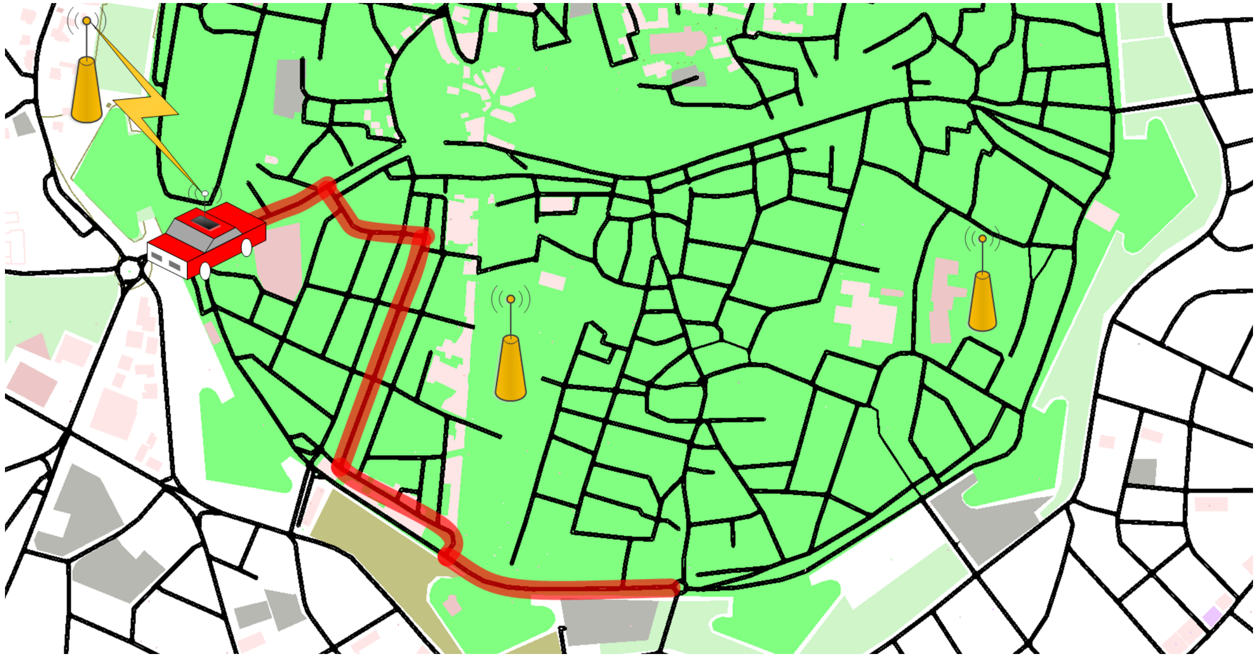
Dynamic demand management and routing in urban traffic networks



STELIOS TIMOTHEOU

ASSISTANT PROFESSOR

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

KIOS RESEARCH AND INNOVATION CENTER OF EXCELLENCE

UNIVERSITY OF CYPRUS

Joint work with C. Menelaou, P. Kolios, C. Panayiotou

KIOS
Research and Innovation Center of Excellence

Name Origin

Greek mythology: “Kios” from the Greek *Κοῖος* (Kee-os) the Titan of inquisitive mind and the questioning intelligence

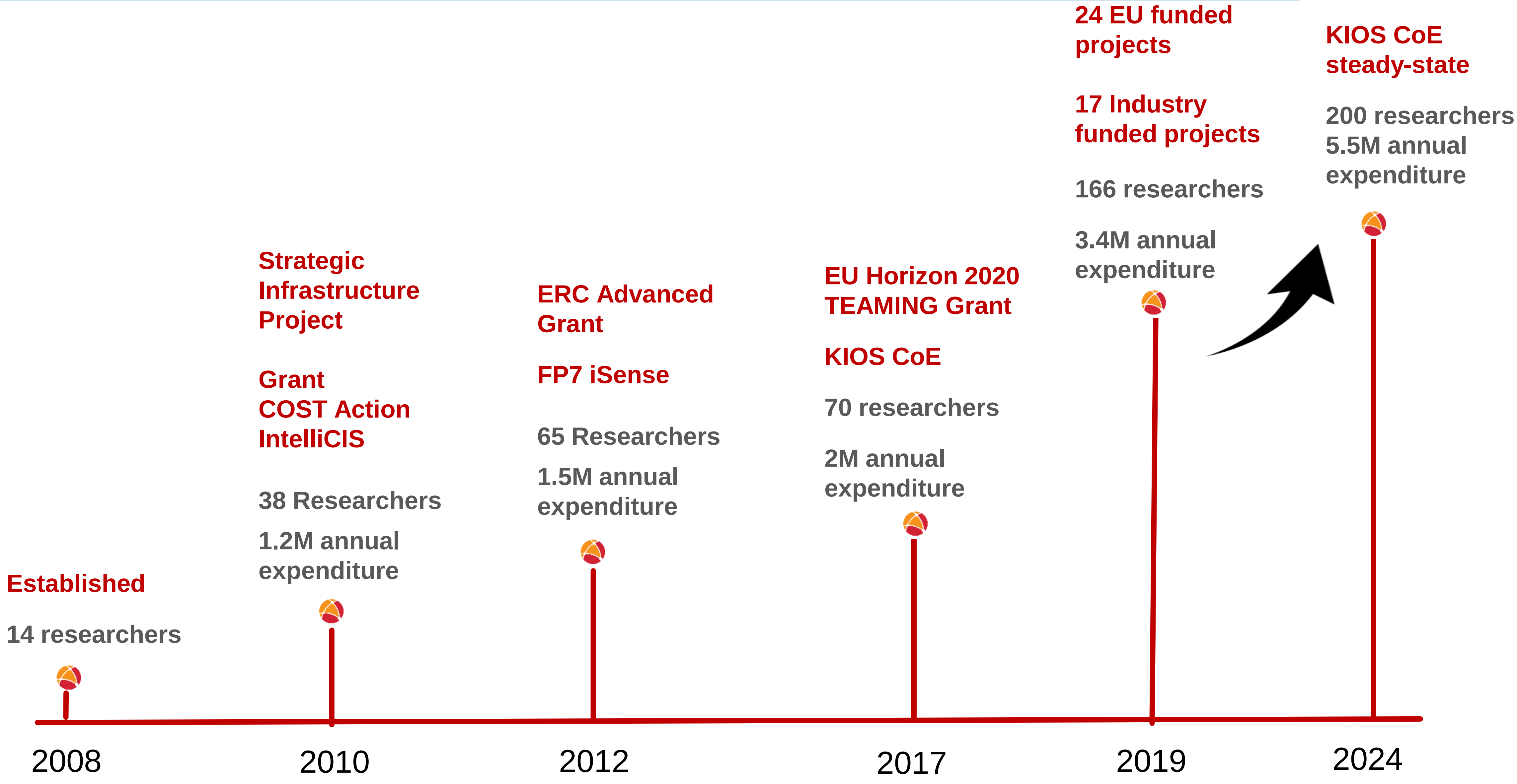
Our Mission & Vision

- To conduct multidisciplinary research and innovation in the area of Information and Communication Technologies (ICT) with emphasis on the Monitoring, Control, Security and Management of Critical Infrastructures
- To provide an inspiring environment for conducting excellent, cutting-edge research at a global scale, producing new knowledge that can be applied to solve timely and real-life problems in the considered Critical Infrastructure Systems (CIS)

KIOS at a Glance

- KIOS Research Center was established as a research unit in 2008
- Strategic Infrastructure Project
  (*Desmi 2008 – EU Structural Funds*)
- KIOS elevated to a Center of Excellence
  (CoE) in 2017 (*EU TEAMING HORIZON 2020*)
- Operates within the University of Cyprus (at the level of Faculty)
- Collaborates strategically with *Imperial College, London*
- Creates synergies with national and international industrial and governmental organizations

KIOS Growth Path



2008

Established

14 researchers

2010

Strategic Infrastructure Project

Grant
COST Action IntelliCIS

38 Researchers

1.2M annual expenditure

2012

ERC Advanced Grant

FP7 iSense

65 Researchers

1.5M annual expenditure

2017

EU Horizon 2020 TEAMING Grant

KIOS CoE

70 researchers

2M annual expenditure

2019

24 EU funded projects

17 Industry funded projects

166 researchers

3.4M annual expenditure

2024

KIOS CoE steady-state

200 researchers
5.5M annual expenditure

KIOS at a Glance - Research

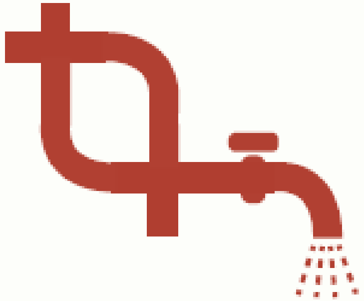
Technical focus & specialization

Intelligent monitoring, control, management and security of complex, large-scale, dynamical systems

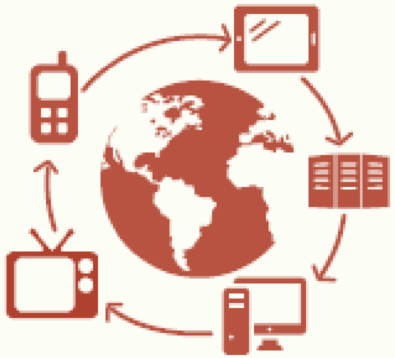
Application Areas → Critical Infrastructure Systems

Energy & Power Systems

Intelligent Transportation Systems



Water Systems & Environmental Monitoring



Telecommunication Systems & Networks

Emergency Management Response

KIOS at a Glance - Research

Critical Infrastructure Systems (CIS)

Heterogeneous - Interdependent - Interconnected

Risks, Faults, Attacks

Information Communication Technologies (ICT)

Sensors, Actuators
Big Data, Internet of Things

Intelligent Systems and Networks

Monitoring, Control
Management, Security

Big Data → Smart Decisions

KIOS CoE Current State

- **153** people at KIOS CoE (+13 people at the KIOS CoE spoke at Imperial College London)
- **24** active multi-disciplinary research projects funded by international, EU and national funding agencies
- **17** active industry funded projects via the **KIOS Innovation Hub**
- **New MSc Program in Intelligent Critical Infrastructures**
- **New CIS testbed facilities**

KIOS CoE group photo September 2019

Motivation

Motivation

Motivation

Daily chart

The hidden cost of congestion

In rich countries, city-dwellers lose nearly $1,000 a year while sitting in traffic

Cost of congestion: The growing problem of advanced economies

Traffic congestion countermeasures

Infrastructure Expansion

- Building new roads.
- Widening arterial roads.
- Widening roads/intersections.

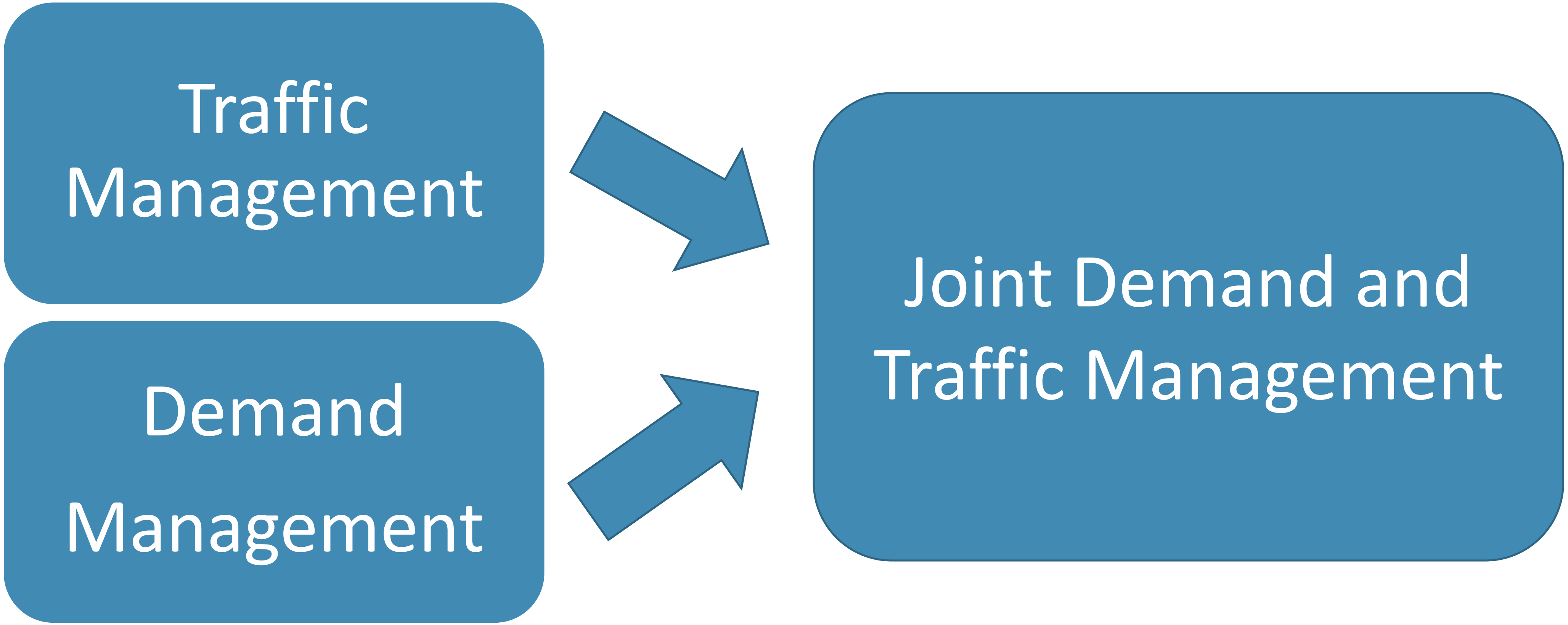
Traffic Management

- Perimeter Control/Gating.
- Ramp Metering.
- Route Guidance.
- Expanding the supply and availability of travelling modes.

Demand Management

- Providing incentives and rewards for sustainable travel habits.
- Imposing pricing and tolling schemes.

Traffic congestion countermeasures



Traffic Management

Demand Management

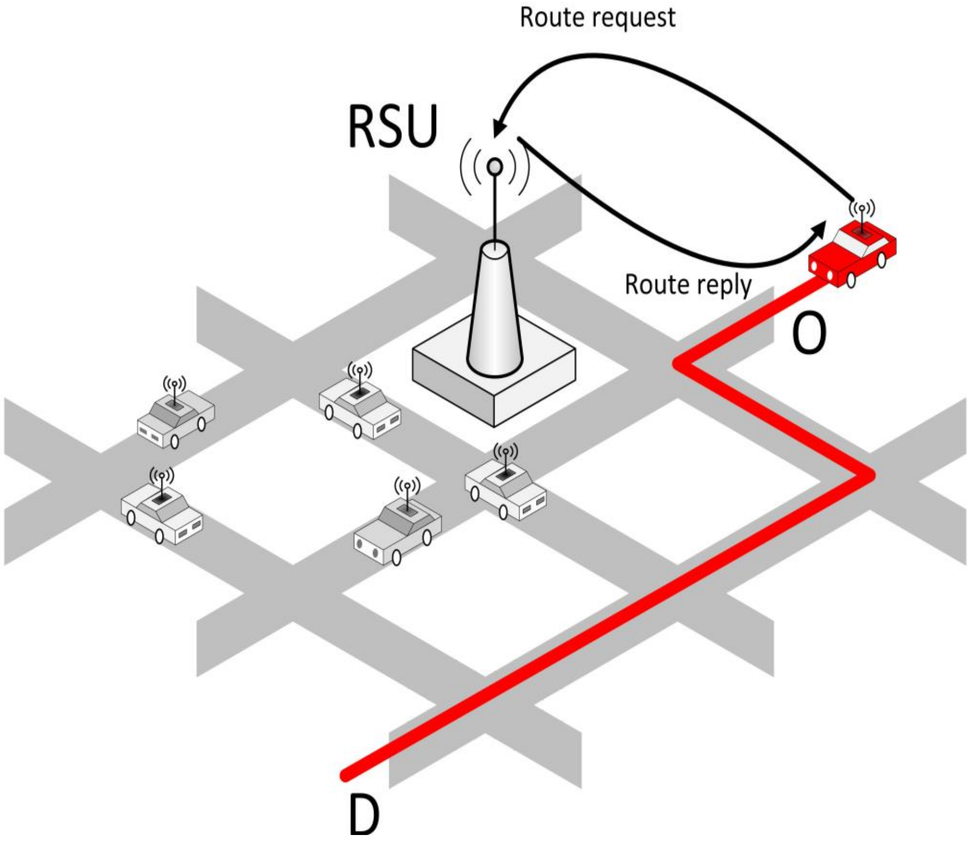
Joint Demand and Traffic Management

Problem statement

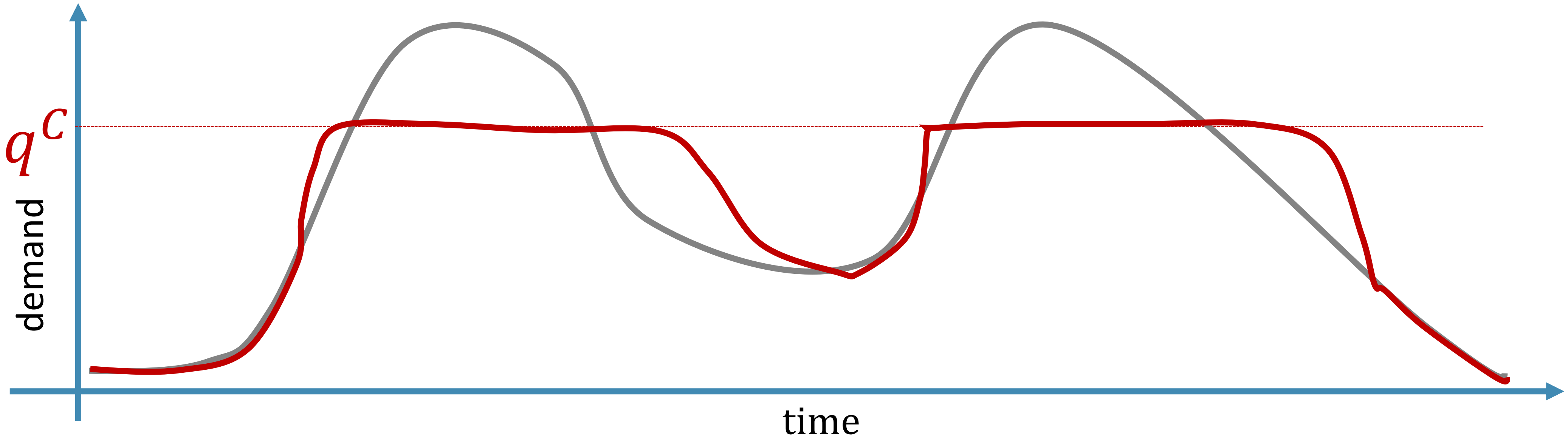
- **Input :**
  - Specific road transportation system operated by connected vehicles
  - Traffic demand

- **Objective:**
  - Minimize some metrics of interest (e.g., total time spent, earliest destination arrival time).

