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Digital Twin & Intelligenza Artificiale.
Innovazione tecnologica "As a Service "
per la gestione operativa
e la pianificazione tattico-strategica
della mobilità urbana sostenibile e interconnessa

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INTELLIGENTE E SOSTENIBILE

Ottimizzazione del Traffico

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Introduction

Agenda

- Introducing the MFD paradigm
- Multi-reservoir models
- Introducing the MPC
- Combined usage of MFD and MPC for control applications
- Example of applications (Route Guidance, Perimeter Control, Variable Speed Limit)

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Macroscopic Fundamental Diagram

Motivation

- Traffic congestion during the peak periods in some metropolitan areas becomes more serious than ever before.
- Numerous valuable studies have been carried out in the field of traffic control

- The complex network topology has influence on the heterogeneous distribution of traffic demands
- Traditional link-level modeling based optimization may lead to high computational effort, especially for large-scale networks.

- MFD rappresenta una tecnica di modellazione del traffico maggiormente aggregata

Macroscopic Fundamental Diagram

Definitions

The MFD is employed to depict the aggregated traffic flow models of traffic states within an urban network.

In this paradigm, the traffic states are described through two variables:
Accumulation;
Production.

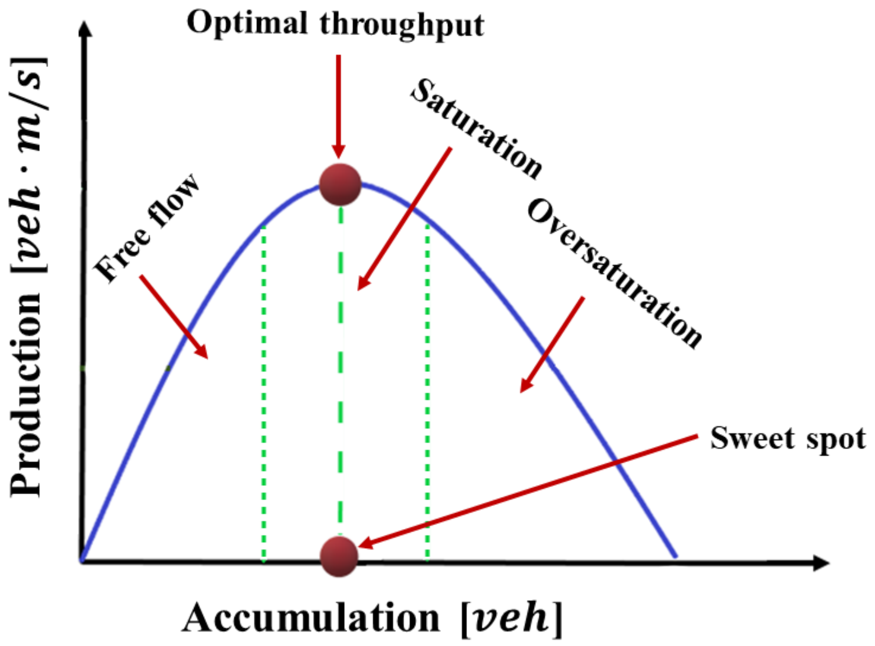
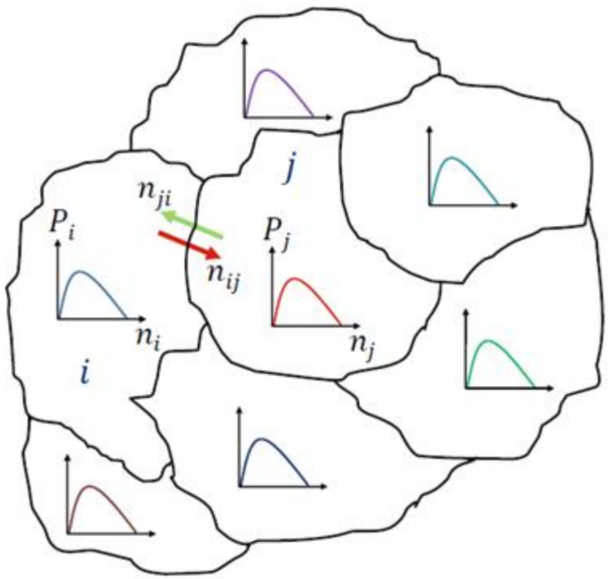


Figure shows a typical MFD curve of an urban network region distinguishing each operating condition on it (free flow, saturation, oversaturation). In the free flow regime, the accumulation values are lower than the critical accumulation value (i.e. sweet spot) and to an increase of accumulation, an increase of production corresponds. Beyond the critical value, the production decreases with the accumulation increasing since the region's capacity is reached. In the saturation regime, the region achieves its optimal operating conditions since the production is maximized and the zone reaches the optimal throughput.

Macroscopic Fundamental Diagram

Multi-reservoir approach

Frequently, the MFD is applied to different portions of an urban network, generating the so-called multi-reservoir models that allow the performing of Hierarchical control schemes. (Aboudolas and Geroliminis, 2013), (Ramezani et al., 2015), (Yildirimoglu et al., 2018), (Mariotte et al., 2020).



