TU Delft

Auction-based approaches for distributed cooperative traffic management

Dr. ir. Marco Rinaldi, TU Delft

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Marco Rinaldi

Assistant Professor | Co-Director **DAIMoNDLab**

m.rinaldi@tudelft.nl

- 2011 – **MSc** degree in Computer Engineering, Automation & Control track
- 2016 – **PhD** degree in Mechanical Engineering, focus on numerical fluid modelling and management of traffic systems
- 2016 – 2020 **Postdoctoral fellowship**, focus on optimization heuristics and algorithms for electrified public transportation operations and charging
- 2020 – now **Assistant professor**, **co-director DAIMoNDLab,** focus on modelling and management of multimodal traffic.

TU Delft

DIT4TraM

Acumen

Outline

01

Fundamentals

- Auctions
- Mechanism design
- Myerson's lemma

02

Knapsack auctions & complexity issues

03

Auction-based traffic management I: traffic signalling

04

Auction-based traffic management II: AV platooning

01

Auctions

Fundamentals

Auctions

- What is an auction?

Auctions

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  - A <u>mechanism</u> to allocate <u>resources</u> among a group of <u>bidders</u>

Auctions

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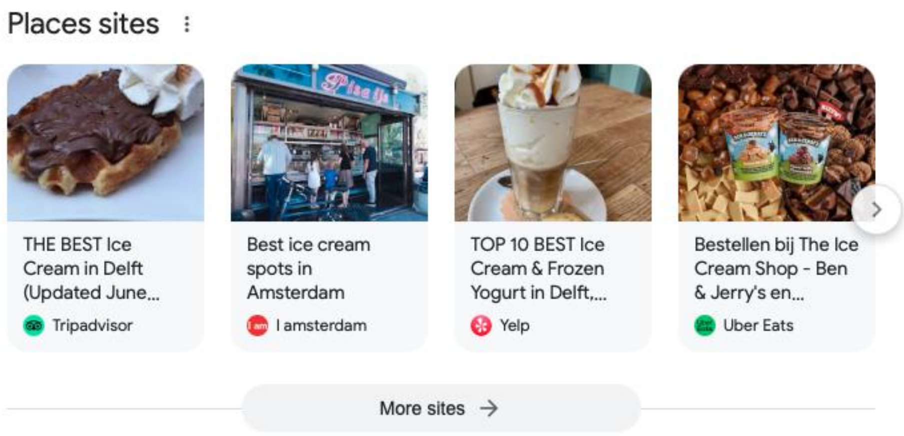
  - A mechanism to allocate resources among a group of bidders



Searching the web for ”ice cream”

- Resources: clicks for sponsored websites
- Bidders: companies sponsoring search results
- Mechanism: search engine decides order!

Auctions

- What is an auction?
  - A mechanism to allocate resources among a group of bidders

Searching eBay for ”fiets”
- Resources: bicycles (sheds..)
- Bidders: someone who loves spiderman
- Mechanism: ?

Auctions

- What is an auction?
  - A <u>mechanism</u> to allocate <u>resources</u> among a group of <u>bidders</u>
- Bidders
  - Have a private **valuation** (i.e. they assign a value to the resources, this is <u>not known</u>)
  - Will be willing to **bid up to that valuation** (ideally, no overbidding)
  - Will be *strategic* in deciding when/what to bid on
- Core mechanism components:
  - Allocation (who gets what?)
  - Payment (how much does that cost?)

Auction mechanisms

- Open auctions (bidders know each other's bids):

“English” auction
- Seller sets a reservation price
- Bidders express their prices, in ascending order
- Highest bidder gets the item at their stated price, once nobody else intervenes

“Dutch” auction
- Seller sets a starting price, this gradually decreases over time
- Bidders wait until they feel the price is right
- Whoever bids first, wins

Auction mechanisms

- Sealed-bid auctions (bidders **don't** know each other's bids):
  - Bidders submit their bid privately to the auctioneer
  - Auctioneer sets allocation and price based on the received bids

"First Price" auction
- Bidders send their price
- Highest bidder gets the item
- Highest bidder pays their bid

"Second Price" auction
- Bidders send their price
- Highest bidder gets the item
- Winner pays the amount of the 2nd highest bid

Mechanism design

- Desirable mechanism properties:
  - Revenue maximization
  - Welfare maximization
  - Fairness (allocation obeys some fair principle)?
  - Truthfulness (bidders pay their true valuation)?
- Bidders are *strategic* – will they always be truthful?

