Improving Urban Transport by Combining Connected Vehicles, Machine Learning and Digital Twins

Prof. Edouard Ivanjko

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- 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
    - https://trafficandtransportation.fpz.hr
    - Cited in WoS, SCIE, Scopus, and SCIMAGO
    - WoS Impact factor in 2023 is 0.8, Q4
  - Organizer of the ZIRP/TRANSCODE international scientific conference
    - https://zirp.fpz.hr/ -> https://transcode.fpz.hr
    - Next in 2025

TRANS CODE THE SCIENCE AND DEVELOPMENT OF TRANSPORT

- Department of intelligent transport systems
  - Head of department Assoc. Prof. Pero Škorput
    - 6 professors, 3 postdoc, 6 young researchers, 1 lecturer
  - Chair of Applied Computing (head Prof. Tonči Carić)
  - Chair of Transport Telematics (head Assist. Prof. Miroslav Vujić)

- Prof. Edouard Ivanjko
  - Research interests
    - Intelligent Transport Systems (ITS)
    - Modelling and simulation of road traffic
    - Forecast of road traffic parameters
    - Connected Autonomous Vehicles
    - Application of computer vision in road traffic
    - Road traffic control systems based on machine learning
    - Digital twins in road transport
  - Contact
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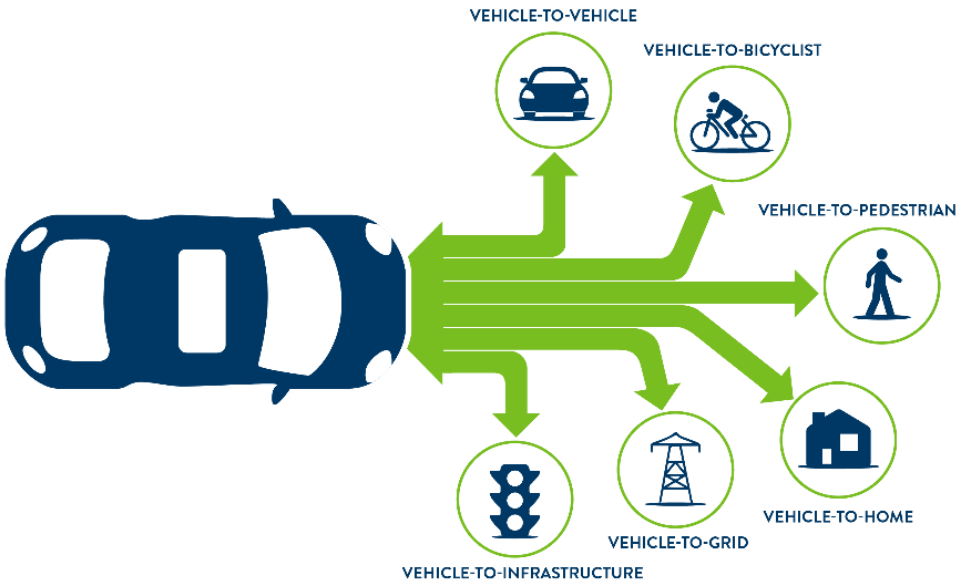
  - Learning based Traffic Control
  - Adaptive Traffic Signal Control
  - Variable Speed Limit
  - Digital Twins in Road Traffic
  - Conclusion

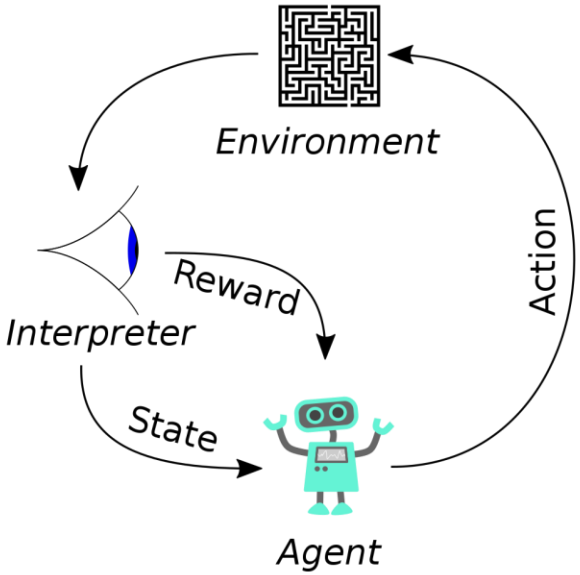
Introduction

- Urban environments prone to significant daily recurrent congestions
- Intelligent Transportation Systems (ITS) introduced to alleviate the problem
  - Tackle the problem of congestion, pollution, sustainability and low level of service
  - Important service of traffic control especially for
    - Signalized intersections
    - Urban motorways

