Cooperative Intelligent Transportation Systems in Urban Traffic Management

Associate Professor Edouard Ivanjko

April, 2019

- Croatia, part of Europe/EU
  - Area of 56,594 square kilometers
  - Around 4 million inhabitants
  - 1,244 small/big islands and reefs
- Capital city is Zagreb

- Touristic and industry country

- University of Zagreb, Croatia
  - Established in 1669 by Jesuits
  - 29 faculties and 3 academies
  - 4,850 research staff members and 50,000 students

- Faculty of Transport and Traffic Sciences
  - Established in 1984
  - 15 departments
    - Cover all transport modes, logistics, ITS, aeronautics
  - 100 research staff members / 2,200 students
  - Publisher of the journal

    PROMET – Traffic&Transportation
    - Cited in WoS, SCIE, Scopus, and SCIMAGO
    - Impact factor in 2017 is 0.456, Q4

- Department of intelligent transport systems
  - Head of department prof. Sadko Mandžuka
    - 6 professors, 1 postdoc, 5 young researchers, 2 lecturer
  - Chair of Applied Computing (head prof. Tonči Carić)
  - Chair of Transport Telematics (head assist. prof. Pero Škorput)
- Assoc. prof. Edouard Ivanjko
  - Research interests
    - Intelligent Transport Systems (ITS)
    - Modelling and simulation of road traffic
    - Road traffic control systems based on machine learning
    - Forecast of road traffic parameters
    - Autonomous vehicles
    - Application of computer vision in road traffic
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DATACROSS
Advanced methods and technologies for data science and cooperative systems

Outline

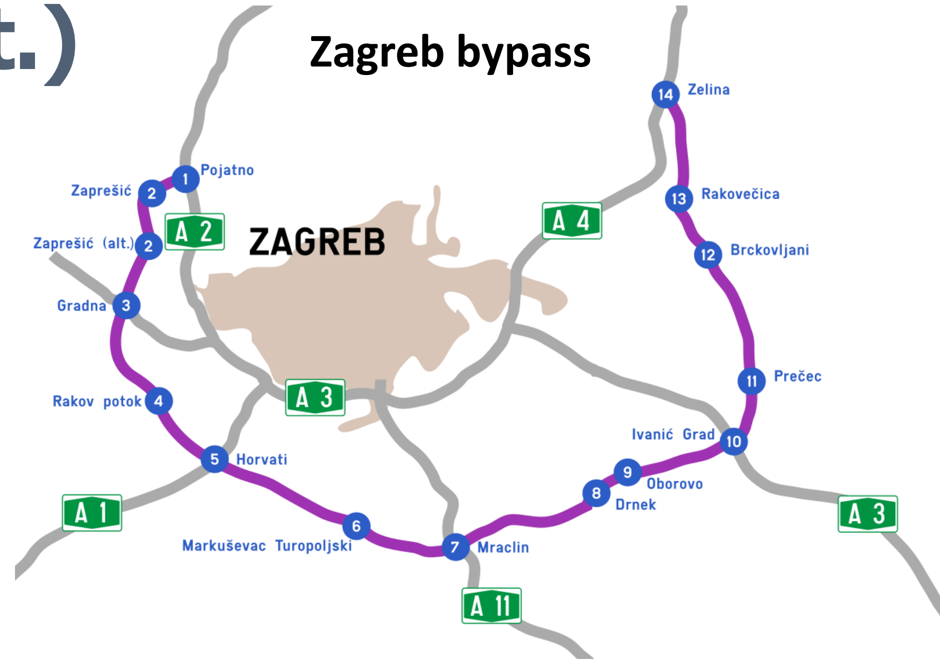
1. Introduction
2. Current problems on urban motorways
3. Simulation of motorway traffic flows
4. Control methods on urban motorways
5. Cooperative control approach for urban motorways
6. Ramp metering based on machine learning
7. Simulation results and discussion
8. Conclusion

1. Introduction

- Significant increase of the numbers of vehicles in urban road networks
  - **is caused by**
    - improved vehicle production technology
    - higher purchasing power of citizen
    - greater need for goods and citizens mobility
  - **and consequentially induces**
    - *higher demand for exploitation of the existing road network capacities*
    - ***congestions*** *– equilibrium of transport demand and road capacity supply is disrupted due to higher transport demand*

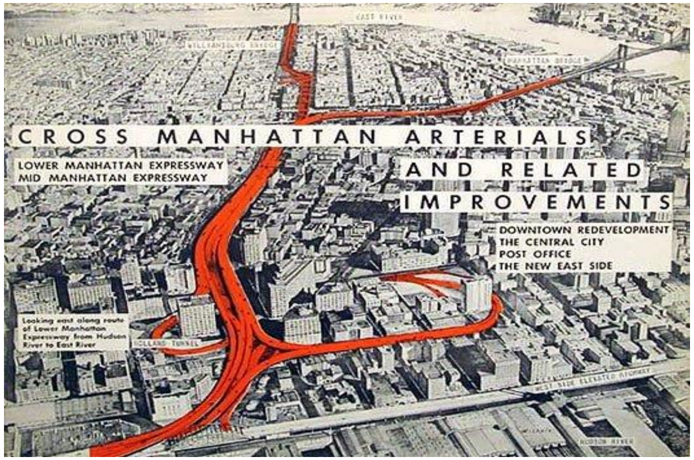
1. Introduction (cont.)

- Construction of urban bypasses is initial solution
  - Serve transit traffic
  - Connect urban traffic network with intercity motorway by several on- and off-ramps
  - Connect fast developing suburbs with urban center



1. Introduction (cont.)

- But by city expansion urban bypasses quickly became
  - Surrounded by urban infrastructure
  - Integrated with the urban traffic network
  - Significantly used by local urban traffic
- Urban bypasses fully integrated in the urban network are urban motorways
- **Result:** Today's urban motorways cannot fulfil desired Level of Service (LoS) due to congestions

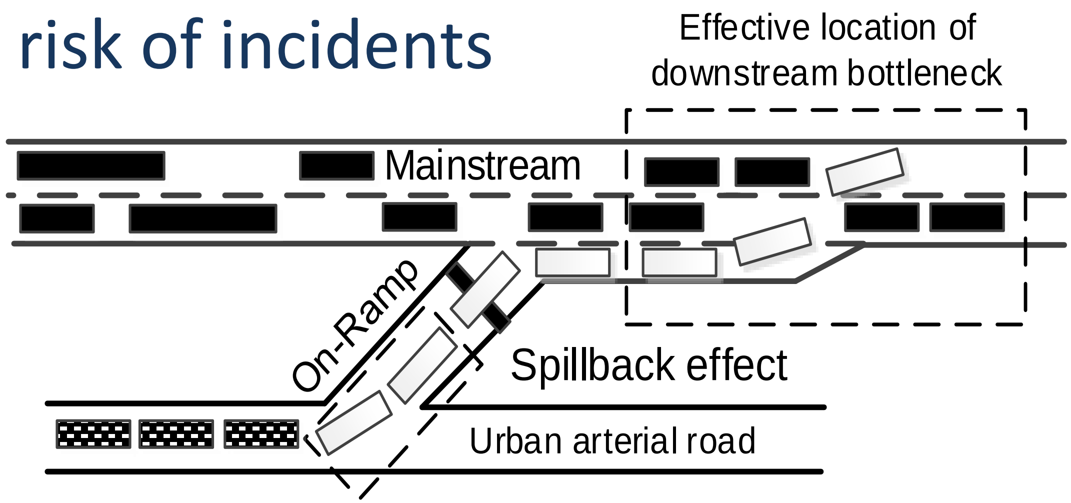


2. Current problems on urban motorways

- Recurrent congestions
  - Causes of congestions in time of peak hours
    - Many near on- and off-ramps
    - Lack of space for infrastructural build-up
    - Serve transit and local urban traffic
  - In spatial context
    - Near on- and off-ramps
  - In temporal context
    - During the early morning or late afternoon (peak hours)
- Non-recurrent congestion
  - Hard to define in spatial and temporal context
  - Consequently hard to predict (solution in better Incident Management)