€1,184,360

Mechanism design

- Bidders are *strategic* – will they always be truthful?

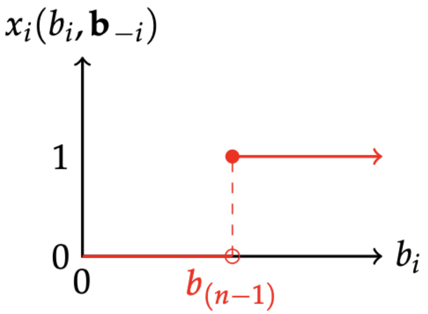
$N = \{1, \dots, n\}$ bidders
$i \in N$ individual bidder
v_i individual bidder's valuation of item (assume: drawn from a probability distribution F_i)
b_i individual bidder's bid
$\boldsymbol{b} = (b_1, \dots, b_n)$ set of all bids received by auctioneer
$\boldsymbol{b_{-i}}$ set of all bids excluding b_i
$p_i(b_i, \boldsymbol{b}_{-i})$ auction price
$x_i(b_i, \boldsymbol{b}_{-i})$ probability of bid allocation for b_i (winning the auction)
$u_i(b_i, \boldsymbol{b}_{-i})$ utility of bidder *i*

€21,896,100

Mechanism design

- Bidders are *strategic* – will they always be truthful?

First-price auction: $p_{i^*} = b_{i^*}$



Bidding higher than the second highest bid $b_{(n-1)}$ ensures winn (probability 1)

Best strategy is not truthful!

$u_i(b_i, \boldsymbol{b}_{-i}) = v_i x_i(b_i, \boldsymbol{b}_{-i}) - p_i(b_i, \boldsymbol{b}_{-i})$ utility of bidder i

$$u_i(b_i, \boldsymbol{b}_{-i}) = \begin{cases} v_i - b_i, & i = i^* \\ 0, & otherwise \end{cases}$$

Bidders maximize their utility: what's the best strategy?

- Overbidding → negative utility ($v_i \leq b_i$)
- Truthful bidding → no utility
- Underbidding → positive utility ($v_i \geq b_i$)

Mechanism design

- We would like to design approaches that..
  - Achieve a desired objective (max revenue, max welfare, …)
  - Induce bidders to bid truthfully (hence, fair)

$$x_i(b_i, \boldsymbol{b}_{-i}) \colon \arg\max_{b_i} u_i(b_i, \boldsymbol{b}_{-i}) = v_i$$

Mechanism design

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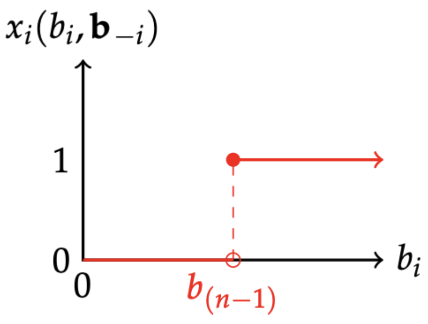
Second-price auction: $p_{i^*} = b_{(n-1)}$

$$\begin{cases} v_i - b_{(n-1)}, & i = i^* \\ 0, & otherwise \end{cases}$$

Truthful bidding is a **dominant** strategy



Bidding higher than the second highest bid $b_{(n-1)}$ ensures winning (probability 1)

- Overbidding → No inherent advantage
- Truthful bidding → Lose if $b_{n-1} > v_i$, win if $b_{n-1} \leq v_i$
- Underbidding → Opportunity loss if $b_i < b_{n-1} \leq v_i$

Mechanism design

- Vickrey auctions (sealed bid, 2nd price)
  - Are **d**ominant-**s**trategy **i**ncentive **c**ompatible (DSIC)

$$\arg\max_{b_i} x_i = v_i \ , \ x_i(b_i, \boldsymbol{b}_{-i}) \geq 0 \mid b_i = v_i$$

  - Maximise social welfare

$$\sum_{i=1}^{n} v_i x_i$$

  - Bid allocation can be solved exactly quickly (in polynomial time)

Questions?

