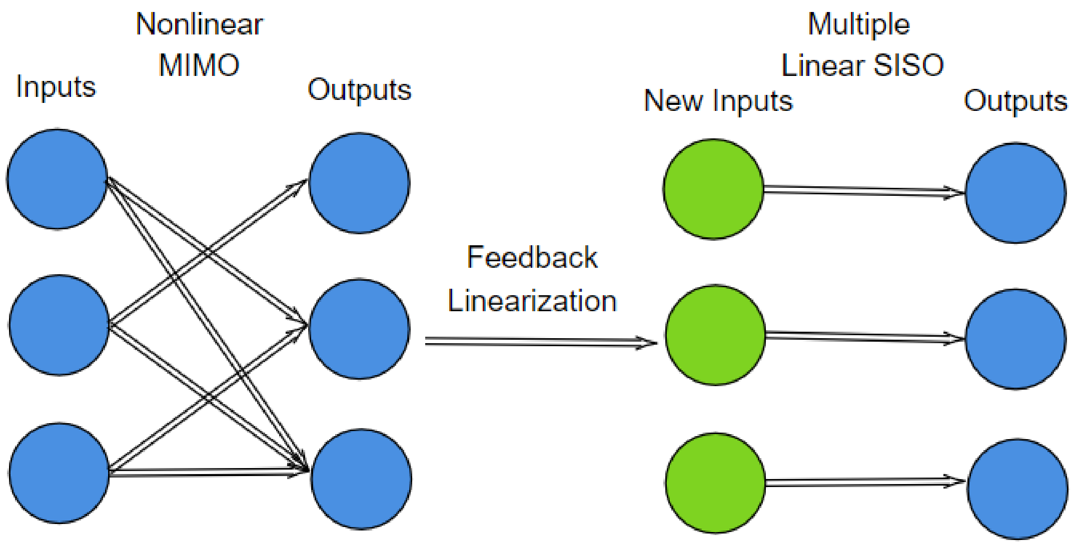
Why feedback linearization is a potential solution?

Macroscopic traffic flow models

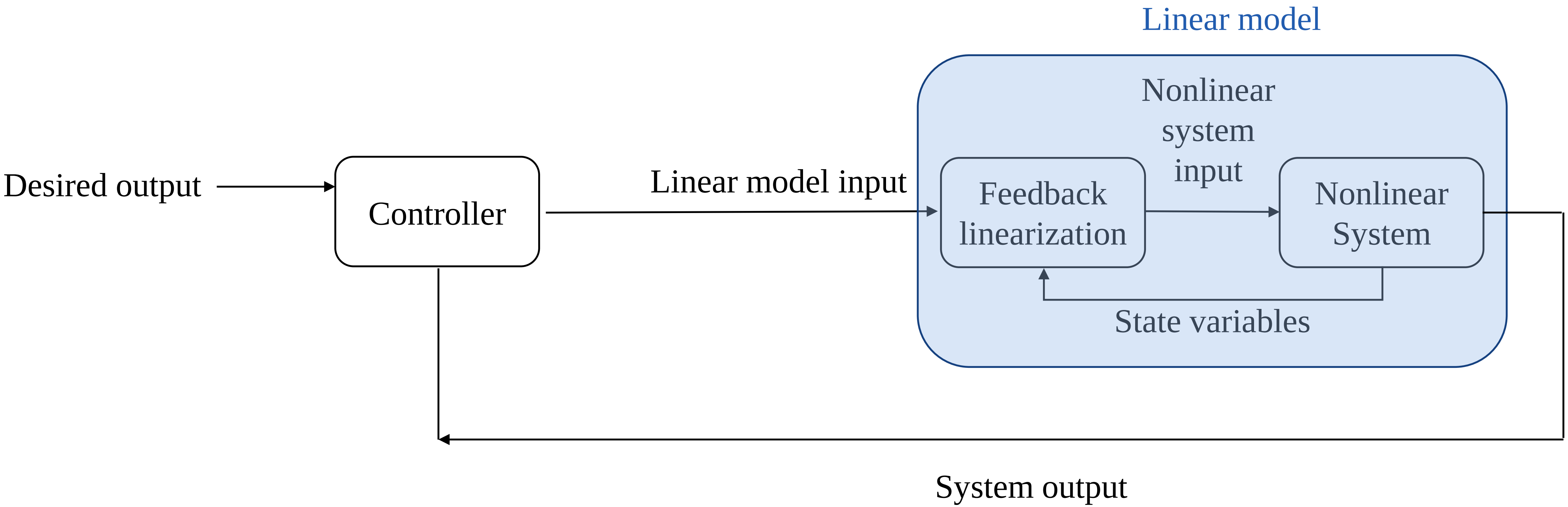
- Nonlinear systems
- Multiple inputs and multiple outputs
- Disturbances

Feedback Linearization

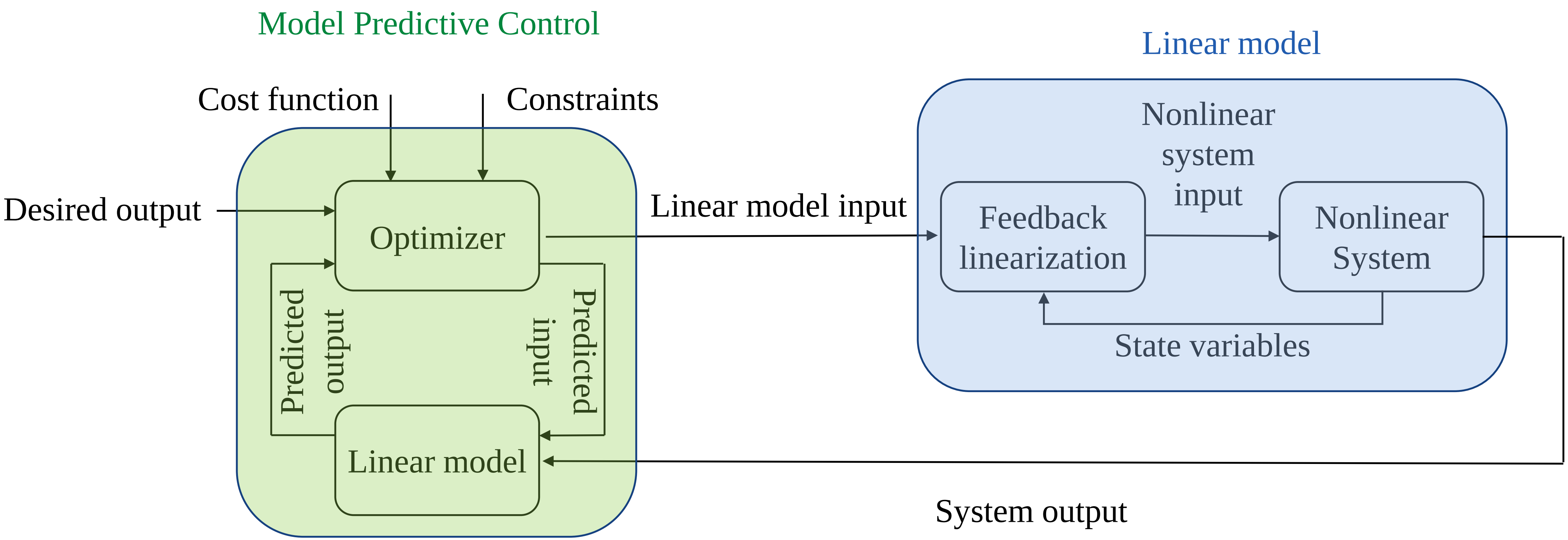
- Linear representation for nonlinear systems
- Clear map between transformed inputs and outputs
- Disturbance decoupling



How to implement feedback linearization-based control?