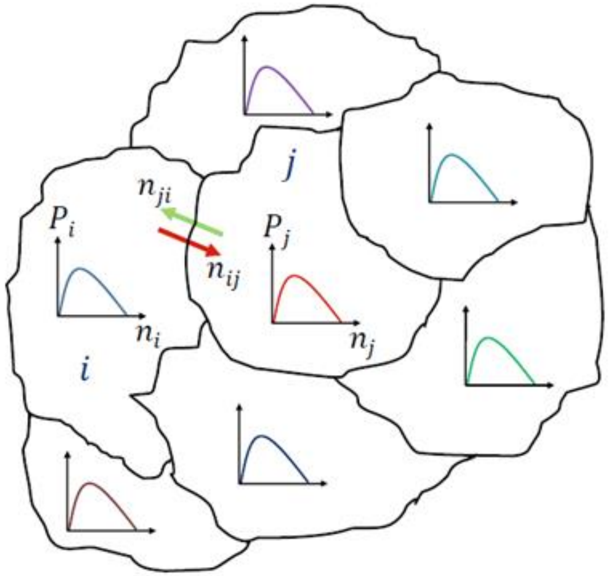
Macroscopic Fundamental Diagram

Multi-reservoir approach

Kouvelas A. et al., 2017

$$n_{ii}(k_p+1) = n_{ii}(k_p) + T_p\left(q_{ii}(k_p) - M_{ii}(k_p) - \sum_{h\in\mathcal{N}_i} M_{ii}^{h}(k_p) + \sum_{h\in\mathcal{N}_i} M_{hi}^{i}(k_p)\right) \quad (1)$$

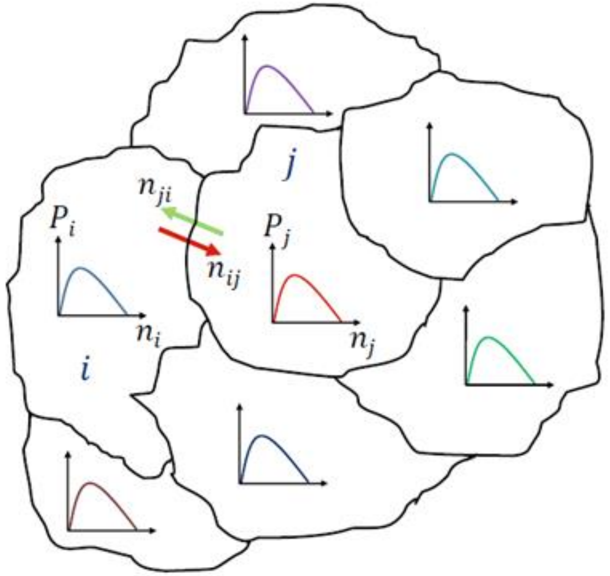
$$n_{ij}(k_p+1) = n_{ij}(k_p) + T_p\left(q_{ij}(k_p) - \sum_{h\in\mathcal{N}_i} M_{ij}^{h}(k_p) + \sum_{h\in\mathcal{N}_i} M_{hj}^{i}(k_p)\right) \quad (2)$$



- $\mathcal{N} = \{1,2,..,N\}$ regions set;
- $\mathcal{N}_i$ set of regions adijacent to i;
- $q_{ij}(k_p)\left[\frac{veh}{s}\right]$ traffic demand flow from i to j, aggregated at time T_p, at the time instant k_p;
- $n_{ij}(k_p)$ number of vehicle in i with j as destination;
- $M_{ii}(k)[veh/sec]$ is the internal trip completion rate of region i (without going through another region);
- $M_{ij}^{h}(k_p)\left[\frac{veh}{s}\right]$ transfer flow from i, to h in order to reach j (*transfer flows*);
- $n_i(k_p) = \sum_{j\in\mathcal{N}} n_{ij}(k_p)$ total accumulation in i.

Macroscopic Fundamental Diagram

Multi-reservoir approach



The transfer flows and the internal trip completion rates have the following expressions:

$$M_{ij}^{h}(k) = \min\left(C_{ih}\left(n_h(k)\right), \theta_{ij}^{h}(k)\frac{n_{ij}(k)}{n_i(k)}\frac{P_i\left(n_i(k)\right)}{L_i}\right),$$

$$M_{ii}(k) = \theta_{ii}(k)\frac{n_{ii}(k)}{n_i(k)}\frac{P_i\left(n_i(k)\right)}{L_i},$$

where:

- $P_i\left(n_i(k)\right)$ $[(vehm)/s]$ represents travel production, calculated through the **MFD function**;
- $\theta_{ij}^{h}(k) \in [0,1]$ and $\theta_{ii}(k) \in [0,1]$ the route choices, that reflect the percentage of choices of the route that involves crossing zone h, starting from zone i, to reach zone j and the percentage of choices of the route that involves remaining in zone i, to reach zone i, respectively;
- L_i the average trip length $[m]$, independent of the time and the destination area associated with the crossing of zone i;
- $C_{ih}\left(n_h(k)\right)$ $\left[\frac{veh}{s}\right]$ is the receiving capacity of the receiving region $h,$ presented as a piecewise function of the receiving zone accumulation n_h (Kouvelas et al., 2017).

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Model Predictive Control

Introduction

Model predictive control (MPC) has a long history in the field of control engineering.