02

Knapsack Auctions

From auctions to transportation problems

Knapsack auctions

- Each bidder i has a known size w_i
- Each bidder i has a private valuation v_i
- The seller has a capacity W
- The feasible set X is the set of (0-1) vectors $(x_1, \ldots, x_n)$: $\sum_{i=1}^{n} w_i x_i \leq W$
  - That is, the allocation rule should be such that size and capacity **match**

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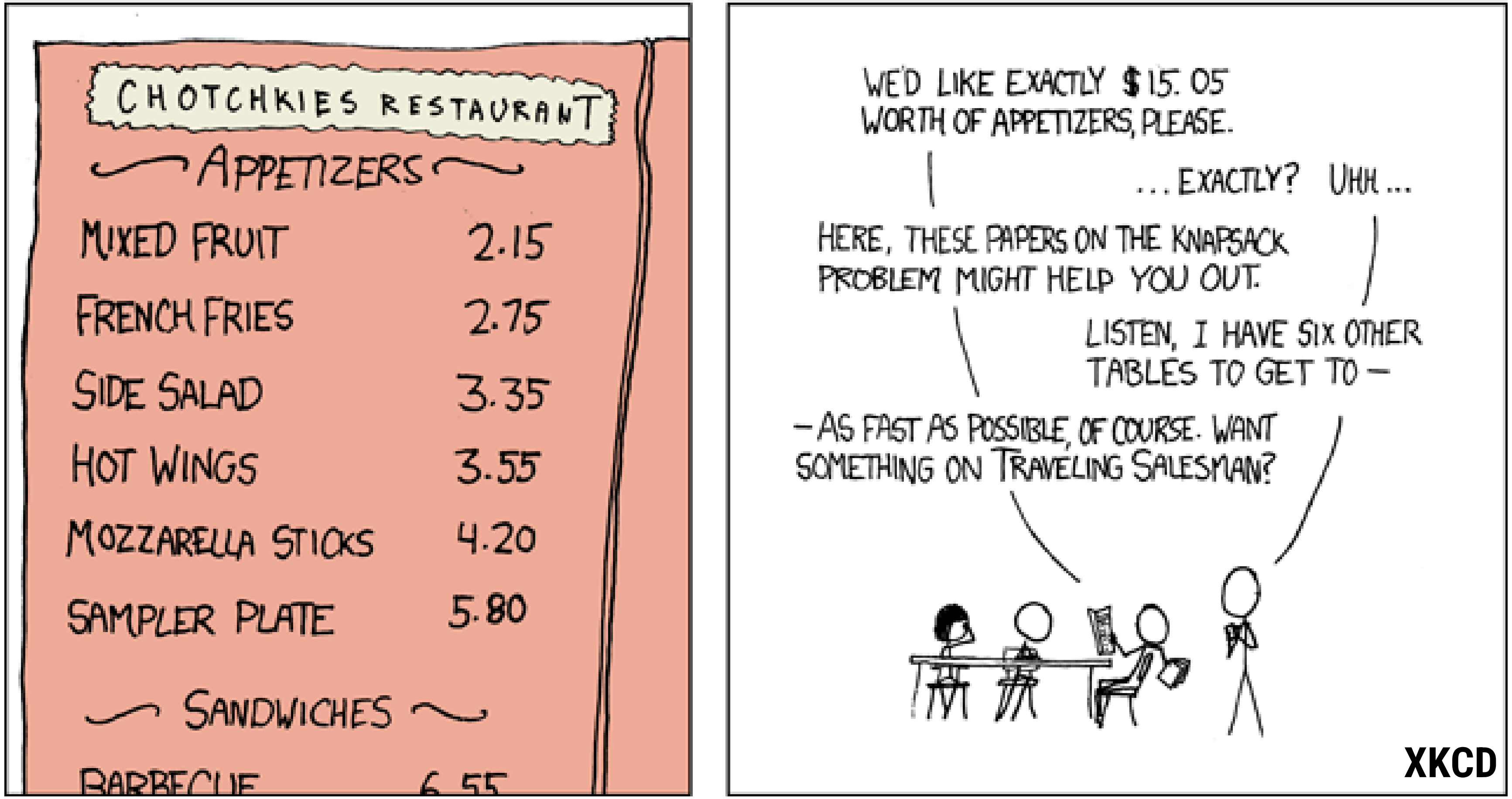
Demand should meet capacity.. sounds familiar?