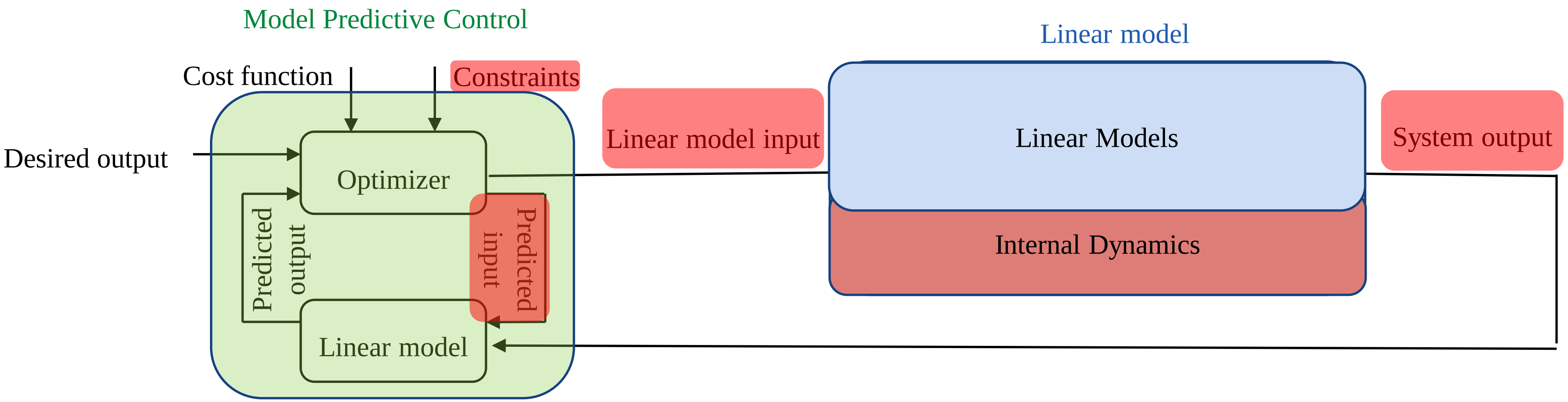


How to design MPC for feedback linearized model?

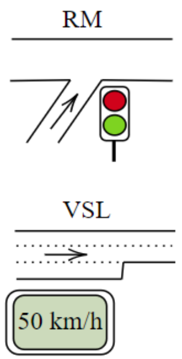


What are the challenges of applying combined Feedback Linearization and MPC (FLMPC) for macroscopic traffic models?

Challenges:	Solutions:
Input affine and disturbance affine	Modifications on mathematical models
Input-output decoupling	Limitation for the location of sensors and actuators
Internal dynamics	Studying the behavior of internal states
Constraints on predicted inputs for MPC	Constraints mapping technique



Application I: Contemporary highways



Research objective: **Real-time and efficient** coordinated control for **large-scale highways**

Traffic control actuators: Ramp Metering (RM) and Variable Speed Limits (VSL)

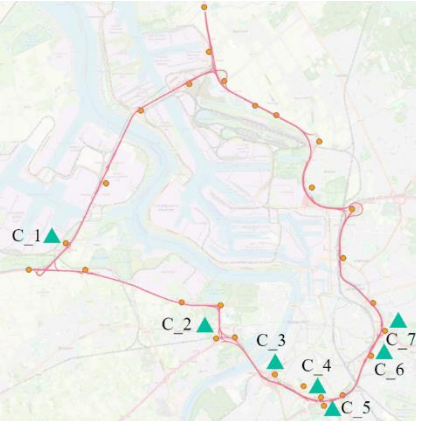
Control method: FLMPC for METANET model

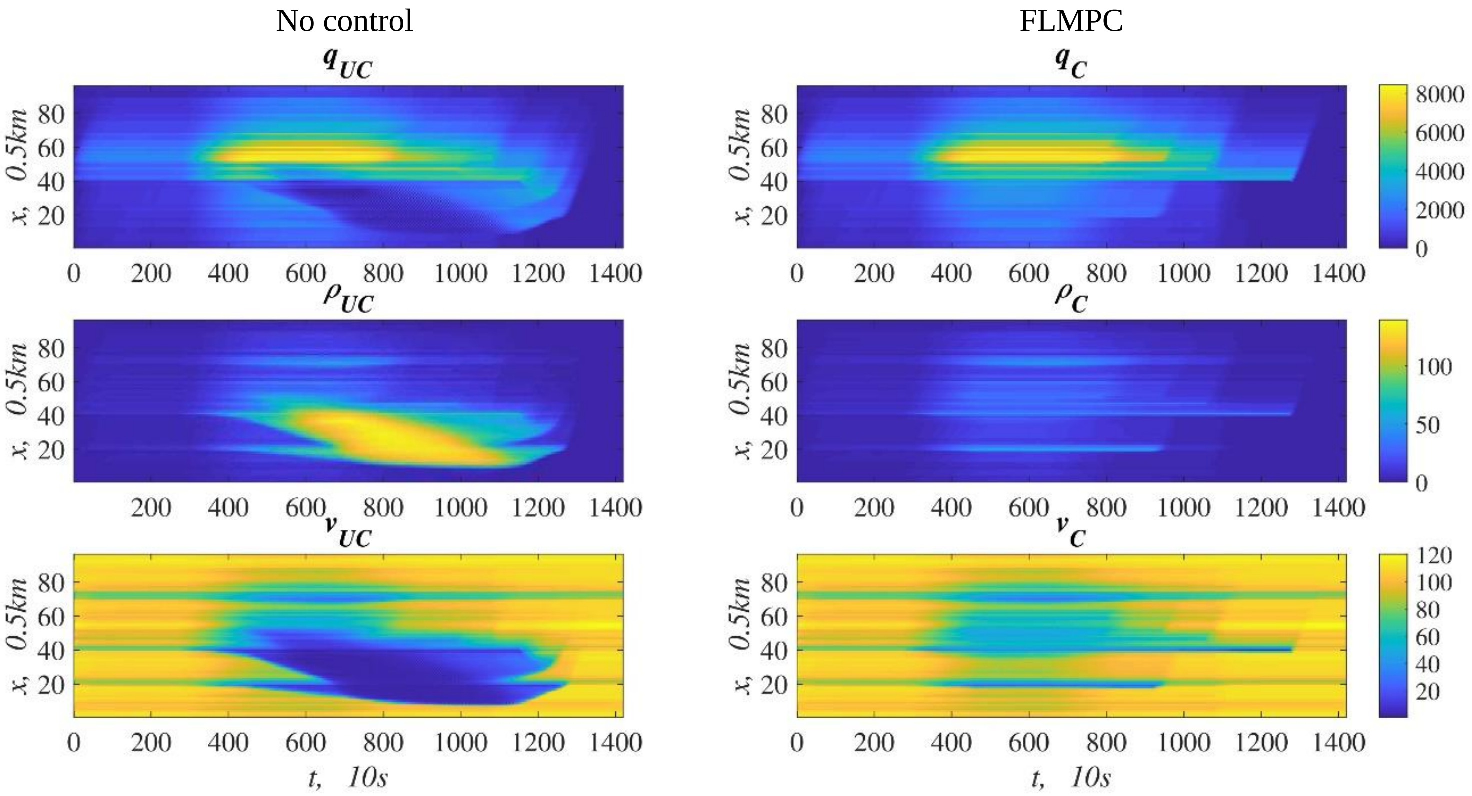
Simulation results:

Case Study	Actuators	VHT Improvement	Computational Time
Lane-drop (7.5 km)	3 VSL	16%	0.18s
On-ramp merging area (6 km)	1 RM and 2 VSL	16%	0.1s
Antwerp ring road (48 km)	7 RM	17%	0.75s

What is the performance of FLMPC for large-scale highways?

Case Study	Actuators	VHT Improvement	Computational Time
Antwerp ring road (48 km)	7 RM	17%	**0.75s**





✓ FLMPC has the potential for **real-time** traffic control for large-scale highway systems.

How does FLMPC compare with other methods?

- Comparison with ALINEA (local feedback controller for RM)
  - Case study: Antwerp ring road
  - Traffic control: Coordinated RM
  - Important result: **11% improvement in VHT**

- Comparison with Nonlinear MPC [1]
  - Case study: 6 km highway with an on-ramp
  - Traffic control: Coordinated RM and VSL
  - Important results: **800 times smaller computational time and comparable VHT**

✓ FLMPC provides **efficient** traffic control for highway systems.

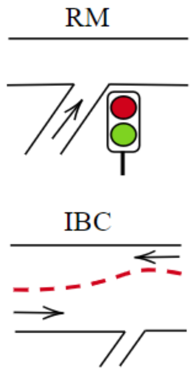
[1] Chavoshi, K., & Kouvelas, A. (2020). Nonlinear model predictive control for coordinated traffic flow management in highway systems. *2020 European Control Conference (ECC)*, 428.