2. Current problems on urban motorways (cont.)

- Uncontrolled platooned vehicle entry from on-ramps (urban arterial roads) into the urban motorway mainstream induce
  - Slowdowns in mainstream
    - Downstream bottleneck
    - Traffic „shock wave” upstream back-propagation
  - Queues at on-ramps
    - Traffic can spill over onto urban arterial roads
  - Higher risk of incidents



3. Simulation of motorway traffic flows

- Traffic simulators can be classified into two broad categories
  - ***Macroscopic models***
    - Traffic is a continuum and modeled by aggregated fluid-like quantities
    - Formulates the relationships among traffic flow parameters

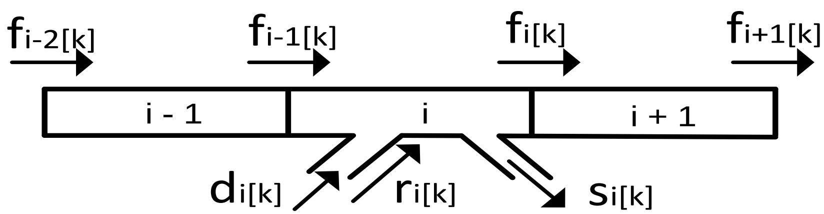
      e.g. Cell Transmission Models (CTM)
  - ***Microscopic models***
    - Dynamics of individual vehicle-driver entities and interactions between them and their surroundings are modeled explicitly

      e.g. Car-following models, Overtaking models, Cellular automata models, etc.

3. Simulation of motorway traffic flows (cont.)

CTMSIM - Matlab based macroscopic motorway traffic simulator

– Based on the Asymmetric Cell Transmission Model (ACTM)



– Traffic demand profile at on-ramps and motorway in/out flows

Cells

Simulation time
5 [min] intervals

demandProfile matrix variable

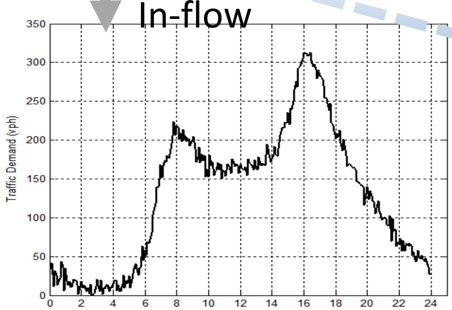
Variables - demandProfile

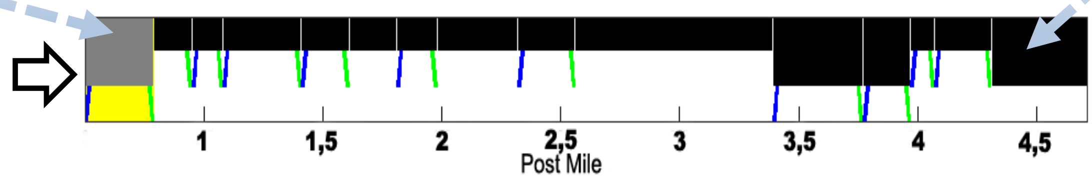
celldata | celldata(1, 1) | defaultCell | configFile | demandProfile

demandProfile <6624x16 double>

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	15	0	0	2	6	2	0	12	0	1	0	1	0	1	10	416
2	14	1	0	2	4	1	0	15	0	0	0	2	0	2	10	416
3	16	3	0	1	5	4	0	14	0	1	0	2	0	1	11	415
4	14	0	0	1	7	1	0	13	0	2	0	1	0	1	10	416
5	14	2	0	0	5	1	0	13	0	1	0	2	0	2	9	414

In-flow

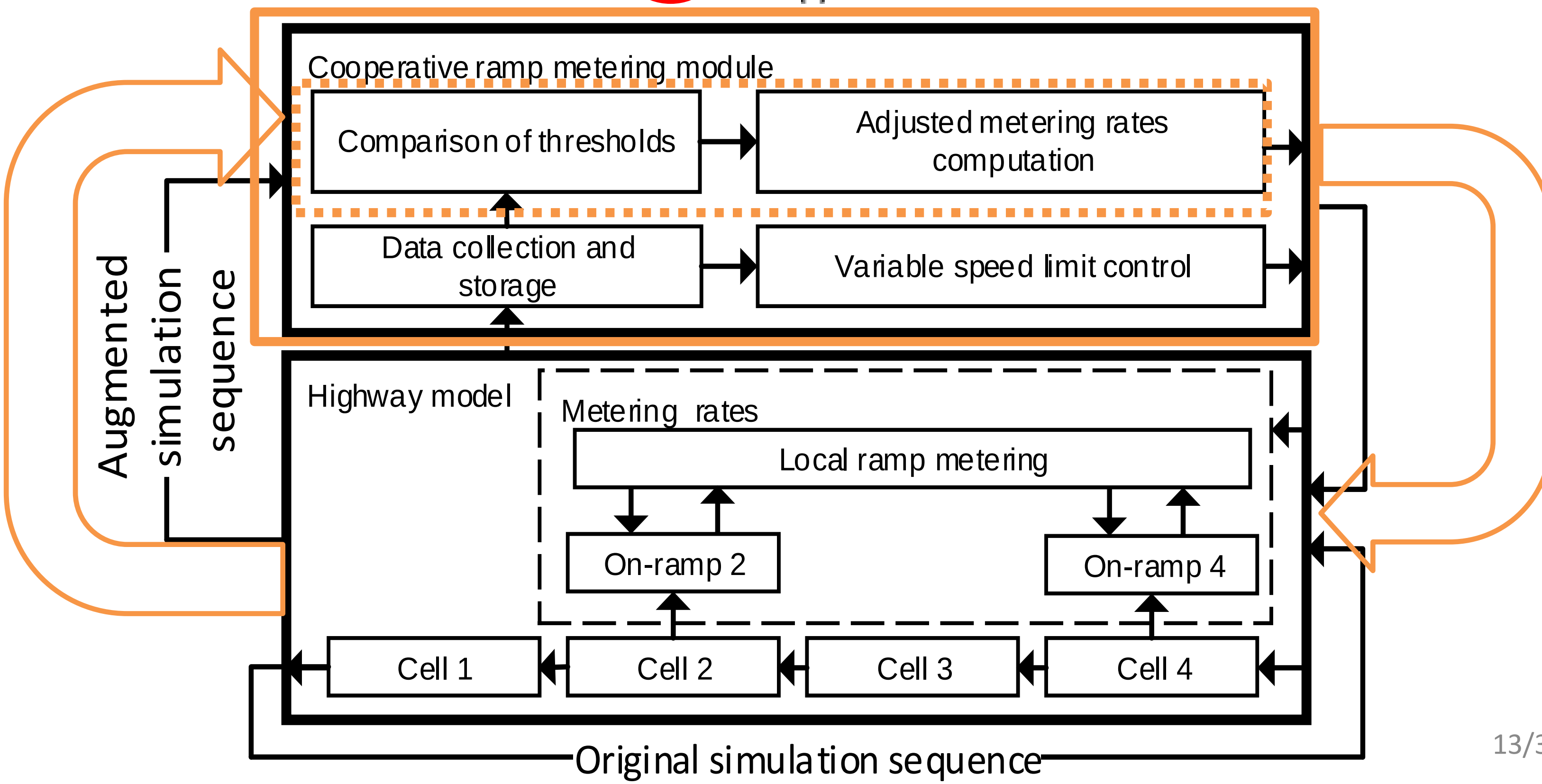




Out-flow

3. Simulation of motorway traffic flows (cont.)

- Augmentations of CTMSIM
  - Cooperative Ramp Metering module with abilities
    - To access data from all cells in the ACTM model
    - To override locally computed metering rates
  - VSLC support $v^{c}_{i[k]} = \min\left(v^{VSLC}_{i[k]}, \frac{f_{i[k]} + r_{i[k]}}{\rho_{i[k]}}, v^{ff}_{i[k]}\right)$