Small detour: knapsack problems

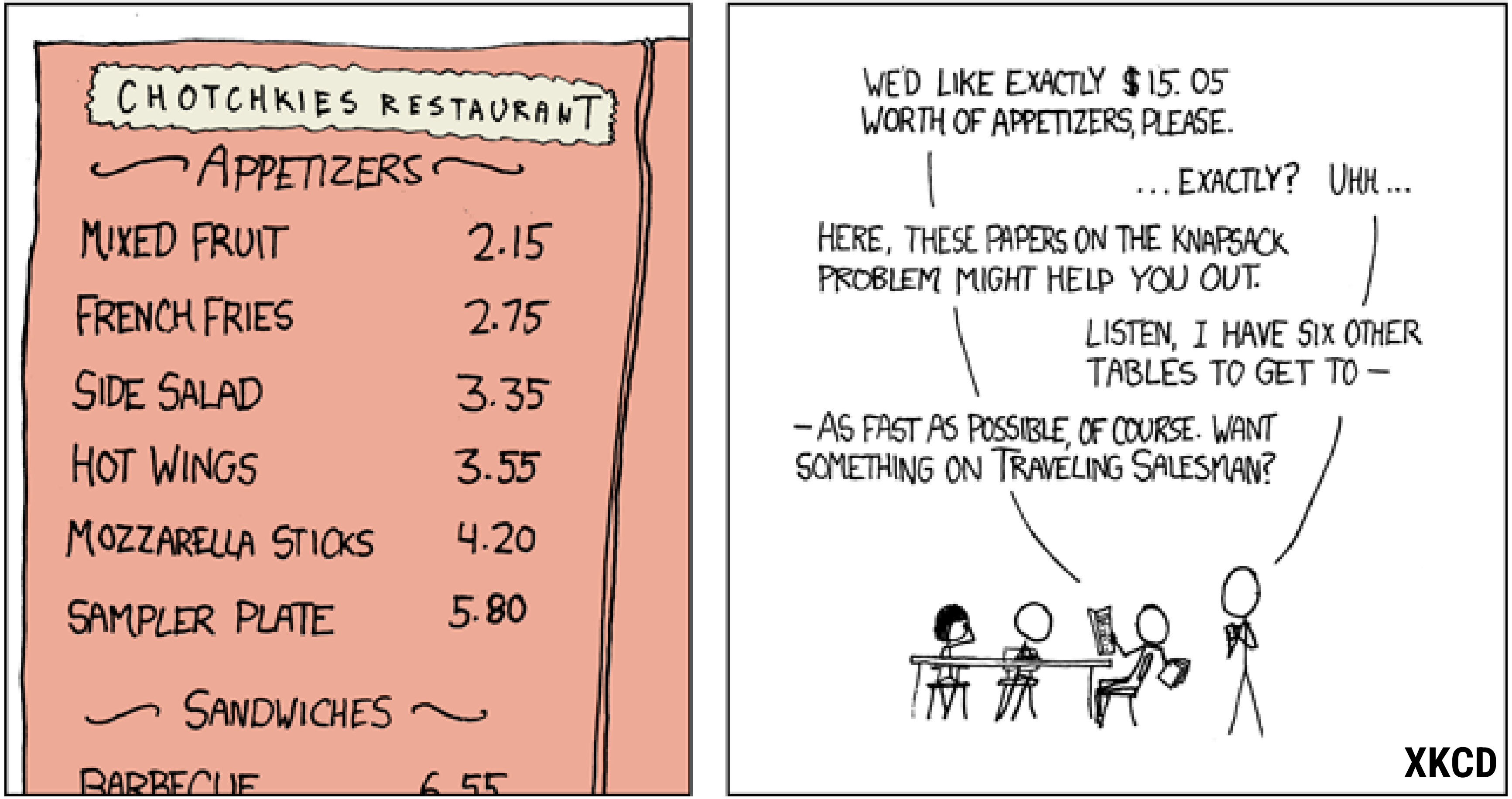
Heard about them before?

Small detour: knapsack problems



Can you think of an answer?

Small detour: knapsack problems



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  - That is, the allocation rule should be such that size and capacity **match**

Can we design a Vickrey mechanism to solve this problem?

- ❑ DSIC
- ❑ Welfare maximizing
- ❑ Polynomial time

Knapsack auctions

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  - That is, the allocation rule should be such that size and capacity **match**

Allocation rule:

$$x(b) = \arg\max_X \sum_{i=1}^{n} b_i x_i$$

(whoever bids highest within their capacity wins)

Payment rule:

