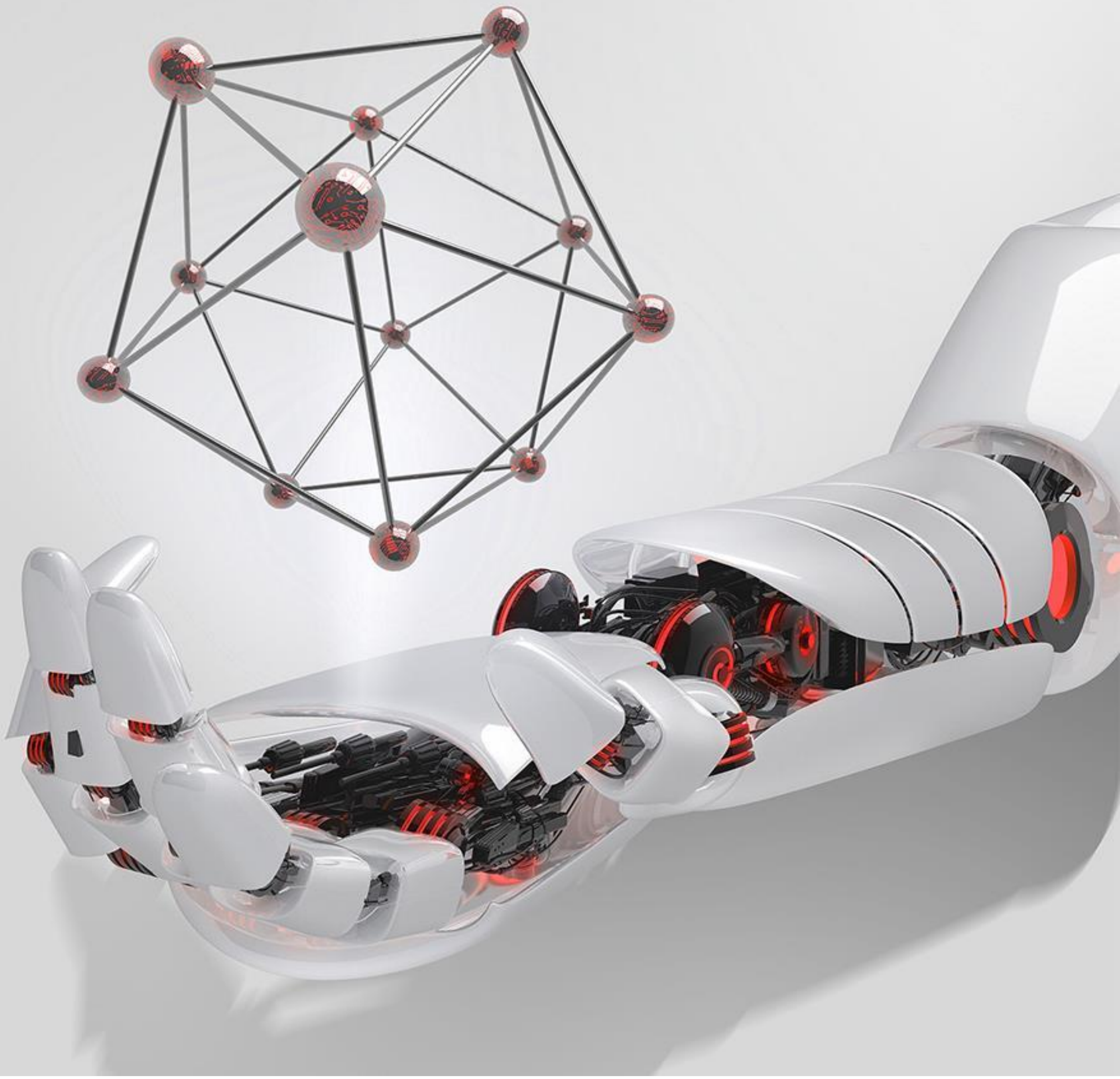
# Large-scale Systems Optimization

## From Oscillatory Physics to High-dimensional Vector Memories



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VSAONLINE
Online Speakers' Corner on Vector Symbolic Architectures and Hyperdimensional Computing
https://sites.google.com/ltu.se/vsaonline/home

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# Contents

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# Traffic Intelligent Twins (TrafficGo)

Inclusive AI, making urban transportation safer while yielding new levels of energy-efficiency

### Traffic Light Optimization

Integration of multiple data sources for 24/7 traffic light coordination; cross-intersection and regional traffic light coordination for real-time optimization; compatible with mainstream traffic signal control systems

### Traffic Prediction

Precise prediction of vehicle and pedestrians flows as well as traffic congestion with the benefit of multiple data sources

### Road Network Analysis

Information from analysis of key roads and intersections summarized to present highly effective suggestions on optimizing traffic flows

### Accident Monitoring and Control

Real-time monitoring and alarm notification of traffic emergencies, violations, heavy congestion, and other incidents; monitoring of trajectories and behaviors for tourist coaches, passenger buses, tanker trucks, taxis, commercial trucks, school buses, and other vehicle types;

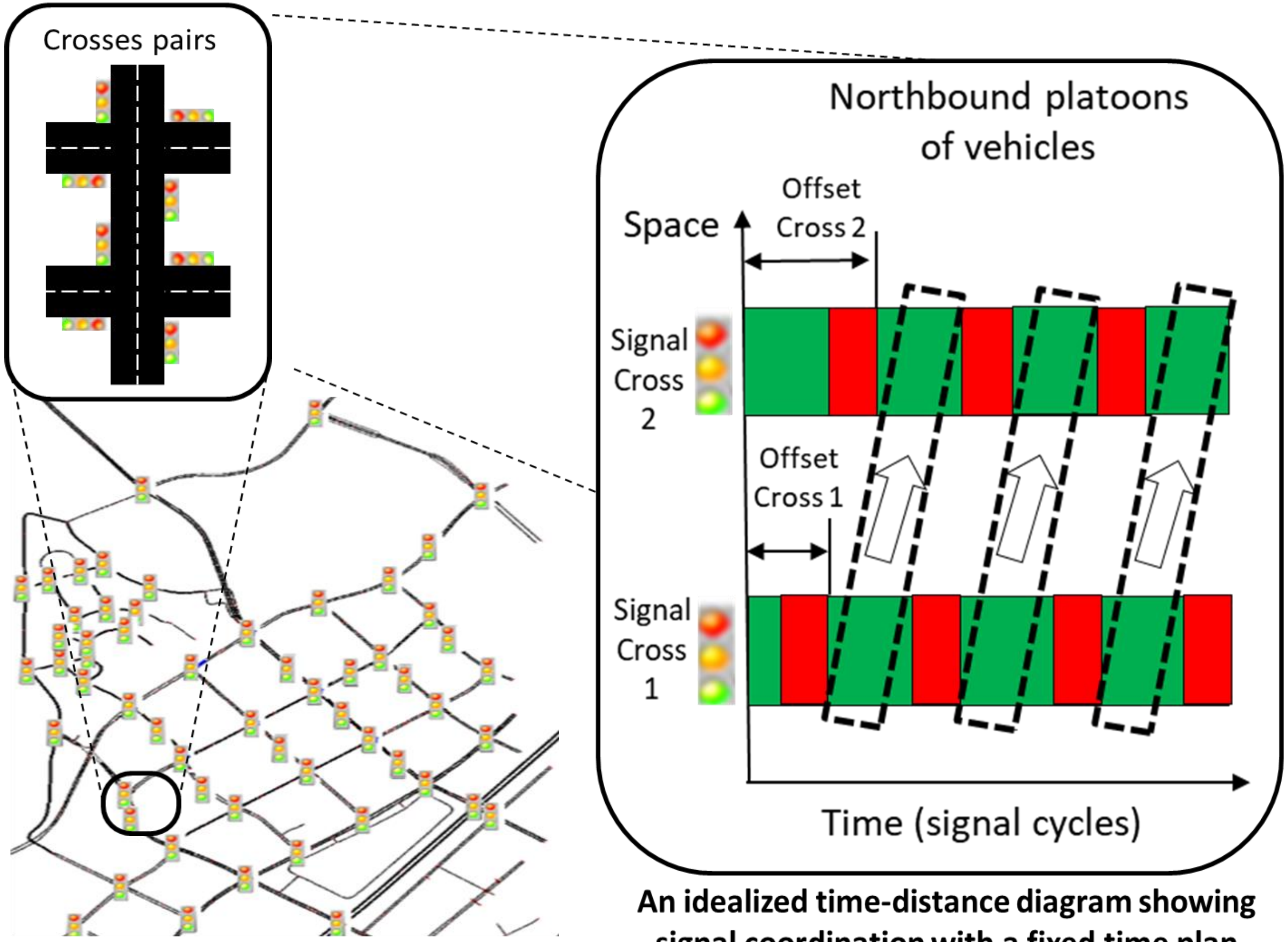
### Traffic Parameter Awareness

Awareness of more than 10 types of traffic parameters involving motor vehicles, non-motorized vehicles, and pedestrians; GIS map displayed on a large HD screen in real time; traffic optimization effect comparison and traffic index ranking

