Practical Pilot Amsterdam

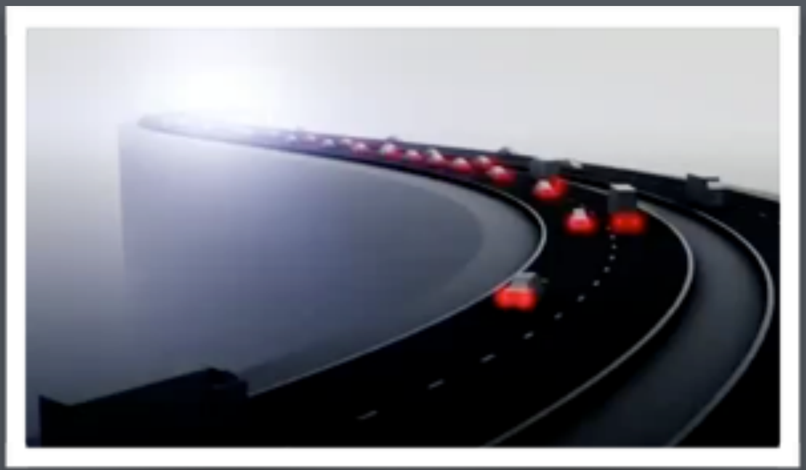
Putting 20 years of research to practice

Prof. dr. Serge Hoogendoorn, Delft University of Technology

“There are serious limitations to the self-organising capacity of traffic systems”

Efficient self-organisation

Capacity-drop and start-stop waves



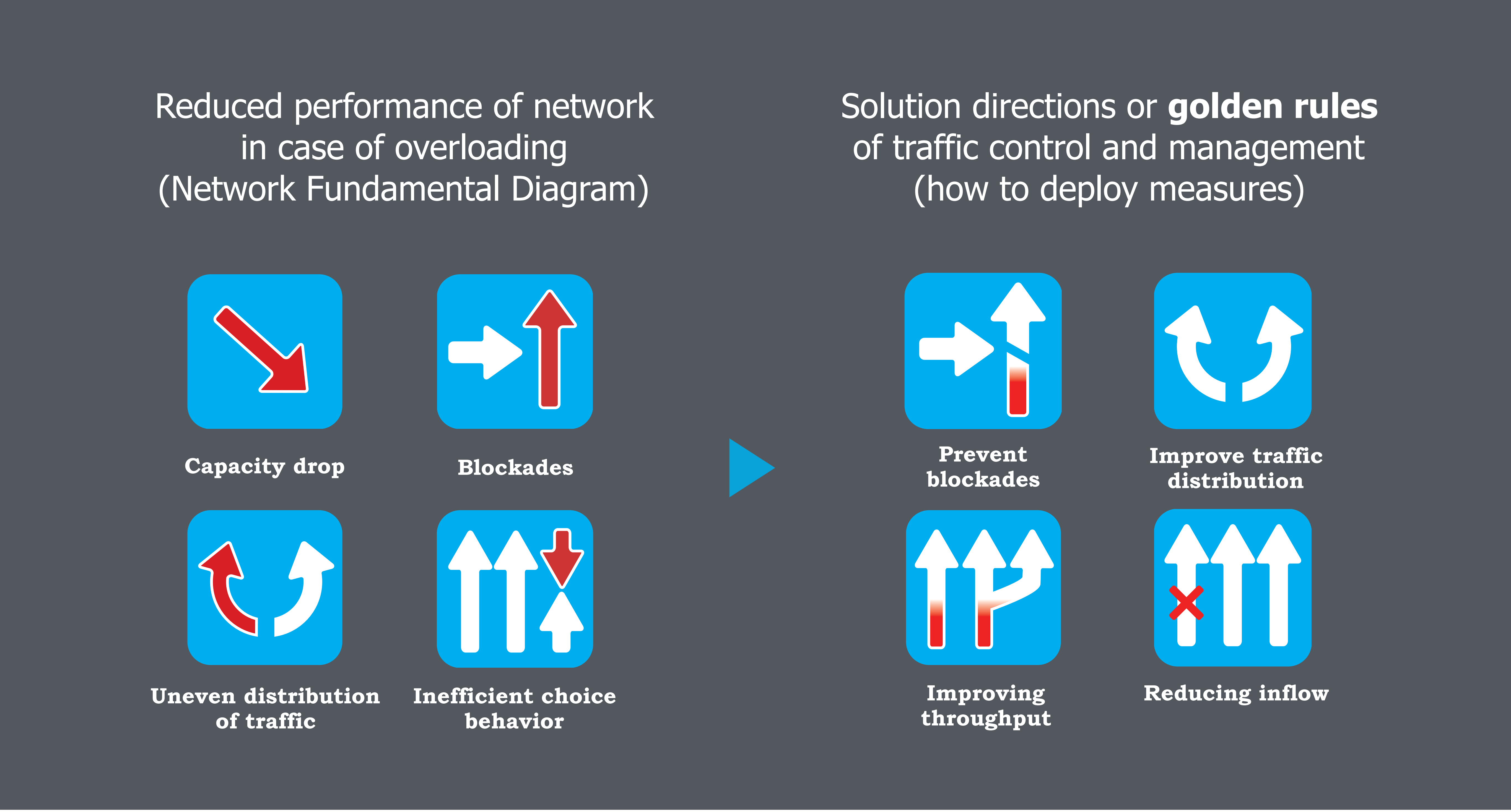
Blockages, gridlock and inefficient choice behaviour

Increasing network load

Reduced production of network

Why do we need to control traffic at all?

- When traffic is dilute, there is little need to intervene to improve throughput
- However, when traffic loads become higher, phenomena occur that reduce there efficiency of network operations dramatically (**Network Fundamental Diagram**)



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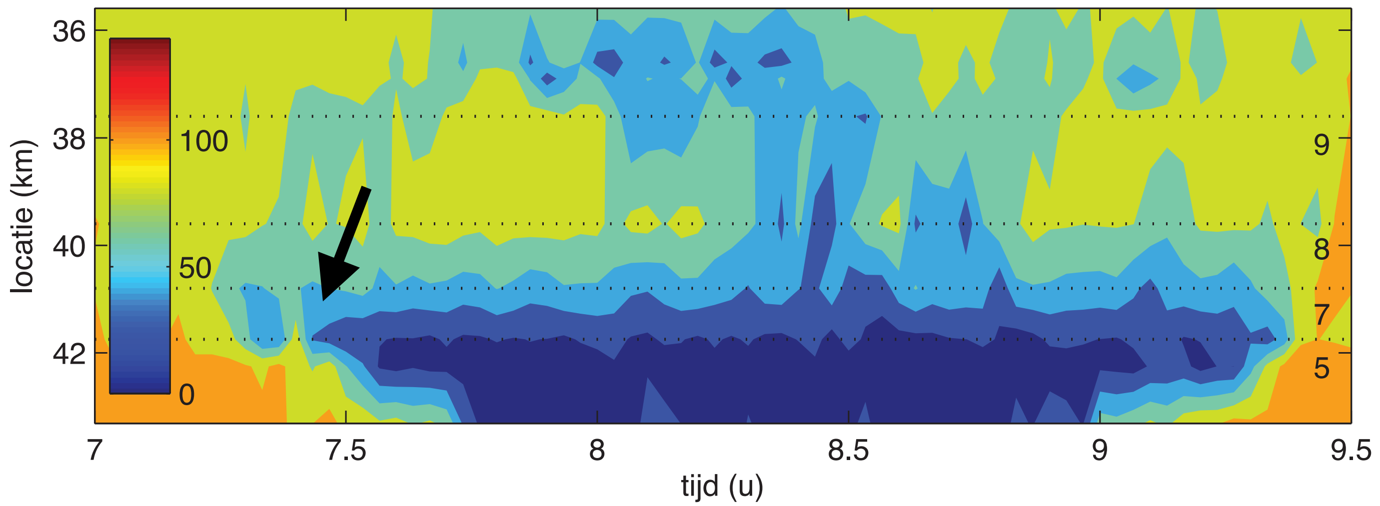
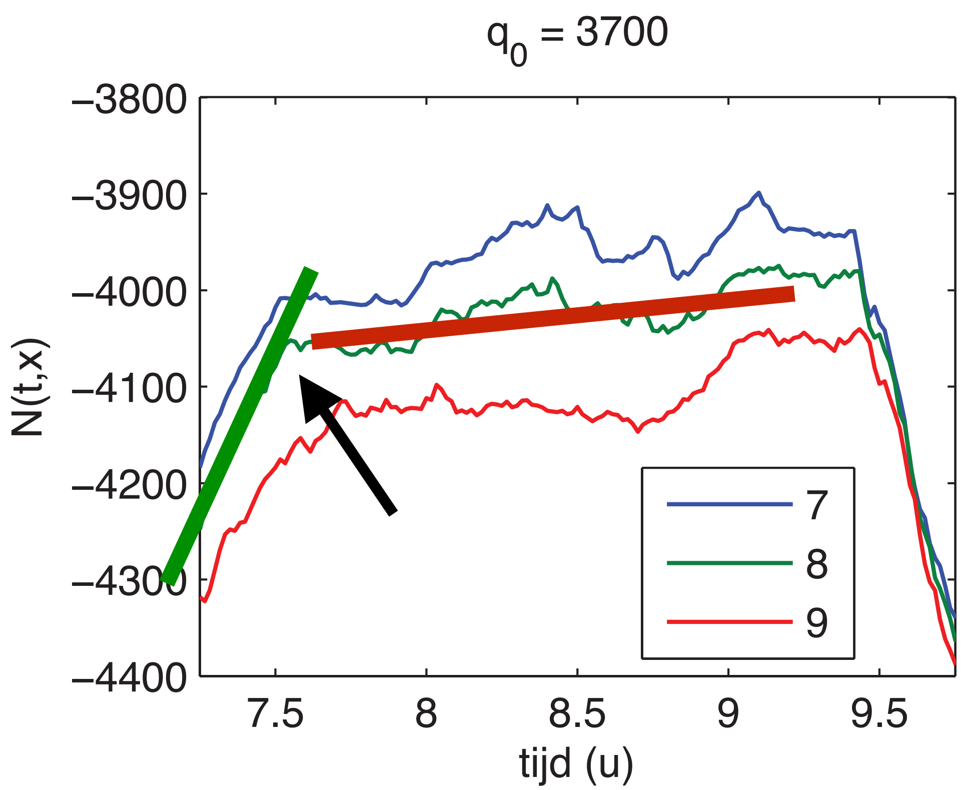
- Figure shows on-ramp bottleneck on Dutch A9 motorway
- Congestion sets in at around 7:30 and lasts until 9:30



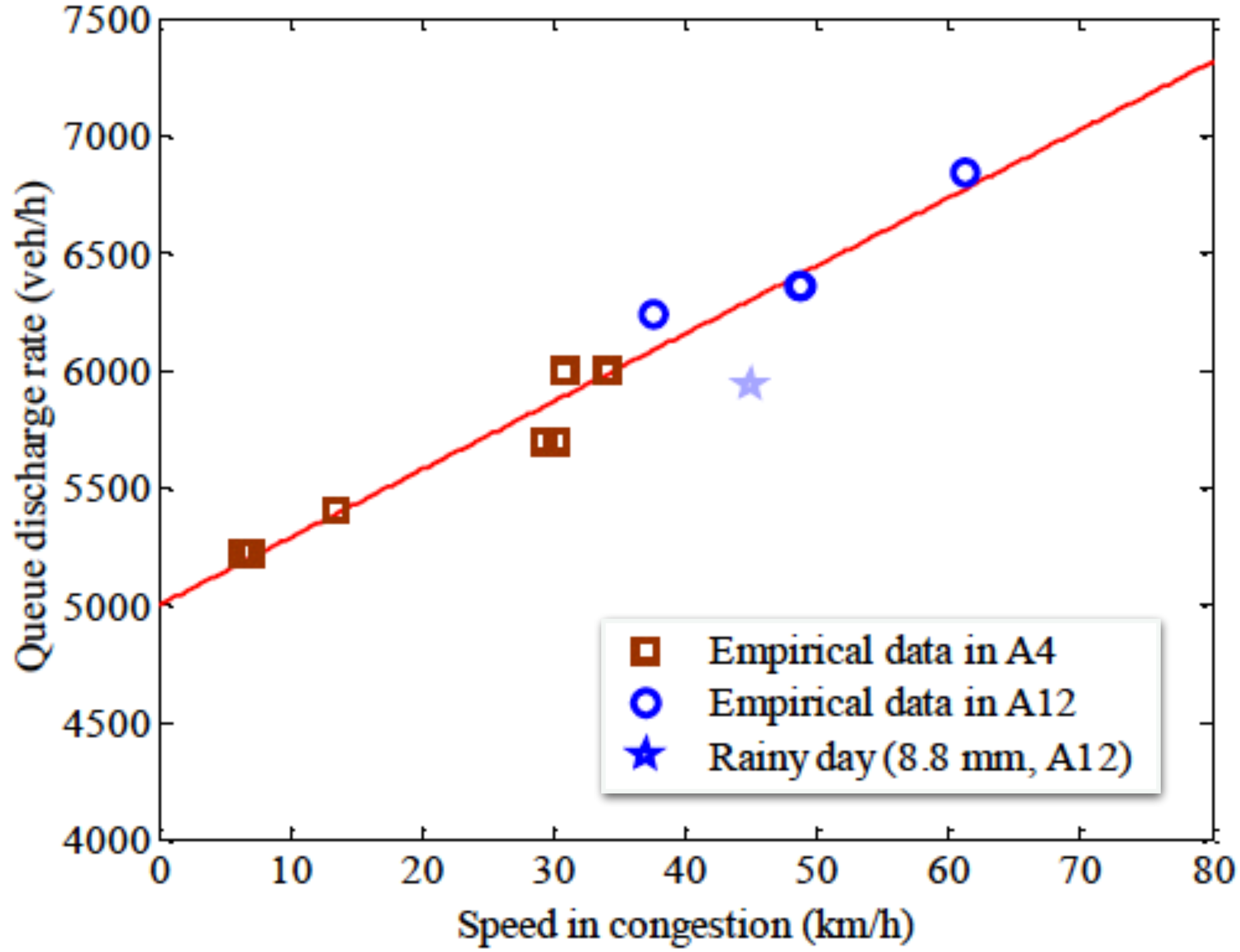
- Middle line in bottom figure shows slanted cumulative curve, slope of which is the flow minus a reference flow (3700 veh/h)
- Pre-queue flow = 4200 veh/h, post-queue flow = 3750 veh/h
- Capacity drop is (at least) 11%, but can be higher depending on the congestion severity



Example phenomena: capacity drop

- Road capacity changes after the on-set of congestion
- Capacity drop magnitude depends on severity of congestion caused by the bottleneck (i.e. the speed in the queue)

- Picture shows relation between speed in the queue upstream and the size of the capacity drop
- Capacity drop goes up to 30% is vehicles in queue as standing still (what type of queue is this?)
- **Preventing** or **removing congestion** will enable flow to operate in a more efficient pre-queue state