[using Myerson's lemma]: 2nd best pricing

☑ DSIC
☑ Welfare maximizing
☒ Polynomial time

03

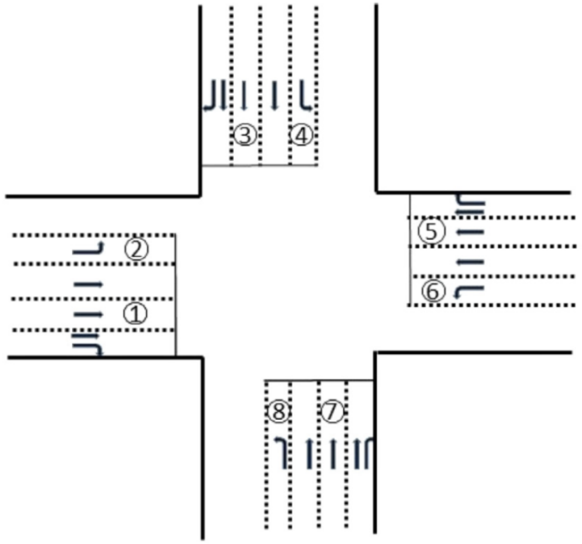
Auction-based traffic management I

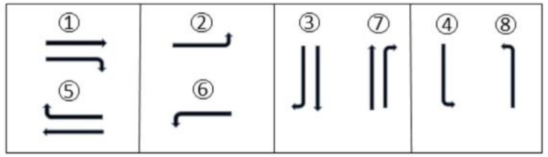
Traffic signalling

Auction-based intersection control

- Each ~~bidder~~ traffic participant i has a known ~~size~~ need for intersection capacity w_i
- Each ~~bidder~~ traffic participant i has a ~~private valuation~~ Value of Time (or Utility) v_i
- The ~~seller~~ intersection has a capacity W
- The feasible set X is the set of (0-1) vectors $(x_1, \dots, x_n)$: $\sum_{i=1}^{n} w_i x_i \leq W$
  - That is, the allocation rule should be such that demand and capacity **match**