Application II: Future highways

Research objective: Coordinated traffic control based on **online optimization** for future lane-free highways

Traffic control actuators: **Ramp Metering (RM)** and Internal Boundary Control (IBC)

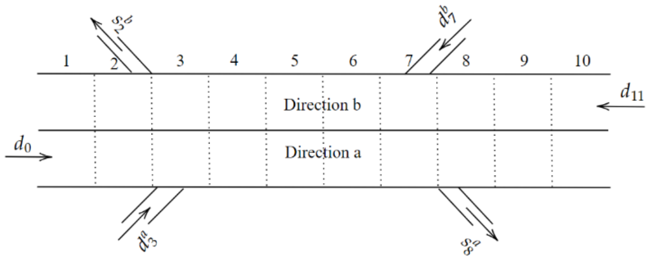
Control method: FLMPC for first order model with driver's anticipation

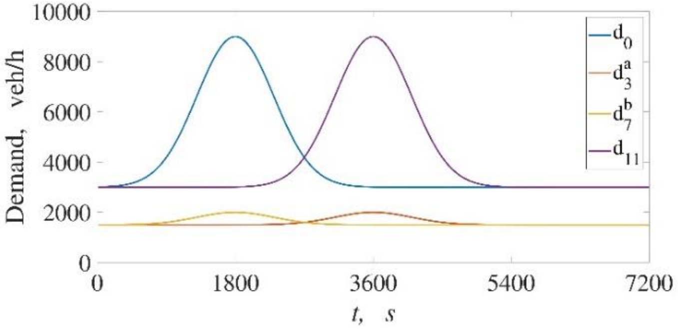


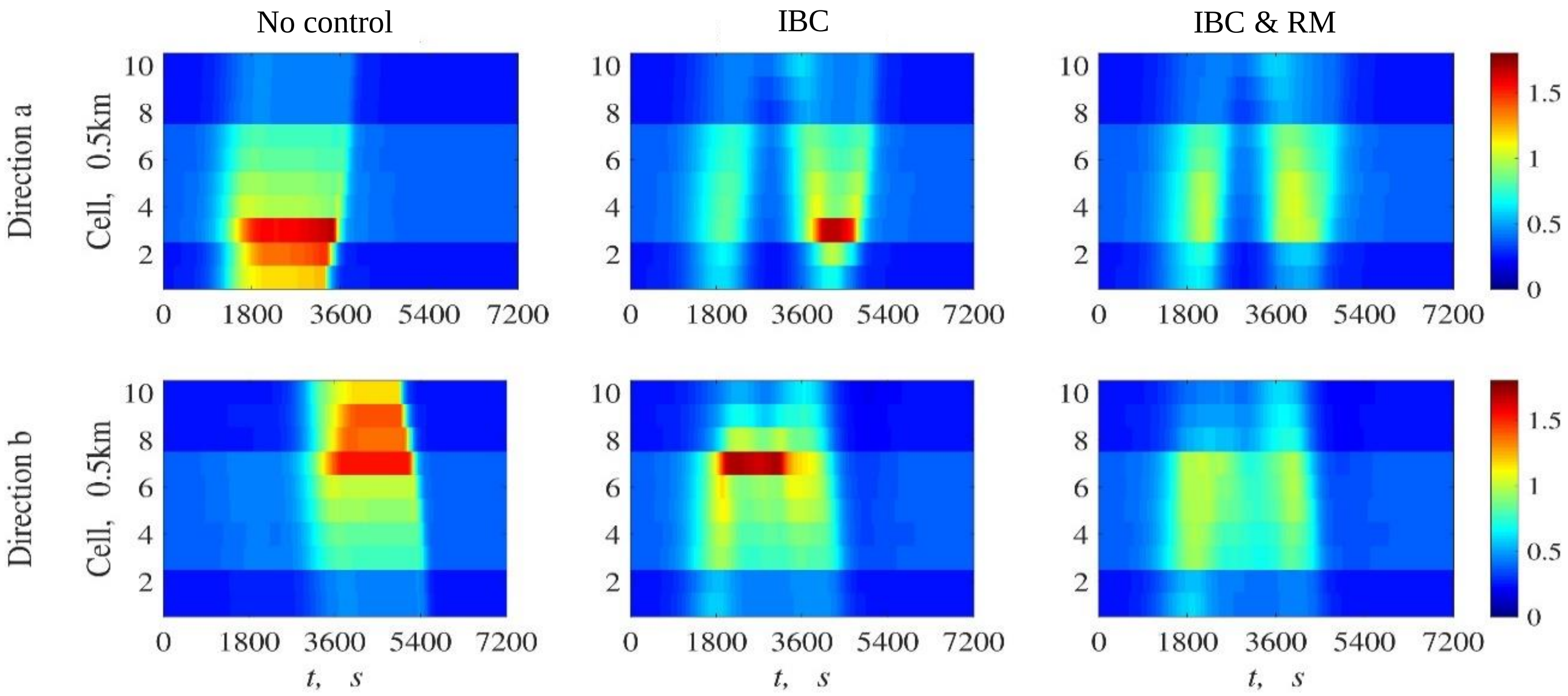
Case Study	Actuators	VHT improvement	Computational Time
On-ramp merging area (4 km)	8 IBC	20%	0.12s
On-ramp merging area (4 km)	8 IBC and 1 RM	21%	0.33s
Unbalanced directional demand (5 km)	10 IBC	19%	0.13s
Unbalanced directional demand (5 km)	10 IBC and 2 RM	22%	0.34s

Application II: Future highways

Case Study	Actuators	VHT improvement	Computational Time
Unbalanced directional demand (5 km)	10 IBC	19%	0.13s
Unbalanced directional demand (5 km)	10 IBC and 2 RM	22%	0.34s







✓ **Integrating RM with IBC** can further improve congestion at the on-ramp merging area.

Conclusion

II. Macroscopic level

Research objective: **Efficient** and **real-time** coordinated traffic control for contemporary and future highways

Contribution: Combined Feedback Linearization and MPC (FLMPC)

- It is formulated for generic highways; thus, it can be formulated for different **highway structures** and various **combinations of traffic control actuators**.
- New research on implementing FLMPC in **micro-simulation** shows the potential for **real-time** coordinated traffic control for **large-scale** highway systems. [1]
- It has the potential to provide the same level of **efficiency** as nonlinear MPC.

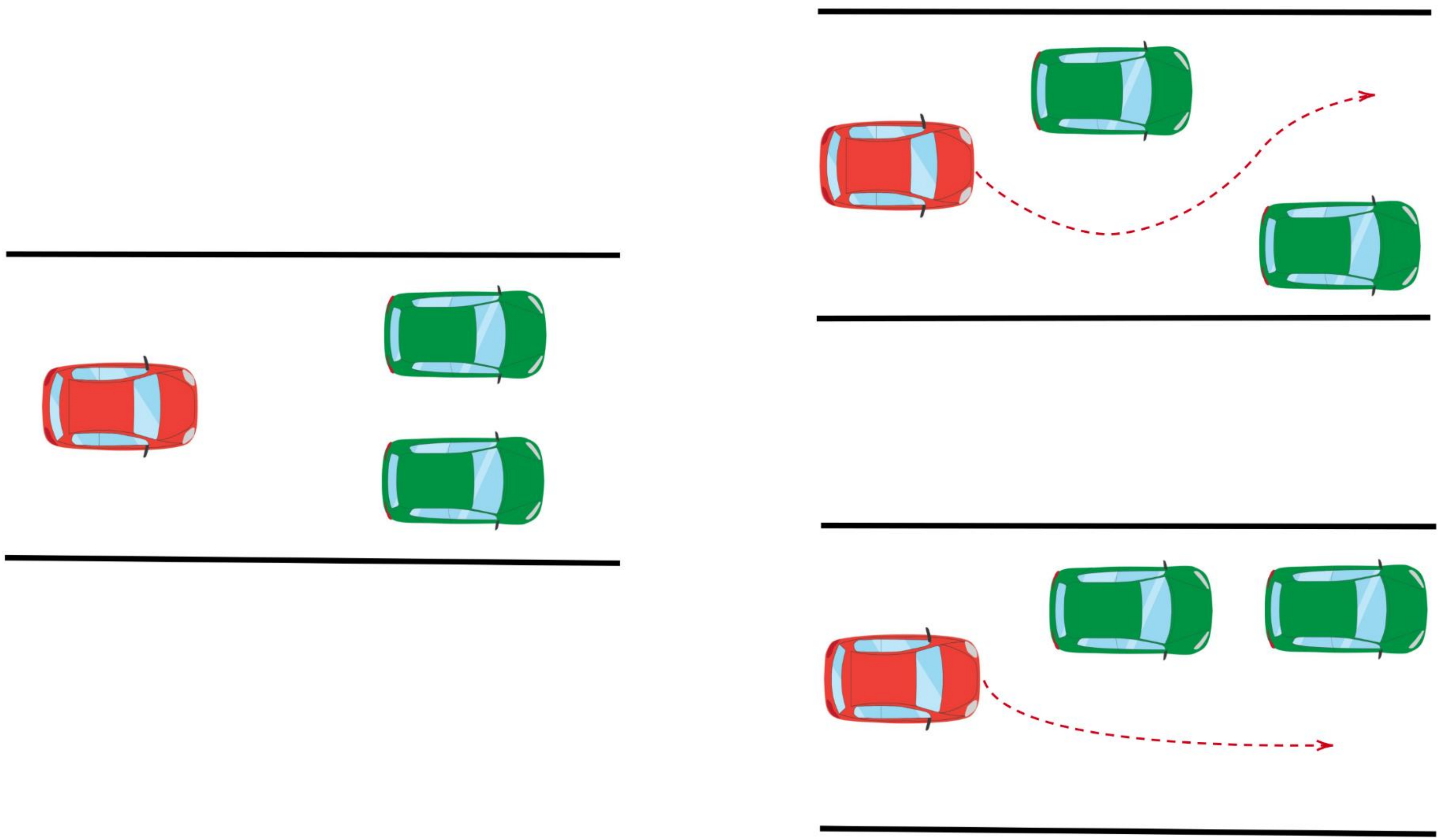
[1] Chuka, R. (2024). *Microscopic simulation for coordinated ramp metering in Antwerp ring road* [Master's thesis, ETH Zurich].

