

Multi-lane traffic: lane change control in theory and practice

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6 February 2023



Scope and relevance

- Cost of traffic jams: several billion euros/yr (10^9)
- Cause: traffic demand exceeds capacity
- Measures to improve road capacity and road use
- How will they work?



Single lane traffic

- The capacity directly relates to the distance between two vehicles
- Much already known

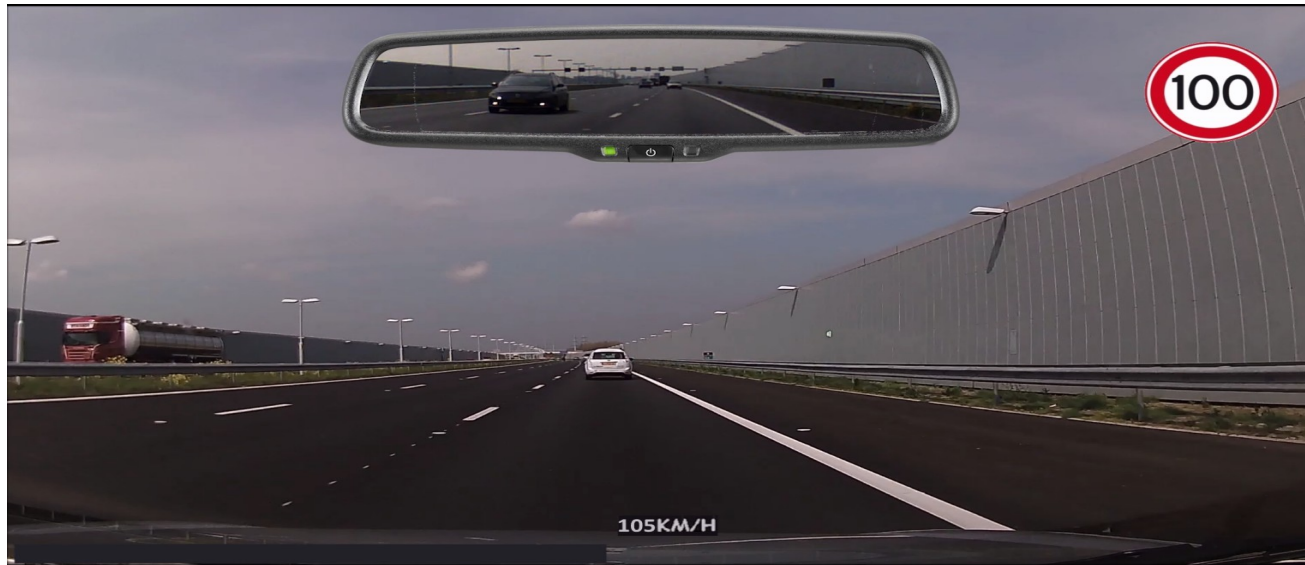
Multi-lane traffic:

- Inefficiency in lane usage (not all lanes are fully used)
- Traffic jams due to merging/ lane changing
- Many unknowns
- In practice, most relevant



Multi-lane traffic

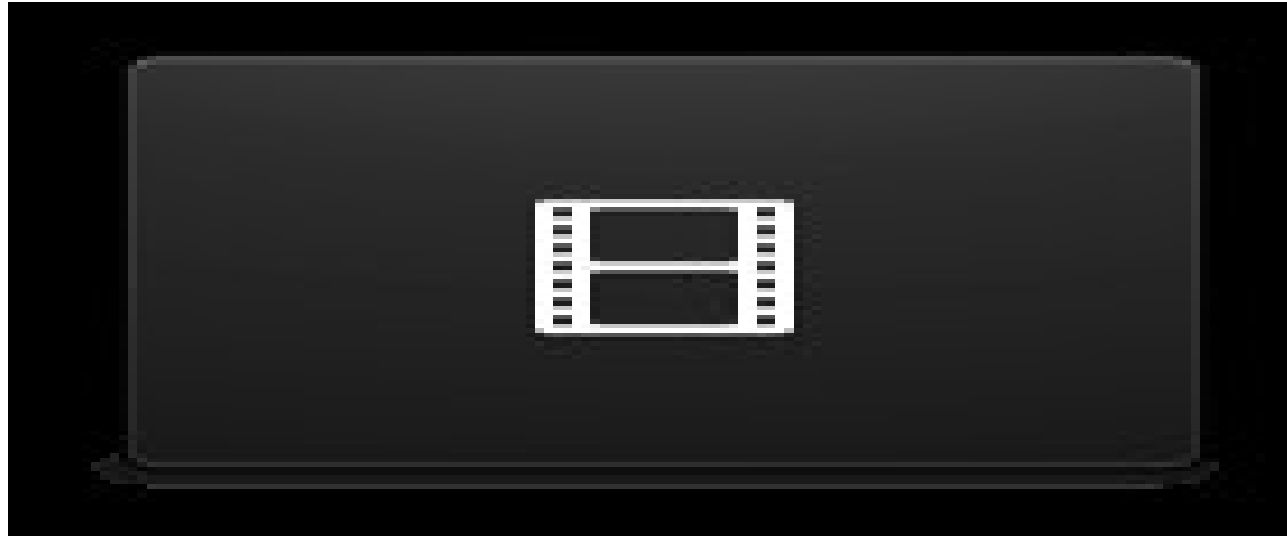
- Inefficient: at busy conditions, many choose the left lane
- How do lane change decisions work?



You are at the right lane, driving at your desired speed. You approach the white car, and the black car passes you at higher speed. What will you do?

Multi-lane traffic

- Choice of lane



You are at the right lane, driving at your desired speed. You approach the white car, and the black car passes you at higher speed. What will you do?

- A. I remain in this lane and will adapt my speed
- B. I change lanes and will keep my current speed
- C. I change lanes and will (temporarily) increase my speed to overtake the white car
- D. I change lanes and increase my speed and will keep following the black car

Dynamic traffic control

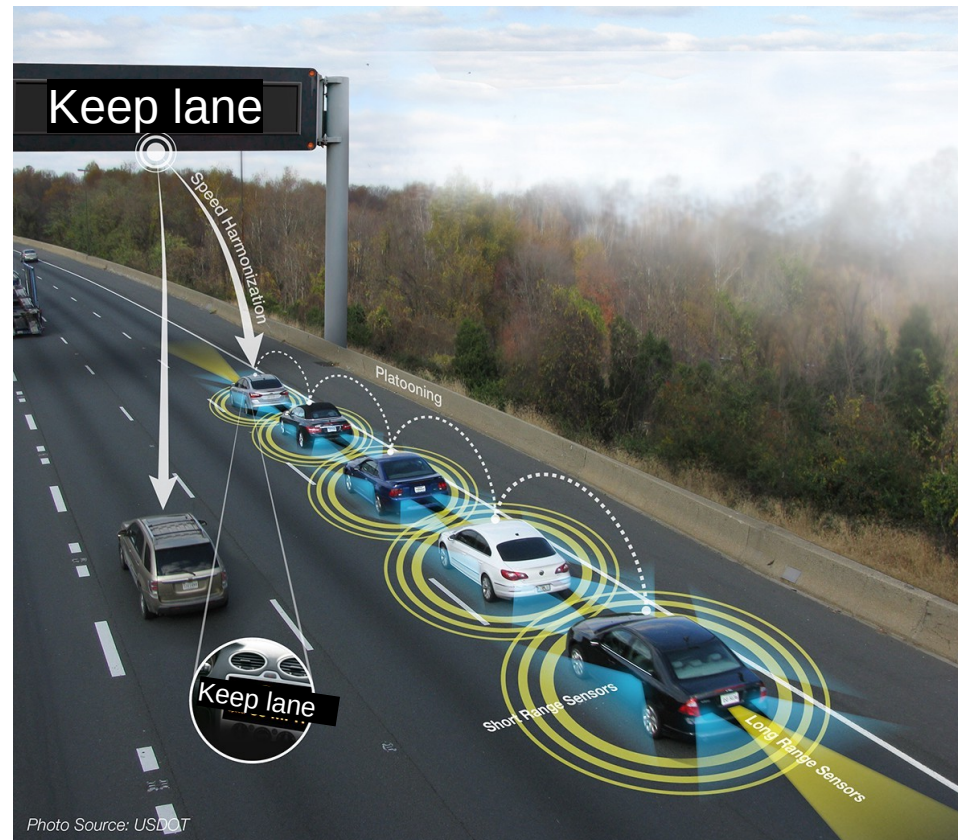
Traditional traffic management strategies



Scientific innovations

Research question

What benefit can connected and automated vehicles bring near an off-ramp or weaving section?



Various potential strategies

- Under diversions

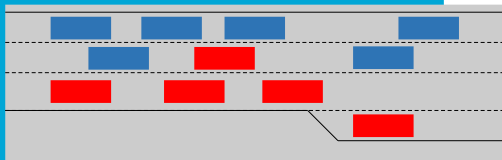
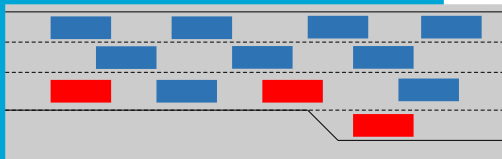
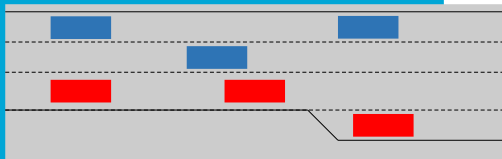
1: Assign all vehicles to lanes based on their destination with respect to the exit [DS1].

2: Assign all exiting vehicles to right lane, as well as some some through vehicles (due to capacity constraints) [DS2].

3: Assign some exit vehicles to the right lane (due to capacity constraints), and all through vehicles to left lanes. [DS3].

- Under weaving: as above +

- 4: Assign some exiting vehicles to a left lane to pass congestion due to merging vehicles.



Contribution

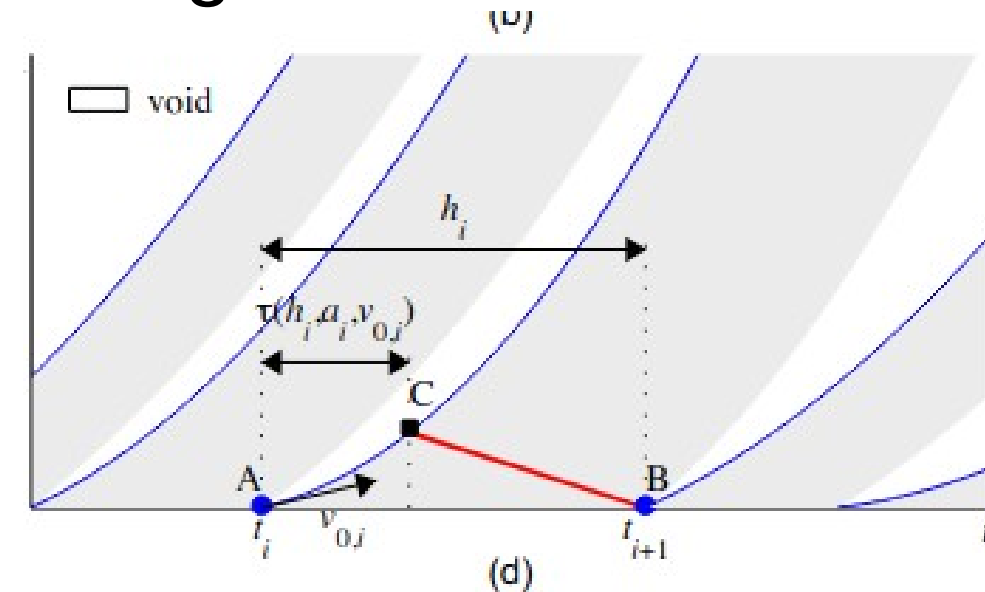
- Analytical description of traffic processes and effect of control strategies
- Insight into strategies to choose under various loads and penetration rate of influencable vehicles (via analytical description)
- Accounting for spatial spread of lane changes (and the voids they create)
- Quantification of effect of strategies for various loads (via simulation)

Motivation

- Lane changes cause reduction of throughput at bottlenecks.
- Consider the spatial distribution of LCs and the effect of reutilization of voids.
- Utilize CAVs to strategically influence LCs at bottlenecks.
- Consider the effect of compensation by human driven vehicles (HDVs) in a mixed traffic.

Voids: Laval and Daganzo

- Lane changes from lower speed to higher speed lane
- Acceleration bounded, leaving a void in the faster lane
- This reduces capacity
- Empirically verified

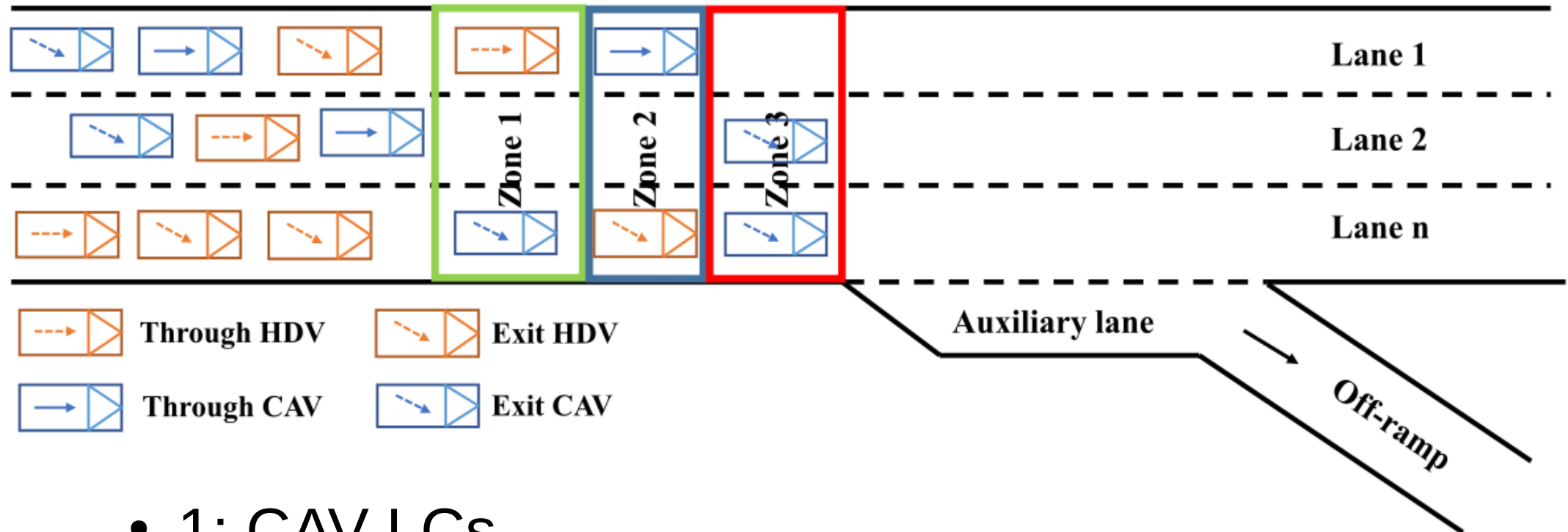


¹Laval, J. A., & Daganzo, C. F. (2006). Lane-changing in traffic streams. *Transportation Research Part B: Methodological*, 40(3), 251-264; Picture: Leclercq, L., Knoop, V.L., Marczak, F., and Hoogendoorn, S.P. (2016) Capacity drops at merges: New analytical investigations, *Transportation Research Part C: Emerging Technologies*, Volume 62, January 2016, Pages 171-181

Potential of CAVs

- Connected and Automated Vehicles (CAVs) can be directed towards a specific lane
- CAVs are 100% compliant
- Fraction of CAVs can vary (“penetration rate”)
- Human drivers (HDV) are not directly influenced
- Compensation of HDVs due to choice of CAV

3 zones



- 1: CAV LCs
- 2: HDV compensation zone
- 3: 'Capacity Impact' (CI) zone: void-creating LCs and remaining voids here create irreversible traffic voids.

Methods

1) Analytical assessment to find which strategies work best

2) Microscopic simulation to quantify their impact under a wide range of conditions

$$\frac{C}{n}(1-\lambda)(n-1) + \frac{p\lambda C}{n}(n\alpha - \alpha_n)$$

Table 2

Metrics for Zone 2 (DS1-C1).

Flow in lane n	Flow in lanes $1:n-1$	# of LCs in this region
Flow in lane n increases (Eq. (12.2) not satisfied) and enough exit HDVs available to compensate (Eq. (15) satisfied)		
$\frac{\lambda C}{n} [1 + (1-\beta)(nap-p)]$	$\frac{\lambda C}{n} \left[1 + \frac{\alpha_i(p(1-na) + \beta(1-p)(1-\alpha_n))}{na - \alpha_n} \right]$	$\frac{\beta p \lambda C}{n^2 \alpha - na_n} (na-1)(n \sum_{i=1}^{n-1} \alpha_i - \sum_{i=1}^{n-1} i \alpha_i)$
Flow in lane n decreases (Eq. (12.2) satisfied) and enough exit HDVs available to compensate (Eq. (15) satisfied)		
$\frac{\lambda C}{n} [1 + (1-\beta)(nap-p)]$	$\frac{\lambda C}{n} \left[1 + \frac{\alpha_i p(1-na)(1-\beta)}{na - \alpha_n} \right]$	$\frac{\beta p \lambda C}{n^2 \alpha - na_n} (1-na)(n \sum_{i=1}^{n-1} \alpha_i - \sum_{i=1}^{n-1} i \alpha_i)$

7

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Transportation Research Part C 127 (2021) 103126

Table 3

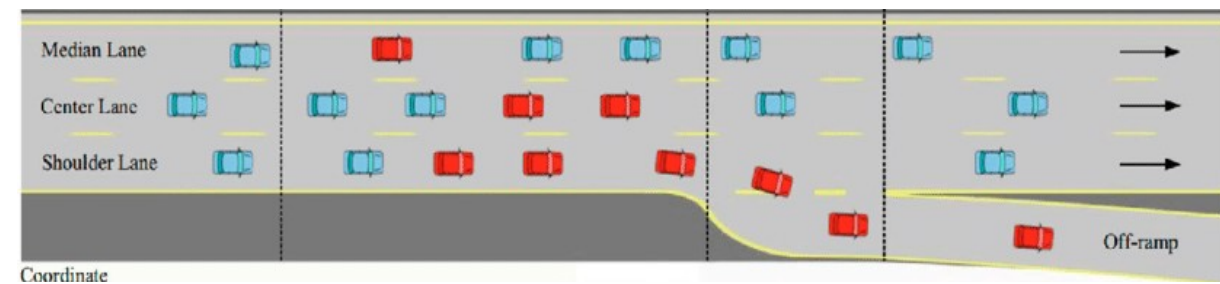
Metrics for Zone 2 (DS1-C2).

Flow in lane n	Flow in lanes $1:n-1$	# of LCs in this region
Flow in lane n decreases (Eq. (12.2) satisfied) and enough exit HDVs available to compensate (Eq. (15) satisfied)		
$\frac{\lambda C}{n} [1 + (1-\beta)(nap-p)]$	$\frac{\lambda C}{n} [1 + p(S_1 - S_1 \alpha_n - \alpha_i)] - \frac{\alpha_i \beta p \lambda C}{n^2 \alpha - na_n} (1-na)$	$\frac{\beta p \lambda C}{n^2 \alpha - na_n} (1-na)(n \sum_{i=1}^{n-1} \alpha_i - \sum_{i=1}^{n-1} i \alpha_i)$

Table 4

Number of LCs in Zone 3 (DS1).

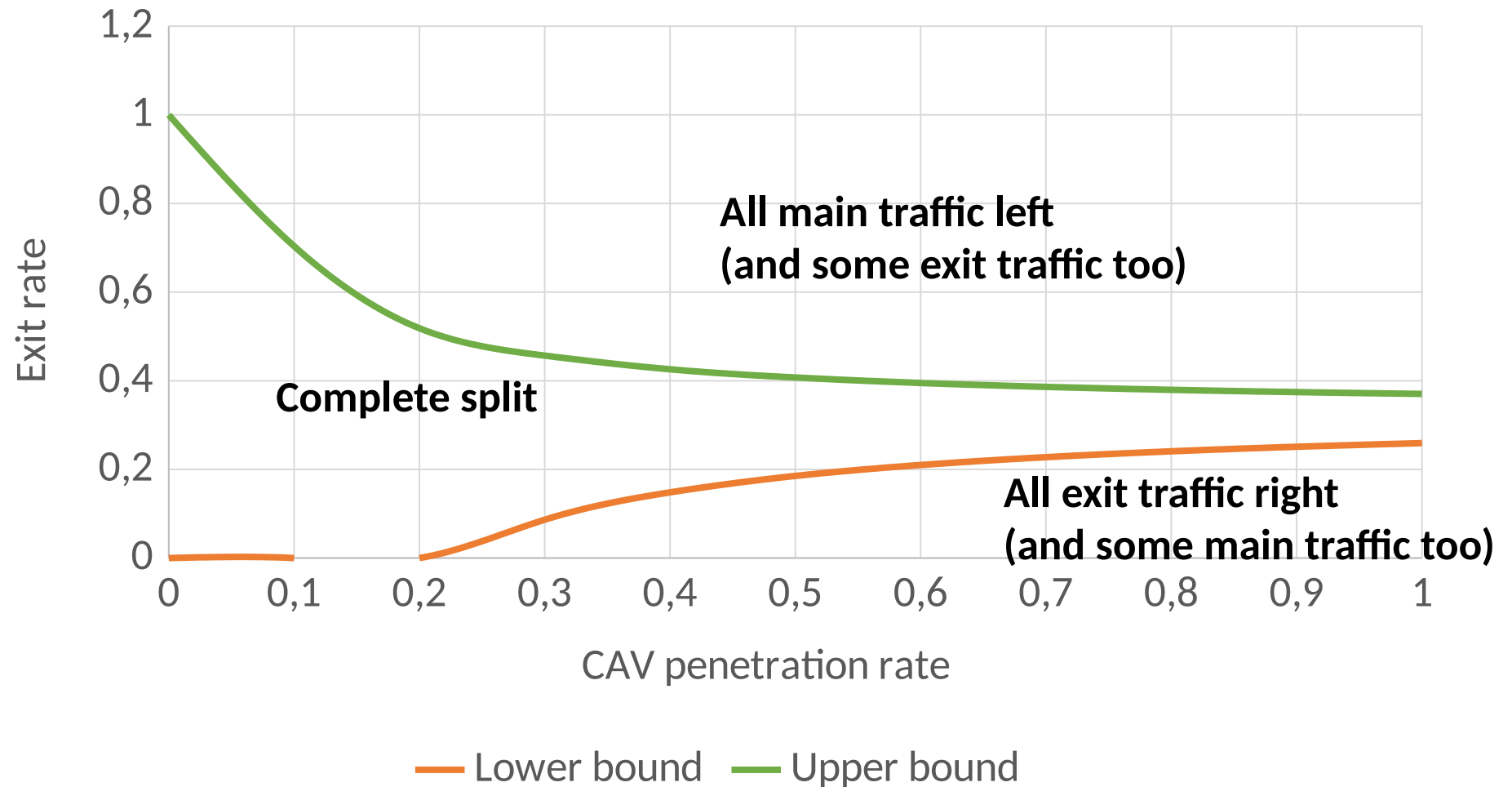
	# of LCs in Zone 3
DS1-C1 (Eq. (12.2) not satisfied)	$(1-p) \frac{\lambda C}{n} \left[n \sum_{i=0}^{n-1} \alpha_i - \sum_{i=1}^{n-1} i \alpha_i \right]$
DS1-C1 and DS1-C2 (Eq. (12.2) and (15) satisfied)	$\frac{\lambda C}{n} \left[1 - p - \frac{\beta p(1-na)}{na - \alpha_n} \right] \left[n \sum_{i=0}^{n-1} \alpha_i - \sum_{i=1}^{n-1} i \alpha_i \right]$



Picture: Dong et al, 2020

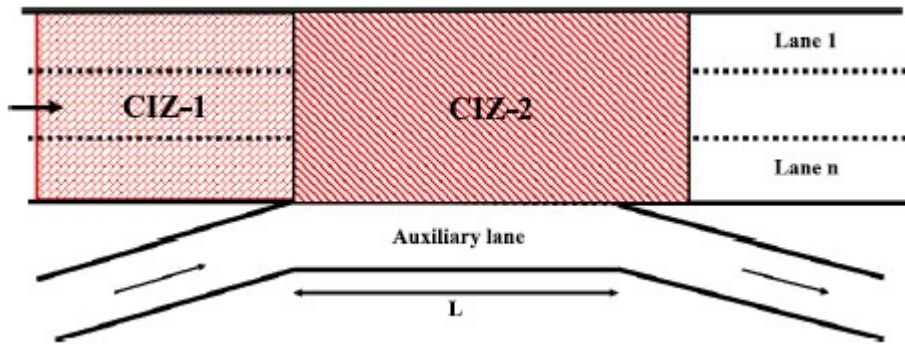
Results

Diverges: analytical result



Weaving: analytical result

- Capacity Impact zone in weaving sections is divided into two parts –
 - area upstream of the on-ramp (CIZ-1).
 - area between the two ramps plus the area extending downstream of the off-ramp (CIZ- 2).



- 1) Low ramp inflow: organize flow approaching weave section to minimize conflicts between through and exit traffic (**similar to diverge sections**). Reduces the space available in the shoulder lane for the incoming ramp demand [WS1].
- 2) High ramp inflow: make space in the shoulder lane by moving vehicles to the inner lanes to accommodate the on-ramp demand and shift the LCs of exit CAVs downstream of the on-ramp in the weaving segment [WS2].

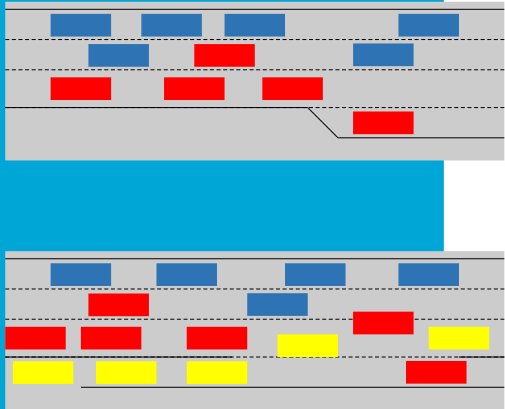
Numerical simulations

Simulation setup

- Aim: quantify the improvements in throughput as a result of implementing these strategies.
- Microscopic simulation, based on Chen and Ahn (2018)
 - Longitudinal model: Newell's car-following model.
 - LC mechanism: Laval and Daganzo (2006)
- Speed reduction instantaneous

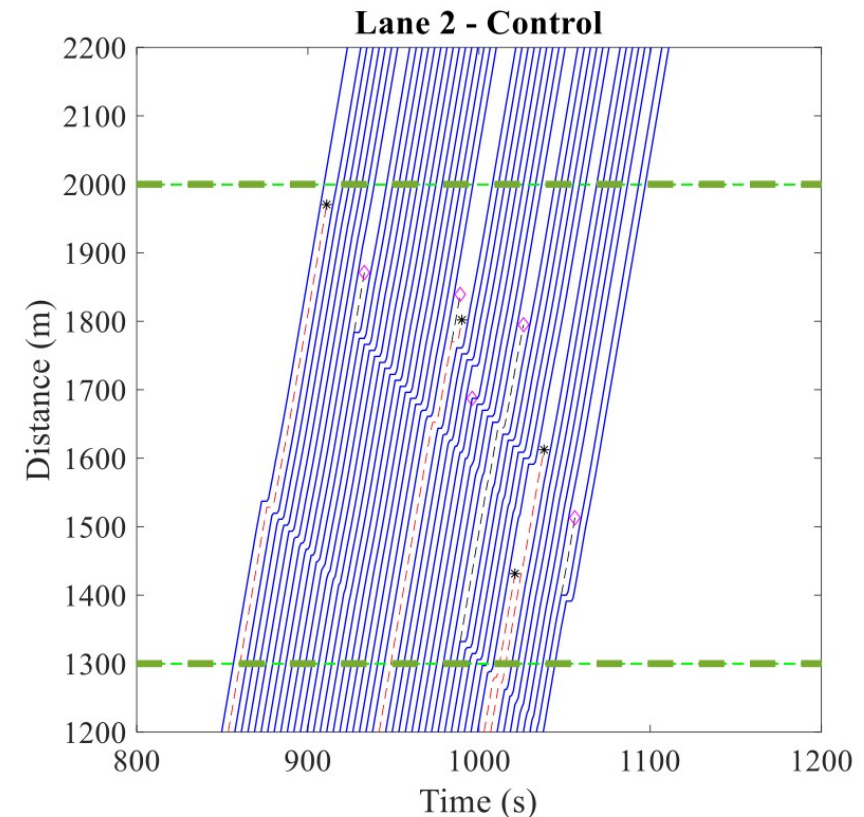
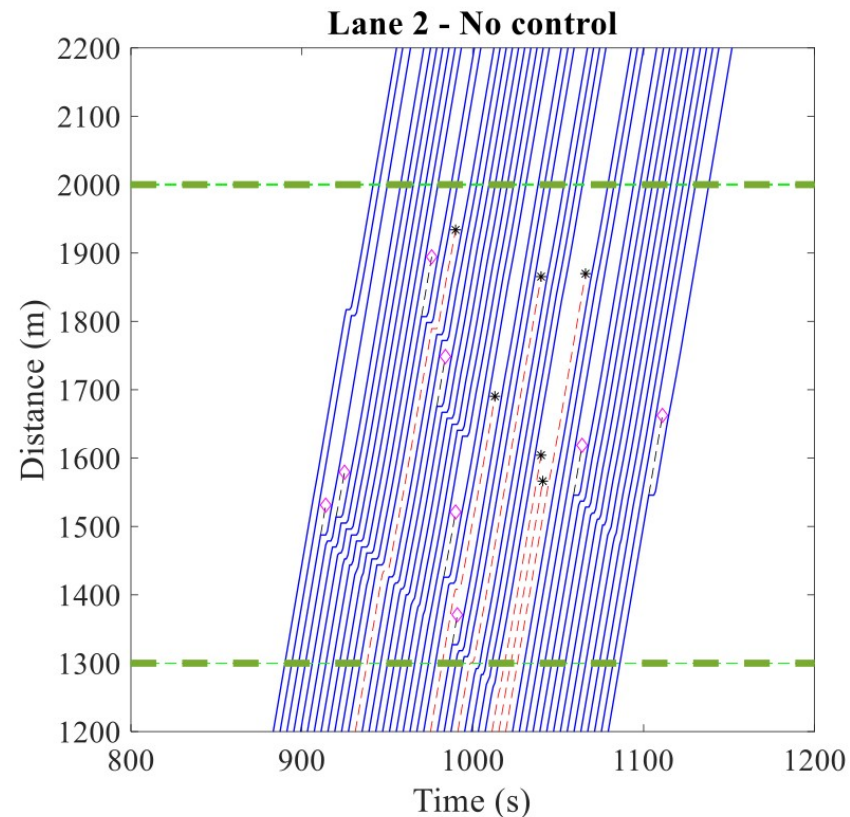
Simulation setup

- Three lane motorway with single lane off-ramp or auxiliary lane (in cases of weaving sections).
- Different free speeds per lane
- LC location and times homogeneously spread over zone
- LC considered always possible

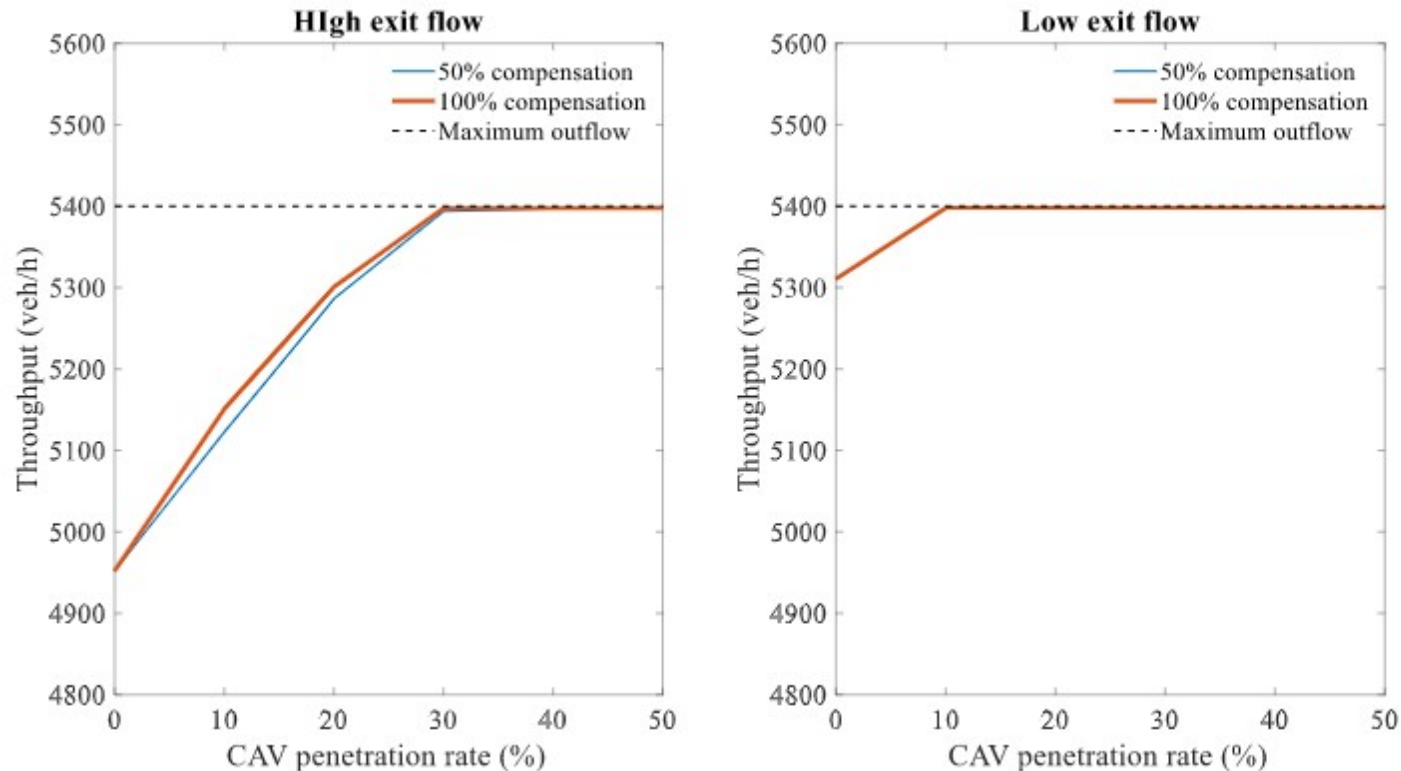


Results diverges

- Maximize flow between 1300-2000 m
- Less lane changes with control
- Less voids with control



Results diverges



- No control reduces maximum outflow: 1.7% to 8.3% lower compared to “no void” case.
- Maximum throughput can be achieved with control; minimum penetration rate depends on exit flows.
- Compensation has larger effect for high exit flows.

Results weaving sections

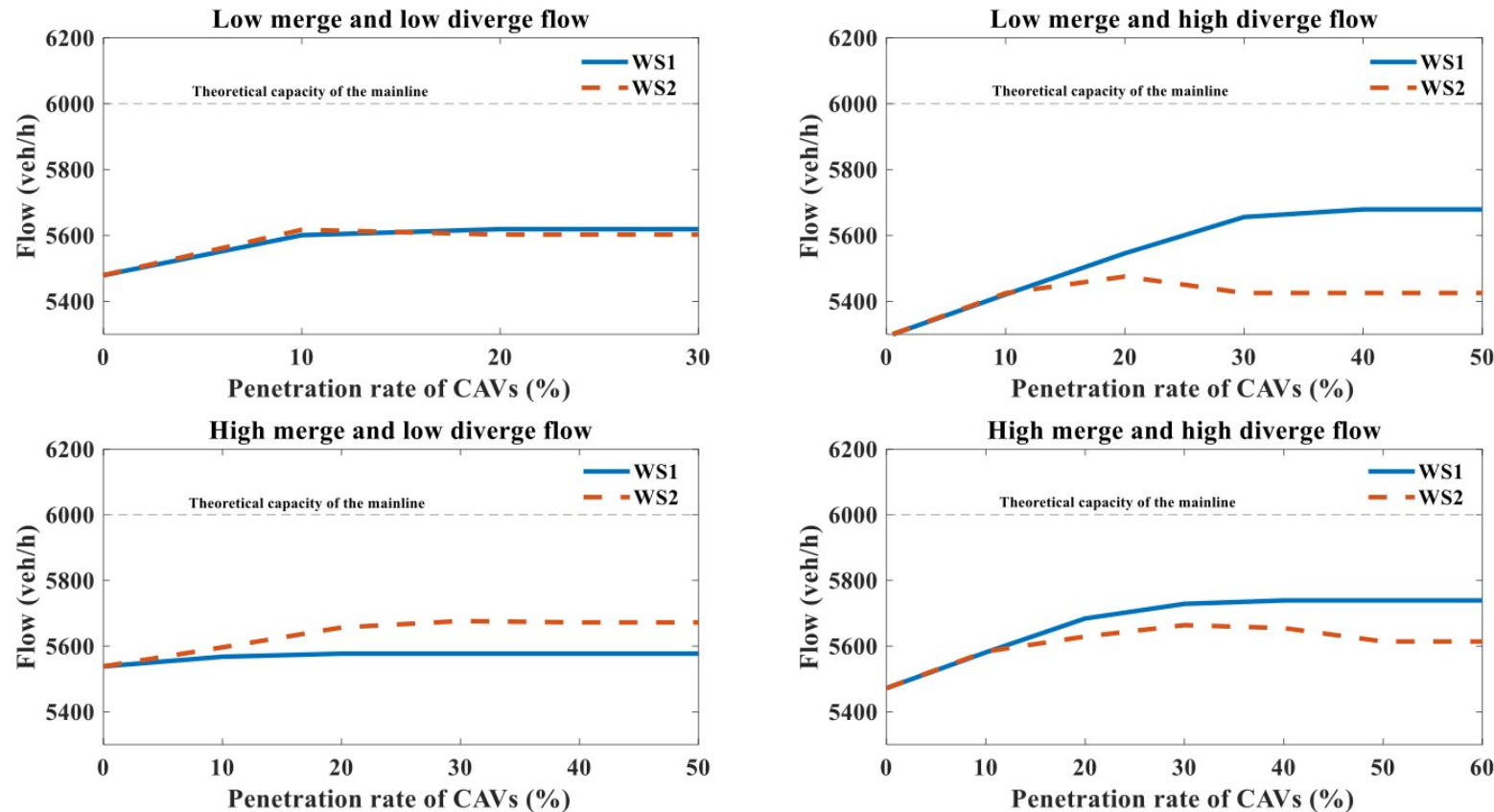


Fig 8. Throughput at weaving section.

- WS1: organize exiting traffic.
- WS2 - through CAVs to the left to make room for merging traffic
- Improvements in the order of several percents
- Traffic flow improves with higher penetration rates
- WS2 works indeed better with high merge and low diverge
- In other cases WS1 better than WS2

Limitations

- Many simplifications in approach:
 - initial distribution of traffic over the lanes
 - speeds set exogeneously
 - instantaneous LC and speed reduction
 - all vehicles are equal
 - LC independent on available gap; no anticipation & relaxation
- Tested under constant conditions: how about changing conditions?
- Big leap to practical application

Findings (theoretical part)

- Lane-assignment strategies can significantly increase flows near diverge or weaving bottlenecks
- Analytical expression for best strategy and lane assignment to choose;
For weaving: two conflicting strategies (exiting traffic left or right) to choose depending on traffic loads
- If the area to perform the LCs is long enough, these LC will not reduce throughput

Practical implementaions

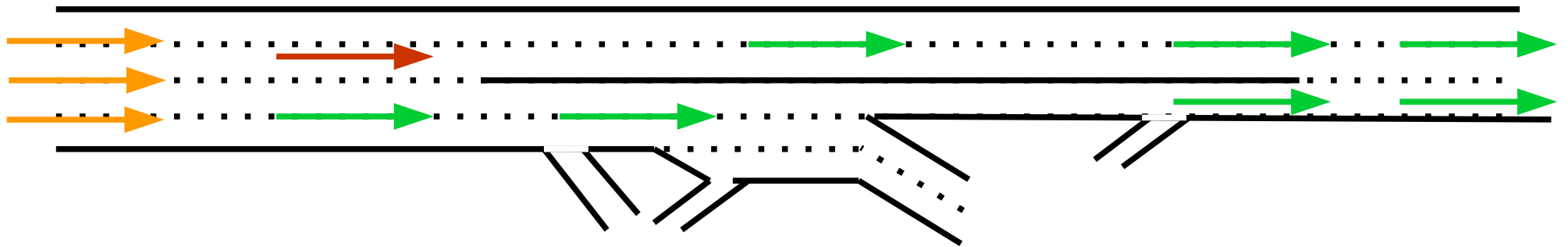
Current situation – video

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Current situation

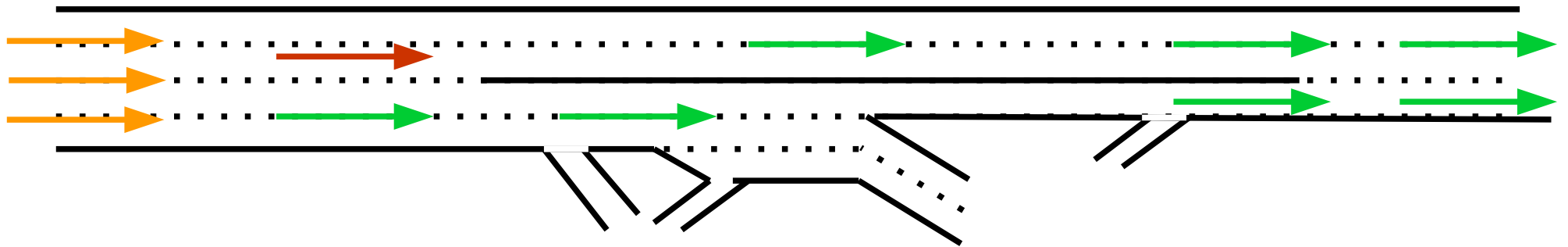
- A4 freeway: delays at diverge



- Alternative route is not used at capacity

Current situation

- A4 freeway: delays at diverge



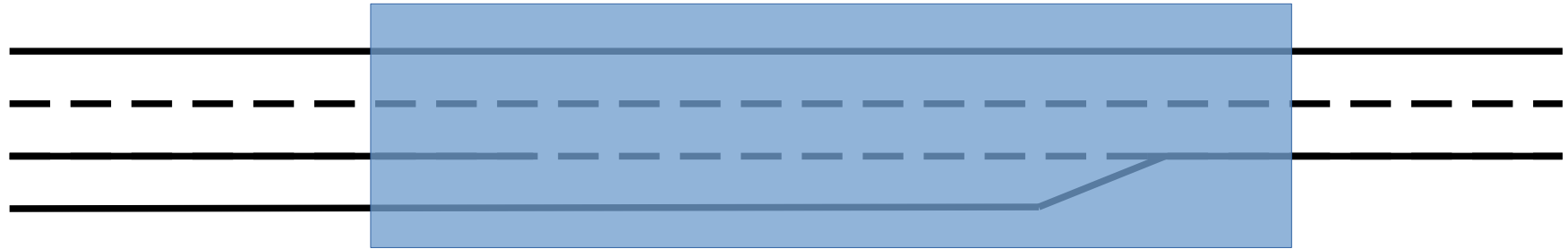
- Alternative route is not used at capacity
- Advise people to take the alternative route, via Flitsmeister (15% penetration rate)
- 20-25% will follow advice (we know after the experiment)
- Advice given to 20% of travellers
- Increase in travel on parallel road reduces demand to main lane
Just operating at capacity – travel time gains.

Ramp metering



- Limit the inflow onto the freeway to reduce *overall* delays

Relevant measure: flow (veh/h)



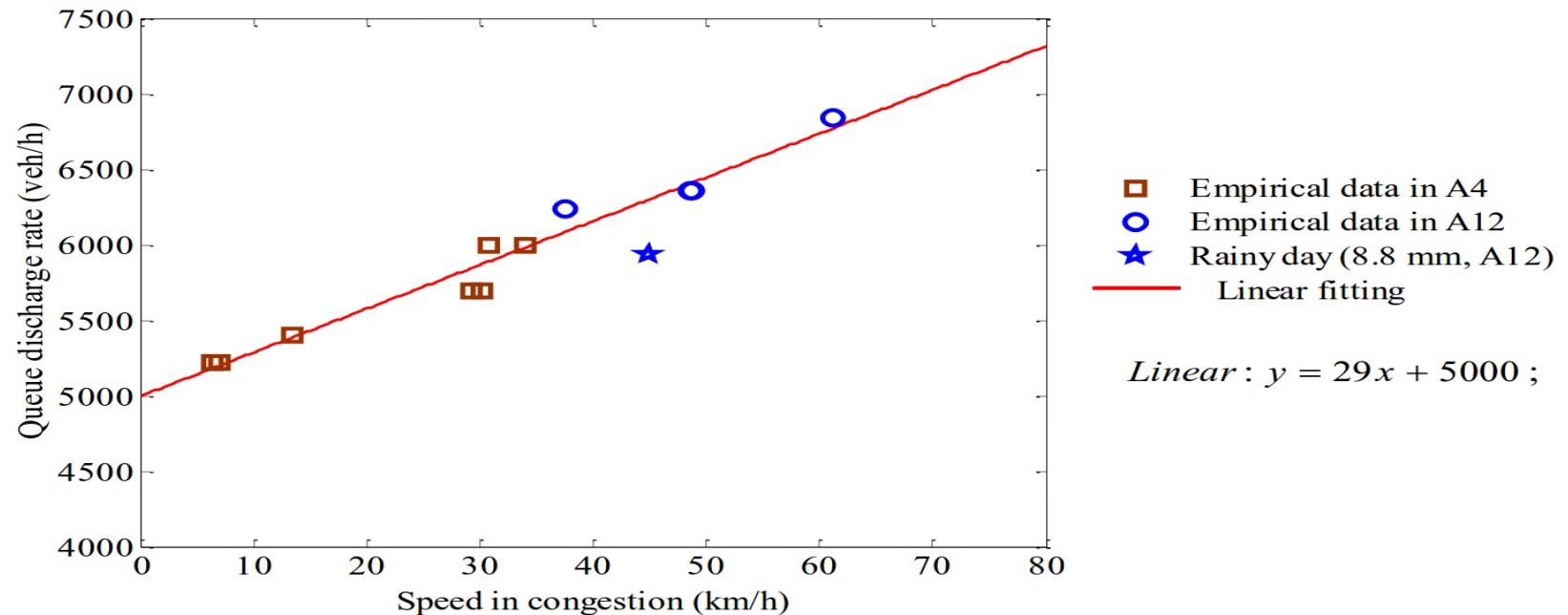
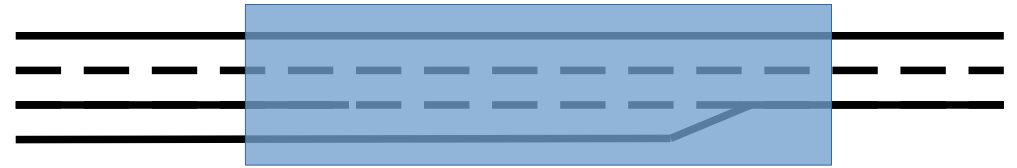
- Consider the area of potential congestion a box
- Delays are determined by the moment flowing into the box and flowing out of the box
- Inflows are fixed, so outflow determines the delay
- Delays are determined by the headway, ie. the time between two vehicles

Effect of ramp metering

- Somehow, drivers keep a larger distance when exiting the queue than before (even though they have been waiting on their predecessor)e
- Ramp metering prevents a queue on the main road, and thus keeps up the high outflow
- If the outflow would be the same as with onramp metering, the delays would have been equal