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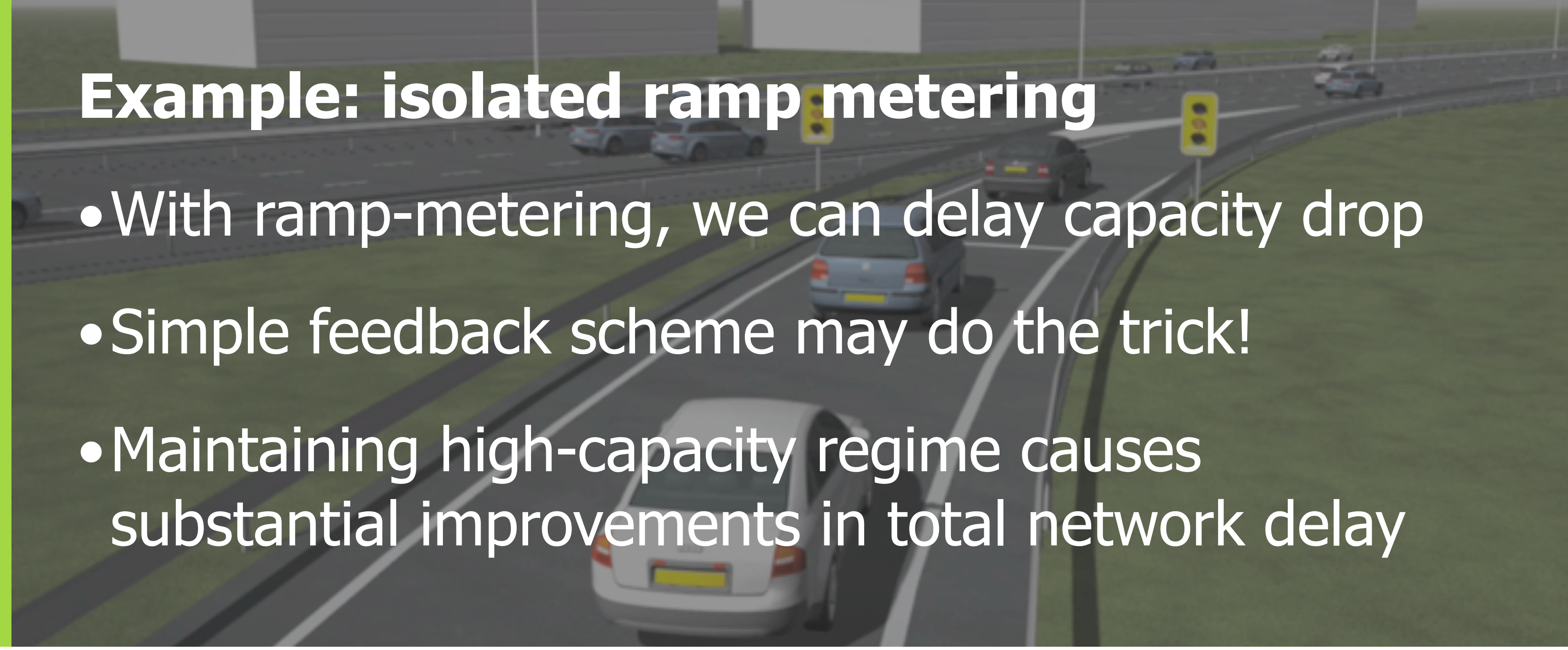
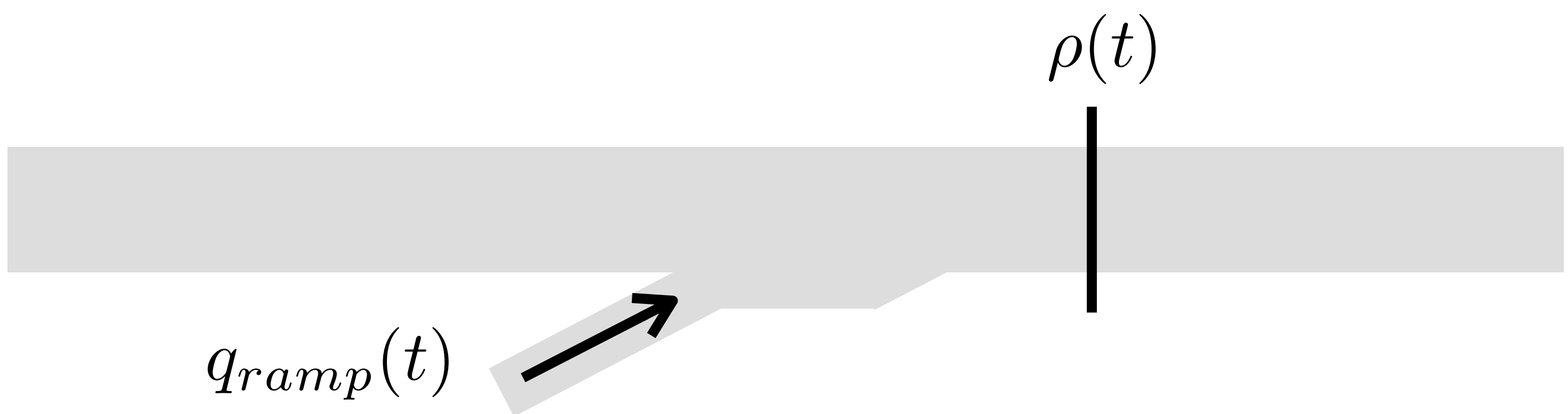


Example: isolated ramp metering

- With ramp-metering, we can delay capacity drop
- Simple feedback scheme may do the trick!
- Maintaining high-capacity regime causes substantial improvements in total network delay

- Example: dynamic ALINEA-type algorithms steers downstream density to optimal value (generally the critical density)
- Test in Amsterdam shows 8% increase in outflow compared to no control case
- Data analysis shows that this leads to an 1:2 gain (freeway):loss (ramp) ratio, which we can further improve by better choosing the target value

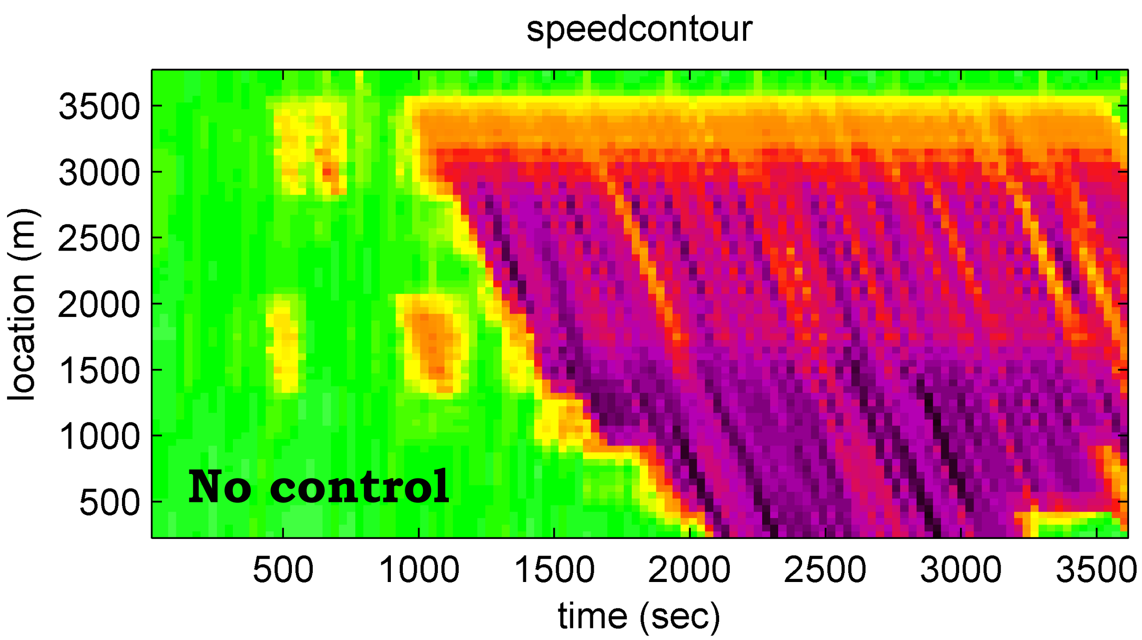


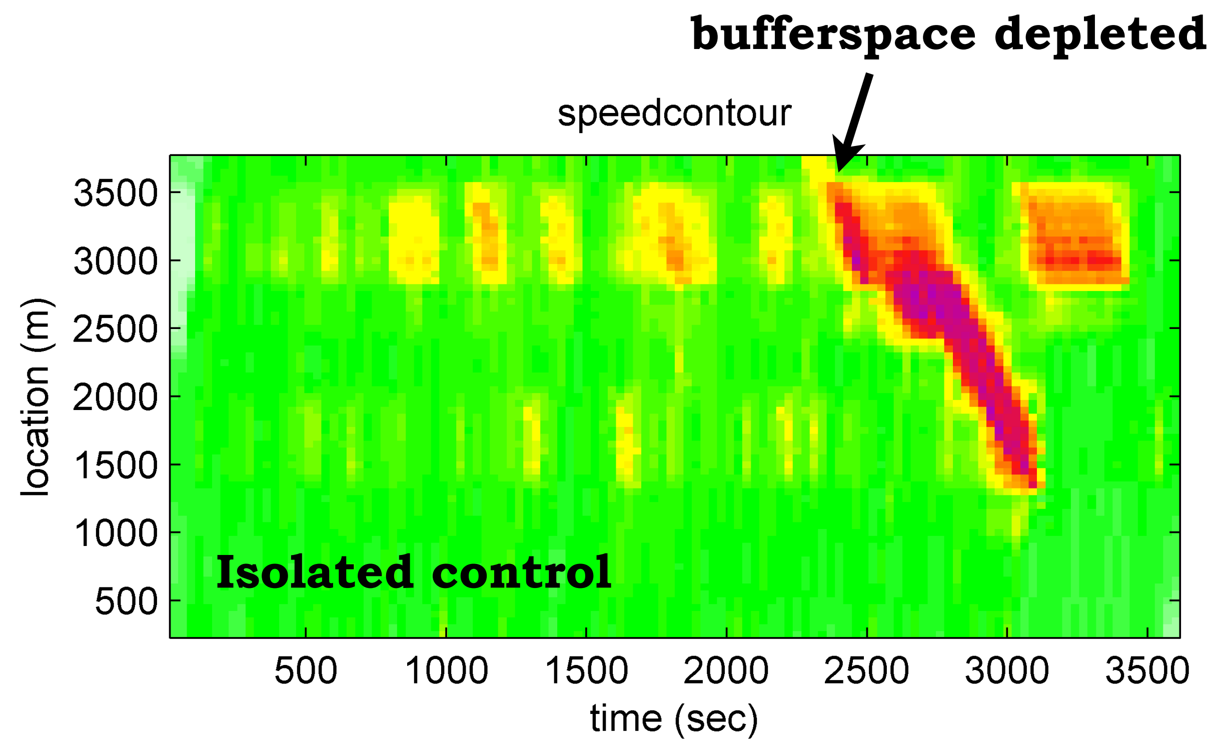
$$q_{ramp}(t+1) = q_{ramp}(t) + K \cdot (\rho^* - \rho(t))$$

Example: isolated ramp metering

- With ramp-metering, we can delay capacity drop
- Simple feedback scheme may do the trick!
- Maintaining high-capacity regime causes substantial improvements in total network delay

- However, metering is terminated if on-ramp queue spills over to urban network
- Limited space to buffer traffic yields large impact on effectiveness of ramp-meters (average up time in The Netherlands = 8 min)

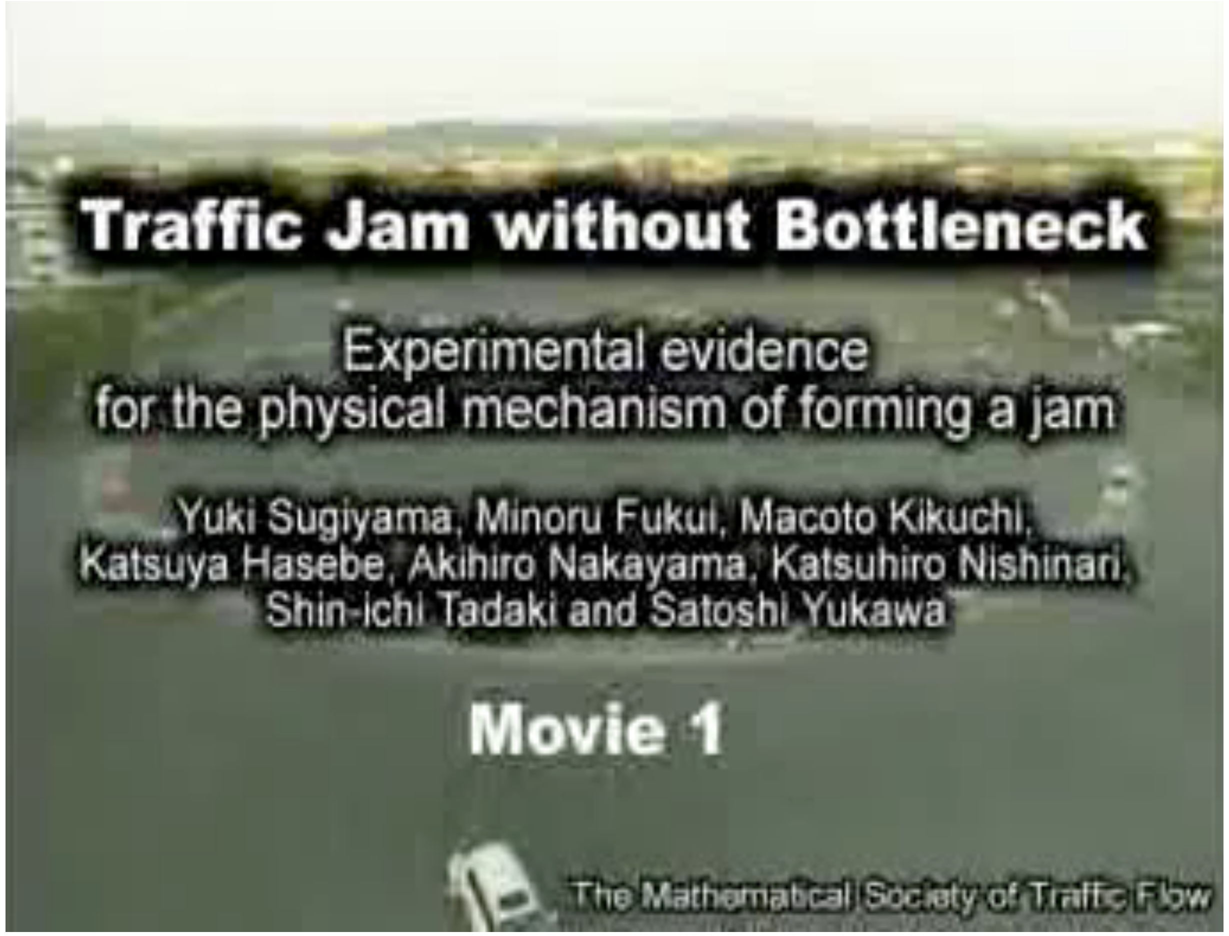


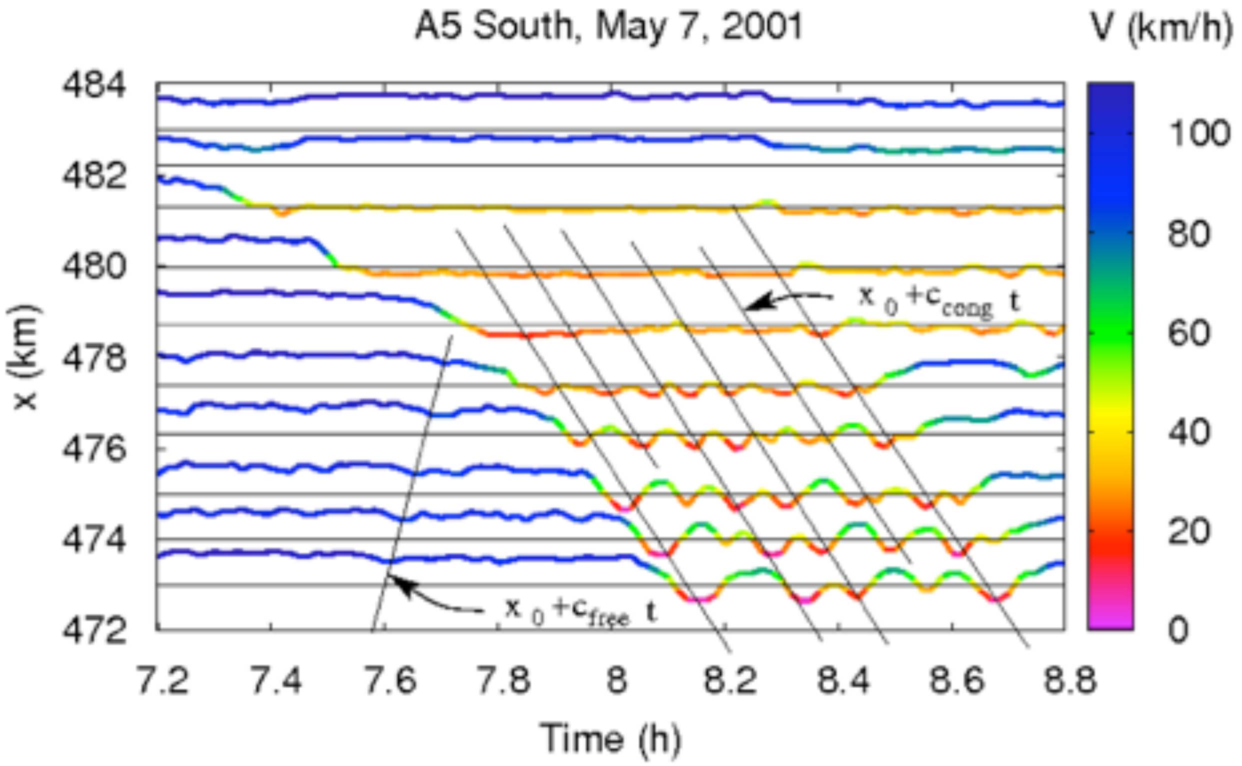


Example phenomena: Start-Stop Waves (or Wide Moving Jams)