III. Microscopic level

Research objective: Fair, safe, and efficient lane-free traffic of CAVs
Contribution: Bi-level collaborative control for threatening vehicle clusters

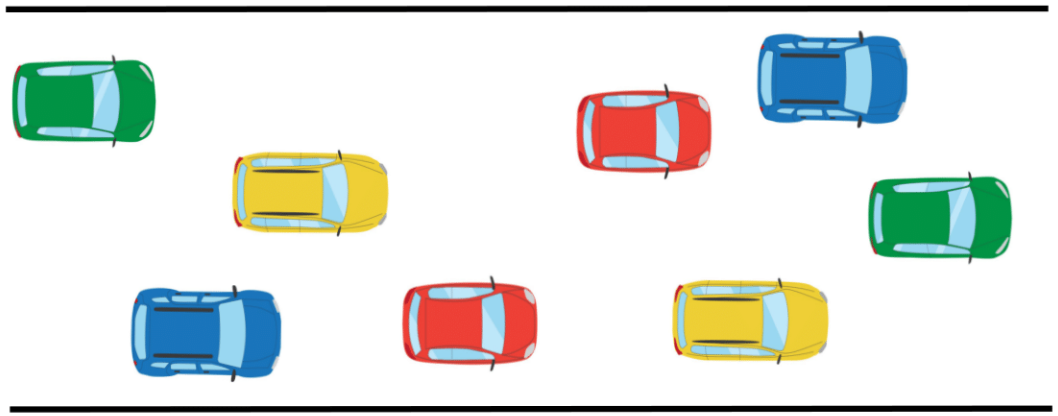
Chavoshi, K., Ferrara, A., & Kouvelas, A. (2024). Introducing fairness in lane-free traffic: The application of karma games to enforce fair collaboration of cavs. *TechRxiv*.

Why is fairness an important aspect of collaboration?



What is a **fair** solution?

Why Karma games are a potential solution for fairness?



"If I give in now, I will be rewarded in the future."[1]

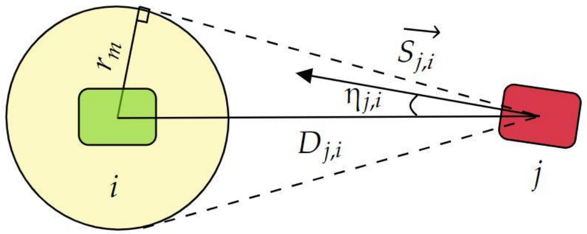
- Karma games are repeated auctions among self-interested **agents** that compete over a **resource**.
- Karma games result in **fair** resource allocation.
- We introduce modified Karma games (proportional resource allocation) for self-interested **CAVs** to compete over **priority values**.

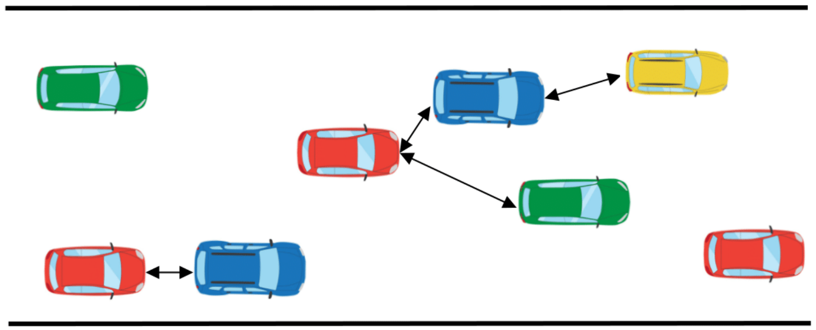
[1] Elokda, E., Bolognani, S., Censi, A., Dörfler, F., & Frazzoli, E. (2024). A self-contained karma economy for the dynamic allocation of common resources. *Dynamic Games and Applications*, *14*(3), 578-610.

Which CAVs should collaborate to ensure safety?

Step 1. Threat Detection:

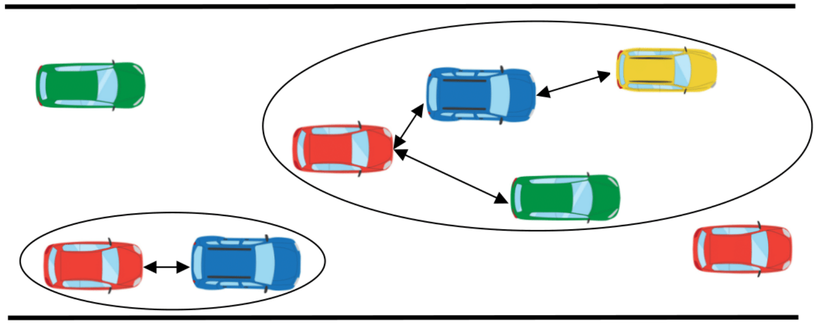
- Relative speed is heading towards safety margin.
- Estimated time to collision is smaller than a critical value.





