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Combining Mechanistic Modelling, Nonlinear Control, and Neuronal Learning for Road Traffic Optimization

Physics-enhanced Machine Learning methods in Engineering practice seminar @ The Alan Turing Institute

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Intelligent Cloud Technologies Laboratory

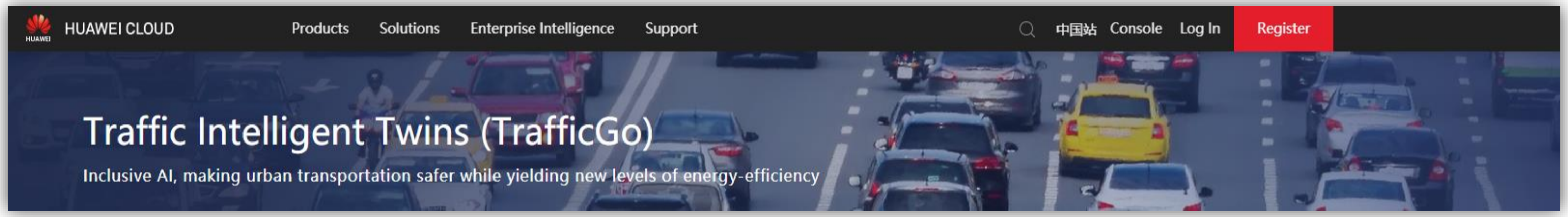
Munich Research Center

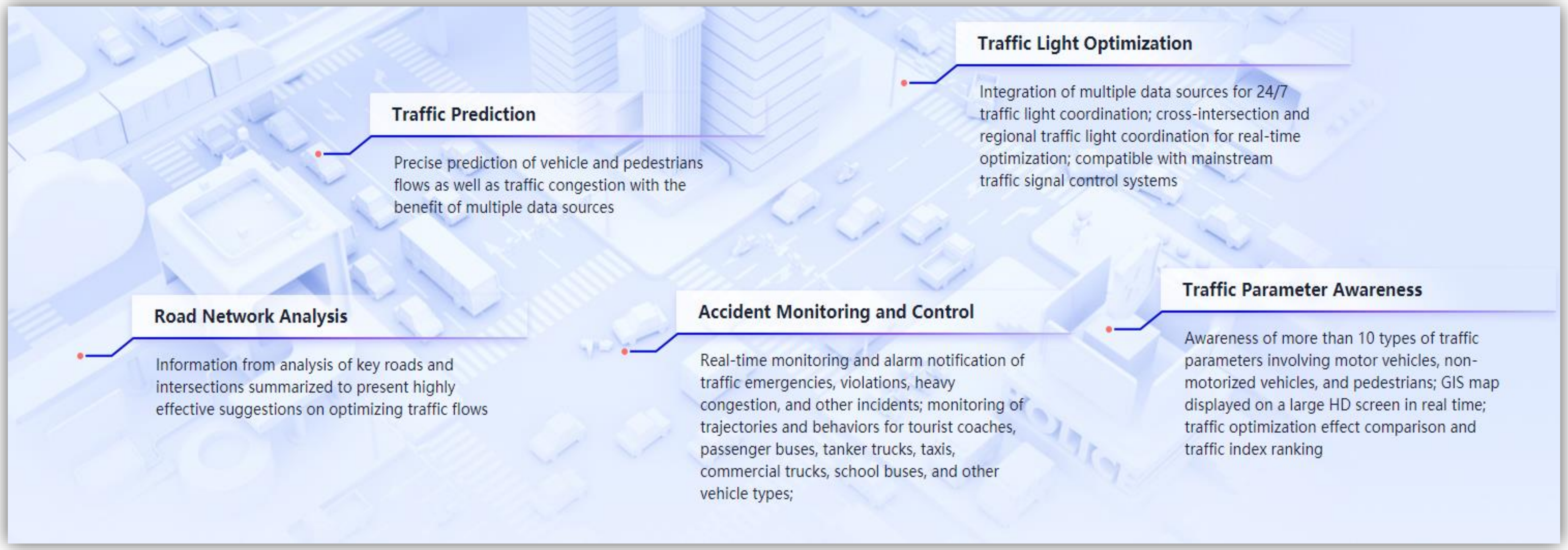
HUAWEI

Agenda

- Huawei TrafficGO Solution
- Real Time Traffic Control at District Level
- Exploiting the physics of traffic
- System design: modelling, control, and learning
- Evaluation
- Conclusions

TrafficGO Solution





Traffic Intelligent Twins (TrafficGO)

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

Lamport Lab

Real-Time Traffic Signal Scheduling

Formulates the first security communication interface standards for intelligence-infused traffic management and signal control systems.

District-wide Coordination

Maximizes traffic volume and minimizes vehicle wait time. Coordinates travel requirements of vehicles and pedestrians for smooth traffic.

Deep Data Mining

Integrates the Internet with big data for traffic control to deepen data mining efforts.

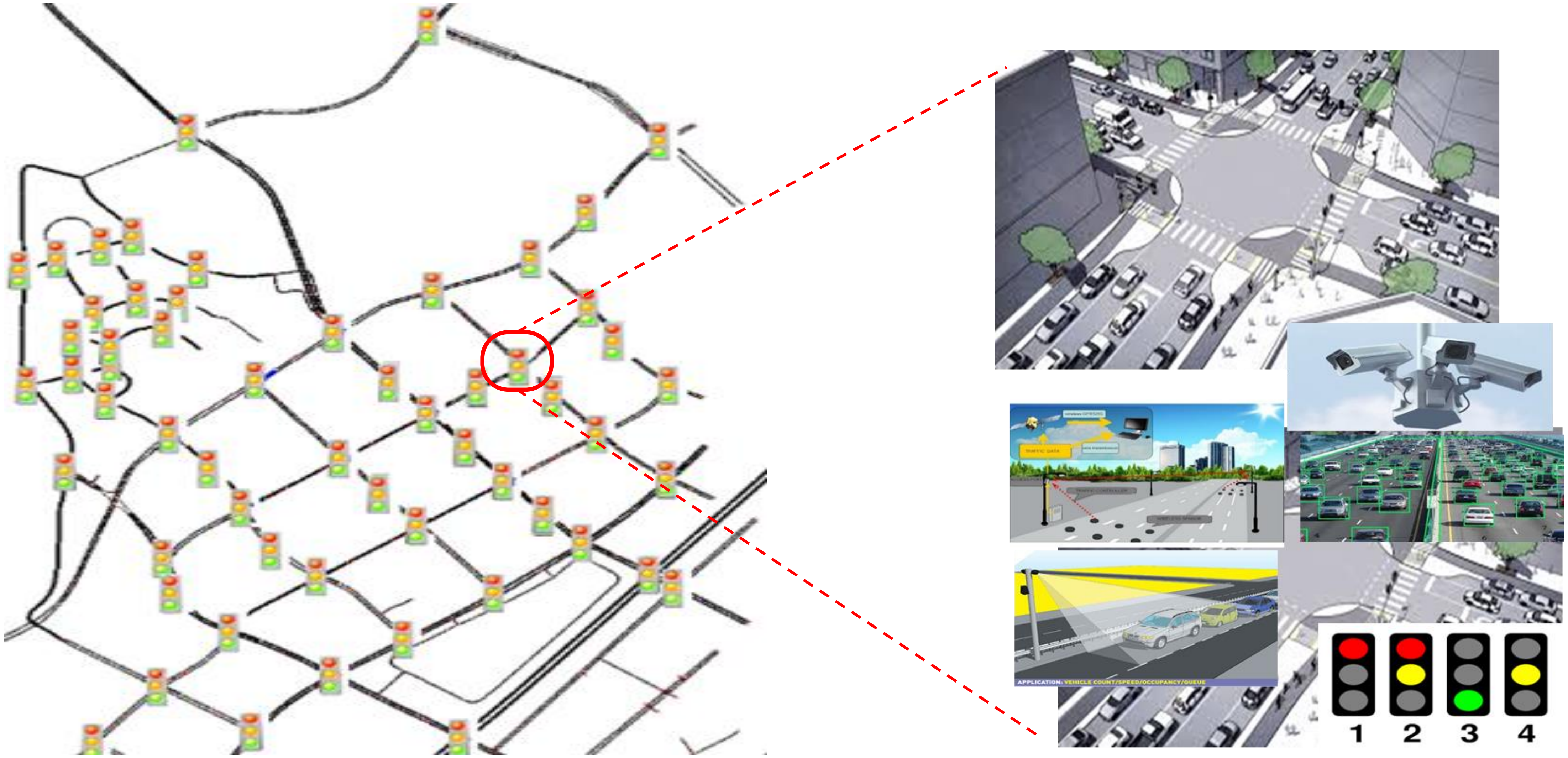
Precise Tracking and Planning

Accurately predicts trajectories and plans routes in advance.

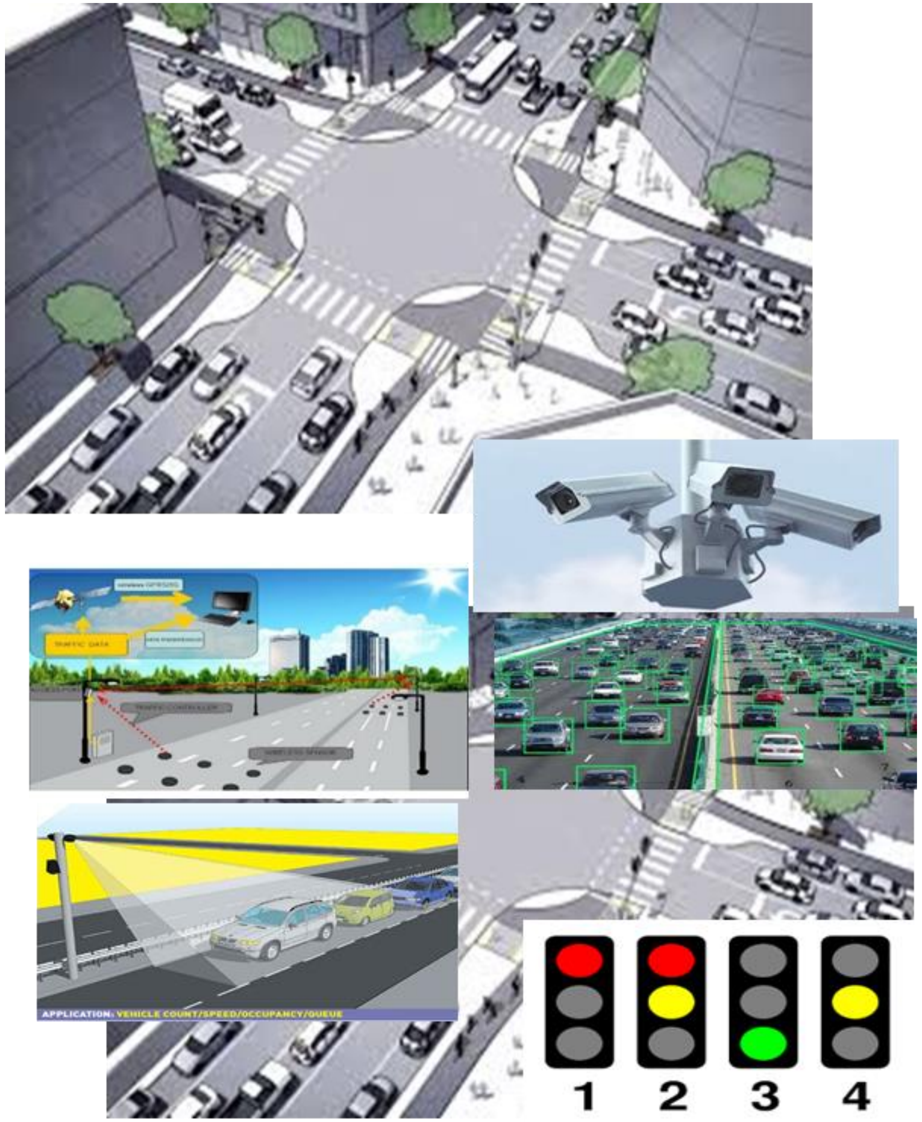
OBELISC

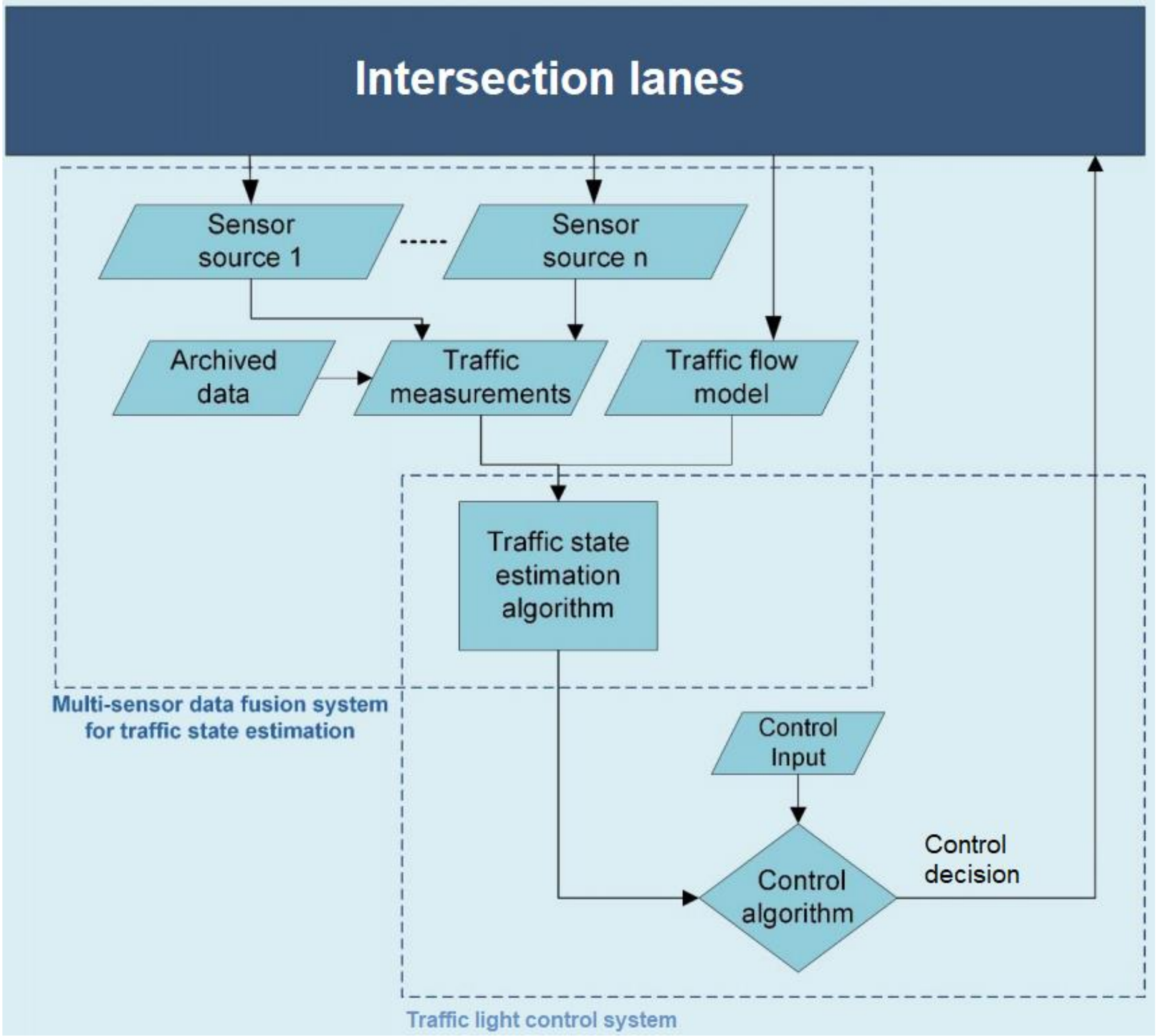
Oscillator-Based Efficient Learning In phase offset State Control

Real Time Traffic Control at District Level

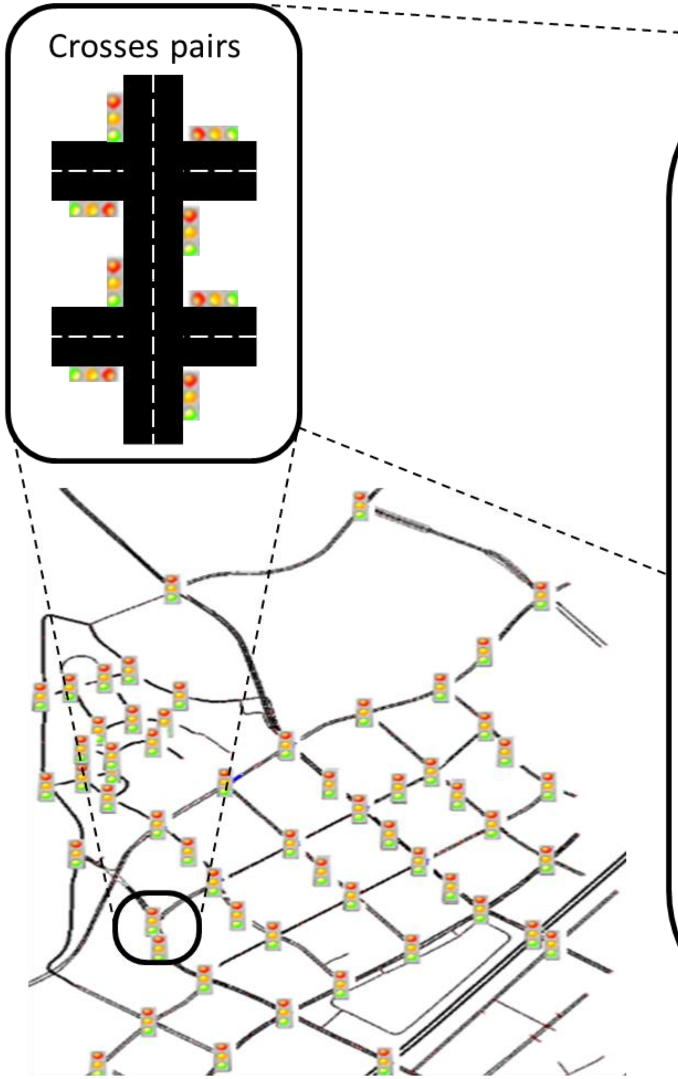


Real Time Traffic Control at District Level

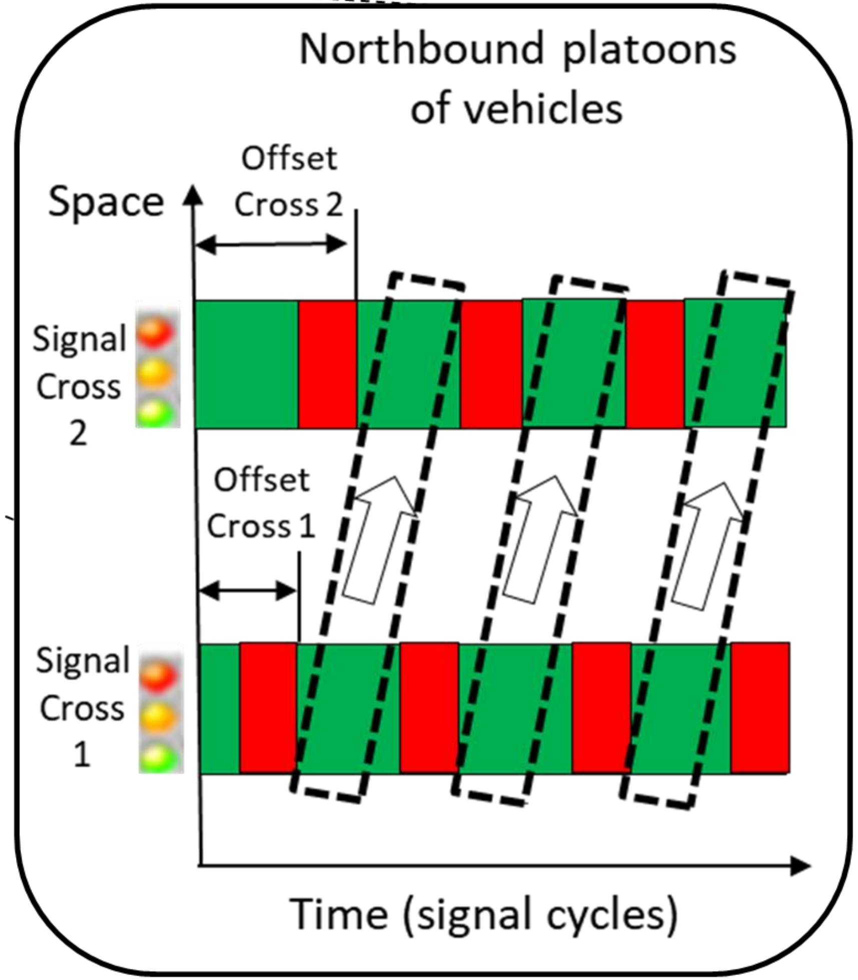




Real Time Traffic Control at District Level

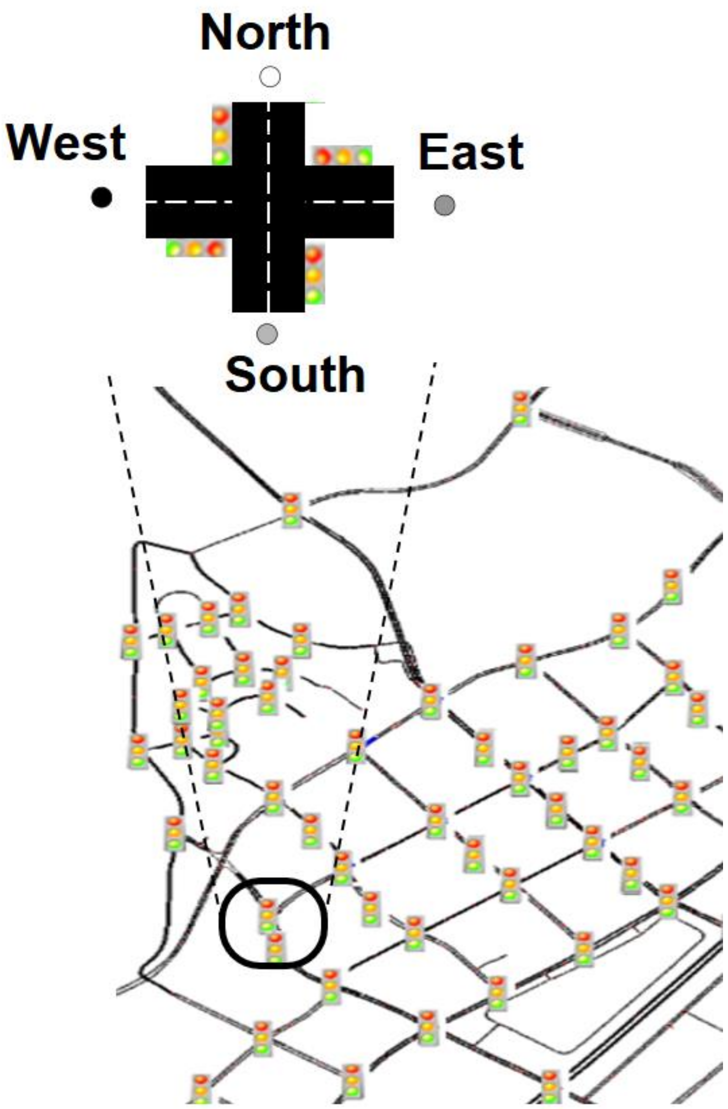


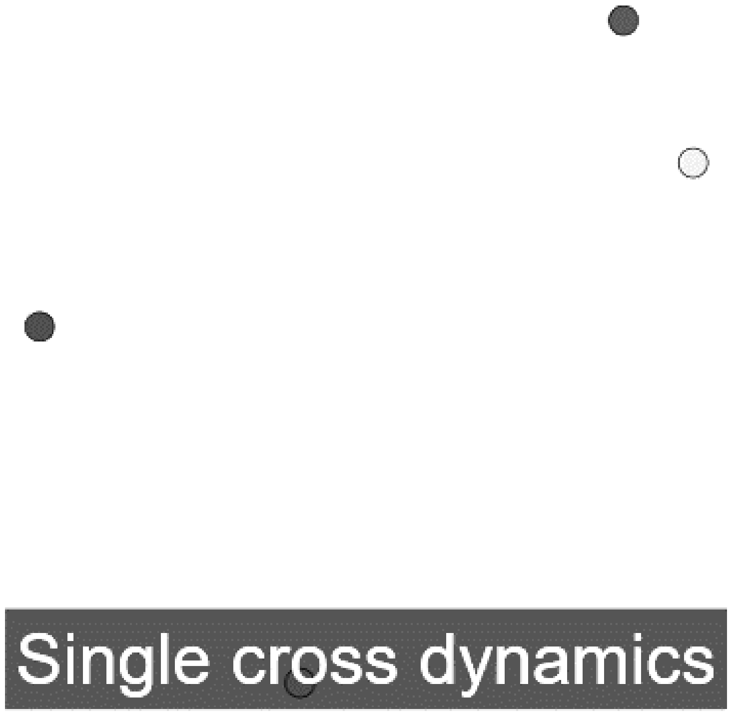
2D Road Network Geometry



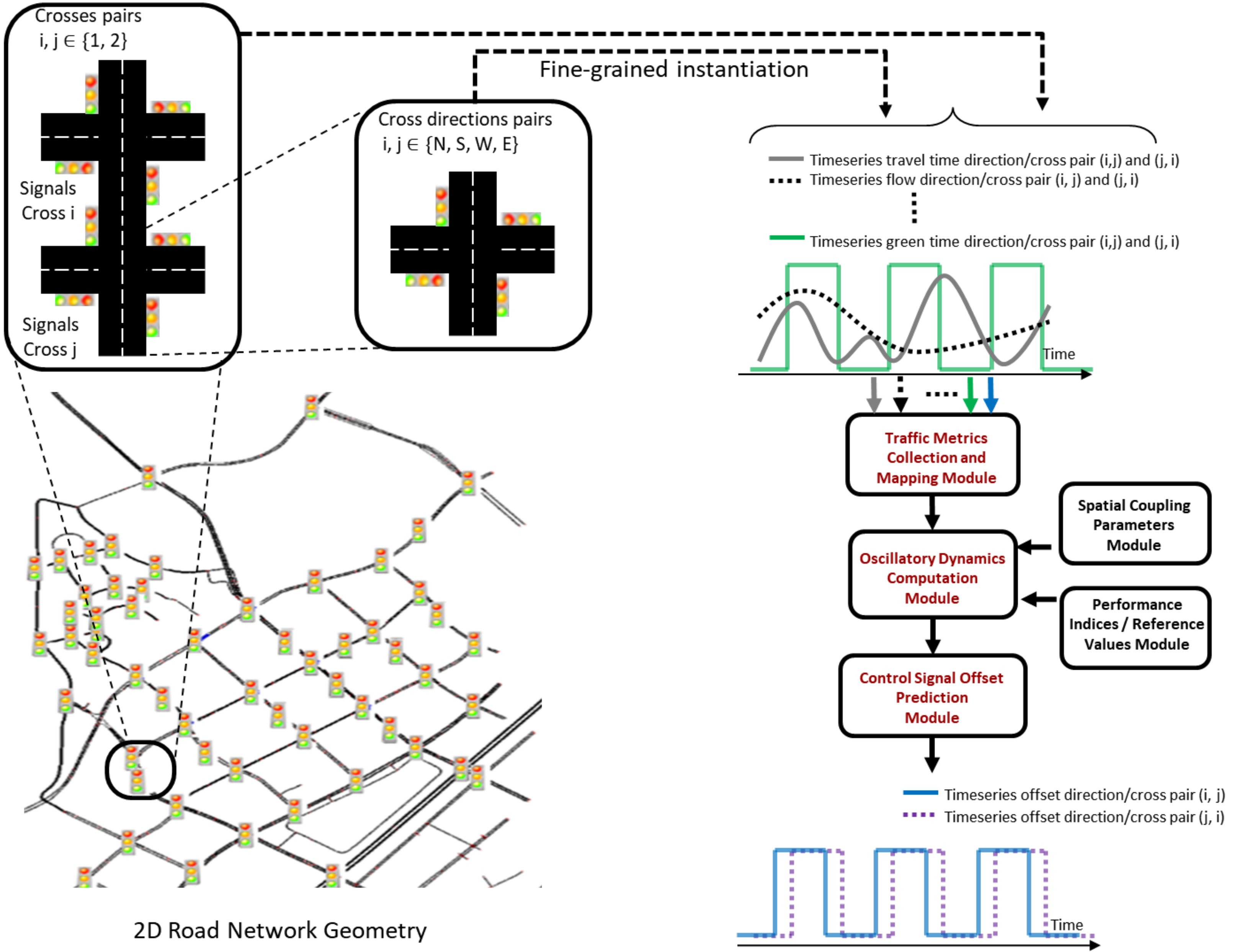
An idealized time-distance diagram showing signal coordination with a fixed time plan and the corresponding offset calculation

Exploiting the Physics of Road Traffic





System design

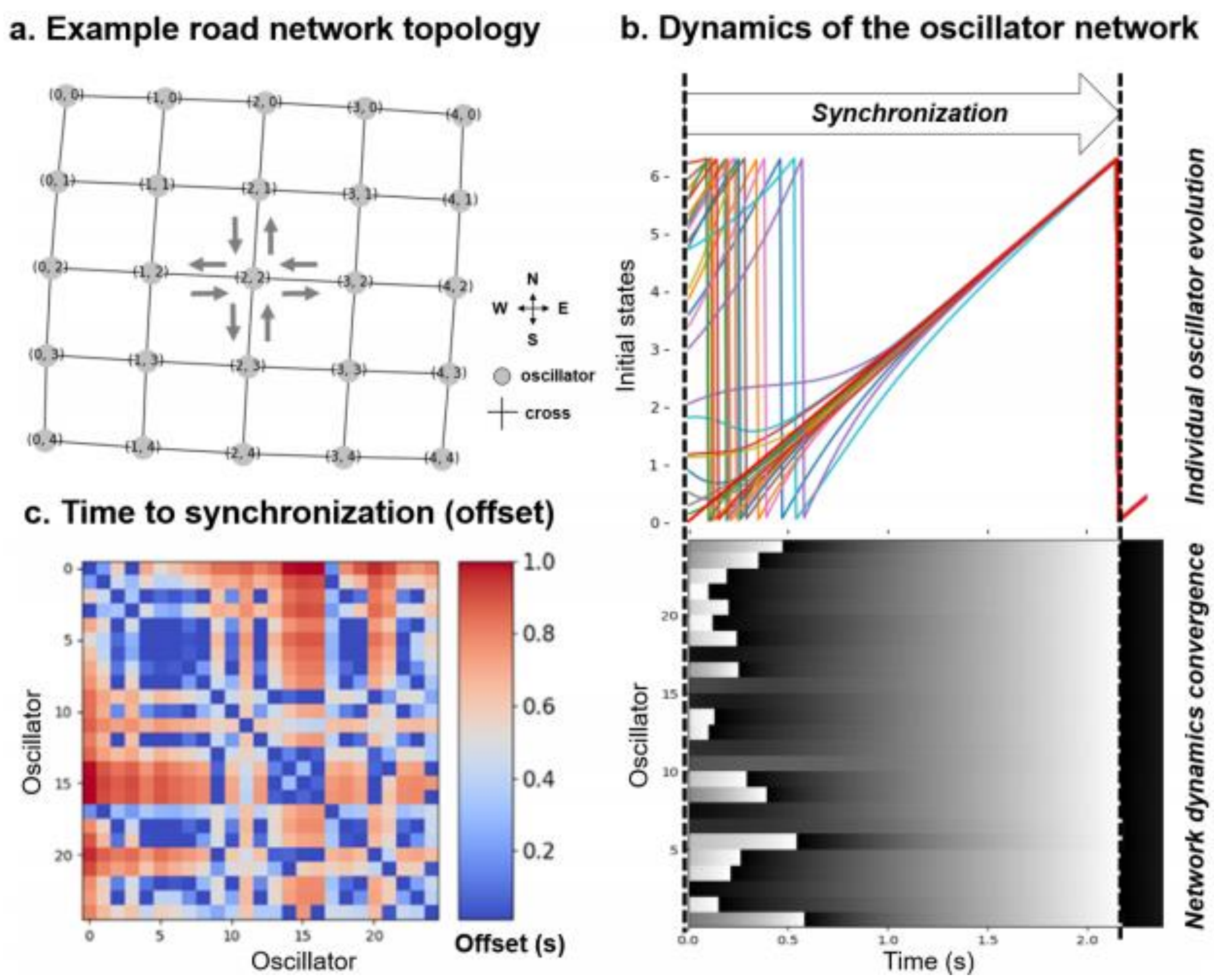


System design: modelling

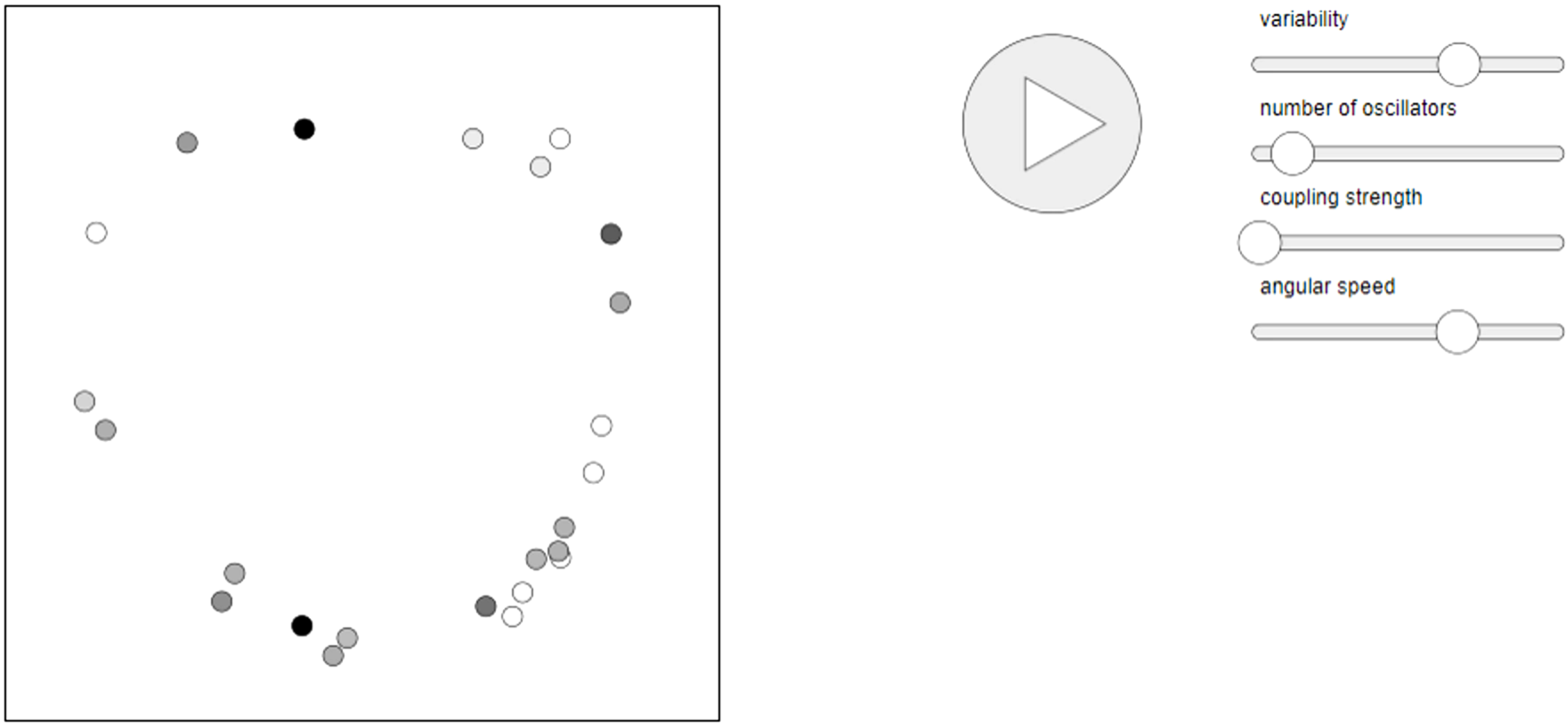
$$\frac{d\theta_i(t)}{dt} = \underbrace{\boxed{\omega_i(t)}}_{\text{Angular speed}} + \underbrace{\boxed{k_i(t)\sum_{j=1}^{N} A_{ij} sin(\theta_j(t) - \theta_i(t))}}_{\text{Coupling strength}} + \underbrace{\boxed{F_i sin(\theta^*(t) - \theta_i(t))}}_{\text{Variability}}$$

where:
θ_i - the amount of green time of traffic light i
ω_i - the frequency of traffic light i oscillator
k_i - the flow of cars passing through the direction controlled by traffic light i oscillator
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 imposed by law)
θ^* - the external perturbation (e.g. the upper limit of green time)

System design: modelling



System design: modelling



System design: control

Oscillator dynamics

Regularizing control law

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

with

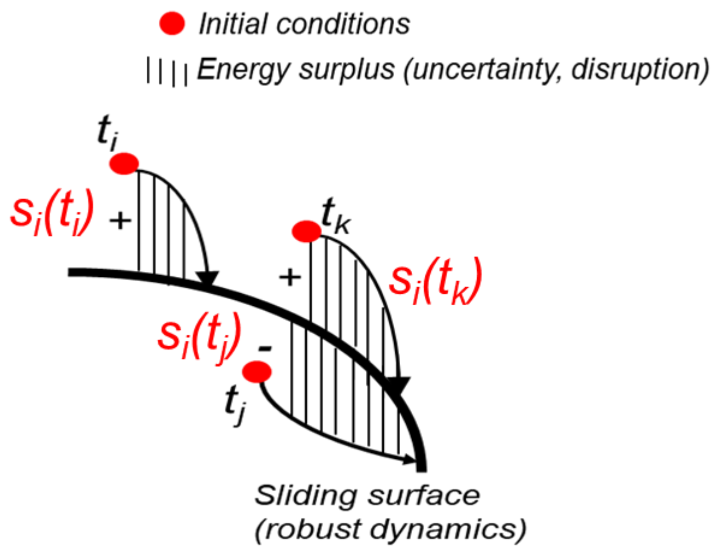
Sliding Mode Control

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

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

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

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

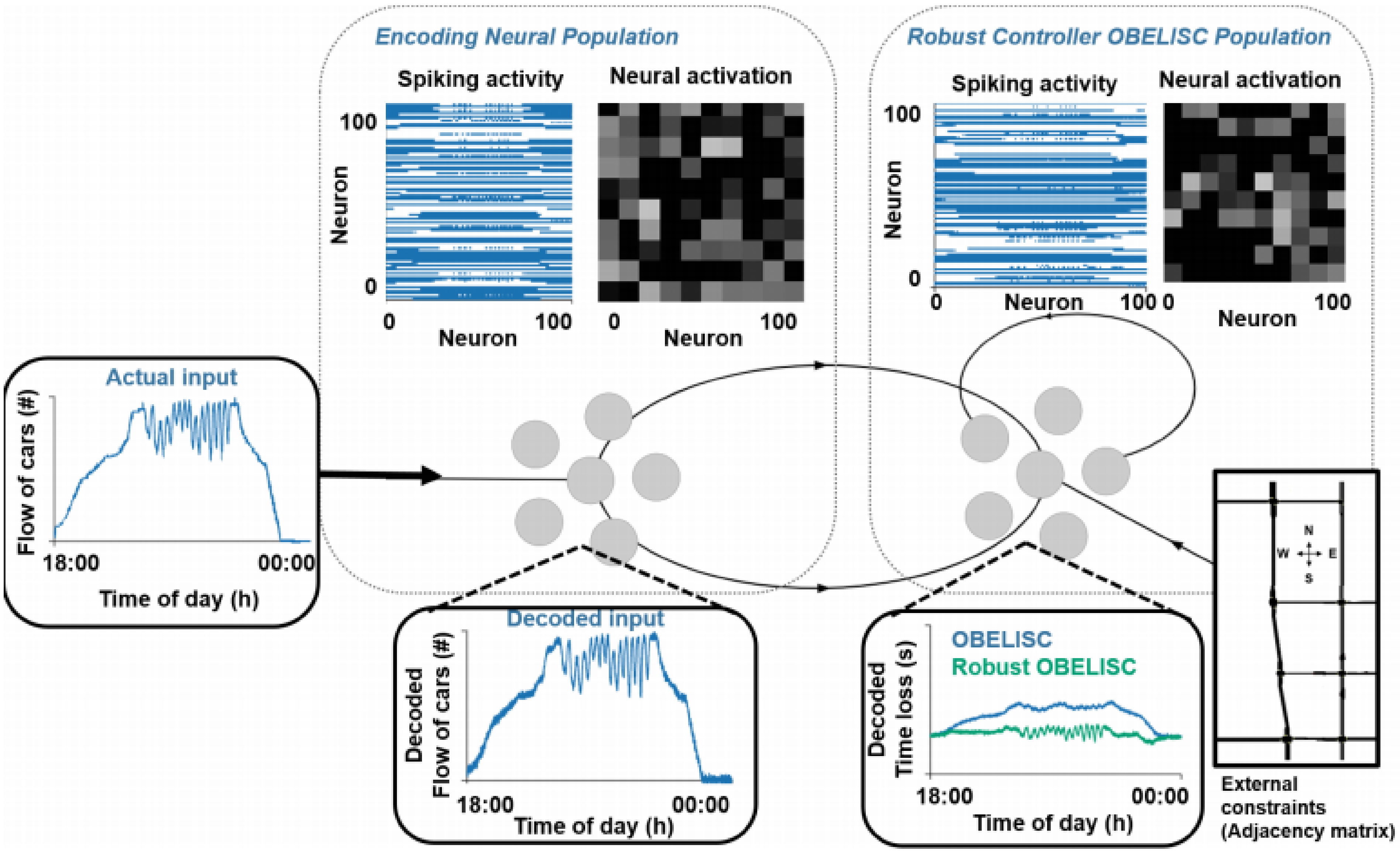


where:

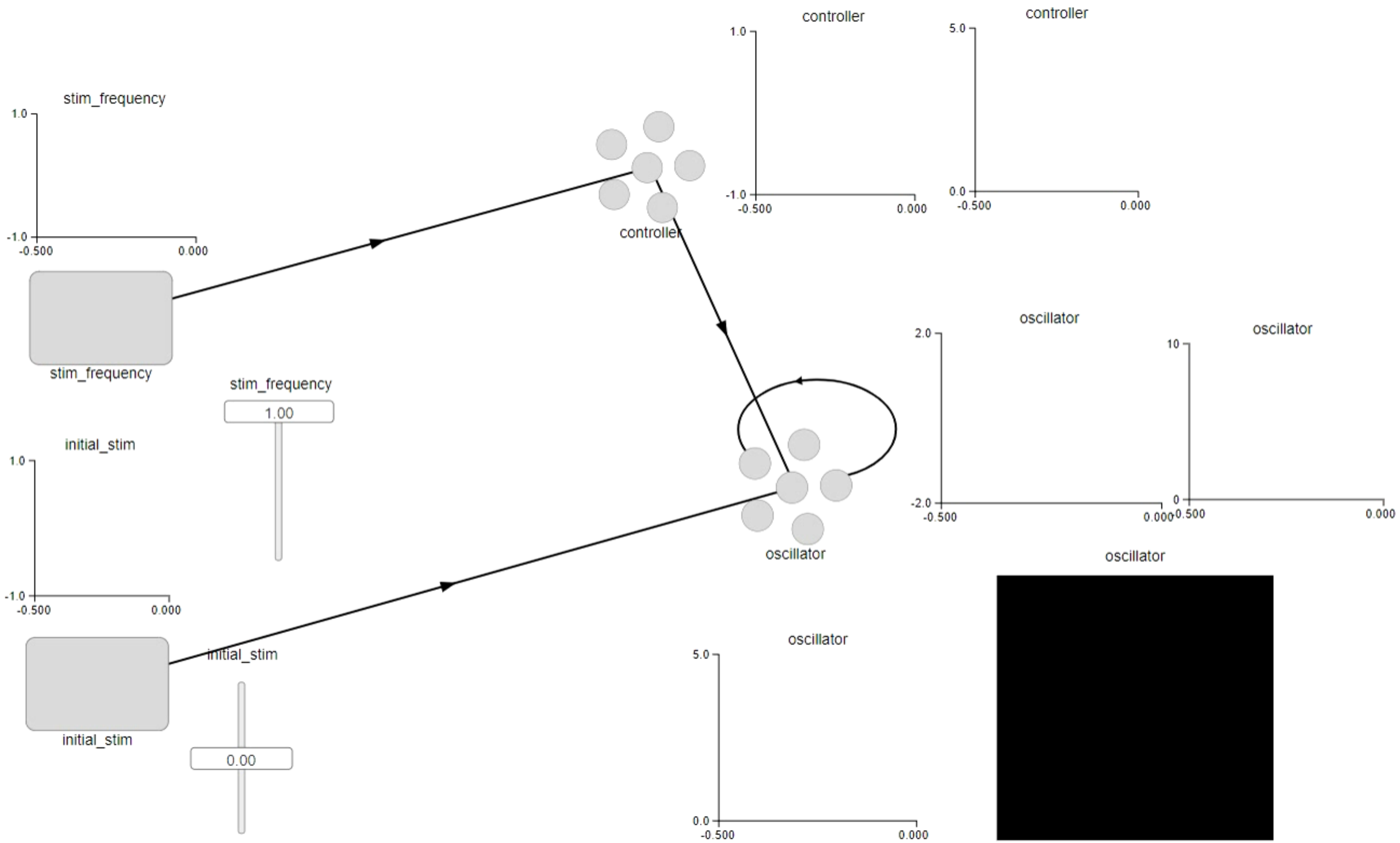
$s_i(t)$ - the surplus energy of traffic light i oscillator

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

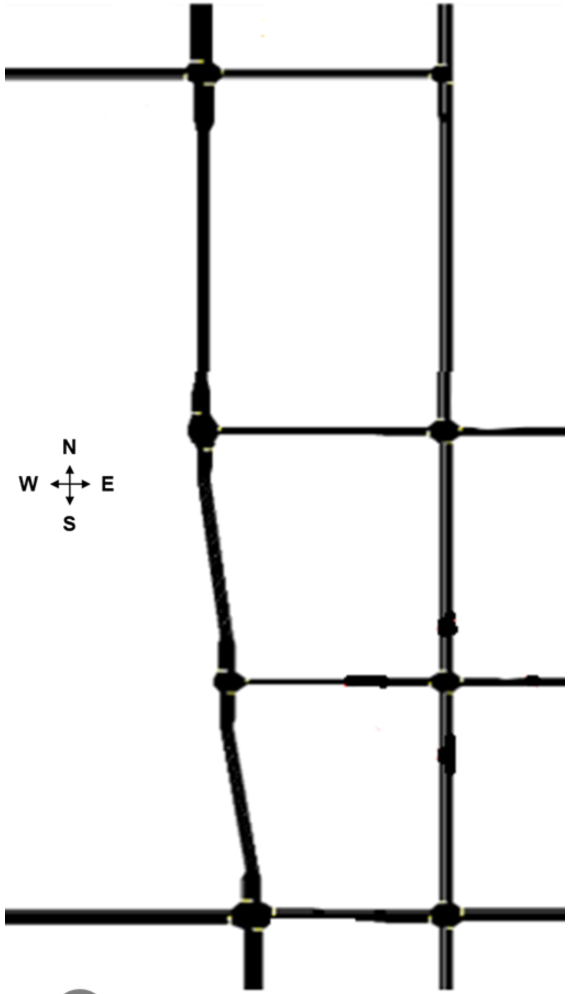
System design: learning



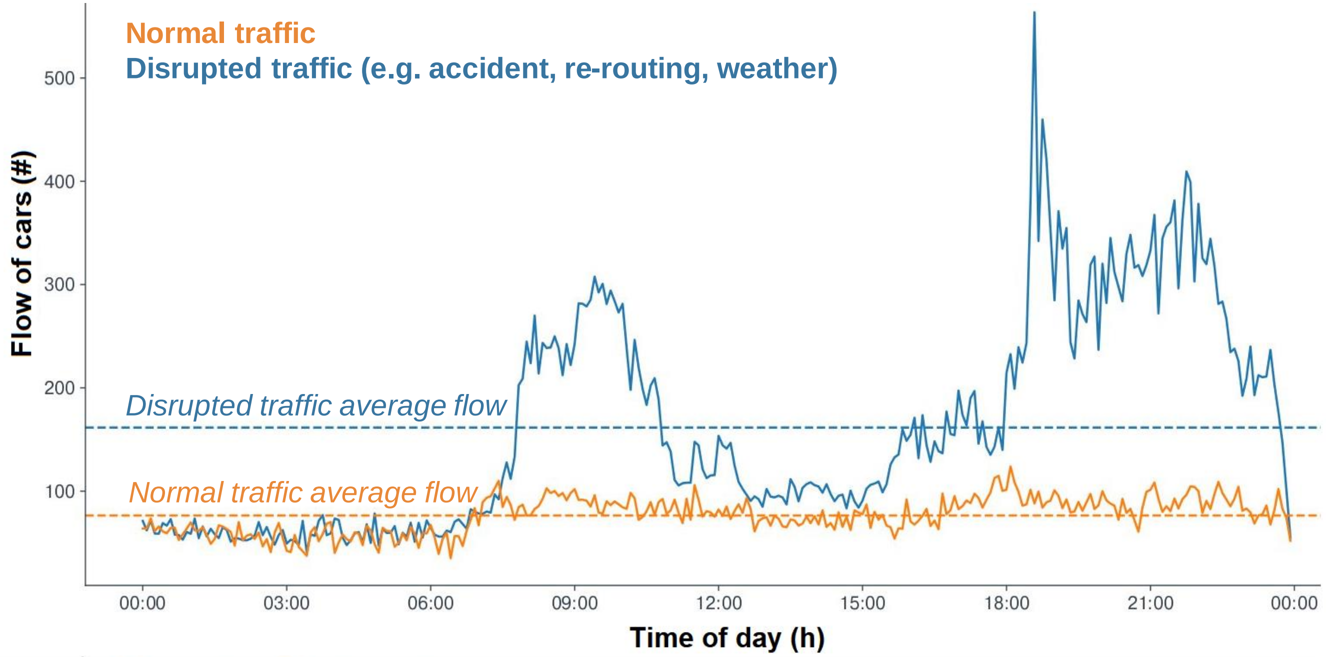
System design: learning

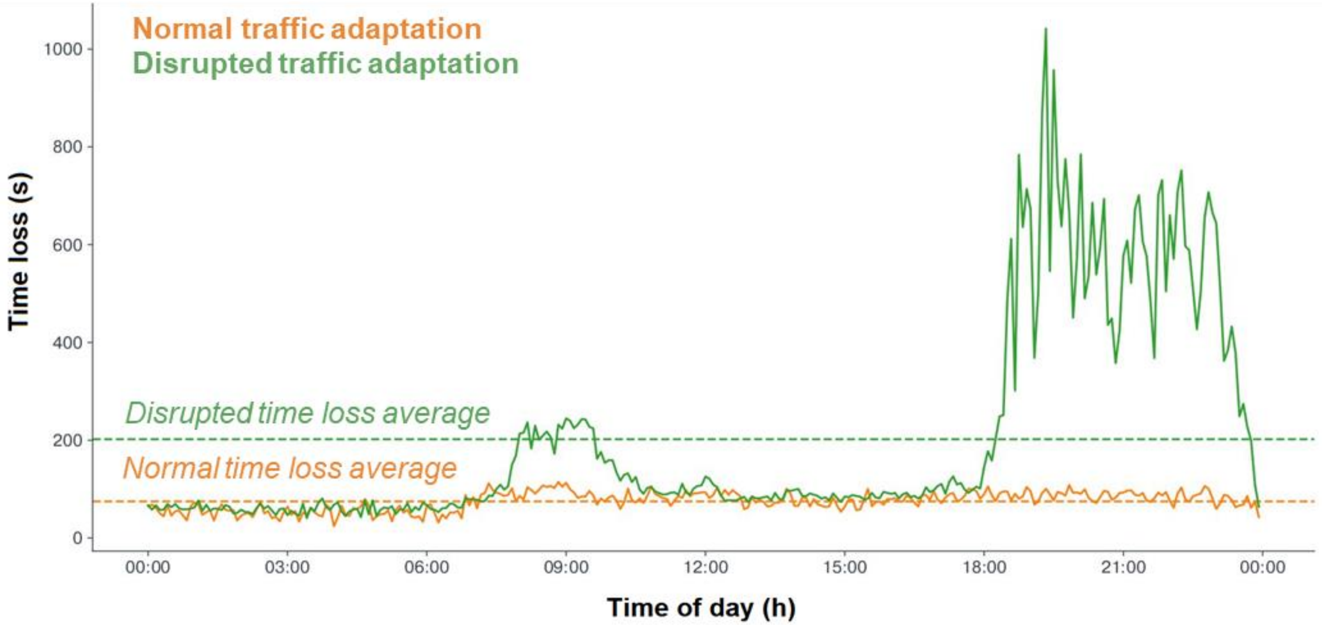


Evaluation



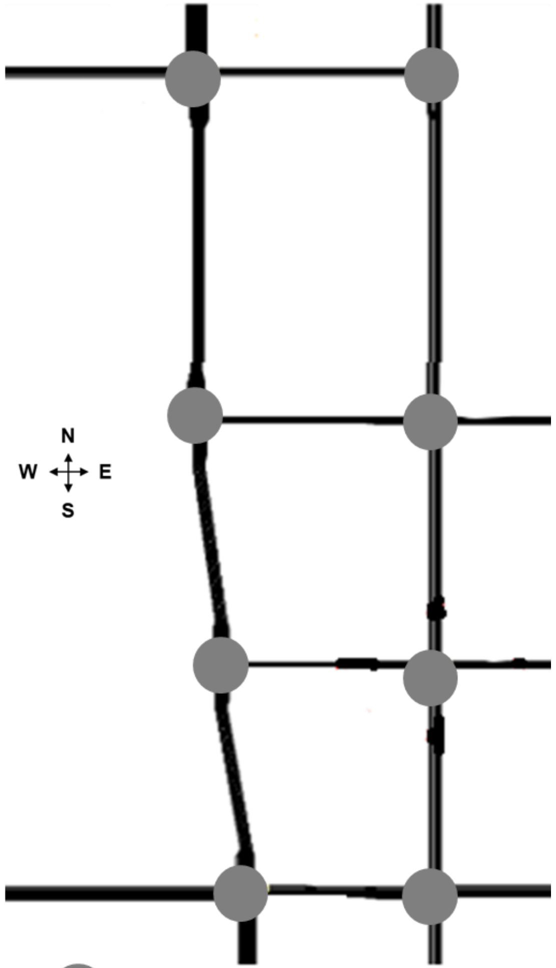
Crosses
1 oscillator per direction
5 crosses with 4 directions
3 crosses with 3 directions





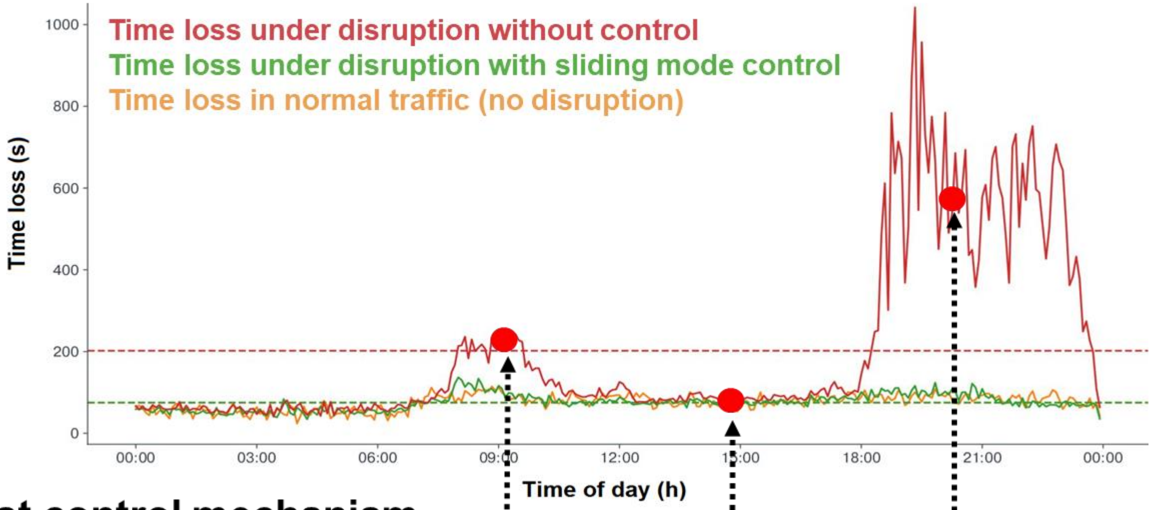
Evaluation

Real road network layout

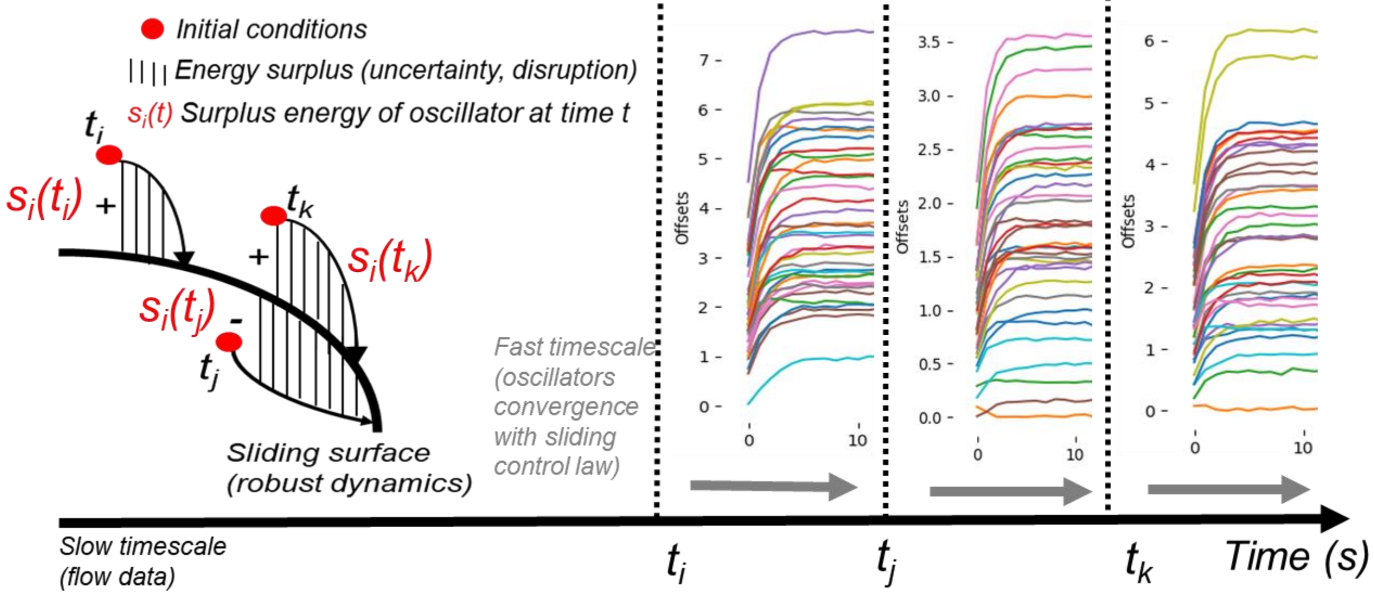


Crosses
1 oscillator per direction
5 crosses with 4 directions
3 crosses with 3 directions