Auction-based intersection control



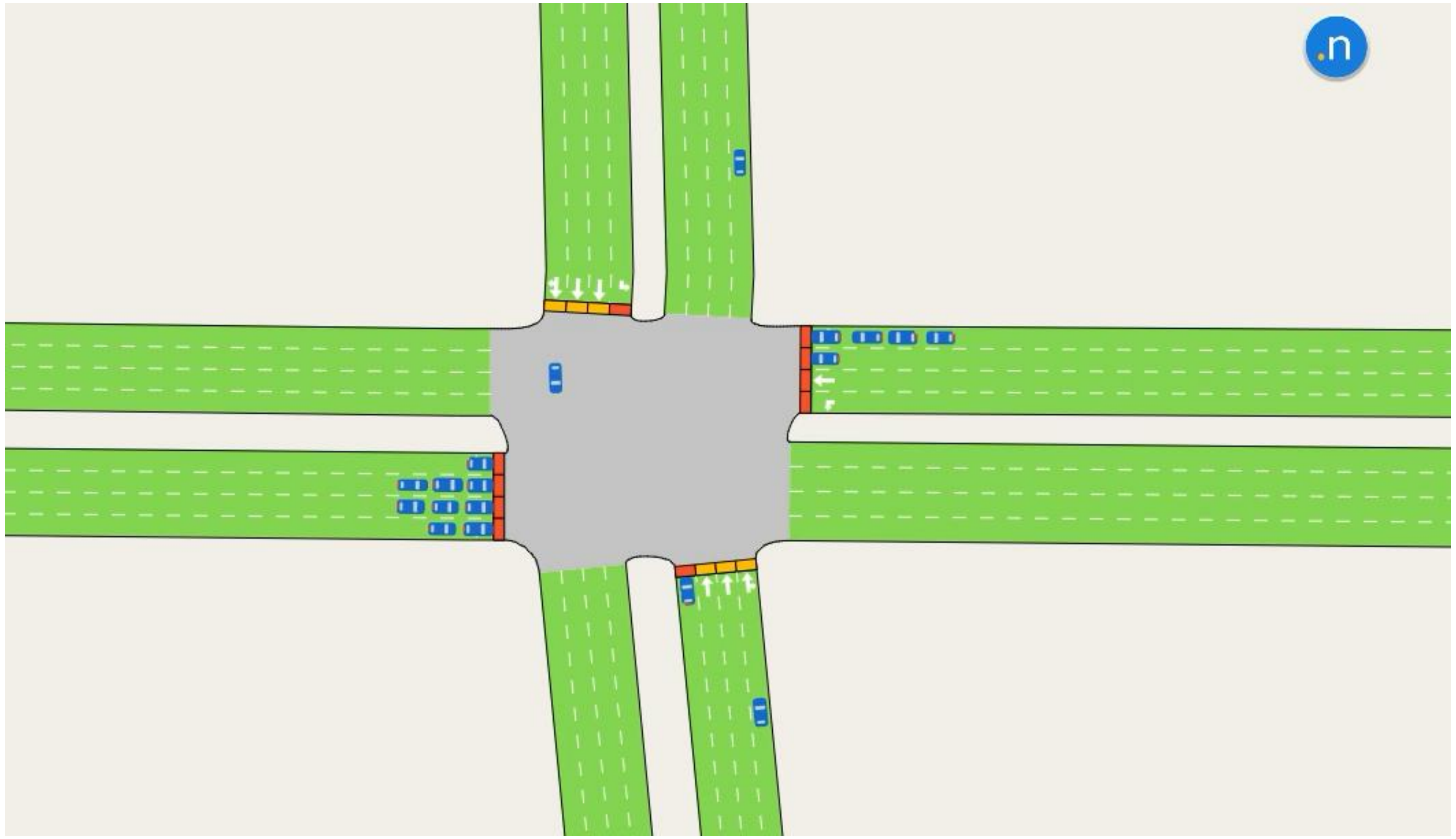


Bidders: the intersection phases (and vehicles therein)

Resources: green time duration / phase s.t. $\leq$ total cycle time

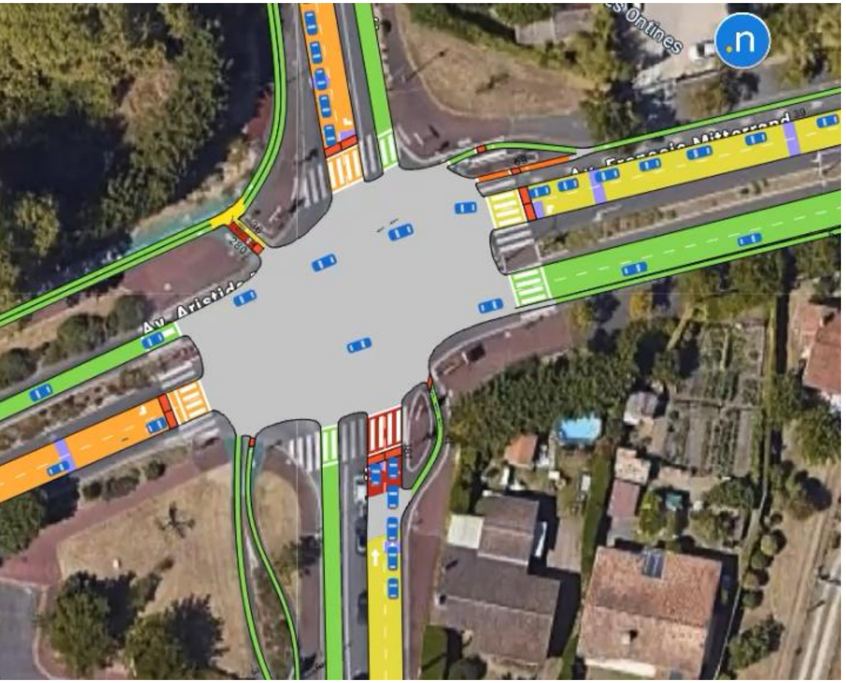
Mechanism: sealed-bid, second-price, **distance-based participation**, **impatience**

Auction-based intersection control

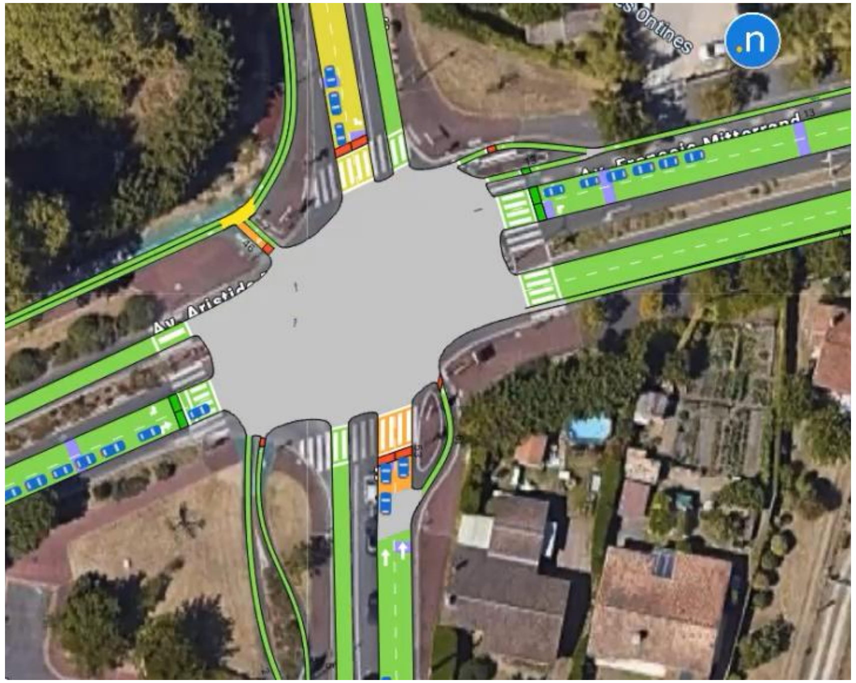


Auction-based intersection control

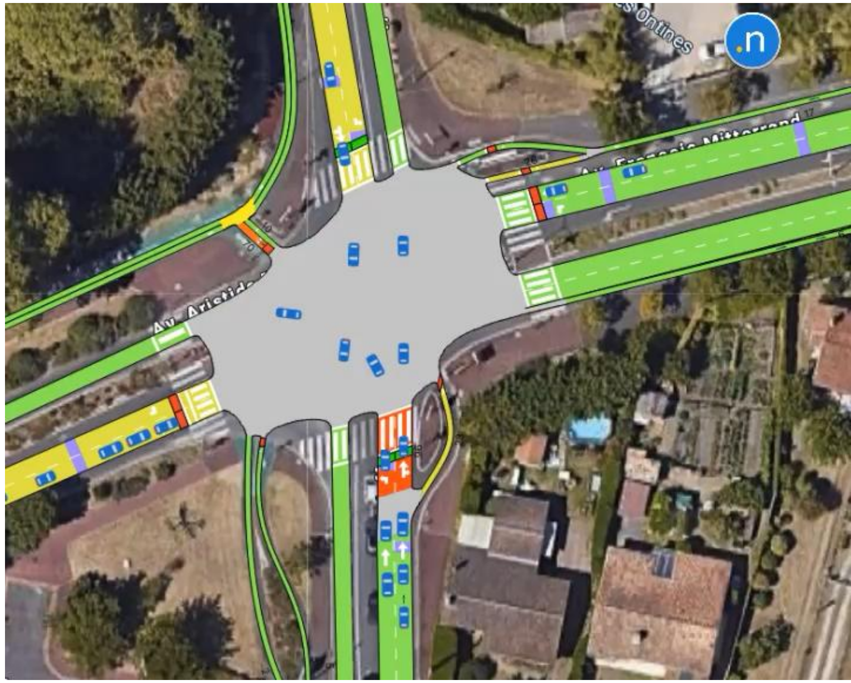
with priority considerations



Fixed-time



Bicycle > Car



Bicycle >> Car

Auction-based intersection control