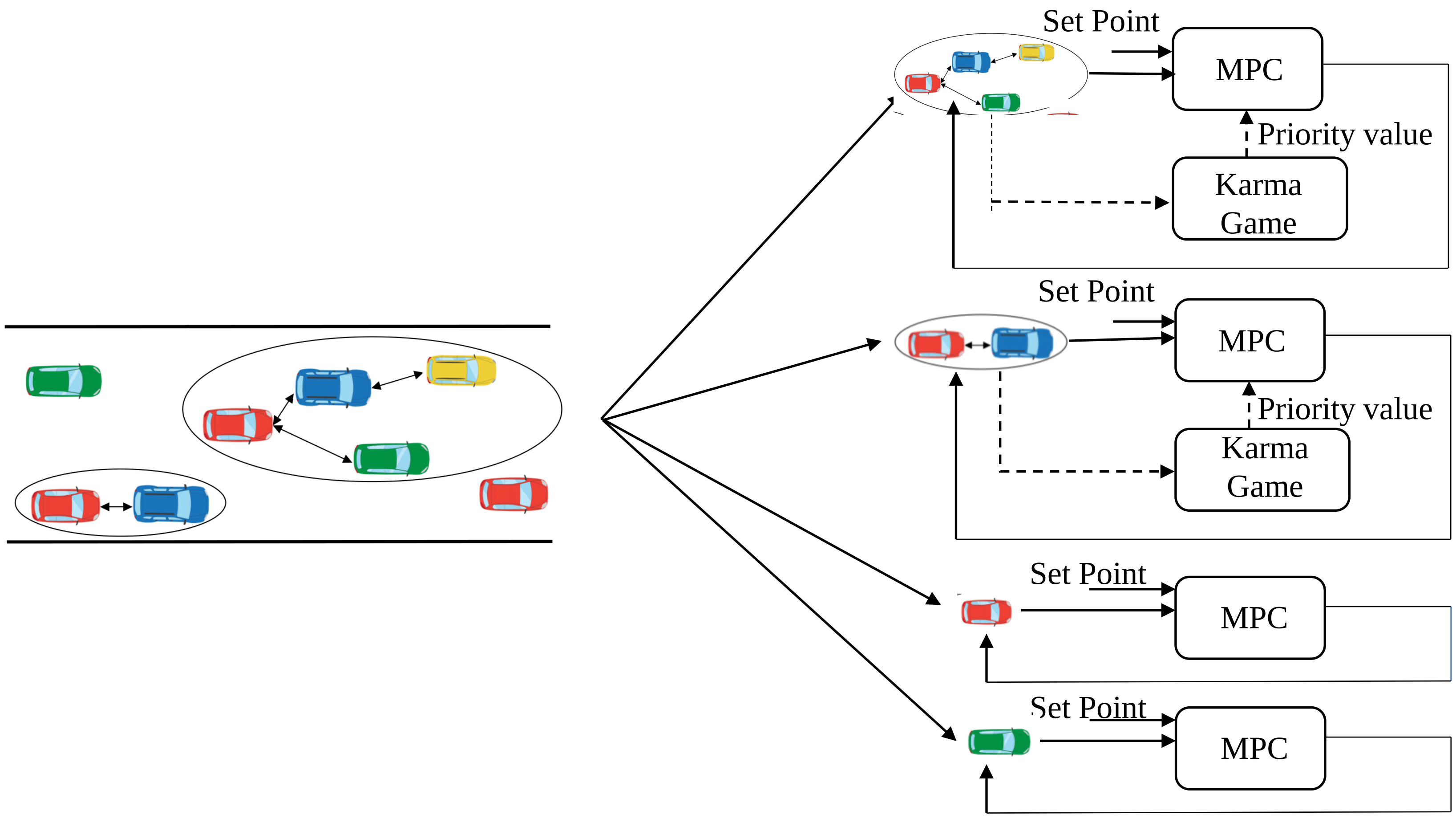
Step 2. Threatening Vehicle Cluster (TVC):

- Create a threat graph with vehicles as nodes and threat relationships as edges.
- Two vehicles are in a TVC if a path exists that connects them.

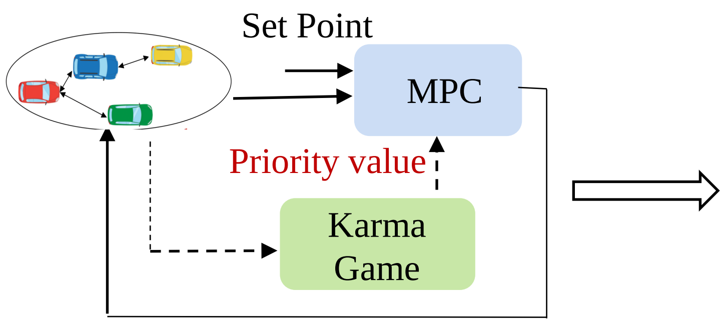


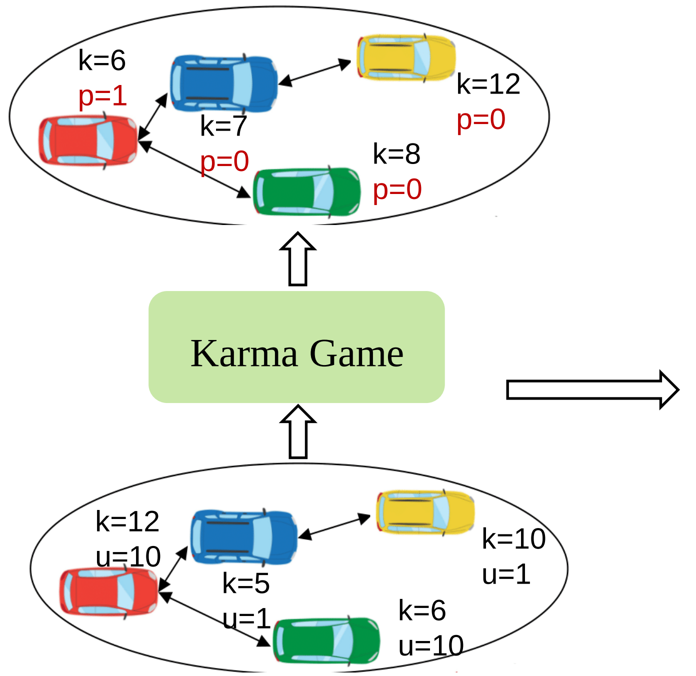
How can introducing TVC simplify the control problem?

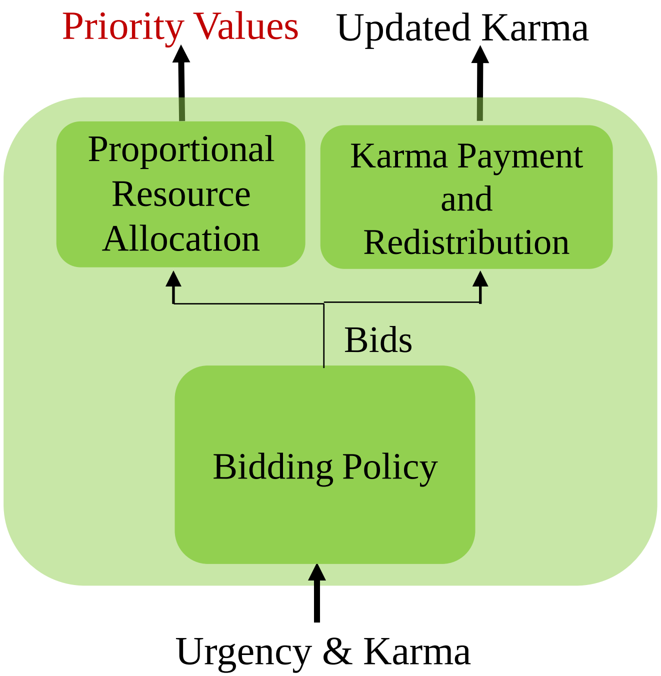
Instead of centralized control for all CAVs, we propose bi-level control for every TVC.



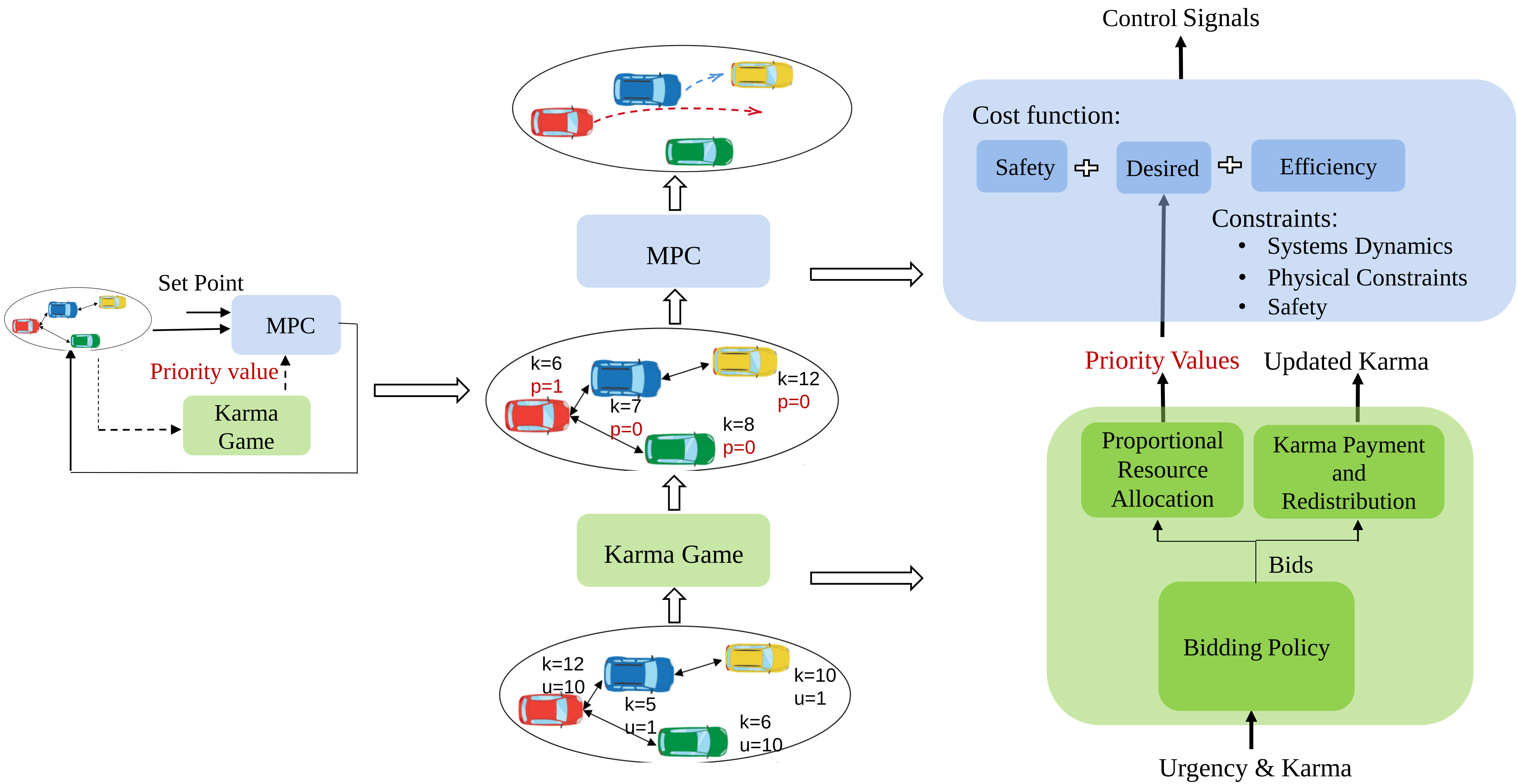
Karma games at lower-level control for TVC