# Optimization based on the traffic physics

Source: https://www.youtube.com/watch?v=6uf2QNtYplI

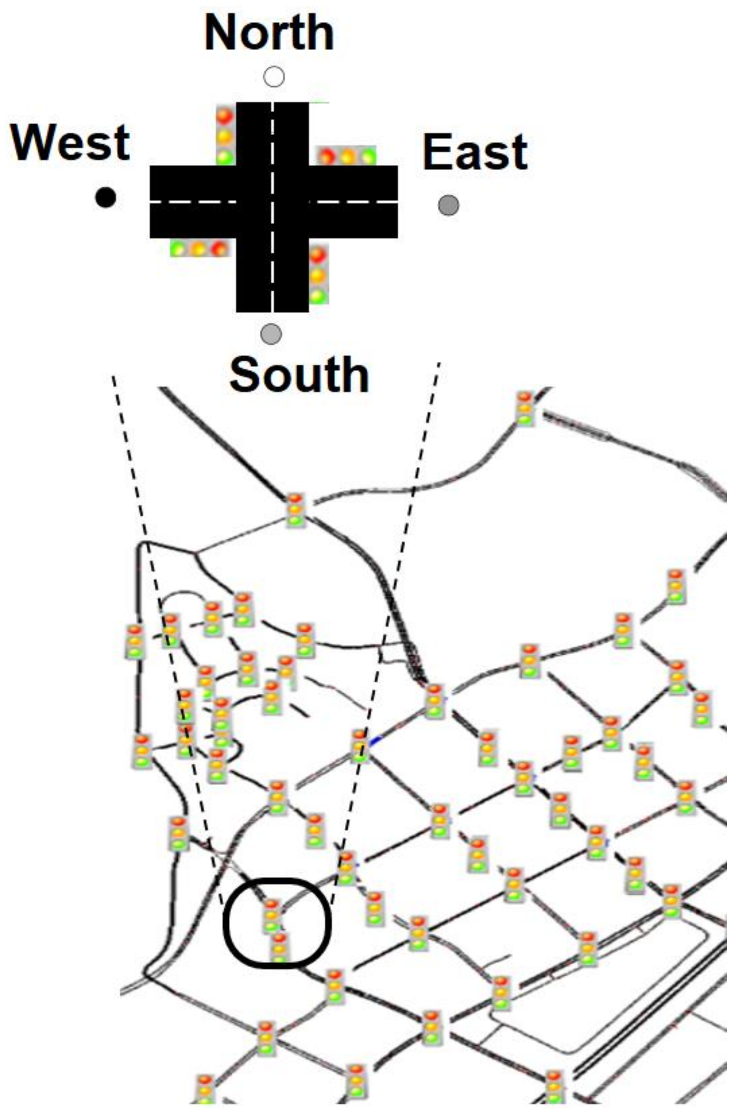
# Space-time physics of traffic

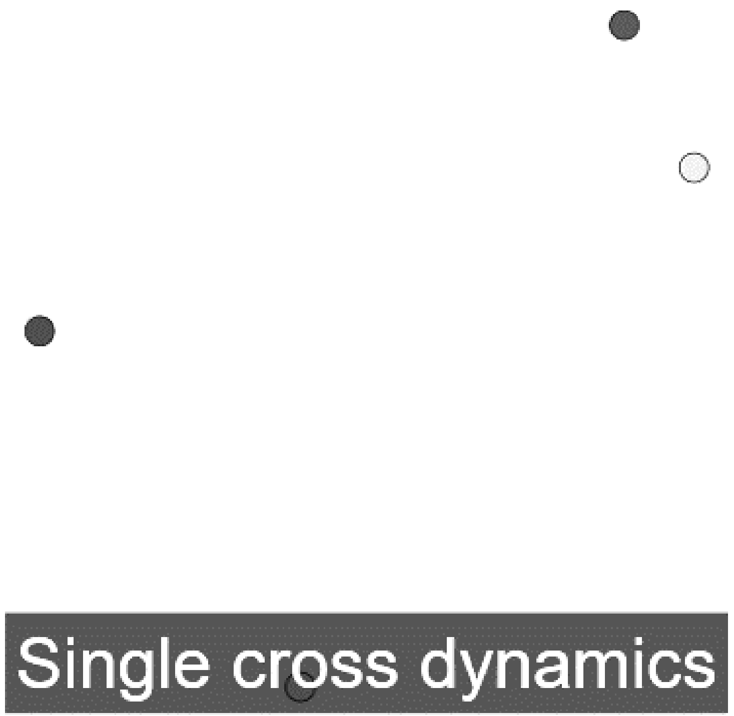



**2D Road Network Geometry**

**An idealized time-distance diagram showing signal coordination with a fixed time plan and the corresponding offset calculation**

# Exploiting the physics of road traffic



# Oscillator-based modelling and nonlinear control

$$\frac{d\theta_i(t)}{dt} = \overset{\text{Internal properties}}{\boxed{\omega_i(t)}} + \overset{\text{Network coupling}}{\boxed{k_i(t)\sum_{j=1}^{N} A_{ij} sin(\theta_j(t) - \theta_i(t))}} + \overset{\text{External coupling}}{\boxed{F_i sin(\theta^*(t) - \theta_i(t))}}$$

where:

$\theta_i$ - the amount of green time of traffic light $i$

$\omega_i$ - the frequency of traffic light $i$ oscillator

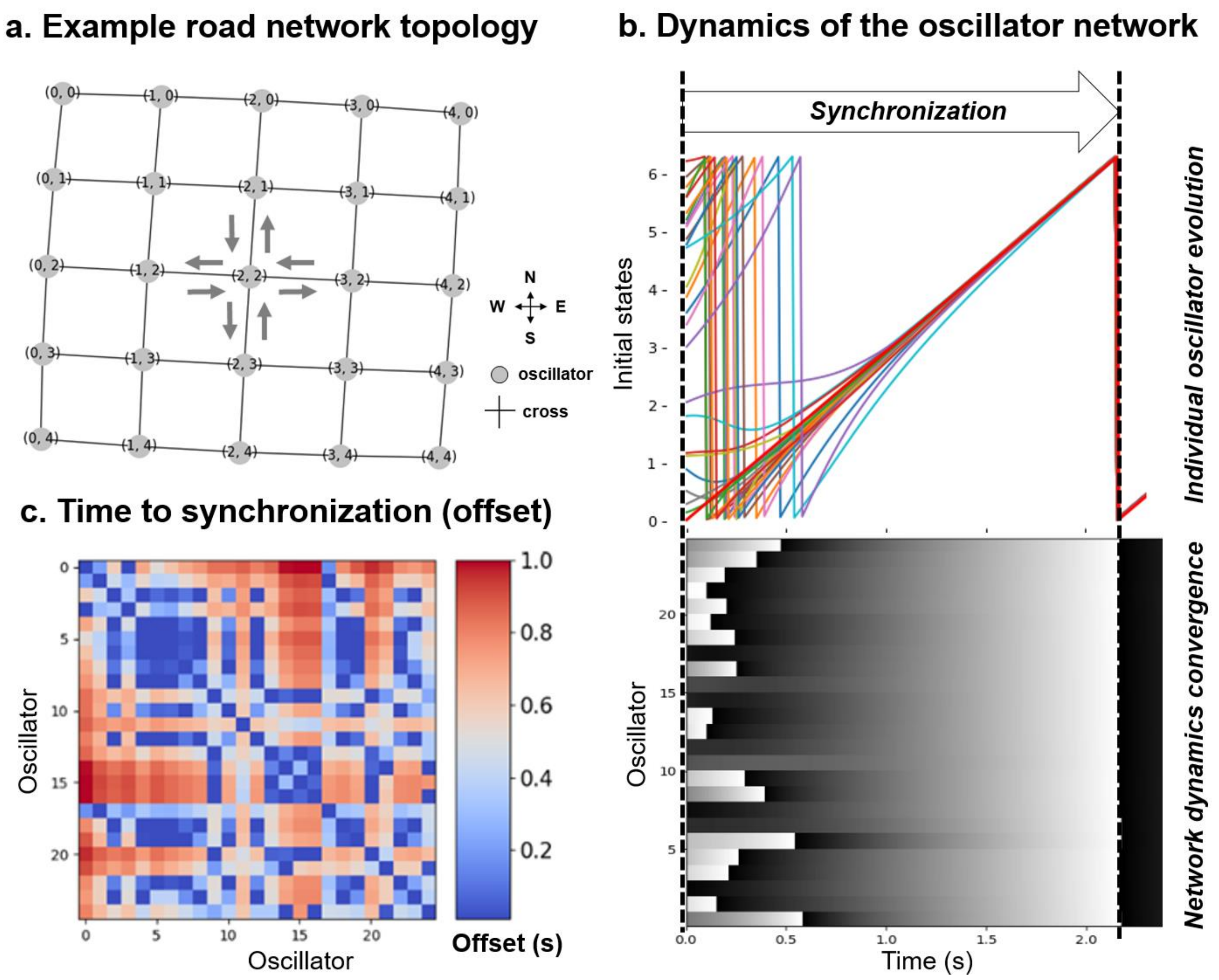
$k_i$ - the flow of cars passing through the direction controlled by oscillator $i$