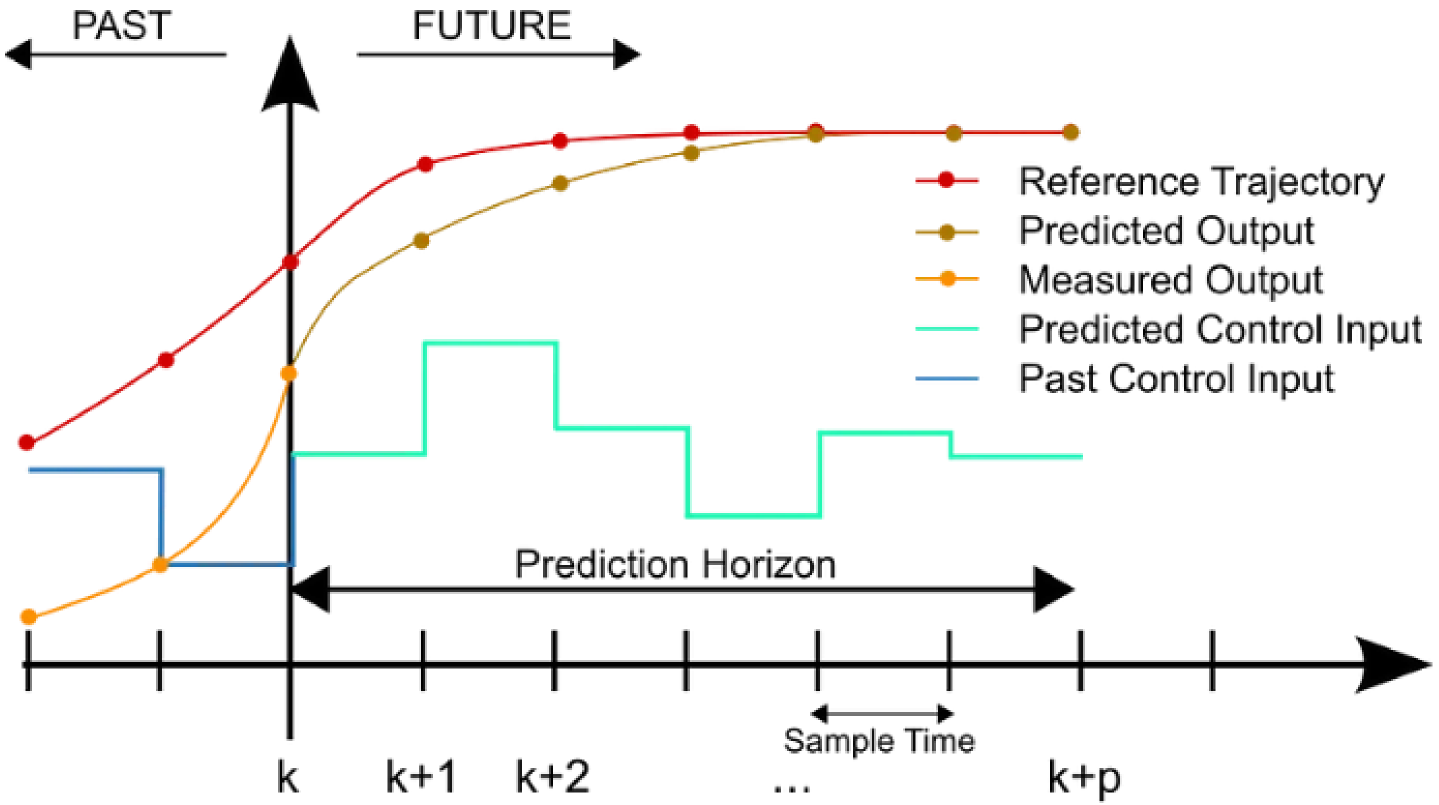
Receive on-going interest from researchers in both the industrial and academic communities.

Four major aspects of model predictive control make the design methodology attractive:

1. **Design formulation**, which uses a **completely multivariable system framework** where the performance parameters of the multivariable control system are related to the engineering aspects of the system; hence, they can be understood and 'tuned' by engineers.
2. **Ability** of the method **to handle both 'soft' constraints and hard constraints** in a multivariable control framework. This is particularly attractive to industries where tight profit margins and limits on the process operation are inevitably present.
3. **Ability to perform on-line process optimization**.
4. **Simplicity of the design framework** in handling all these complex issues.

Model Predictive Control

Functioning



Model Predictive Control

Equations

$$x(k+1) = Ax(k) + B\Delta u(k)$$

$$y(k) = Cx(k).$$ **(STATE SPACE MODEL A,B,C)**

Prediction of State and Output Variables:

Assuming that at the sampling instant $k_i, k_i > 0$, the state variable vector $x(k_i)$ is available through measurement, the state $x(k_i)$ provides the current plant information. The future control trajectory is denoted by

$$\Delta u(k_i), \Delta u(k_i + 1), \ldots, \Delta u(k_i + N_c - 1),$$

where N_c is called the control horizon dictating the number of parameters used to capture the future control trajectory (typically $N_c \leq N_p$).