- Busy traffic is inherently unstable
- Small disturbances increase in amplitude as they move from vehicle to vehicle and may eventually cause vehicles to stop
- Start-stop wave is born and will remain until inflow is lower than outflow for sufficiently long period

- Note that outflow of wave is **around 30% less** than the free road capacity
- Waves can persist for a very long period
- From the road-user they are unexpected and hence unsafe





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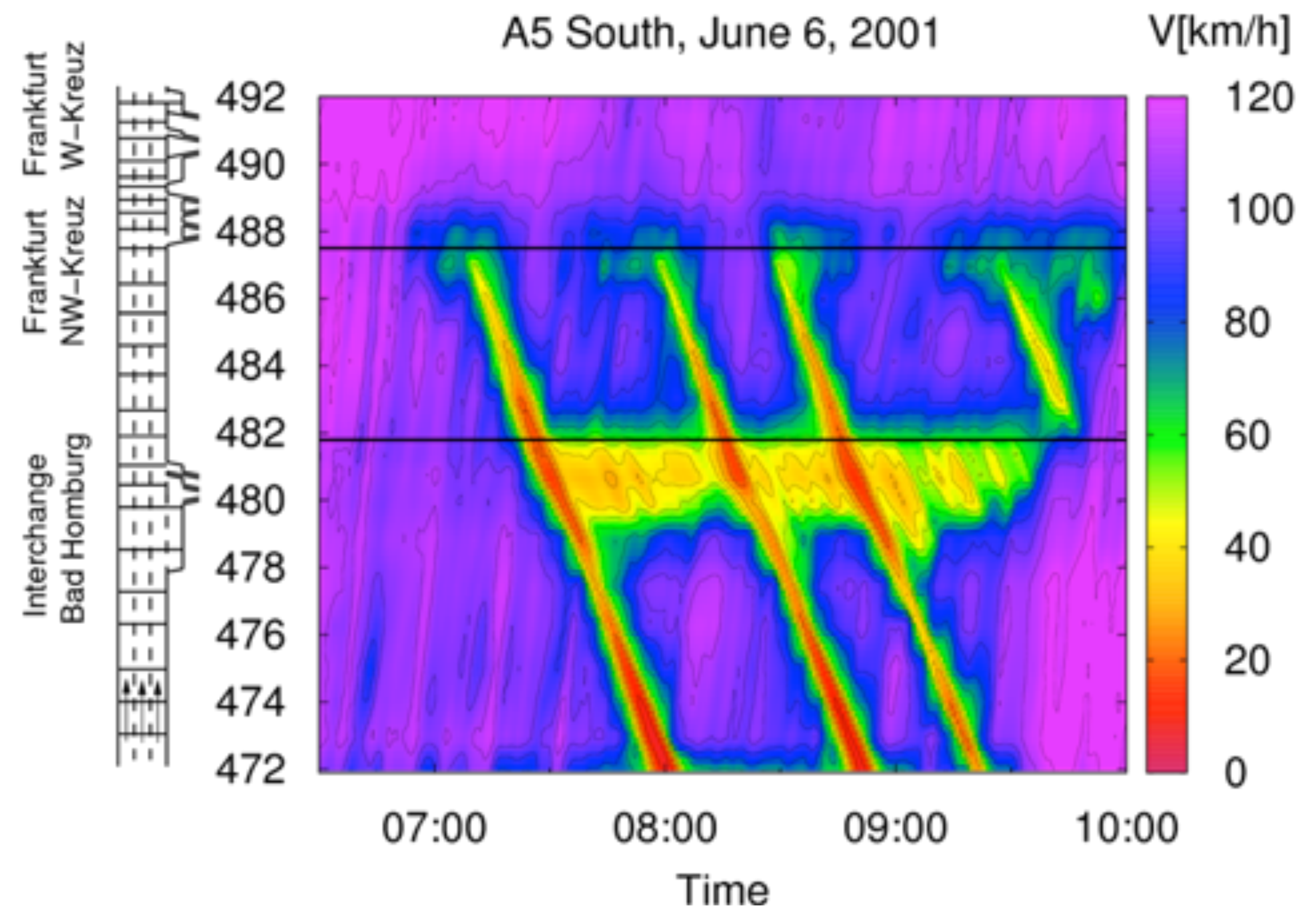

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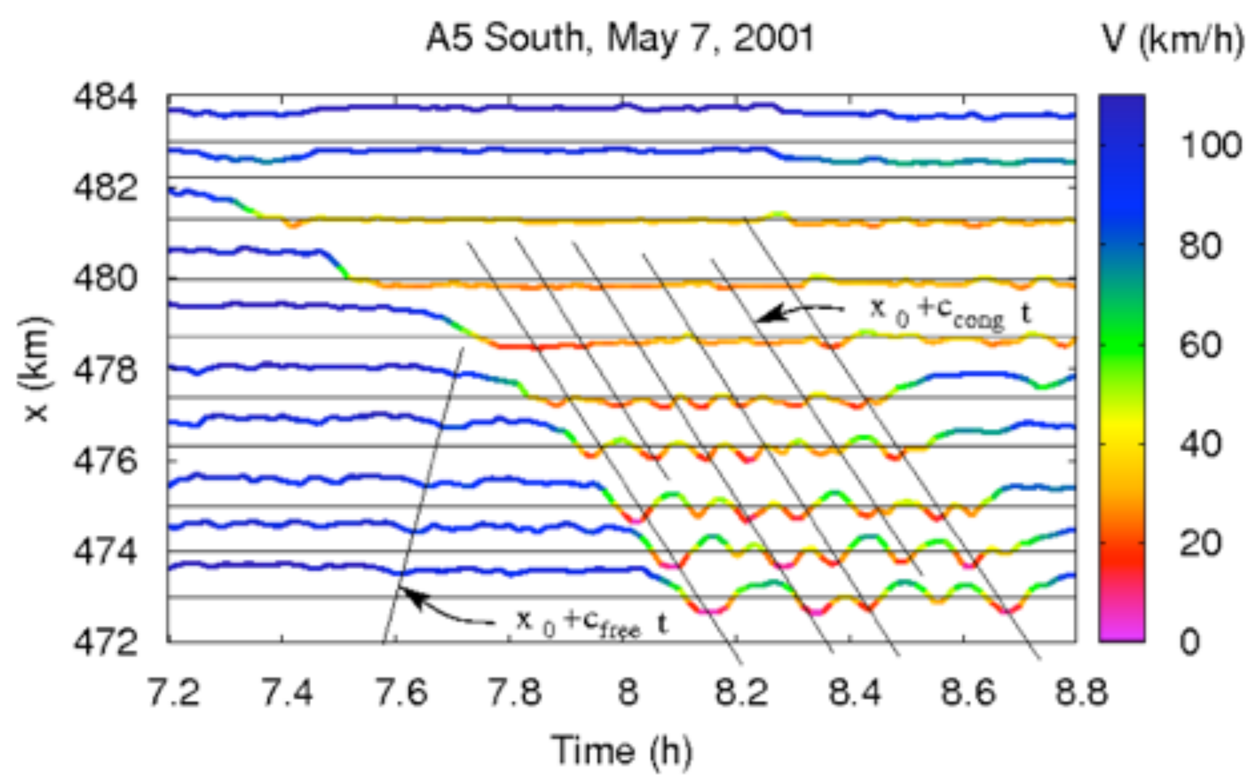
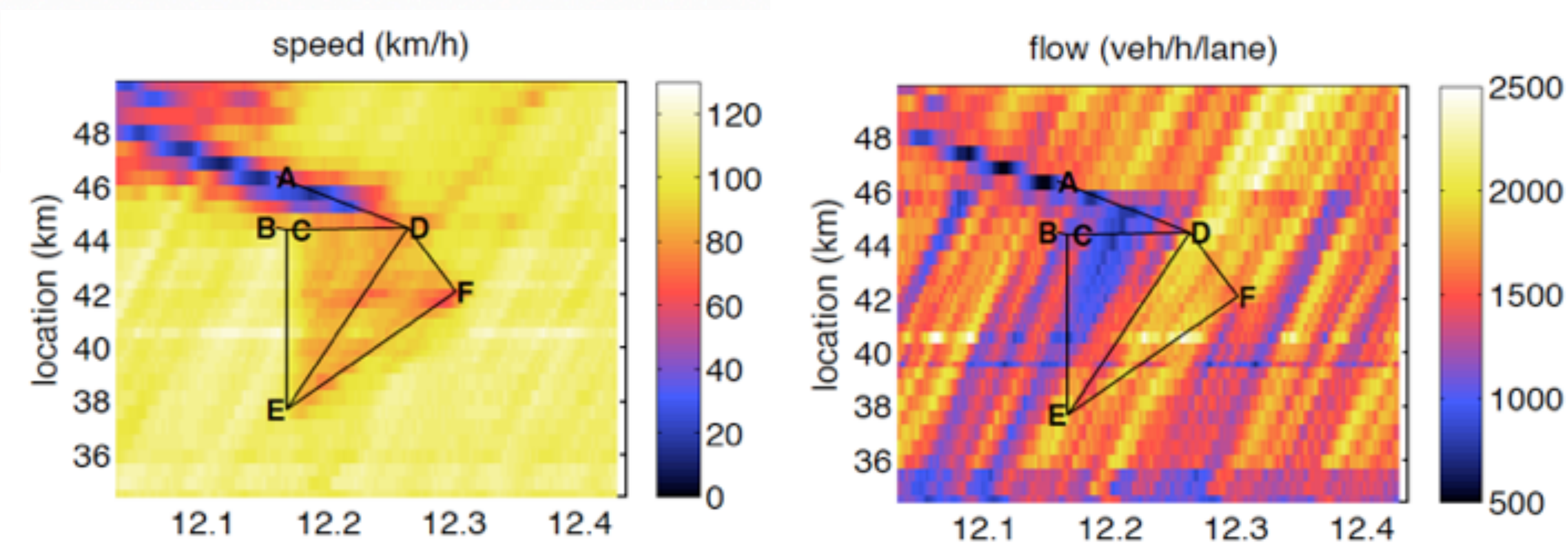


Example: using Specialist to remove wide-moving jams

- Specialist removes these jams by means of speed-limit control
- By reducing inflow into wave sufficiently and sufficiently long



- After tuning, we had 2.8 activations per day resolving the jam in 72% of the cases
- What limits number of activations?

- **How to increase the effectiveness of the local controllers considered?**
- In examples shown effectiveness of local controllers is limited due to limited buffer space (e.g. on-ramp, roadway stretch along which speed limit is applied)

Increasing effectiveness by coordination

Use 'control space' elsewhere in the network

But do it wisely!

Intermezzo: what we could not sell…

Model Based Predictive Control approaches

Computation time is not necessarily the problem…

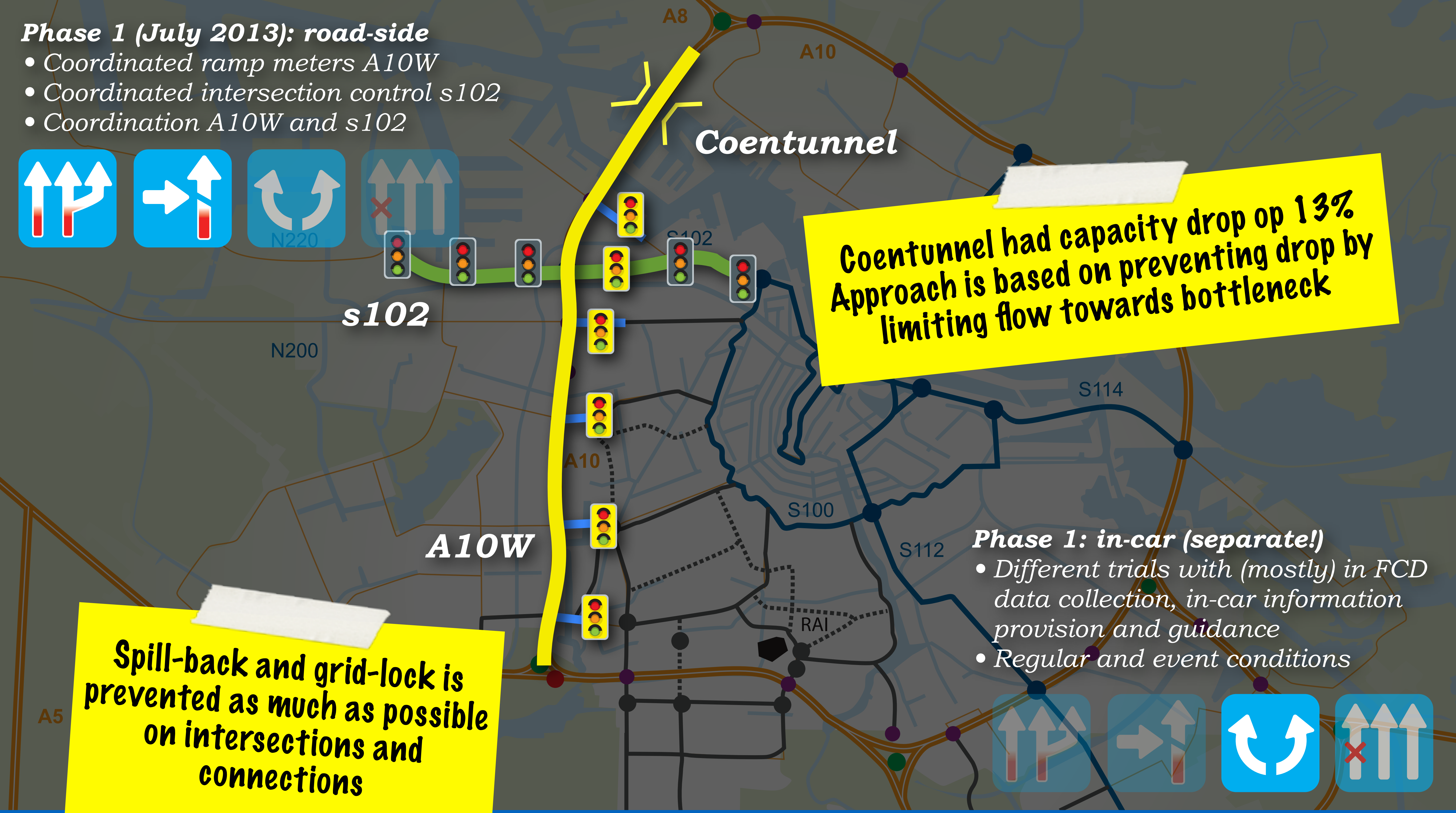
- Recent MPC-based network-wide control approaches with colleagues at Swinburne (with Tung Le, Hai le Vu, and Han Yu) allows including main phenomena observed in traffic flow (capacity drop, spillback, congestion dynamics)
- Formulation of the MPC problem as a LQ controller with inequality constrains can be solved efficiently using dedicated solvers (CPLEX)

$$\min \sum_{i=n}^{n+N-1} \widehat{X}_{D,R,Q}(i+1)' Q \widehat{X}_{D,R,Q}(i+1) + RU(i)$$

$$\text{s.t. } F_x \widehat{X}_{D,R,Q}(i) + F_u U(i) \leqslant g(i), \quad i = n, \ldots, n+N-1.$$