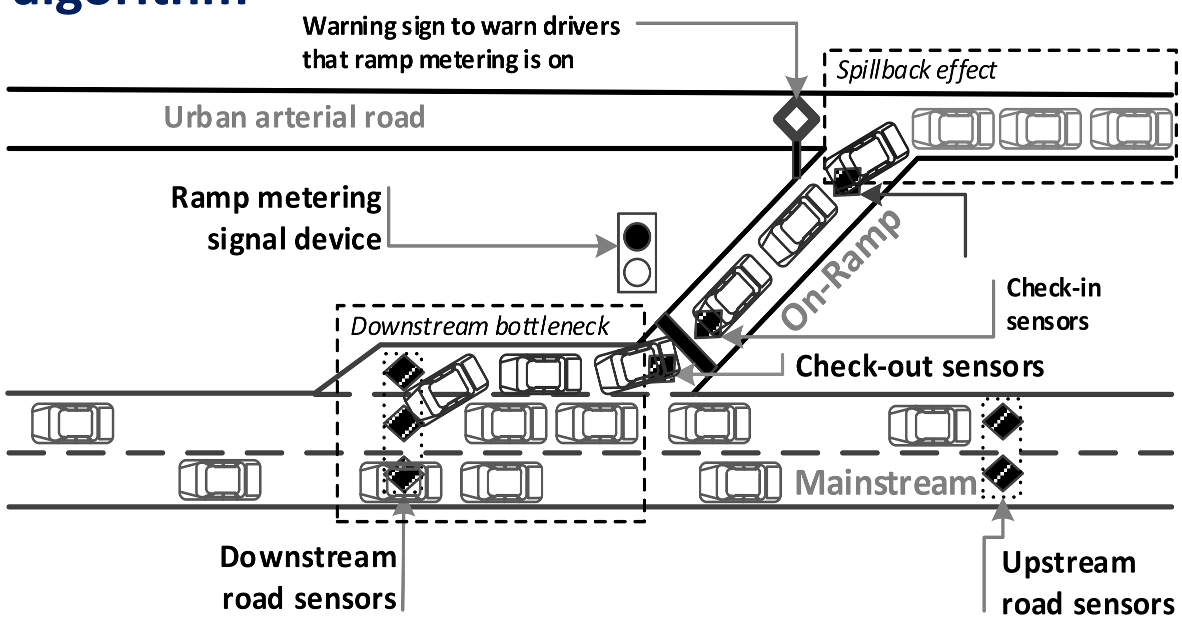


4. Control methods on urban motorways

- Current control methods for improvement of the urban motorway Level of Service (LoS)
  - Ramp Metering (RM)
  - Variable Speed Limit Control (VSLC)
  - Prohibiting Lane Use System (PLUS)
  - Driver Information System (DIS) - rerouting, etc.
- Latest approaches in motorway control strategies
  - Cooperation between several on-ramps
  - Cooperation between several different motorway control systems
  - Cooperative control of vehicles
- Most used control techniques in latest research
  - Control algorithms based on machine learning
  - Advanced optimization methods
  - Algorithms based on predictive control

4. Control methods on urban motorways (cont.)

- Ramp Metering
  - Controls (metering) rate of the on-ramp traffic flow entering the motorway by using
    - **Traffic lights**
    - **Measured traffic data in real time**
      - Mainstream sensors (upstream or/and downstream group)
      - On-ramp queue length sensors (check-in and check-out sensor)
    - **Control algorithm**



4. Control methods on urban motorways (cont.)

- Local RM algorithms
  - Consider only traffic condition on a particular on-ramp and its nearby motorway segment
  - **ALINEA** - keeps the downstream occupancy of the on-ramp area at a specified level by adjusting the metering rate

$$r_i(k) = r_i\,(k-1) + \;K_R\big[O_i - O_i^{out}(k)\big]$$

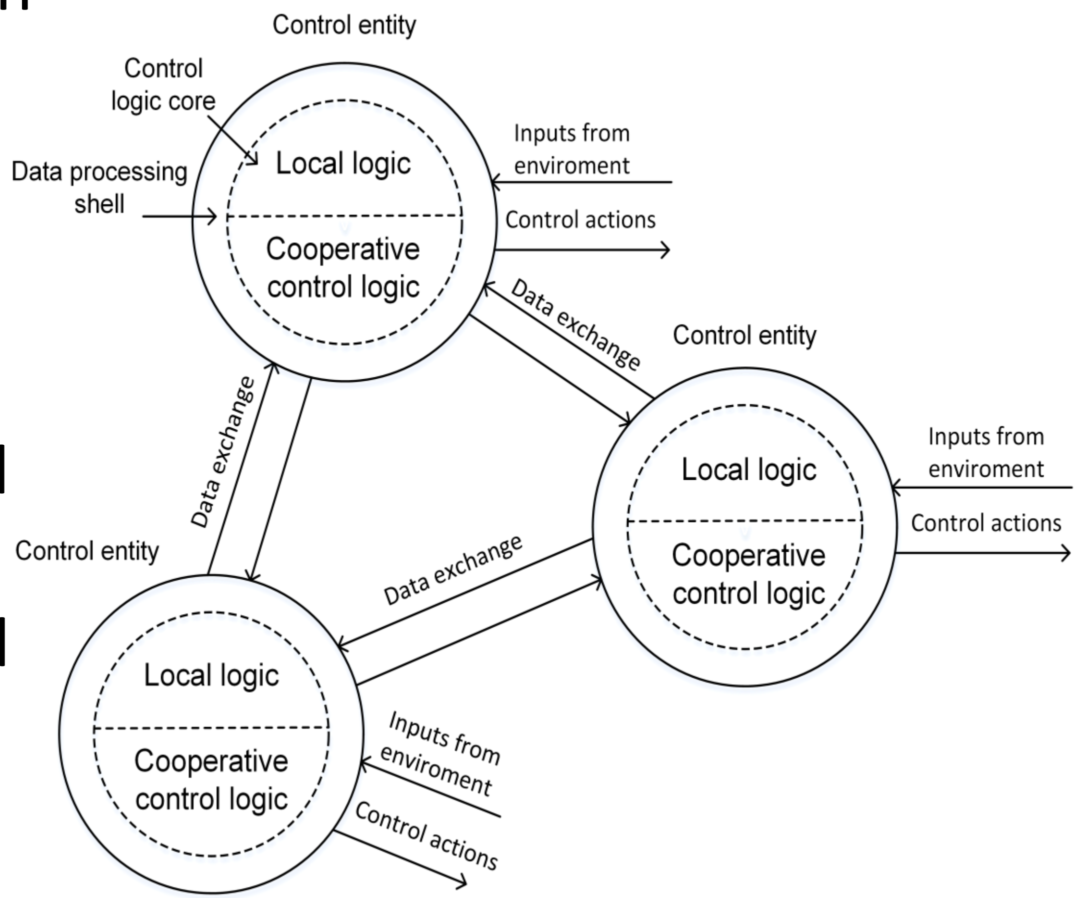
- Area-wide RM algorithms
  - Consider the overall traffic situation on the entire controlled motorway segment
    - **Competitive** – contain two control logics local and global, the more restrictive metering rate is chosen as the final one
      - **SWARM** – algorithm uses local and short-term predictive logics
    - **Cooperative** – provide exchange of information between local on-ramps
      - **HELPER** – algorithm creates virtual on-ramp queues when congested on-ramp is detected
    - **Integrated** - algorithms contain a control module based on an optimization engine (defined constraints and goal)

4. Control methods on urban motorways (cont.)

- Variable Speed Limit Control (VSLC)
  - System computes and displays speed limit information on appropriate Variable Message Signs (VMSs)
- Impact of VSLC which aims to improve the performance of traffic flow
  - Reduction of the mean speed at under critical densities
  - Homogenization of speeds
- VSLC Time Reactive (VSLCTR) algorithm changes speed limits which are fixed in predefined time intervals
- VSLC Density Reactive (VSLCDR) algorithm computes the change in posted speed limit value by using four different conditions

5. Cooperative control approach for urban motorways

- The process of information or task sharing between control entities to accomplish a common objective
- Each individual entity can have their locally oriented goals as well
- Some of these goals could be more important than goals of the other control entities
  - Implies possible hierarchical forms in cooperation