Introduction

- New technologies being more and more utilized in ITS service of traffic control
  - Online machine learning approaches like reinforcement learning
  - Connected Autonomous Vehicles (CAVs)
  - Digital Twins (DT) for preparation of training scenarios





Learning based Traffic Control

- The controller trains its control law during operation
- Reinforcement learning applied
  - Based on Thorndike's law of effect – trial and error theory
    - Actions that in a specific situation provide satisfactory effects become more probable to occur again in that situation, and the responses with negative impact in a specific situation become less likely to occur again in that situation
      - Good actions or weights are rewarded
      - Bad actions or weights are punished
- Q-Learning algorithm

$$Q^*(s_t, a_t) \coloneqq (1 - \alpha_{(s_t,a_t)})Q(s_t, a_t) + \alpha_{(s_t,a_t)}(r_t + \lambda r_{t+1} + \lambda^2 \max_{a' \in A} Q(s_{t+2}, a'_{t+2}))$$

  - s - environment state
  - a - action and A is a set of available actions
  - λ - discount factor
  - α - learning rate
  - t - time step
  - r - reward

Learning based Traffic Control

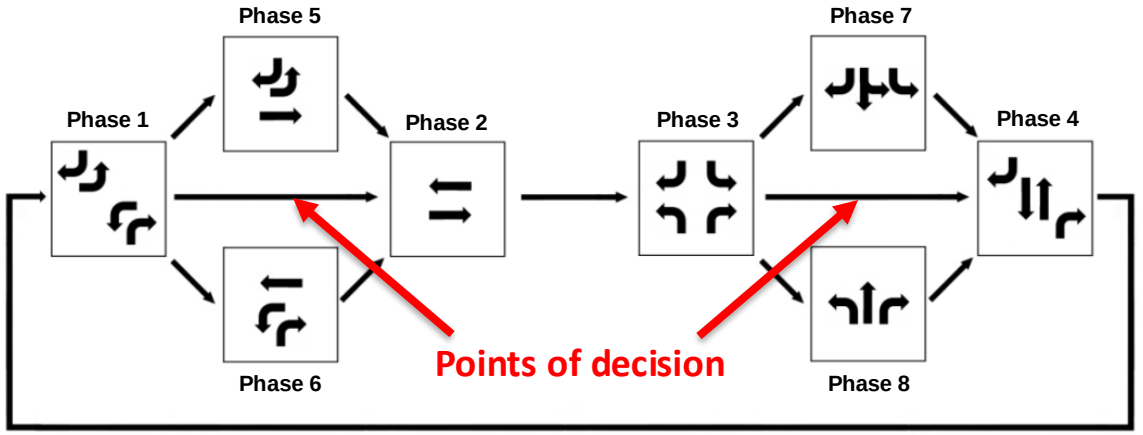
- Problem of Q-learning algorithm is that every state-action pair has to be visited enough times
  - Complex processes have many state-action pairs
  - Curse of dimensionality
- Complex problems can be divided into smaller simpler ones using multiple agents
  - One agent per control point required
  - Cooperation and coordination of agents – multiagent systems
- Reinforcement learning can be applied for multiagent systems also
  - W-Learning algorithm

$$W_i(s_t) := (1-\alpha_W)W_i(s_t) + \alpha_W(1-\alpha_Q)^w(Q_i(s_t,a_i) - (r_{i,t+1} + \gamma max Q_i(s_{t+1},a'))$$

    - *W* value expresses how important an action is
      - What happens when the agent's suggested action is not executed
    - Used combined with the Q-Learning algorithm
    - Enables cooperation of agents