- Contributions of Le et al (2013), Yu et al (2015) on this subject available (send me an email)

Phase 1 (July 2013): road-side
- *Coordinated ramp meters A10W*
- *Coordinated intersection control s102*
- *Coordination A10W and s102*



Coentunnel had capacity drop op 13%
Approach is based on preventing drop by limiting flow towards bottleneck

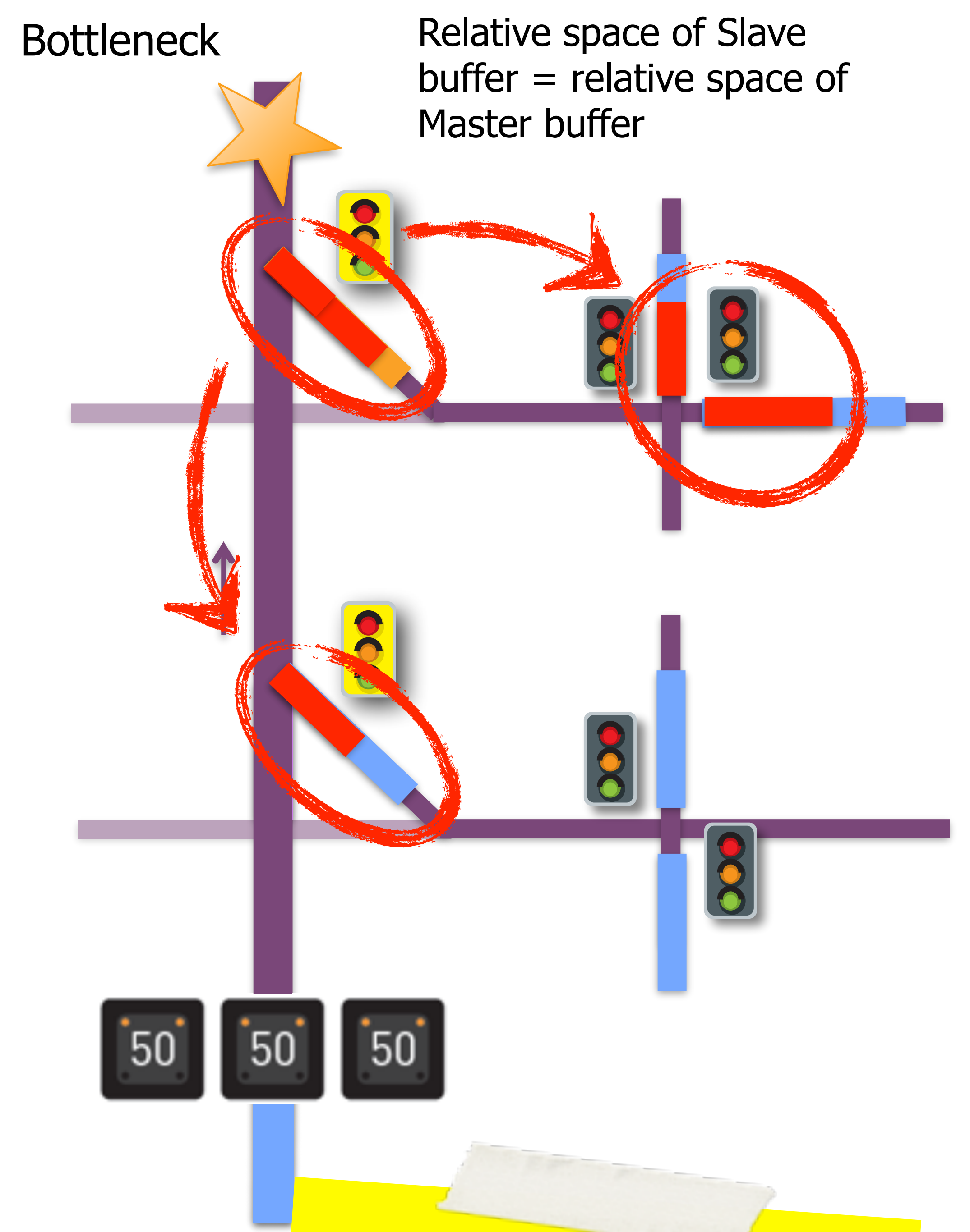
Spill-back and grid-lock is prevented as much as possible on intersections and connections

Phase 1: in-car (separate!)
- *Different trials with (mostly) in FCD data collection, in-car information provision and guidance*
- *Regular and event conditions*

Introducing the Praktijkproef Amsterdam

- Phase 1 focusses on A10W and s102 (this presentation)
- Phase 2 considers other locations + integration road-side / in-car (monitoring)
- Phase 3 considers integration road-side / in-car (control / actuation)

- Bottleneck is detected (or predicted)
- Nearby local measure starts resolving problem by deploying **local control approach**
- The local measure (Master) is supported by measures elsewhere (Slaves):
  - Slave ramp-meters limit flow towards bottleneck causing reduced flow on freeway
  - Slave traffic controllers limit flow to ramp
  - Slave VSL control reduces flow towards the bottleneck (using VMS or in-car devices)
- Ensure efficient distribution of queues over available buffers using feedback mechanisms (generalisation of HERO principe)



Note that similar approaches work on different types of bottlenecks

Increasing effectiveness by coordinatio

Use ‘control space’ elsewhere in the network

But do it wisely!

- Master ramp controller:

$$q_{ramp}(t+1) = q_{ramp}(t) + K \cdot (\rho^* - \rho(t))$$

- Slave ramp controller:

$$q_{ramp}(t+1) = q_{ramp}(t) + K_1 \cdot e(t) + K_2 \cdot \Delta e(t)$$

with: $e(t) = s^{rel}_{Master}(t) - s^{rel}_{Slave}(t)$

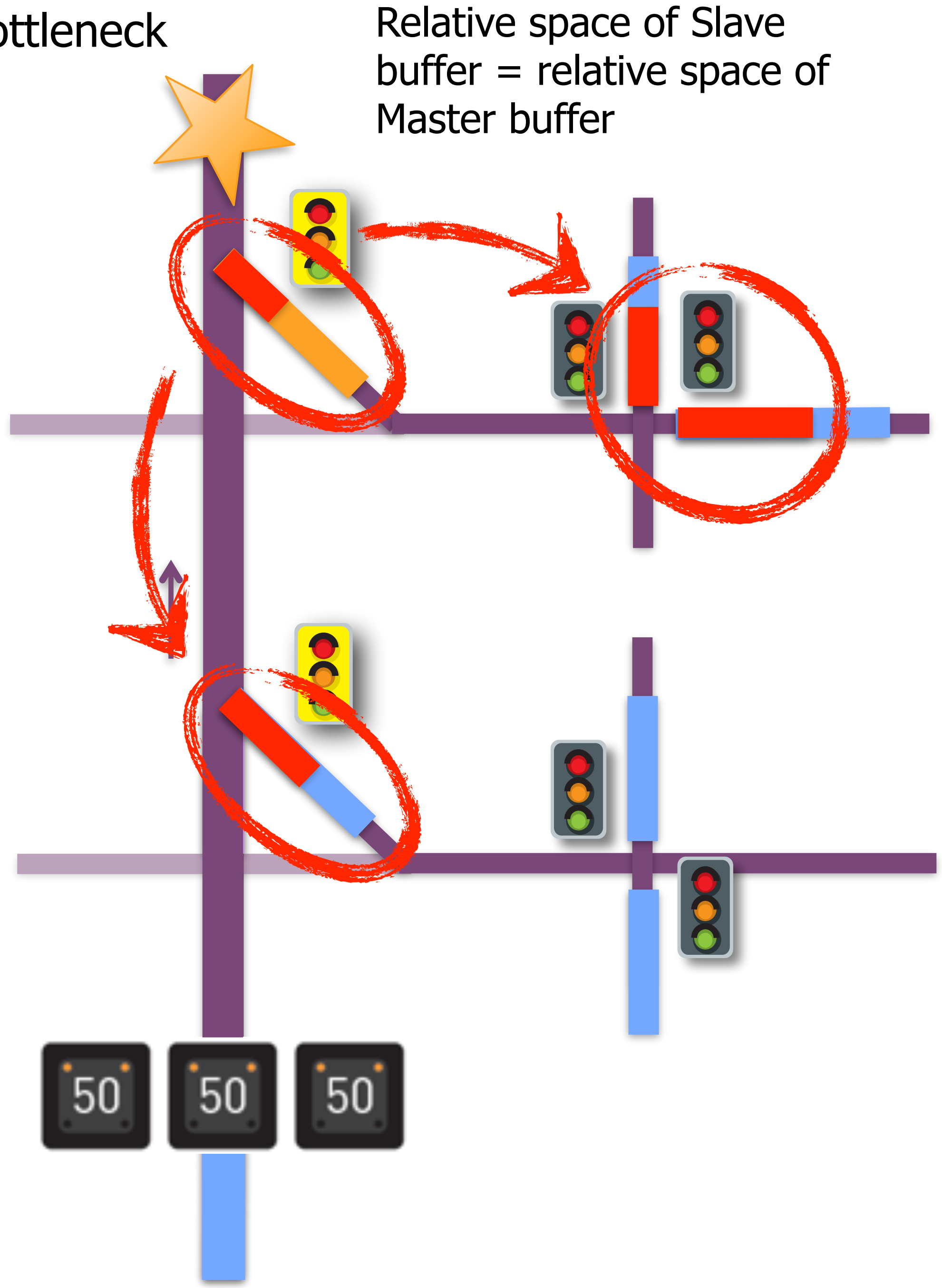
and: $\Delta e(t) = e(t) - e(t-1)$

- Intersection controller (adaptation of vehicle-response controller):

$$G^{ext}_j(t+1) = G^{ext}_j(t) + k_1 \cdot e(t) + k_2 \cdot \Delta e(t)$$

with: $e(t) = s^{rel}_{Master}(t) - s^{rel}_j(t)$

- VSL control (not implemented) based on changing region location



Increasing effectiveness by coordination

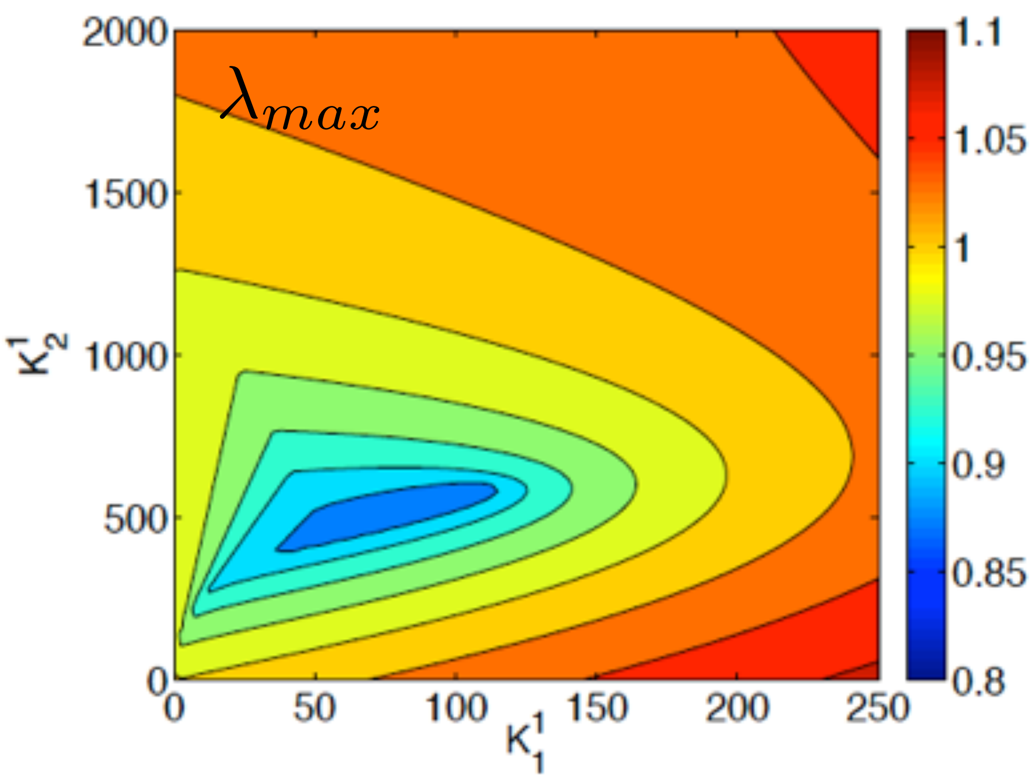
Use 'control space' elsewhere in the network

But do it wisely!

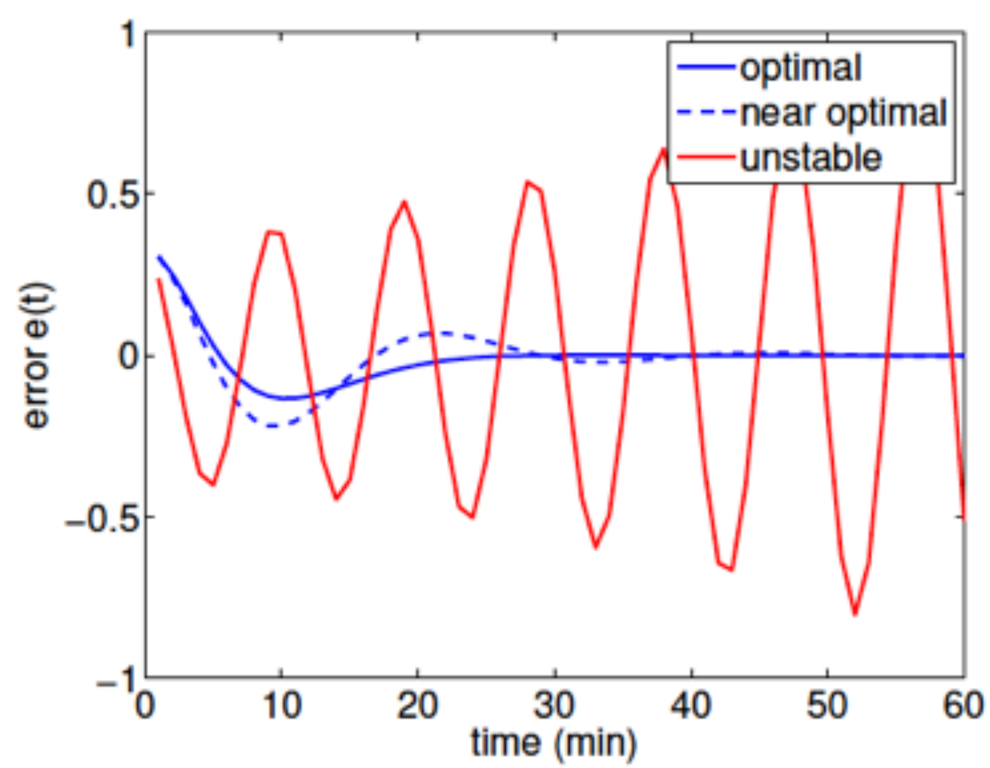
Before field deployment, system was analysed

- Tuning of control parameters
- Test in simulation environment (macroscopic models, microscopic simulation with Vissim)

- Tuning by naive trial and terror? We can do better!
- Using mathematical systems' theory to study convergence behaviour via max eigenvalue for gains K1 and K2 (TRB paper 2015): $|e(t+1)| \approx \lambda_{max} \cdot |e(t)|$