5. Cooperative control approach for urban motorways (cont.)

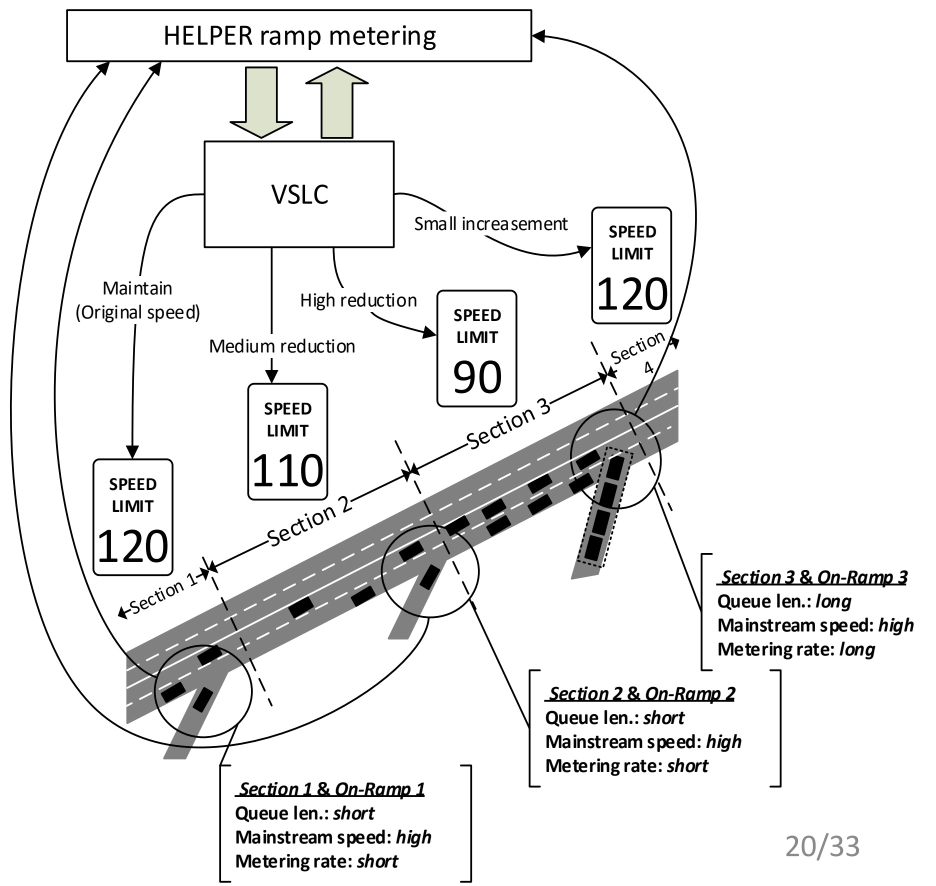
- Cooperation between several on-ramps works in three phases
  - **<u>1. Phase</u>:** metering rate for each on-ramp is computed by its local algorithm
  - **<u>2. Phase</u>:** locally collected traffic data is exchanged between on-ramps (or it is collected on one place and than distributed)
  - **<u>3. Phase</u>:** further adjustment of local metering rates

    (*if congestion on one of the controlled on-ramps is detected*)
    - Creation of „virtual queues” on upstream on-ramps (Slave on-ramps)
    - Increase metering rate on congested on-ramp (Master on-ramp)
- Those phases represent core control strategy of the HELPER algorithm

5. Cooperative control approach for urban motorways (cont.)

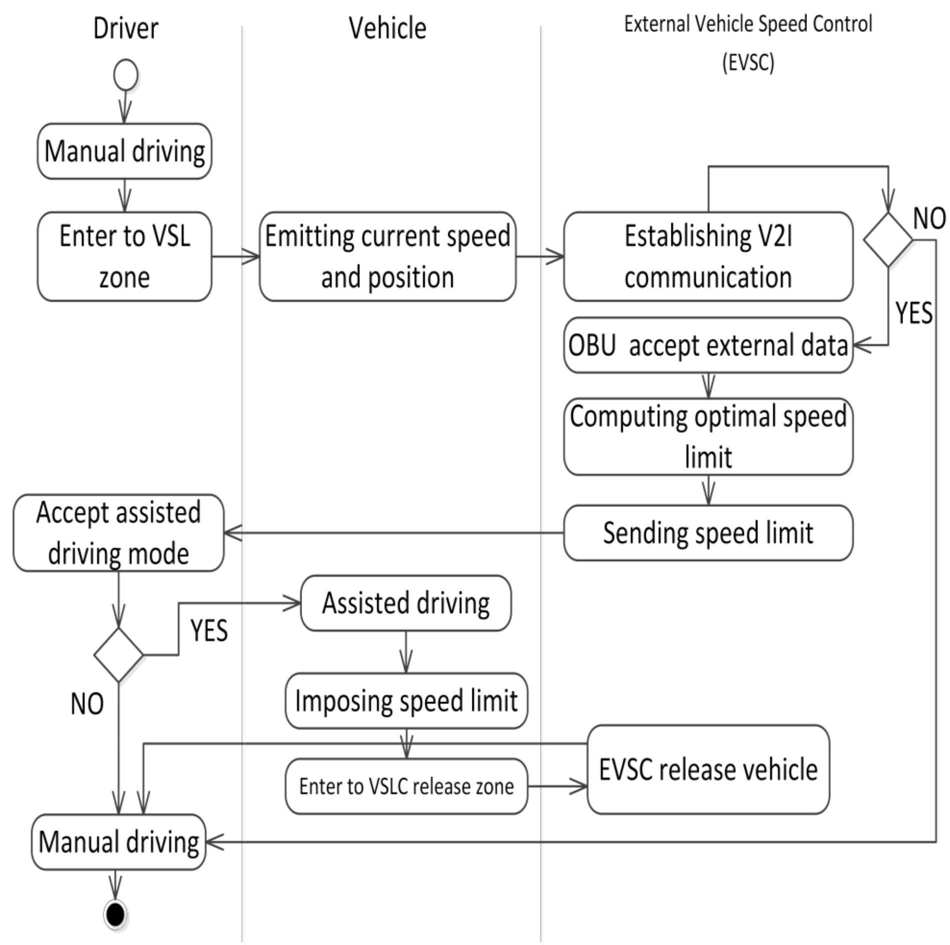
- VSLC in cooperation with RM gradually decreases the speed of the upstream flow (according to the congested on-ramp)

- VSLC in cooperation with HELPER in area between last “slave” and congested on-ramp
  - Reduces input of vehicles in mainstream flow by „virtual queues” (HELPER)
  - Speed reduction induces lower speed of vehicles which are heading towards the congested on-ramp (VSLC)



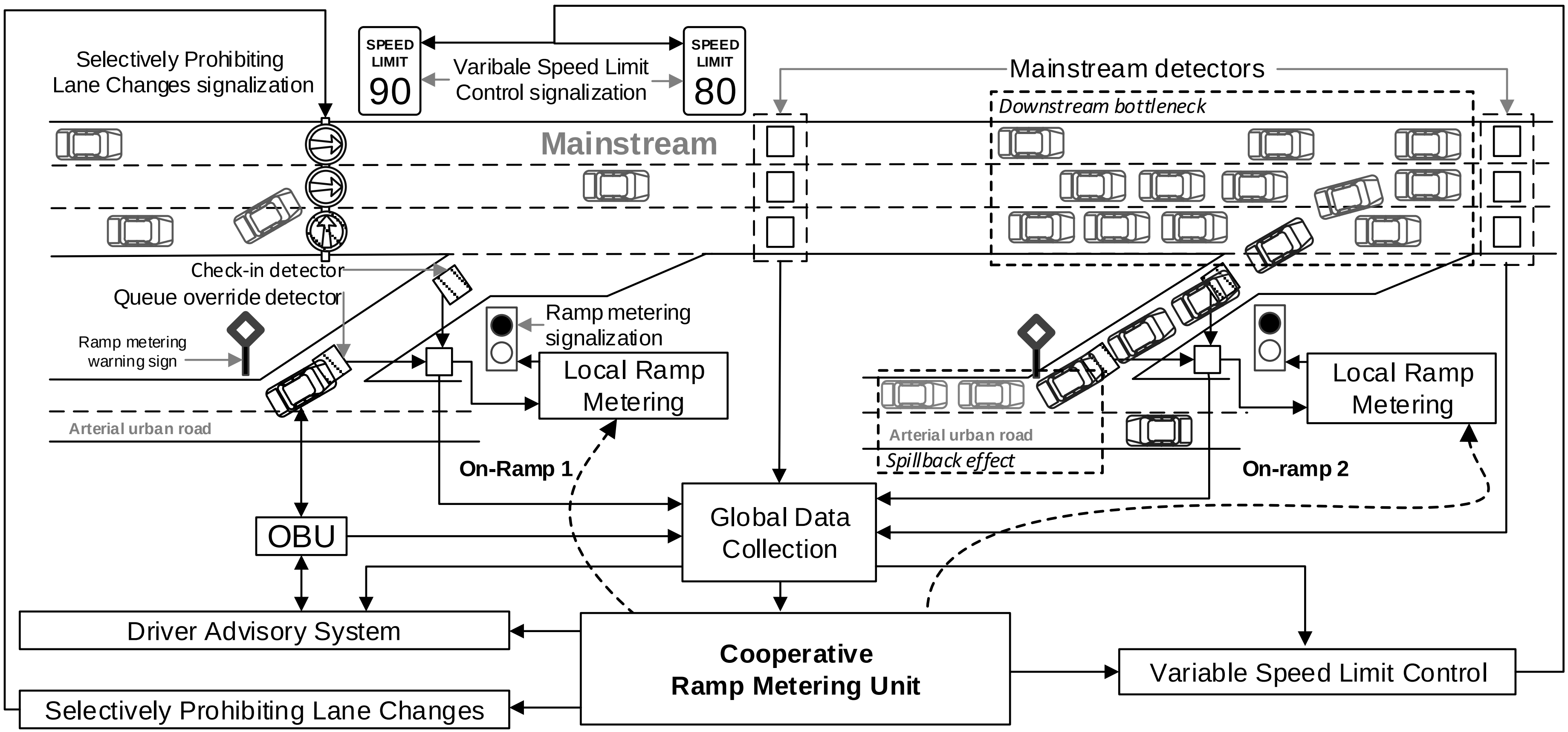
5. Cooperative control approach for urban motorways (cont.)