Adaptive Traffic Signal Control

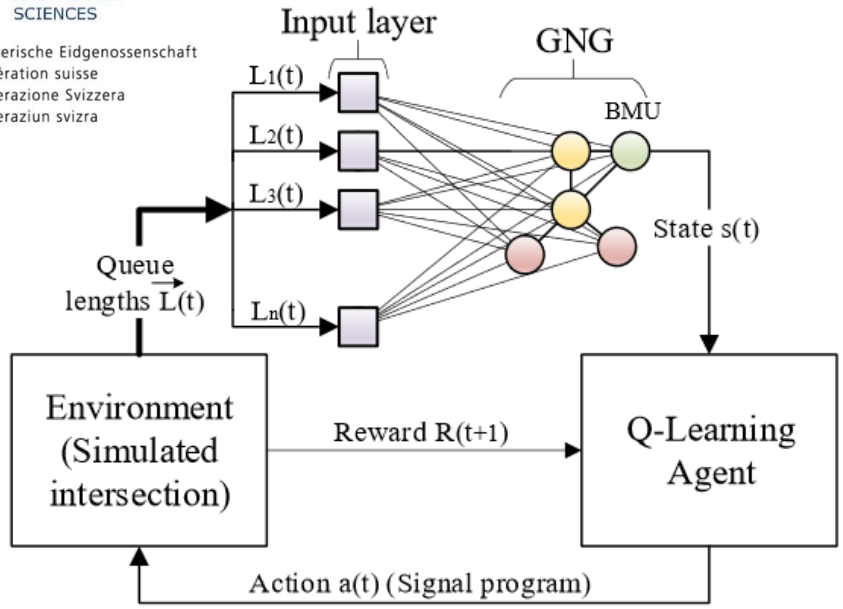
- Adaptive Traffic Signal Control (ATSC) applies changes to the signal program changes according to current traffic/intersection state
  - Phase duration
  - Phase sequence
  - Selecting appropriate signal program among existing ones
- Adaptation to satisfy desired operational objective
  - Smooth traffic flow
  - Maximization of throughput
  - Access equity
  - Queue management
- NEMA (National Electronic Manufacturer Association) signal program standardization
  - Implementation of high- (urban traffic control center) and low-level (local intersection controller) control

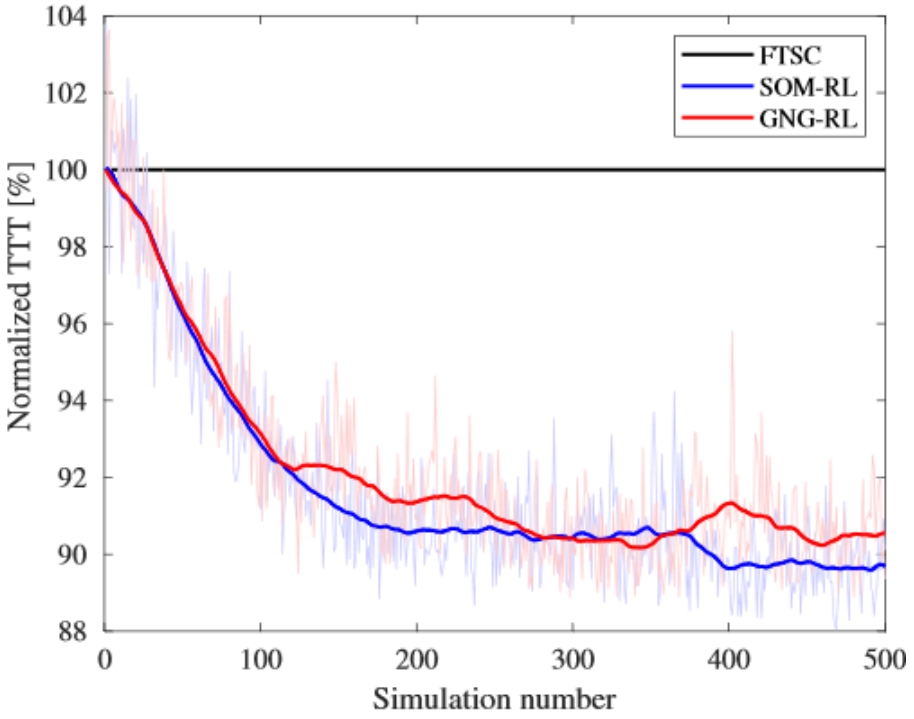


Adaptive Traffic Signal Control

Urban traffic use case

- Application of Q-Learning algorithm combined with neural network based state-action pair complexity reduction
  - Self-Organizing Map (SOM) – offline training
    - State-action pair representation reduction by grouping of similar pairs
    - Trained before operation (control law training)
  - Growing Neural Gas (GNG) – online training
    - Simultaneous state-action representation and control law training