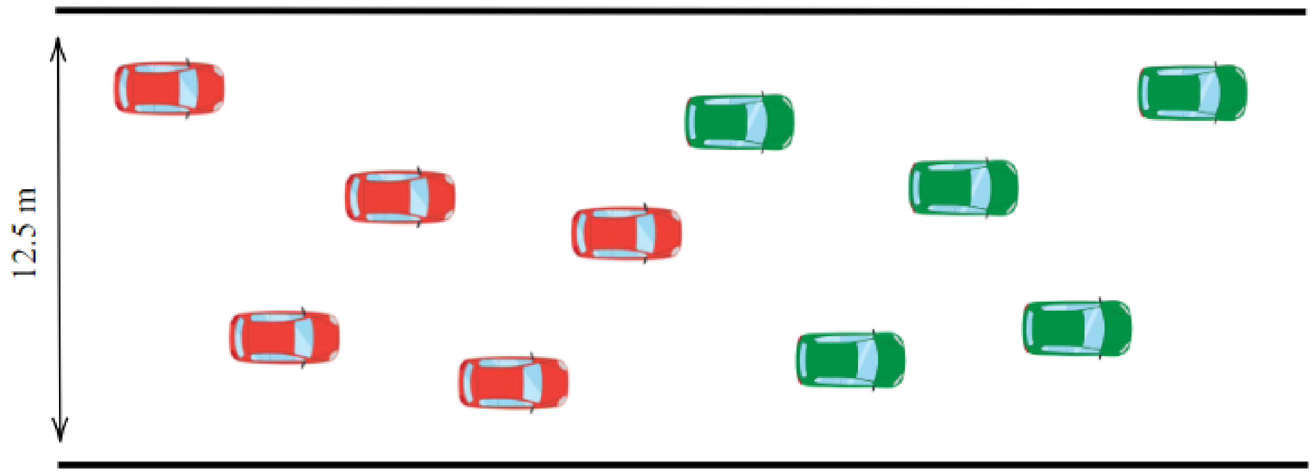


MPC at upper-level control for TVC



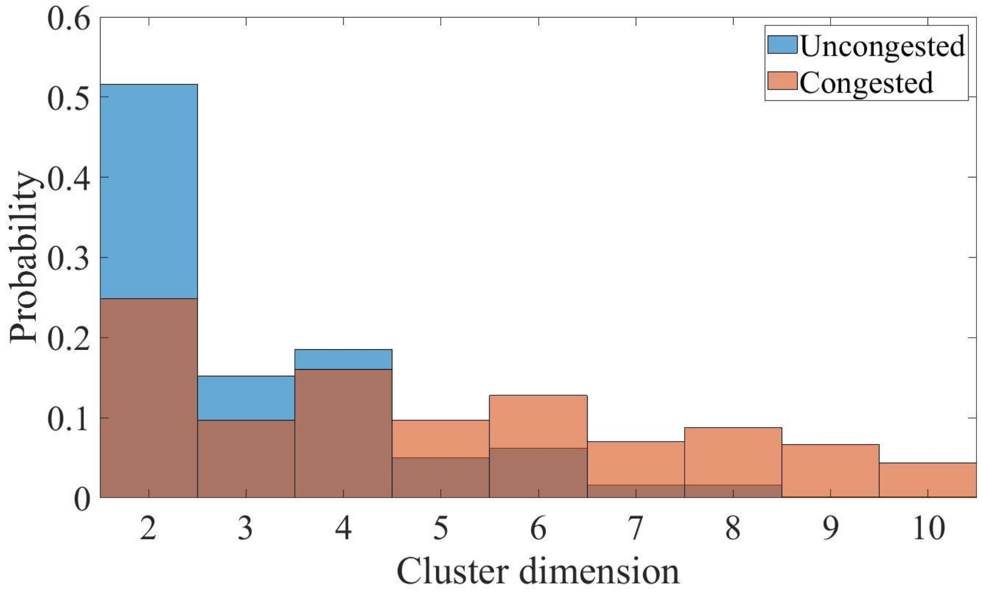
Simulation case study: Group overpass maneuver

- Green CAVs with desired speeds of 80km/h and red CAVs with desired speeds of 100km/h
- Uncongested (1s time gap) and congested (0.5s time gap) scenarios
- Every scenario is repeated ten times with random positioning of CAVs



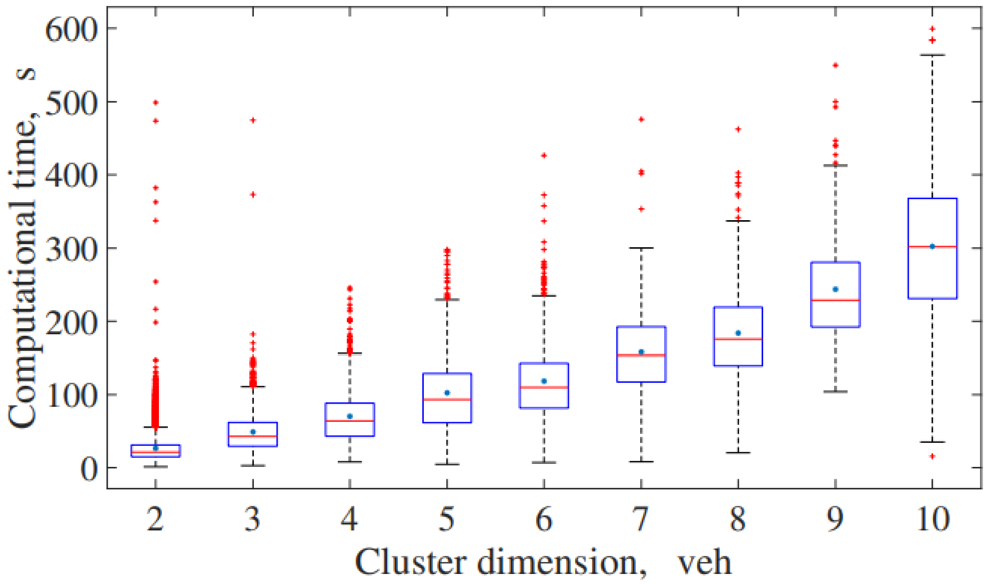
Analysis of TVCs at upper-level control

Cluster dimension:



✓ Denser Traffic flow leads to larger TVCs.

Computational time:



✓ Larger TVCs require higher computational time.