- Cooperation between vehicle On-Bord Unit (OBU) and roadside infrastructure in form of the External Vehicle Speed Control (EVSC) system
  - Advising the driver about needed actions regarding its current speed
  - Automatic adjustment of vehicle speed according to the posted speed limit
    - Intelligent Speed Adaptation (ISA)



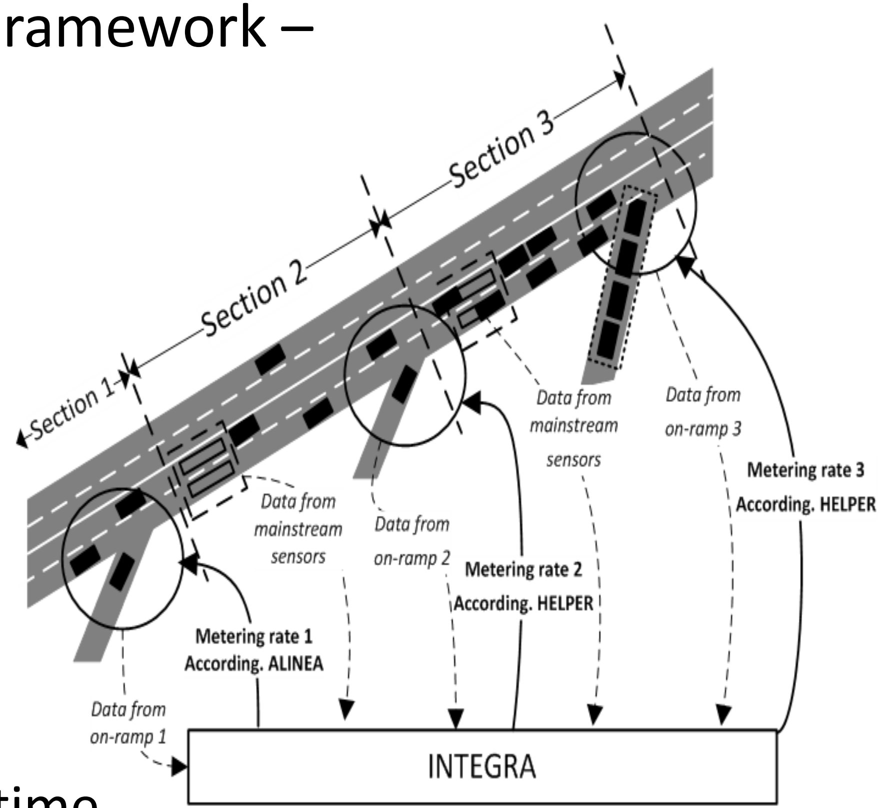
5. Cooperative control approach for urban motorways (cont.)

- Cooperation between several control systems



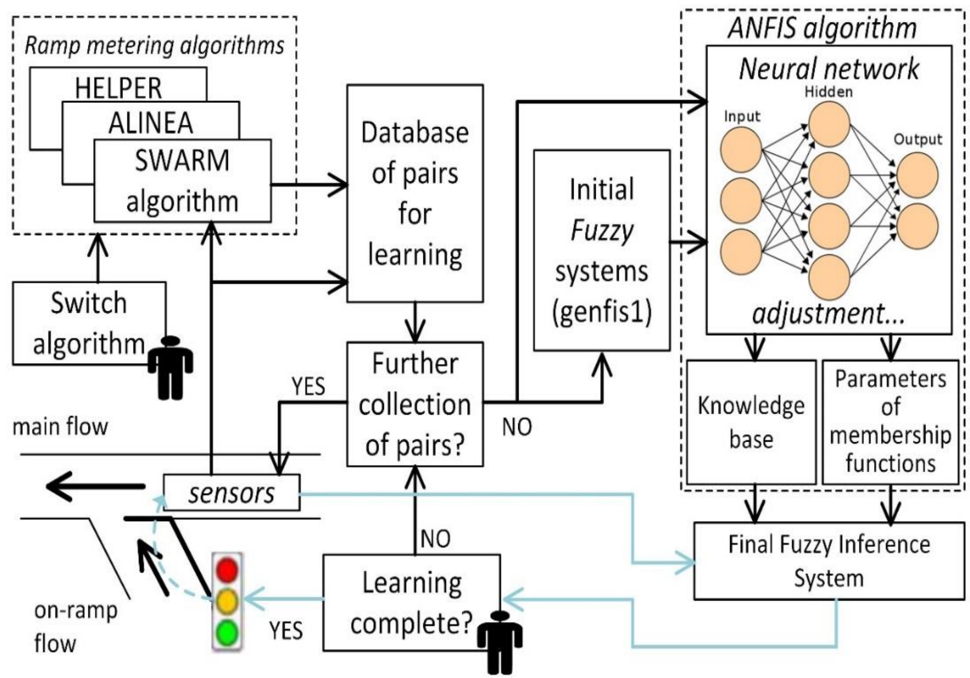
6. Ramp metering based on machine learning

- Proposed RM algorithm based on the Adaptive Neural Fuzzy Inference System (ANFIS) contains two parts
  - Fuzzy Inference System (FIS)
  - Artificial Neural Network (ANN)
- RM algorithm built based on ANFIS Framework – INTEGRA has the goal to provide
  - Integrated control knowledge of different RM algorithms
    - Every RM algorithm provides best results under a specific traffic scenario
  - Mitigation of congestions which are varying in strength and in time



6. Ramp metering based on machine learning (cont.)

- The INTEGRA learning dataset contains a set of traffic solutions (set of inputs and output) for one particular traffic scenario derived from different teaching RM algorithms during 30 working days
  - ALINEA (local RM)
  - SWARM (competitive RM)
  - HELPER (cooperative RM)
- Brute force optimization applied to find most <u>suitable inputs for learning</u>
- Criteria function finds <u>most suitable solutions</u>
  - Derived from adequate teaching RM algorithms