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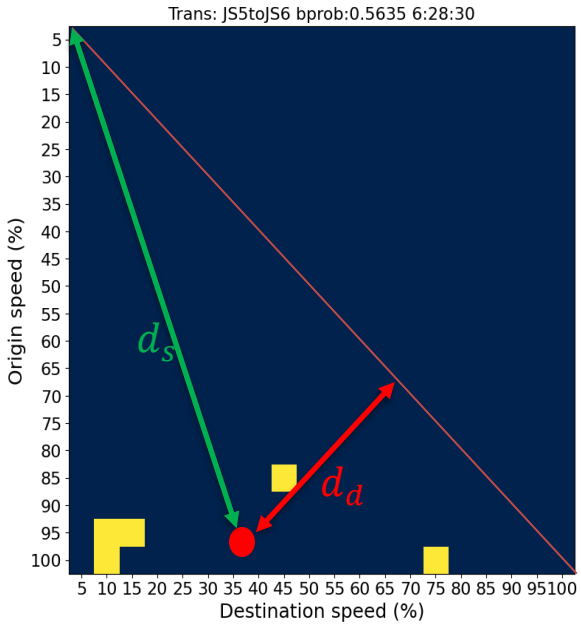
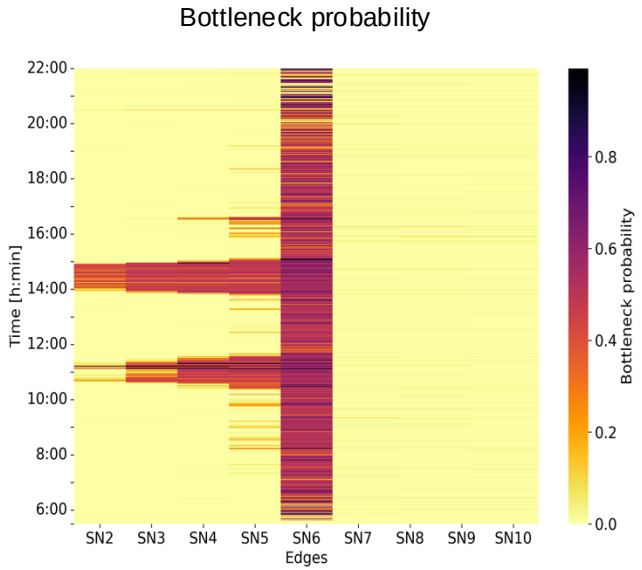
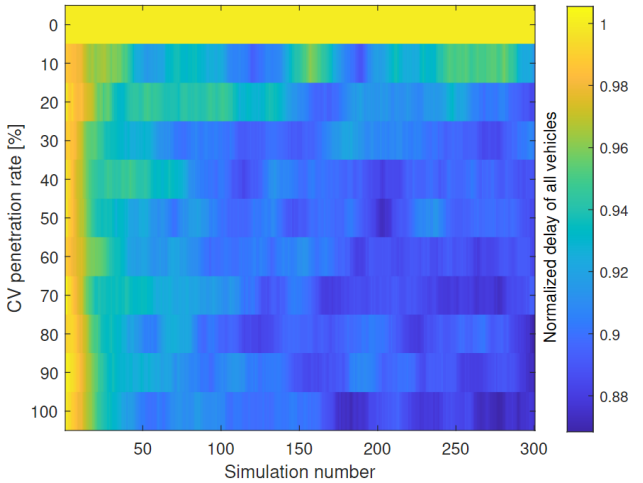
Adaptive Traffic Signal Control

- Adding CAVs into the control loop
  - Moving sensors and actuators
  - Collecting data for traffic state estimation on the microscopic (vehicle) level
    - Vehicle type, speed and position
- Speed Transition Matrix used to process vehicle data
  - Road network divided into segments
  - Speed change between segments detected
- Higher CAV penetration rate further improves ATSC training convergence







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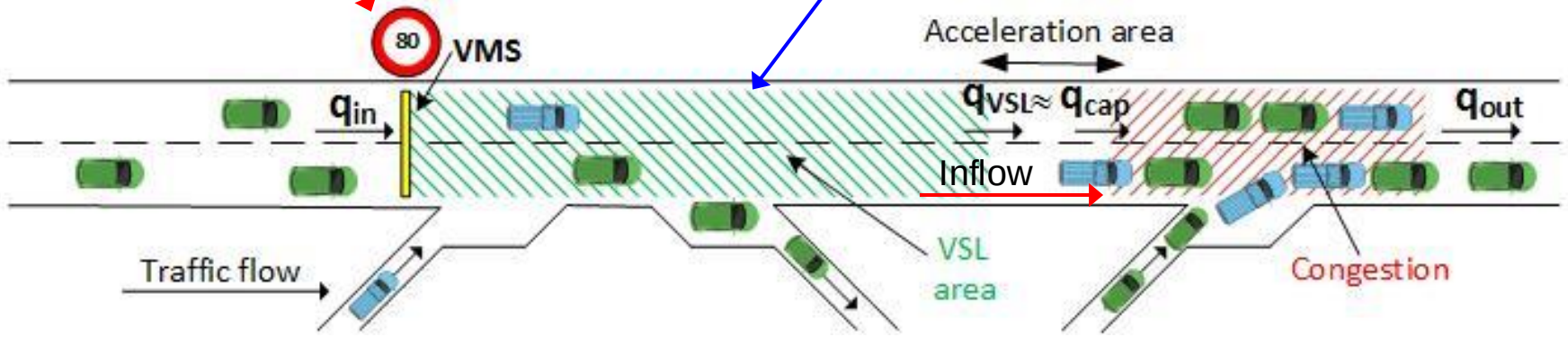
Variable Speed Limit

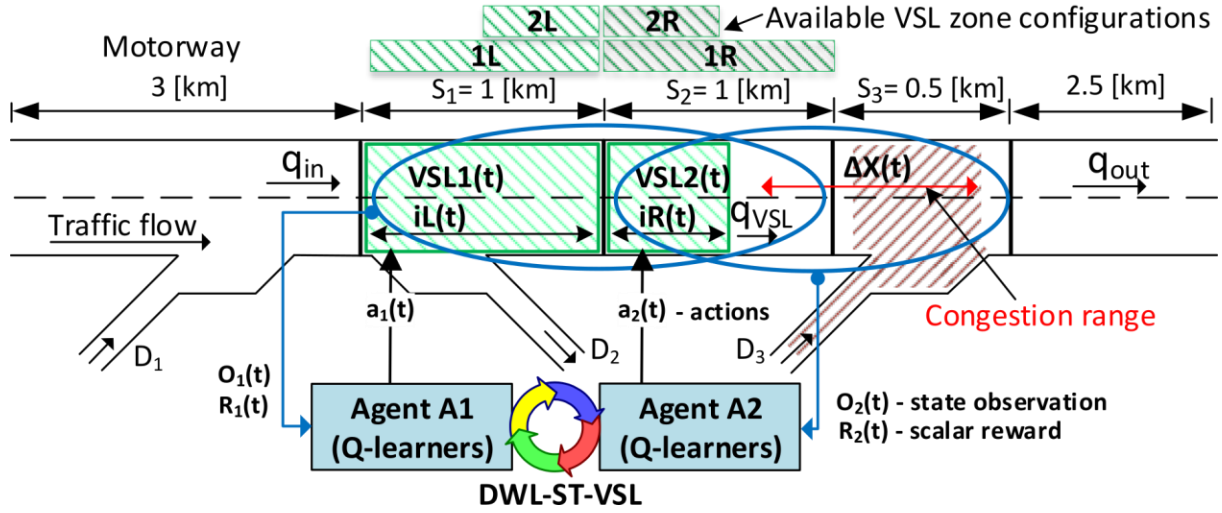
- Variable Speed Limit (VSL) directly controls mainstream traffic flow entering bottlenecks by adjusting the speed limits posted upstream of the controlled section
- Length and position of VSL application and acceleration area are essential for optimal VSL control
- Congestion spatially varies in time
  - Static VSL zone operate suboptimally
  - CAVs applied as moving sensors and actuators covering large motorway segments with congestion problems

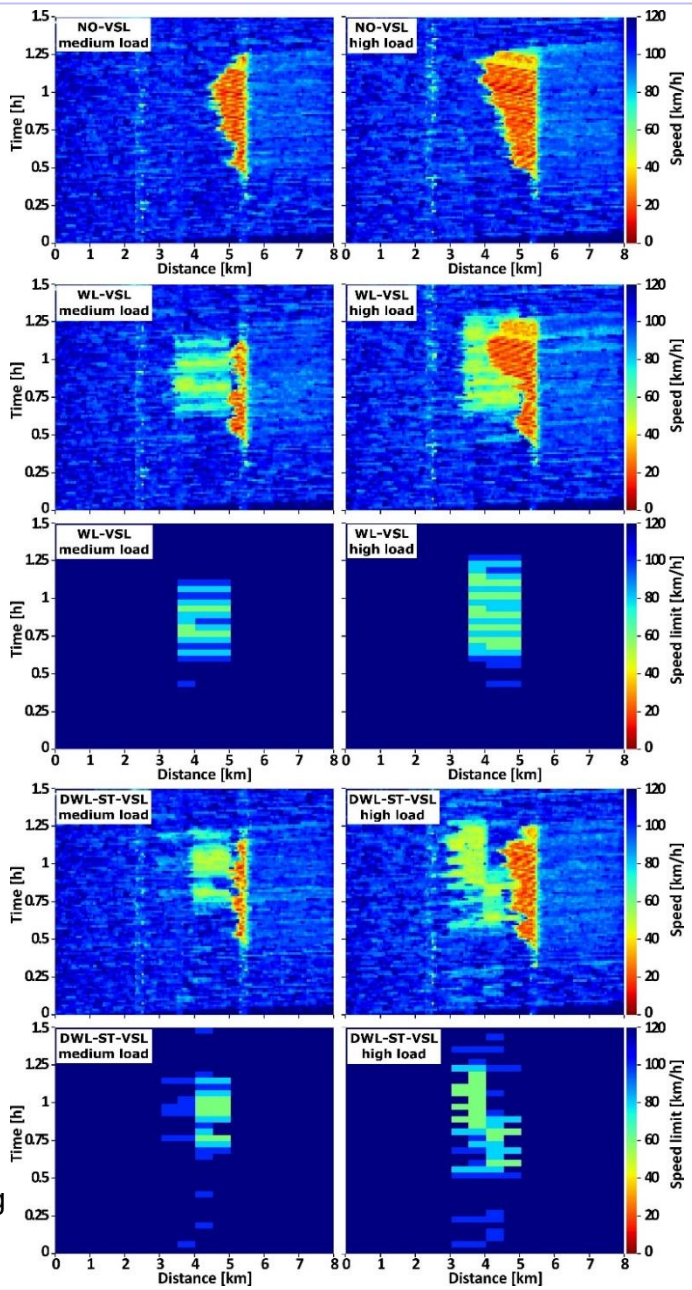
The area under VSL is an active mainstream artificially created "controllable" bottleneck limiting the inflow into the congested area to ensure that it operates near its operational capacity



Variable Speed Limit

- Adjustable VSL zones according to the different spatial distribution of congestions using multiple agents
- Multi-policy optimization
  - Each agent has its local policy (Q-Learning)
  - Cooperation achieved considering other agent's actions) using remote policy ((Distributed) W-Learning)





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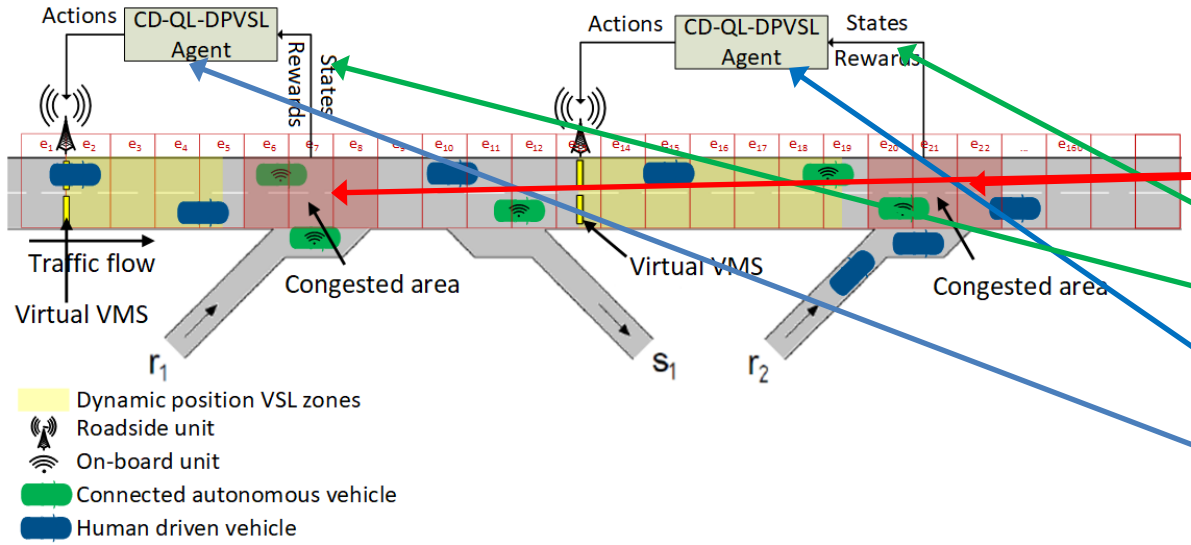
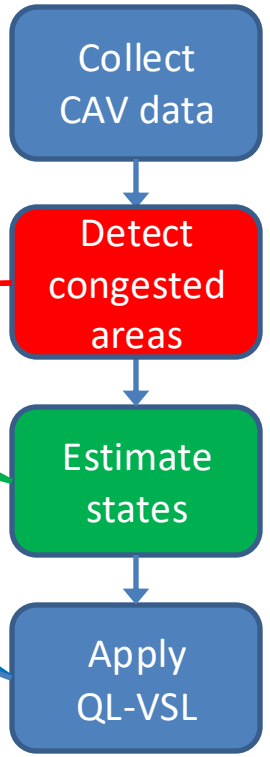
Variable Speed Limit

- Dynamic VSL with congestion detection using CAVs
  - Motorway divided into smaller segments
    - CAVs collect data for whole managed motorway
  - STMs used to detect congested areas
    - Length and level of congestion
  - VSL (de)activated according to estimated state
    - CAVs impose the speed limit





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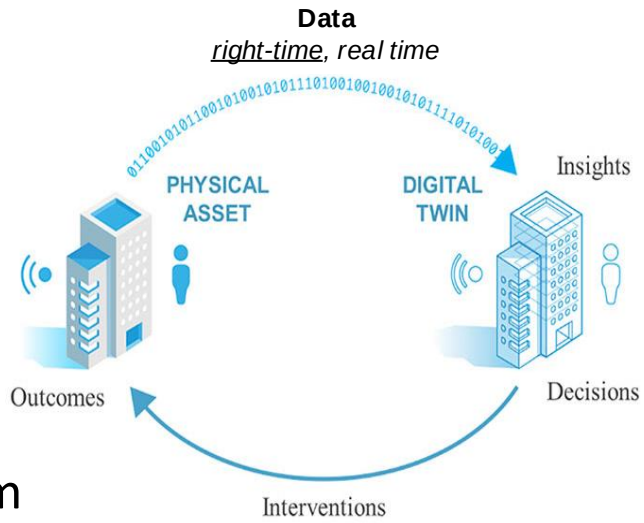
Digital Twins in Road Traffic

- A DT is a virtual instance of a physical systems (twin) that is continuously updated with the latter's performance, maintenance, and health status data throughout the physical system's life cycle
  - Madni, A.M., Madni, C.C., Lucero, S.D., 2019. Leveraging digital twin technology in model-based systems engineering. Systems 7. doi:10.3390/systems7010007
  - Simulation model connected with the physical system
  - Real-time data used to improve the simulation model accuracy during simulation



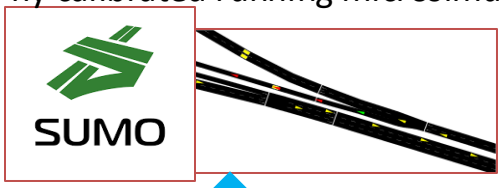
https://www.arup.com/expertise/services/digital/digital-twin

- Ingredients to build a DT
  - Real-time data of the physical system
  - A simulator that can adjust on the fly
  - A simulation model of the underlying system

Digital Twins in Road Traffic

- Creating a motorway digital twin
  - Open data platform mobility Switzerland
    - Real-time motorway traffic data
  - Microscopic simulator SUMO
  - Geneva motorway as use case

Digital twin
(on-the-fly calibrated running microsimulation)



- Measurement station #
- Traffic counters for each direction (lanes)

Real-time traffic data flow

Open data platform mobility Switzerland (ODPMS),
Federal Roads Office (FEDRO)

Traffic Data (per min)
- Traffic flow
- Traffic speed
- Vehicle types

Database
- Local data storage

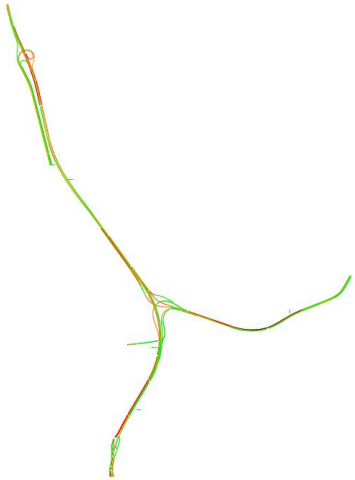
Digital Twins in Road Traffic

- Comparison of actual traffic and real-time simulation
  - GEH value always < 5
    - Good calibration in all cases

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}}$$

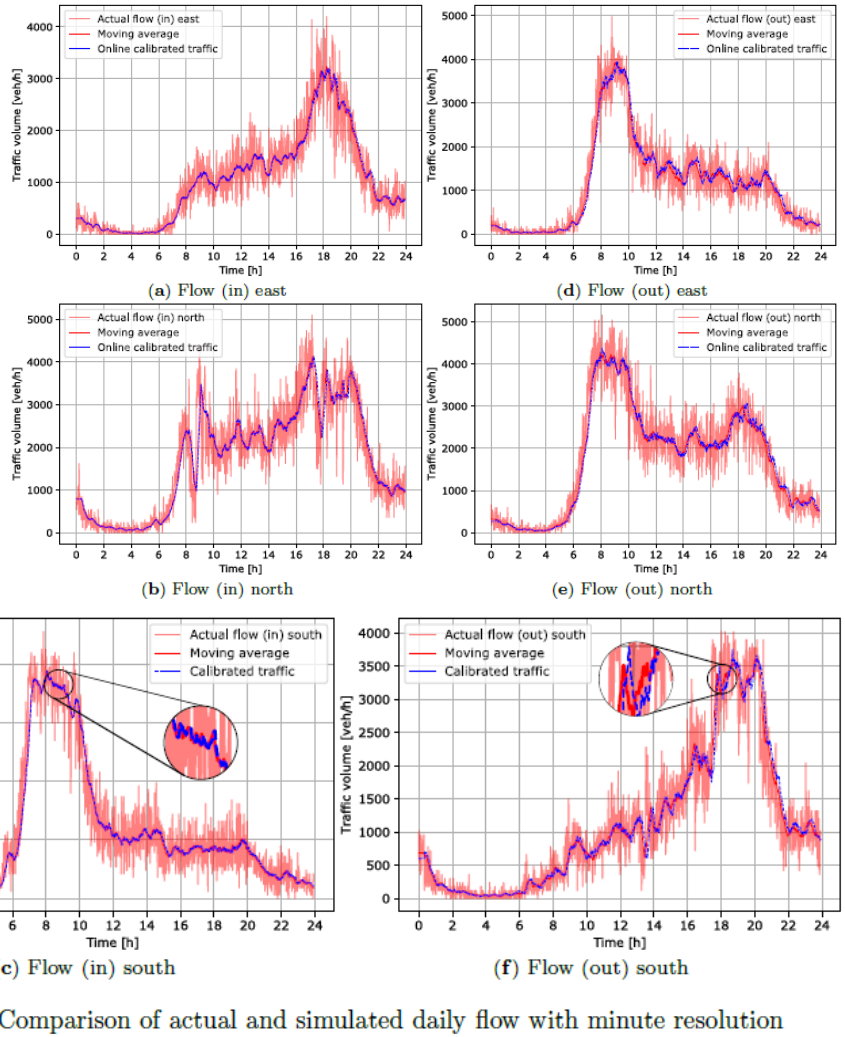
- M – Simulated traffic flow
- C – Measured traffic flow

(a) Actual traffic



(b) Run-time DT-GM

Comparison of spatio-temporal speed distribution between actual real traffic and run-time DT-GM



(a) Flow (in) east (d) Flow (out) east

(b) Flow (in) north (e) Flow (out) north

(c) Flow (in) south (f) Flow (out) south

Comparison of actual and simulated daily flow with minute resolution

K. Kušić, R. Schumann, and E. Ivanjko, "A digital twin in transportation: Real-time synergy of traffic data streams and simulation for virtualizing motorway dynamics", Advanced Engineering Informatics, vol. 55, 2023, doi: https://doi.org/10.1016/j.aei.2022.101858

Conclusion

- New technologies improve control of complex urban traffic
- (Multi-agent) Reinforcement learning can be successfully implemented for complex control of urban roads
  - Control law obtained and refined during operation
- Application of GNG for state complexity reduction in Q-Learning improves its convergence rate enabling simultaneous training of the state-action representation and the control law
  - Open question regarding complexity of state-action representation
- CAVs used as sensors and actuators enable spatiotemporal VSL control of significantly changing motorway bottleneck areas
  - Dynamic spatiotemporal VSL control with included bottleneck location and intensity detection for larger motorway segments also enabled
  - Multi-agent systems applied
- Digital twins enable creation of on-line calibrated traffic simulation models on microscopic level
  - All occurring traffic scenarios and not just rush hours included
  - Good foundation for traffic controller training
- Open problem related to ensuring good performance of learning-based traffic controllers for unknown traffic scenarios
  - Scenarios not presented during training
  - Structured training emphasizing bad performing scenarios

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    - Control system of the spatial-temporal variable speed limit in the environment of connected vehicles
    - Adaptive Cooperative Control of Signalized Intersections in Mixed Traffic Flow Environment
  - Swiss Federal Office for Education, Research and Innovation
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