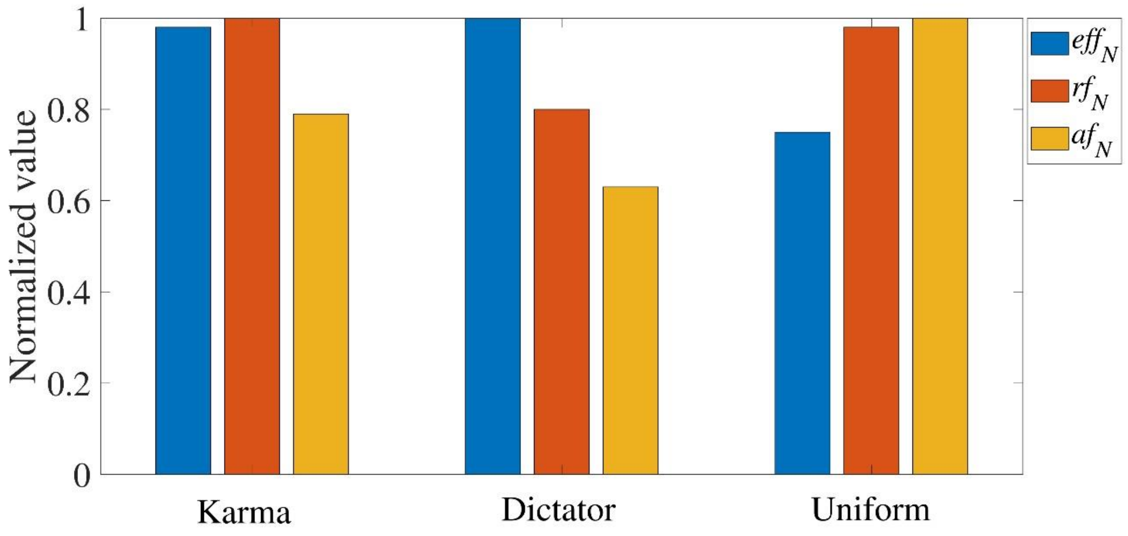
Evaluation of Karma game at lower-level control

Efficiency (*eff*):
Expected average reward (urgency times priority) per game

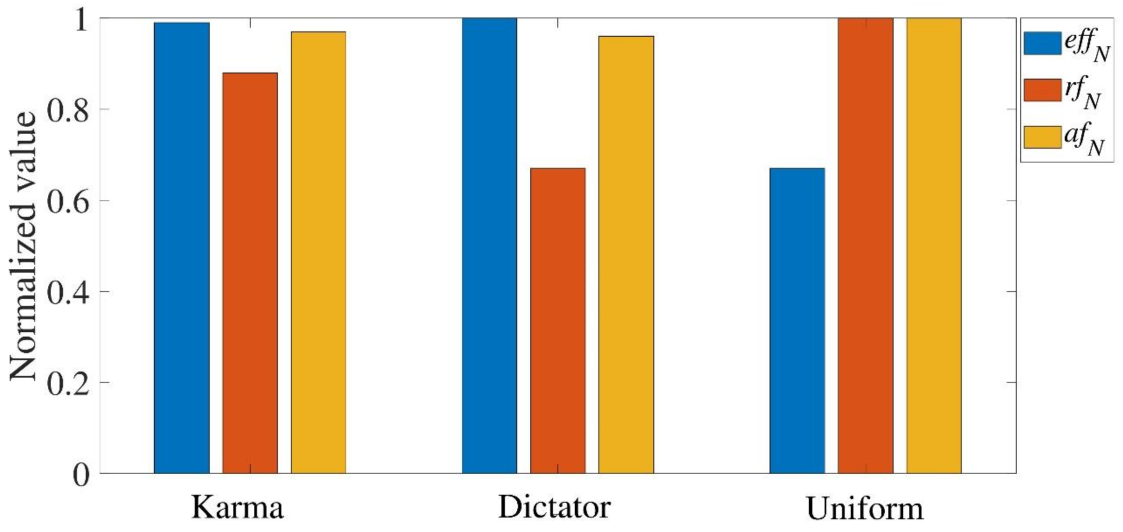
Reward Fairness (*rf*):
Standard deviation of Agent's average reward

Access Fairness (*af*):
Standard deviation of Agent's average access to resource

✓ Karma game is a **balanced approach** regarding **fairness and efficiency.**



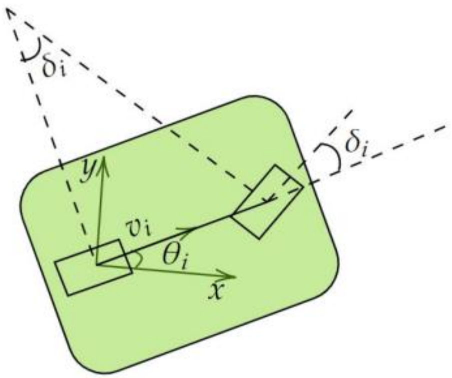
Uncongested scenario



Congested scenario

Analysis of collaborative bi-level controller

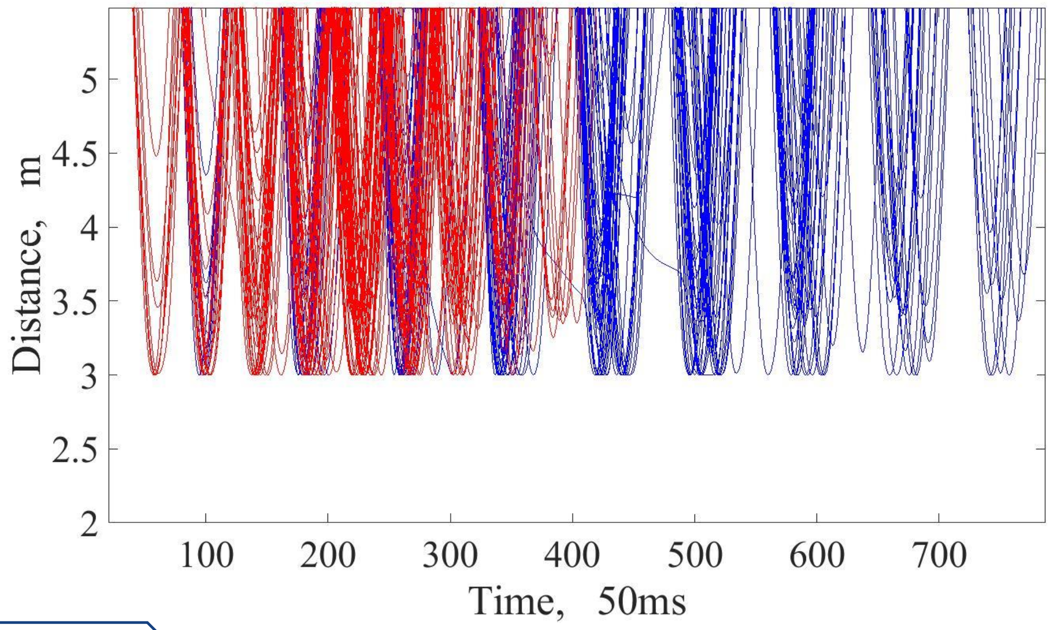
Efficiency:



Criterion	Uncongested Scenario		Congested Scenario	
	Mean	Max	Mean	Max
v_{rmse} (m/s)	0.359	0.495	0.322	0.428
θ_{rmse} (rad)	0.009	0.015	0.006	0.009
a_{rmse} (m^2/s)	0.465	0.636	0.463	0.605

✓ Controller provides **efficient** solution.

Safety:



✓ No **collision** was observed.