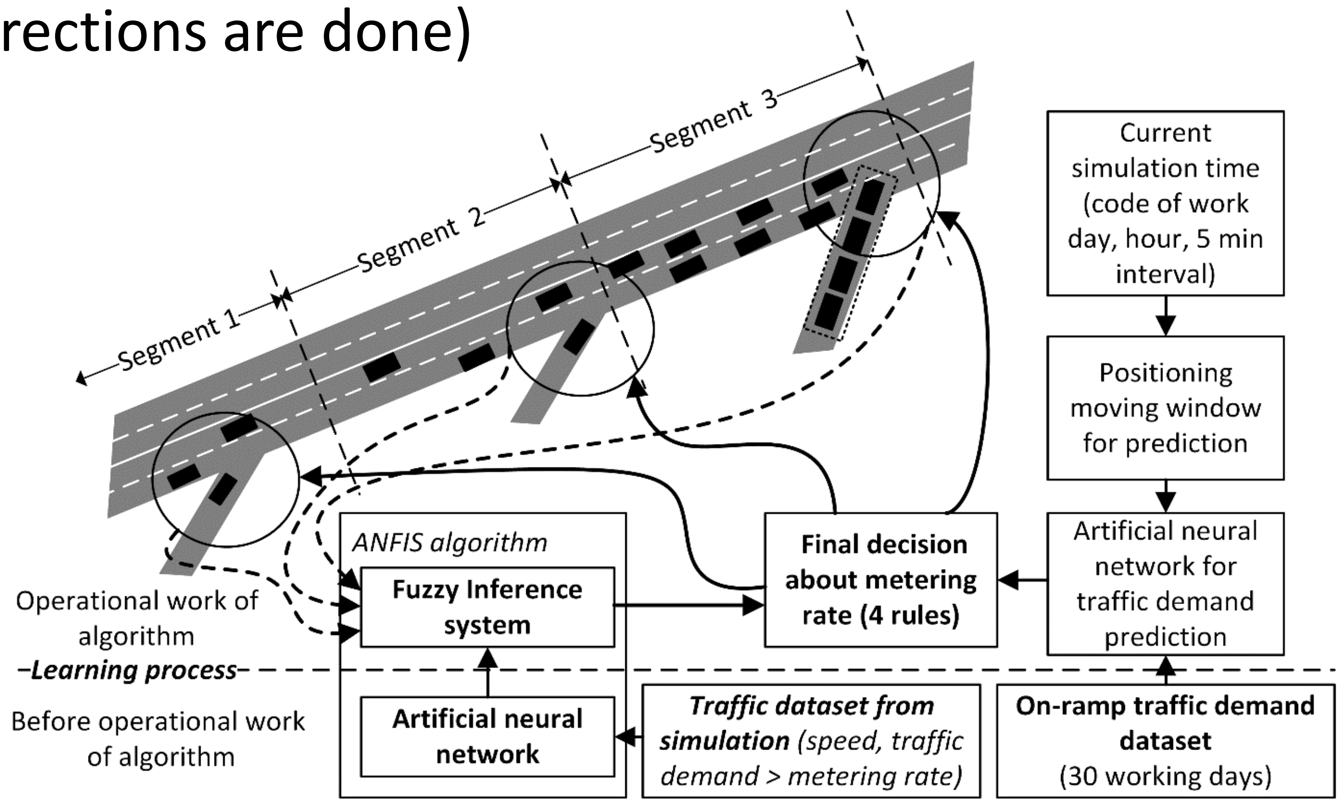


$$f(r) = 0.6\,TT + 0.4\,D$$

- Learning process performs self-tuning in order to satisfy solutions selected by the criteria function

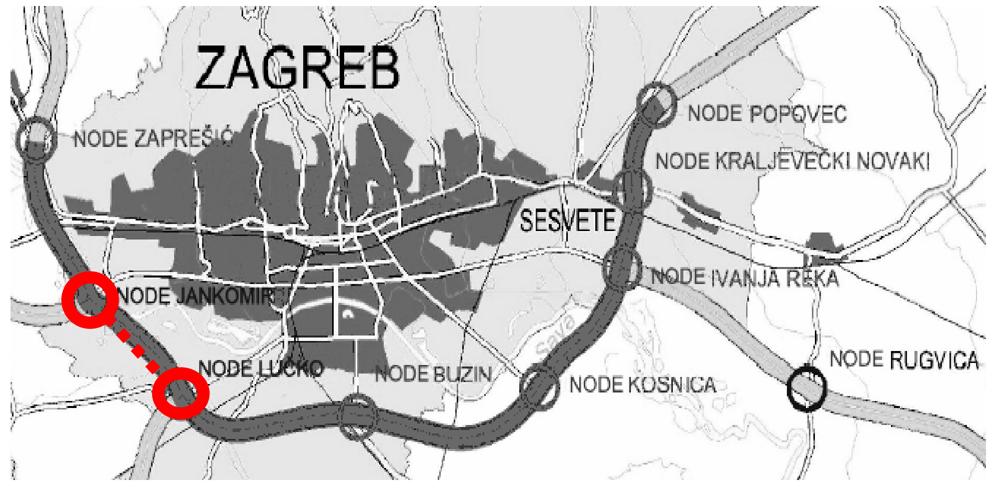
6. Ramp metering based on machine learning (cont.)

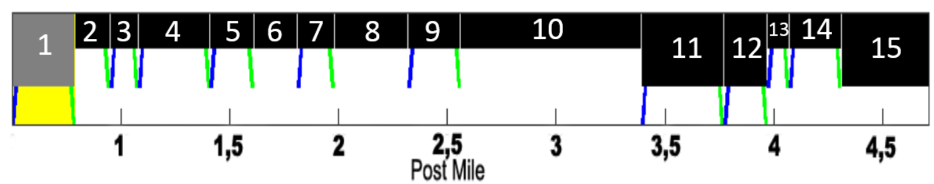
- Augmented version of the INTEGRA algorithm is based on the prediction of on-ramp traffic demand
  - Enables correction of the previously computed metering rate
  - Uses short-term traffic flow predictions
  - Uses a set of four simple IF-THEN rules (based on which corrections are done)



7. Simulation results and discussion

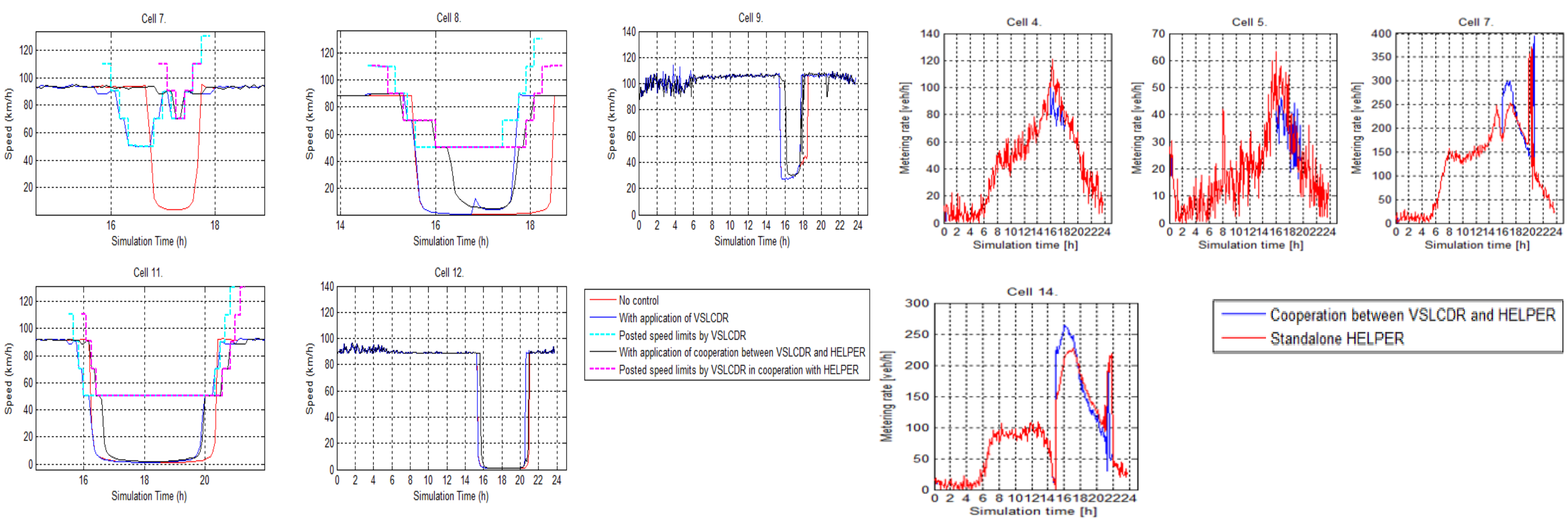
- Zagreb bypass urban motorway, section between nodes Lučko and Jankomir as use case
- Congestion created near *Lučko node*
- Measures of Effectiveness (MoE)
  - Travel Time (TT)
  - Delay
  - Total Time Spent (TTS)
  - On-ramp queues
- 24 hour simulation run
- Zagreb bypass modelled in CTMSIM





7. Simulation results and discussion (cont.)

- Cooperation between HELPER (RM) and VSLCDR
  - Oriented in order to resolve congestion in cell 7 and 14
  - VSLCDR in cells 7, 8 and 11 produces upstream speed reduction
    - In cooperation induced higher speed during congestion
  - HELPER RM in cooperation induce
    - Additional virtual queues at cells 4 and 5 compared to HELPER standalone application
    - Higher metering rates during congestion in the cell 7 and congested cell 14



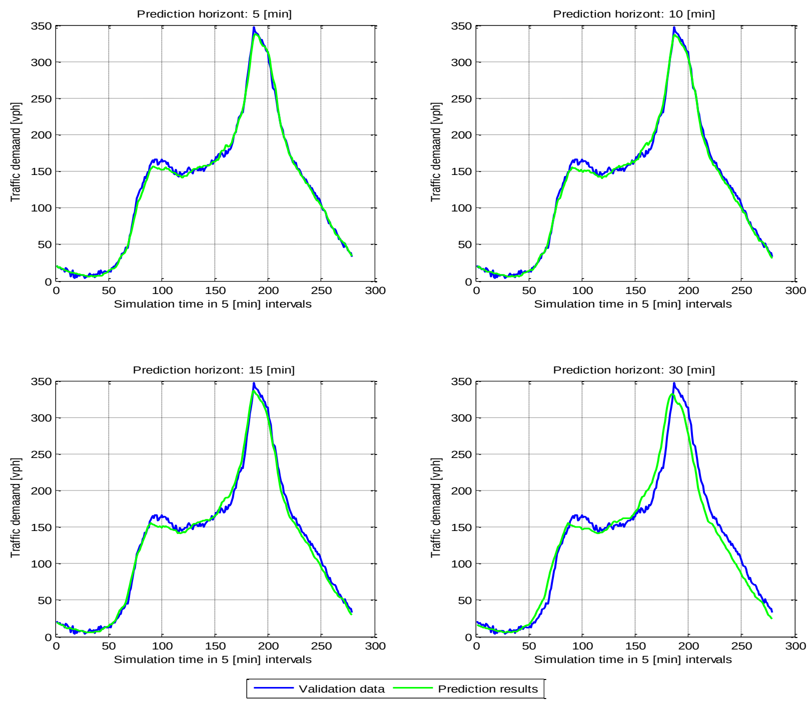
7. Simulation results and discussion (cont.)

- Cooperation between HELPER (RM) and VSLCDR has achieved
  - Lower average **TT** than VSLCDR algorithm
  - Lower average **On-ramp maximal and average queue length** than HELPER and parallel work of VSLCDR and HELPER
  - Lower **Delay** and **TTS** than **parallel work of VSLCDR and HELPER**
  - Lower average **Delay** than **HELPER**

	No control	ALINEA	SWARM	HELPER	VSLCTR	VSLCTR HELPER	VSLCDR	VSLCDR HELPER	Cooperation VSLCDR HELPER
Average Travel Time [min]	14.46	7.39	5.58	6.82	10.05	6.75	11.97	9.53	10.28
Average Delay [veh h]	6.06	8.8	8.03	7.29	4.85	7.59	4.20	8.75	7.02
TTS [veh h]	2949	2780	2857	2823	3005	3020	2610	3589	3001
Average on-ramp queue [veh]	0	16	18	17	13	18	13	18	16
Maximal on-ramp queue [veh]	0	40	49	40	15	42	13	36	31

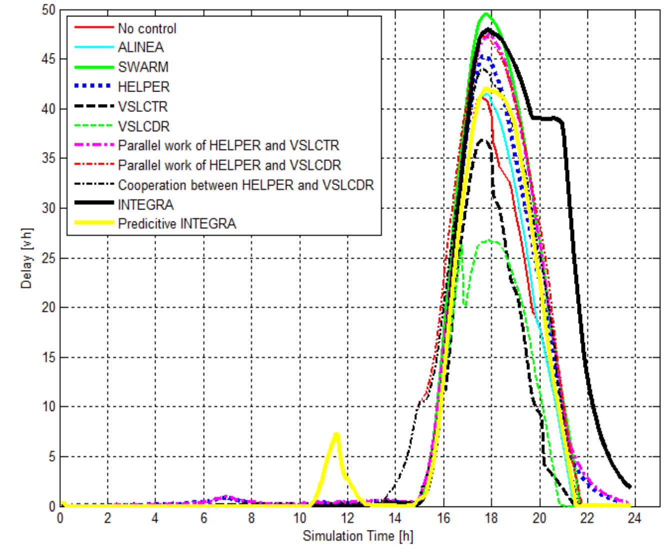
7. Simulation results and discussion (cont.)

- Recurrent Neural Networks (RNN) are used for on-ramp traffic demand prediction
  - Nonlinear autoregressive exogenous (NARX) model of RNN
  - 182 neurons in hidden layer, delay on each input
  - For prediction accuracy analysis 1 and 5 working days are used
- RNN has achieved a 2.60 Root Mean Square Error (RMSE) for the 5 minute long prediction horizon

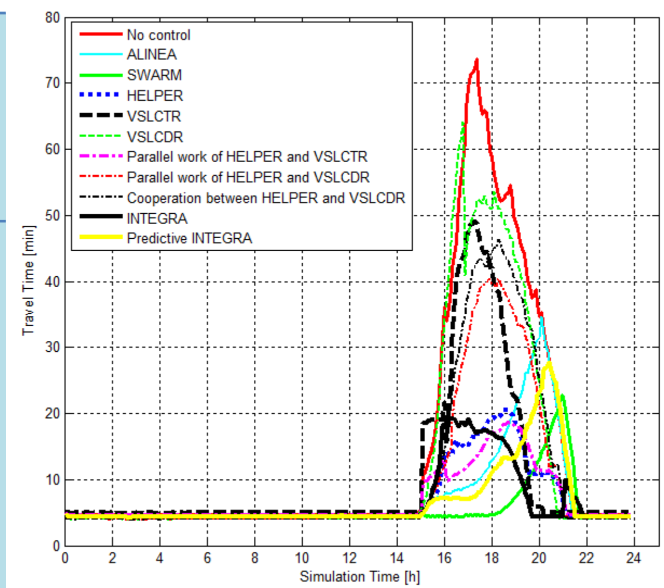


7. Simulation results and discussion (cont.)

- The **INTEGRA RM without prediction**
  - The **second lowest** average **TT** value
  - **High Delay** (due to criteria function setup – oriented towards specific goal – smaller TT)
  - Within boundaries of teaching RM algorithms
- The **INTEGRA RM with prediction**
  - Slightly higher value of TT compared to the INTEGRA without prediction
  - **Lower average Delay and lower average on-ramp queue compared to the INTEGRA** algorithm without prediction
  - Higher Delay before congestion



	No control	Teaching ramp metering algorithms ALINEA	SWARM	HELPER	VSLCTR	VSLCTR HELPER	VSLCDR	VSLCDR HELPER	Cooperation VSLCDR HELPER	INTEGRA	Predictive INTEGRA
Average Travel Time [min]	14.46	7.39	5.58	6.82	10.05	6.75	11.97	9.53	10.28	6.43	6.69
Average Delay [veh h]	6.06	8.8	8,03	7.29	4.85	7.59	4.20	8.75	7.02	10.01	7.03
TTS [veh h]	2949	2780	2857	2823	3005	3020	2610	3589	3001	3436	3102
Average on-ramp queue [veh]	0	16	18	17	13	18	13	18	16	19	16
Maximal on-ramp queue [veh]	0	40	49	40	15	42	13	36	31	42	41



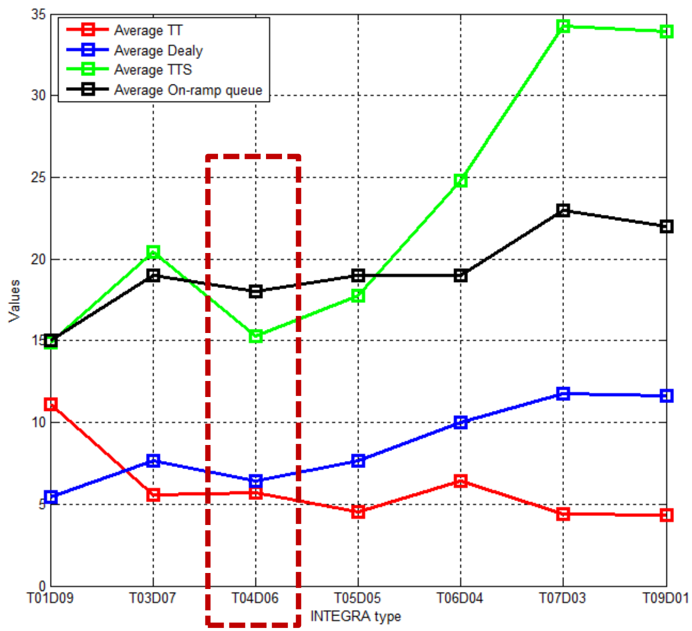
7. Simulation results and discussion (cont.)

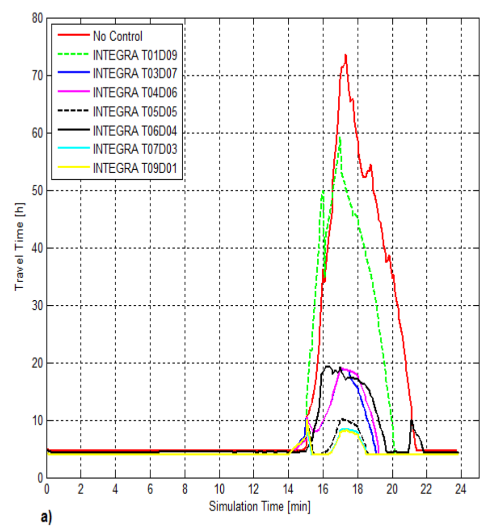
- Impact **of criteria function** weighting factors on INTEGRA RM overall performance

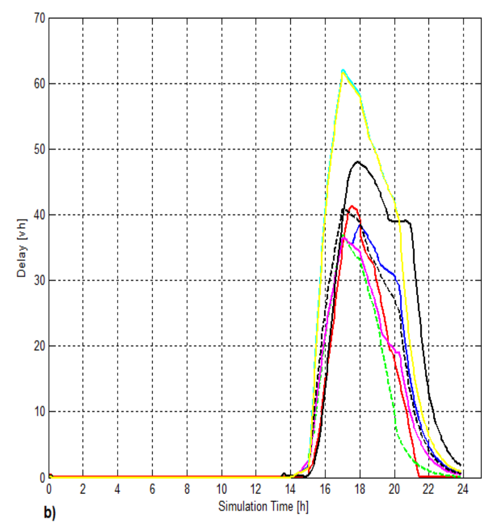
$$f(r) = X \cdot TT + Y \cdot D$$

Type of INTEGRA algorithm	Value of travel time weight (X)	Value of delay weight (Y)
INTEGRA T01D09	0.1	0.9
INTEGRA T03D07	0.3	0.7
INTEGRA T05D05	0.5	0.5
INTEGRA T06D04	0.6	0.4
INTEGRA T07D03	0.7	0.3
INTEGRA T09D01	0.9	0.1

- Adequate weighting factors in INTEGRA criteria function produce better overall results compared to the original INTEGRA RM
- INTEGRA RM type T04D06 produces best overall results



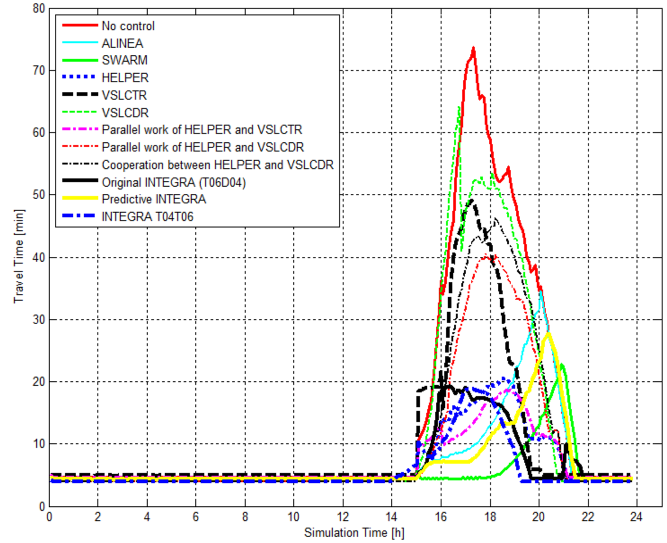


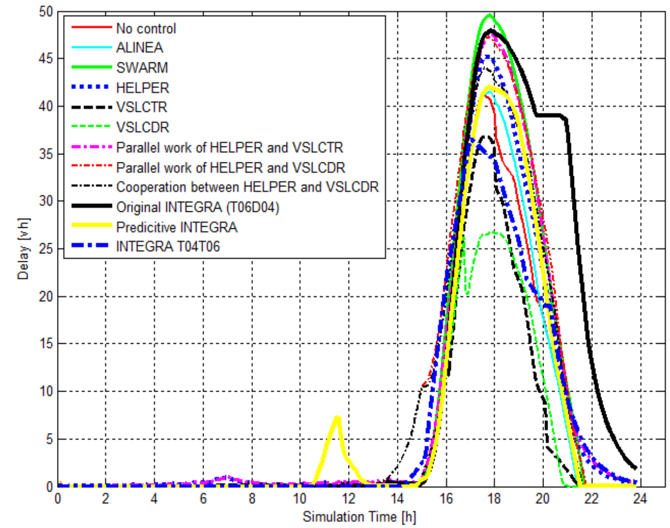


7. Simulation results and discussion (cont.)

- The **INTEGRA RM T04D06** has **outperformed both** previously analyzed **INTEGRA RM algorithms**
  - INTEGRA RM with prediction has achieved slightly lower average on-ramp queues
  - It still produces second lowest TT (SWARM first) and Delay (VSLCDR first)

	No control	ALINEA	SWARM	HELPER	VSLCTR	VSLCTR HELPER	VSLCDR	VSLCDR HELPER	Cooperation VSLCDR HELPER	Predictive INTEGRA	INTEGRA T06D04	INTEGRA T04D06
Average Travel Time [min]	14.46	7.39	5.58	6.82	10.05	6.75	11.97	9.53	10.28	6.69	6.43	5.69
Average Delay [veh h]	6.06	8.8	8.03	7.29	4.85	7.59	4.20	8.75	7.02	7.03	10.01	6.39
TTS [veh h]	2949	2780	2857	2823	3005	3020	2610	3589	3001	3102	3436	2186
Average on-ramp queue [veh]	0	16	18	17	13	18	13	18	16	16	19	18
Maximal on-ramp queue [veh]	0	40	49	40	15	42	13	36	31	42	42	36





8. Conclusion

- Cooperation between HELPER RM and VSLCDR produced
  - Lower Delay and on-ramp queues than HELPER RM
  - Lower TT than VSLCDR (other MoEs better than cooperation)
- INTEGRA RM algorithm based on the ANFIS framework
  - Criteria function goes in favor of reducing TT compared to Delay
  - Produced second best TT
- Augmented INTEGRA RM with on-ramp traffic demand predictions
  - Produce slightly larger value of TT compared to the original INTEGRA, but all other MoEs are showing better results
- INTEGRA RM T04D06 produced best overall MoEs results
  - Criteria function goes in favor of reducing Delay compared to TT

8. Conclusion (cont.)

- Future work
  - Usage of microscopic simulator
  - Training INTEGRA RM algorithm on larger learning dataset
  - More robust and comprehensive logic for adjusting computed metering rates according to the predictions in predictive INTEGRA RM
  - INTEGRA (ANFIS framework) with ability to integrate several VSLC and RM control methods

Thank you for your attention!

Cooperative Intelligent Transportation Systems in Urban Traffic Management

Associate Professor Edouard Ivanjko

April, 2019