- **Outputs**:
  - Route followed by each vehicle (or traffic flow) in the network
  - Time to start the journey for each vehicle (or traffic flow)



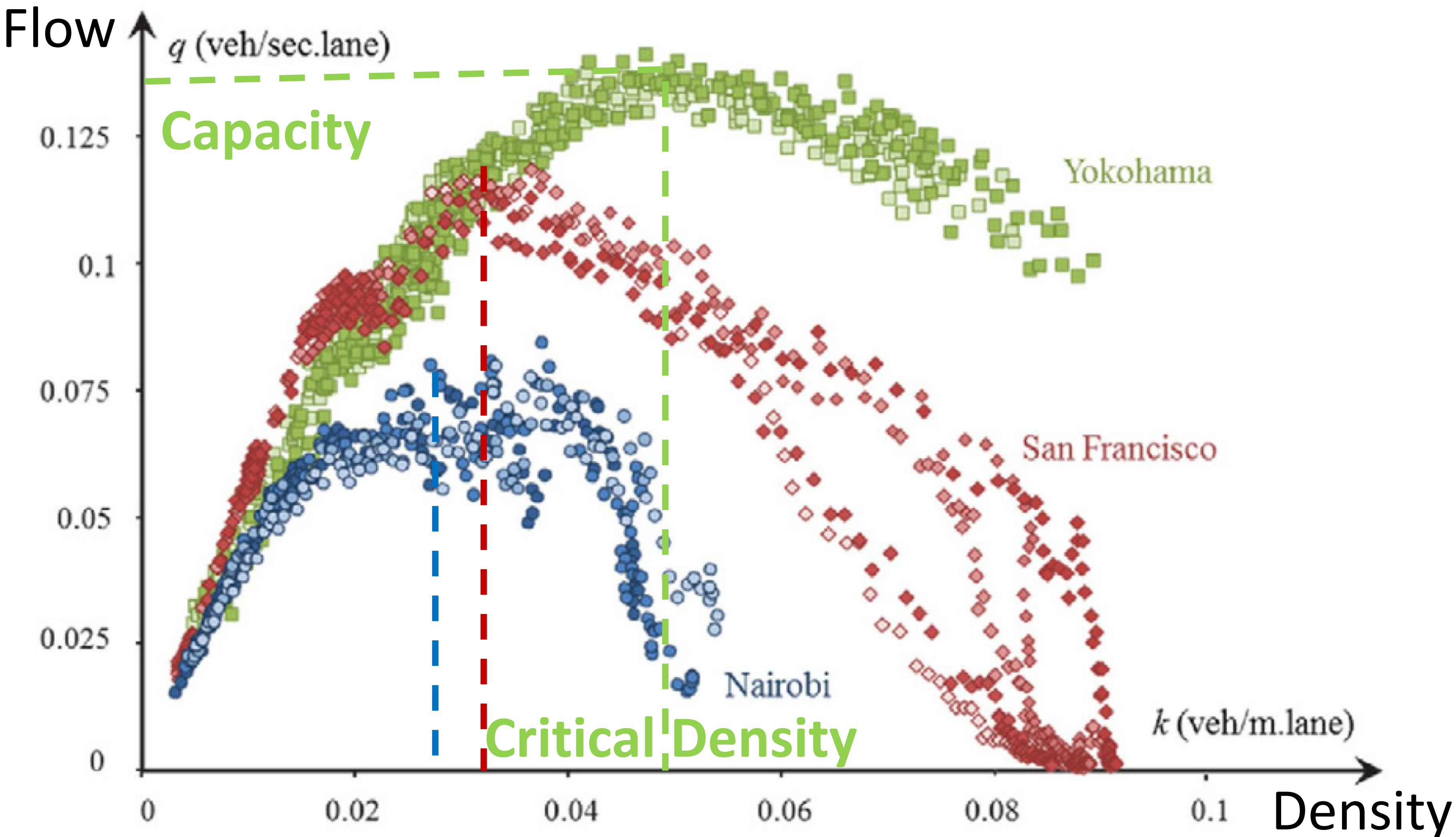
Manage Demand



Objective

- Shift (in-time): delay vehicles at the origin (demand management)
- Shift (in-space): utilize alternative paths (traffic management)

Macroscopic Fundamental Diagram



Source: Gonzales, Chavis, Li and Daganzo, 2011

Objective

- Maintain the network’s outflow **below** the critical capacity
- Maximize the utilization of the infrastructure

Individual vs Collective Optimum

Technology

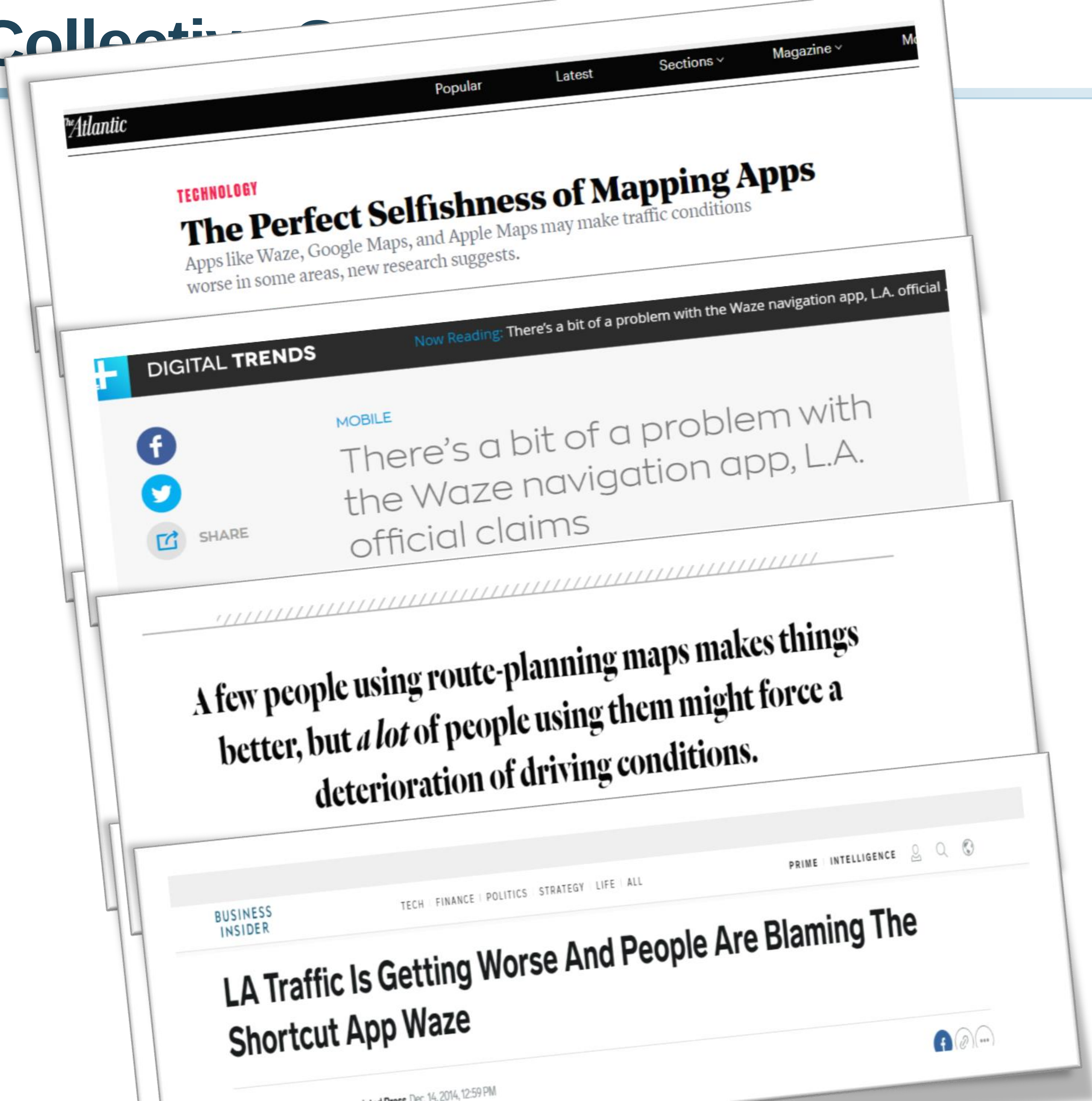
Your selfish driving is making urban congestion worse

- Routing methods should consider the benefit of the “whole” as opposed to the benefit of the individual [*]

[*] Çolak, Serdar, Antonio Lima, and Marta C. González. "Understanding congested travel in urban areas." Nature communications 7 (2016): 10793.

Individual vs Collective Optimum

Individual vs Collectiv



TECHNOLOGY

The Perfect Selfishness of Mapping Apps

Apps like Waze, Google Maps, and Apple Maps may make traffic conditions worse in some areas, new research suggests.

MOBILE

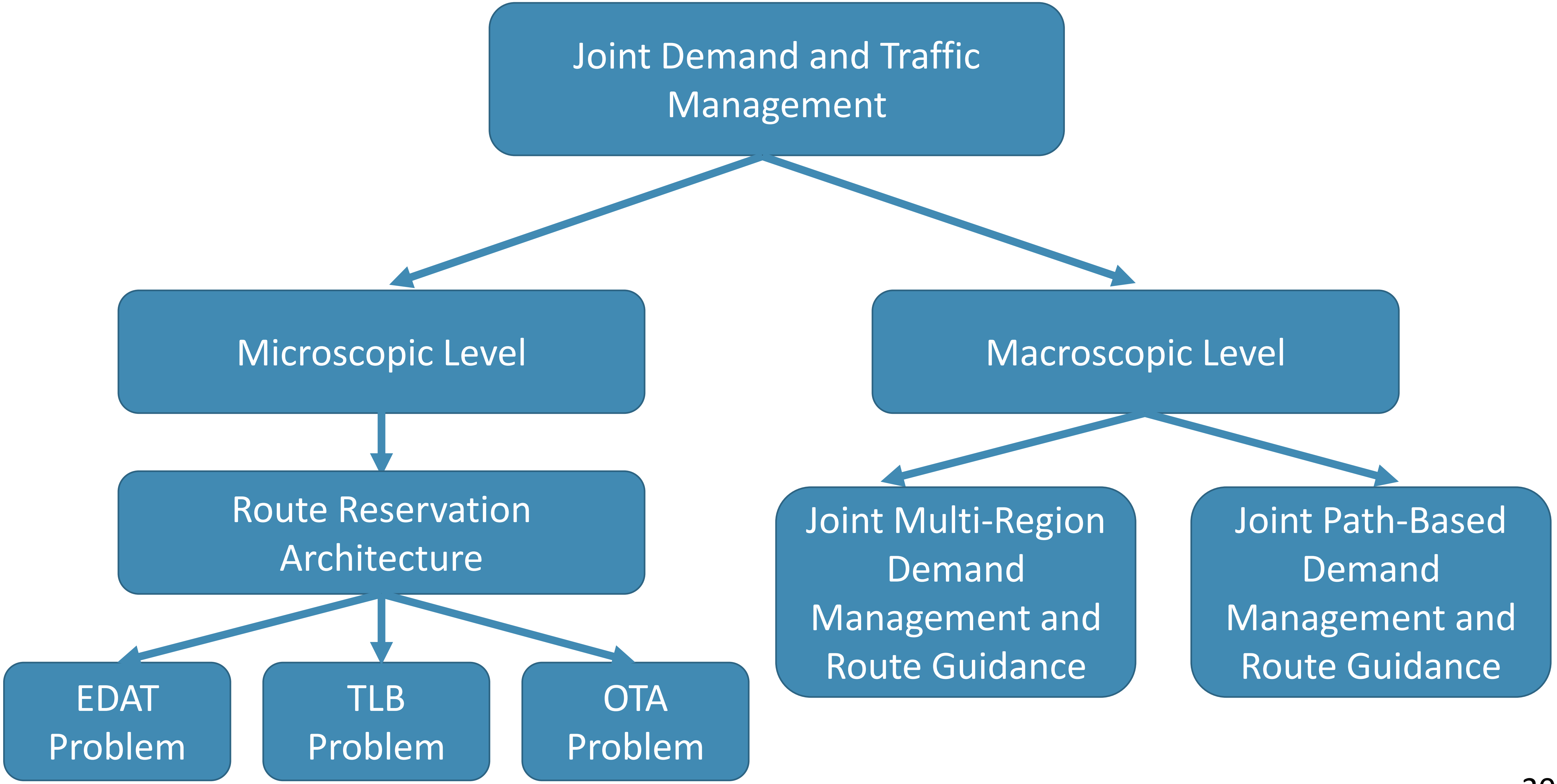
There's a bit of a problem with the Waze navigation app, L.A. official claims

A few people using route-planning maps makes things better, but *a lot* of people using them might force a deterioration of driving conditions.

LA Traffic Is Getting Worse And People Are Blaming The Shortcut App Waze

Dec. 14, 2014, 12:59 PM

Overview



Joint Demand and Traffic Management

Microscopic Level

Macroscopic Level

Route Reservation Architecture

Joint Multi-Region Demand Management and Route Guidance

Joint Path-Based Demand Management and Route Guidance

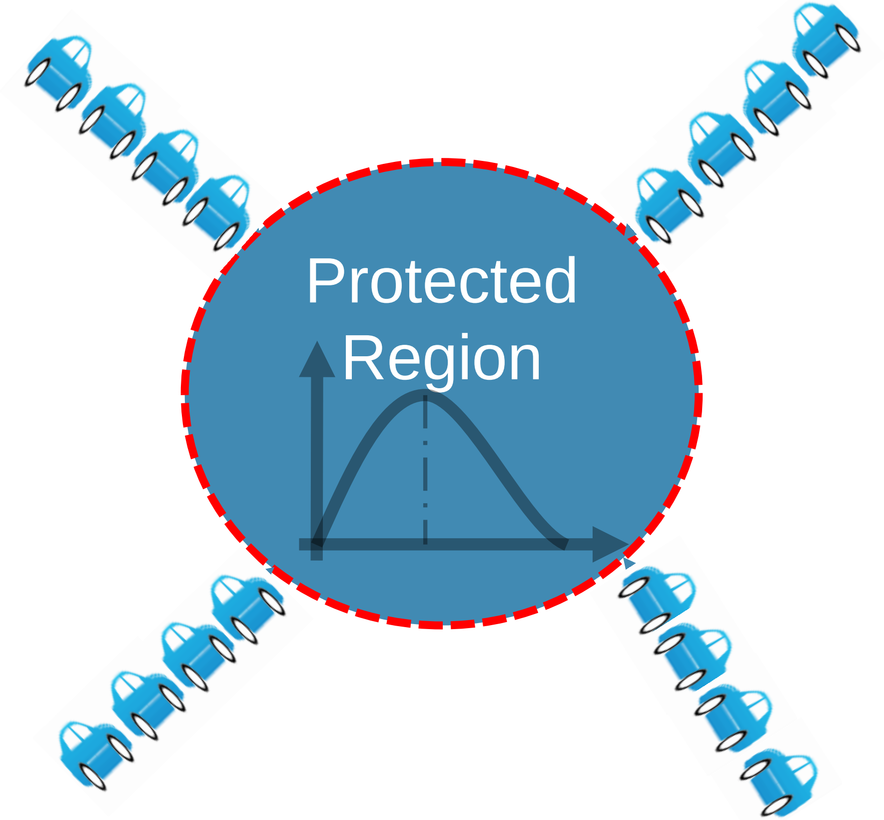
EDAT Problem

TLB Problem

OTA Problem

Related Work

Perimeter Control / Gating / Ramp Metering



Objective

- Restrict the inflow in a protected region such that the density does not exceed the capacity

- Approach does not take any control action for the endogenous flows (flows initiated in the region)
- Unwanted queues may be observed at the boundaries

- ➢ Keyvan-Ekbatani, M., Kouvelas, A., Papamichail, I. and Papageorgiou, M., 2012. Exploiting the fundamental diagram of urban networks for feedback-based gating. Transportation Research Part B: Methodological, 46(10), pp.1393-1403.
- ➢ Geroliminis, N., Haddad, J. and Ramezani, M., 2012. Optimal perimeter control for two urban regions with macroscopic fundamental diagrams: A model predictive approach. IEEE Transactions on Intelligent Transportation Systems, 14(1), pp.348-359.
- ➢ Papageorgiou, M., Hadj-Salem, H. and Blosseville, J.M., 1991. ALINEA: A local feedback control law for on-ramp metering. Transportation Research Record, 1320(1), pp.58-67.
- ➢ Papamichail, I., Papageorgiou, M., Vong, V. and Gaffney, J., 2010. Heuristic ramp-metering coordination strategy implemented at Monash freeway, Australia. Transportation Research Record, 2178(1), pp.10-20.
- ➢ Carlson, R.C., Papamichail, I. and Papageorgiou, M., 2014. Integrated feedback ramp metering and mainstream traffic flow control on motorways using variable speed limits. Transportation research part C: Emerging technologies, 46, pp.209-221.

Policy Based Approaches

Objective

- Implement policies that can change demand patterns
  - Congestion Pricing
  - Parking fees
  - Public transportation

- Non-popular measures

- Jaensirisak, S., Wardman, M. and May, A.D., 2005. Explaining variations in public acceptability of road pricing schemes. Journal of Transport Economics and Policy (JTEP), 39(2), pp.127-154.
- Verhoef, E.T., 2002. Second-best congestion pricing in general networks. Heuristic algorithms for finding second-best optimal toll levels and toll points. Transportation Research Part B: Methodological, 36(8), pp.707-729.

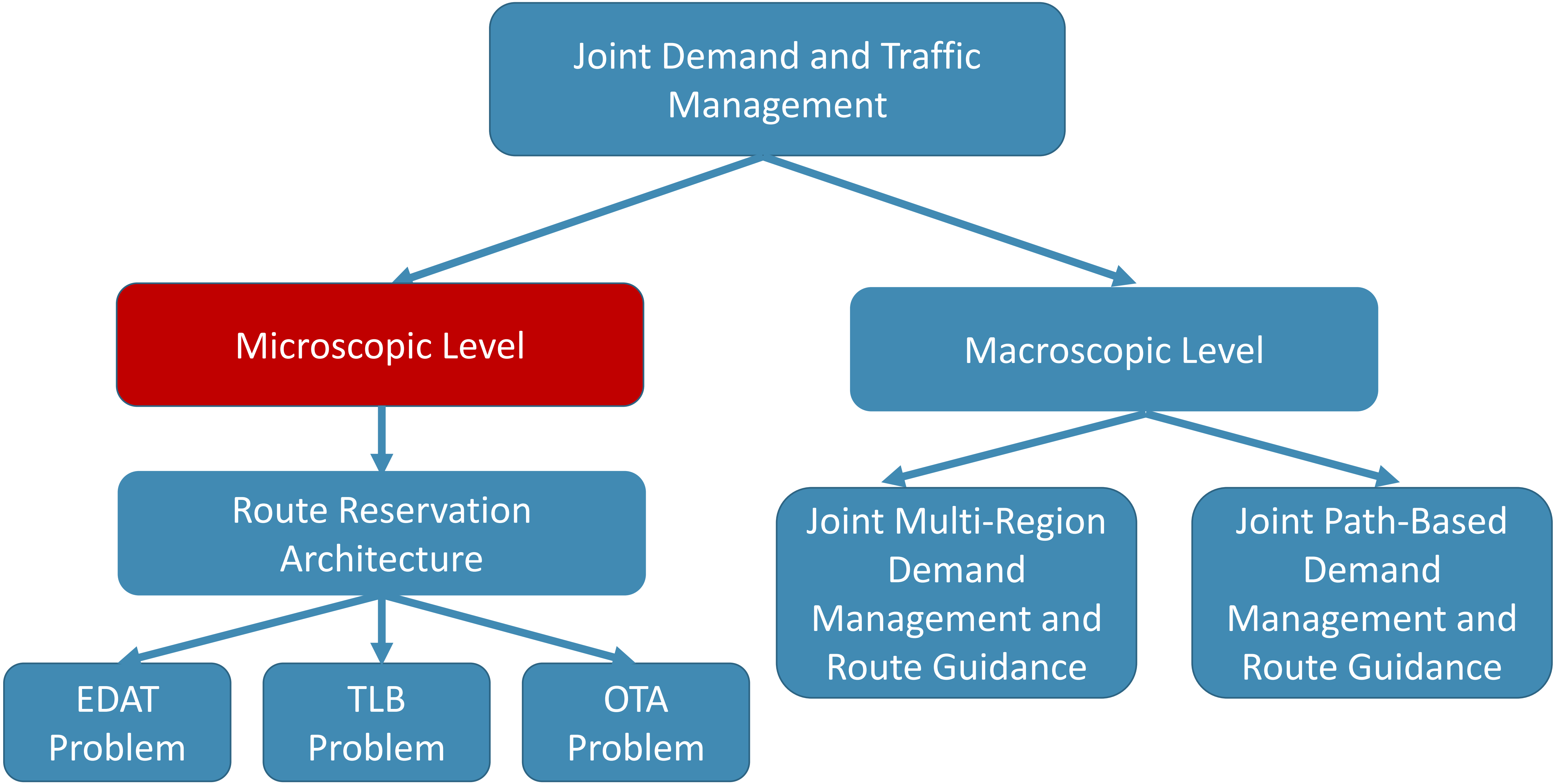
Route Guidance / Routing Methods

Objective

- Guide vehicles through alternative routes to reduce the imbalance in congestion distribution.
- Determine best route from origin to destination using time-varying networks.

- Not very effective in high demand scenarios

- Knoop, V.L., Hoogendoorn, S.P. and Van Lint, J.W.C., 2012. Routing strategies based on macroscopic fundamental diagram. Transportation Research Record, 2315(1), pp.1-10.
- Papageorgiou, M. Yildirimoglu, M., Ramezani, 1990. Dynamic modeling, assignment, and route guidance in traffic networks. Transportation Research Part B: Methodological, 24(6), pp.471-495.
- Yildirimoglu, M., Ramezani, M. and Geroliminis, N., 2015. Equilibrium analysis and route guidance in large-scale networks with MFD dynamics. Transportation Research Procedia, 9, pp.185-204.
- Yildirimoglu, M., Sirmatel, I.I. and Geroliminis, N., 2018. Hierarchical control of heterogeneous large-scale urban road networks via path assignment and regional route guidance. Transportation Research Part B: Methodological, 118, pp.106-123.



Joint Demand and Traffic Management

Microscopic Level

Macroscopic Level

Route Reservation Architecture

Joint Multi-Region Demand Management and Route Guidance

Joint Path-Based Demand Management and Route Guidance

EDAT Problem

TLB Problem

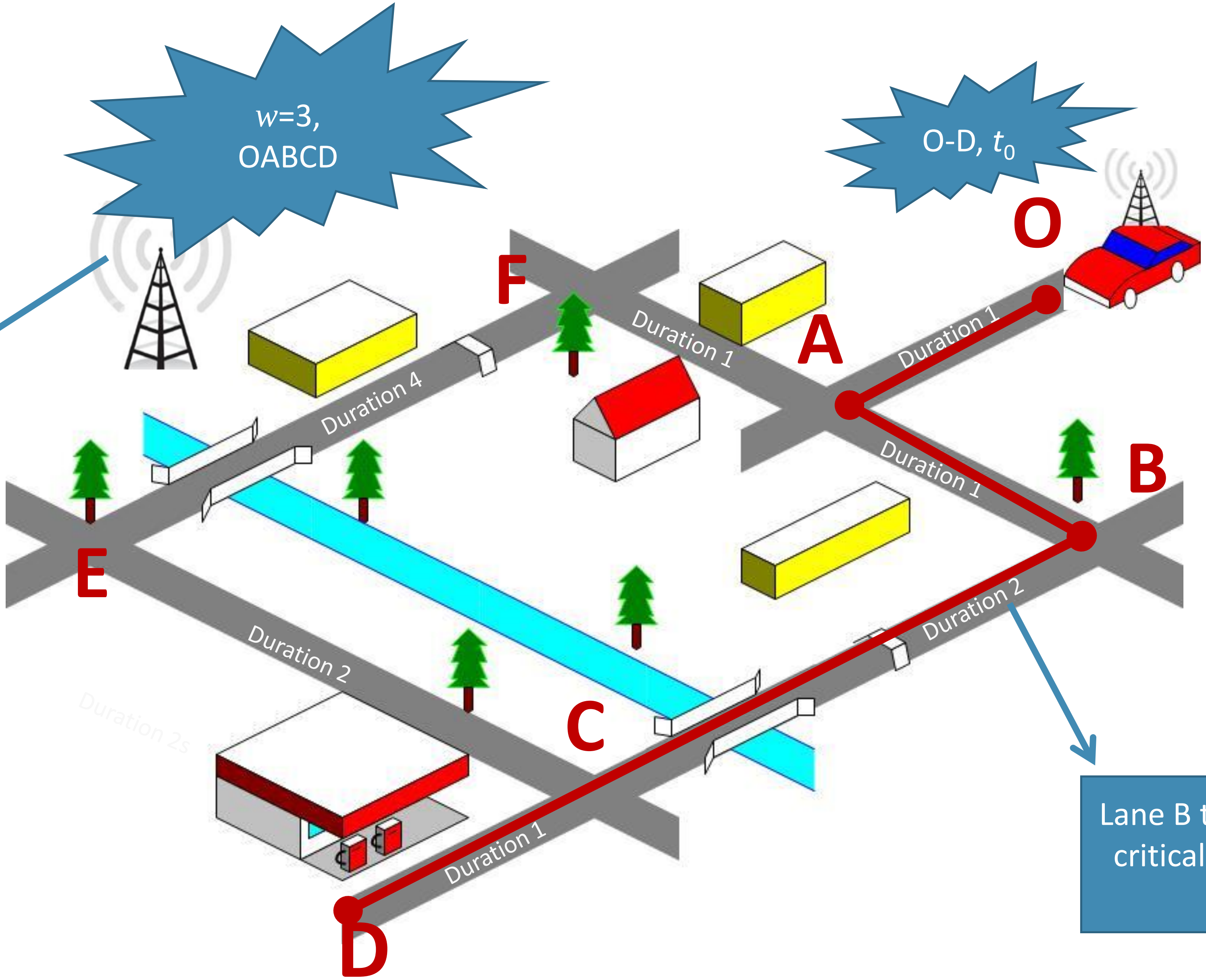
OTA Problem

Route Reservation Architecture

Reservation Architecture

RSU State

- Network topology
- Past reservations
- $\rho_{ij}(t) \le \rho_{ij}^{C}, \Rightarrow u_{travel} = u_f$



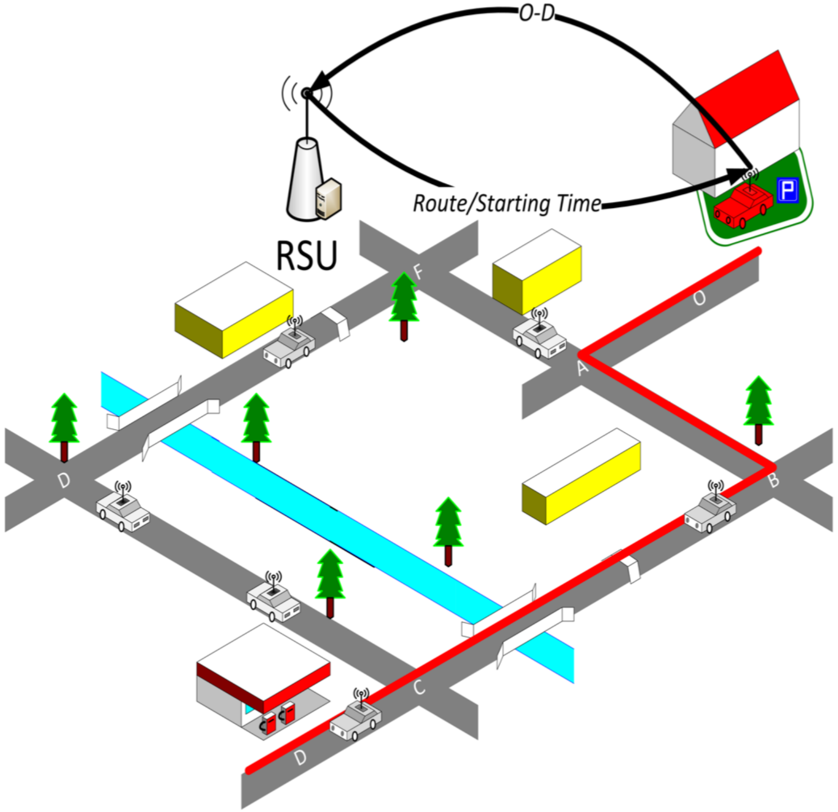
Update reservations

Lane B to C will reach its critical density from 2 until 5

Link O - A at 3 to 4.
Link A - B at 4 to 5.
Link B - C at 5 to 7.
Link C - D at 7 to 8.

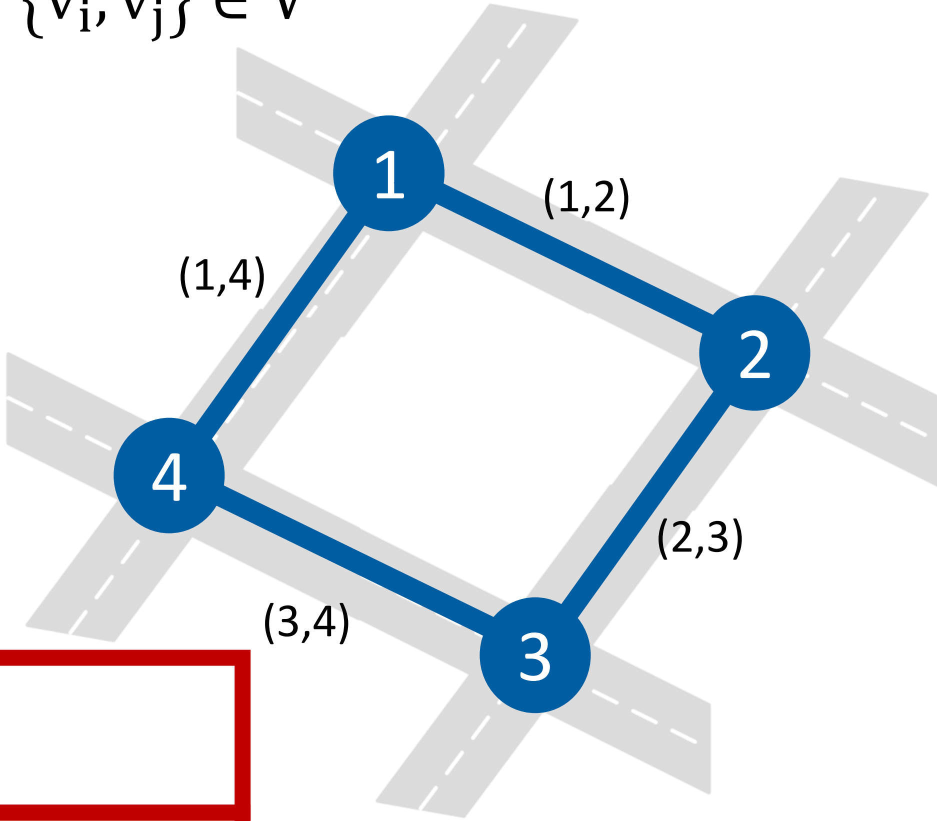
Earliest Destination Arrival Time (EDAT) Problem

- **Input :**
  - Reservation status
  - Vehicle request: Origin - Destination Nodes (O-D pair)
  - Time of request
- **Objective**
  - Minimize the arrival time at destination
  - Route traffic through congestion free routes
- **Output:**
  - Initial delay at the origin
  - Route to be followed



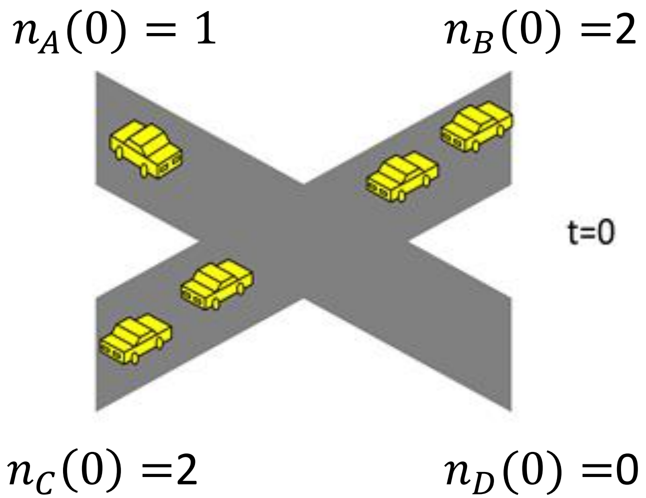
Notation

- Road network as a graph $G(V, E)$ with $(i, j) \in E$ and $\{\mathrm{v_i}, \mathrm{v_j}\} \in \mathrm{V}$
- For every road segment (i, j)
  - ➢ l_{ij} segment's length
  - ➢ λ_{ij} segment's number of lanes
  - ➢ $\rho_{ij}^{J} = l_{ij}\rho^{J} / \sum_{(i,j)\in E} l_{ij}$ jam density
  - ➢ $\rho_{ij}(t)$ instantaneous segment's density
  - ➢ $\rho_{ij}^{C} = \left(\frac{\rho^{C}}{\rho^{J}}\right)\rho_{ij}^{J}$ critical density
  - ➢ $\bar{c}_{ij} = \lceil l_{ij}/u_f/T \rceil$ time-slots required to traverse (i, j)
  - ➢ $n_{ij}(\mathrm{t})$ cumulative vehicle reservations within the road segment (i, j)
  - ➢ d_{v_i} earliest arrival time at junction v_i



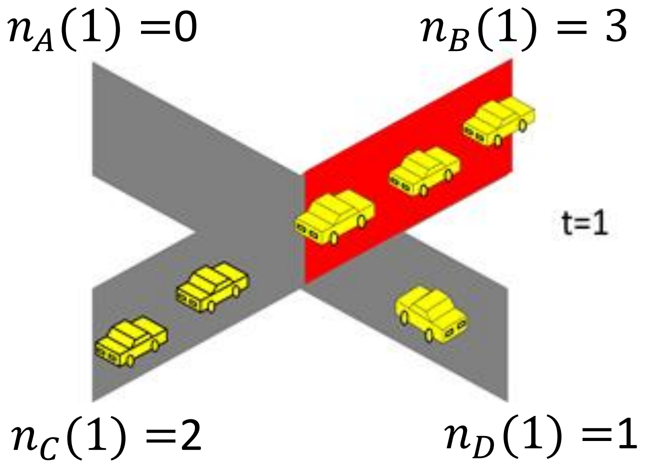
Adminisibility and travel cost

- A road segment (i, j) is ***admissible*** at time t=d_{v_i} if the number of reservations is not larger than the segment's critical density for the required traversal time:



$$x_{ij}(d_{v_i}) = \begin{cases} 1, & \text{if } \dfrac{n_{ij}(\tau)}{\lambda_{ij} l_{ij}} \leq \rho_{ij}^{C} \ \forall \tau = d_{v_i}, \ldots, d_{v_i} + \bar{c}_{ij} \\ 0, & \text{otherwise} \end{cases}$$

- Cost to traverse road segment (i, j):



$$c_{ij}(d_{v_i}) = \begin{cases} \bar{c}_{ij}, & \text{if } x_{ij}(d_{v_i}) = 1 \\ \infty, & \text{if } x_{ij}(d_{v_i}) = 0 \text{ and } i \neq O \\ \bar{c}_{ij} + w & \text{if } x_{ij}(d_{v_i}) = 0 \text{ and } i = O \end{cases}$$

where, w denotes the least number of time-slots that a vehicle should wait at v_i

Earliest Destination Arrival Time (EDAT) Problem

- Let p_h be the h_{th} path from O to D:

$$p_h = (v_o^h, v_1^h), (v_1^h, v_2^h), (v_2^h, v_3^h), \ldots, (v_{L_h-1}^h, v_{L_h}^h)$$

where, $v_j^h \in V, L_h$the length of path, $v_o = O \; and \; v_{L_h}^h = D$ and

$$d_{v_O^h}^h = t_0, \qquad w \geq 0$$

$$d_{v_1^h}^h = d_{v_O^h}^h + C_{v_O^h, v_i^h}(d_{v_O^h}^h, t_0)$$

$$\vdots$$

$$d_{v_{L_h}^h}^h = d_{v_{L_h-1}^h}^h + C_{v_{L_h-1}^h, v_{L_h}^h}(d_{v_{L_h-1}^h}^h, t_0)$$

- Then, the **EDAT** problem determines the path that allows the vehicle to arrive at the destination at the earliest arrival time such that only admissibe links are used:

$$d_D^* = \min_{w, p_h} d_D^h$$

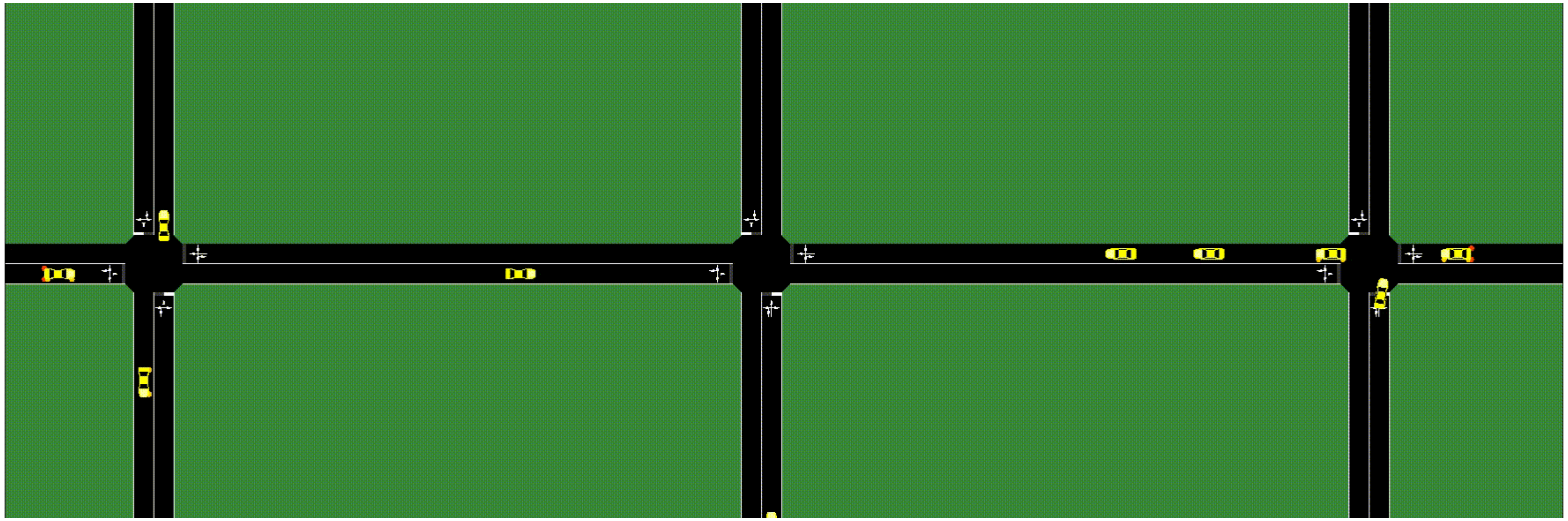
$$s.t. \text{ Model Dynamics}$$

Solutions to the EDAT problem

- **Theorem:** EDAT is an NP-Complete problem.
- **Solutions:**
  - **Directed Acyclic Graph (DAG) Based Algorithm (Optimal in Discrete Time)**
    - Creates a time-space graph with **every** possible admissible path from any node to any other node
    - A dynamic programming methodology that returns the optimal solution (discrete time) of the EDAT problem, but suffers from the curse of dimensionality
  - **Time Expanded (TE) (heuristic)**
    - Creates a graph with “delayed” copies for the original graph with the non-admissible links removed
    - Use Dijkstra’s algorithm to find the best path
  - **Route Reservation Algorithm (RRA) (heuristic)**
    - Solves the Relaxed EDAT problem using a modification of Dijkstra’s Algorithm
    - If solution does not involve waiting at intermediate node, then return path
    - Otherwise, increase waiting at the origin and resolve
  - **MILP solution (Optimal)**
    - Solves the EDAT problem Mixed Integer Linear Program with a continuous time formulation

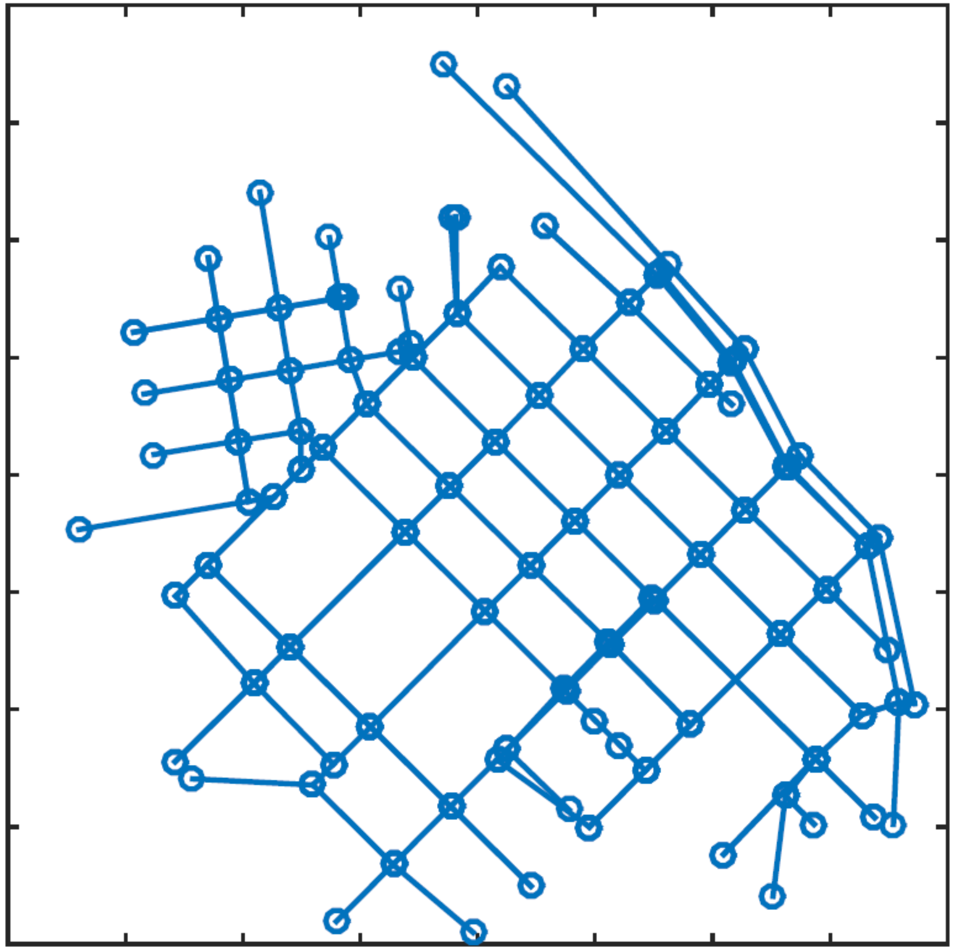
Performance Evaluation - Setup

- Evaluation is done using the **SUMO**-Simulation of Urban MObility Micro-Simulator.
- **Simulator parameters:**
  - Krauss-Car-following model
  - Driver reaction time = 0.5 s
  - Maximum speed = $14\ \mathrm{m}/s$
  - Vehicle length = $5\ \mathrm{m}$
  - Speed deviation = 0.9
  - Acceleration = $2.5\ \mathrm{m}/s^2$
  - Deceleration = $4.5\ \mathrm{m}/s^2$
  - Minimum-gap = $2.5\ \mathrm{m}$



➢ *Behrisch, et al. "SUMO–simulation of urban mobility: an overview." Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation ThinkMind, 2011.*

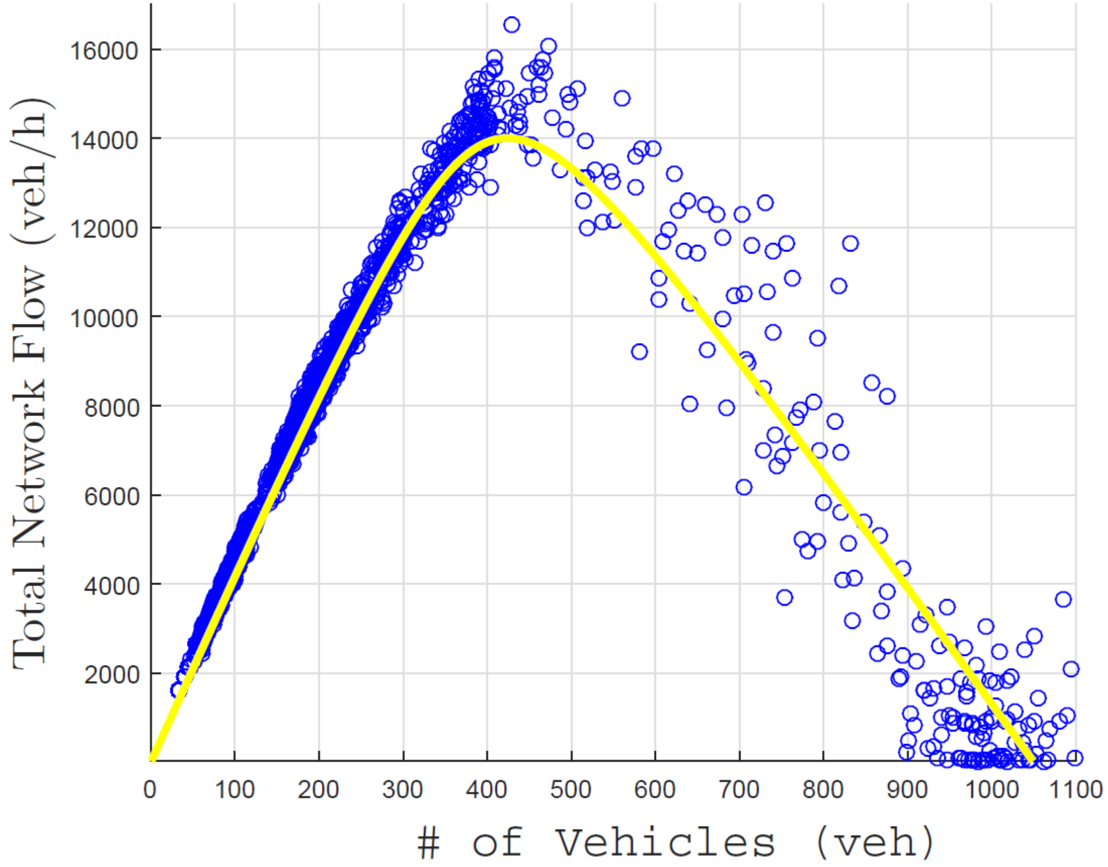
Performance Evaluation - Setup

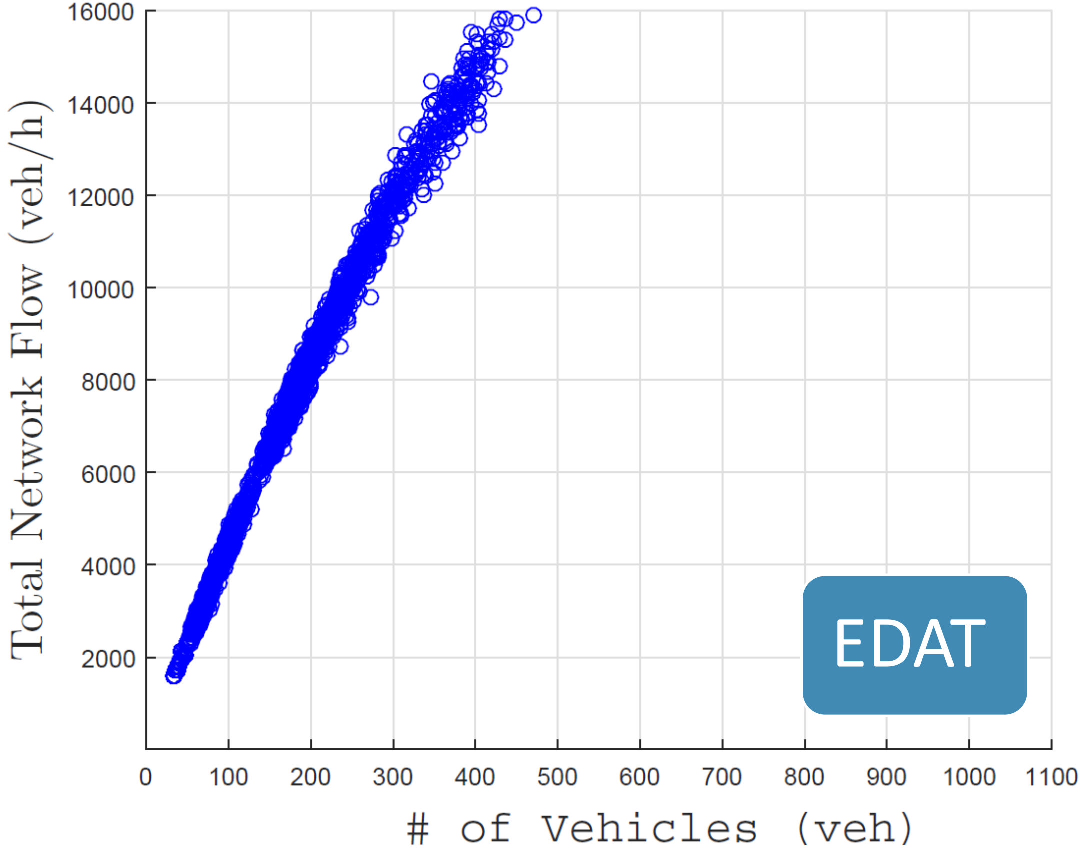


San Francisco Area

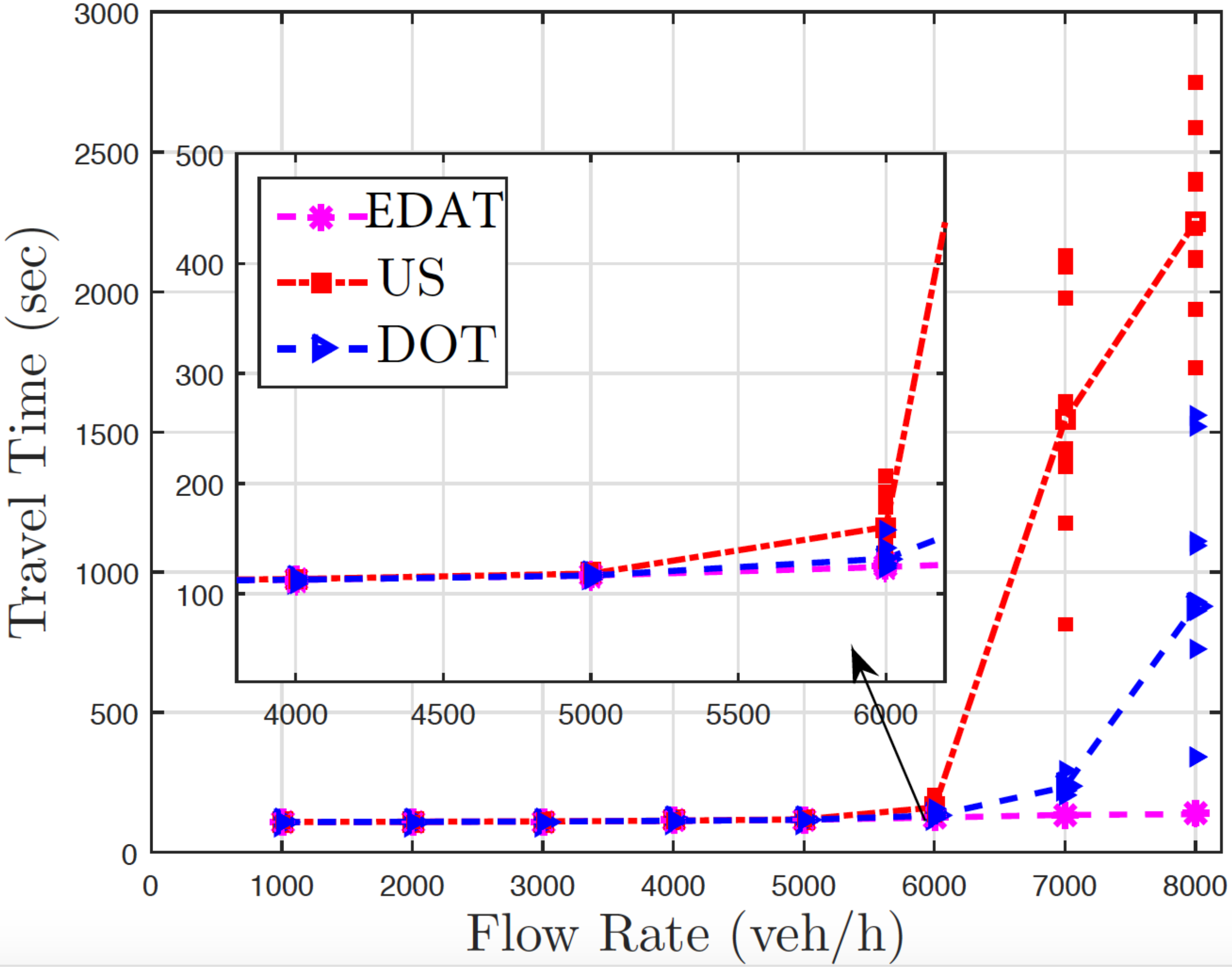
- 1.8 Km^2 area of Downtown of San Francisco
  - **208** two-way, single-lane road segments
  - **99** road-junctions
- Monte-Carlo simulations were conducted for different flow rates in the range of $1000 - 8000\ veh/h$.
- Selected $\rho_{ij}^{C} = \frac{44veh}{\mathrm{km}}/\mathrm{lane}$ (through calibration)

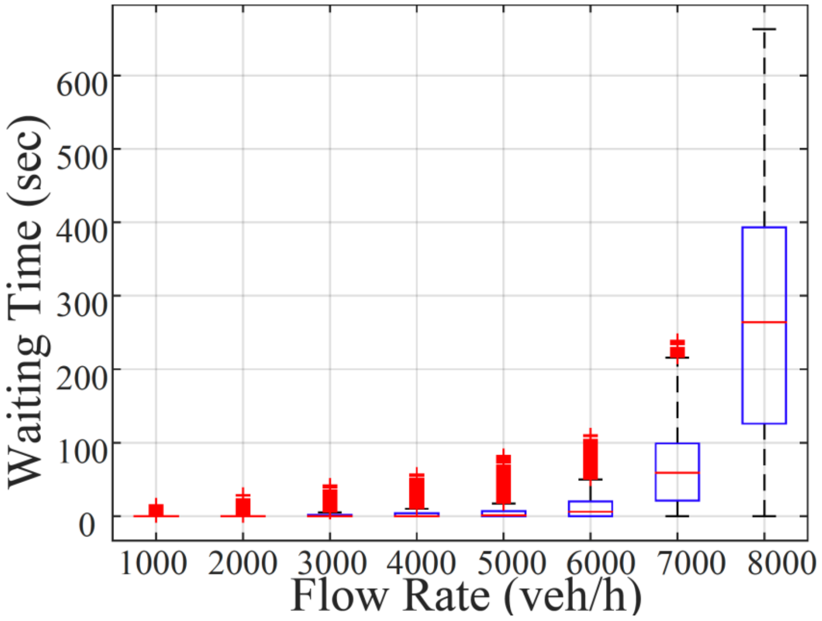
Flow/Density Simulation Results

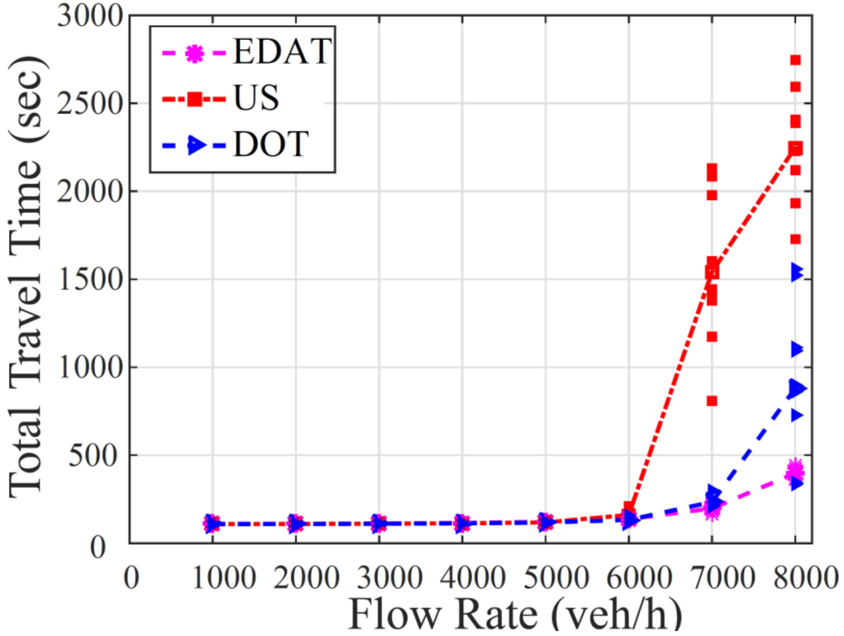




Travel Time Simulation Results:



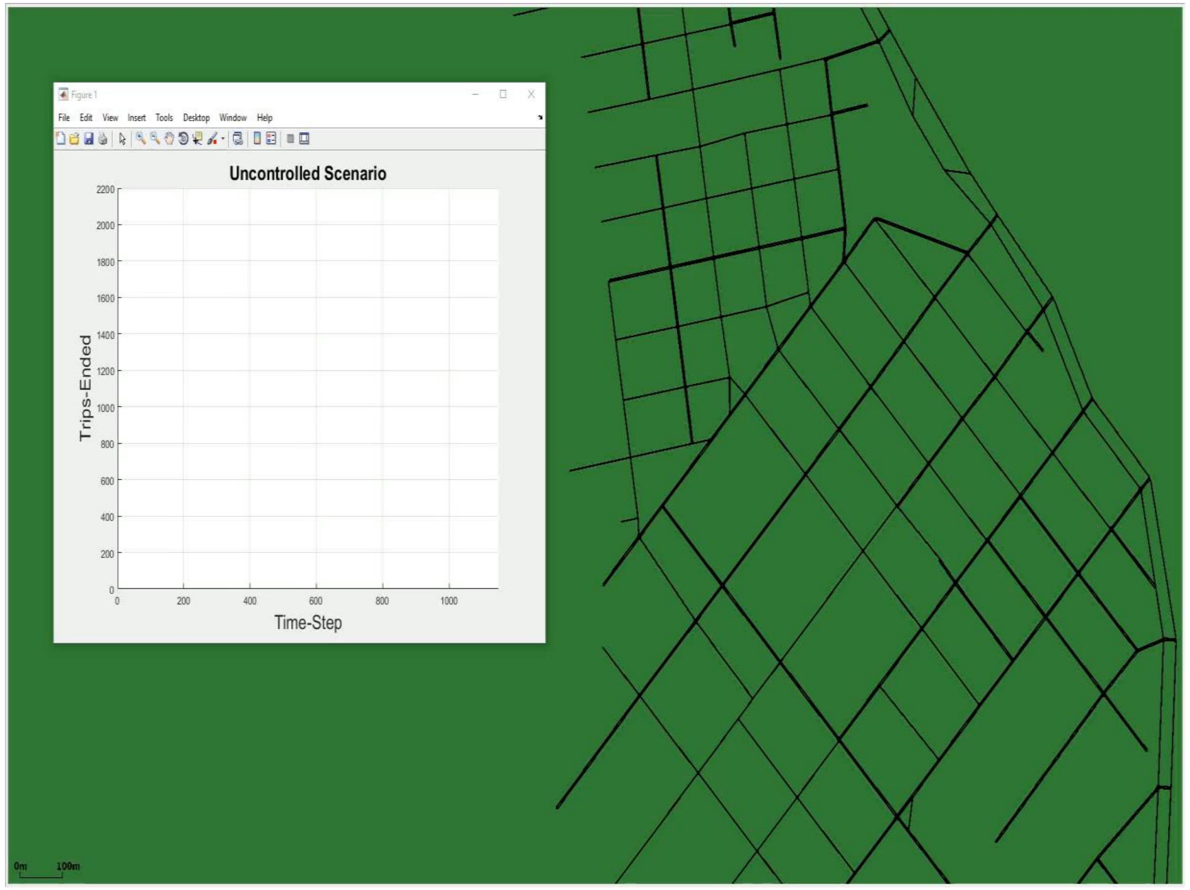


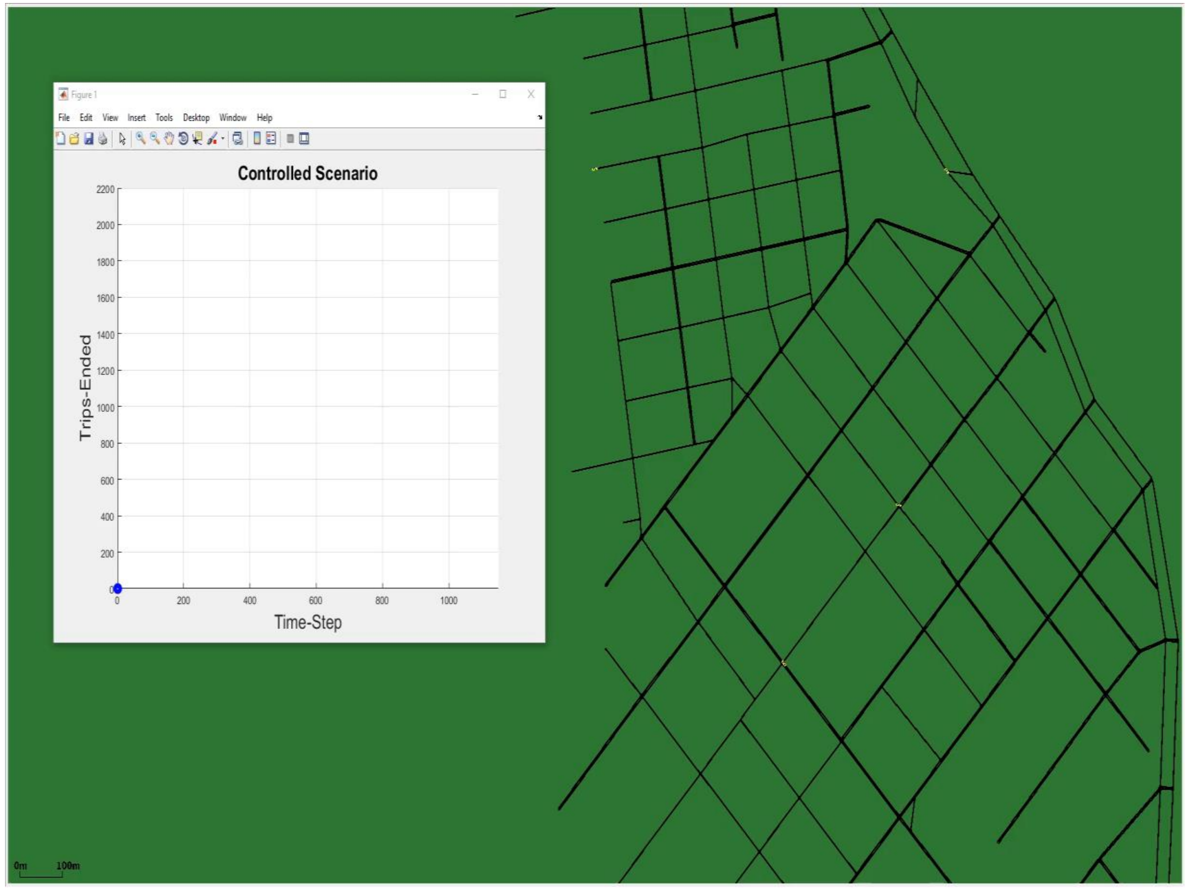


Total Time = Travel Time + Waiting Time

- *I. Chabini, Discrete dynamic shortest path problems in transportation applications: Complexity and algorithms with optimal run time, Transportation Research Records 1645 (1998) 170–175*

Simulation Video





Extensions and Improvements

Other extensions

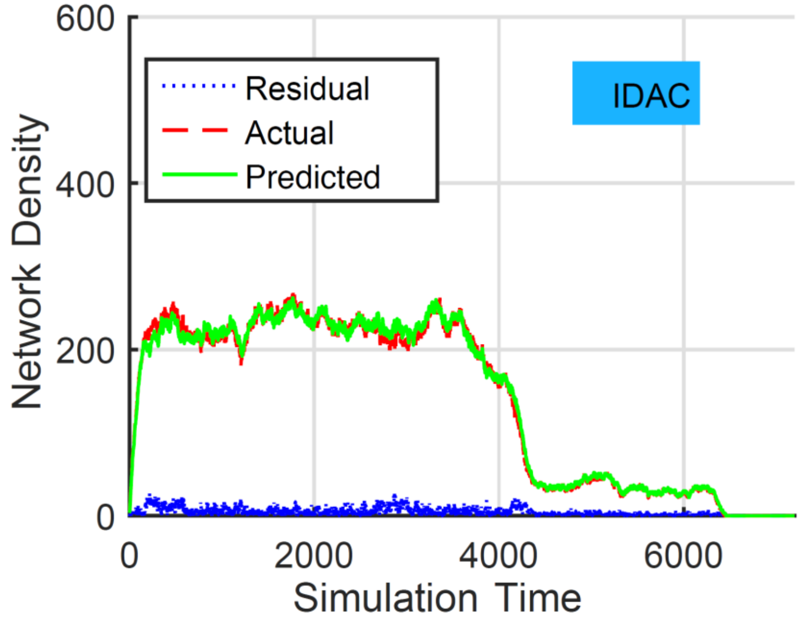
1. **Predict travel times of road links**

   Challenge

   - In reality the average speed of vehicles is not constant (free-flow)

   Solution

   - Exploit vehicle connectivity to collect real-time travel time information
   - Predicts transit-times to improve the route reservations performance



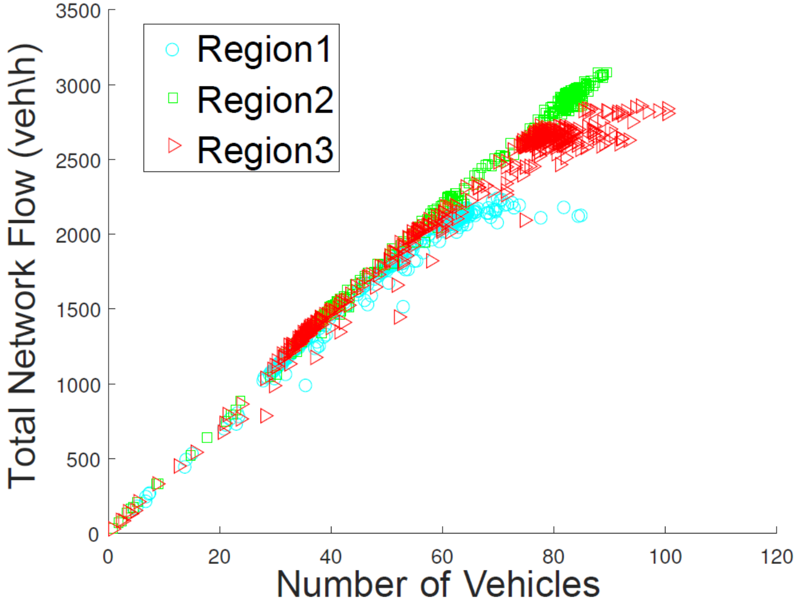
2. **Hierarchical multi-regional demand management and routing**

   Challenge

   - Scalability issue for large networks

   Solution

   - Hierarchical approach performs both inter-regional and intra-regional vehicle routing



Other extensions

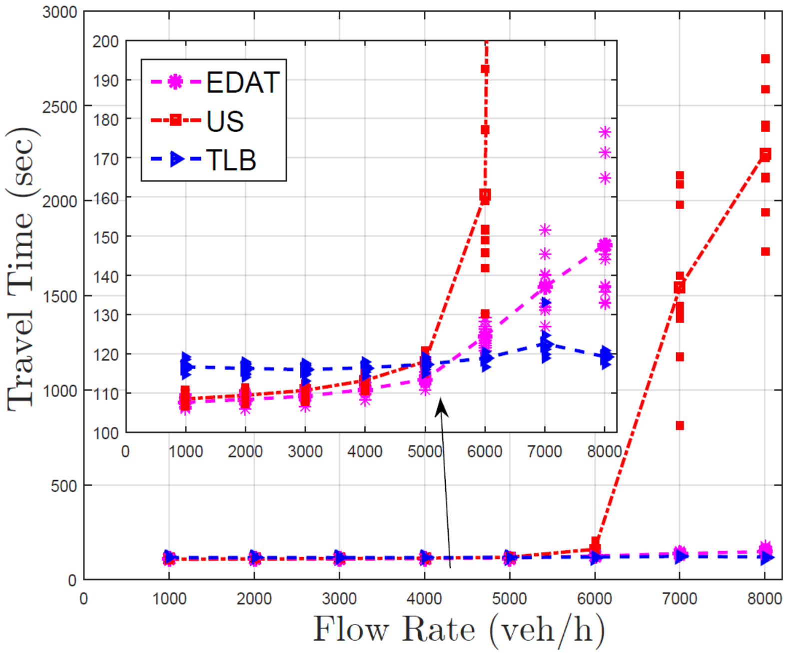
3. Traffic load balancing

Challenge

- Maintain long-term homogeneity of traffic
- Vehicles may have to take much longer paths

Solution

- Solution to EDAT ($d_D^* = \min_{w,p_h} d_D^h$)
- Find alternative admissible paths from O to D such that vehicle can arrive at D at time $d_D^* \leq d_D \leq a \times d_D^*$ where $a > 1$ aiming to minimize the spatio-temporal variance of traffic densities in the network.



On-Time Arrivals Using Route Reservations

On-Time Arrivals (OTA) Problem

- **Input**
  - Reservation status
  - Vehicle requested *O-D* pair
  - Vehicle desired time at the destination

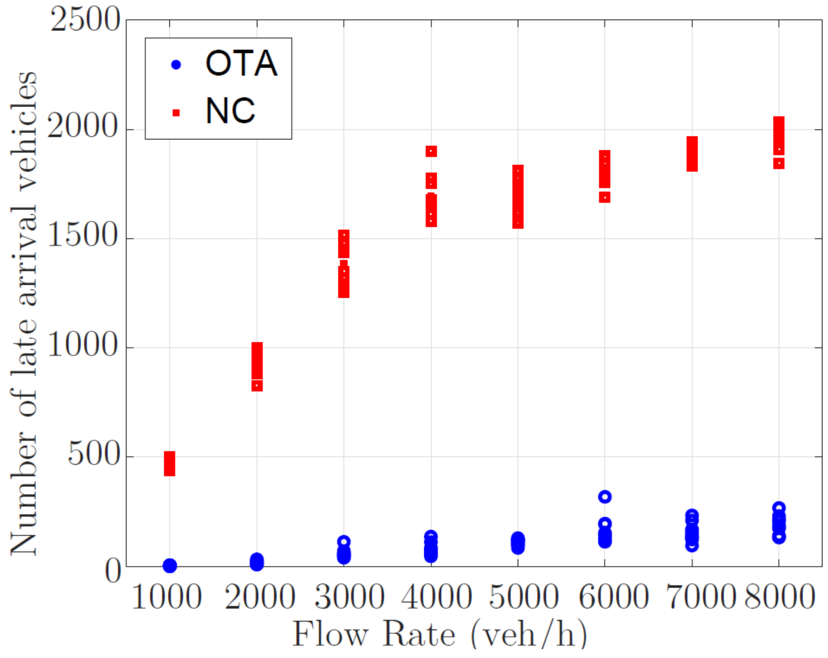
- **Objective**
  - Minimize the difference between the actual departure and the desired arrival times such that congested links are avoided and travelers do not arrive too early at their destination

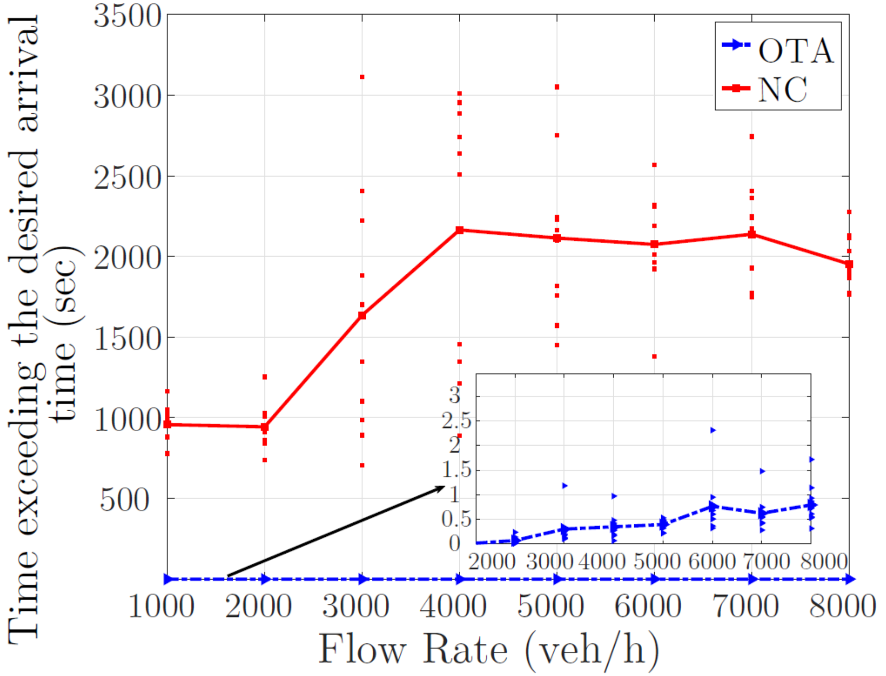
- **Output**
  - Vehicle departure time
  - Admissible path from *O* to *D*

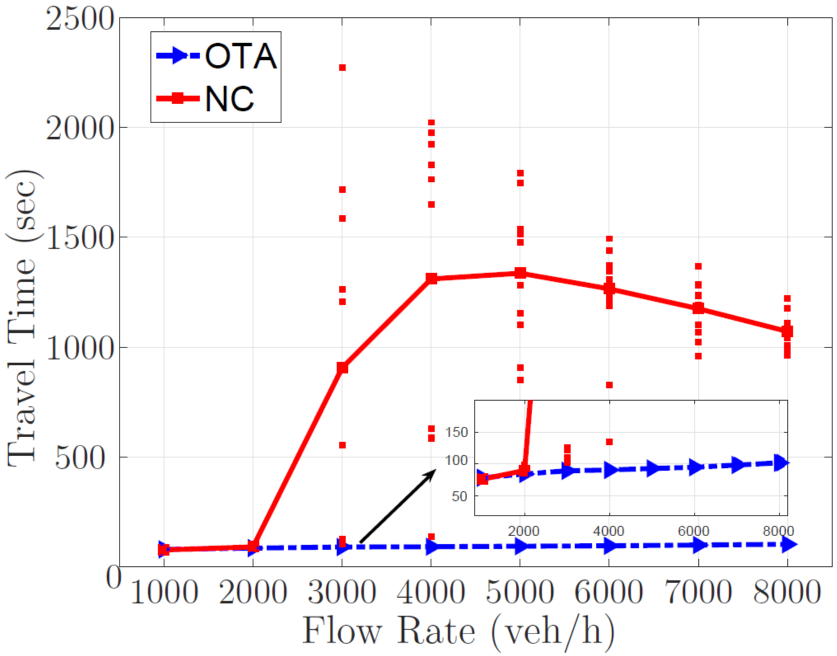
- **Solution approach**
  - The solution to the OTA problem is obtained, based on dynamic programming, by constructing a time-space graph

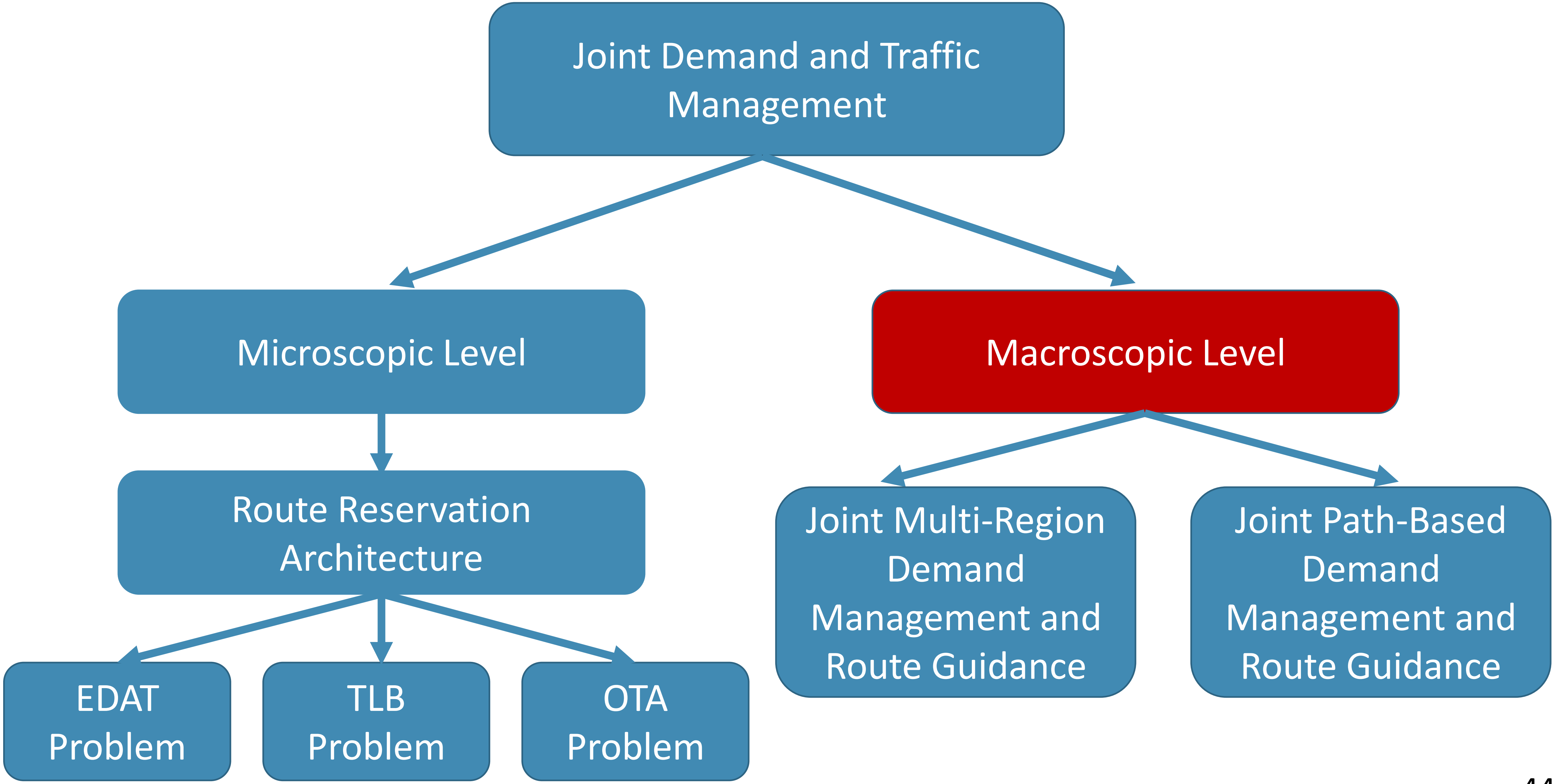
OTA Results

- Evaluation is done using SUMO microsimulator.
- We consider the Downtown of San Francisco.








Joint Demand and Traffic Management

Microscopic Level

Macroscopic Level

Route Reservation Architecture

Joint Multi-Region Demand Management and Route Guidance

Joint Path-Based Demand Management and Route Guidance

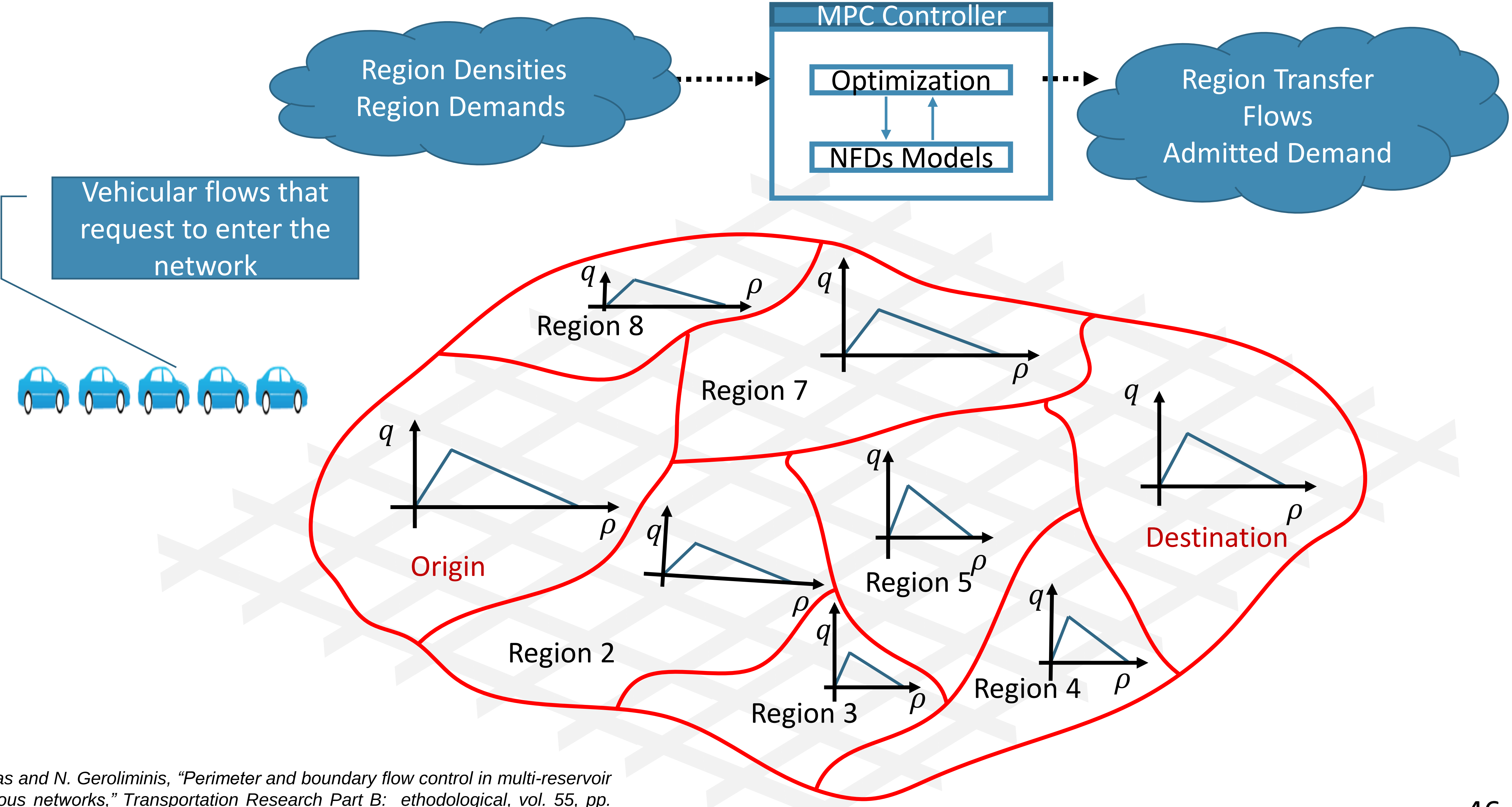
EDAT Problem

TLB Problem

OTA Problem

Joint Multi-Region Demand Management and Route Guidance

Joint Demand Management and Route Guidance



Region Densities
Region Demands

MPC Controller

Optimization

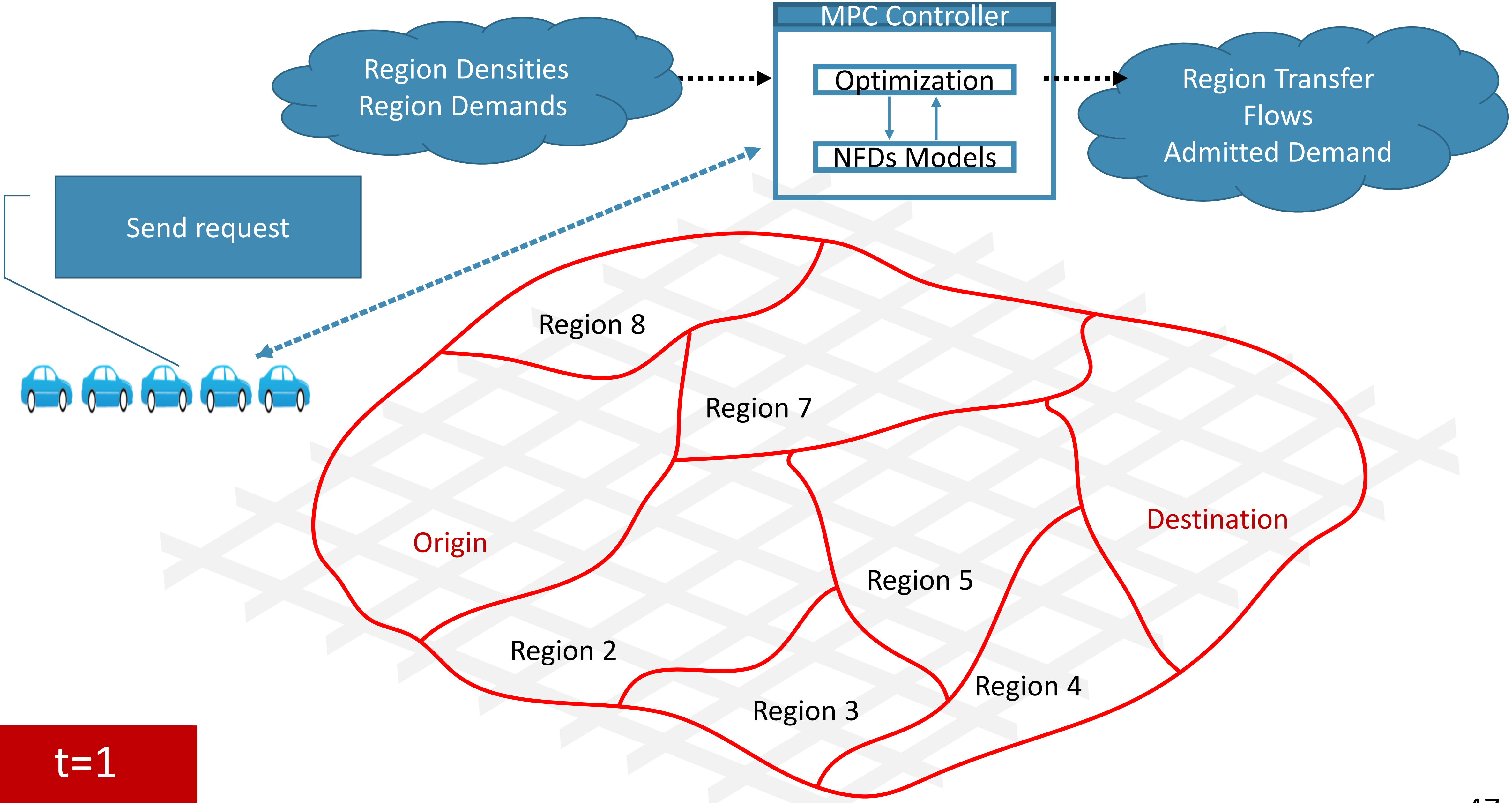
NFDs Models

Region Transfer
Flows
Admitted Demand

Vehicular flows that request to enter the network

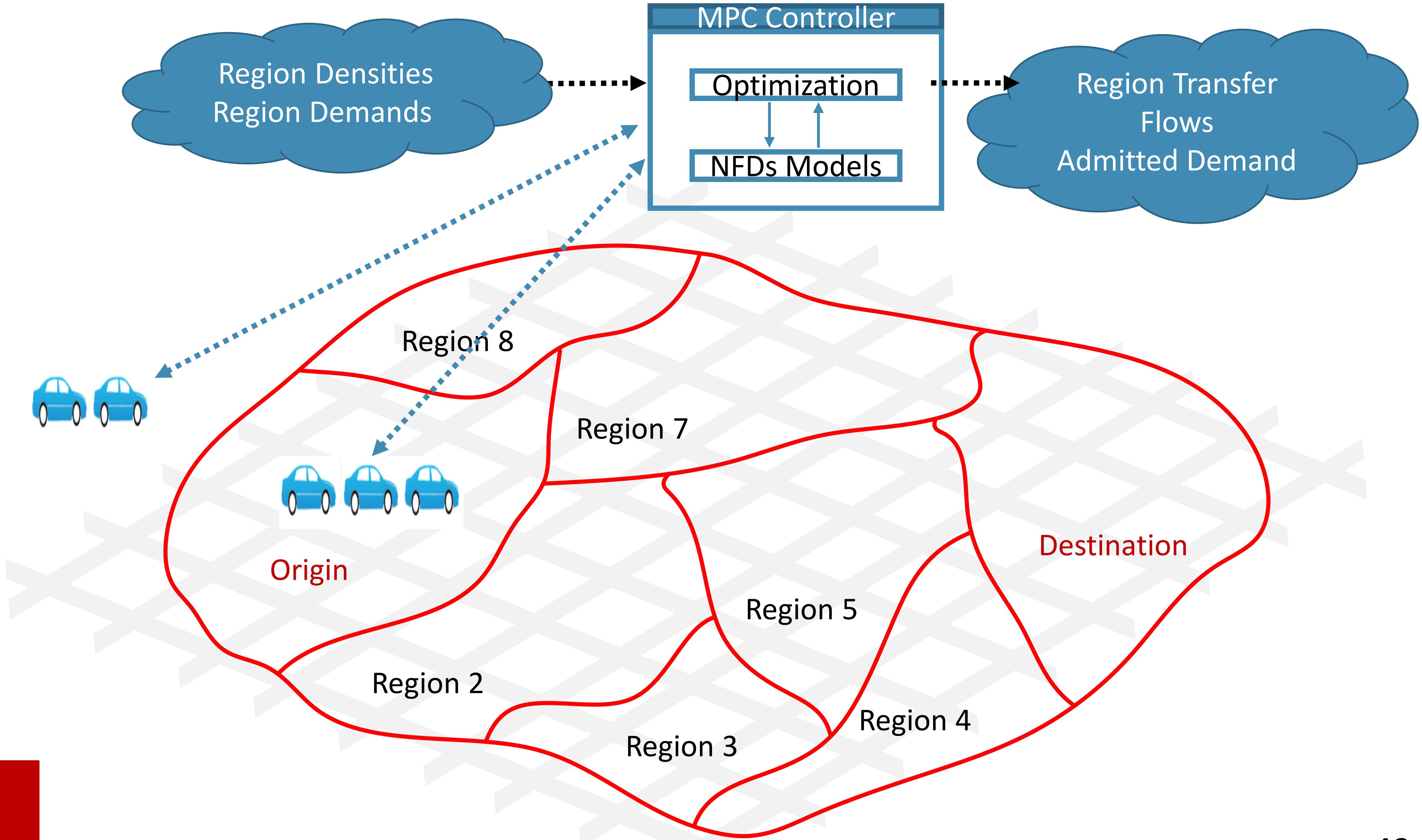
- K. Aboudolas and N. Geroliminis, *“Perimeter and boundary flow control in multi-reservoir heterogeneous networks,” Transportation Research Part B: ethodological, vol. 55, pp. 265–281, 2013.*

Joint Demand Management and Route Guidance



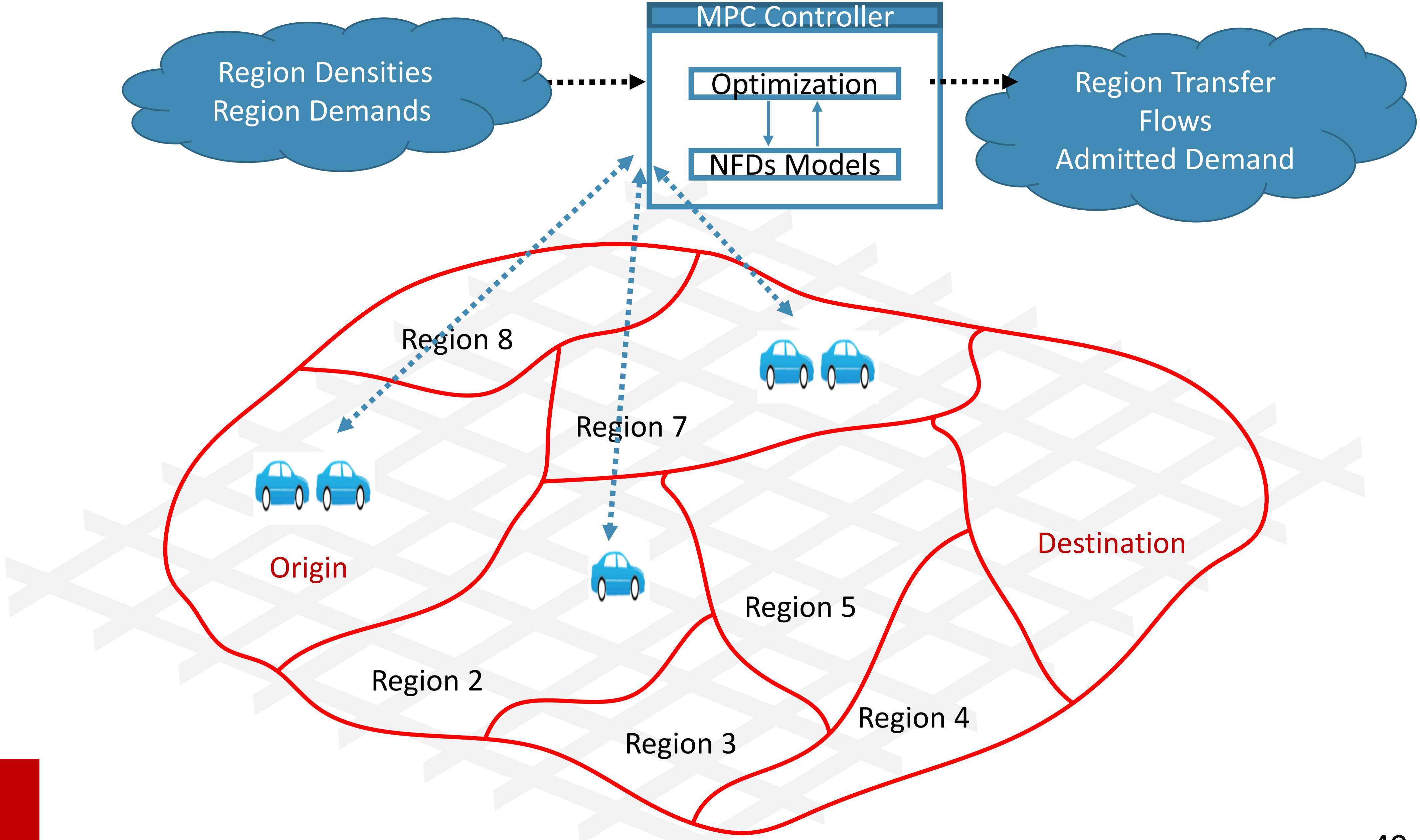
t=1

Joint Demand Management and Route Guidance



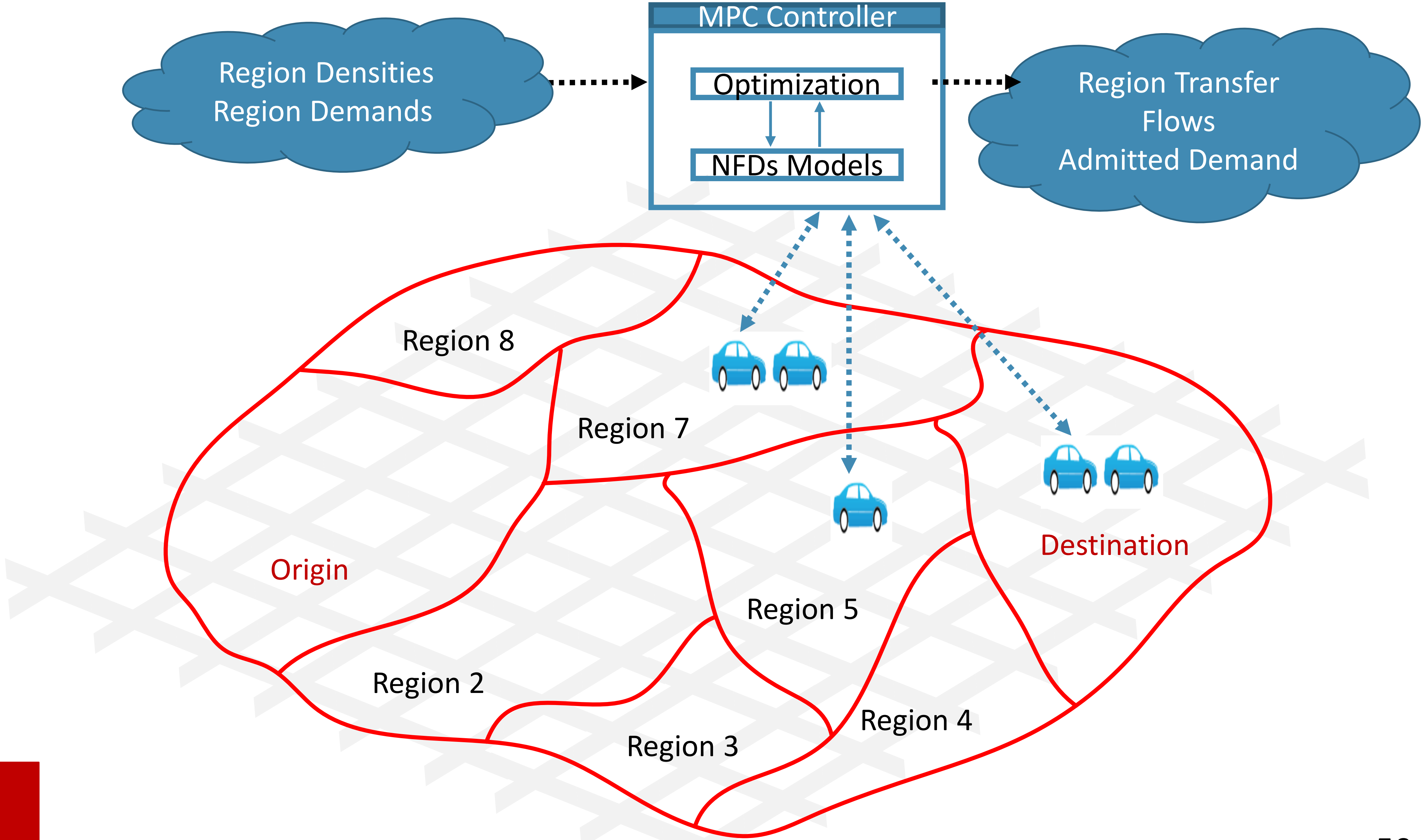
t=2

Joint Demand Management and Route Guidance



t=3

Joint Demand Management and Route Guidance



Region Densities
Region Demands

MPC Controller

Optimization

NFDs Models

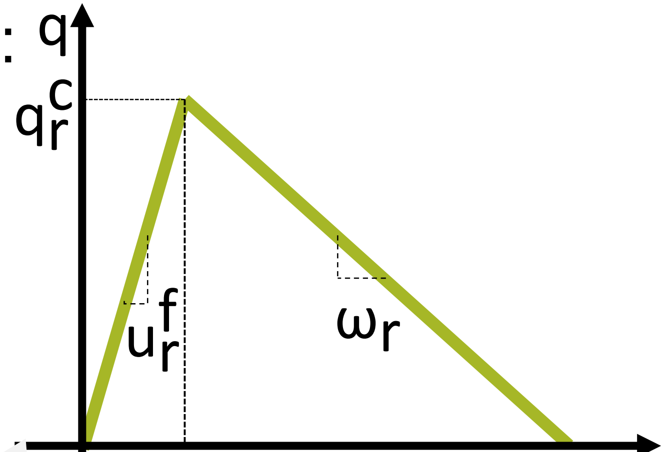
Region Transfer
Flows
Admitted Demand

t=4

System Model

- The intended outflow (i.e., $q_r(\rho_r(k))$) is denoted by the NFD as:

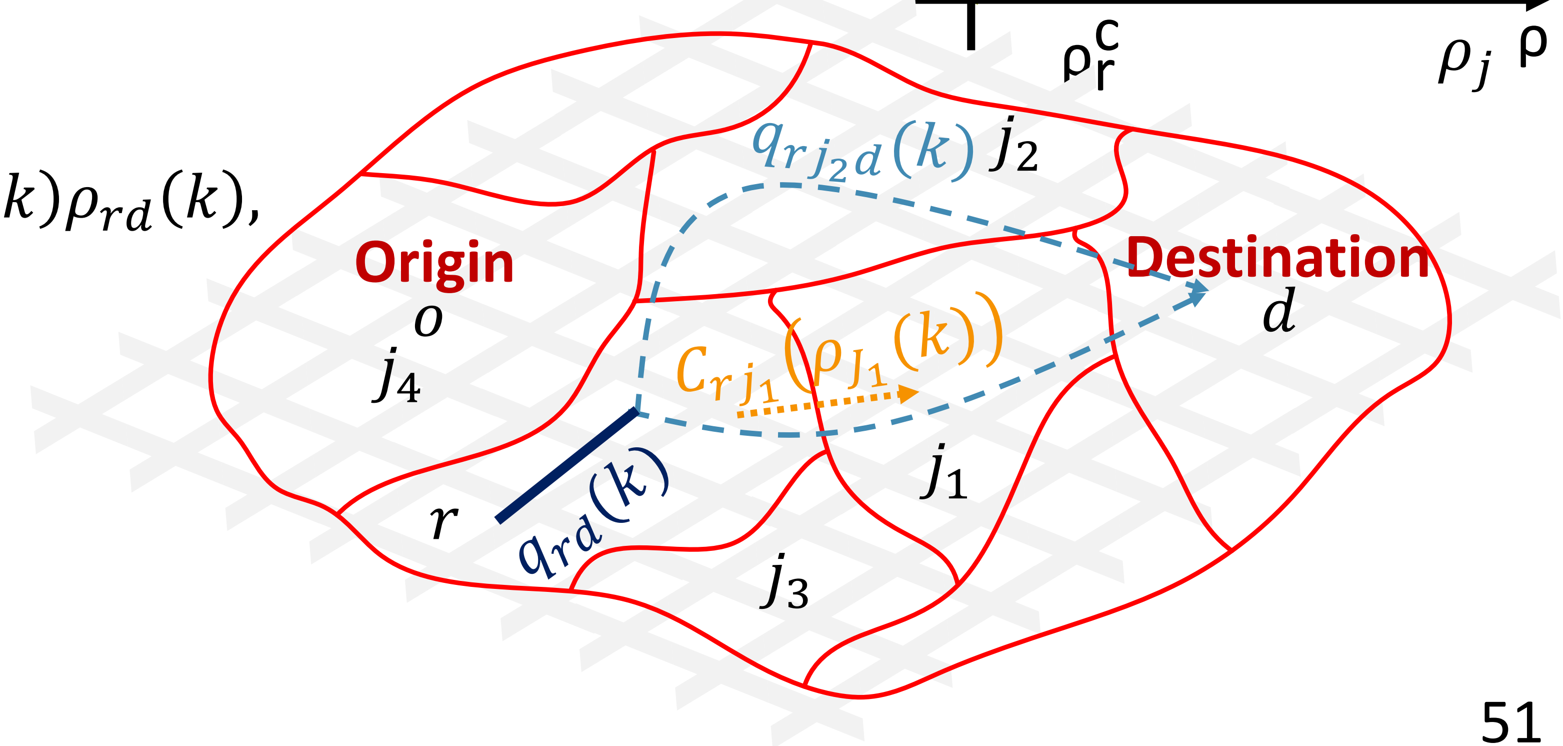
$$q_r\big(\rho_r(k)\big) = \begin{cases} \frac{q_r^C}{\rho_r^c}\rho_r(k), \ \text{if} \ 0 \le \rho_r(k) \le \rho_r^C \\ \frac{q_r^C}{\left(\rho_r^J - \rho_r^C\right)}\left(\rho_r^J - \rho_r(k)\right), otherwise \end{cases}$$



$$q_{rd}(k) = \frac{q_r\big(\rho_r(k)\big)}{\rho_r(k)}\,\rho_{rd}(k) = u_r(k)\rho_{rd}(k),$$

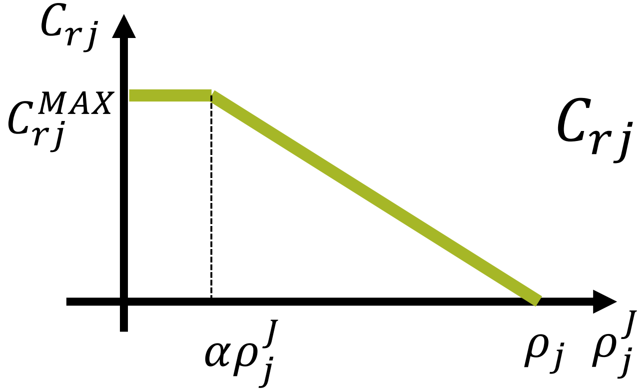
$$q_{rd}(k) = \sum_{j\in\mathcal{J}_r} q_{rjd}(k)\,,$$

$$q_r(k) = \sum_{d\in\mathcal{D}} q_{rd}(k).$$



System Model

- C_{rj}^{MAX} is the maximum physical flow that can be exchanged between two regions
- The inter-boundary capacity of each region is



$$C_{rj}\left(\rho_j(k)\right) = \begin{cases} C_{rj}^{MAX}, & if \quad \rho_j(k) \leq \alpha\rho_j^J, \\ \dfrac{C_{rj}^{MAX}}{1-\alpha}\left(1 - \dfrac{\rho_j(k)}{\rho_j^J}\right), otherwise \end{cases}$$

with $\alpha\rho_j^J$ is the point where the inter-boundary capacity starts to decrease $(0 < \alpha < 1)$.

- The actual transfer flow between neighboring regions relies on its remaining storage capacity and thus,

$$\tilde{q}_{rjd}(k) = \min\left(q_{rjd}(k), C_{rj}\left(\rho_j(k)\right)\frac{q_{rjd}(k)}{\sum_{y\in\mathcal{D}} q_{rjy}(k)}\right)$$

System Model

- The demand dynamics on each region can be defined as:

Cumulative External Demand

Instantaneous External Demand

$$D_{od}(k+1) = D_{od}(k) - \tilde{d}_{od}(k) + d_{od}(k),\ k = 1, \dots,\ \text{with } D_{od}(0) = 0,$$

Admitted External Demand

- The traffic dynamics on each region can be defined as:

$$\rho_{rd}(k+1) = \rho_{rd}(k) + \frac{1}{L_r}\,\tilde{d}_{rd}(k) + \frac{T_s}{L_r}\sum_{j\in\mathcal{J}_r}(\tilde{q}_{jrd}(k) - \tilde{q}_{rjd}(k)),$$

$$\rho_r(k) = \sum_{d\in\mathcal{D}}\rho_{rd}(k)$$

System Model

- $S^a(k)$ be the cumulative number of vehicles that request to enter the network

$$S^a(k+1) = S^a(k) + \sum_{o\in\mathcal{O}} \sum_{d\in\mathcal{D}} d_{od}(k)\,,$$

- $S^b(k)$ be the cumulative number of vehicles that successfully arrive at their destination

$$S^b(k+1) = S^b(k) + T_s \sum_{d\in\mathcal{D}} \tilde{q}_{rjd}(k)\ \{r,j\} \in \mathcal{D},$$

with $S^a(0) = S^b(0) = 0.$

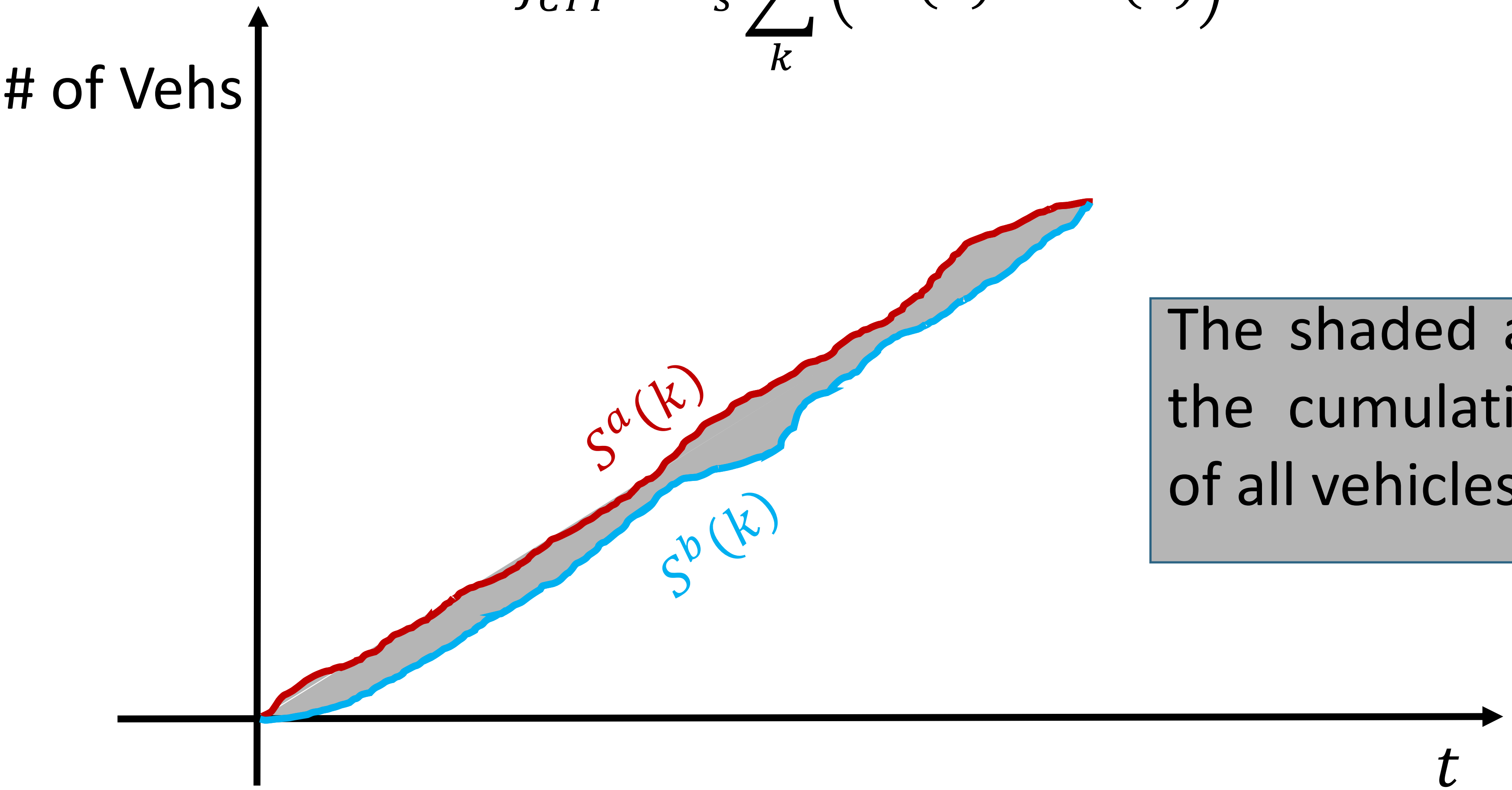
- **Objective Function:**

Is the cumulative travel time of all vehicles J_{CTT} (veh.h) over all time-steps k

$$J_{CTT} = T_s \sum_{k} \left(S^a(k) - S^b(k)\right),$$

Objective Function

$$J_{CTT} = T_s \sum_k \left(S^a(k) - S^b(k) \right)$$



The shaded area represents the cumulative time spend of all vehicles J_{CTT} (veh.h).

Note that the CTT includes the time spend in network and the waiting time at the origins.