$A_{ij}$ - the static spatial adjacency coupling between oscillator $i$ and oscillator $j$

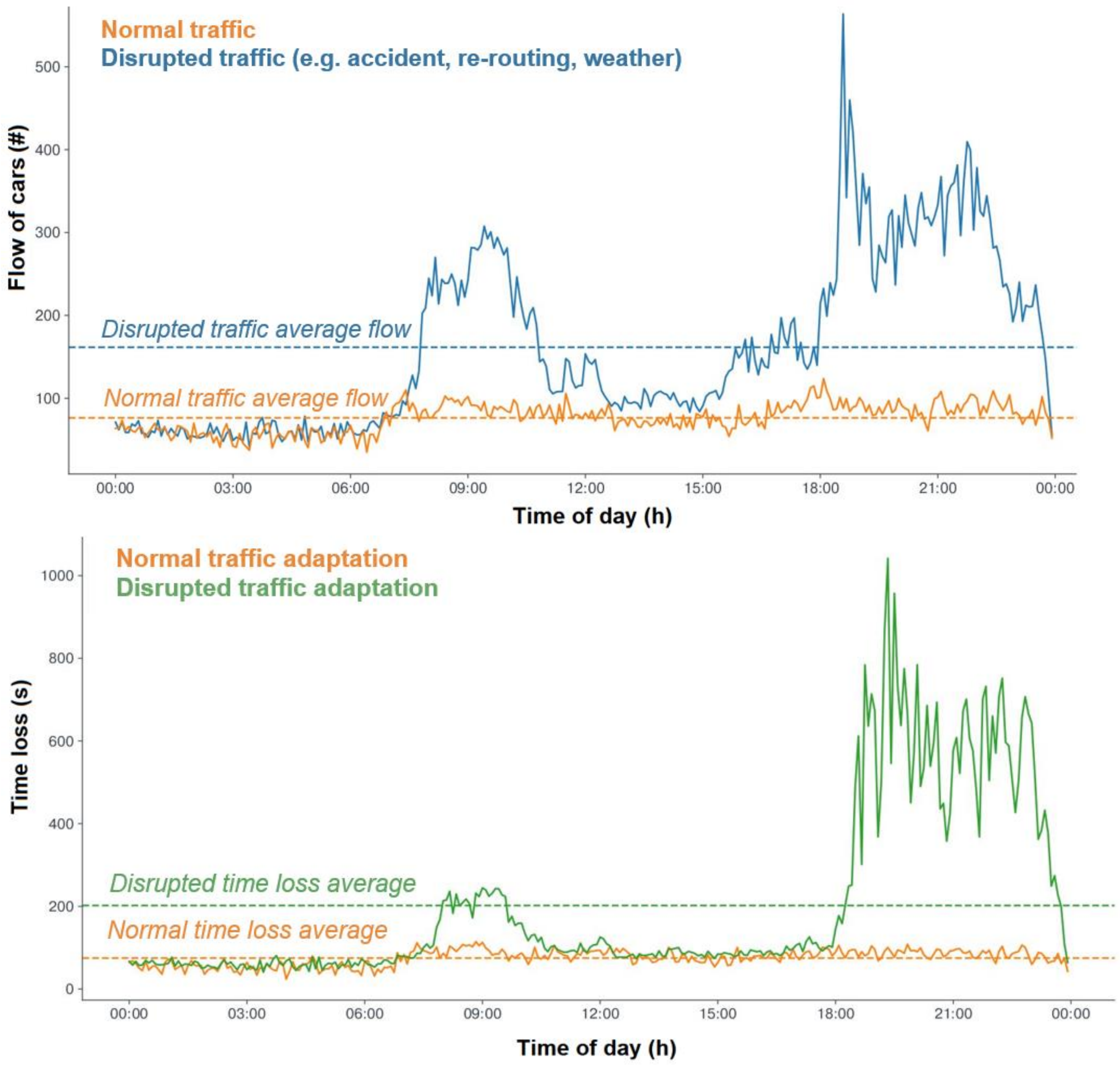
$F_i$ - the coupling of external perturbations (e.g. maximum cycle time per phase)

$\theta^*$ - the external perturbation (e.g. traffic signal limits imposed by law)

# Oscillator-based modelling and nonlinear control



# Oscillator-based modelling and nonlinear control



# Oscillator-based modelling and nonlinear control

Internal properties

Network coupling

External coupling

Regularizing control law

$$\frac{d\theta_i(t)}{dt} = \boxed{\omega_i(t)} + \boxed{k_i(t)\sum_{j=1}^{N} A_{ij}\, sin(\theta_j(t) - \theta_i(t))} + \boxed{F_i\, sin(\theta^*(t) - \theta_i(t))} + \boxed{u_i(t)}$$

with

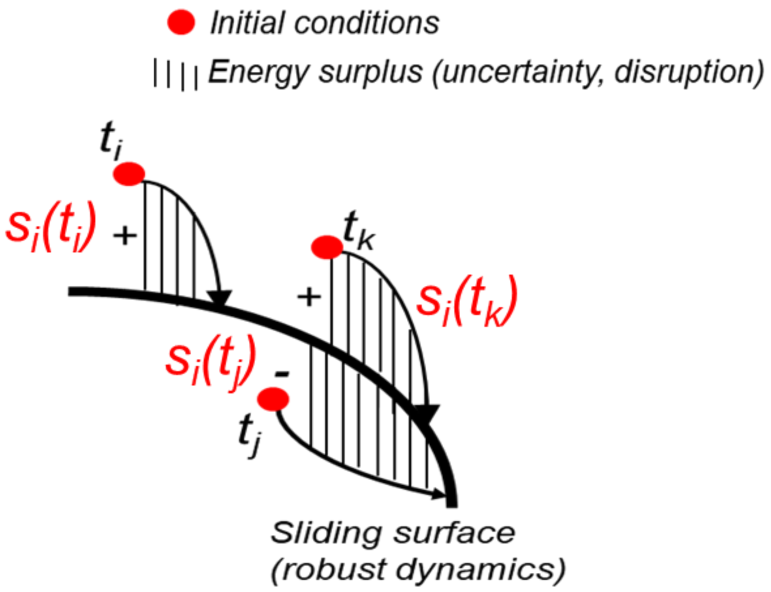
**Sliding Mode Control**

$$u_i(t) = \epsilon_1 \int_0^t \hat{s}_i(\tau)d\tau$$

$$\frac{\hat{s}_i(t)}{dt} = \epsilon_2\Big(\sum_{i,j}(\hat{s}_j(t) - \hat{s}_i(t)) + s_i(t)\Big)$$

$$\frac{s_i(t)}{dt} = \epsilon_3 \sum_j \Big(s_j(t) - \frac{\hat{s}_i(t)}{dt}\Big) - sign(\hat{s}_i(t))\frac{d^2\theta_i(t)}{dt^2}$$