With given information $x(k_i)$, the future state variables are predicted for N_p number of samples, where N_p is called the prediction horizon and it also represents the length of the optimization window. We denote the future state variables as

$$x(k_i + 1 \,|k_i), x(k_i + 2 \,|k_i), \ldots, x(k_i + m \mid k_i), \ldots, x(k_i + Np \mid k_i),$$

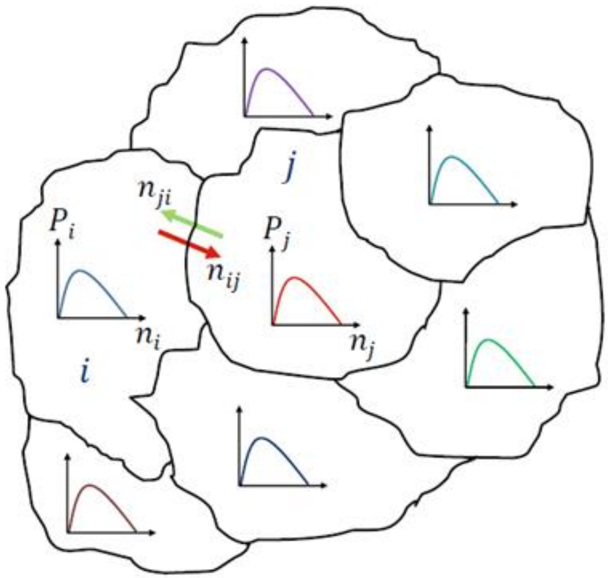
where $x(k_i + m \,|k_i)$ is the predicted state variable at $k_i + m$ with given current plant information $x(k_i)$.

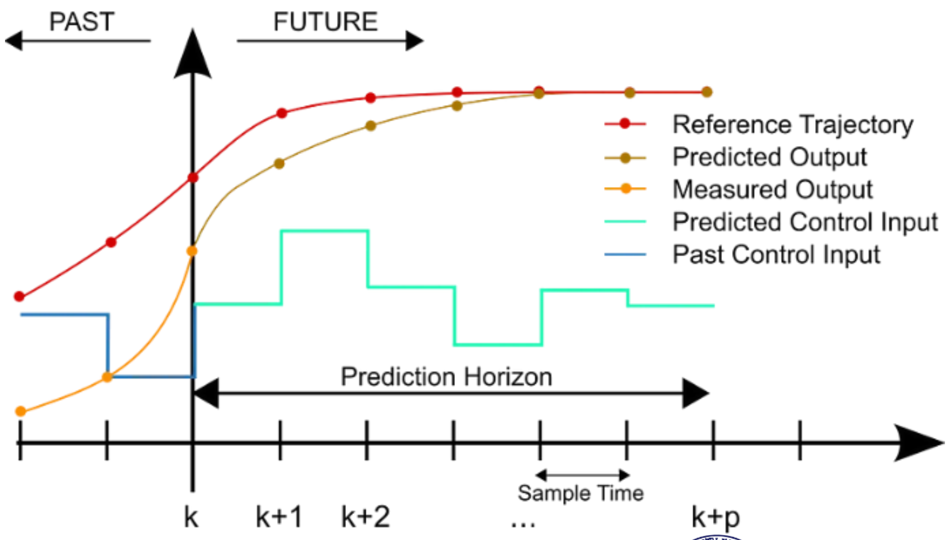
Model Predictive Control

Adaptation to the traffic control

Using an MPC for traffic control applications:

1. Defining constraints to apply to traffic states and control inputs.
2. Utilizing a mathematical model to represent the traffic states.
3. Considering the potential access to forthcoming information regarding the network's status.