NLP Formulation

- A new problem is solved every m time-steps assuming that the control and prediction horizons are equal to mN_p.
- For the l-th MPC problem solution $l = 1, \dots,$ we define the time horizon $\mathcal{K}_l$ where:

$$\mathcal{K}_l = \left\{m(l-1)+1, \dots, m\left((l-1)+N_p\right)\right\}.$$

- Under these conditions we formulate the l-th problem of finding $q_{rjd}(k)$ and $\tilde{d}_{od}(k)$ as:

$$min\ J_{CTT}^{MPC}(l) = T_S \sum_{k\in\mathcal{K}_l} \left(S^a(k) - S^b(k)\right)$$

s.t. Traffic Dynamics

$$\tilde{d}_{od}(k) \leq D_{od}^{MAx}, k \in \mathcal{K}_l, o \in \mathcal{O}, d \in \mathcal{D},$$

$$\tilde{d}_{od}(k) \leq D_{od}(k), k \in \mathcal{K}_l, o \in \mathcal{O}, d \in \mathcal{D},$$

$$0 < \rho_r(k) \leq \rho_r^J(k), k \in \mathcal{K}_l, r \in \mathcal{R},$$

$$S^a(0) = S^b(0) = 0,$$

Variables: $\rho_r(k), \rho_{\mathrm{rd}}(\mathrm{k}), \tilde{\mathrm{d}}_{\mathrm{od}}(\mathrm{k}), \mathrm{D}_{\mathrm{rd}}(\mathrm{k}), \mathrm{q}_{\mathrm{rjd}}(\mathrm{k}), \mathrm{q}_{\mathrm{rd}}(\mathrm{k}), \mathrm{q}_{\mathrm{r}}\left(\rho_r(k)\right), \tilde{\mathrm{q}}_{\mathrm{rjd}}(\mathrm{k}), \mathrm{S}^{\mathrm{a}}(\mathrm{k}), \mathrm{S}^{\mathrm{b}}(\mathrm{k}), \mathrm{u}_{\mathrm{r}}(\mathrm{k})$

NLP Formulation

- The Problem (14) is a non-convex non-linear problem due to the following constraints

$$q_r\left(\rho_r(k)\right) = \begin{cases} \frac{q_r^C}{\rho_r^c}\rho_r(k), \text{ if } 0 \leq \rho_r(k) \leq \rho_r^C \\ \frac{q_r^C}{\left(\rho_r^J - \rho_r^C\right)}\left(\rho_r^J - \rho_r(k)\right), otherwise \end{cases}$$

$$q_{rd}(k) = \frac{q_r\left(\rho_r(k)\right)}{\rho_r(k)}\ \rho_{rd}(k) = u_r(k)\rho_{rd}(k)$$

$$C_{rj}\left(\rho_j(k)\right) = \begin{cases} C_{rj}^{MAX}, \quad if \quad \rho_j(k) \leq \alpha\rho_j^J, \\ \frac{C_{rj}^{MAX}}{1-\alpha}\left(1 - \frac{\rho_j(k)}{\rho_j^J}\right), otherwise, \end{cases}$$

$$\tilde{q}_{rjd}(k) = \min\left(q_{rjd}(k), C_{rj}\left(\rho_j(k)\right)\frac{q_{rjd}(k)}{\sum_{y\in\mathcal{D}} q_{rjy}(k)}\right)$$

- In order to handle these constraints we develop two approximate formulations:
  1) A non-congested linear formulation that leads to a feasible solution (upper bound)
  2) A relaxed linear formulation which provides a lower bound solution

Non-congested Linear Feasible Solution

- To guarantee an operation in the congestion free regime we restrict the maximum value of the density of each region as $0 \le \rho_r(k) \le \min(\rho_r^C, \alpha\rho_r^J)$

$$q_r(\rho_r(k)) = \begin{cases} \frac{q_r^C}{\rho_r^c}\rho_r(k), & \text{if } 0 \le \rho_r(k) \le \rho_r^C \\ \frac{q_r^C}{(\rho_r^J - \rho_r^C)}\left(\rho_r^J - \rho_r(k)\right), & otherwise \end{cases} \longrightarrow q_r(\rho_r(k)) = \frac{q_r^C}{\rho_r^C}\rho_r(k) = u_r^f \rho_r(k)$$

$$q_{rd}(k) = \frac{q_r(\rho_r(k))}{\rho_r(k)}\rho_{rd}(k) = u_r(k)\rho_{rd}(k) \longrightarrow q_{rd}(k) = u_r^f \rho_{rd}(k)$$

$$C_{rj}\left(\rho_j(k)\right) = \begin{cases} C_{rj}^{MAX}, & if \quad \rho_j(k) \le \alpha\rho_j^J, \\ \frac{C_{rj}^{MAX}}{1-\alpha}\left(1 - \frac{\rho_j(k)}{\rho_j^J}\right), & otherwise, \end{cases} \longrightarrow C_{rj}\left(\rho_{rj}(k)\right) = C_{rj}^{MAX}$$

$$\tilde{q}_{rjd}(k) = \min\left(q_{rjd}(k), C_{rj}\left(\rho_j(k)\right)\frac{q_{rjd}(k)}{\sum_{y\in\mathcal{D}} q_{rjy}(k)}\right) \longrightarrow \begin{array}{l} \tilde{q}_{rjd}(k) = q_{rjd}(k) \\ \sum_{d\in\mathcal{D}} \tilde{q}_{rjd}(k) \le C_{rj}^{MAX} \end{array}$$

Linear Relaxation (Lower Bound)

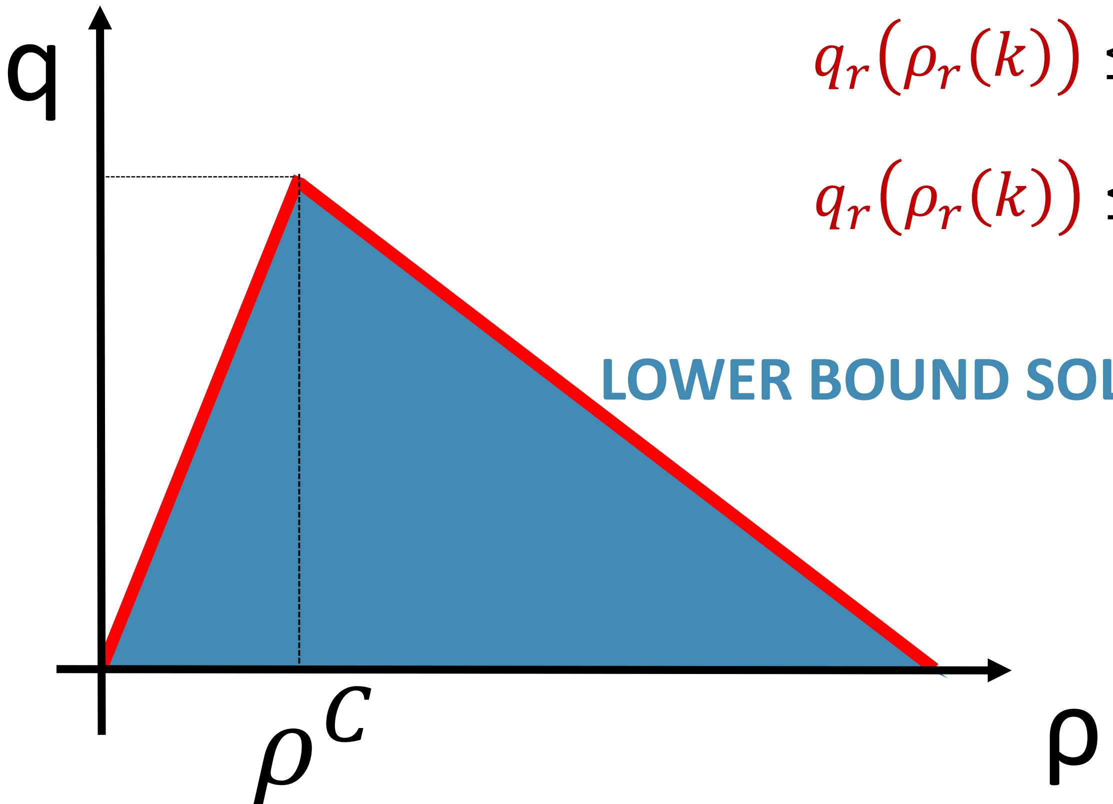
- Considering the triangular NFD form its true that the intended outflow can be equivalently be written as

$$q_r(\rho_r(k)) = \min\left(\frac{q_r^c}{\rho_r^C}\rho_r(k), w_r\left(\rho_r^J - \rho_r(k)\right)\right)$$

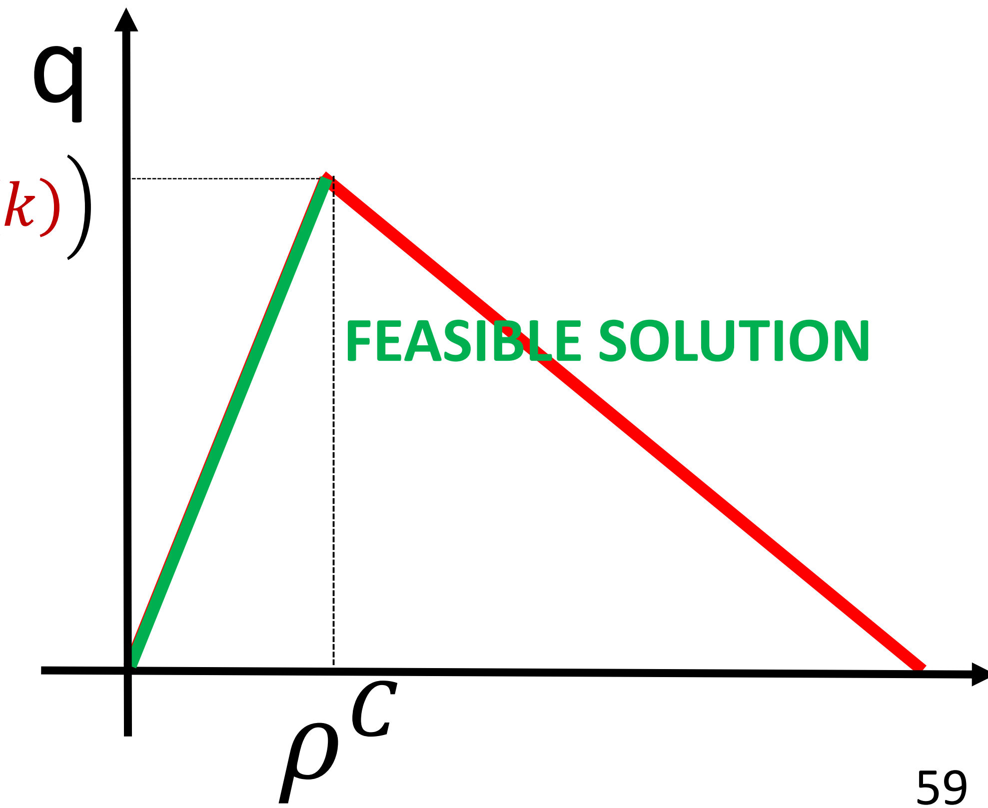
- Thus the intended outflow rate of each region can be relaxed by bounding $q_r(\rho_r(k))$ to be smaller than two linear terms as

$$q_r(\rho_r(k)) \leq \frac{q_r^c}{\rho_r^C}\rho_r(k)$$

$$q_r(\rho_r(k)) \leq w_r\left(\rho_r^J - \rho_r(k)\right)$$



LOWER BOUND SOLUTION



Linear Relaxation (Lower Bound)

- The problem can be relaxed into a Linear program as fillos

$0 \leq \rho_r(k) \leq \rho_r^J$ holds,

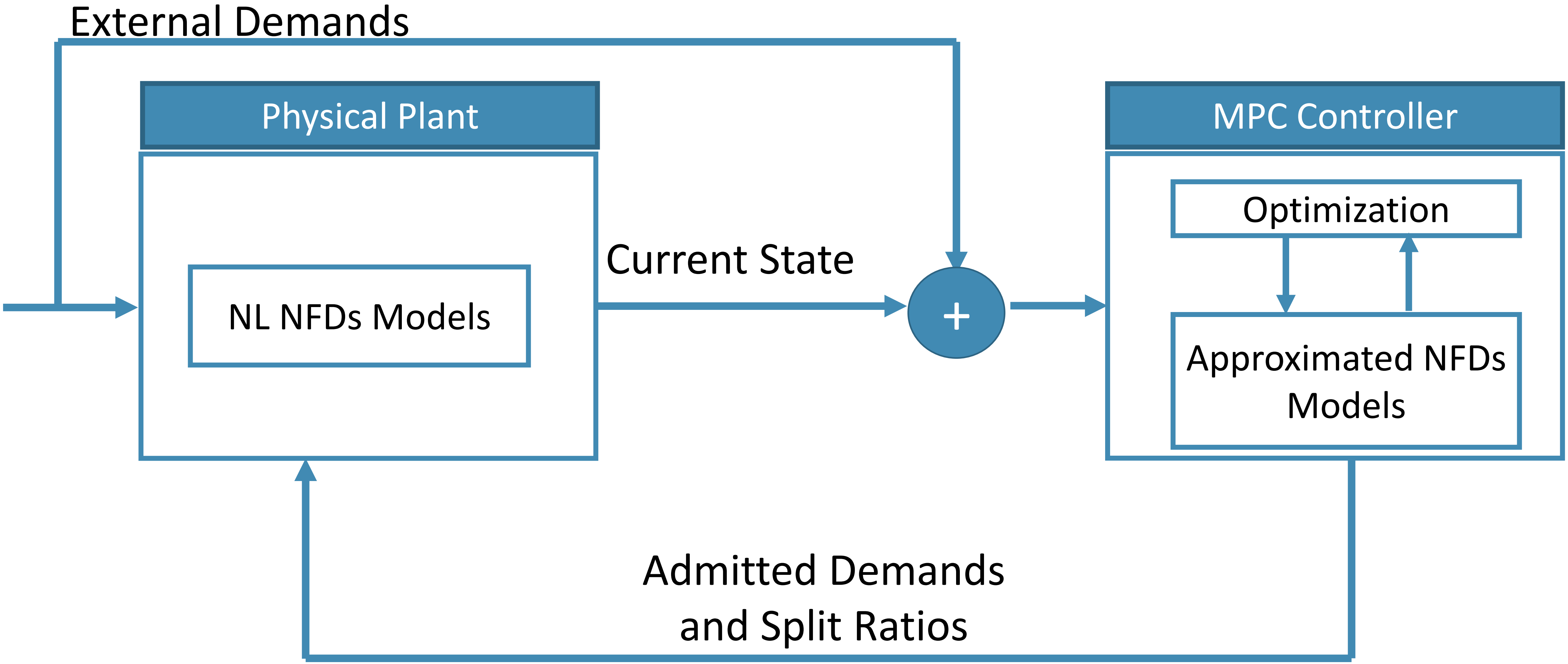
$$q_r\left(\rho_r(k)\right) = \begin{cases} \frac{q_r^C}{\rho_r^c}\rho_r(k), \text{ if } 0 \leq \rho_r(k) \leq \rho_r^C & \longrightarrow \quad q_r\left(\rho_r(k)\right) \leq \frac{q_r^c}{\rho_r^C}\rho_r(k) \\ \frac{q_r^C}{\left(\rho_r^J - \rho_r^C\right)}\left(\rho_r^J - \rho_r(k)\right), otherwise & \longrightarrow \quad q_r\left(\rho_r(k)\right) \leq w_r\left(\rho_r^J - \rho_r(k)\right) \end{cases}$$

$$q_{rd}(k) = \frac{q_r\left(\rho_r(k)\right)}{\rho_r(k)}\rho_{rd}(k) = u_r(k)\rho_{rd}(k) \longrightarrow q_{rd}(k) \leq u_r^f \rho_{rd}(k)$$

$$C_{rj}\left(\rho_j(k)\right) = \begin{cases} C_{rj}^{MAX}, \quad if \quad \rho_j(k) \leq \alpha\rho_j^J, & \longrightarrow \quad C_{rj}\left(\rho_j(k)\right) \leq C_{rj}^{MAX} \\ \frac{C_{rj}^{MAX}}{1-\alpha}\left(1 - \frac{\rho_j(k)}{\rho_j^J}\right), otherwise, & \longrightarrow \quad C_{rj}\left(\rho_j(k)\right) \leq \frac{C_{rj}^{MAX}}{1-\alpha}\left(1 - \frac{\rho_j(k)}{\rho_j^J}\right) \end{cases}$$

$$\tilde{q}_{rjd}(k) = \min\left(q_{rjd}(k), C_{rj}\left(\rho_j(k)\right)\frac{q_{rjd}(k)}{\sum_{y\in\mathcal{D}} q_{rjy}(k)}\right) \begin{array}{l} \nearrow \quad \tilde{q}_{rjd}(k) \leq q_{rjd}(k) \\ \searrow \quad \sum_{d\in\mathcal{D}} \tilde{q}_{rjd}(k) \leq C_{rj}\left(\rho_j(k)\right) \end{array}$$

Implementation



External Demands

Physical Plant

NL NFDs Models

Current State

+

MPC Controller

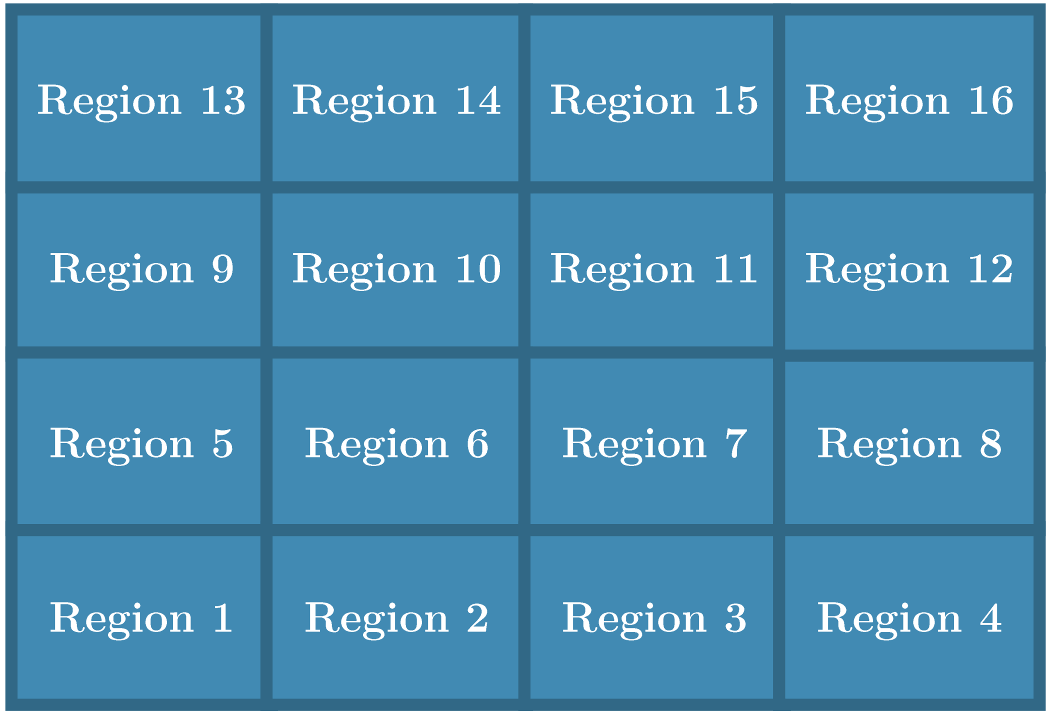
Optimization

Approximated NFDs Models

Admitted Demands
and Split Ratios

Simulation Setup

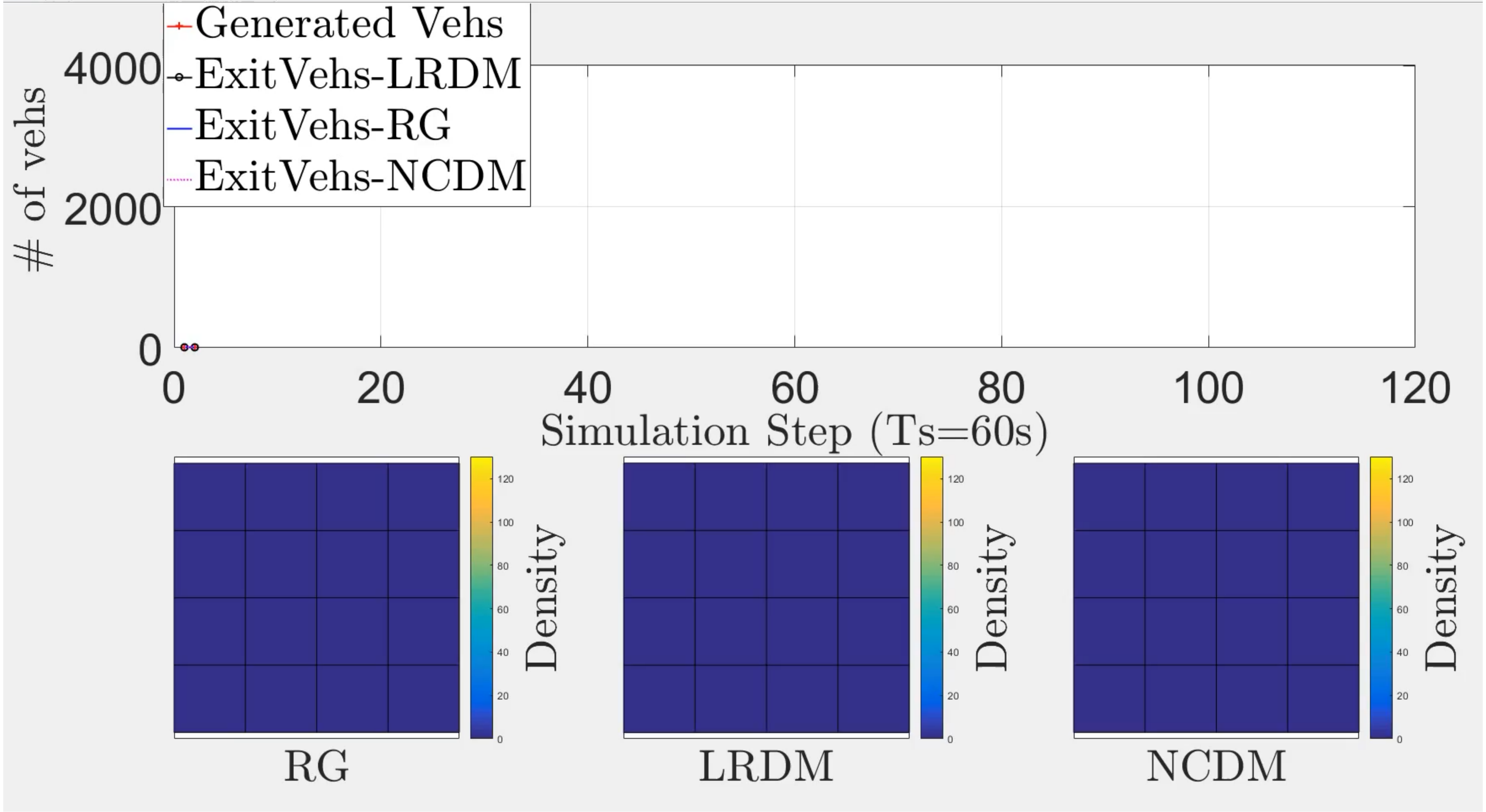
- The simulated urban area consists of 16 regions of which four regions considered as origins (i.e., regions: 1, 4, 11 and 16) and four region considered as destinations (i.e., regions: 2, 8, 9 and 14).
- All regions are assume to have identical triangular NFD as follows : $\rho_r^C = 30$ veh/km, $\rho_r^j = 130$ veh/km, $L_r = 1$ km, $u_r^f = 60$ km/h, $q_r^C = 1800$ veh/h, $C_{rj}^{MAX} = 2000$ veh/h, $\alpha = 0.25$, $mN_p = 20$, and $m = 5$.