$$0 < \epsilon_1 < \epsilon_2 < \epsilon_3 < 1$$

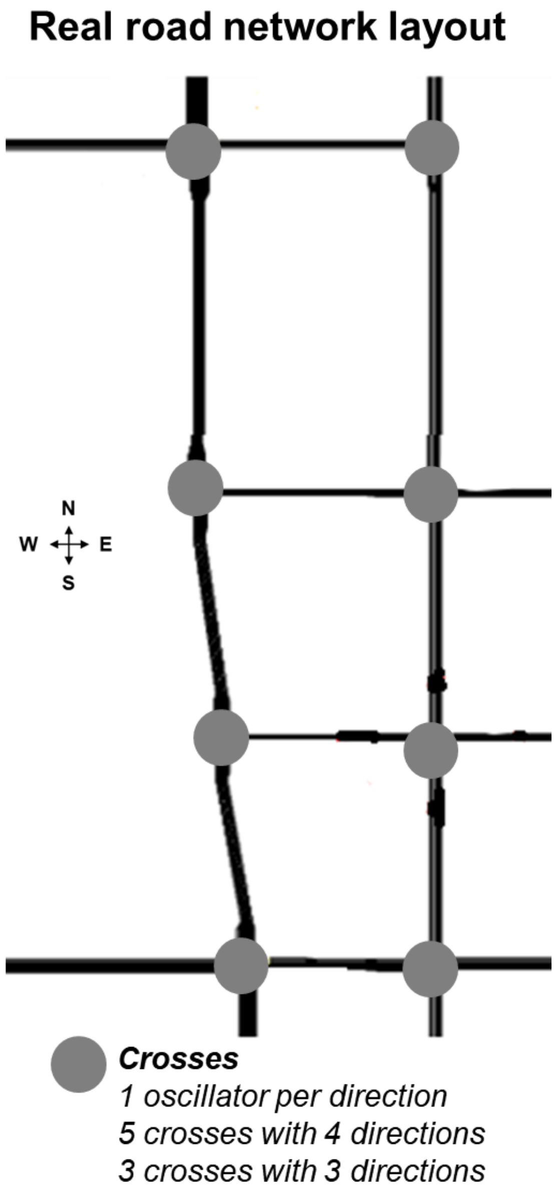


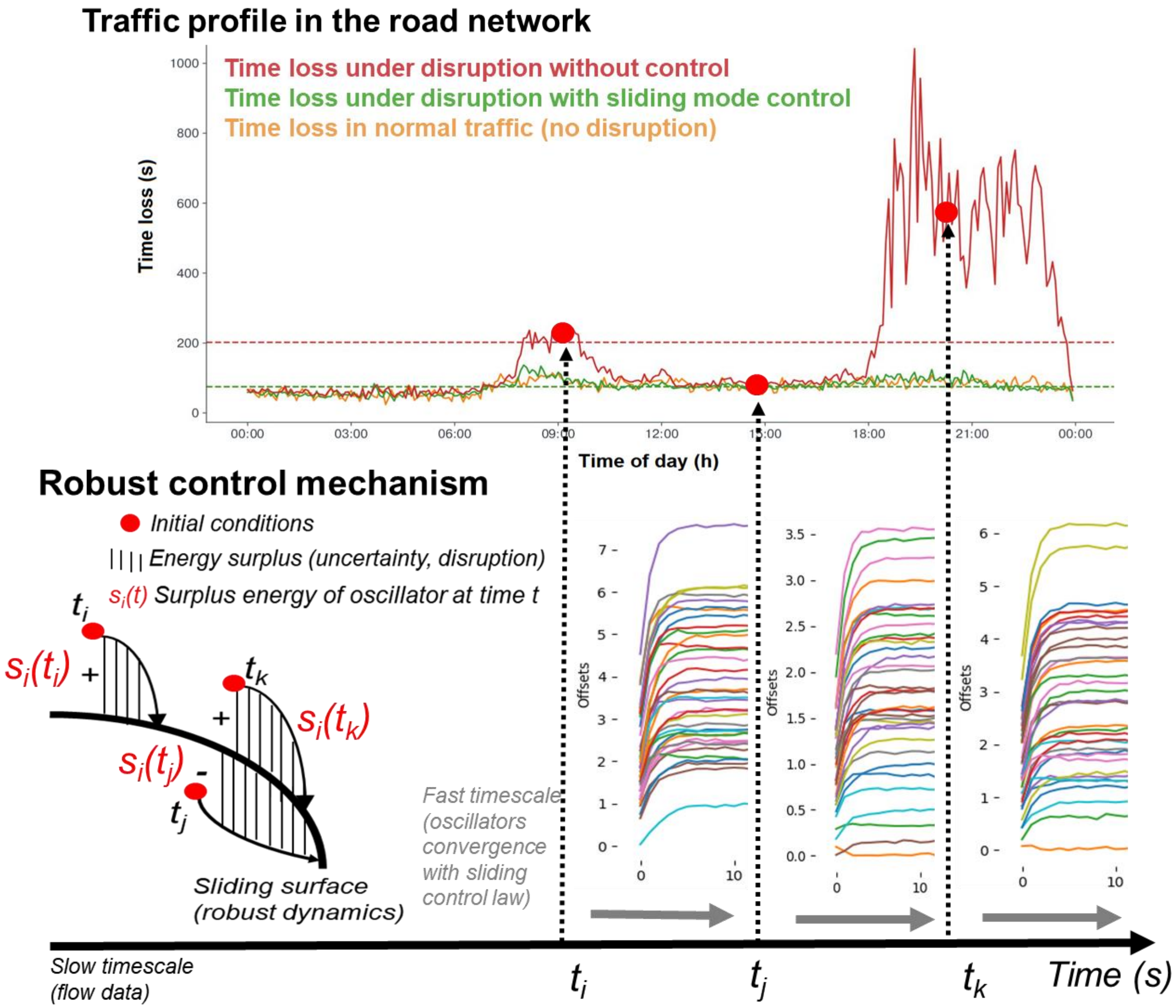

where:

$s_i(t)$ - the surplus energy of traffic light $i$ oscillator

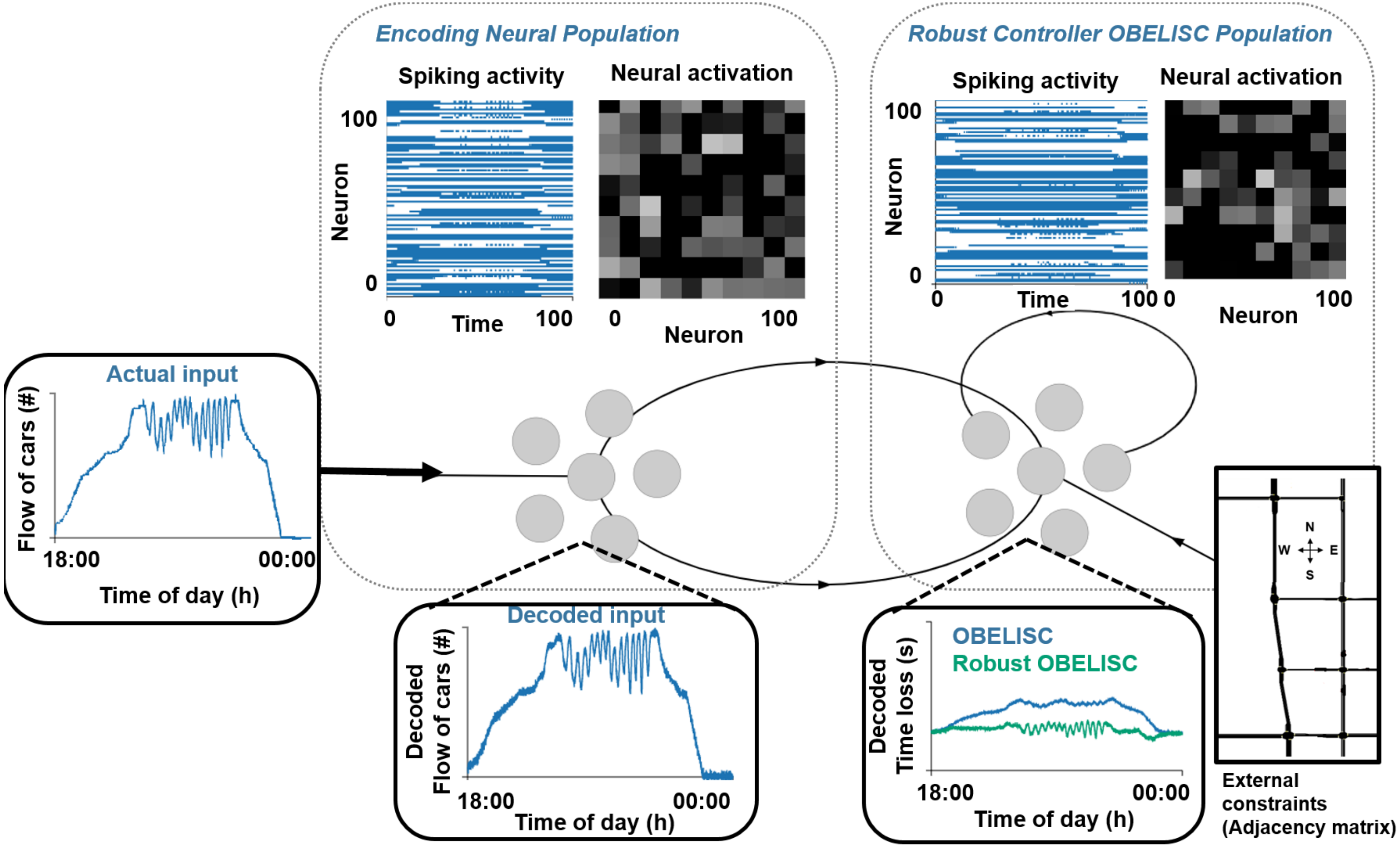
$\hat{s}_i(t)$ - the estimated surplus energy of traffic light $i$ oscillator

# Oscillator-based modelling and nonlinear control



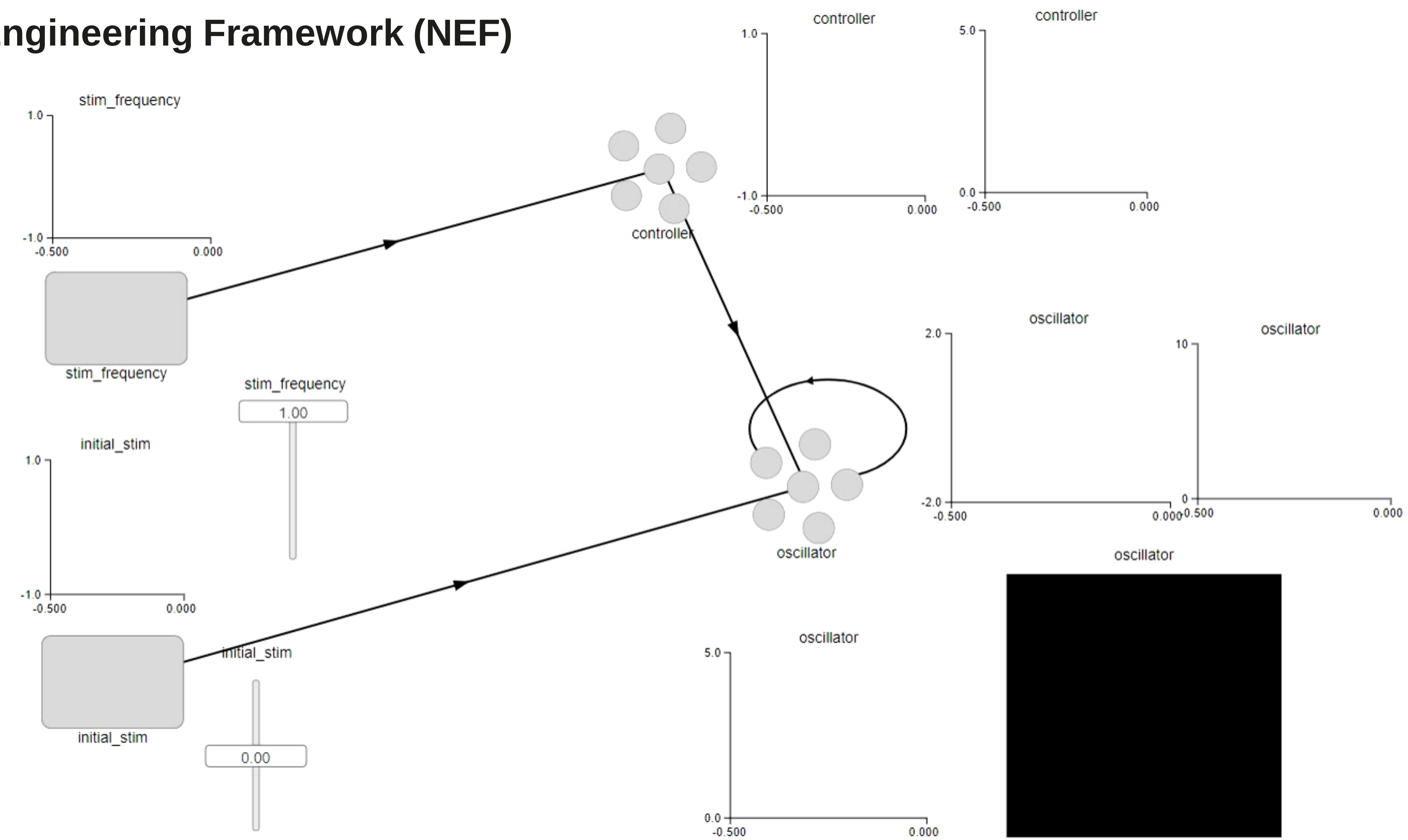
# Efficient neural learning



# Efficient neural learning

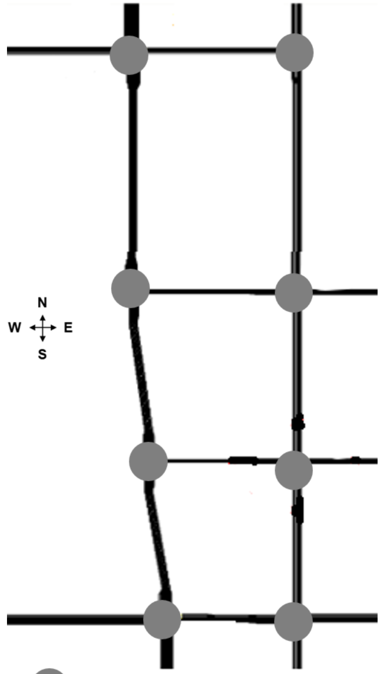
*Learning in spiking neural networks*

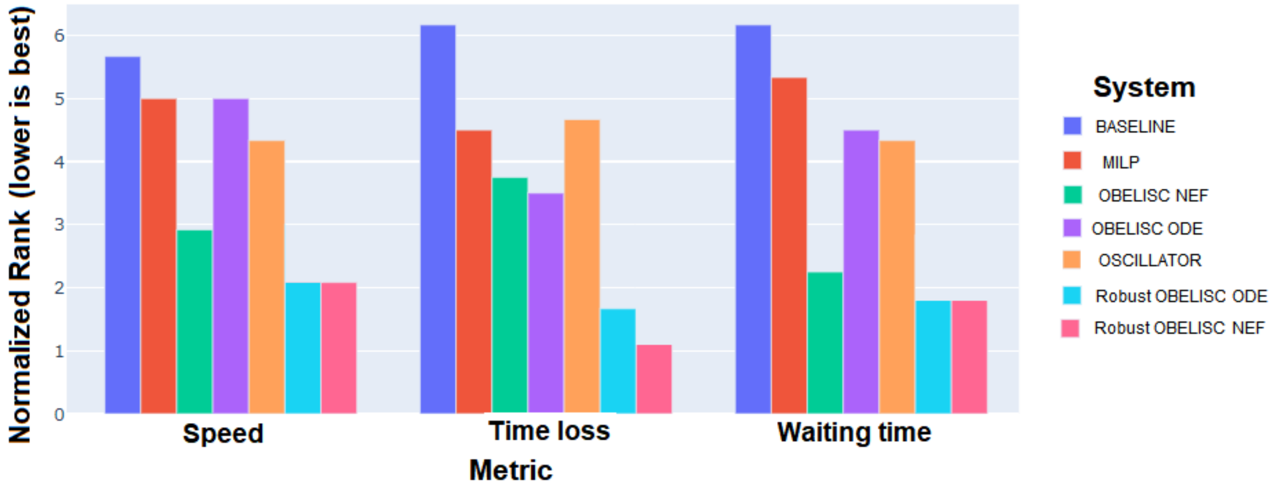
## Neural Engineering Framework (NEF)



# Experiments & Results

The **experiments and evaluation** use the **SUMMER-MUSTARD** (Summer season Multi-cross Urban Signalized Traffic Aggregated Region Dataset) real-world dataset, which contains 59 days of real urban road traffic data from 8 crosses in a city in China*




| Model | Single cross | Region (8 crosses) |
|---|---|---|
| MILP | 0.0510 | 0.3930 |
| OSCILLATOR | 0.0568 | 0.4544 |
| Robust OBELISC ODE | 0.0489 | 0.4534 |
| **Robust OBELISC NEF** | **0.0071** | **0.0426** |

* http://doi.org/10.5281/zenodo.5025264

# Observations

## OBELISC

Oscillator-Based Modelling and Control using Efficient Neural Learning for Intelligent Road Traffic Signal Calculation

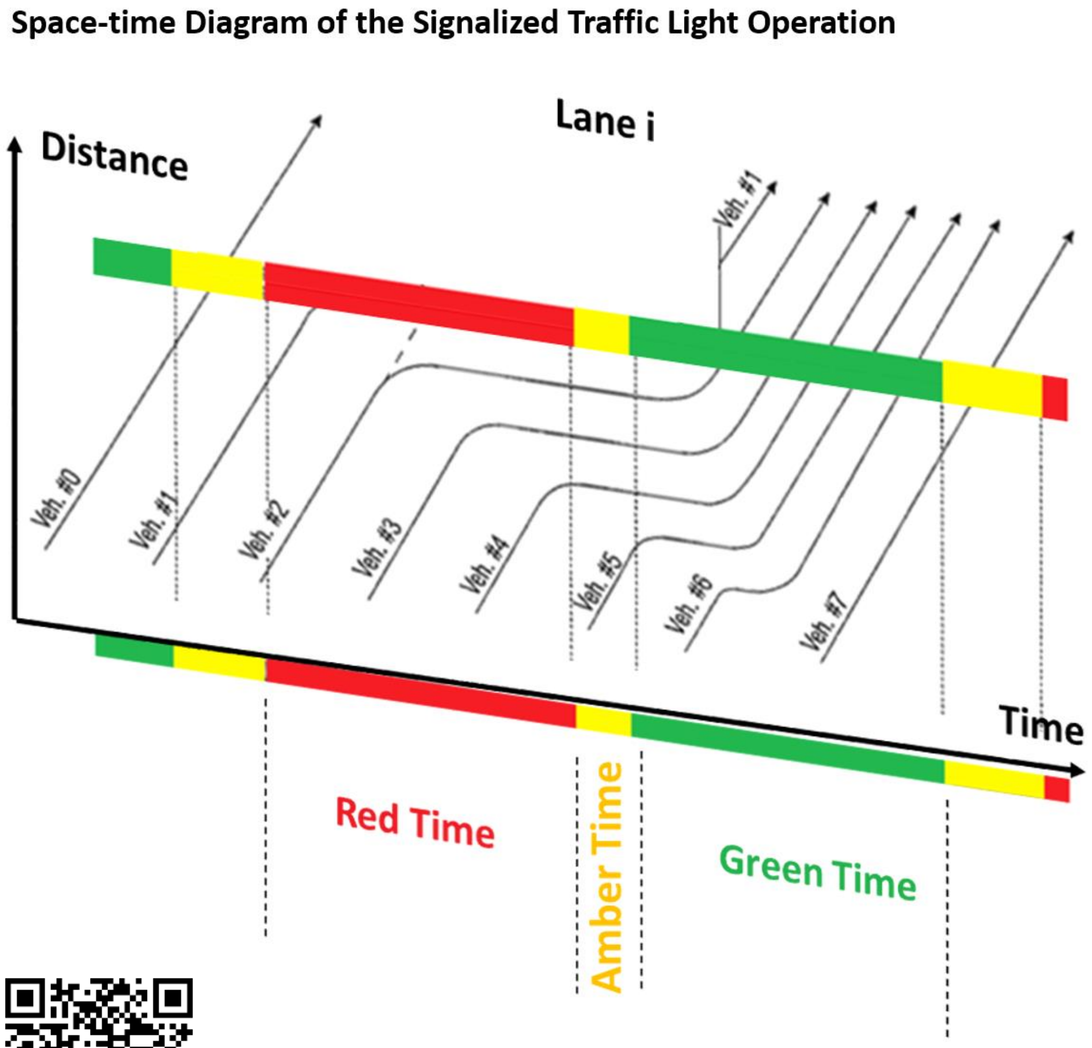
- Traffic control is a **multi-dimensional problem** to be optimized under **deep uncertainty**.
- A system using a **network of oscillators** capturing **the (periodic) spatial and temporal interactions** among different crosses in a **road traffic network**.
- A **control mechanism** that strengthens the **adaptation capabilities** towards global consensus under **high-magnitude traffic disruptions**.
- A **lightweight learning system** that exploits the **coupling interactions** among different controlled oscillators.
- An **end-to-end system (modelling, control, inference)** with proven potential for real-world deployment.

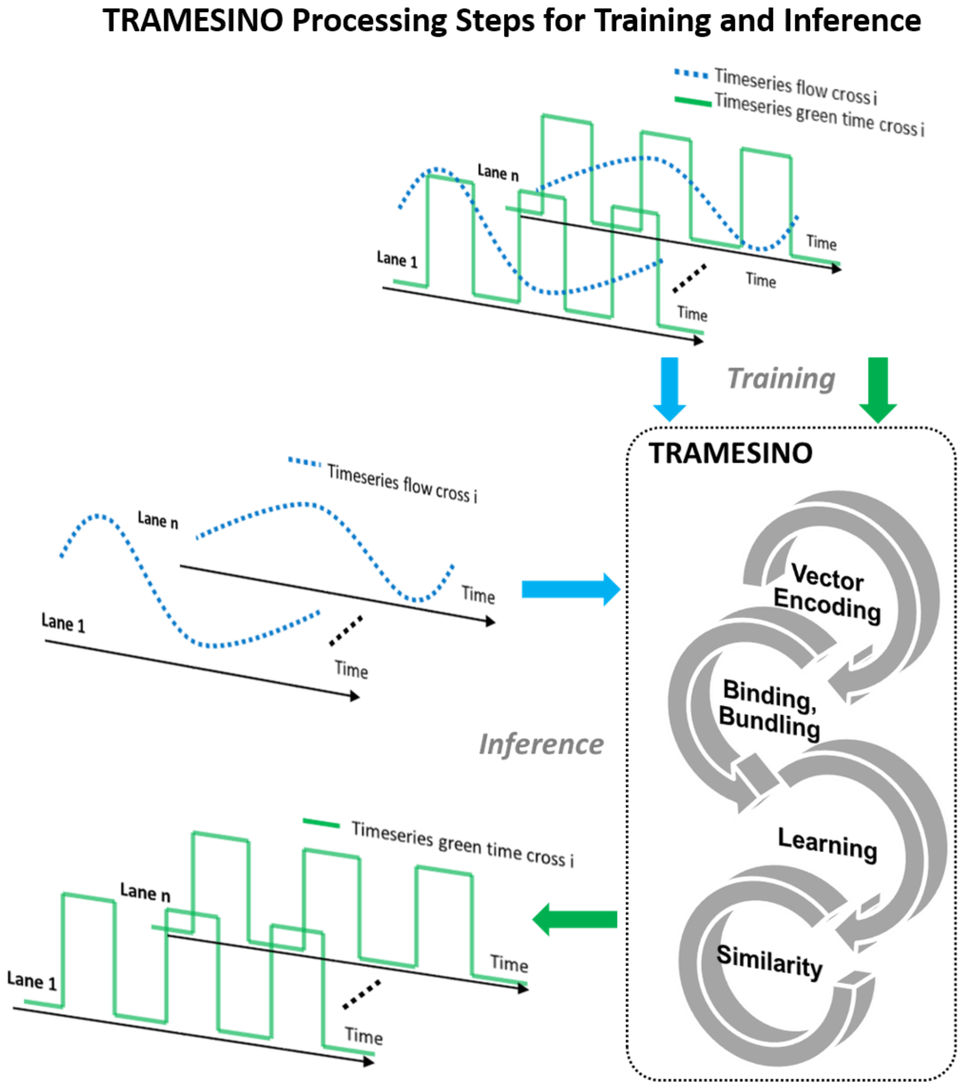
Axenie et al. , OBELISC @ ECML 2021

# Optimization based on traffic causality

Source: https://www.youtube.com/watch?v=6uf2QNtYpII

# Exploiting causality in road traffic control

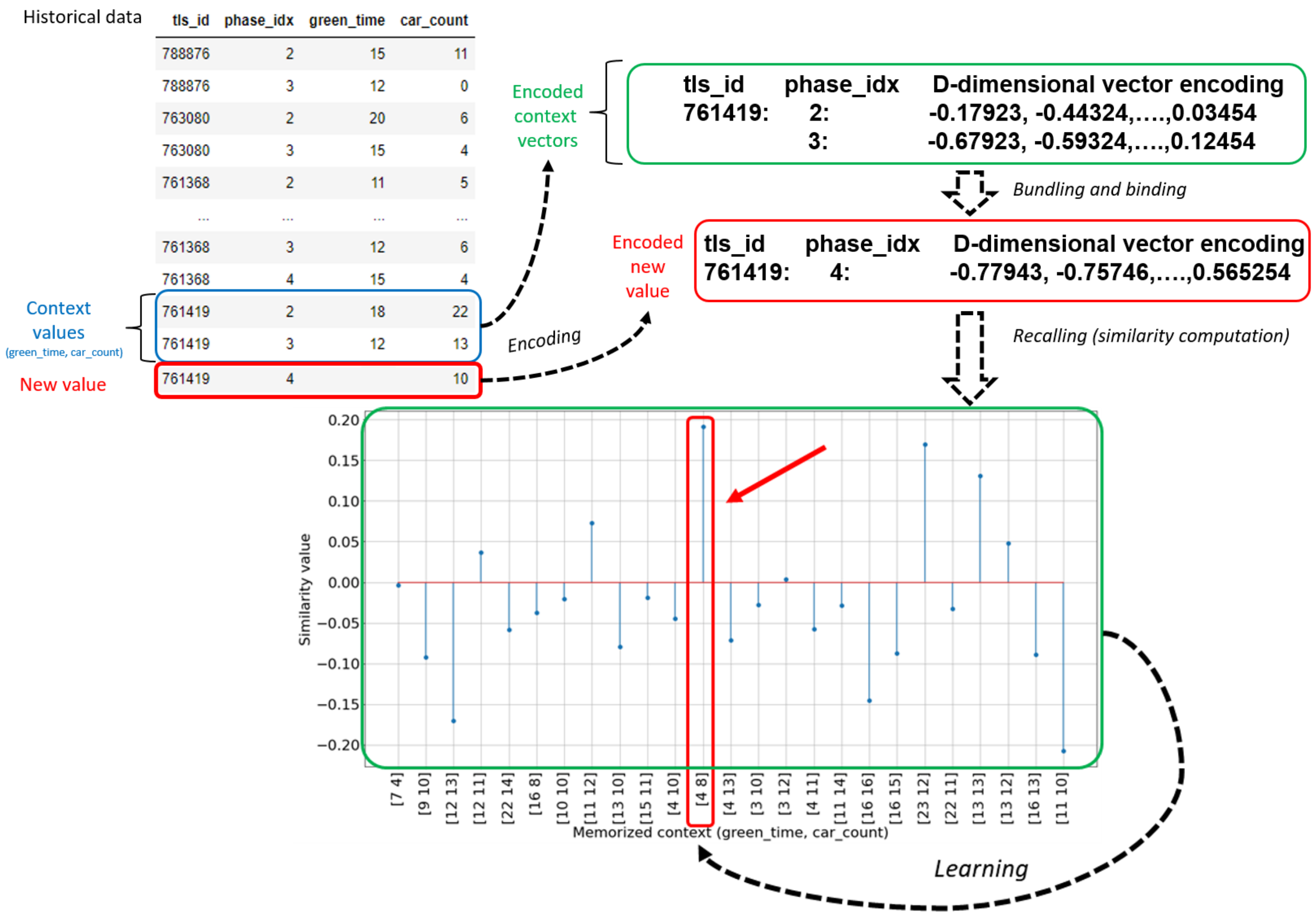



Axenie et al. , TRAMESINO @ AALTD 2021

# High-dimensional vector algebra for associative memories

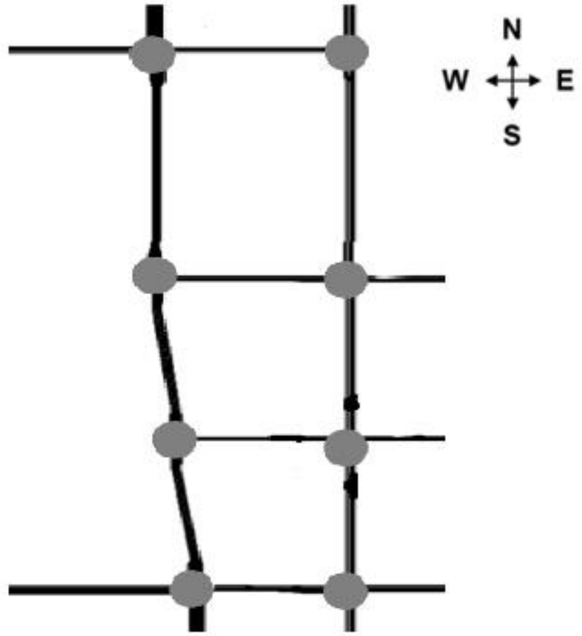
*High-dimensional vector representation and computation*

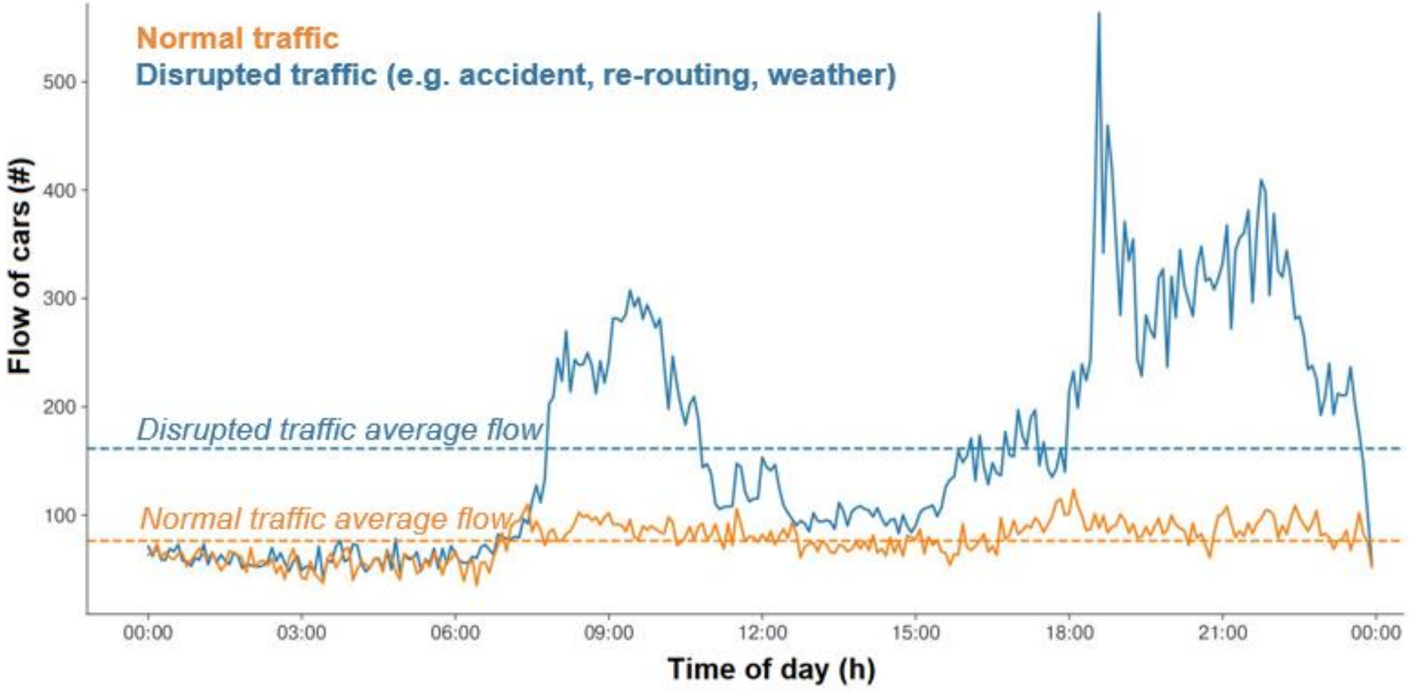



| tls_id | phase_idx | green_time | car_count |
|---|---|---|---|
| 788876 | 2 | 15 | 11 |
| 788876 | 3 | 12 | 0 |
| 763080 | 2 | 20 | 6 |
| 763080 | 3 | 15 | 4 |
| 761368 | 2 | 11 | 5 |
| ... | ... | ... | ... |
| 761368 | 3 | 12 | 6 |
| 761368 | 4 | 15 | 4 |
| 761419 | 2 | 18 | 22 |
| 761419 | 3 | 12 | 13 |
| 761419 | 4 | | 10 |

# Experiments & Results

The **experiments and evaluation** use the **SUMMER-MUSTARD** (Summer season Multi-cross Urban Signalized Traffic Aggregated Region Dataset) real-world dataset, which contains 59 days of real urban road traffic data from 8 crosses in a city in China* **reproduced** in **SUMO simulator**.




* http://doi.org/10.5281/zenodo.5025264

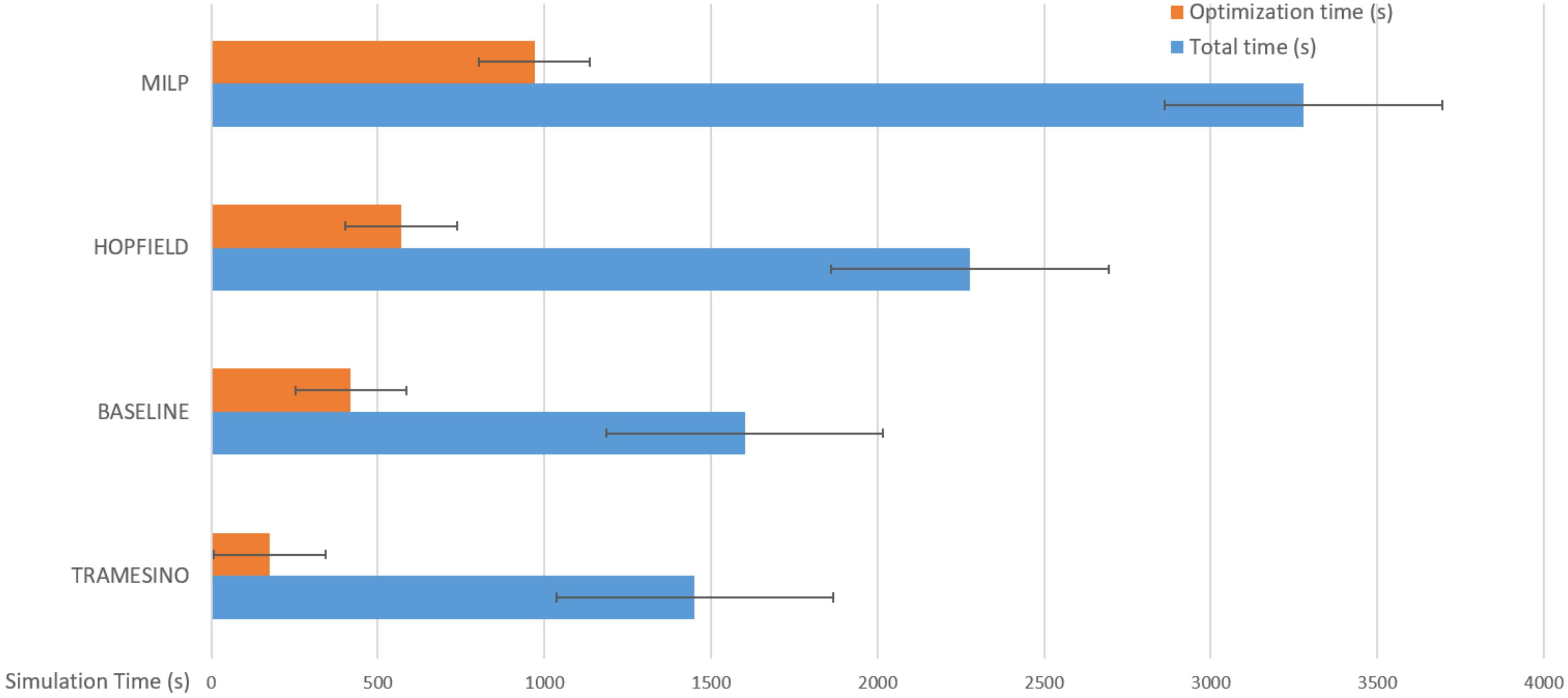
# Experiments & Results

Traffic Key Performance Indices (KPI) evaluation

| System/ Disruption level | N | L | M | H | Ranking | Deviation |
|---|---|---|---|---|---|---|
| *Average trip duration(s)* | | | | | | |
| BASELINE | 168.805 | 181.217 | 265.546 | 270.167 | 4 | 49.86% |
| MILP | 118.336 | 132.406 | 167.173 | 167.673 | 1 | 0.0% |
| HOPFIELD | 151.281 | 151.381 | 223.017 | 257.464 | 3 | 32.28% |
| TRAMESINO | 156.379 | 157.371 | 203.775 | 236.224 | 2 | 28.44% |
| *Average speed(km/h)* | | | | | | |
| BASELINE | 58.15 | 56.78 | 49.38 | 47.50 | 4 | 10.95% |
| MILP | 59.30 | 60.00 | 59.40 | 59.10 | 1 | 0.0% |
| HOPFIELD | 59.48 | 59.97 | 49.28 | 46.18 | 3 | 9.84% |
| TRAMESINO | 59.78 | 59.02 | 52.08 | 48.28 | 2 | 8.14% |
| *Waiting time(s)* | | | | | | |
| BASELINE | 16.45 | 18.53 | 32.59 | 35.13 | 4 | 7.02% |
| MILP | 13.98 | 16.14 | 15.14 | 15.07 | 1 | 0.0% |
| HOPFIELD | 13.98 | 14.96 | 29.32 | 37.29 | 3 | 5.84% |
| TRAMESINO | 14.95 | 14.57 | 22.16 | 29.01 | 2 | 2.96% |

# Experiments & Results

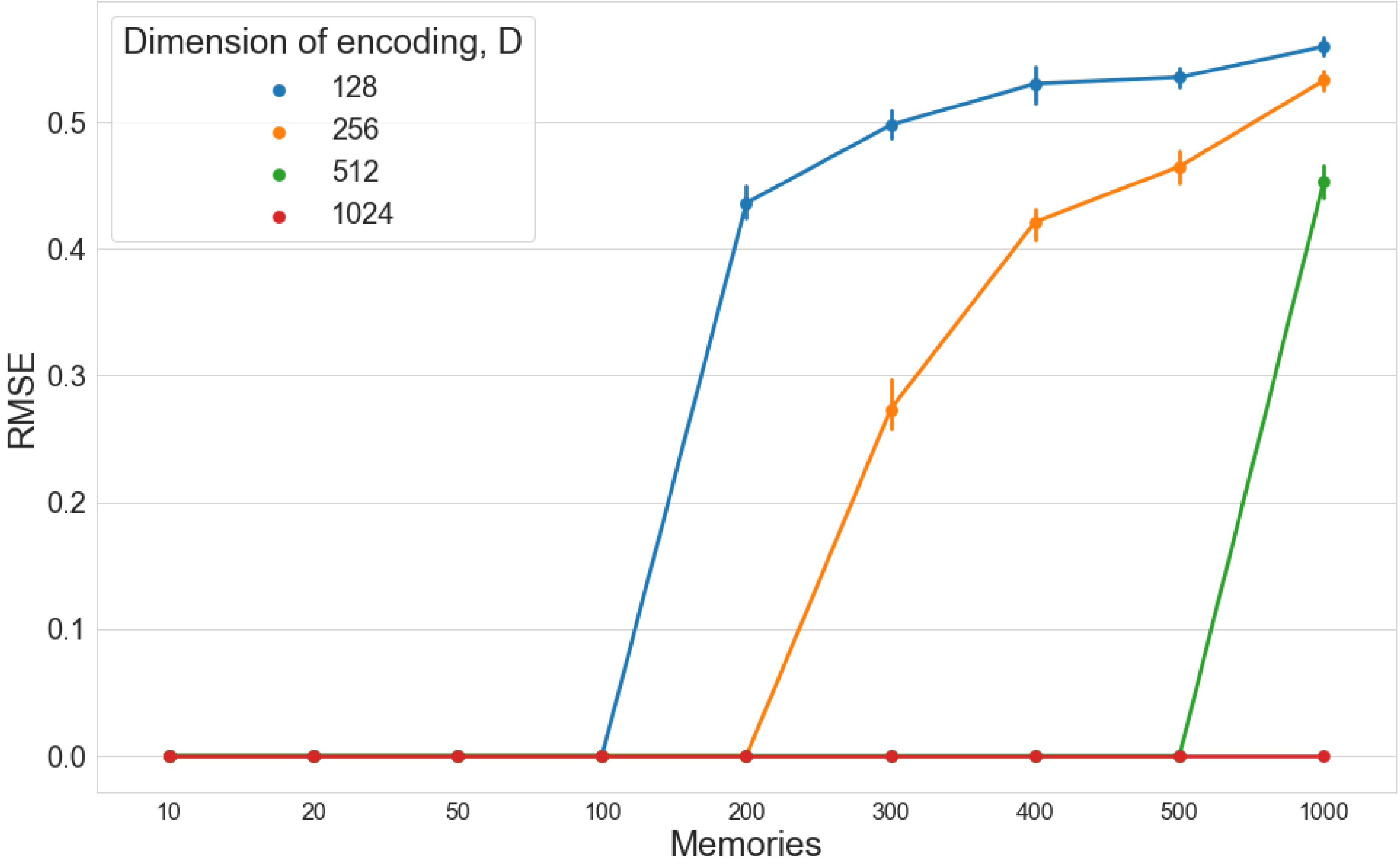
## Run-time performance evaluation




| | TRAMESINO | BASELINE | HOPFIELD | MILP |
|---|---|---|---|---|
| Optimization time (s) | 175.2699437 | 418.8146019 | 570.0803573 | 970.0803573 |
| Total time (s) | 1451.665398 | 1601.359572 | 2278.111582 | 3278.111582 |

# Experiments & Results

Encoding/decoding accuracy of TRAMESINO memories



# Observations

## TRAMESINO

Trainable Memory System for Intelligent Optimization of Road Traffic Control

- The highly **non-linear and unpredictable** real-world **road traffic** situations need **timely actions**.

- A system that **models** only **relevant causal action-consequence pairs** within traffic data (i.e. green time – traffic count).

- A **memory mechanism** to store **traffic patterns** and **retrieve plausible decisions**.

- A **lightweight learning system encoding** and **manipulating traffic data** encoded in **high-dimensional vectors** using **spiking neural networks.**

- An **end-to-end system** that **learns temporal regularities** in traffic data and **adapts** to **abrupt changes**, while keeping **computation efficient** and **fast**.

# Thank you.

Bring digital to every person, home, and organization for a fully connected, intelligent world.