Conclusion

III. Microscopic level

Research objective: **Fair**, **safe**, and **efficient** lane-free traffic of CAVs

Contribution: Bi-level collaborative control for Threatening vehicle clusters (TVC)

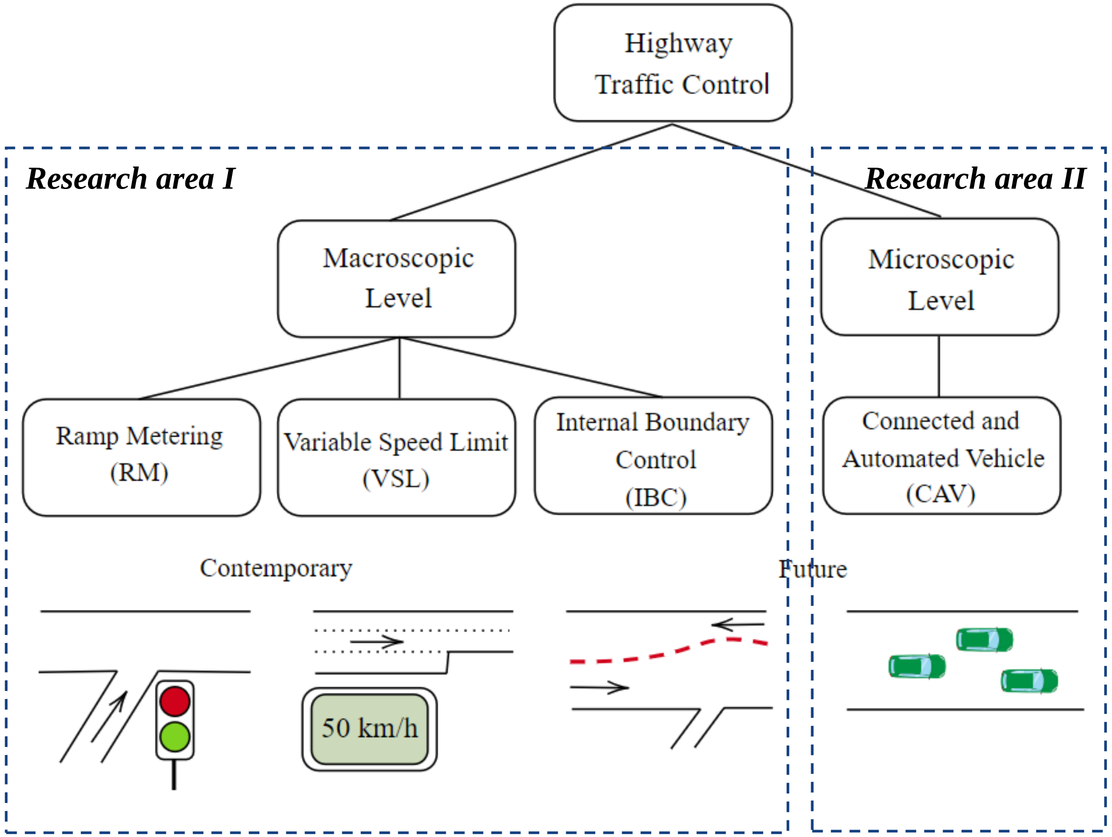
- Threat detection algorithm and TVC to ensure **safety** while **simplifying the problem**.
- Karma game at the lower level provides a **fair** distribution of priorities.
- MPC at the upper level provides multi-objectives (**fair**, **efficient**, and **safe)** control of CAVs within a TVC.

IV. Outlook

What is the outlook on future research?

Comprehensive traffic control

- Connecting **macroscopic** and **microscopic** levels
- **Integrate actuators** from both levels
- **Unify** traffic control **objectives** from both levels



Acknowledgment

- Committee:

Dr. Anastasios Kouvelas	(ETH Zurich)
Prof. Dr. Kay W. Axhausen	(ETH Zurich)
Prof. Dr. Francesco Corman	(ETH Zurich)
Prof. Dr. Antonella Ferrara	(University of Pavia)
Prof. Dr. Nikolas Geroliminis	(EPFL)
Prof. Dr. Mohsen Ramezani	(The University of Sydney)

- Chair:

Prof. Dr. Andrea Frangi	(ETH Zurich)

I sincerely appreciate all my research collaborators and scientific community members who supported me throughout this journey.

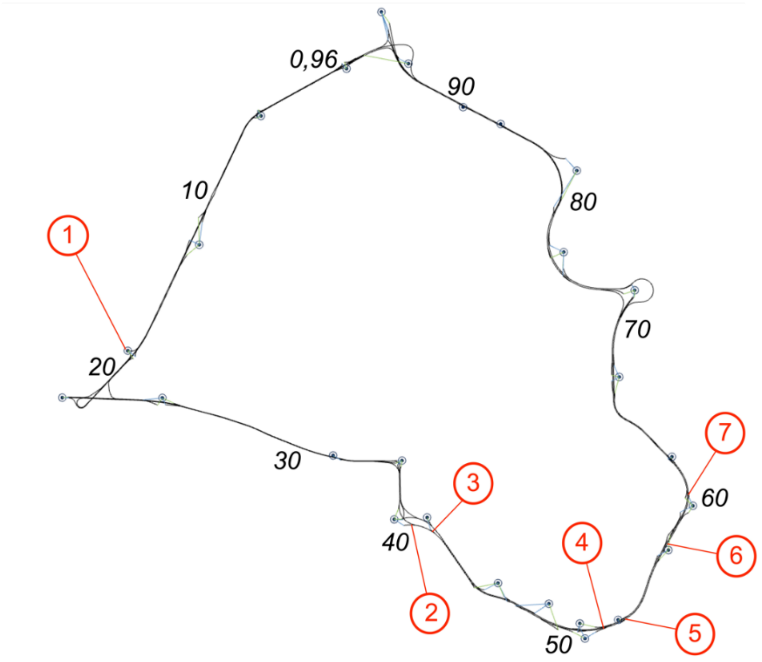
Discussion

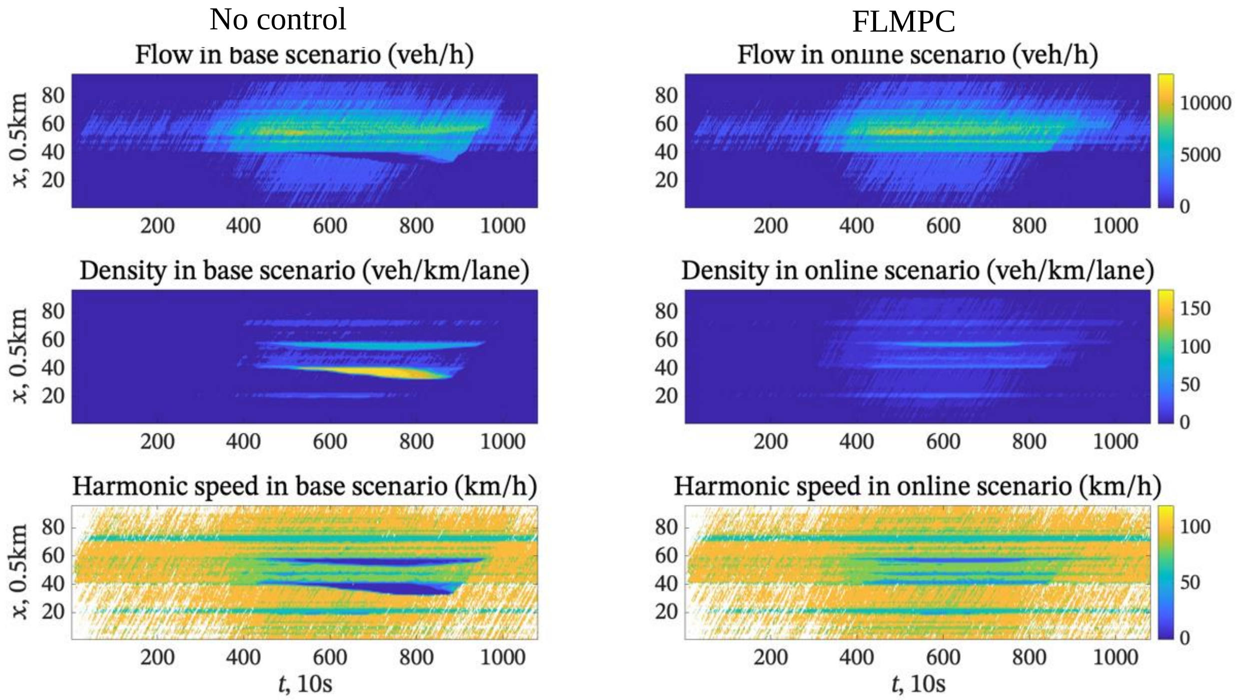
Backup

Micro-simulation for FLMPC

- Simulation software: AIMSUN
- Summary of results:

Case Study	Actuators	VHT Improvement	Computational Time
Antwerp ring road (48 km)	7 RM	9.7%	**0.9s**





Micro-simulation for FLMPC

Challenges: High fluctuation of control signals for RM.
Solution: An auxiliary variable defined as $\varepsilon_i(k) = U_i(k) - U_i(k-1)$, with $U_i(k)$ (input for nonlinear system) written as a function of $V_i(k)$(input for linear model).

$$\min \sum_{i=1}^{N} \sum_{k=t}^{t+k_{\mathrm{p}}-1} \left[(\rho_i(k) - \rho_i^{cr})^2 + \omega \varepsilon_i^2(k) \right],$$

Results: Ramp metering ratios in various scenarios, with different smoothing parameters: