Fundamentals of Traffic Operations and Control

Freeway control – On-ramp metering

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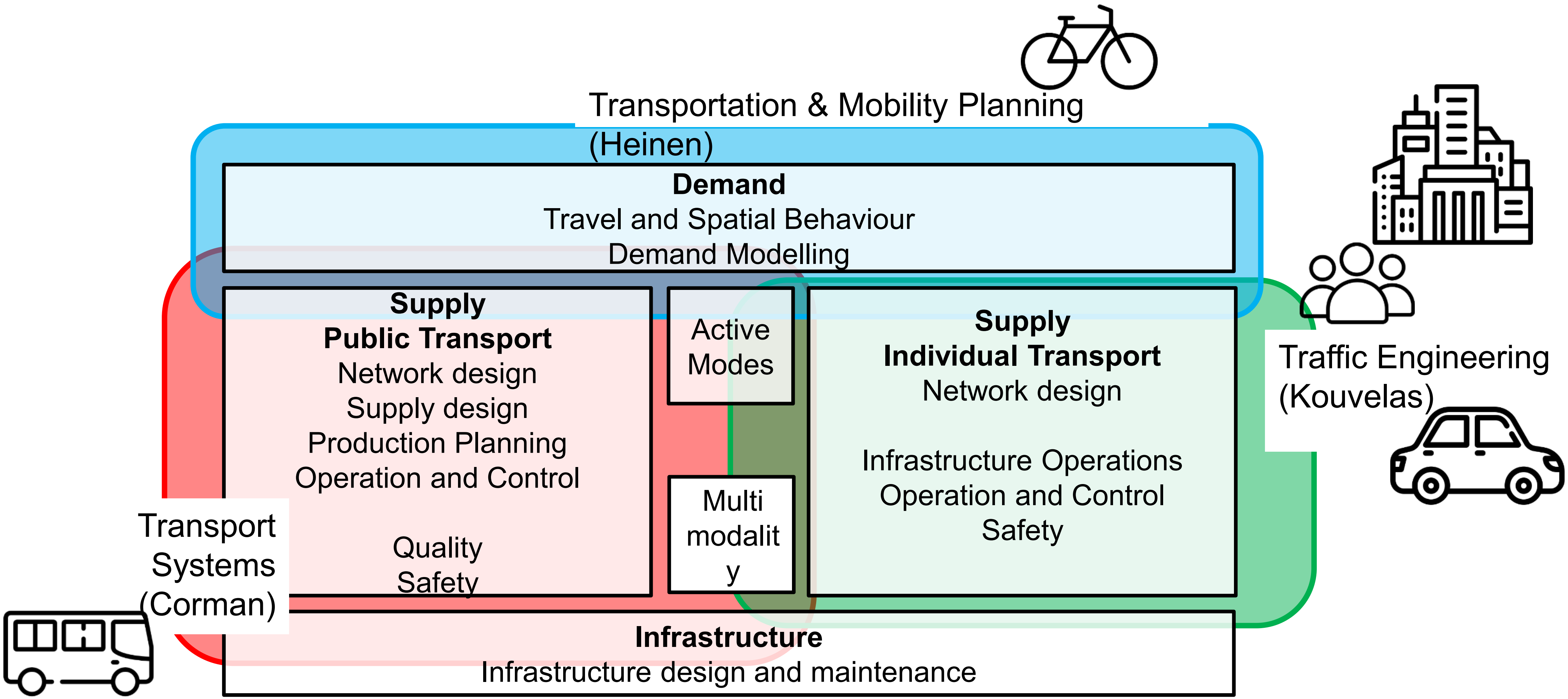
Institute for Transport Planning and Systems (IVT)



SVT activities

Topics

- Traffic flow theory
- Cycling dynamics
- Intelligent Transportation Systems
- Traffic management
- Autonomous vehicles
- Driver behavior

Directions

- Reproducibility
- Disruption management
- Fairness and Equity
- Resource allocation
- Active mobility

Tools

Artificial Intelligence Modeling
Simulation Optimization Control
Experiments Game theory

Today's contents

- Ramp metering (RM)
  - Concept and terminology
  - Why it works
  - When RM does not help
  - Implementation (traffic lights)
- Local RM / Coordinated RM
- Ramp metering case studies
- Bicycle dynamics (BikeZ)

Highway on-ramp metering

Motorway networks

motorway / highway / freeway

- **Originally:**

  sufficient capacity for virtually unlimited mobility (without need for control)

- **Ever increasing demand**
  - Congestion
  - Degraded infrastructure use

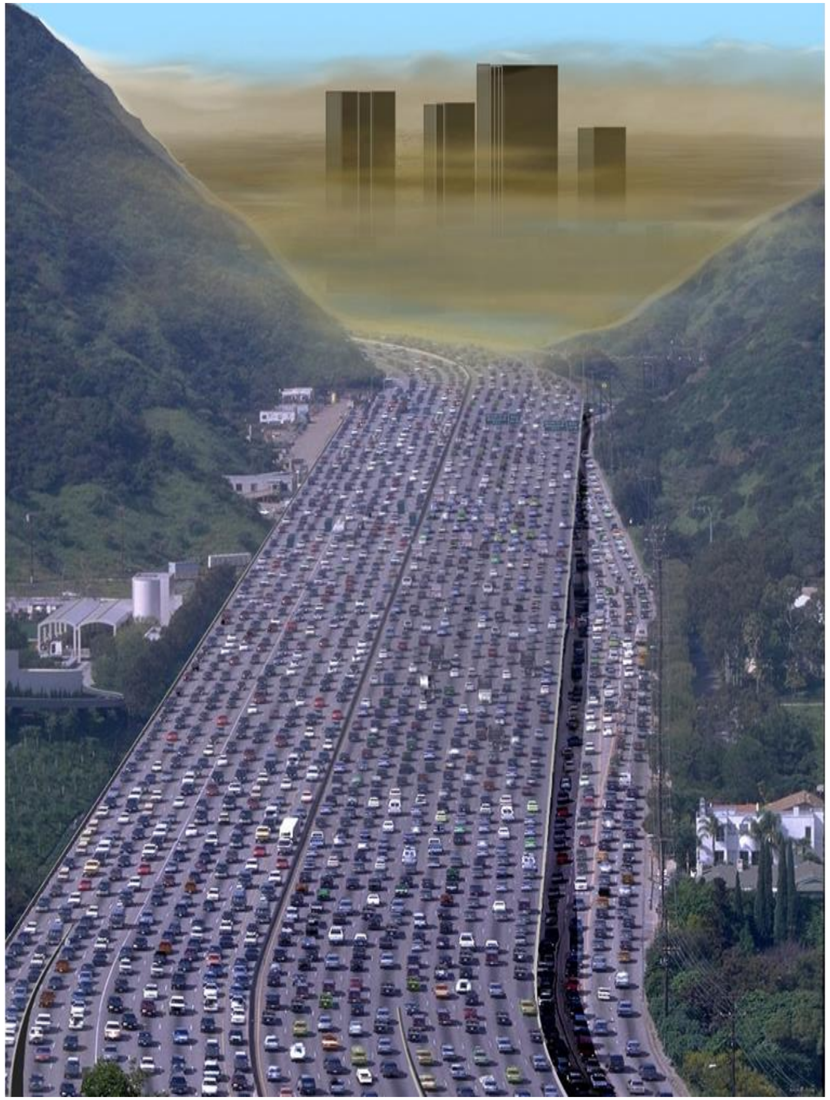
    (at the time it is most urgently needed)

- **Congestion: recurrent and non-recurrent**
- **Control goal: Operate freeway networks optimally**

  (as a controllable system)

If we build it…

They will come…



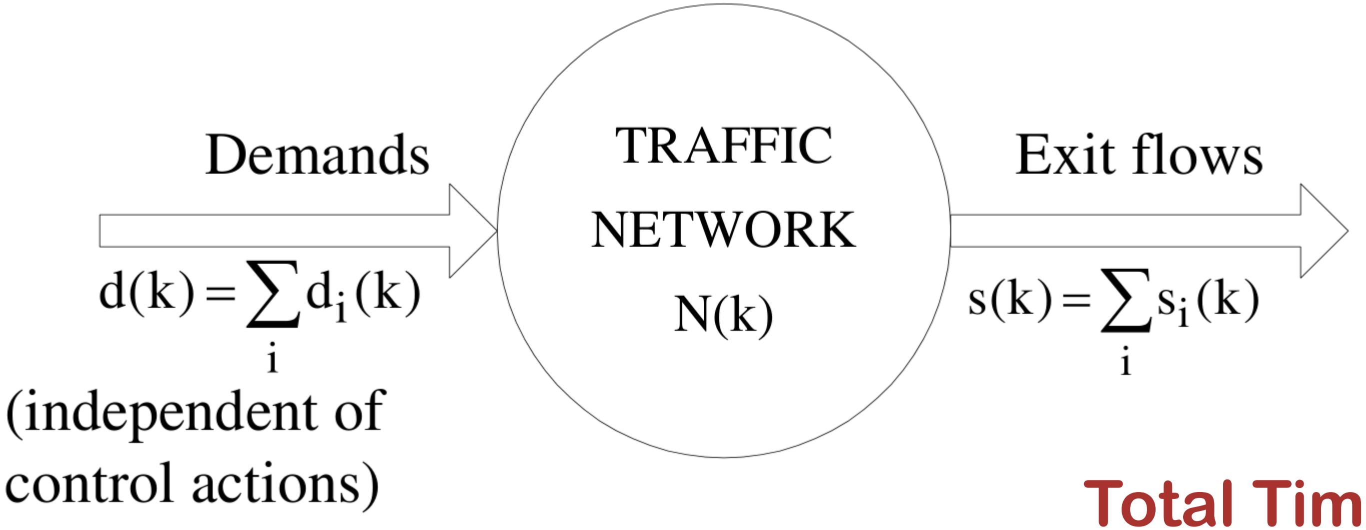
Motorway congestion today

- **Today: Underutilization of freeway networks due to recurrent and non-recurrent congestion:**
  - downstream of congestion
  - off-ramp blocking (e.g. beltways!)
  - underutilized parallel arterials

- **Congestion cause:**
  - demand exceeds capacity at some specific location and time period
  - eventually congestion becomes largely self-contained due to degradation of infrastructure!

Demand-Supply system (control objective)

Ramp Metering: direct impact on density → congestion



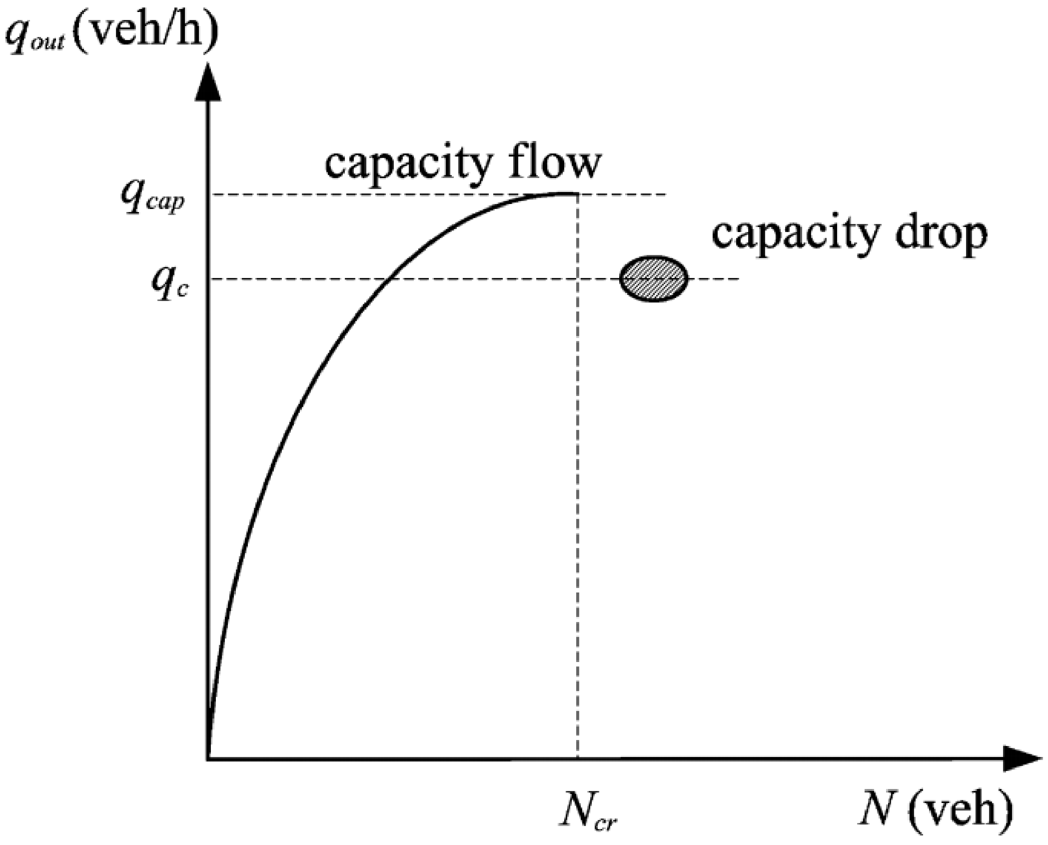
Total Time Spent (veh·h): $T_S = T \sum_{k=0}^{K} N(k)$

$$T_S \rightarrow \text{Min} \longleftrightarrow \sum_{k=0}^{K} (K-k)s(k) \rightarrow \text{Max}$$

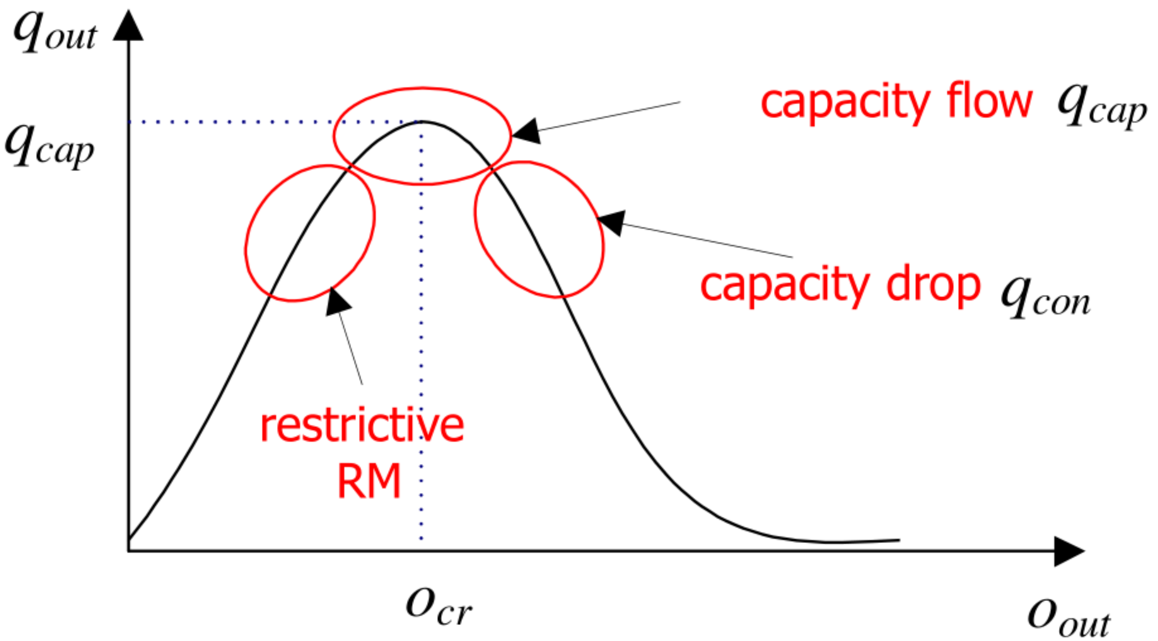
Capacity drop

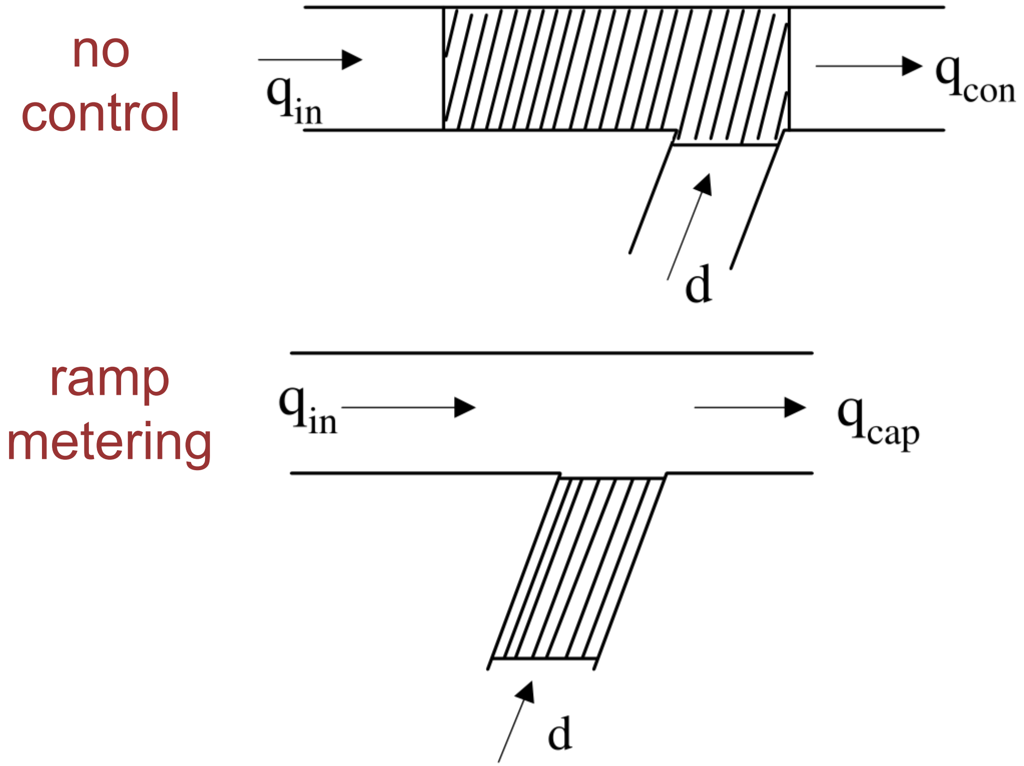
- Motorway on-ramps
- Merging traffic infrastructures (M → μ lanes)
- If arriving flow on M lanes > Capacity of μ lanes ⇒ Congestion ⇒ Capacity drop
- Merging traffic control to restore capacity flow

FD of a merging area



Why ramp metering works? (1/3)





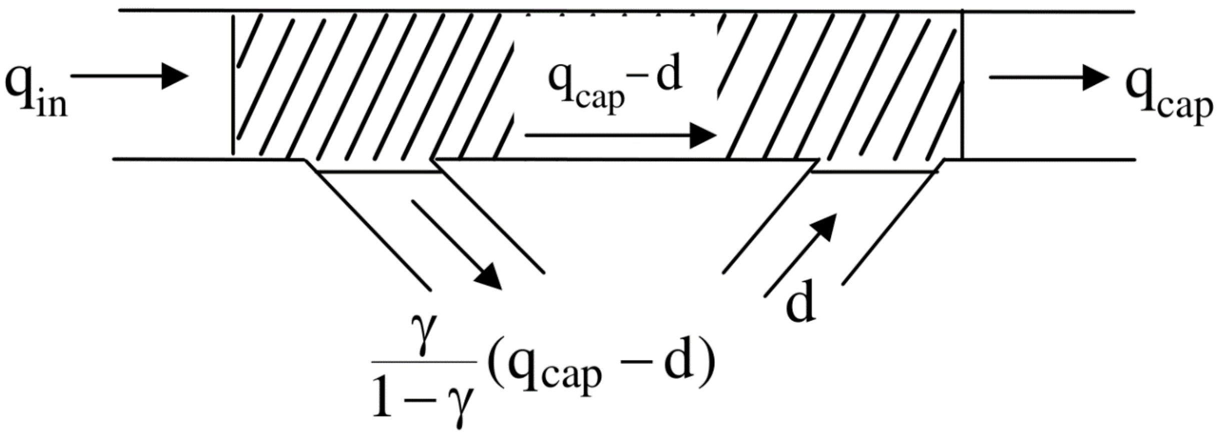
steady-state performance improvement:

$$\Delta \overline{T}_s = \lim_{T\to\infty} \Delta T_s = \frac{T_s^{nc} - T_s^{rm}}{T_s^{nc}} = \frac{q_{cap} - q_{con}}{q_{in} + d - q_{con}}$$

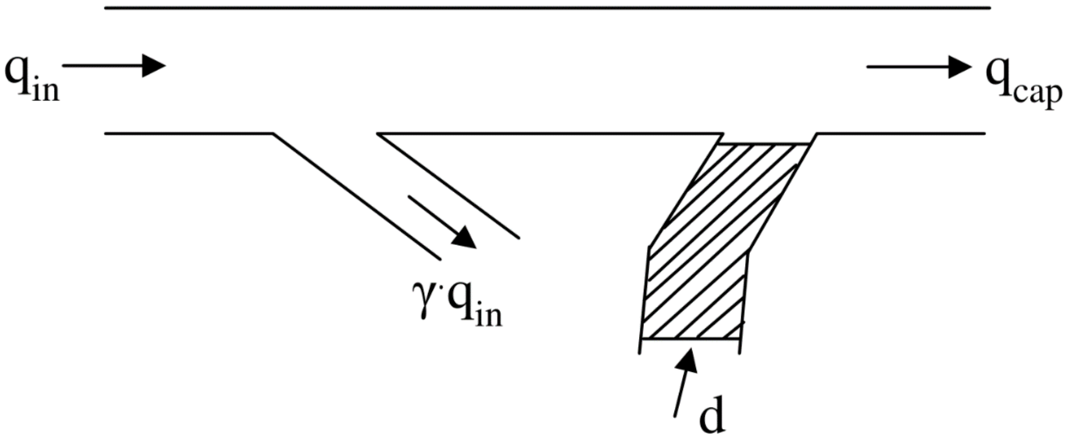
e.g. $q_{con} = 0.95\, q_{cap}$; $q_{in} + d = 1.2\, q_{cap}$

$\rightarrow \Delta T_s \mathrel{\hat{=}} 20\%$

Why ramp metering works? (2/3)



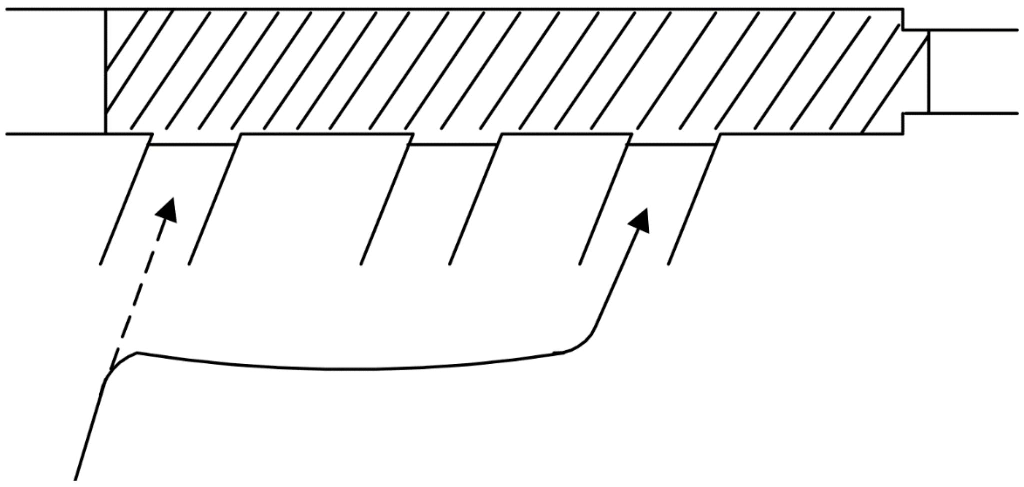
$$\Delta\overline{T}_s = \lim_{T\to\infty} \Delta T_s = \frac{T_s^{nc} - T_s^{rm}}{T_s^{nc}} = \gamma$$



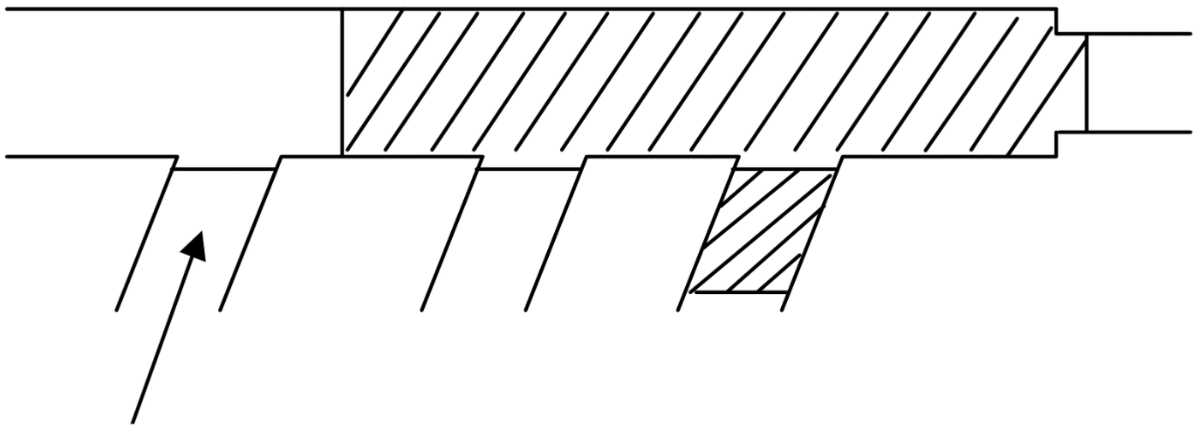
Note:

On-ramp queue should not interfere with surface street traffic.

Why ramp metering works? (3/3)



- Control of route choice phenomena!

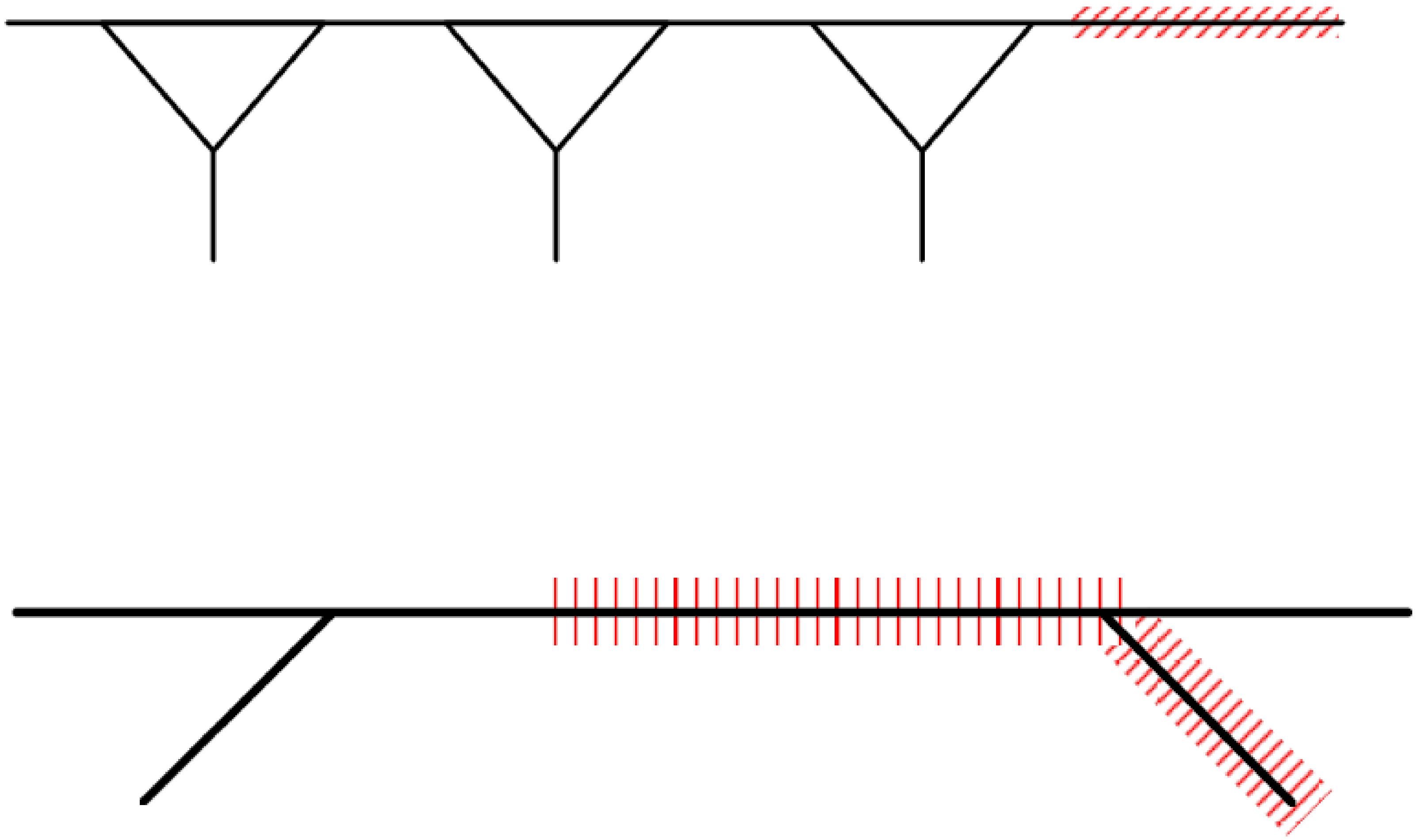


- Utilization of reserve capacity on parallel arterials.

Further Effects of Ramp Metering

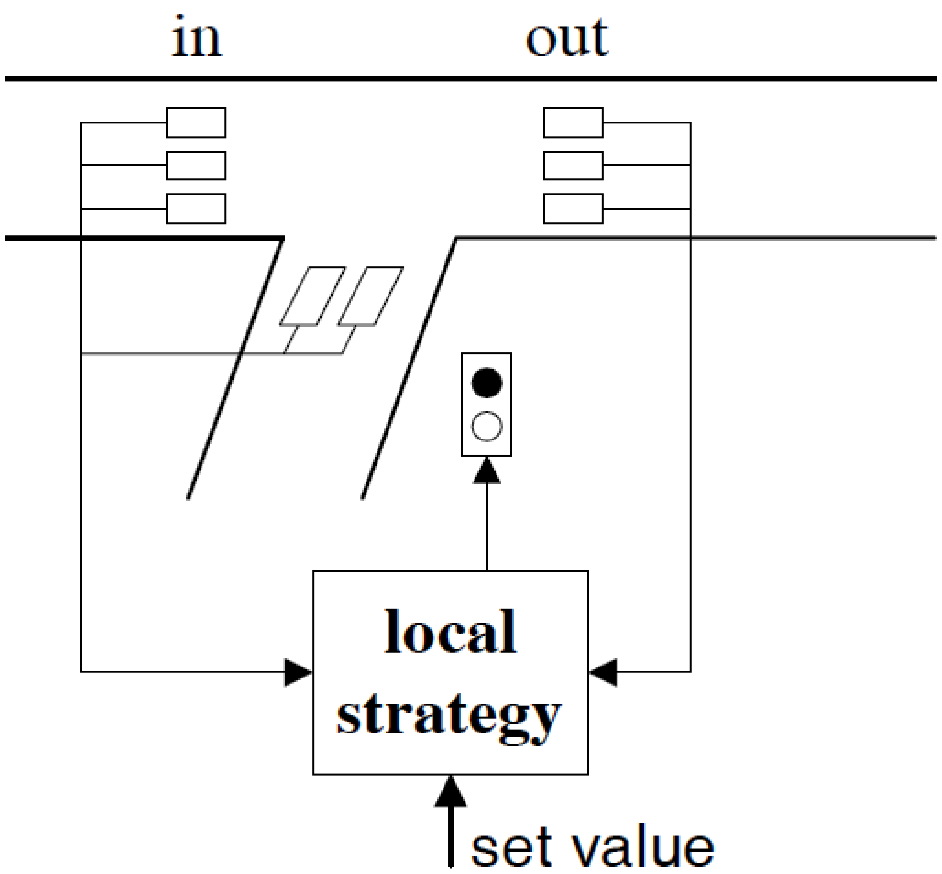
- Incident response
- Increased traffic safety: less congestion, safer merging

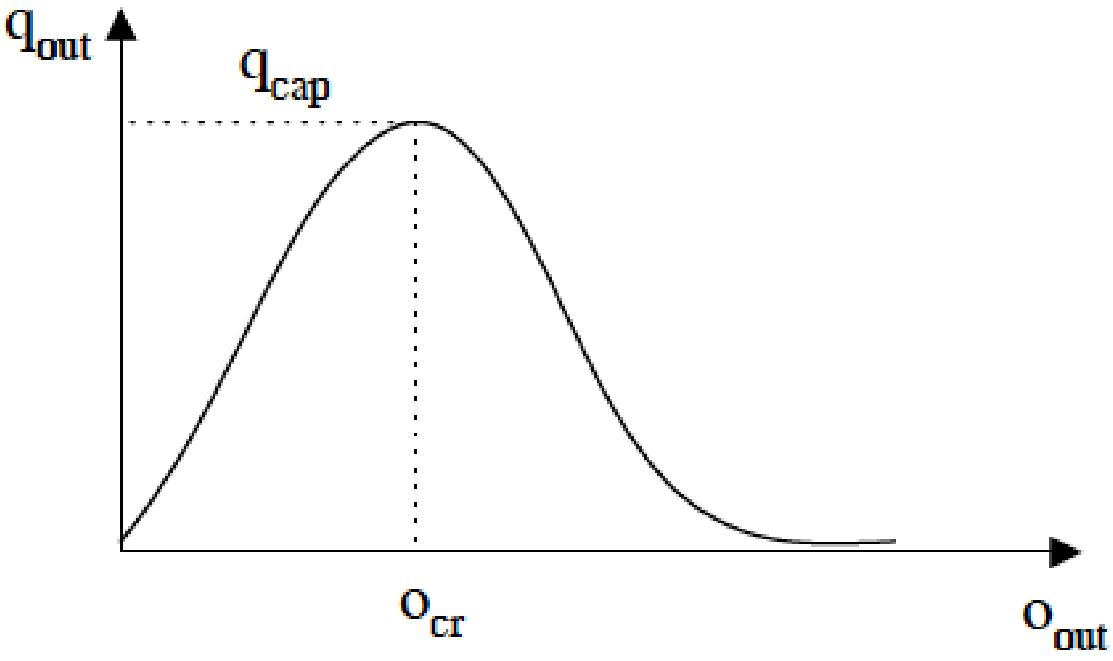
When ramp metering is virtually useless?



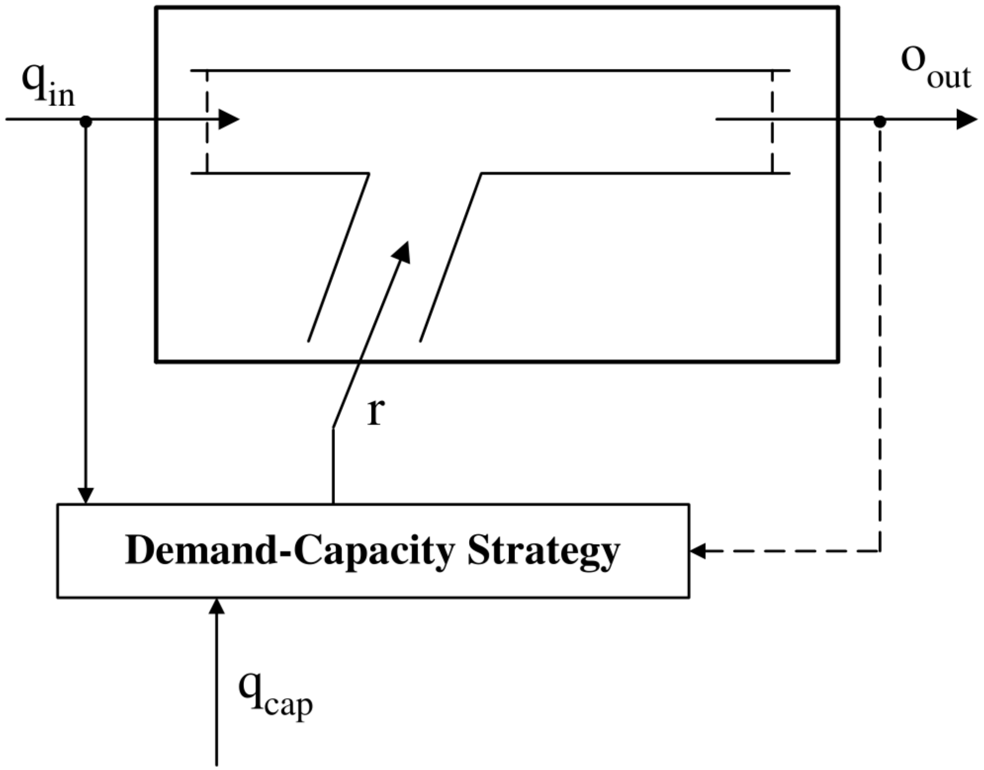
Exit flow problems!

Local ramp metering

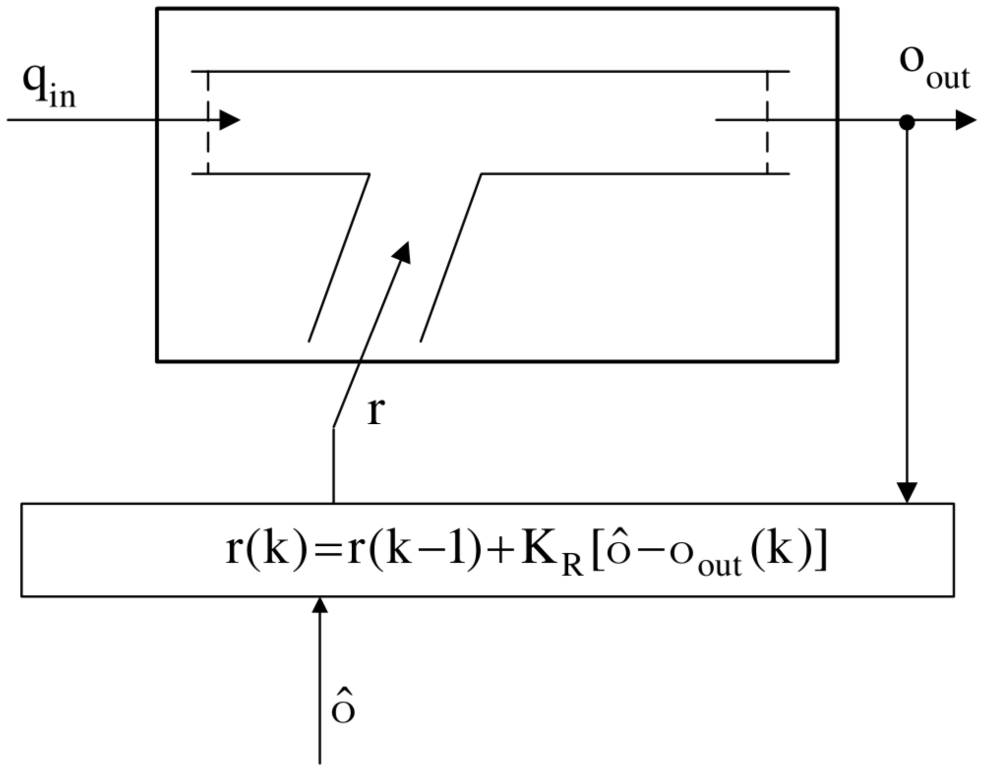




Demand-Capacity / ALINEA



FEEDFORWARD
(open loop)



ALINEA
(I-type regulator)

Implementation issues

- **Implementation: traffic lights**
  - one car at a time (control via red phase duration)
  - traffic cycles
- **Intermediate possibilities:**
  - n cars at a time (n = 2, 3,…)
  - very short traffic cycles (c = 20 sec)
  - variable traffic cycles (short when possible, long when necessary)
- **Ramp capacity: Important for efficiency**

  (skip the red phase!)

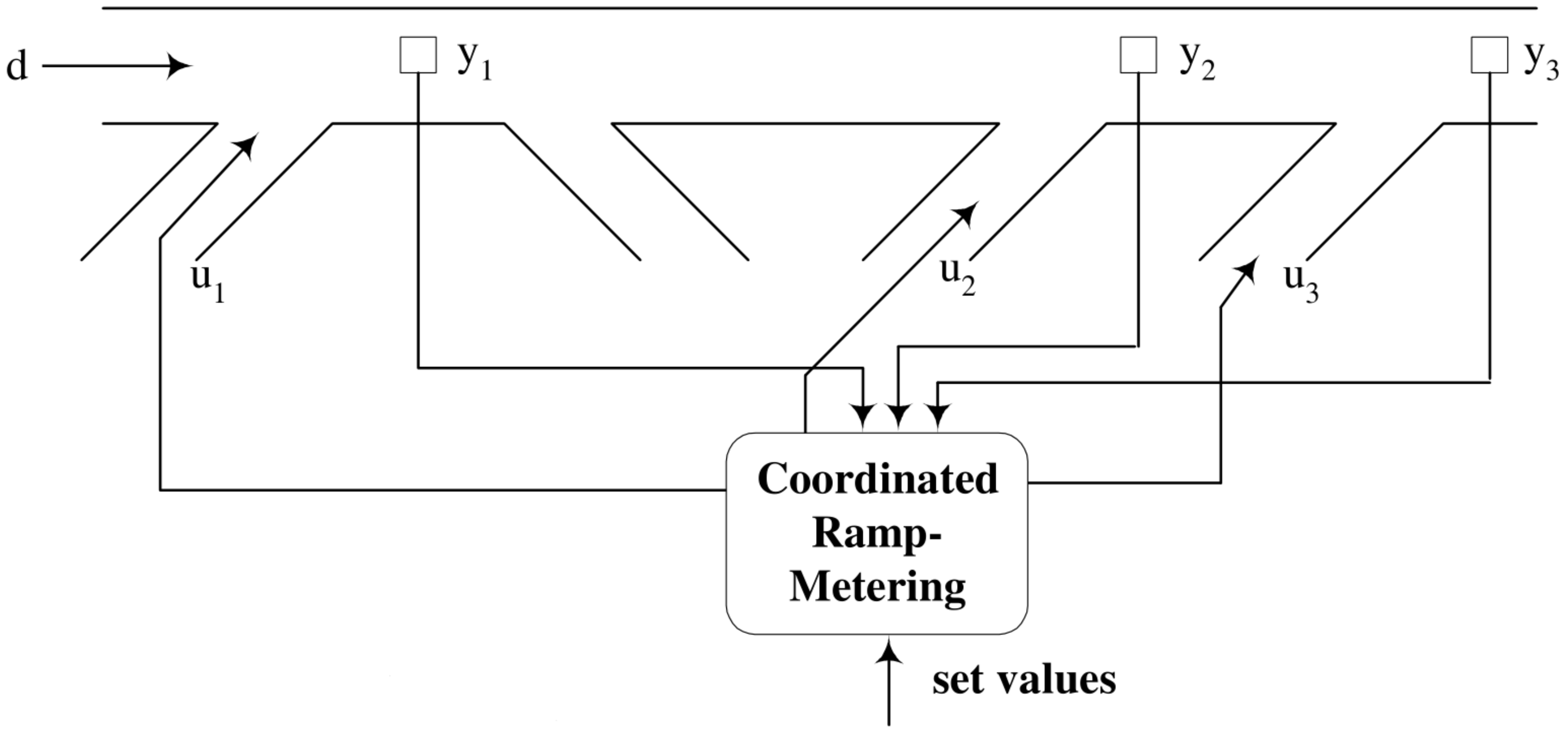
Implementations around the world

- **Applications:**
  - mainly North America (some 3000 metered ramps)
  - more recently: Europe, Israel, New Zealand, Japan, Australia

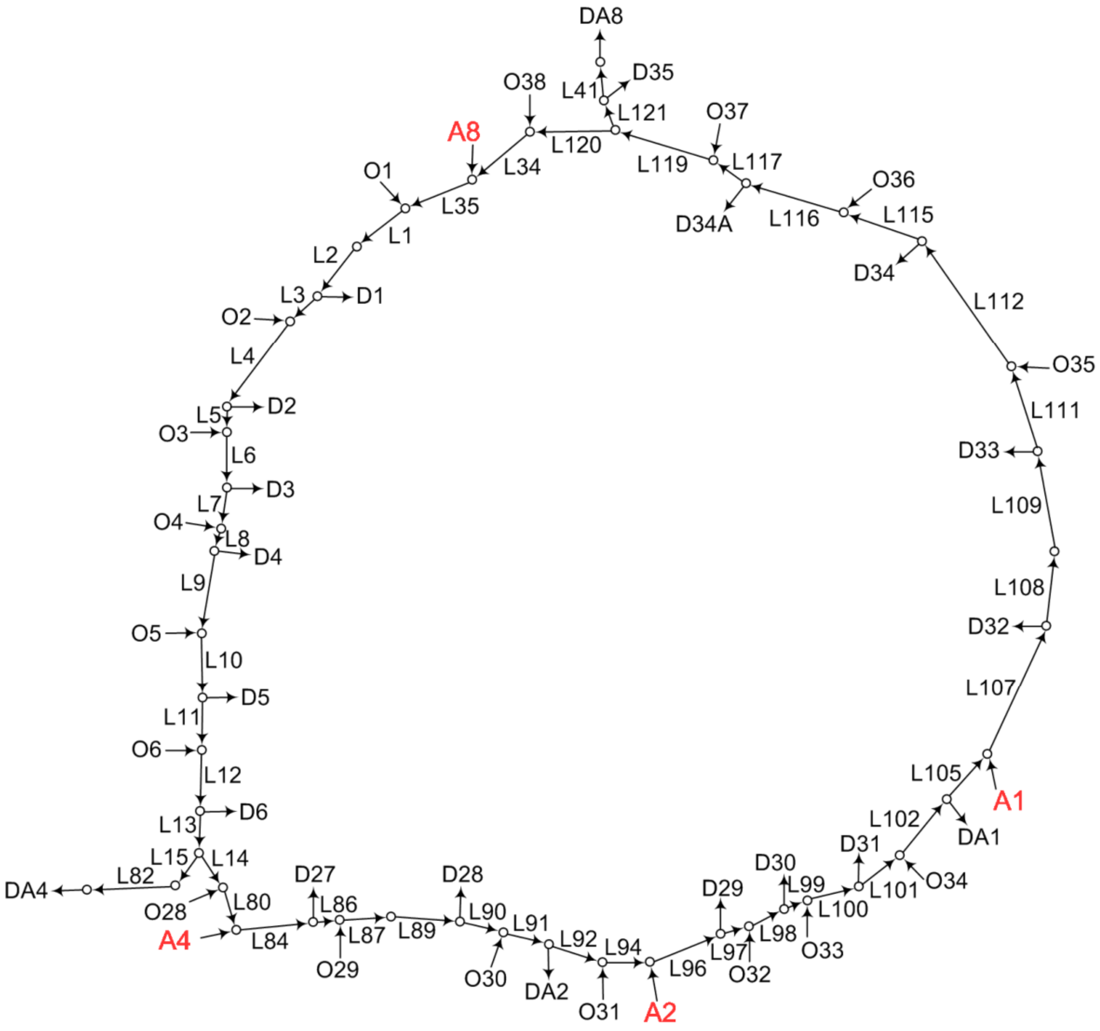
- **Controllability Limitations:**
  - amount of controlled ramps
  - minimum ramp volumes
  - ramp length (interference with surface street traffic)

Coordinated ramp metering

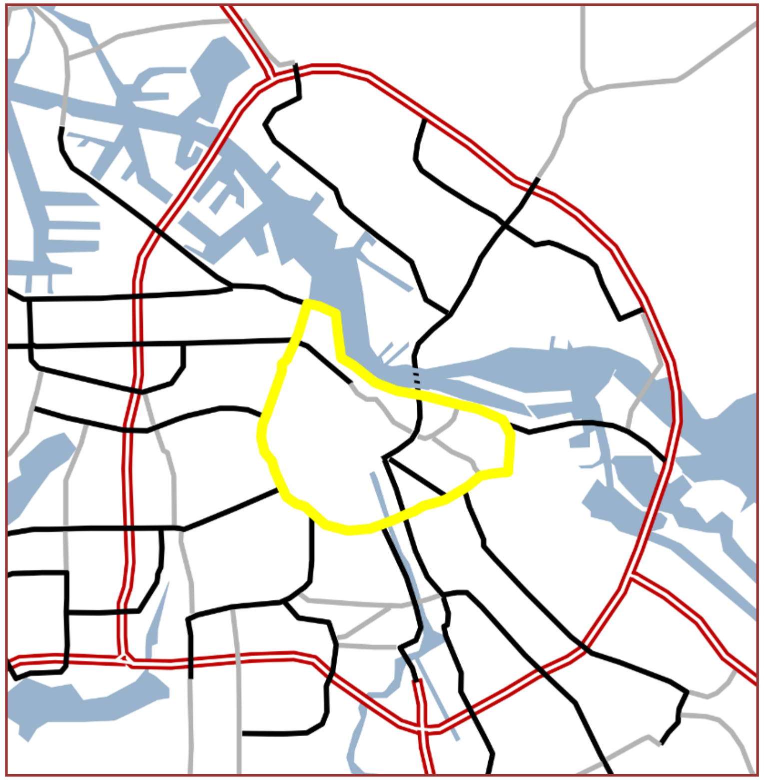
- Limited ramp storage capacity:
  - significant improvement of both efficiency and equity via appropriate coordination



Case study: Amsterdam Ring Road

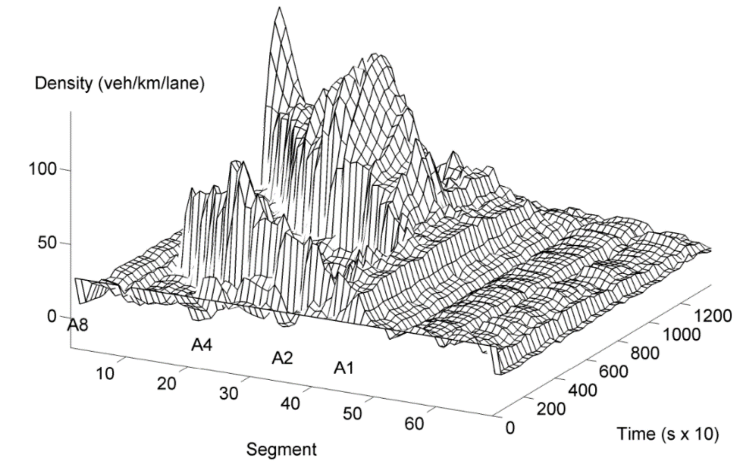


Nonlinear Optimal Control



Kotsialos, A. and Papageorgiou, M., 2004. Efficiency and equity properties of freeway network-wide ramp metering with AMOC. Transportation Research Part C, 12(6), pp.401-420.

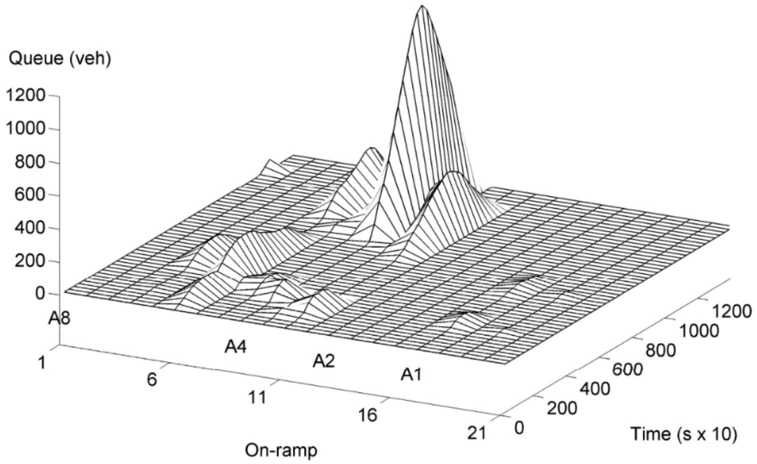
Simulation results: densities, queues



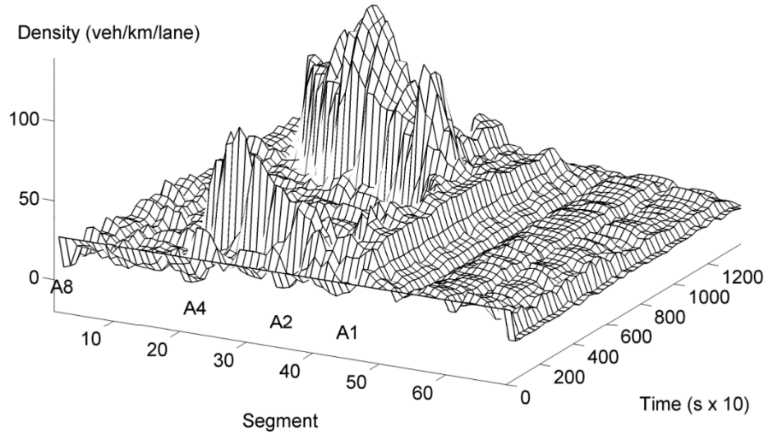
(Density profile)

No RM

T_S=14’163 veh·h



(Ramp queue profile)

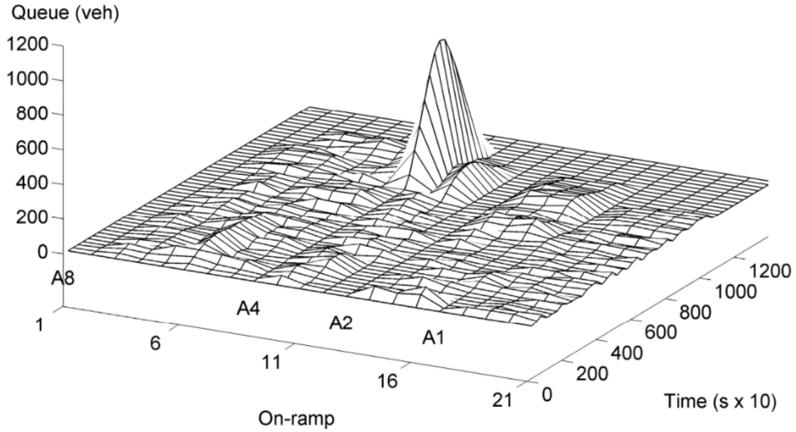


(Density profile)

Optimal RM

T_S=11’023 veh·h

(–22%)

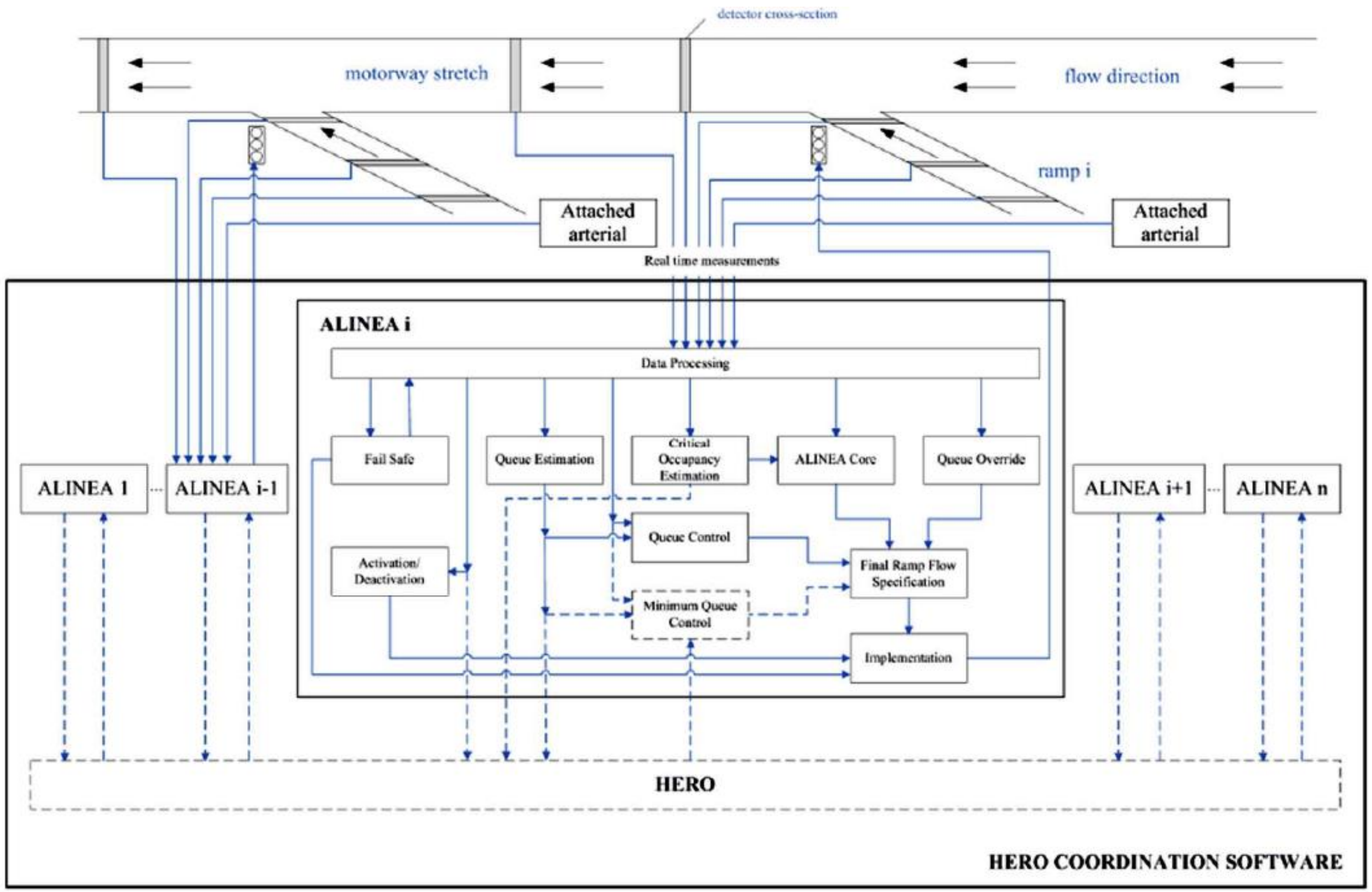


(Ramp queue profile)

HERO (heuristic ramp coordination)

HEuristic **R**amp metering co**O**rdination:

- Rule-based central control
- Suitable modification of the subordinate ALINEA controller
- Real-time input: only current ramp storages $l_{i}(k)$
- Efficiency: close to nonlinear MPC
- MPC has computational restrictions

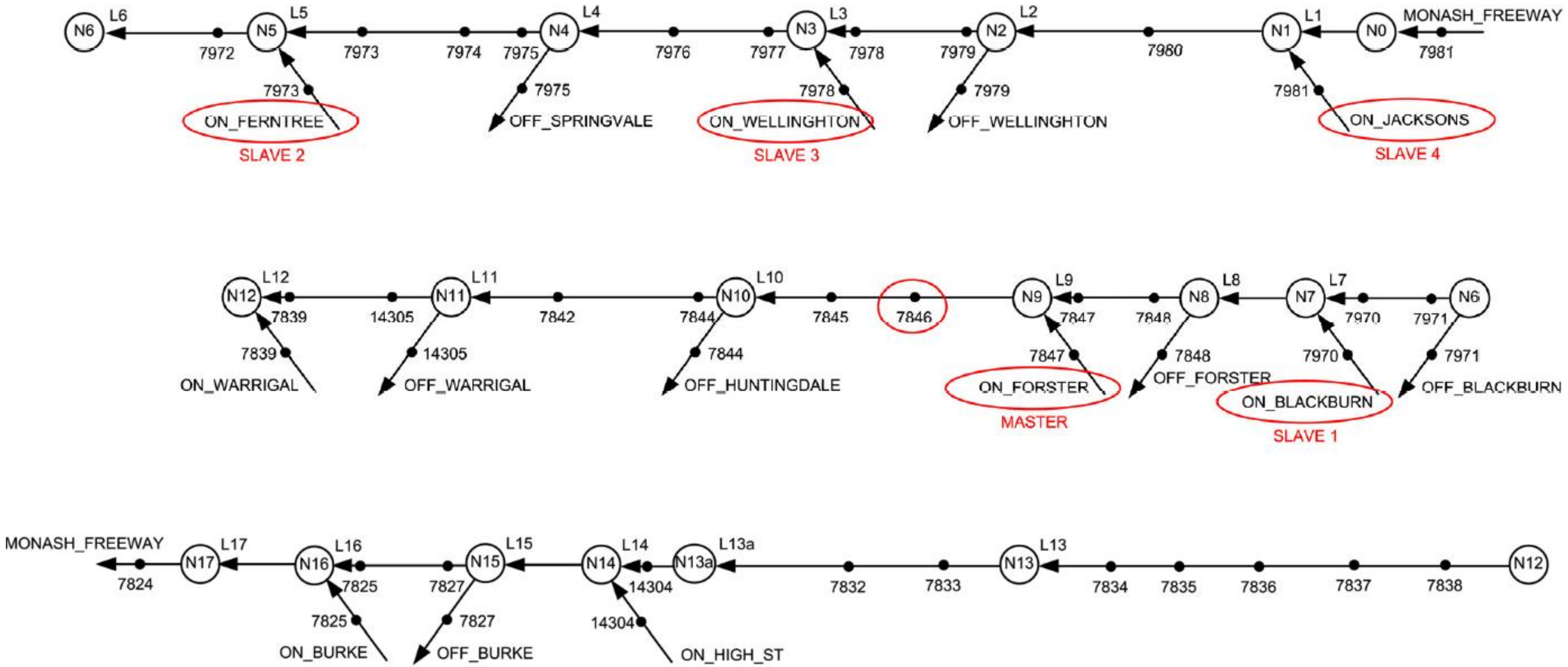


HERO: rule-based coordination

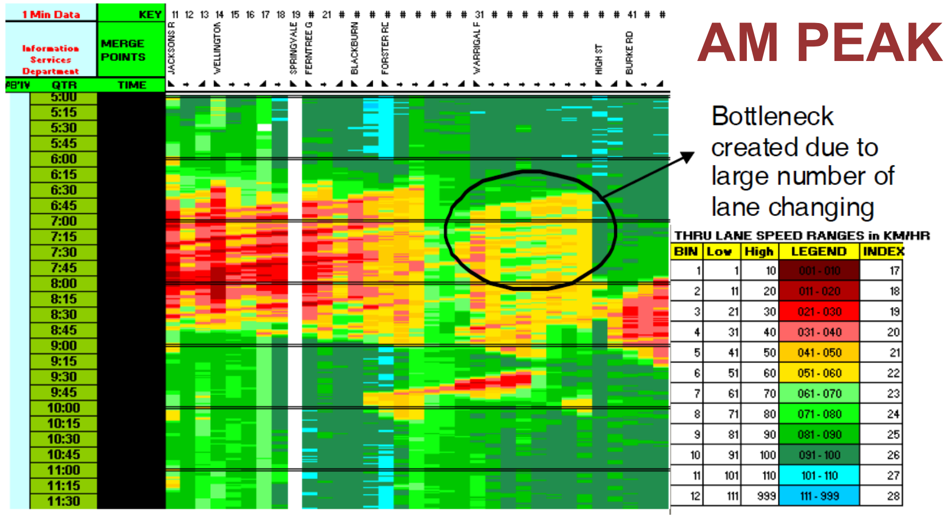
- Apply ALINEA to each ramp with $\hat{o} = o_{cr}$ and $l_{\min}$ constraint.
- If ALINEA active at ramp i (master) and $l_i > \text{threshold1}$, then set an analogous $l_{\min}$ for the next upstream ramp $i-1$ (slave) (i.e. enlarge the available storage space).
- If $l_i + l_{i-1} > \text{threshold2}$, then set an analogous l_{min} for the next upstream ramp $i-2$ (slave)...
- ... and so forth, up to ramp $i-M$ or encounter of another ramp cluster.
- De-activation logic (based on congestion).

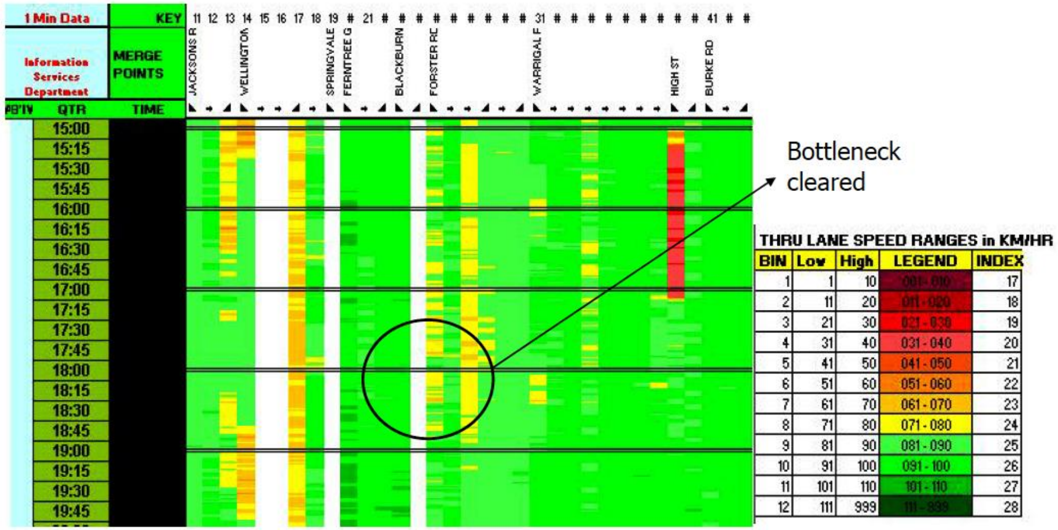
HERO implementation in Melbourne, Australia

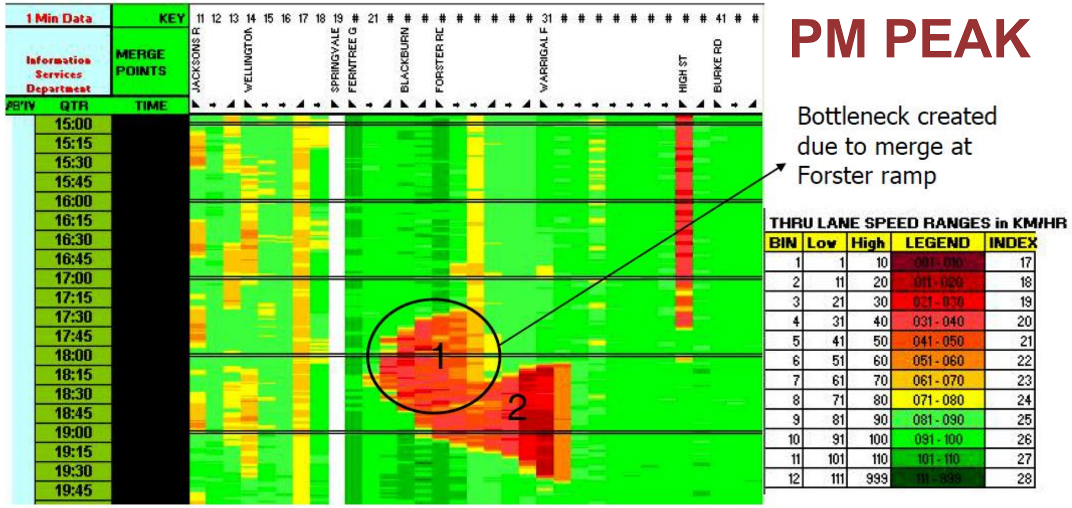
Monash freeway (Melbourne) link-node model



Typical day – RM vs. No RM







Papamichail, I., Papageorgiou, M., Vong, V. and Gaffney, J., 2010. Heuristic ramp-metering coordination strategy implemented at Monash freeway, Australia. Transportation Research Record, (2178), pp.10-20.

BikeZ project (ETHZ and EPFL)

The E-Bike City project (2022 – 2025)

Design Principles of the E-Bike City

- ❑ Half of every street will be converted to safe and comfortable infrastructure for micromobility users.
- ❑ The other half provides basic access for motorized vehicles through a network of one-way streets.
- ❑ Public transport can operate along existing corridors with similar or higher speeds than today. Its capacity responds to the demand.
- ❑ The overall organization discourages motorized traffic through neighborhoods, creating safe and quiet spaces for local communities.

Check out project's results

https://www.ebikecity.ch/en.htm

Remaining gaps and concerns

- ❑ Uncertainty on how efficient the bicycles are – assuming that everyone was using them.
  - ❑ Do bicycles increase the **capacity**?
  - ❑ What **traffic dynamics** might arise (oscillations, stop&go, capacity drop)?
  - ❑ Are there **safety concerns** under bicycle congestion?

- ❑ Bicycle lanes “eat” space which not infinite.
  - ❑ Should **car traffic be penalized**?
  - ❑ How **urban planning** should evolve?
  - ❑ What are the best practices to handle **multimodal conflicts**?

- ❑ Simulation of bicycle movement is underdeveloped.
  - ❑ Is the **“car-following” logic** accurate for bicycles?
  - ❑ Should **traffic signal control** redesigned?
  - ❑ Are generalized multimodal microscopic **simulations trustworthy**?

BikeZ project: Model Suite for Mass Cycling as a Service Simulation

- Funded by Innosuisse

Innovation project supported by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Innosuisse – Swiss Innovation Agency

- Partners:

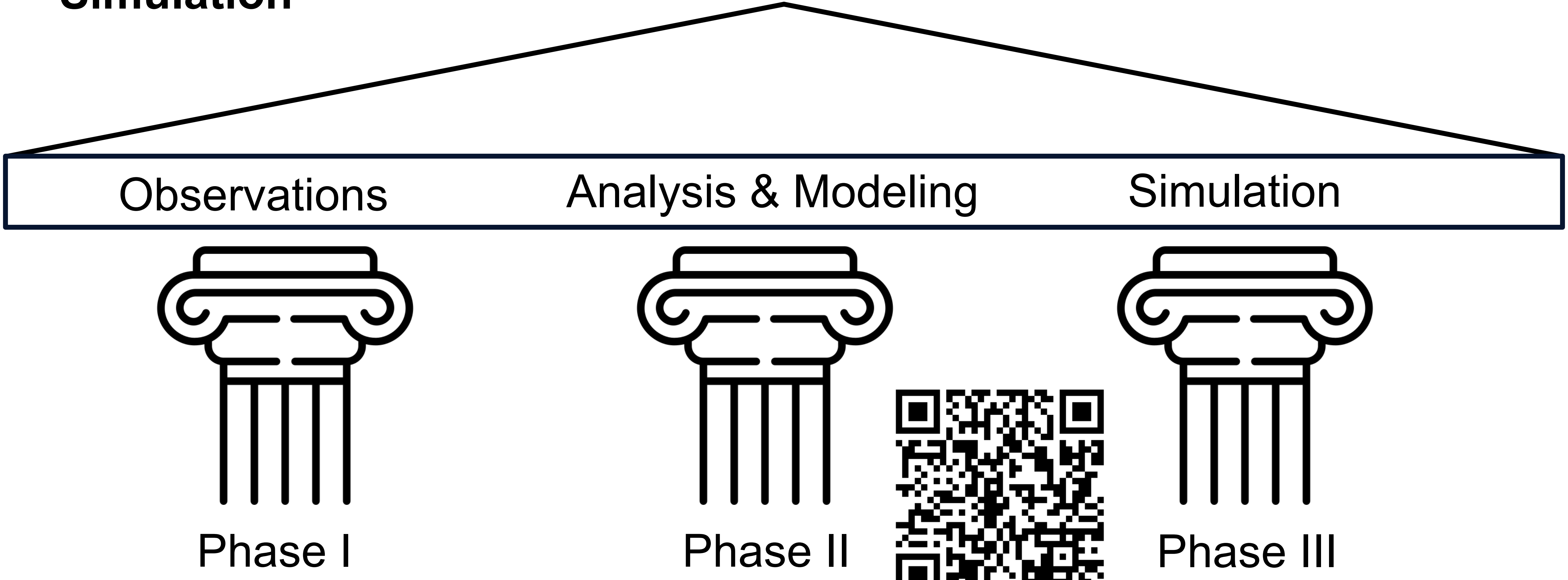
TRANSCALITY

PRO VELO KANTON ZÜRICH

aimsun.

MOBILYSIS

BikeZ project: Model Suite for Mass Cycling as a Service Simulation



BikeZ project: WP1 – Experiments and open dataset

BikeZ project: WP1 – Experiments and open dataset

Experiment 2 – Done!

BikeZ Project - Experiment
Envisioning the Future of Cycling in Zurich

A research project at ETH zürich - Funded by **Innosuisse**

What is this about?
We are launching an innovative field experiment to observe cyclists with drones over intersections in Zurich

Our goal
We aim to produce an open-access bicycle trajectory dataset and develop models to simulate cyclists' movement

Who we are
Traffic Engineering Group
Institute for Transport Planning and Systems

How you could help
Actually quite simple! Please pass by the below experiment intersections on your bicycles at the described time slots

Location
- Langstrasse & Zollstrasse
- Kasernenstrasse & Lagerstrasse

When
16. & 17.06.2025
07:00-10:00 & 16:00-19:00

Data collection
- Aerial observations via drones
- Trajectory extraction from videos
- Conducted by MobiLysis
- Compliance with regulations

We thank all participants and partners
TRANSCALITY, AGIROO, aimsun, PRO VELO KANTON ZÜRICH

Innovation project supported by
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Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Innosuisse – Swiss Innovation Agency

Experiment 3 – Done!

BikeZ Project - Experiment III
Envisioning the Future of Cycling in Zurich

A research project at ETH zürich- Funded by **Innosuisse**

What is this about?
The Traffic Engineering Group at ETH Zurich is launching the next innovative field experiment to observe cyclists' movement with drones

Our goal
We aim to develop a model to simulate mass bicycle traffic flow for Zurich

Meeting point
Baslerstrasse 30, Zürich
(Intersection with Hardgutstrasse)

Date and time
23.09.2025 Tuesday
17:30-18:30

Gift
20 CHF voucher at Ochsner Sport

Aerial data collection by MobiLysis

Sign up here and come ride for us!

In collaboration with
TRANSCALITY, PRO VELO KANTON ZÜRICH, MOBILYSIS, aimsun, AGIROO

Innovation project supported by
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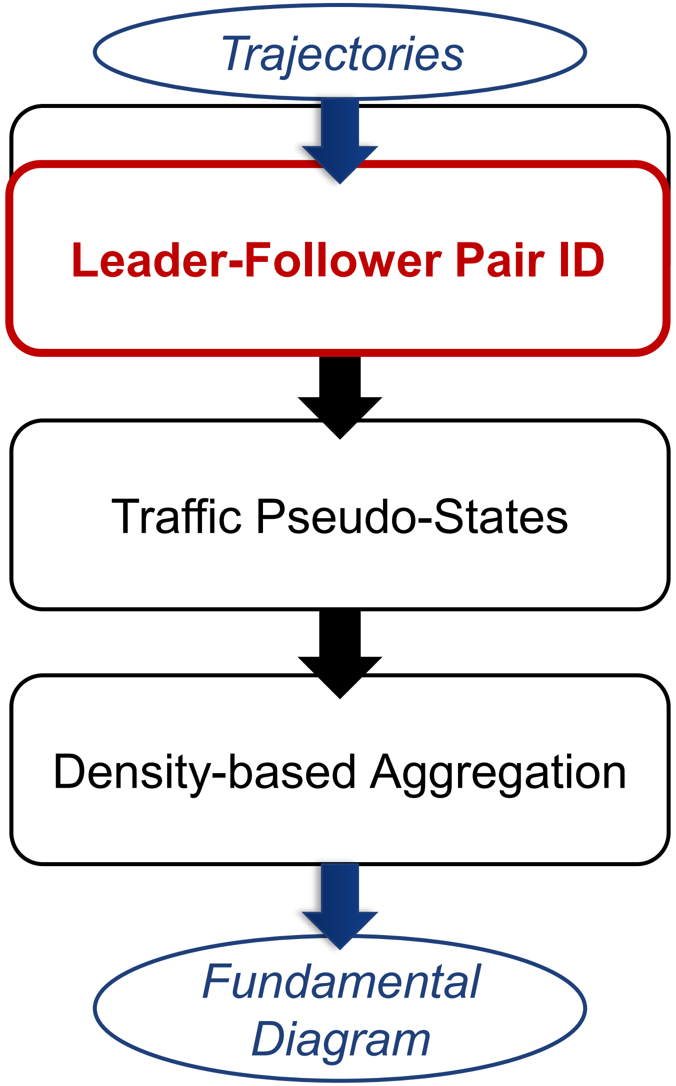
Swiss Confederation
Innosuisse – Swiss Innovation Agency

BikeZ project: WP2 – Analysis – BicycleFD



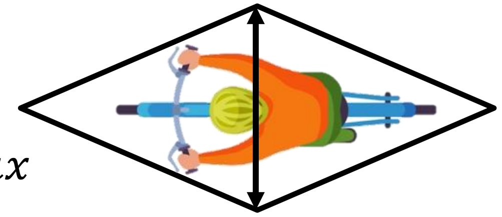
1 For each cyclist i, at a time instant t, the leader cyclist L_i is given by

$$L_i = \underset{j \in B, j \neq i}{\operatorname{argmin}} \left| x_i^P(t) - x_j^P(t) \right|$$

$$s.t.\ \Delta x_{min}^P \leq x_j^P(t) - x_i^P(t) \leq \Delta x_{max}^P$$

$$s.t.\ \left| y_i^P(t) - y_j^P(t) \right| \leq \frac{1}{2} w_b$$

$$\Delta x_{min}^P = 5°, \qquad \Delta x_{max}^P = 60°$$



$w_b = 0.8\ m$

2

- If infeasible, the leader cyclist L_i is given by

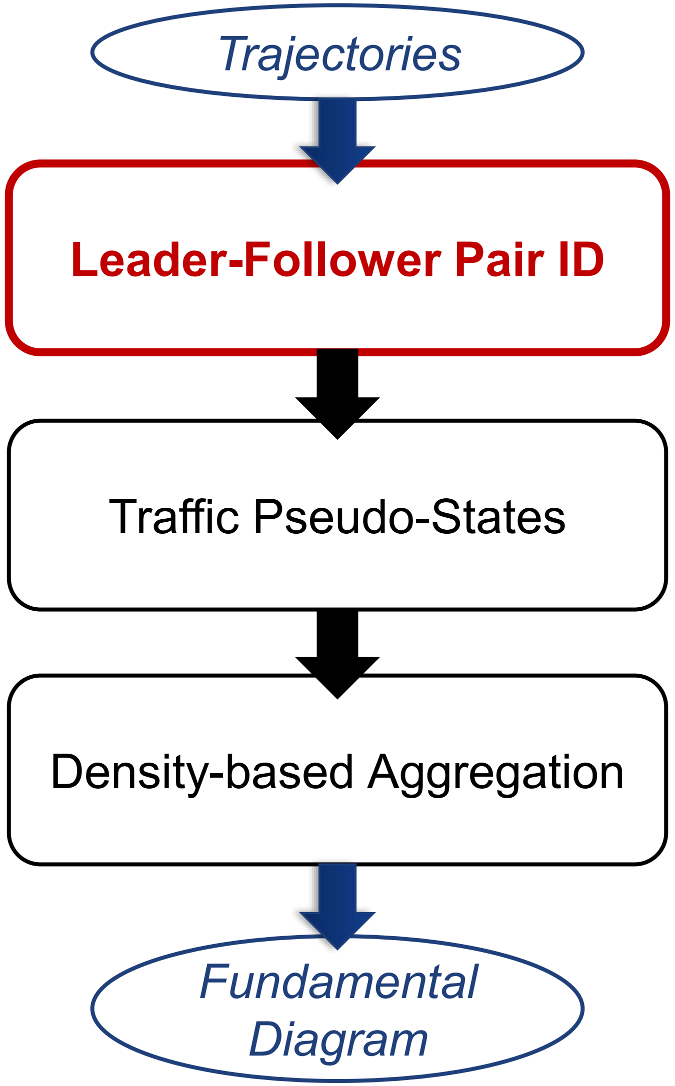
$$L_i = \underset{j \in B, j \neq i}{\operatorname{argmin}}\ \alpha_X^P \left| x_i^P(t) - x_j^P(t) \right| + \alpha_Y^P \left| y_i^P(t) - y_j^P(t) \right|$$

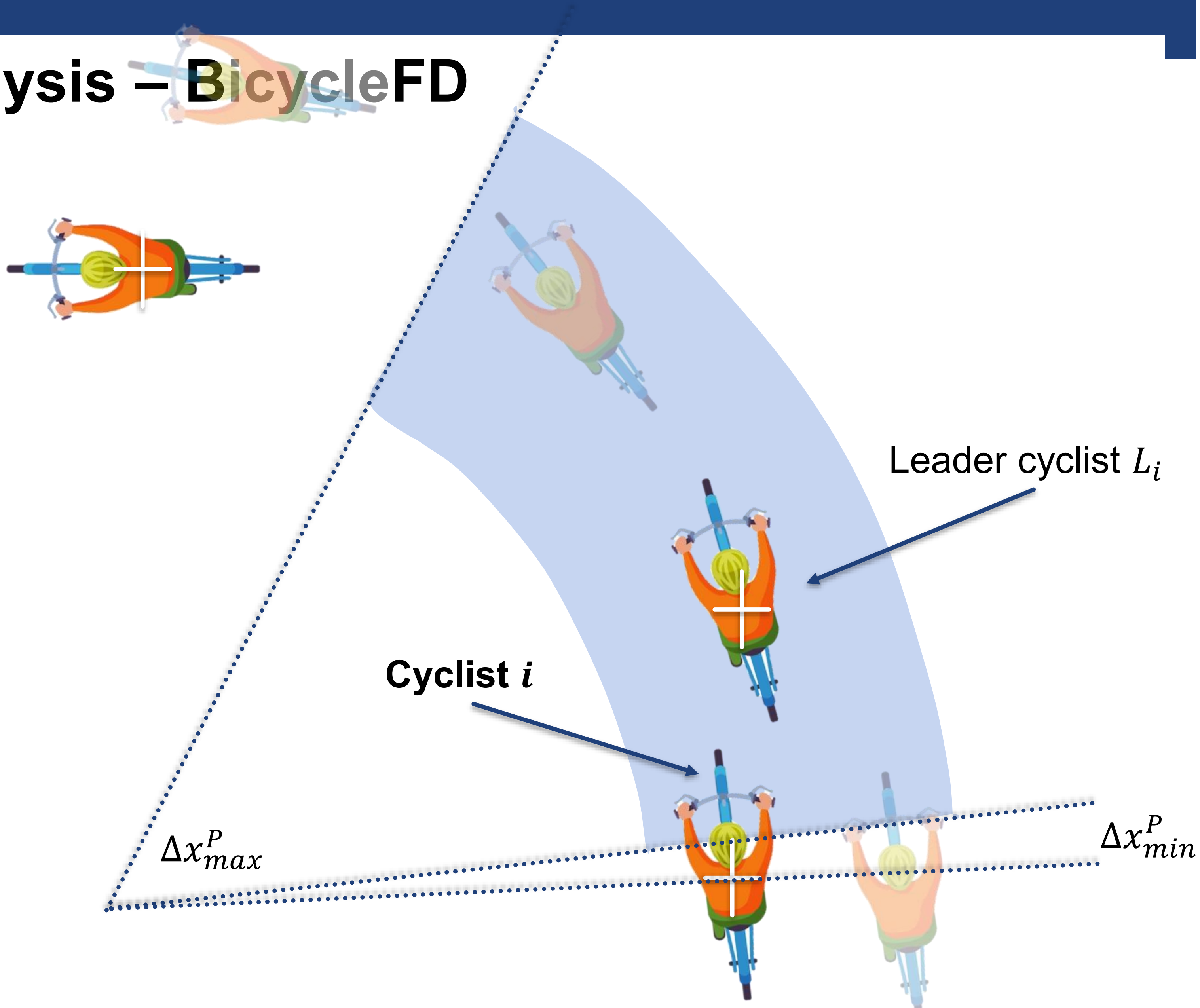
$$s.t.\ x_j^P(t) - x_i^P(t) \geq \Delta x_{min}^P$$

$$\alpha_X^P = \frac{2}{\pi}, \qquad \alpha_Y^P = \frac{1}{3.75}$$

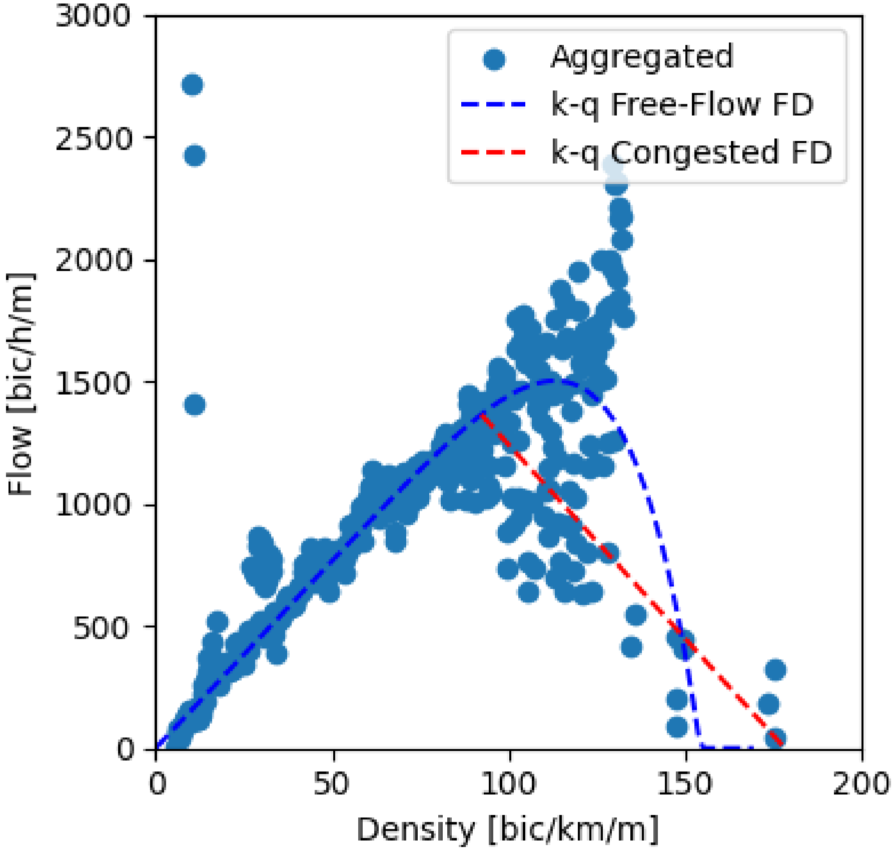
x_i^P = Polar_X for cyclist i
y_i^P = Polar_Y for cyclist i
B = set of all cyclists' IDs

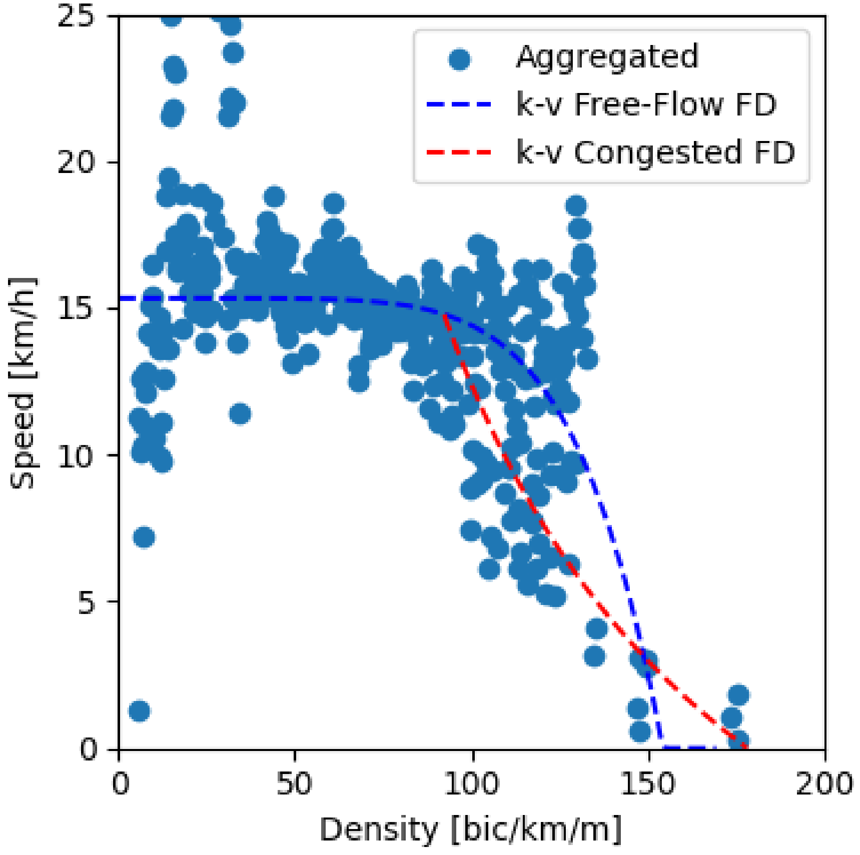
BikeZ project: WP2 – Analysis – BicycleFD





BikeZ project: WP2 – Analysis – BFD – 2.5m lane width





Wu's FD (functional form):

$$v(\kappa) = v_f - (v_f - v_{cr})\left(\frac{\kappa}{\kappa_{cr}}\right)^{\delta}$$

$v_f = 15.3\ km/h$

$\delta = 6.5$

$\kappa_{cr} = 141.6\ bic/km/m$

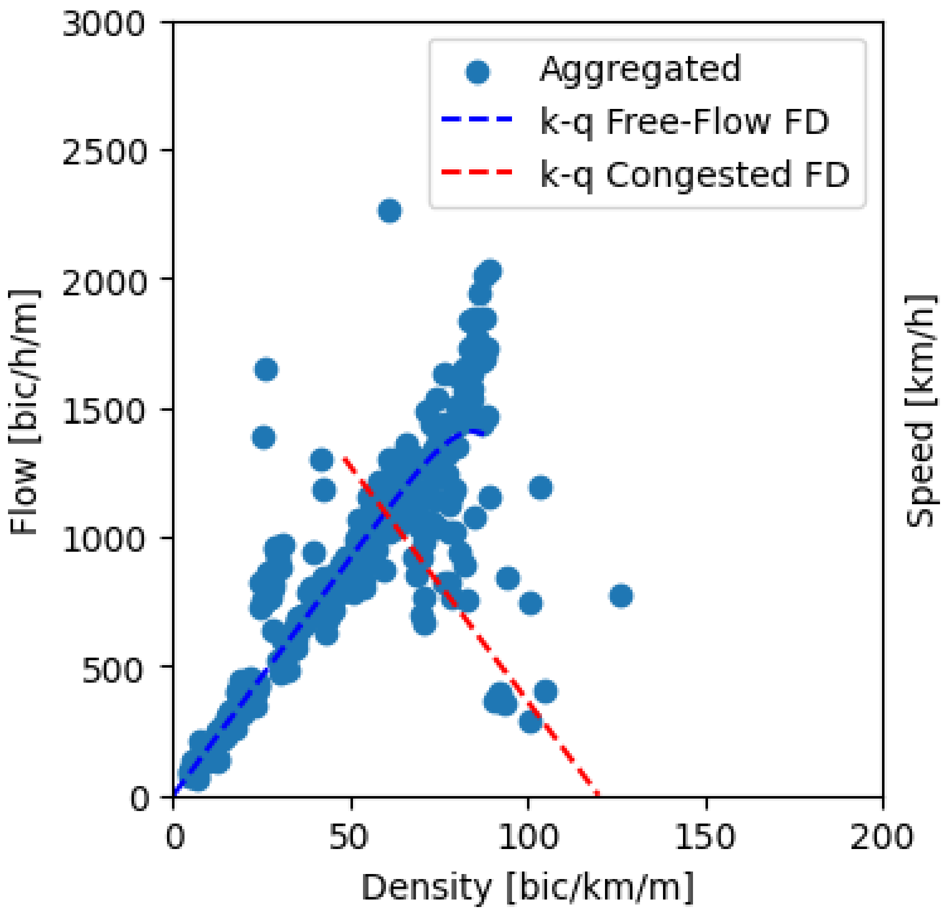
$v_{cr} = 6.5\ km/h$

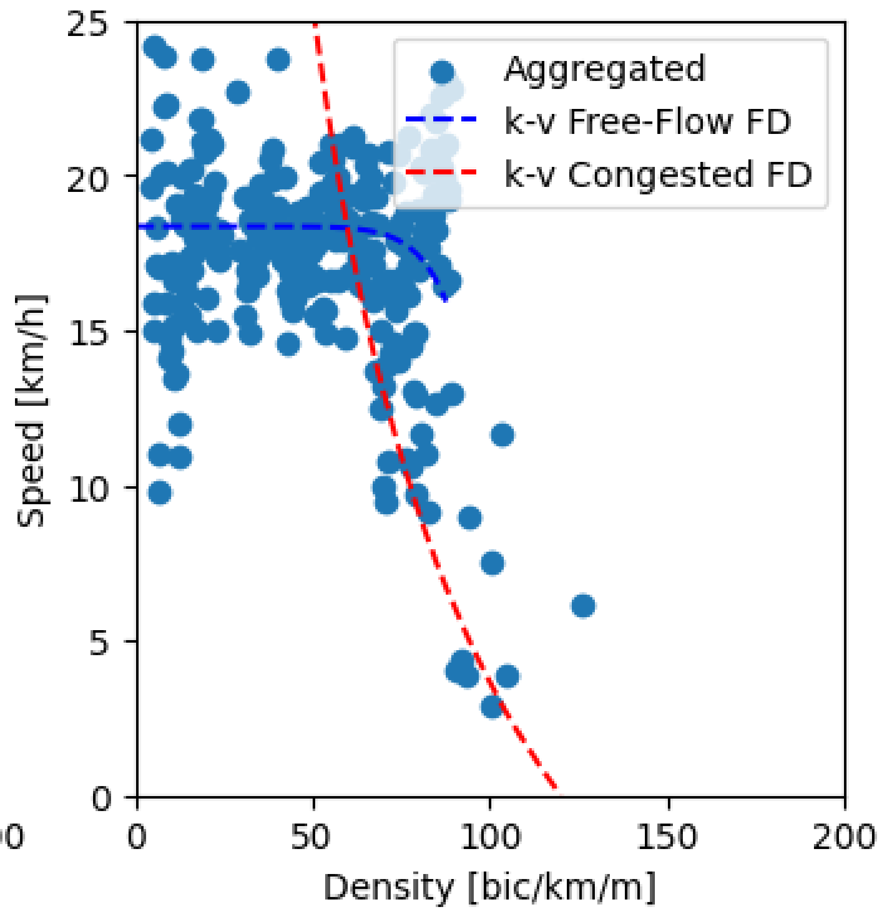
$$q(\kappa) = w(\kappa - \kappa_{jam})$$

$w = -15.8\ km/h$

$\kappa_{jam} = 178.3\ bic/km/m$

BikeZ project: WP2 – Analysis – BFD – 3.75m lane width





Wu's FD (functional form):

$$v(\kappa) = v_f - (v_f - v_{cr})\left(\frac{\kappa}{\kappa_{cr}}\right)^{\delta}$$

$v_f = 18.4\ km/h$

$\delta = 10$

$\kappa_{cr} = 74\ bic/km/m$

$v_{cr} = 17.9\ km/h$

$$q(\kappa) = w(\kappa - \kappa_{jam})$$

$w = -28.2\ km/h$

$\kappa_{jam} = 120\ bic/km/m$

Increasing the lane width increases the free-flow speed but decreases the critical density → No perceived gains in efficiency (probably due to increased heterogeneity in cycling behavior).

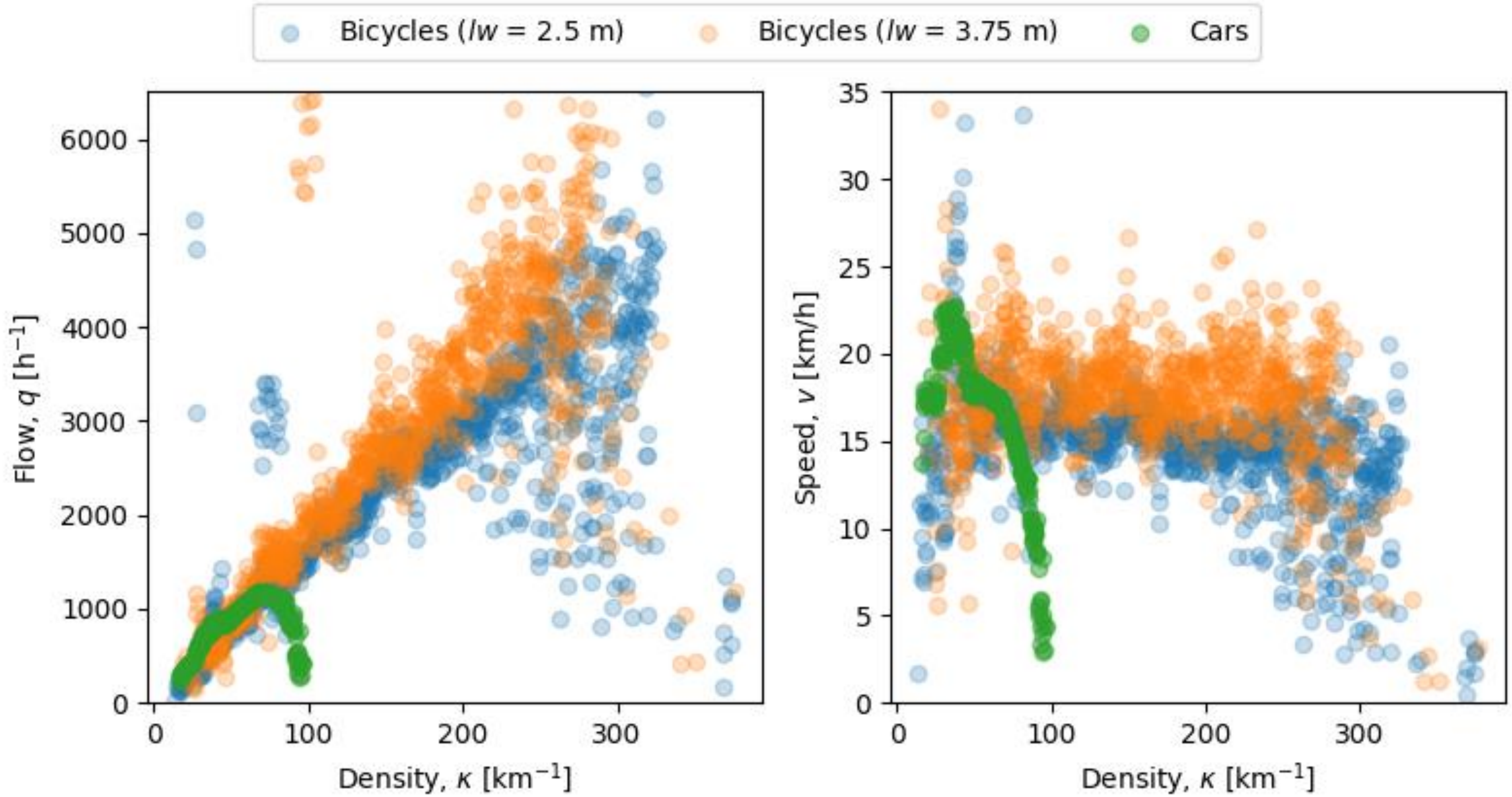
BikeZ project: WP2 – Analysis – Comparison with cars

Scientific Reports

Data in Briefs

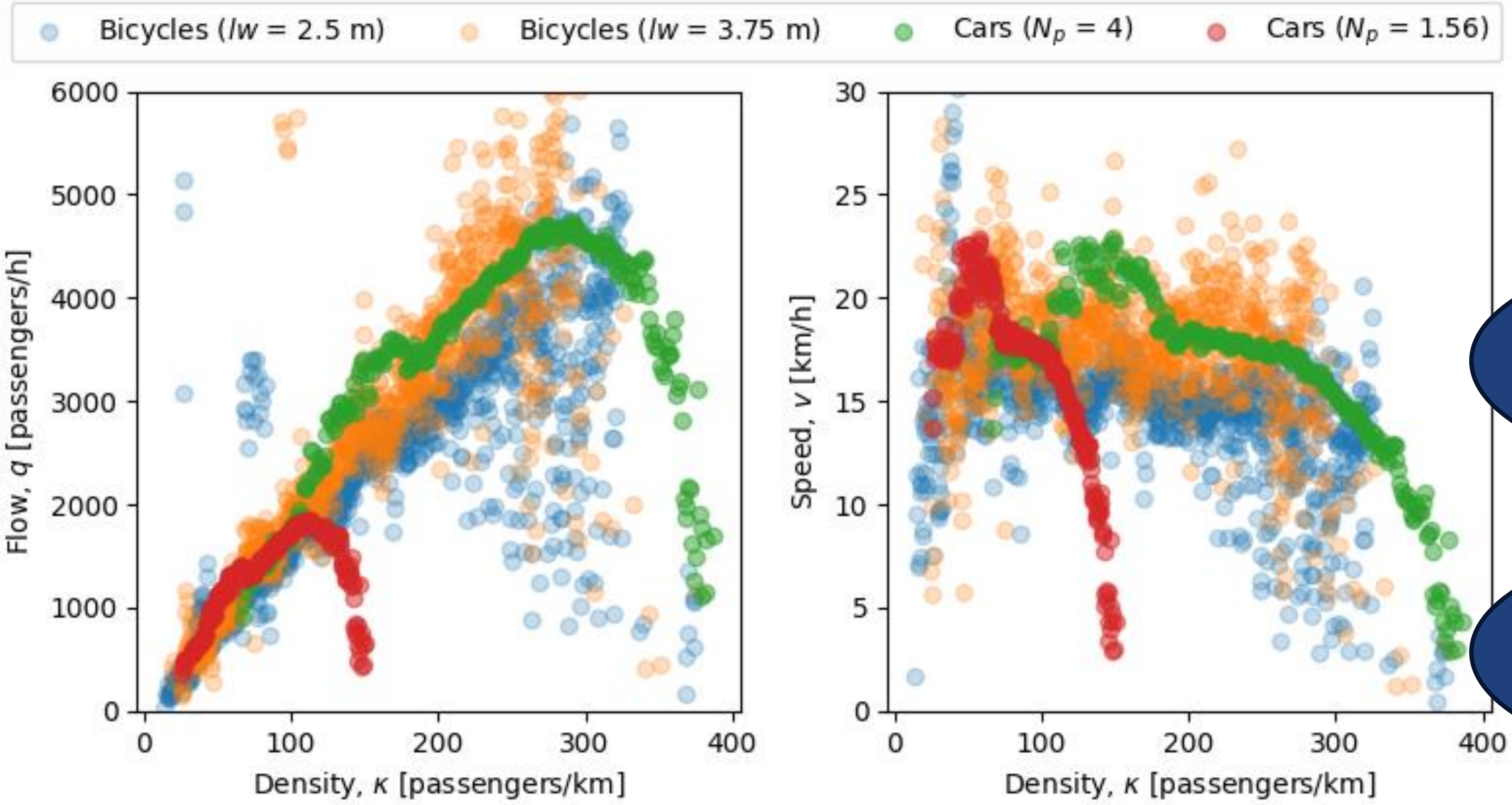
YouTube

BikeZ project: WP2 – Analysis – Comparison with cars



Data exists in different ranges! → For a meaningful comparison, we apply some scaling/transformations.

BikeZ project: WP2 – Analysis – Comparison with cars



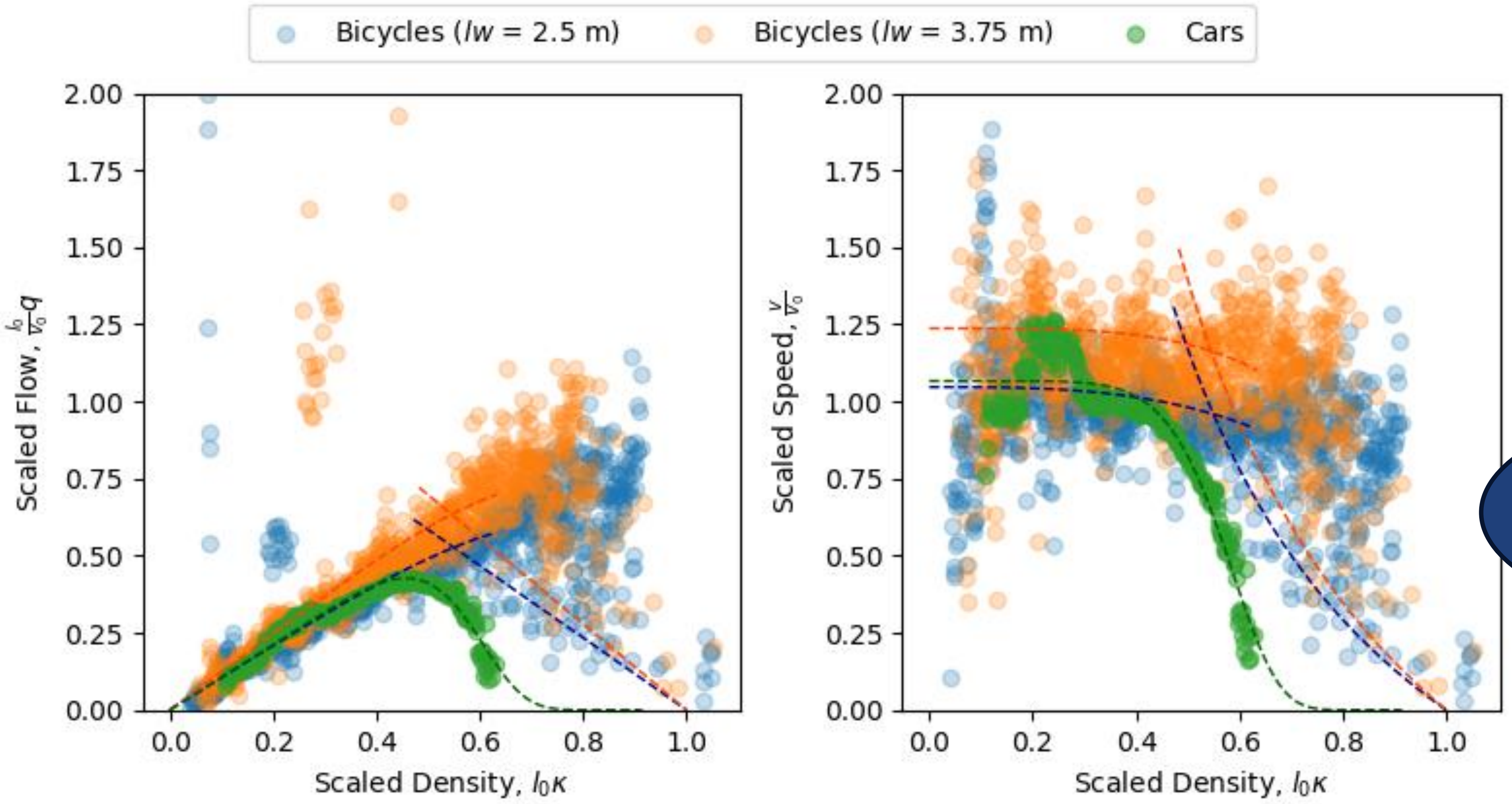
Passenger Perspective

To reach same traffic capacity, cars should be at maximum occupancy!

Swiss average occupancy* is 1.56 passenger per car!

* Swiss Federal Office for Spatial Development (ARE), “Population’s travel behaviour 2015,” *Admin.ch*, 2015. (accessed Sep. 12, 2025).

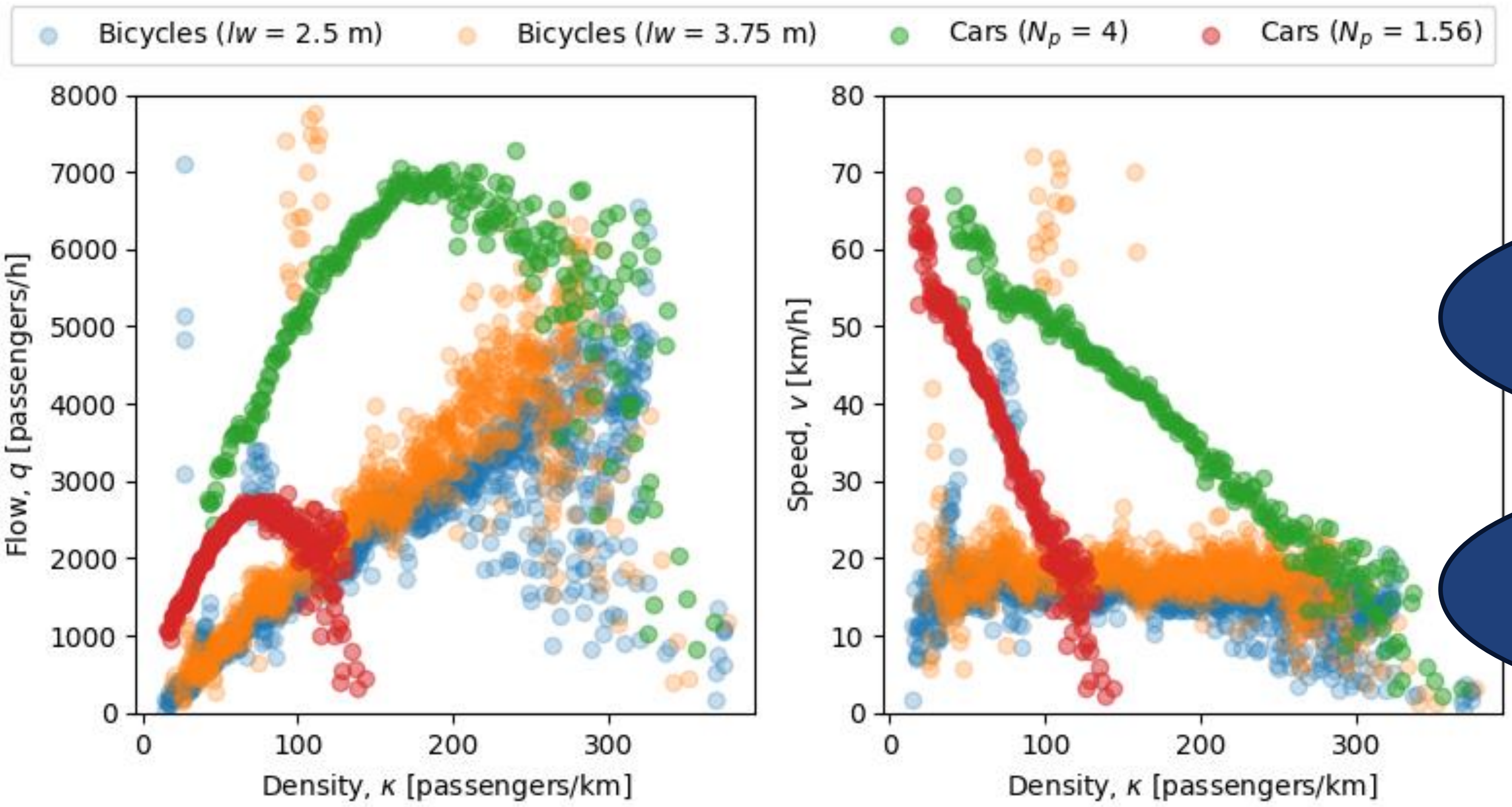
BikeZ project: WP2 – Analysis – Comparison with cars



Space Perspective

Bicycles are more spatially efficient and have higher <u>critical and jam densities</u>!

BikeZ project: WP2 – Analysis – Comparison with cars

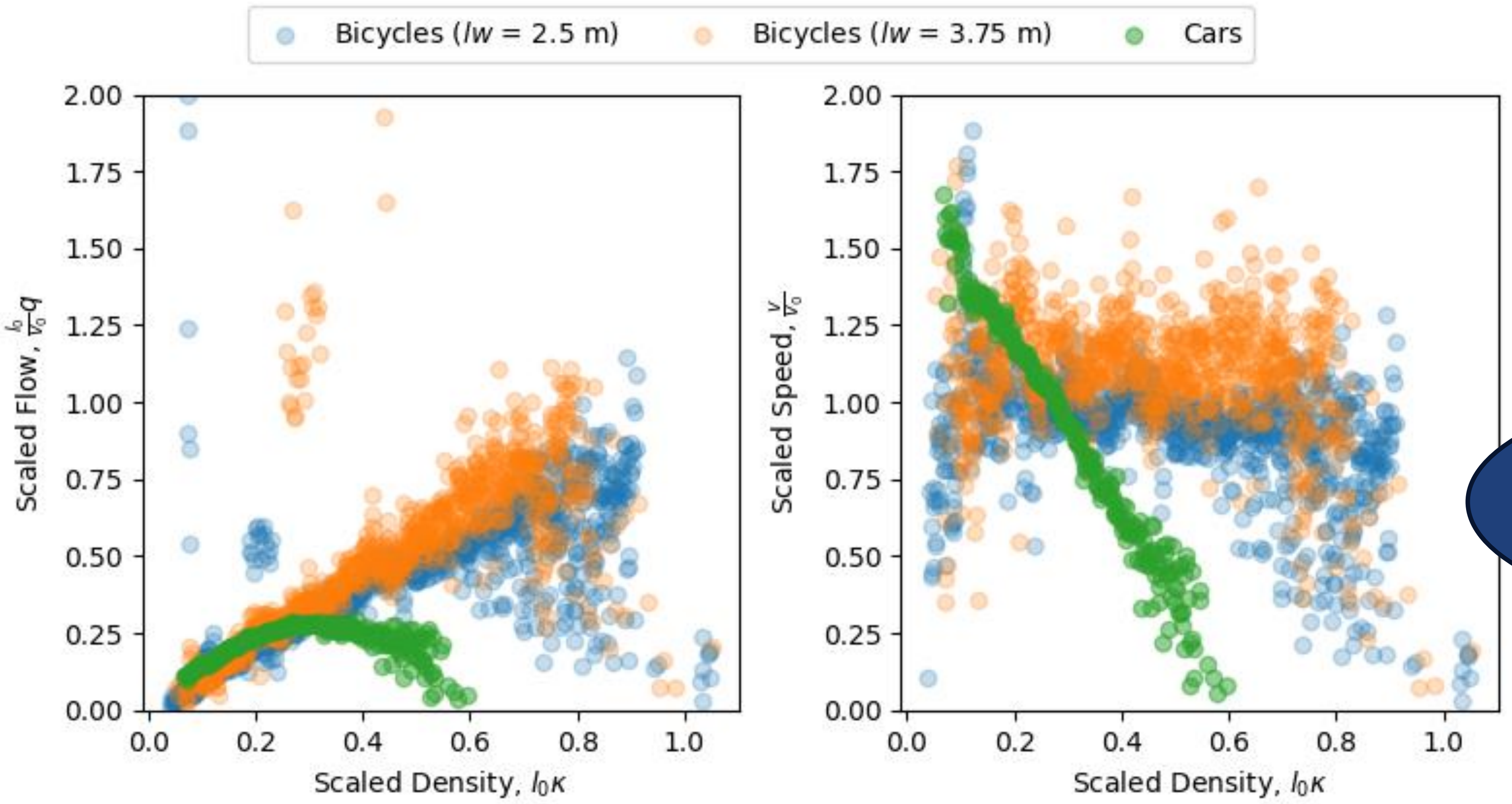


Passenger Perspective

NGSIM here is a highway dataset → explains the higher capacities.

At average occupancy, the critical density for cars mode is lower than that for bicycles mode!

BikeZ project: WP2 – Analysis – Comparison with cars



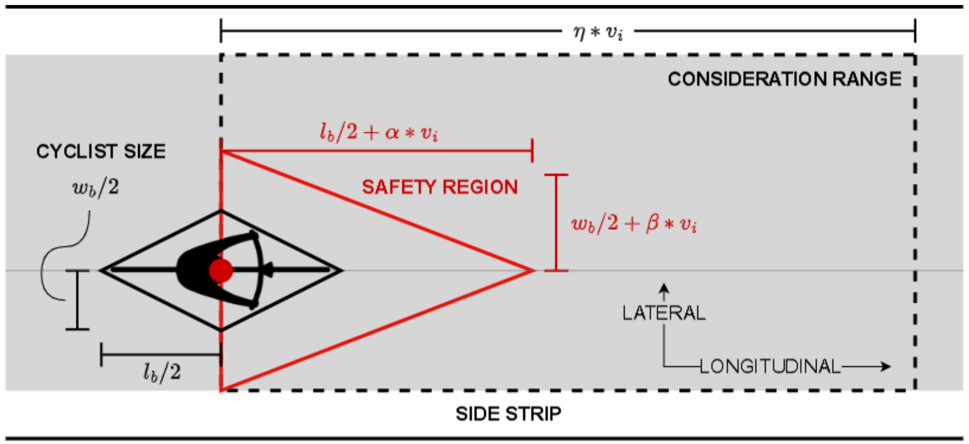
Space Perspective

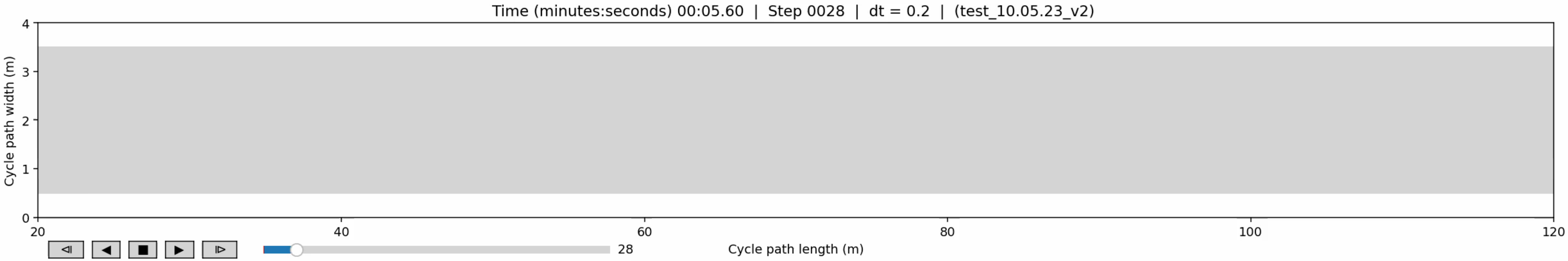
$$l_0^{car} = 4.5 + 2\ m$$
$$v_0^{car} = 40\ km/h$$
$$l_0^{bic} = 1.8 + 1\ m$$
$$v_0^{bic} = 16\ km/h$$

Same observations regarding spatial efficiency and critical and jam densities!

BikeZ project: WP2 – Modeling

- Non-lane-based operational-level behavior models Mental perception
  - Mental decision-making (movement strategy)
  - Physical process





BikeZ project: WP2 – Modeling

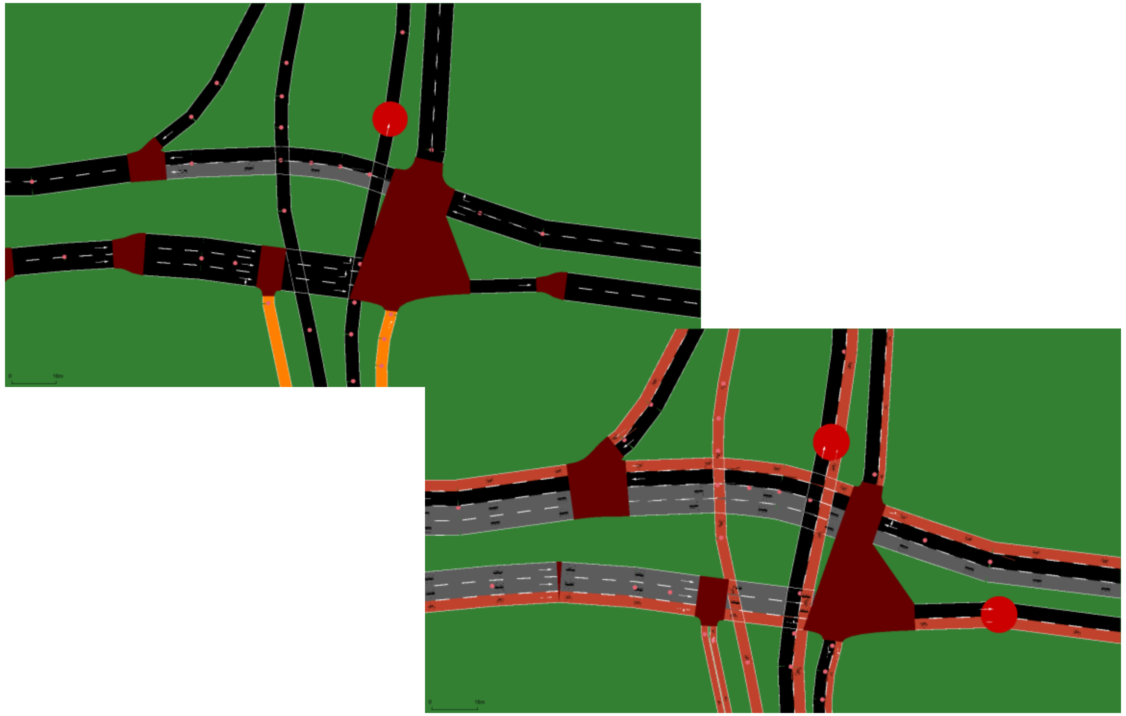
There are more issues for model refinement:

- Overtaking (uninterrupted flow)
- Discharging (interrupted flow)
- Stopping/queueing (interrupted flow)

- Other challenges:
  - Turning
  - Lateral movement due to the desired downstream turning
  - Merging/yielding due to turning, change of lane width, and unsignalized conflicts, etc.

BikeZ project: WP3 – Simulation

- The city center of Zurich in SUMO
- E-Bike City network 1
- Zurich network with optimized car-bicycle road space allocation



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Questions and discussion!