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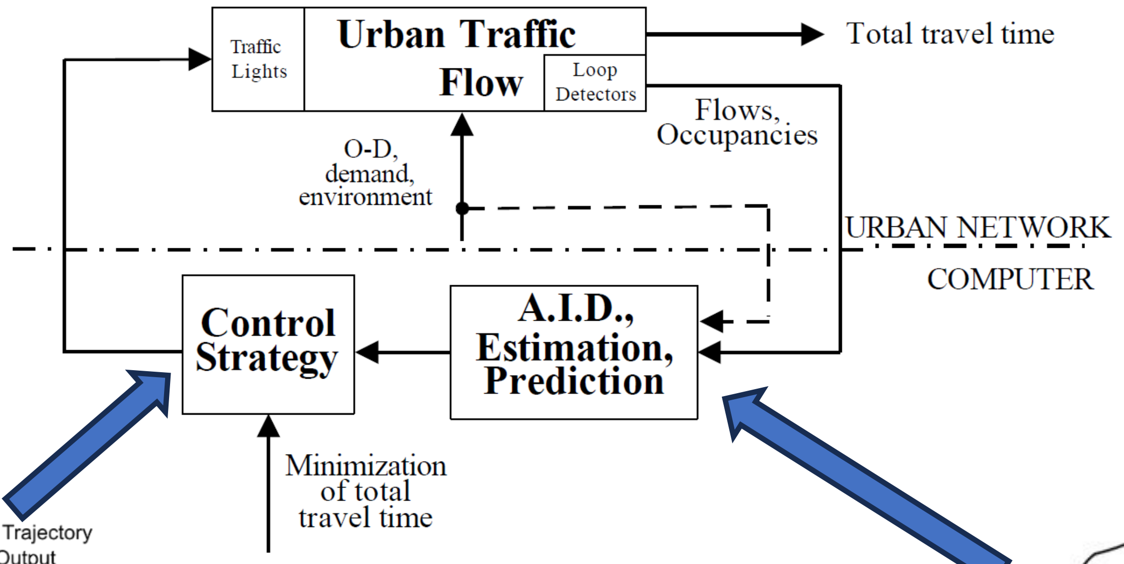
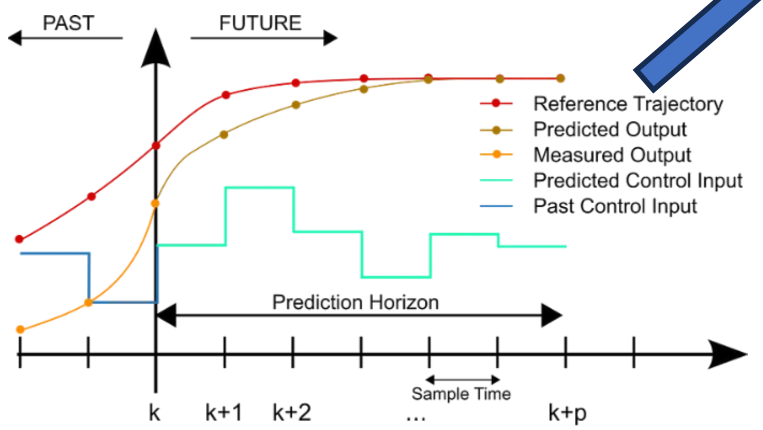
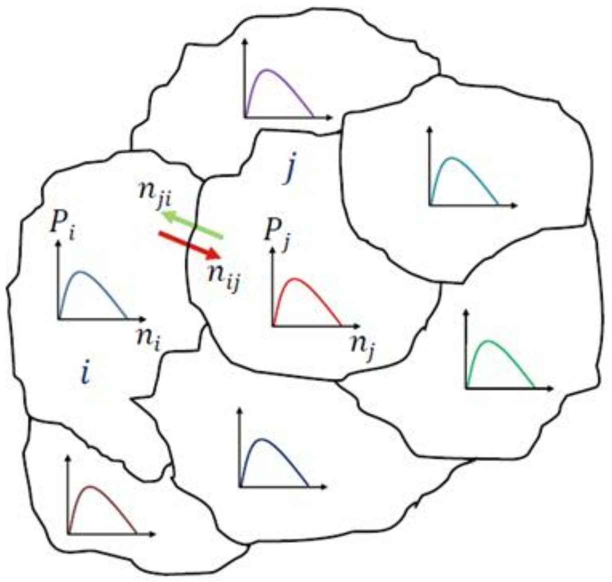
Model Predictive Control

Adaptation to the traffic control





Example: Urban traffic control system



Applications

Main applications

The combined use of Macroscopic Fundamental Diagram (MFD) and Model Predictive Control (MPC) enables efficient management of traffic flow through diverse applications. This integration is pivotal for adaptive and effective traffic control.

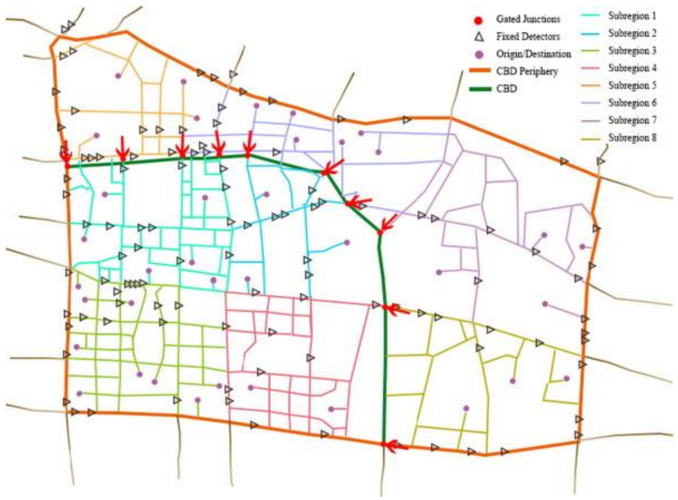
Key Control Application

1) Route Guidance

- Directs vehicles towards optimized routes to avoid congestion and improve traffic distribution.
- MFD provides real-time traffic conditions across regions.
- MPC predicts traffic evolution and dynamically updates routing recommendations.

2) Perimeter Control

- Regulates the inflow and outflow of vehicles into urban regions or controlled areas to prevent over-saturation.
- MFD monitors traffic density and critical thresholds.
- MPC optimizes gate control policies to balance traffic inside and outside the perimeter.



Fu, H. et al. (2017).