Region 13	Region 14	Region 15	Region 16
Region 9	Region 10	Region 11	Region 12
Region 5	Region 6	Region 7	Region 8
Region 1	Region 2	Region 3	Region 4

- The following MPC schemes are examined:
  1. **RG** The ordinary Route Guidance scheme, according to a MILP formulation.
  2. **LRDM** The linear relaxation of the joint demand management and route guidance. (lower bound solution)
  3. **NCDM** The non-congested feasible solution of the joint demand management and route guidance. (upper bound solution)

Simulation Results



Optimality Gap

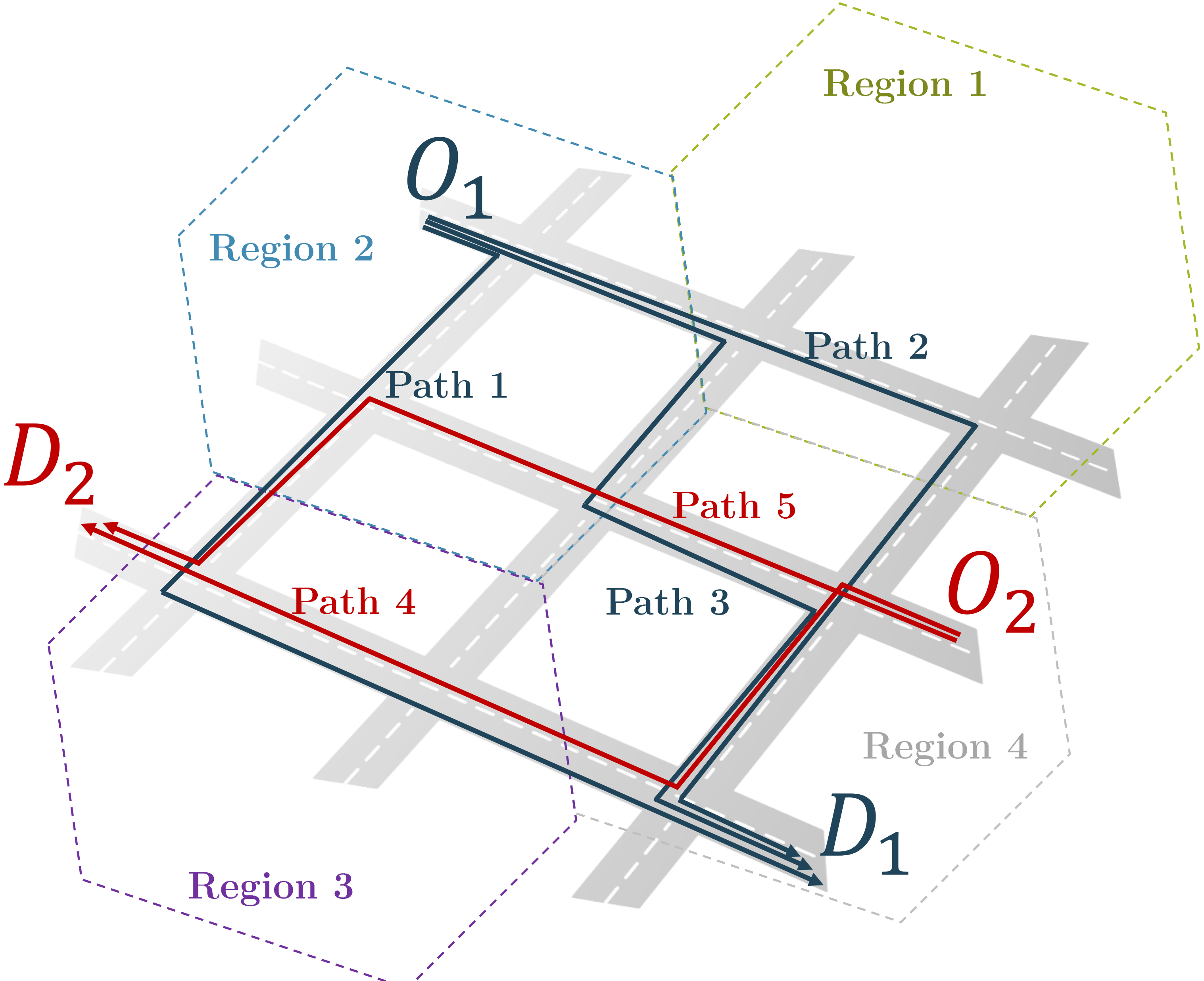
Demand Scenarios	1	2	3	4	5	6	7	8
NCDM	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0005%
RG	0.0%	0.0%	0.8%	5.4%	29%	82.5%	NSF	NSF

$$Optimality\ Gap = \frac{Objective(Alg) - Objective(LRDM)}{Objective(LRDM)} * 100\%, \qquad Alg = [NCDM, RG]$$

NSF= No solution Found within the simulation period.

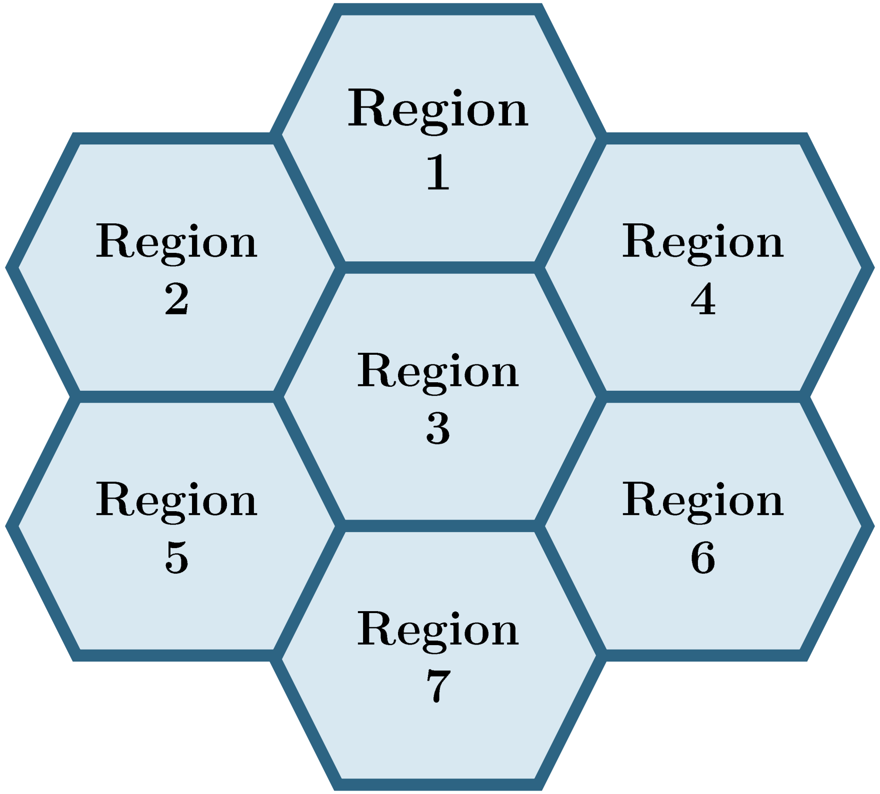
Path-Based Joint Demand Management and Route Guidance

Path-Based Joint Demand Management and Route Guidance



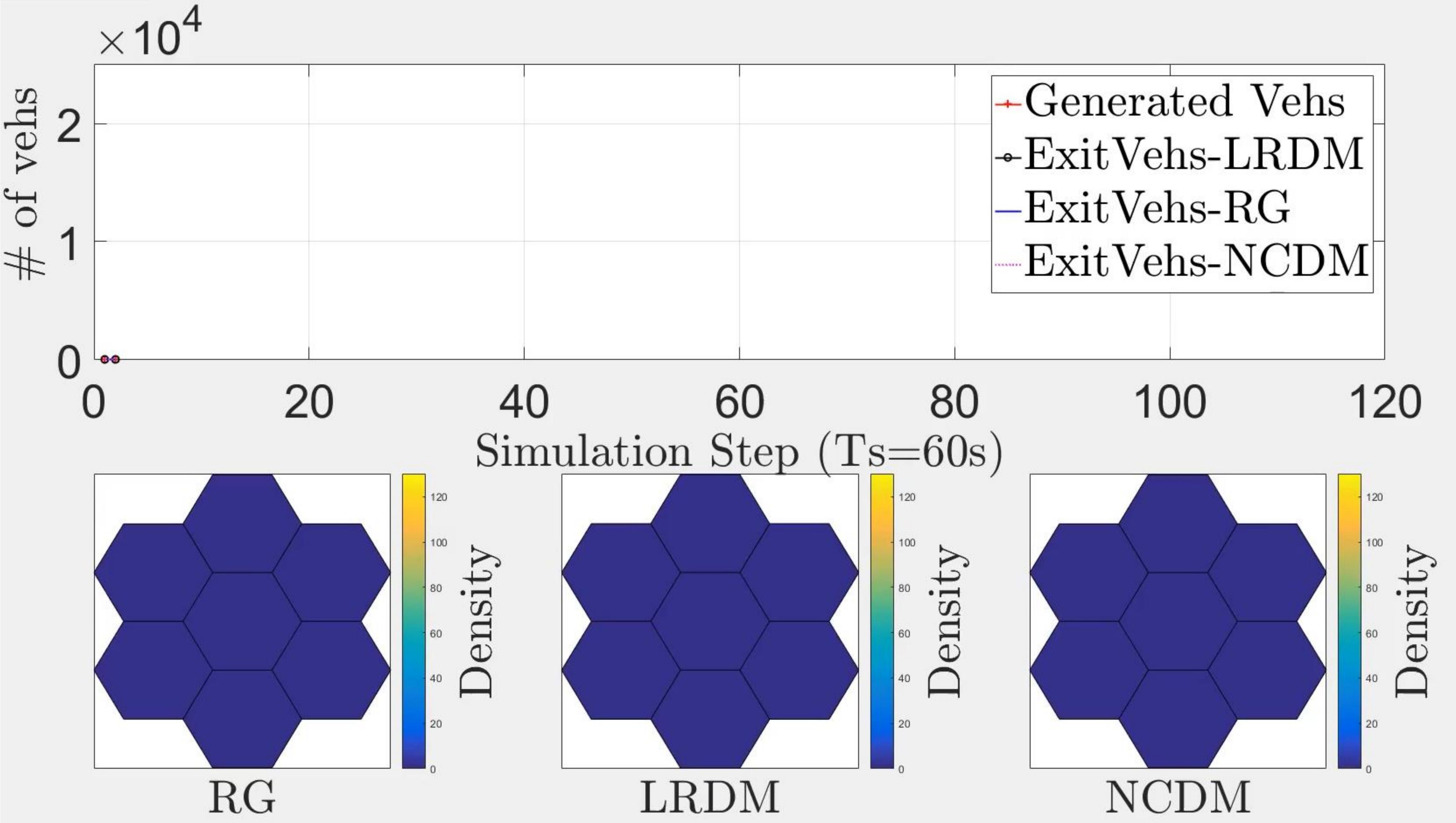
Simulation Results

- The simulated urban area consists of 7 regions of which three regions are considered as origins (i.e., regions 1, 2 and 6) and three region as destinations (i.e., regions 4, 5, and 7).
- All regions are assumed to have identical triangular NFDs with parameters: $\rho_r^C = 30$ veh/km, $\rho_r^j = 130$ veh/km, $L_r = 1$ km, $u_r^f = 60$ km/h, $q_r^C = 1800$ veh/h, $C_{rj}^{MAX} = 2000$ veh/h, $\alpha = 0.25$, $mN_p = 30$, and $m = 2$.

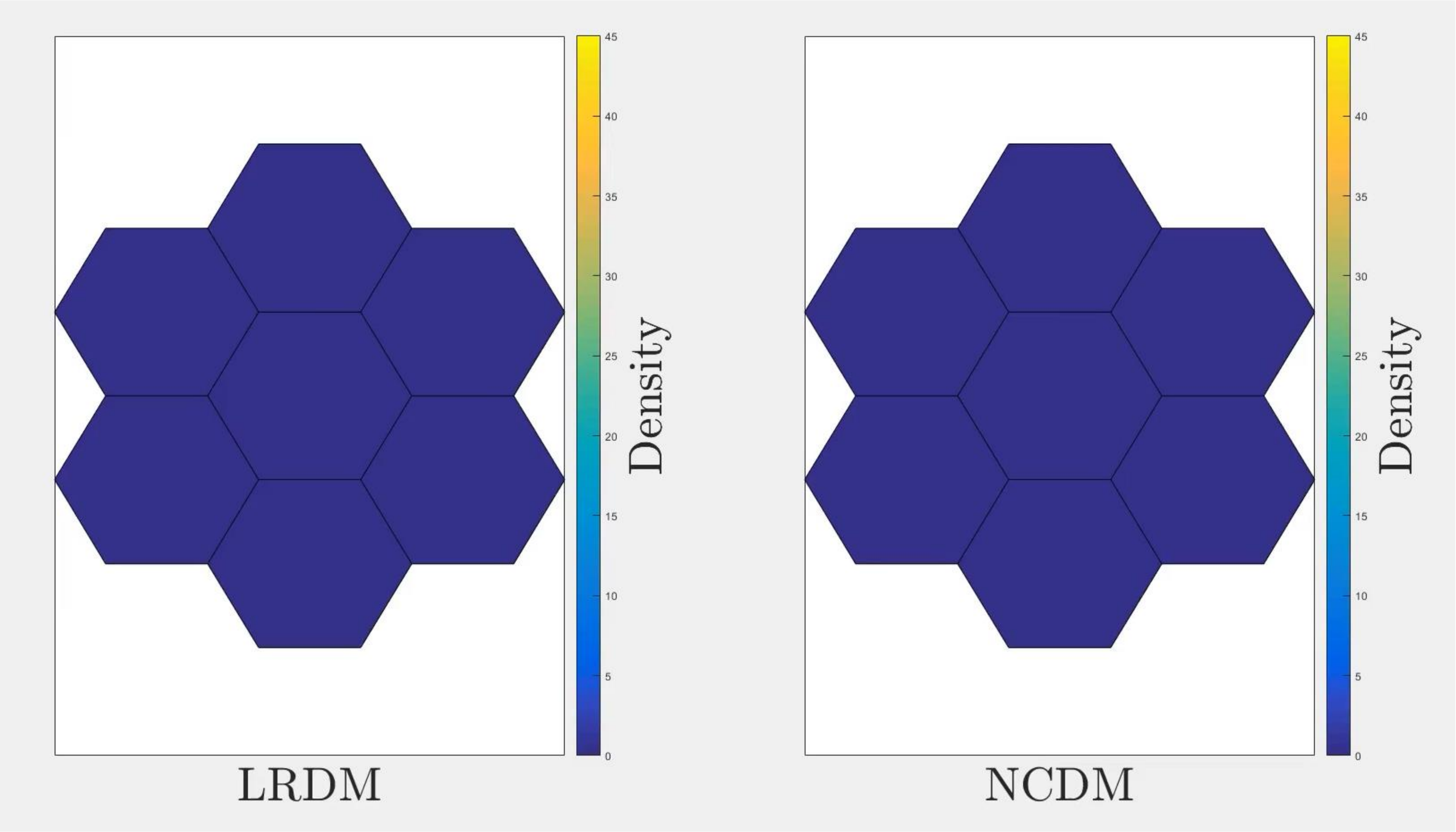


- The following MPC schemes are examined:
  1. **RG:** The ordinary Route Guidance scheme, according to a MILP formulation.
  2. **LRDM:** The linear relaxation of the joint demand management and route guidance.
  3. **NCDM:** The non-congested feasible solution of the joint demand management and route guidance.

Simulation Results



Simulation Results



Optimality Gap

Demand Scenarios	1	2	3	4	5	6
NCDM	0.0463%	0.0211%	0.0526%	0.0857%	0.0955%	0.0587%
RG	0.8%	6.09%	435%	NSF	NSF	NSF

$$Optimality\ Gap = \frac{Objective(Alg) - Objective(LRDM)}{Objective(LRDM)} * 100\%, \qquad Alg = [NCDM, RG]$$

NSF= No solution Found within the simulation period.

Other group contributions

- Unsignalized Intersection Crossing using Connected and Autonomous Vehicles
- Distributed Network Traffic Signal Control
- Traffic state estimation with bound guarantees
- Fault-tolerant traffic state estimation
- Electric vehicle routing with charging in transportation networks using probabilistic models
- Origin-destination matrix estimation using Bayesian theory
- Event-based communications in public transportation systems
- Data offloading transfers through intervehicle communication transmissions

Conclusions

- Proposed a novel route reservation architecture aiming to maximize the efficiency of the urban transport system
- Proposed algorithms can **eliminate congestion altogether** through:
  - waiting at home
  - intelligent routing
- The emergence of connected and automated vehicles can make this reservation architecture a reality

Future Work

- **Reservation Architecture**
  - Distributed Reservation Architecture.
  - **Closed Loop**: Re-route / Reschedule vehicles if an accident occurs or vehicles significantly deviate from their scheduled path.
  - Investigate the on-time arrival problem with stochasticity in which vehicles are probabilistically compliant to their given instructions.

- **Macroscopic Approaches**
  - Formulate the problem as a robust optimization problem to deal with noise and uncertainty.
  - Investigate the effect and the performance of this MPC approach in other strategies such as Ramp metering and Variable Speed Limit.

Related Publications

Journal Publications

1. C. Menelaou, P. Kolios, S. Timotheou, C.G. Panayiotou, and M.M. Polycarpou, ``Controlling road congestion via a low-complexity route reservation approach'', Transportation Research Part C: Emerging Technologies, vol. 81, pp. 118–136, 2017.
2. C. Menelaou, S. Timotheou, P. Kolios, and C.G. Panayiotou, ``Improved Road Usage Through Congestion-Free Route Reservations'', Journal of the Transportation Research Board, vol.2621, pp. 71–80, 2017.
3. C. Menelaou, S. Timotheou, P. Kolios, C.G. Panayiotou, and M.M. Polycarpou, ``Minimizing traffic congestion through continuous-time route reservations with travel time predictions'',IEEE Transactions on Intelligent Vehicles, vol. 4, no. 1, pp. 141–153, March 2019.
4. C. Menelaou, S. Timotheou, P. Kolios, and C.G. Panayiotou, ``Joint route guidance and demand management for real-time control of multi-regional networks‘’, submitted to the IEEE Transactions on Intelligent Transportation Systems (June 2019).

Conference Proceedings

1. C. Menelaou, P. Kolios, S. Timotheou, and C.G. Panayiotou, ``Congestion free vehicle scheduling using a route reservation strategy'', IEEE 18th International Conference on Intelligent Transportation Systems, Las Palmas de Gran Canaria , Spain, Sep. 15 2015, pp. 2103-2108.
2. C. Menelaou, P. Kolios, S. Timotheou, and C.G. Panayiotou, ``On the complexity of congestion free routing in transportation networks'', IEEE 18th International Conference on Intelligent Transportation Systems, Las Palmas de Gran Canaria, Spain, Sep. 15 2015, pp. 2819-2824.
3. C. Menelaou, P. Kolios, S. Timotheou, and C.G. Panayiotou, ``A congestion-free vehicle route reservation architecture'', in 18th Mediterranean Electrotechnical Conference, Limassol, Cyprus, April 18 2015, pp. 1-6.
4. C. Menelaou, P. Kolios, S. Timotheou, and C.G. Panayiotou, ``Improved road usage through congestion-free route reservations'', Transportation Research Board (TRB), 96th Annual Meeting, Washington DC. USA, Jan 8 2017
5. C. Menelaou, S. Timotheou, P. Kolios, C.G. Panayiotou, and M.M. Polycarpou, ``Optimal Path Selection in a Continuous-Time Route Reservation Architecture'', IEEE 20th International Conference on Intelligent Transportation Systems, Yokohama, Japan, Oct. 16 2017, pp. 1-6.
6. C. Menelaou, P. Kolios, S. Timotheou, and C.G. Panayiotou, ``Effective Prediction of Road Segment Occupancy for the Route-Reservation Architecture'', 15th IFAC Symposium on Control in Transportation Systems, Savona, Italy, Jun. 6 2018, pp. 470-475.
7. C. Menelaou, P. Kolios, S. Timotheou, and C.G. Panayiotou, ``Effective Multi-region Traffic Control and Demand Management Using an Overlay Route-Reservation Scheme'' IEEE 21th International Conference on Intelligent Transportation Systems, Maui Hawaii, USA, Nov. 4 2018, pp. 1852-1857.
8. C. Menelaou, S. Timotheou, P. Kolios, and C.G. Panayiotou, ``Estimating the Critical Density of Road Transportation Networks using Infinitesimal Perturbation Analysis of Hybrid Systems.'' IEEE 57th Conference on Decision and Control, Miami Beach, FL, USA, Dec. 17 2018, pp. 1809-1814.
9. C. Menelaou, S. Timotheou, P. Kolios, and C. Panayiotou, ``Joint route guidance and demand management for multi-region traffic networks'' , to appear in the Proceedings of the 2019 European Control Conference, June 2019.
10. C. Menelaou, S. Timotheou, P. Kolios, C.G. Panayiotou, and M.M. Polycarpou, ``Path-based joint demand management and route guidance for multi-region traffic networks'', submitted to IEEE 22th International Conference on Intelligent Transportation Systems (ITSC'2019), Auckland, New Zealand, Oct. 27-30 (2019) (accepted).
11. C. Menelaou, S. Timotheou, P. Kolios, C.G. Panayiotou, and M.M. Polycarpou, ``Scheduling Vehicles for On-Time Arrival using Route-Reservations'', submitted to IEEE 22th International Conference on Intelligent Transportation Systems (ITSC'2019), Auckland, New Zealand, Oct. 27-30 (2019) (accepted).

Special Thanks

Charalambos Menelaou

Panayiotis Kolios

Christos Panayiotou

THANK you for your attention !

?