Eigenwaarde shows speed of convergence (blue is better)



Example of controller behaviour for three choices of (K1,K2)

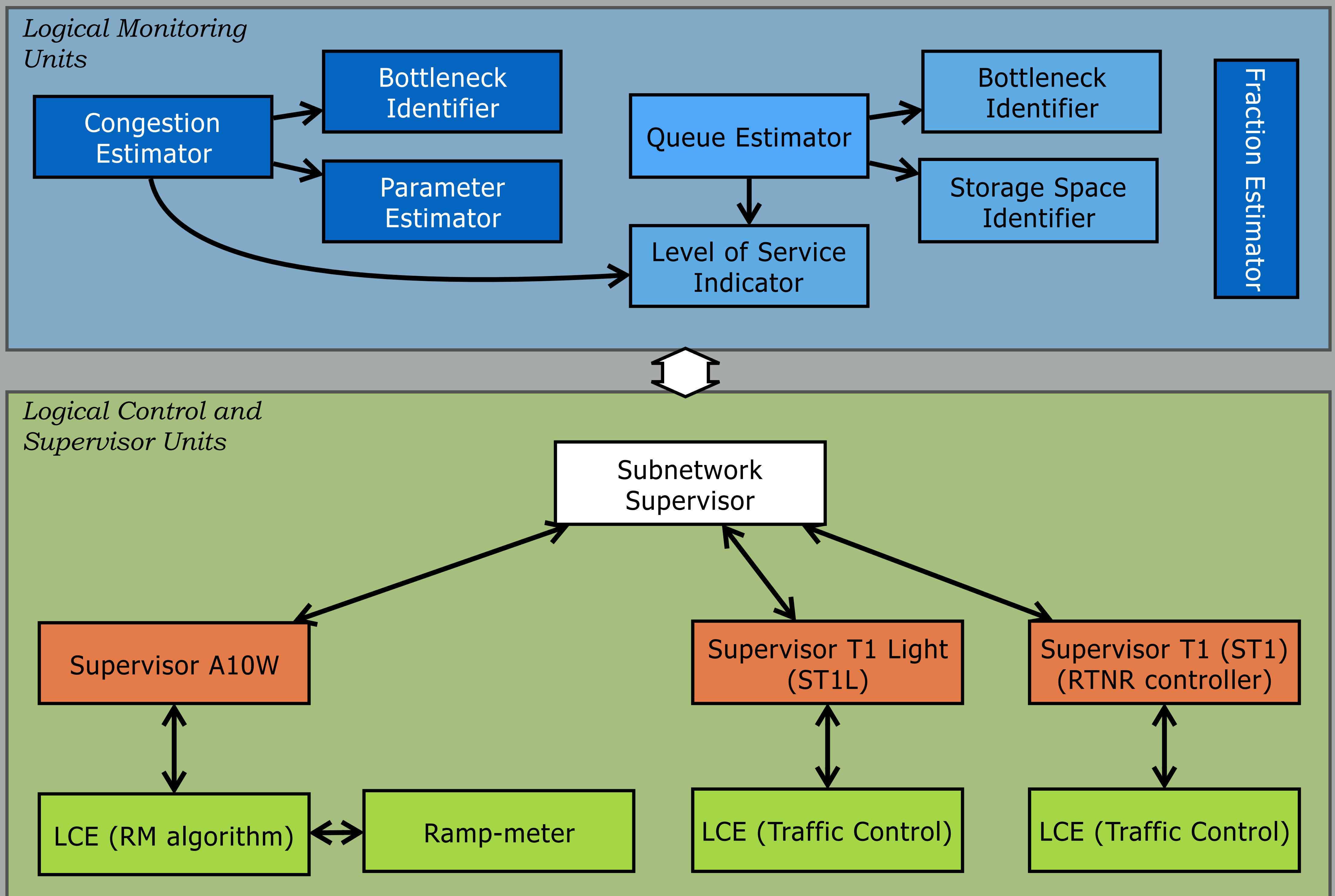
Which monitoring and control functions are needed?

Towards a functional architecture and design

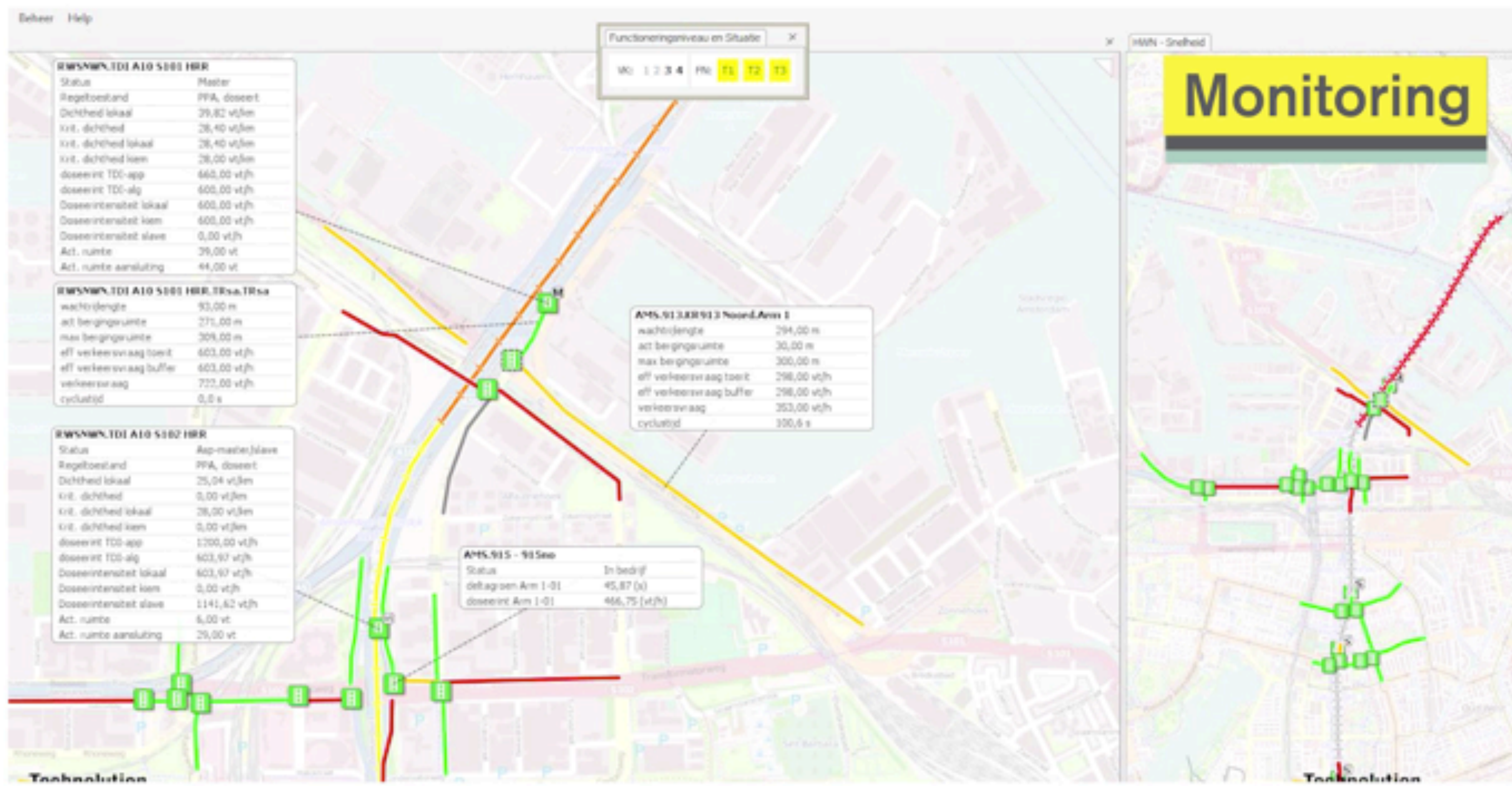
• Detect or predict occurrence of a bottleneck (3-5 minutes ahead)	Bottleneck Identifier
• Determine ramp-metering control target (e.g. critical density)	Parameter Estimator
• Estimate queue lengths on-ramps and urban arterials	Queue Estimator
....	
• Determine metering rate at the Master ramp	LCE (RM algorithm)
• Determine which buffers to use for coordination support	Subnetwork Supervisor
• Determine metering rate of the Slave ramp meters	Supervisor A10W
• Determine extension green Traffic Controllers for rel. buffers	Supervisor T1 (ST1) (RTNR controller)

Distinguished monitoring and control functions

The Functional Architecture of the PPA system



- PPA substantially improves freeway throughput (daily reduction delays of 300 veh-h)
- Increase delays on urban arterials, can be reduced by about 80% by better tuning and configuring system and by use of in-car technology / data fusion
- Expected gross impact of 220 veh-h on daily basis (around 1 million Euro/year)



S102-Transformatorweg

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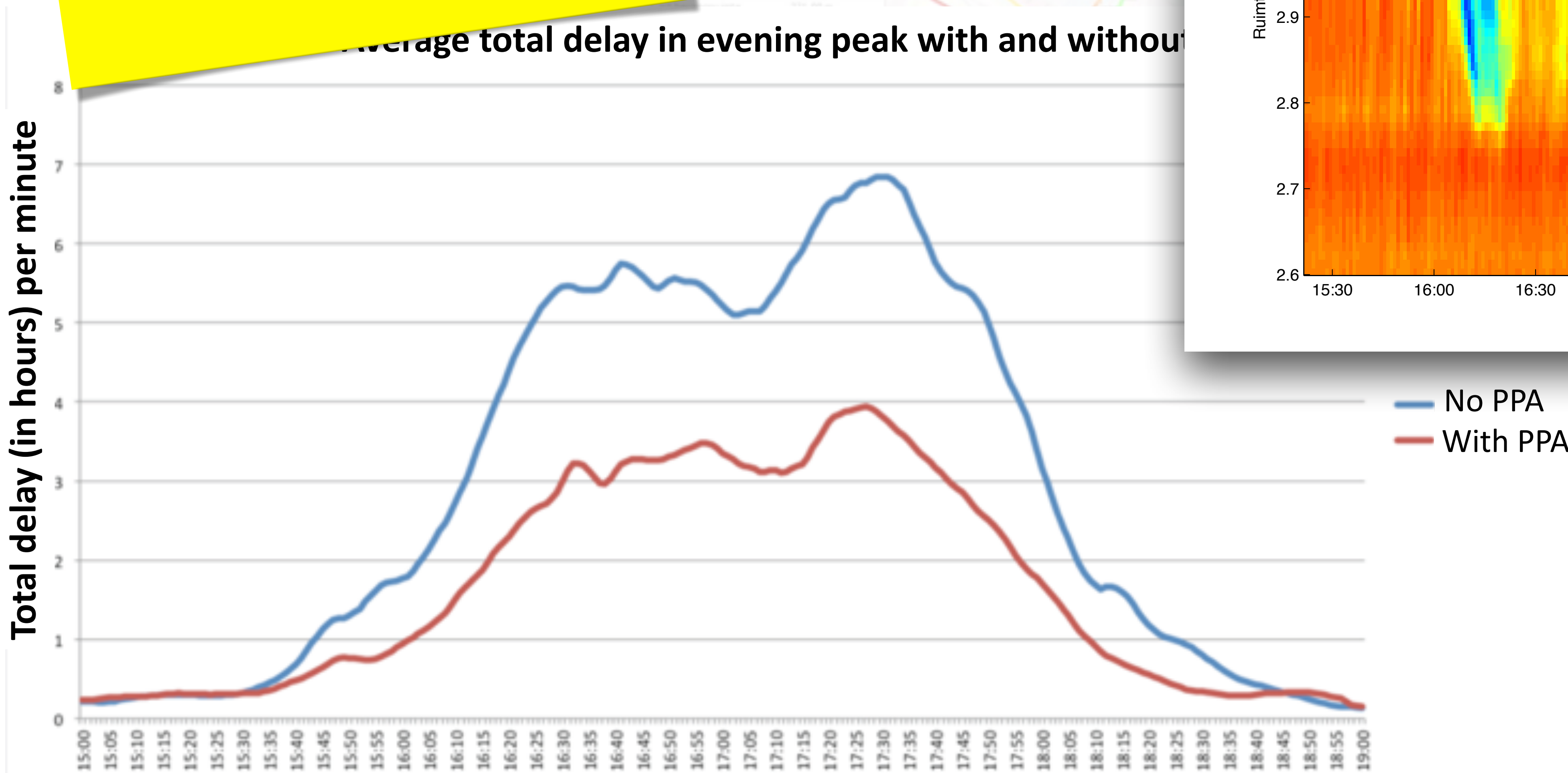
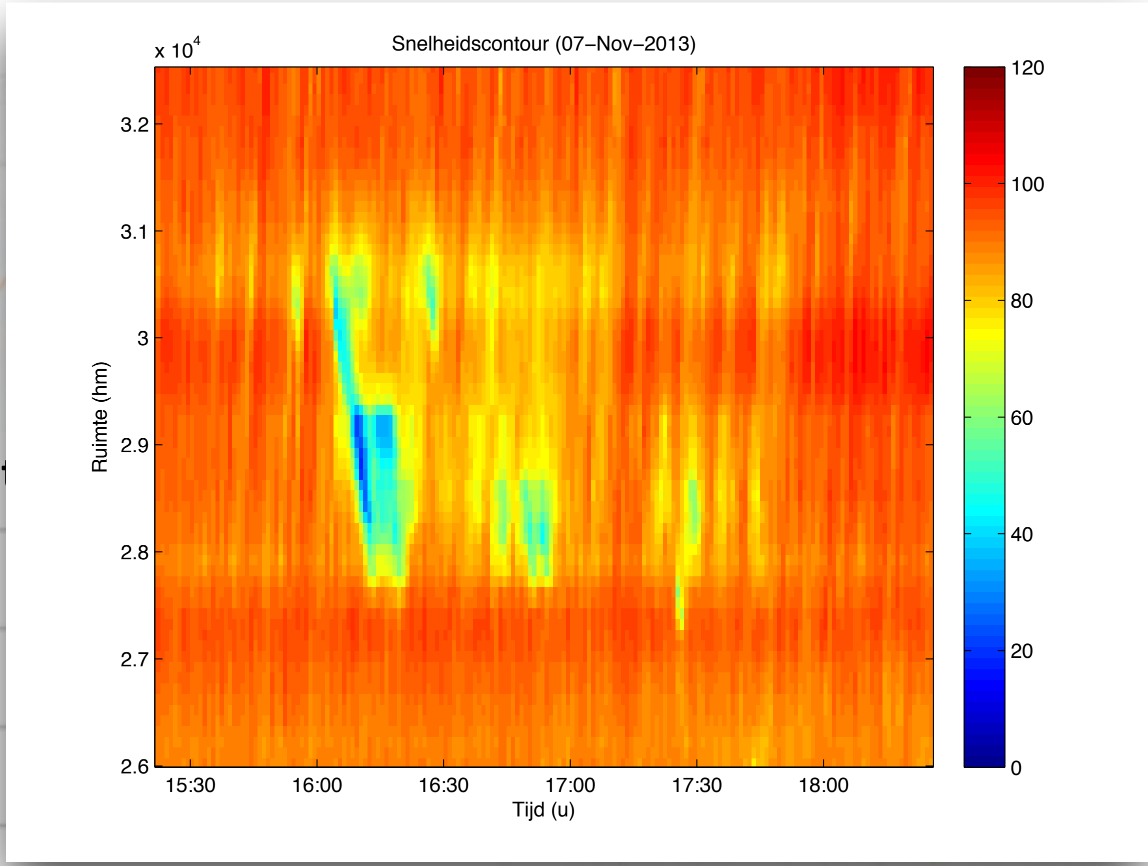
Coordination allowed us to meter 3-5 times longer than with local metering





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Picture shows locations where delays improved or got worse

Correction for demand levels for considered days

Lessons learnt from phase 1 of the pilot

Value of carefully assessing impacts

Steps towards phase 2 of the pilot

- Overall conclusion: advanced INM is feasible
- Careful and thorough analysis of the outcomes has led to a number of important lessons, amongst which are the following:
  1. The value of prediction and good monitoring approaches
  2. Bottleneck diversity
  3. Buffer effectiveness
- These lessons **are effectuated in phase 2** of PPA, where also integration with in-car data collection will be considered…
- Let’s take a closer look at these improvements…

Lessons learnt from phase 1 of the pilot

The value of prediction and good monitorin

Steps towards phase 2 of the pilot

Can models predict on-set of congestion with a sufficiently high probability given high variation is demand and supply?
How to effectively use models?