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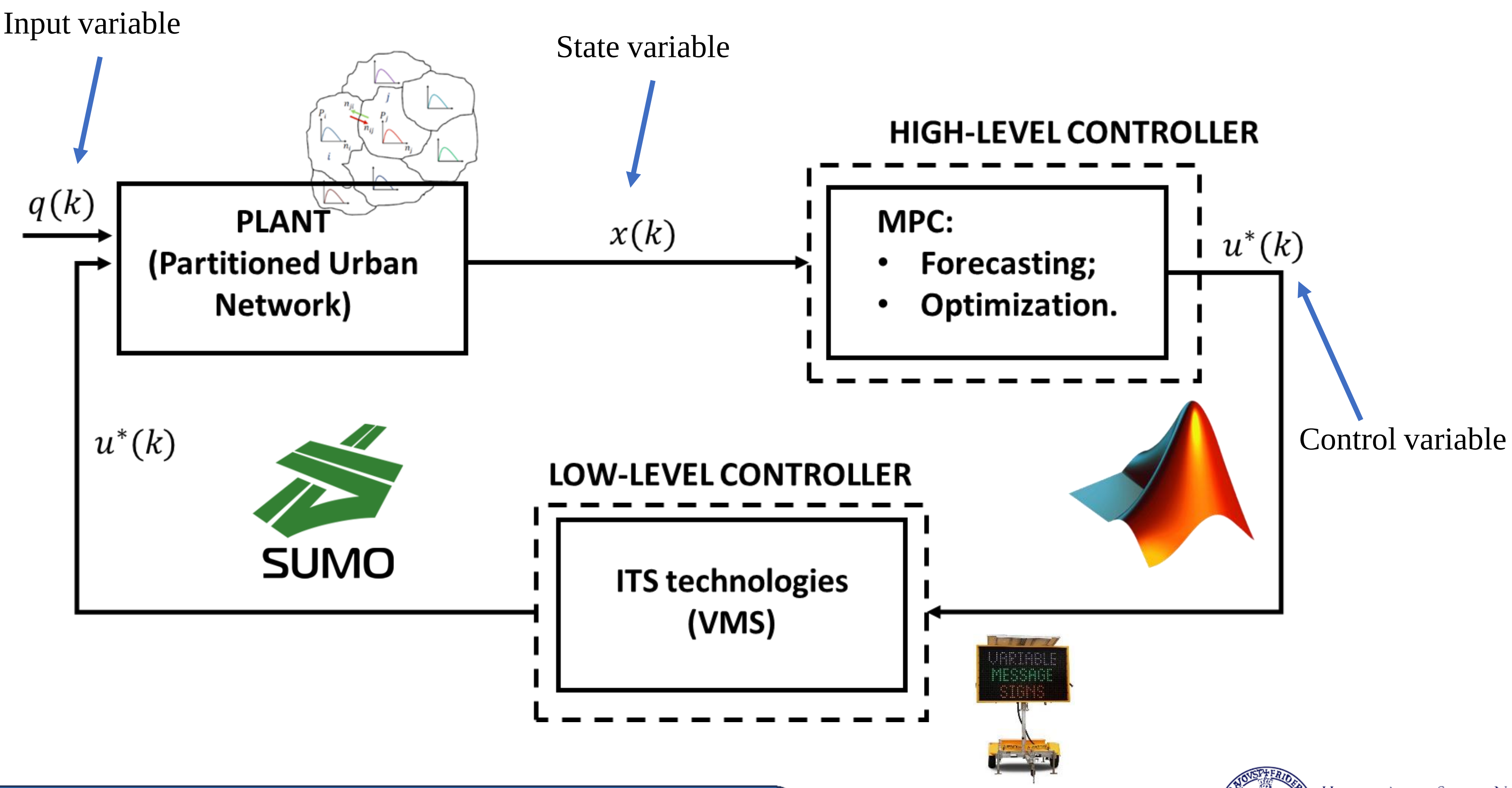
Applications

Routing application example

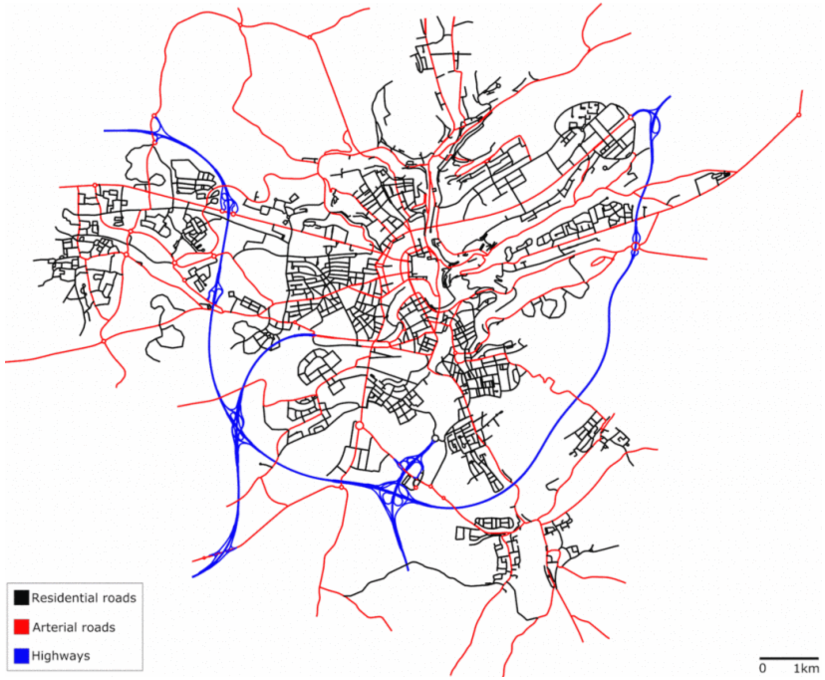
Block Diagram:



Applications

Luxemburg case study

Area	$155.95km^2$	**Intersections**	4473
Total roads	$930.11km$	**Traffic lights**	203
Highways only	$88.79km$	**Inductive loops**	3157
Bus Stops	561	**Car Parks**	175
Bus lines	38	**Buildings**	13553