Outflow depends on the speed in congestion

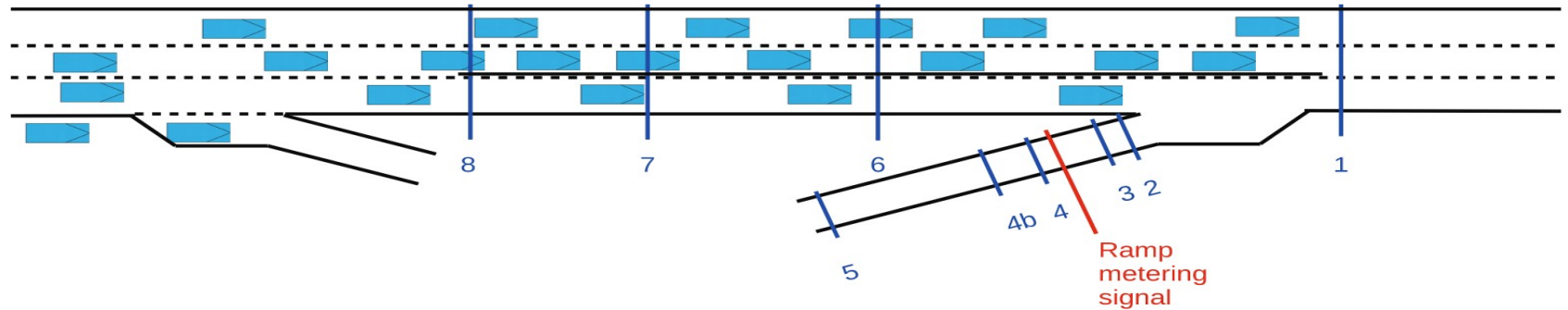
- We relate the outflow out of a queue to the speed in the queue
- Data: A4 motorway



Improve ramp metering

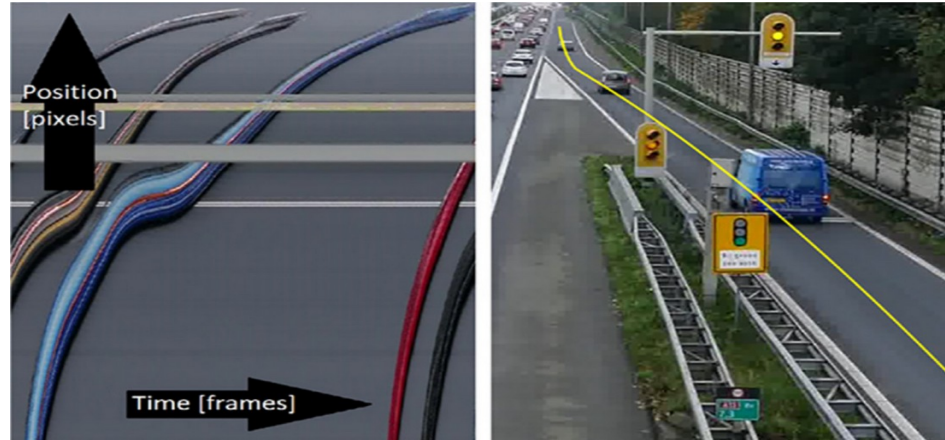
- Current ramp metering involves limiting flows per minute
- Can we give green to a vehicle to direct him to a specific gap?
- Possible with coordination and communication between vehicles
- How to do with current equipment?

Improve ramp metering



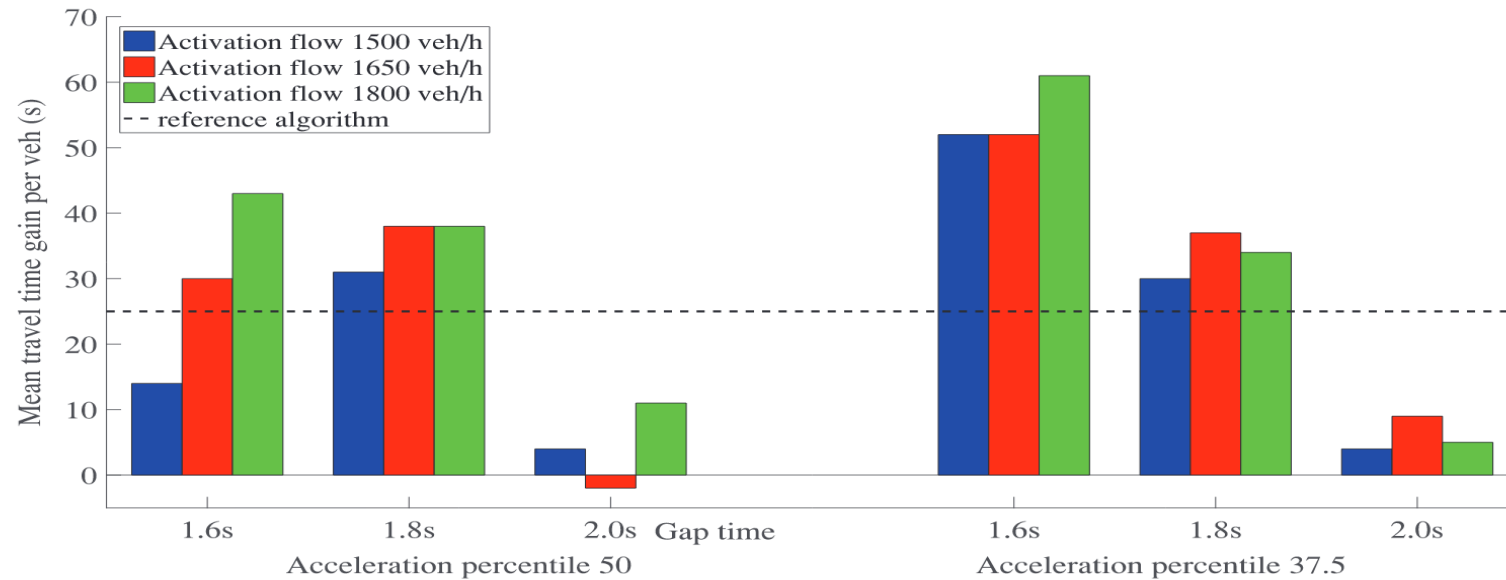
- Measure gaps with loop detectors upstream
- Give green to the waiting vehicle at the right time
- Test using traffic simulation
- Crux: right prediction of acceleration
(simulation program too favorable)

Measure acceleration



- Video of road from a overpass near Delft Noord
- Pixels vs time
- Calibrate with a known vehicle passing at constant speed

Method works



- Implemented at a simulation with realistic behavior
- Method works in reducing delay

Overall conclusions

- Traffic jams occur at multi-lane roads and not all capacity is being used
- Conceptual and theoretical work shows an increase in capacity of several percents by appropriate lane changes if well executed
- Field test shows that people do follow lane (road?) advise
- Traffic scientists can actually reduce congestion :)



References

- Stefan Klomp (2020) Ramp metering: a microscopic control approach
- Klomp, S.R., Knoop, V.L., Taale, H., Hoogendoorn, S.P., (2021) Transportation Research Records. Ramp Metering With Microscopic Gap Detection: Algorithm Design And Empirical Acceleration Verification Matching data can be found here
- Knoop, V.L., Keyvan-Ekbatani, M., De Baat, M.J., Taale, H, and Hoogendoorn, S.P. (2018) Lane-Change Behavior on Freeways: an On-Line Survey Using Video Clips. In Journal of Advanced Transportation, vol. 2018, article ID: 9236028, <https://doi.org/10.1155/2018/9236028>.
- Nagalur Subraveti, H.H.S., Knoop, V.L. and Van Arem, B. (2020) Improving Traffic Flow Efficiency at Motorway Lane Drops by Influencing Lateral Flows. Transportation Research Records, Volume 2674 issue 11, pp. 367-378