Traffic profile in the road network

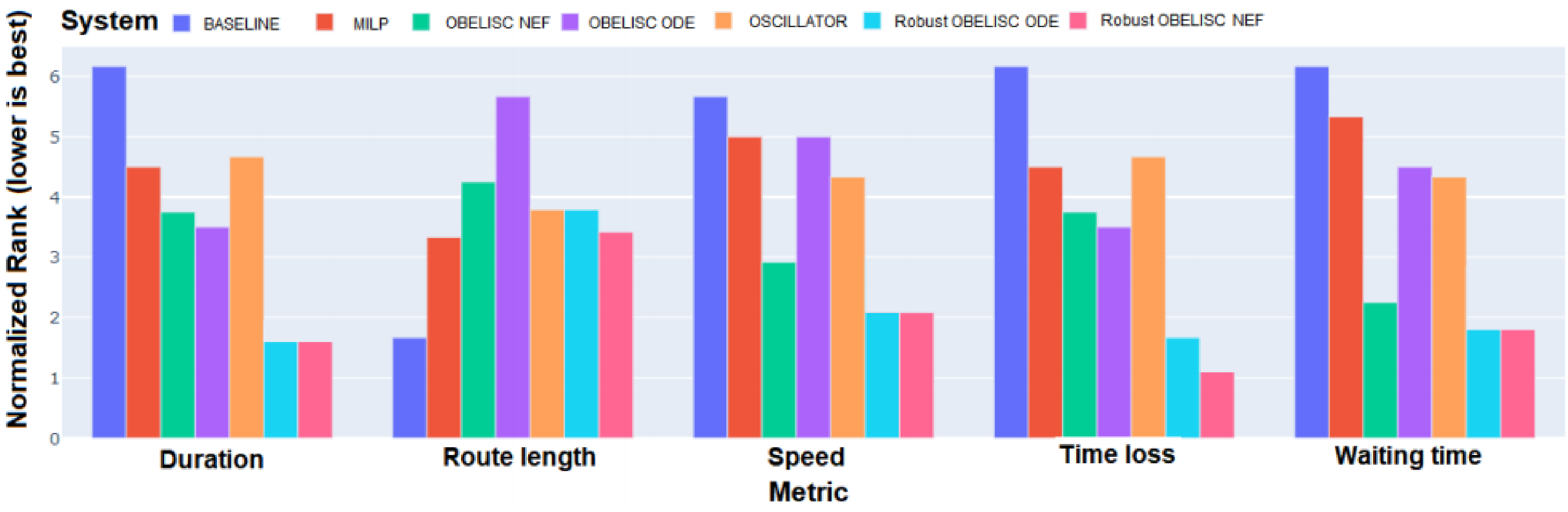


Robust control mechanism



Evaluation

Performance

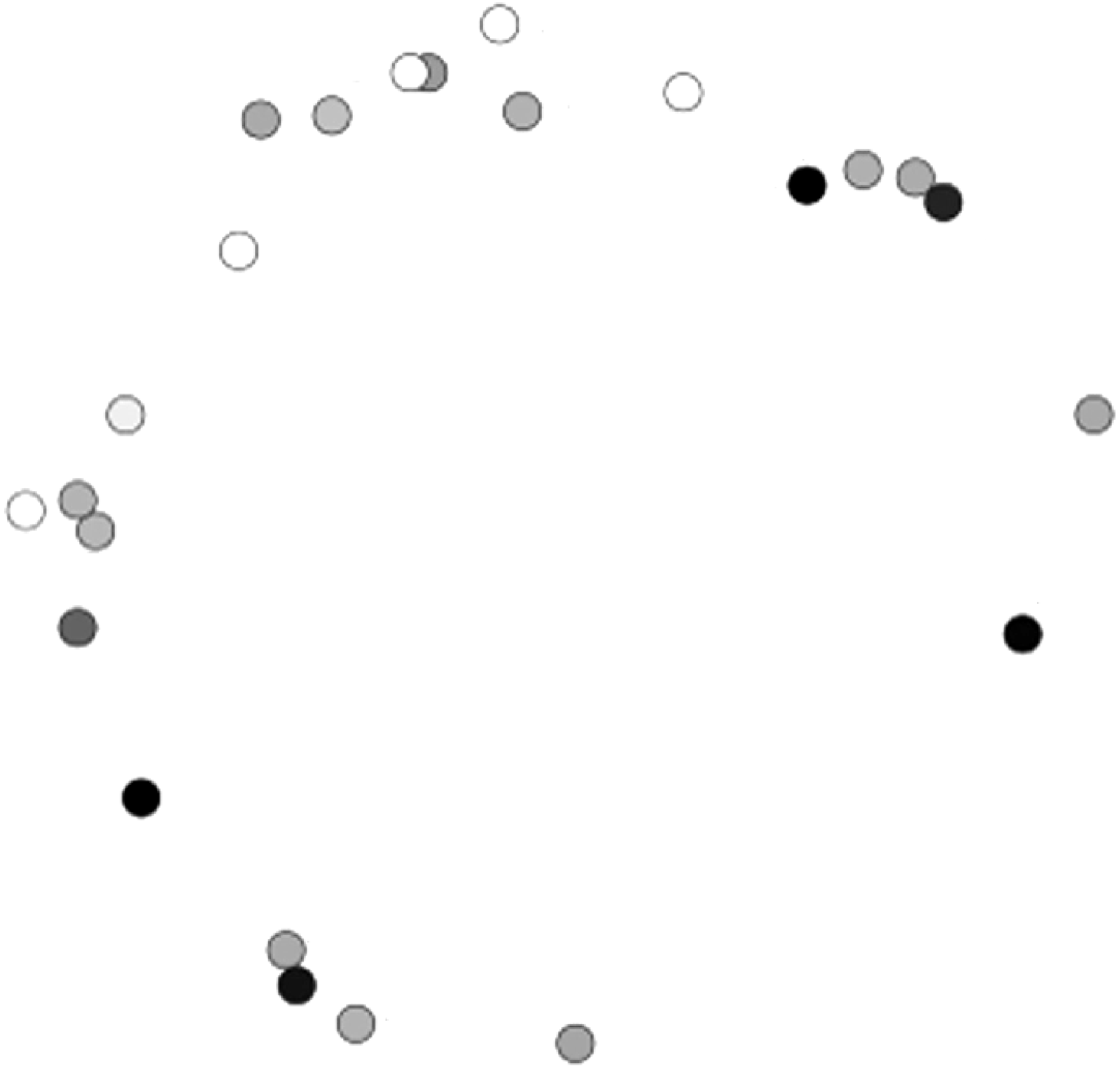


Run-time

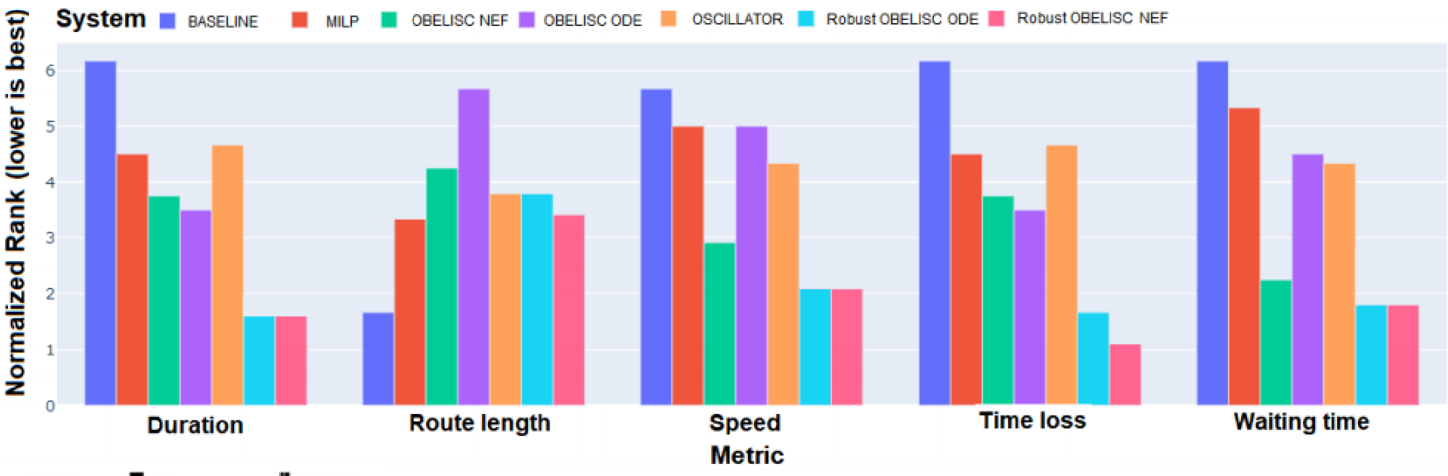
Model	Single cross	Region (8 crosses)
MILP	0.0510	0.3930
OSCILLATOR	0.0568	0.4544
OBELISC ODE	0.0489	0.4534
OBELISC NEF	**0.0071**	**0.0426**

Conclusions

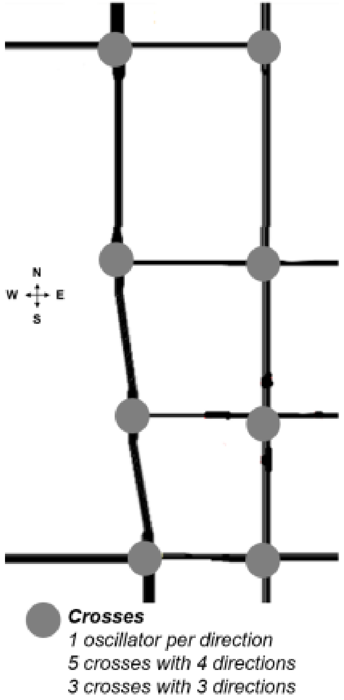
- **modelling** is a fundamental dimension for **control**
- **network of oscillators** capturing the **spatial** and **temporal interactions** among different crosses in a traffic network
- **adaptively** cope with **unexpected** traffic flow **disruptions**
- **sliding mode controller** that extends the adaptation capabilities of the model towards handling **high-magnitude high-frequency disruptions**
- lightweight **learning system** using **spiking neural networks** exploiting the **coupling** interactions among the different **controlled oscillators**
- overcoming state-of-the-art approaches



Full evaluation



System/ Disruption level	normal flow	1.1	1.2	1.3	1.4	1.5
Average trip duration(s)						
BASELINE	1688.057	1812.174	2033.401	3096.471	2655.146	2701.367
MILP	1512.481	1532.351	2033.201	3096.751	2230.817	2574.464
OSCILLATOR	1314.648	1618.713	2123.501	3056.571	1997.297	4971.24
OBELISC (ODE)	1318.425	2701.767	1310.277	1512.481	3096.271	1342.357
OBELISC (NEF)	1553.055	1557.982	1535.124	2002.165	1993.757	2169.219
Robust OBELISC (ODE)	1535.524	1535.924	1556.024	1595.874	2002.565	2200.408
Robust OBELISC (NEF)	1412.581	1513.681	1531.401	1310.618	1366.307	1310.477
Average time loss(s)						
BASELINE	102.535	114.600	136.229	241.383	197.399	202.113
MILP	151.281	153.781	203.301	309.671	223.017	257.464
OSCILLATOR	131.468	161.871	203.301	309.671	199.797	497.124
OBELISC (ODE)	131.825	270.167	131.077	151.281	309.671	134.257
OBELISC (NEF)	135.355	155.782	153.524	200.265	199.357	216.919
Robust OBELISC (ODE)	133.524	143.904	147.524	153.524	200.265	220.008
Robust OBELISC (NEF)	85.726	88.326	89.726	84.165	89.889	84.291
Average speed(km/h)						
BASELINE	58.15	56.78	54.68	50.26	49.38	47.50
MILP	59.78	58.78	54.68	50.26	49.28	46.18
OSCILLATOR	59.48	58.13	54.68	50.26	52.97	45.54
OBELISC (ODE)	59.78	47.50	51.49	52.21	50.26	51.12
OBELISC (NEF)	58.99	59.09	59.80	52.91	53.16	51.05
Robust OBELISC (ODE)	59.80	59.10	58.80	59.70	52.91	50.49
Robust OBELISC (NEF)	59.78	59.78	59.41	51.79	50.70	51.49
Average route length (km)[a]*						
BASELINE	7.5	8.2	9.0	9.1	10.5	11.2
MILP	7.4	7.5	9.0	9.1	10.3	11.1
OSCILLATOR	6.7	8.2	9.0	9.2	10.4	9.2
OBELISC (ODE)	5.6	11.2	5.8	7.5	9.1	5.5
OBELISC (NEF)	6.4	7.4	7.5	10.3	10.4	11.1
Robust OBELISC (ODE)	7.5	7.7	7.6	7.8	10.3	11.1
Robust OBELISC (NEF)	7.4	7.4	7.5	5.7	5.6	5.6
*Waiting time(s)**						
BASELINE	164.5	185.3	222.8	294.5	325.9	351.3
MILP	148.7	148.7	212.8	234.5	293.2	372.9
OSCILLATOR	115.7	142.2	215.8	286.5	208.5	418.3
OBELISC (ODE)	160.3	351.3	158.7	148.7	294.5	161.2
OBELISC (NEF)	137.1	137.6	139.4	216.0	204.2	236.3
Robust OBELISC (ODE)	139.4	141.4	149.4	169.8	216.8	252.5
Robust OBELISC (NEF)	128.7	145.7	148.8	159.2	162.4	158.7



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