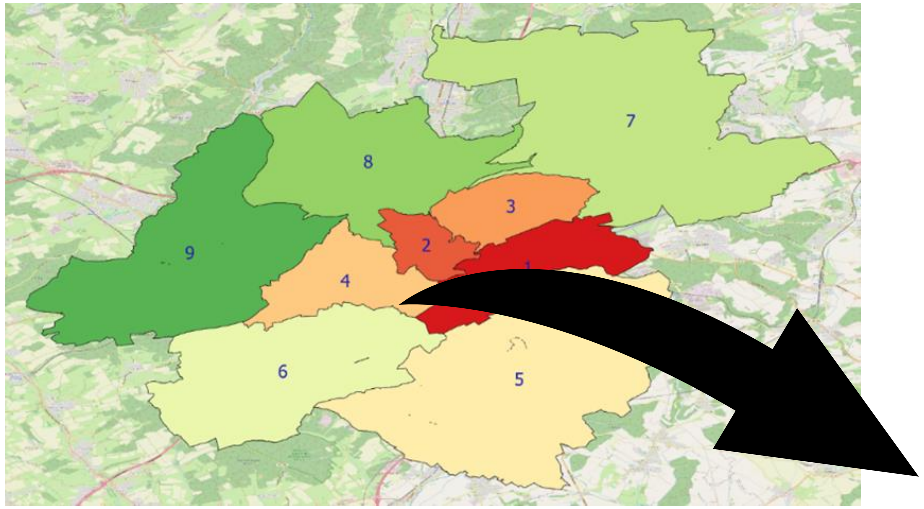
(Codeca et al., 2015)

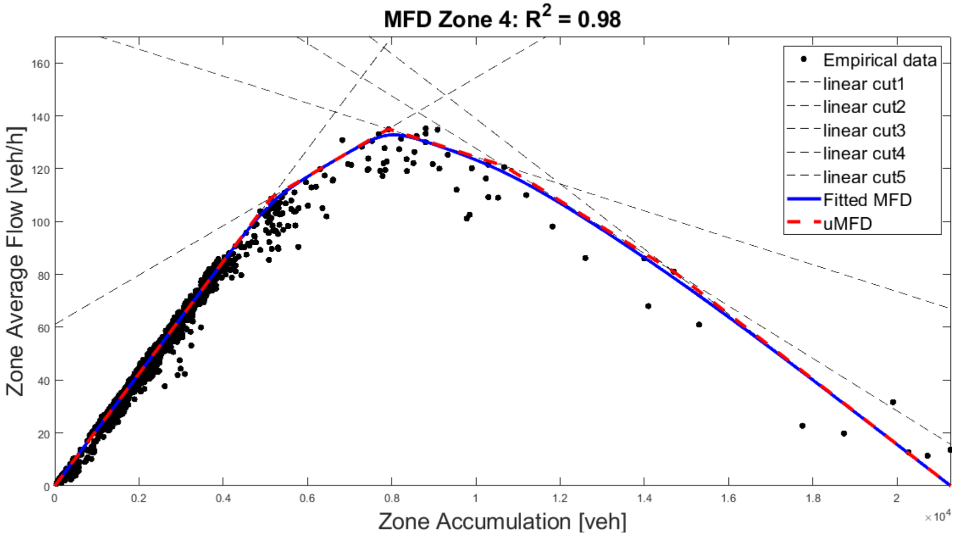
To achieve realistic traffic patterns data published by the government are used, which is available on the Internet site of the Luxembourg National Institute of Statistics and Economic Studies (STATEC) (https://www.statistiques.public.lu) (e.g. population, age distribution). The used traffic demand is characterized by 300000 vehicles per day.

Applications

Luxemburg schematization

<u>Zoning of the network and MFDs calibration</u> :





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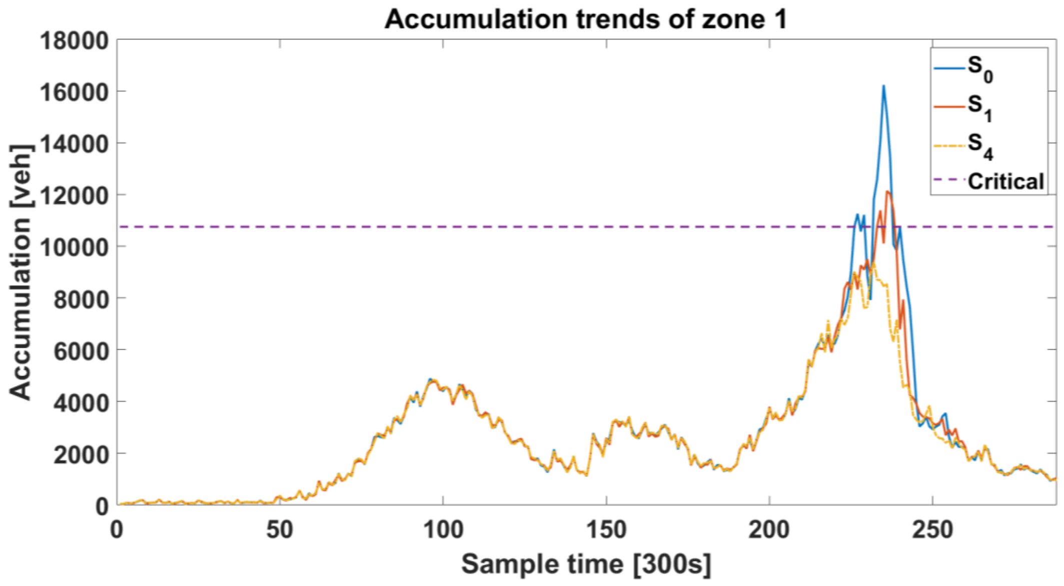
Applications