- Bottleneck inspector used advanced data mining
  modelling to predict if in the next 3-5 minutes c
  which the system would start intervening
- Due to high change of false positives, the system generally started too soon (our data analysis shows 34 minutes too soon) with reducing inflow / filling up buffers
- Overall result: expected reduction delays on urban network of around 40% due to
  - removing unnecessary delays on on-ramp and urban arterials
  - increasing effectiveness ramp metering (since one buffer space was needed, part was already used)
- **In phase 2 we therefore refrain from use of prediction** (for this type of bottleneck)**, instead opting for timely detection of bottleneck instead**

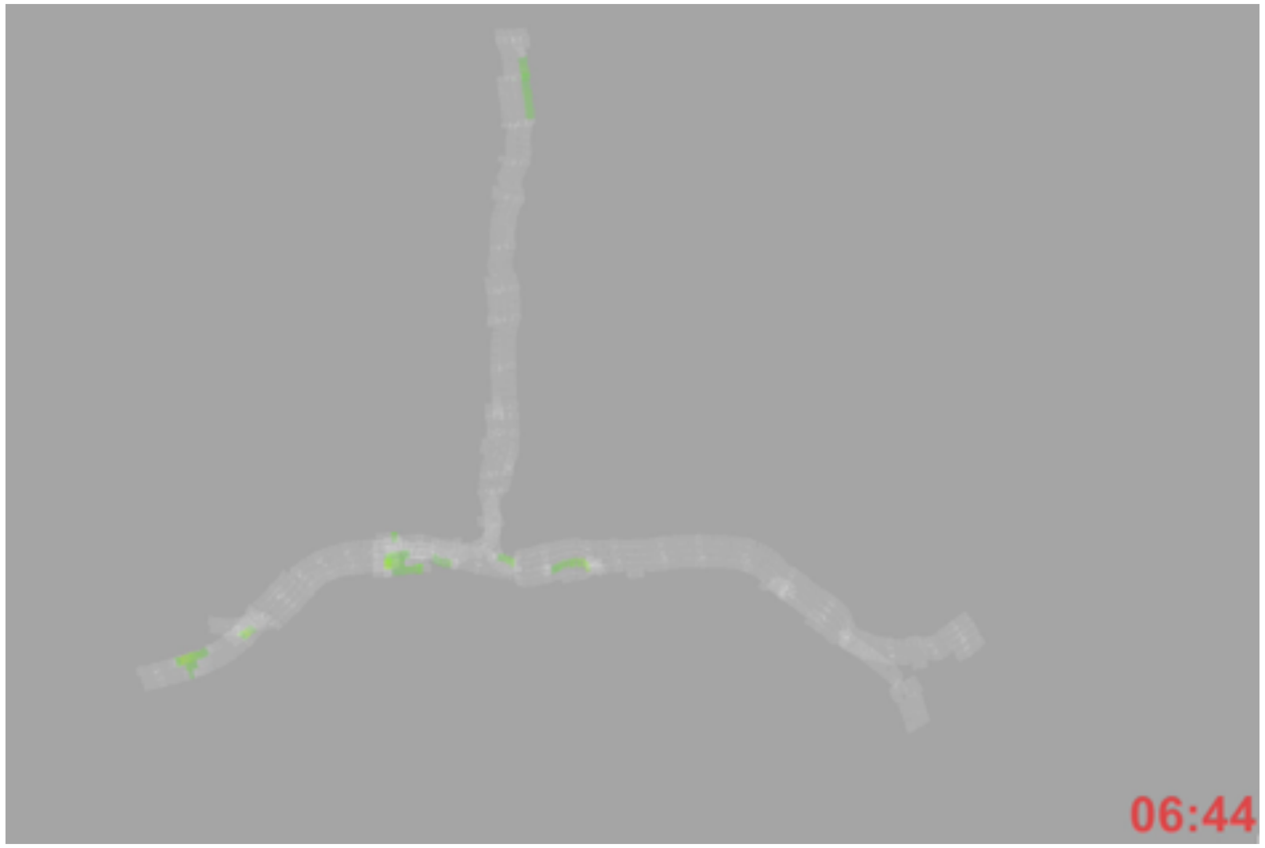
Lessons learnt from phase 1 of the pilot

Bottleneck diversity

Steps towards phase 2 of the pilot

- Approach cannot distinguish between on-ramp bottleneck, spill back from downstream bottleneck, or congestion due to incidents
- Control strategy is not dependent on bottleneck type (also holds for local meas.)
- In case of incident, normal strategy will not be effective in removing problem

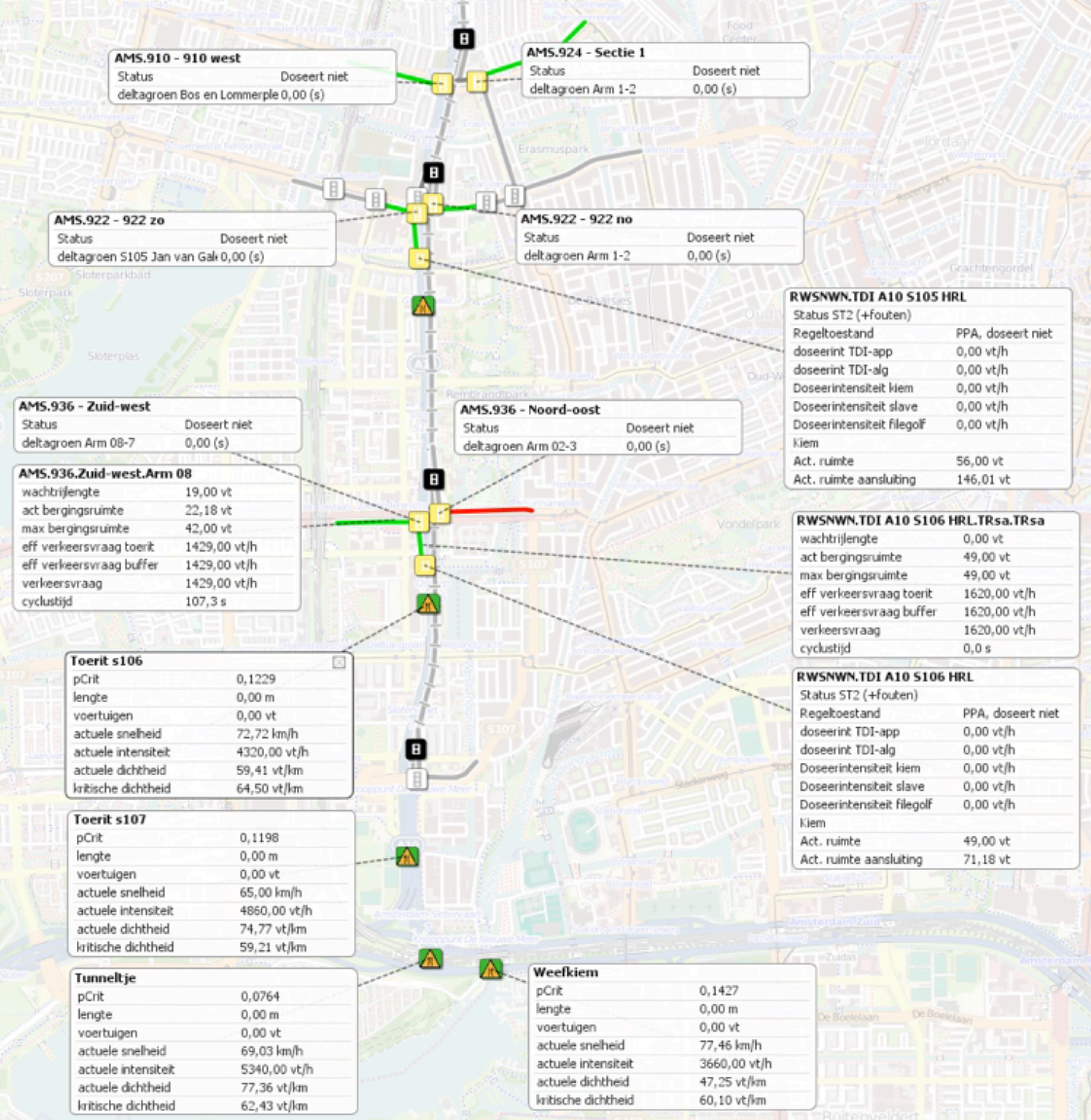
- **In phase 2, bottleneck inspector will distinguish between different types of bottlenecks and control strategy will be dependent on it**
- Example shows different bottlenecks that occur (on-ramp queue, merge queue, wide-moving jam)



PPA phase 2

Bottleneck diversity

- Animation shows the GUI developed for phase 2
- Approach can deal with four types of congestion using separate control strategies (weaving areas, infrastructure bottleneck, on-ramp bottleneck and wide-moving jam)
- Animation shows different types occurring during the morning peak



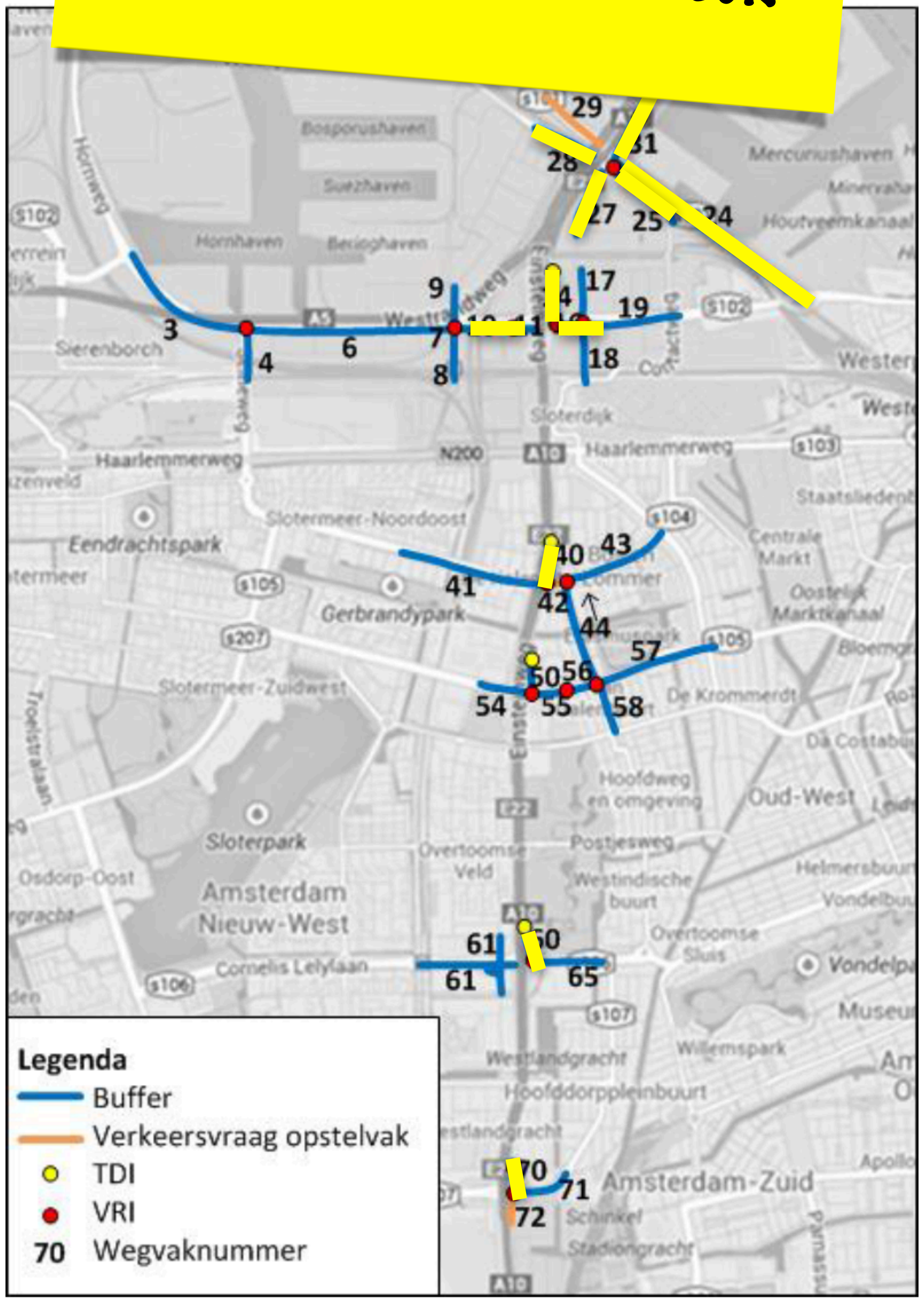
Lessons learnt from phase 1 of the pilot

Buffer effectiveness

Steps towards phase 2 of the pilot

In general, effective buffers are only found in proximity of bottleneck

- We determined that for each vehicle we held back for 1 min, we save 2 veh-min delay on the freeway
- This means that for buffers with less than 50% of the vehicles actually traveling to the bottleneck the delay we incur is actually larger than the improvement we make
- Large share of the buffers were not effective at all! Additional reduction of urban delays with about 42%
- **Phase 2 will involve the use of FCD data to determine the actual shares and include / exclude buffers dynamically**



Transitions in Traffic Management

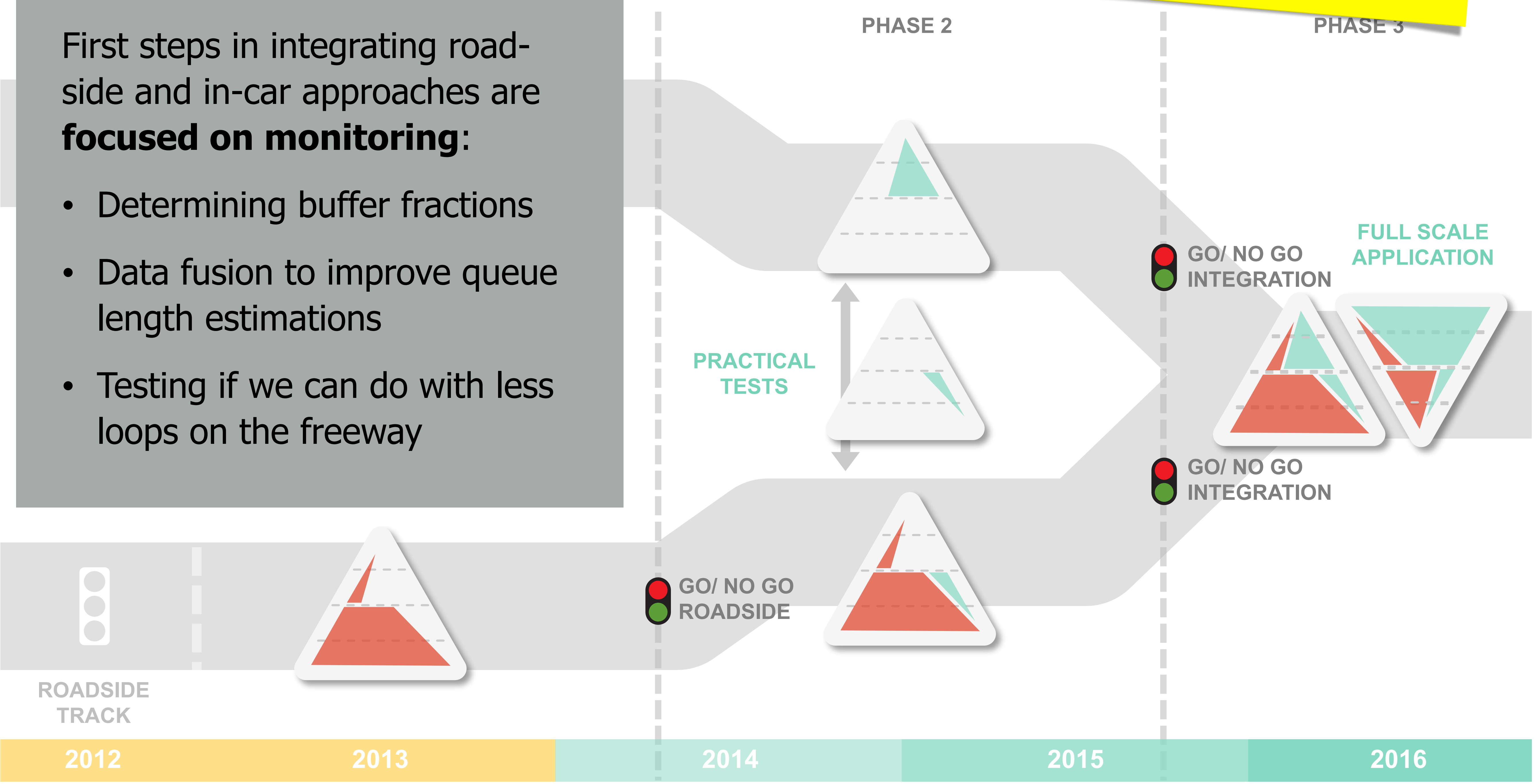
Combining road-side and in-car approaches

Steps towards phase 2 of the pilot

What about phase 3?

First steps in integrating road-side and in-car approaches are **focused on monitoring**:

- Determining buffer fractions
- Data fusion to improve queue length estimations
- Testing if we can do with less loops on the freeway

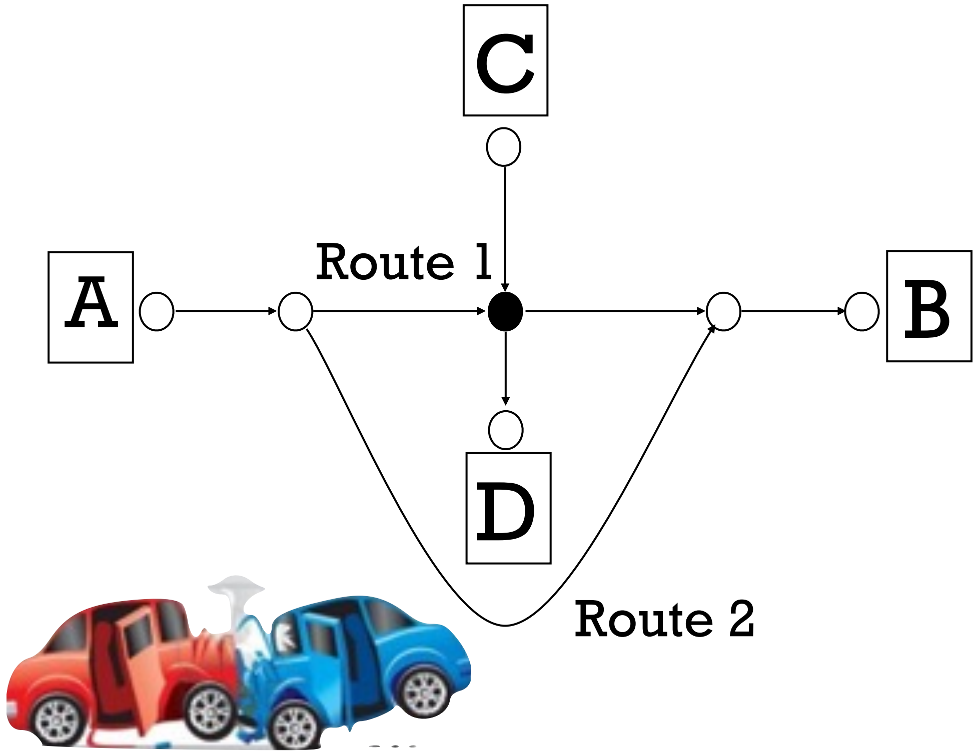


A Simple Quiz

Anticipating Intelligent Intersections

Need of including traveler response into the design

- Case with 2 OD pairs and perfectly informed traveler from A to B having 2 options
- Intelligent intersection controller optimises locally capacity use at intersection evenly (equal delays for both directions)
- Most travellers choose route 2 under normal circumstances
- Event (incident) occurs; flow conditions route 2 worsen (from 120 to 80 km/h)



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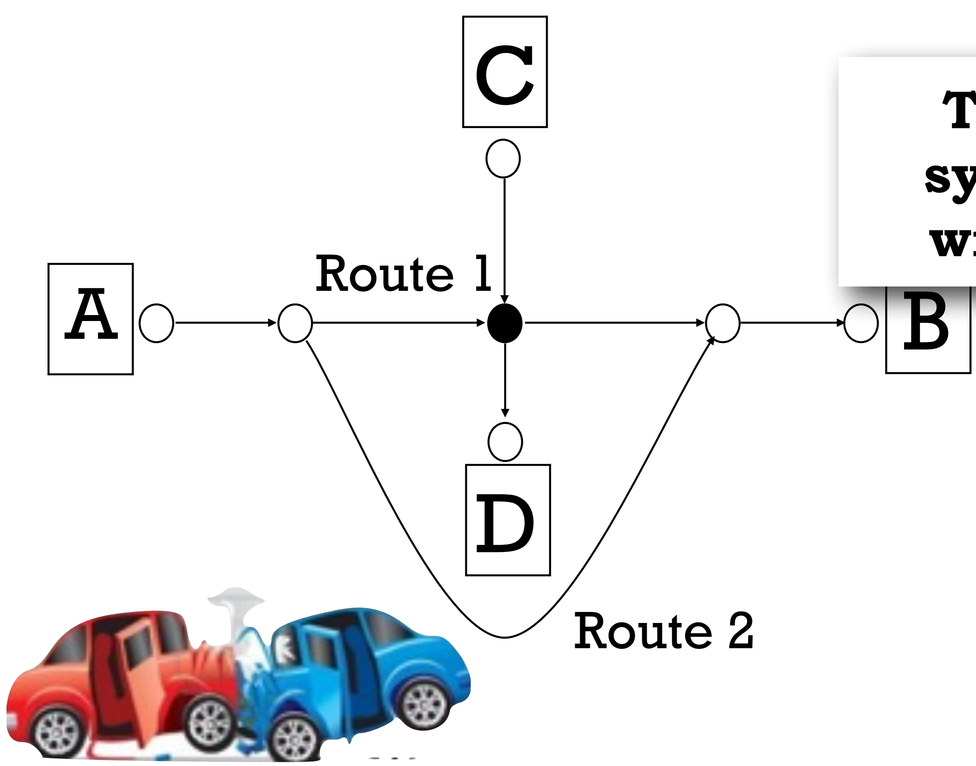
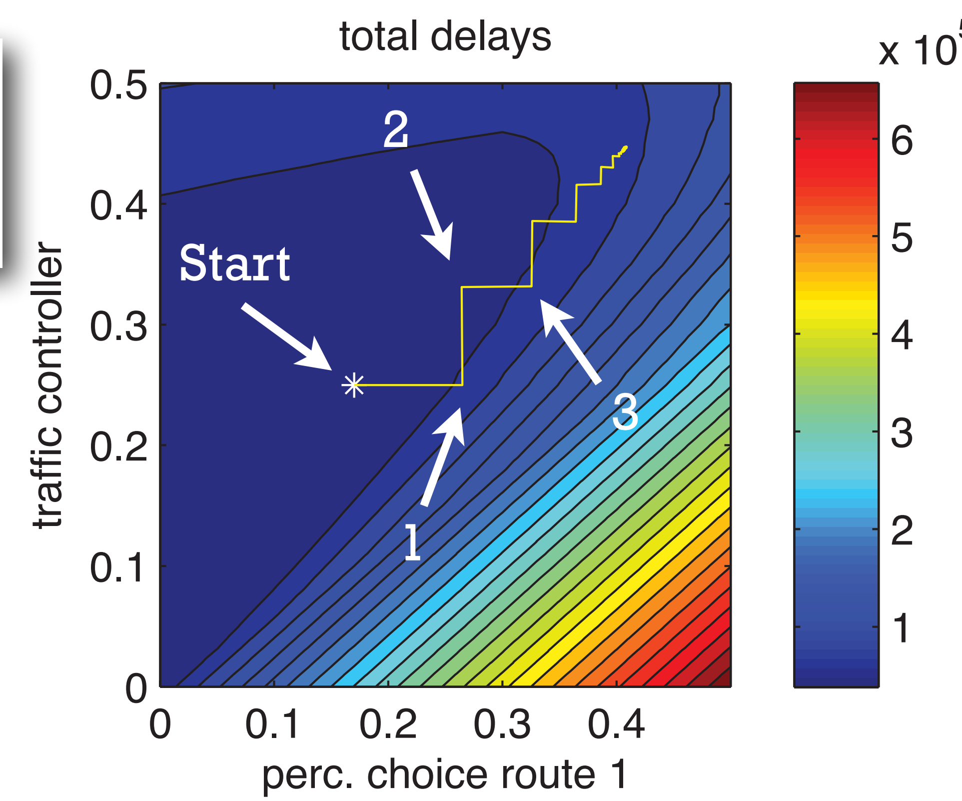


Total delays in system increase with about 30%



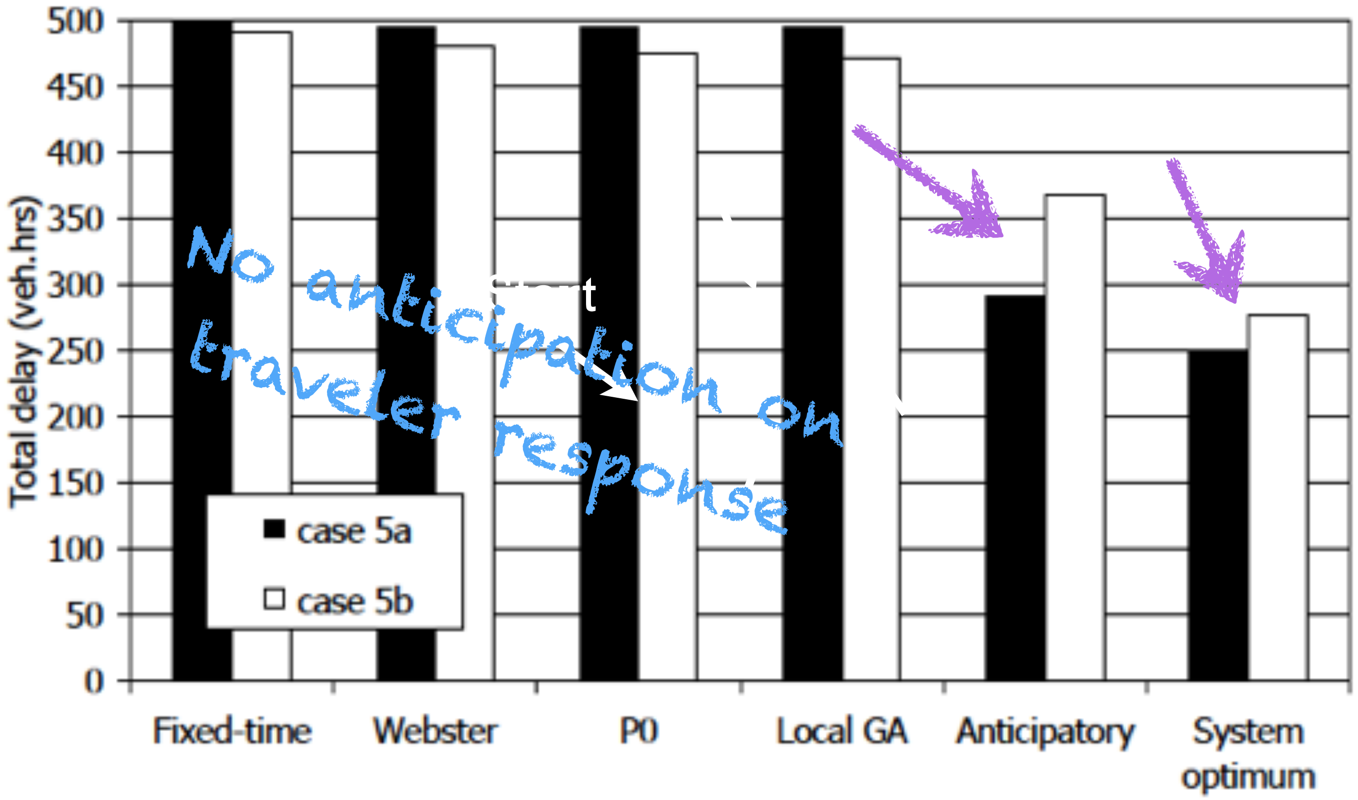
A Simple Quiz

Anticipating Intelligent Intersections

Need of including traveler response into the design

- Data fusion is in-car and road-side data is not the only opportunity!
- **Anticipatory network management**: optimise traffic management and control measures anticipating on the impacts it has on travel decision
- Theoretical studies show that we can get very close to system optimum
- Future use of the 'car' as a traffic management measure

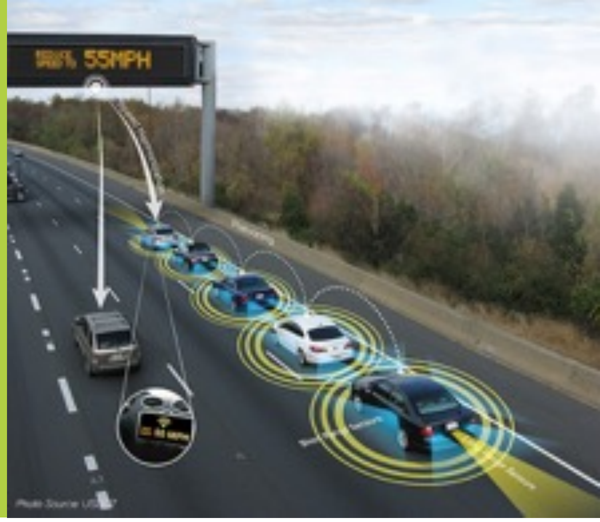
Conclusion: intelligent intersection control can be designed to achieve good network performance if it anticipates correctly on travel responses due to advanced information services



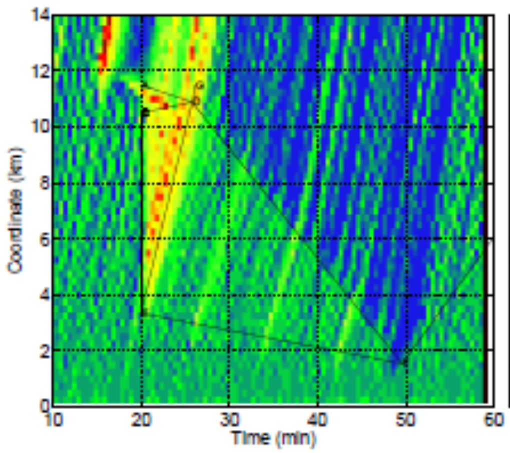
Cooperative version of Specialist

Application of shockwave suppression algorithm

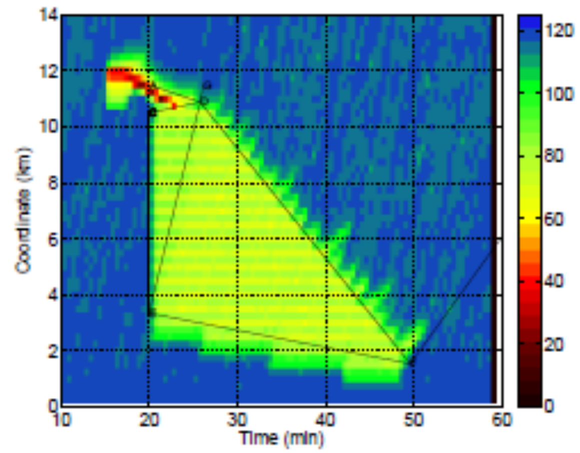
V2I approach allows application at different penetration rates



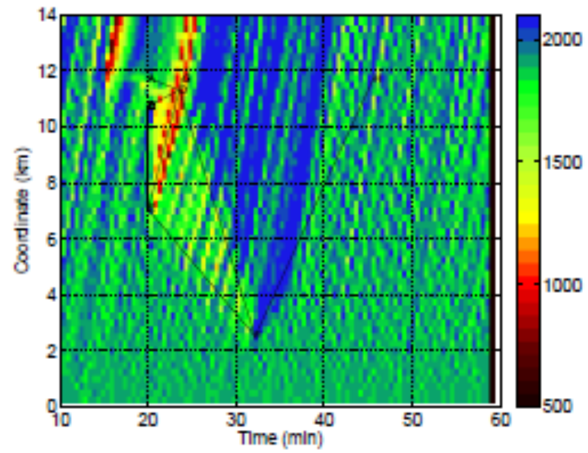
- Important note: **modification of Specialist control algorithm required** to incorporate changes in flow operations for different penetration levels



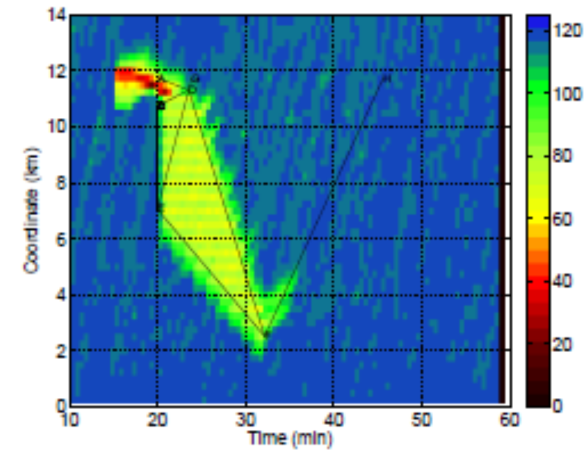
(a) Flow of scenario 6 (0% ACC)



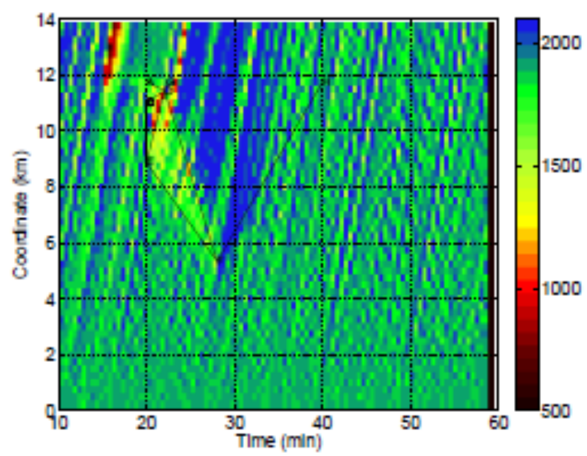
(b) Speed of scenario 6 (0% ACC)



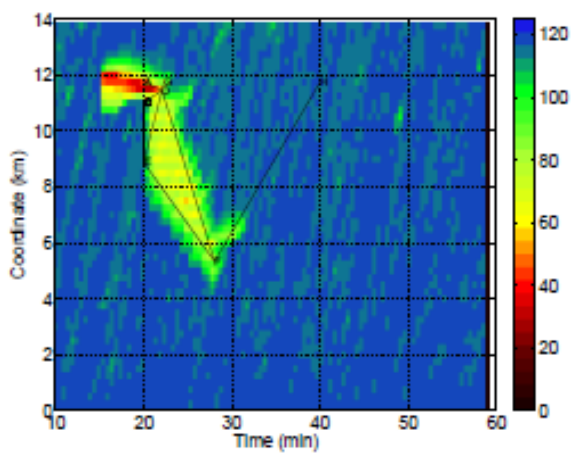
(c) Flow of scenario 7 (5% ACC)



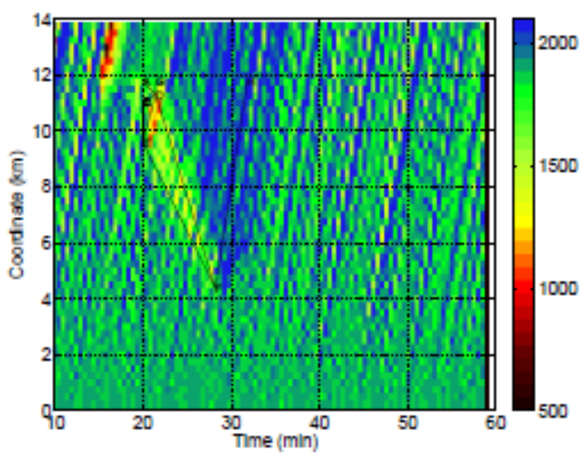
(d) Speed of scenario 7 (5% ACC)



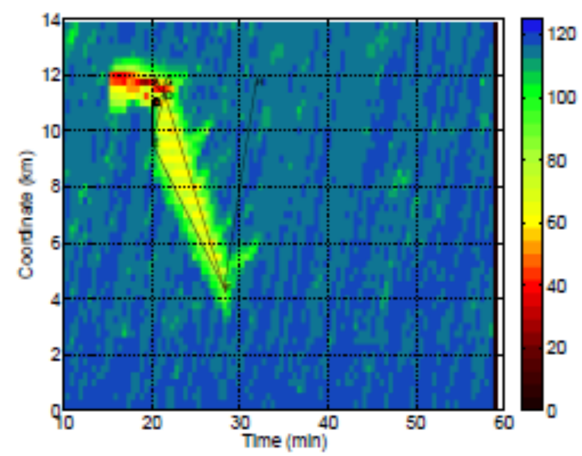
(e) Flow of scenario 8 (10% ACC)



(f) Speed of scenario 8 (10% ACC)



(g) Flow of scenario 9 (50% ACC)



(h) Speed of scenario 9 (50% ACC)

Closing remarks

Lessons learnt and future steps

And some other considerations

- Presented approach has been successfully generalised to other bottlenecks (including spill-back), including those on urban roads
- Work presented is aimed at developing methods that can be applied in practise, which has implications for transparency and allotted complexity
- Questionable if “adding complexity” will yield major improvements:
  - In practise, relation between buffers and bottleneck becomes weak quickly (in a spatial sense) so controlled subnetworks are relatively small
  - Stochasticity in demand and supply makes it very hard to predict moment of congestion on-set and thus limits applicability of prediction models (not saying that they are of no use!)
- Queue estimation (with loops) turned out to be a major challenge, consider use of alternative monitoring technology or other control variables (which?)
- Concepts are not only applicable to vehicular traffic…

“There are serious limitations to the self-organising abilities of pedestrian flow operations”

Efficient self-organisation

Faster = slower effect

Blockades and turbulence

Reduced production of pedestrian network

Flow operation ‘self-degradation’ also occurs in pedestrian flow

- Dilute pedestrian traffic organises itself very efficiently (bi-directional / crossing flows)
- When network loads increase, phenomena occur that severely reduce production
- Need for crowd management!

Crowd Management Dashboard

- Generate and visualise information to support operations and analysis (during the day, after each day), by…
- Collecting real-time data about pedestrian flows (travel times, crowdedness, route choice, background visitors)
- Combining these multiple sources to get best picture of current situation, overcoming limitations of individual data sources

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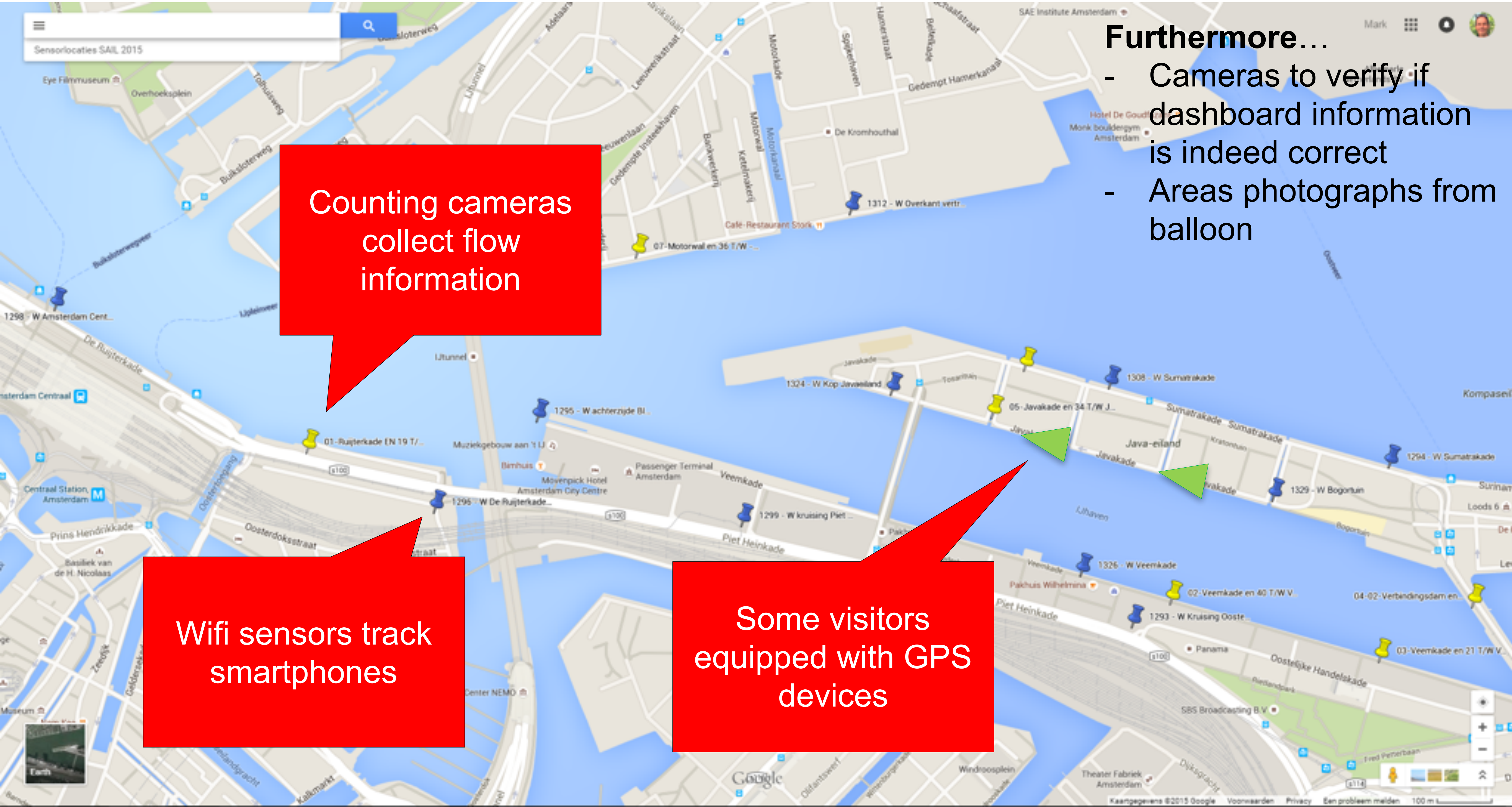
REAL-TIME DATA COLLECTION USING MULTIPLE SOURCES

Social Media data (social-media activity per area, visitor characteristics)



Counting cameras collect flow information

Wifi sensors track smartphones

Some visitors equipped with GPS devices

Furthermore…

- Cameras to verify if dashboard information is indeed correct
- Areas photographs from balloon

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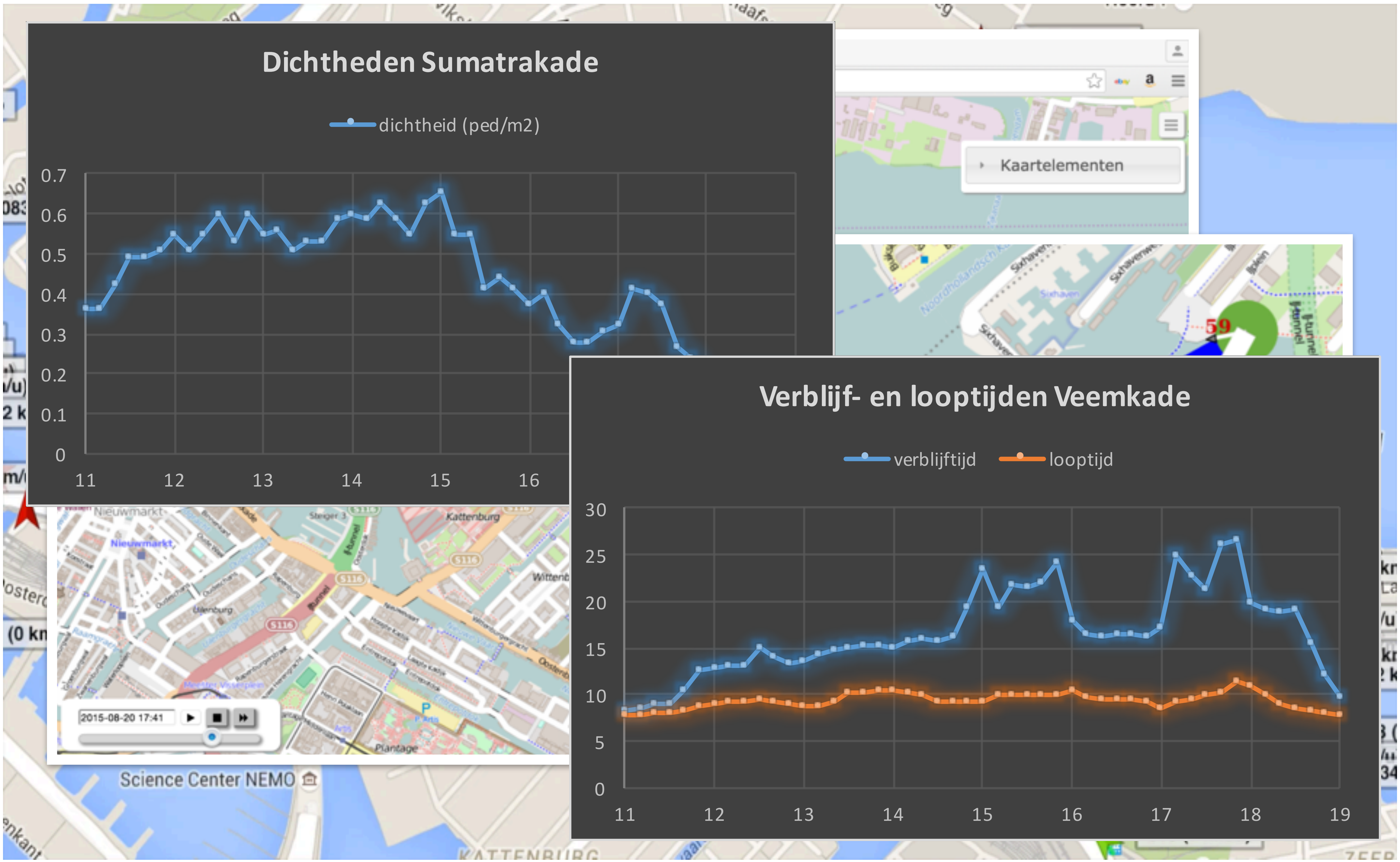
EXAMPLE PILOT STUDY RESULTS



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RESULTS OF PILOT

Future research steps…

- Validated and generic system that will work for 'any' outdoor (& indoor) event / regular situation
- Trial **prediction capabilities** to warn crowd managers in advance for risky situation
- Visitor information provision (signs, Smartphone)
- Provide advice to crowd managers on which measures to deploy
- Support **optimal use** of available infrastructure for safe and comfortable stay in city

Practical Pilot Amsterdam

Putting 20 years of research to practice

Prof. dr. Serge Hoogendoorn, Delft University of Technology

Questions

TU Delft