Controller tuning

T_p [min]	$N_p = 4$	$N_p = 5$	$N_p = 6$	$N_p = 7$
5	S_1	S_2	S_3	S_4
10	S_5	S_6	S_7	S_8
15	S_9	S_{10}	S_{11}	S_{12}
20	S_{13}	S_{14}	S_{15}	S_{16}

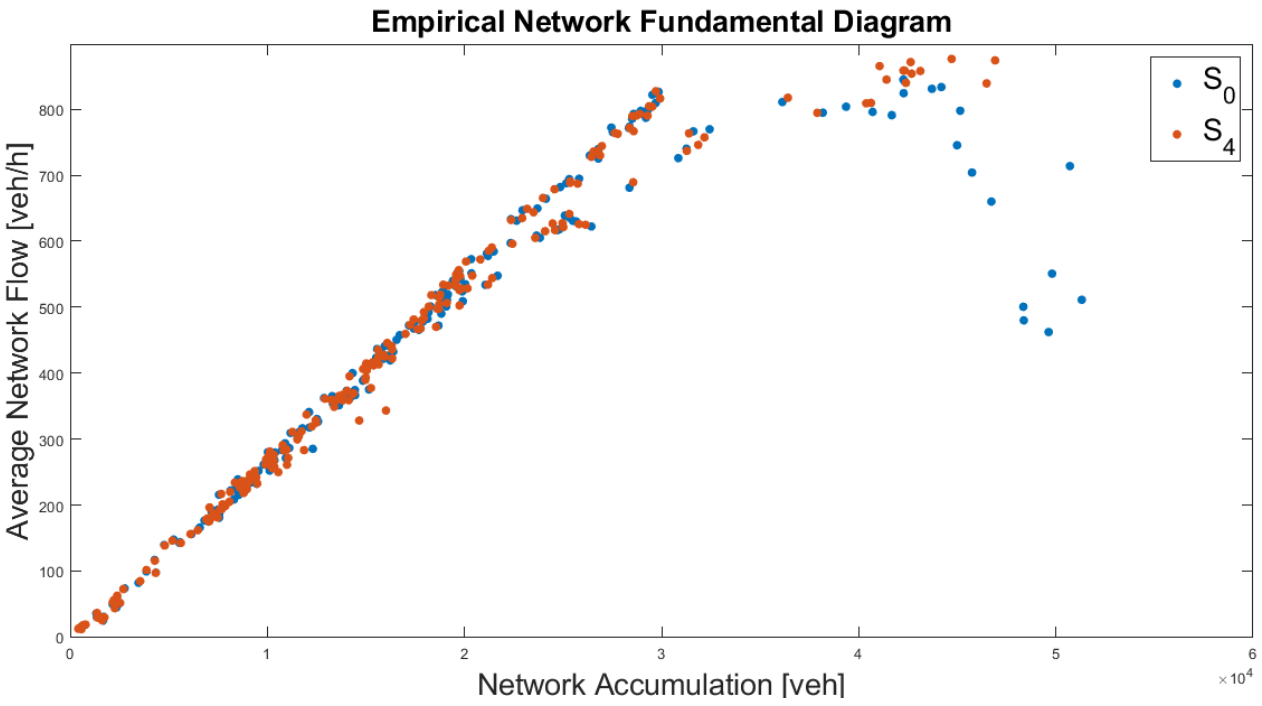


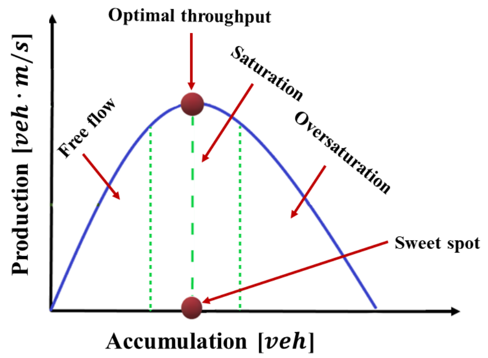
Scenarios	Zone 1		Zone 2		Zone 4	
	$s_{\%}$	$\Delta[min]$	$s_{\%}$	$\Delta[min]$	$s_{\%}$	$\Delta[min]$
S_0	51	35	193	183	23	20
S_1	8	13	161	178	20	25
S_2	-2	0	168	169	14	20
S_3	-25	0	170	166	17	20
S_4	**-25**	**0**	**170**	**165**	**17**	**20**

Applications

Improvements

Scenario	Number of arrived vehicles
S_0	266604
S_1	+6.2%
S_2	+6.5%
S_3	+6.8%
S_4	+7.0%
S_{23}	255595
S_{24}	+13.3% (w.r.t. S_{23})





Future perspectives

- Generally speaking the proposed approach is fascinating
- Worthy of further investigation

- **More interestingly**, fully compatible with the OPTIFaaS environment

- Integration and experiments already ongoing

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Grazie per l'attenzione!

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