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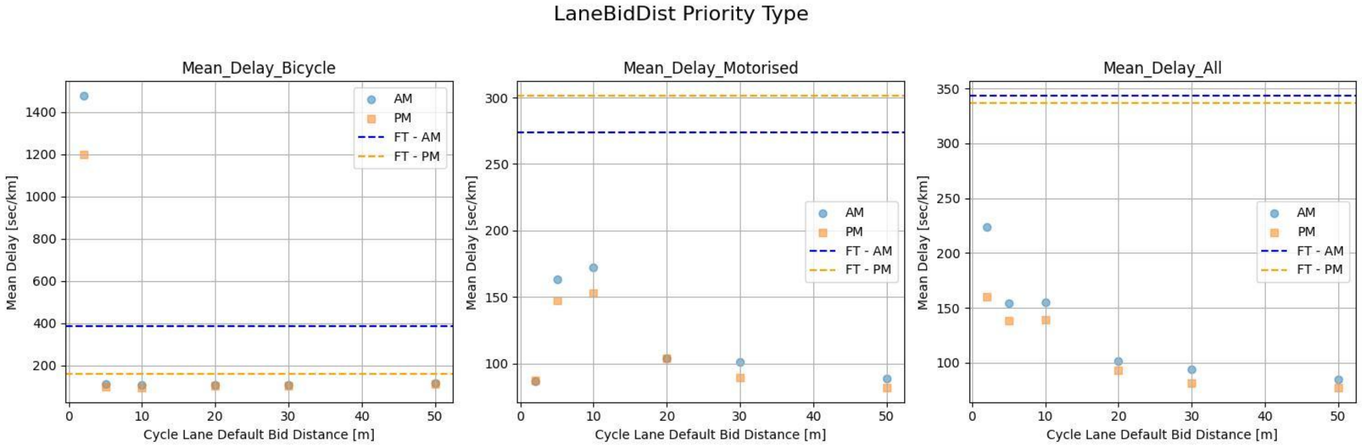
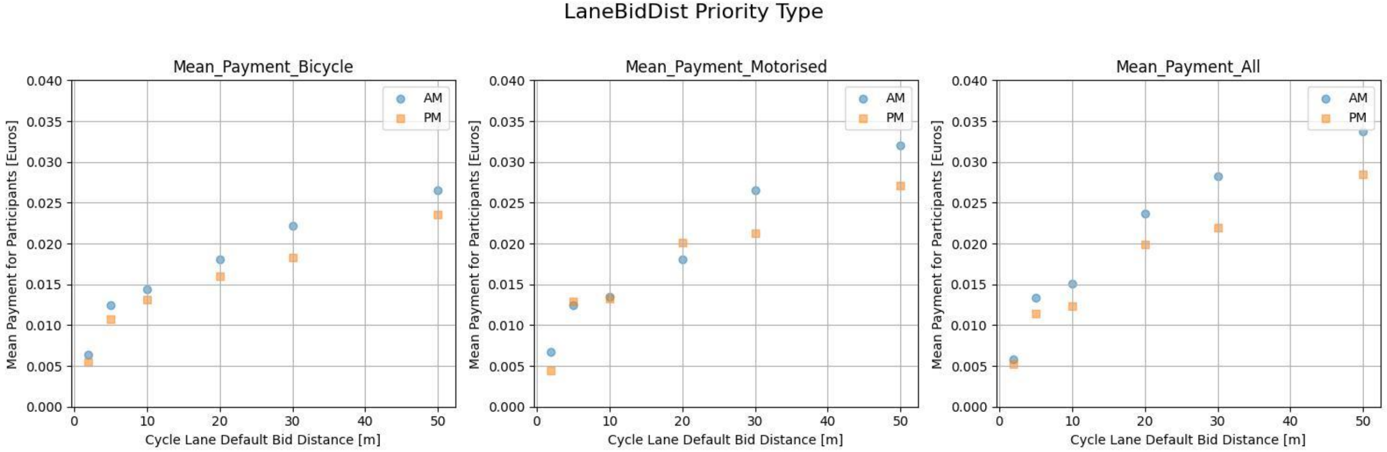




MERIGNAC
Bus

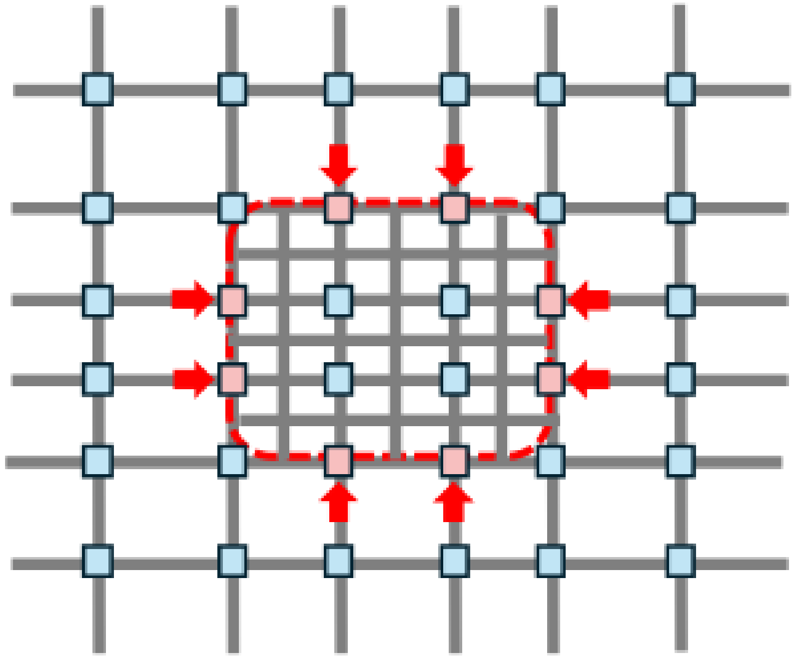
Auction-based intersection control

from priority to hybrid functionality

Could we design a hybrid controller, that

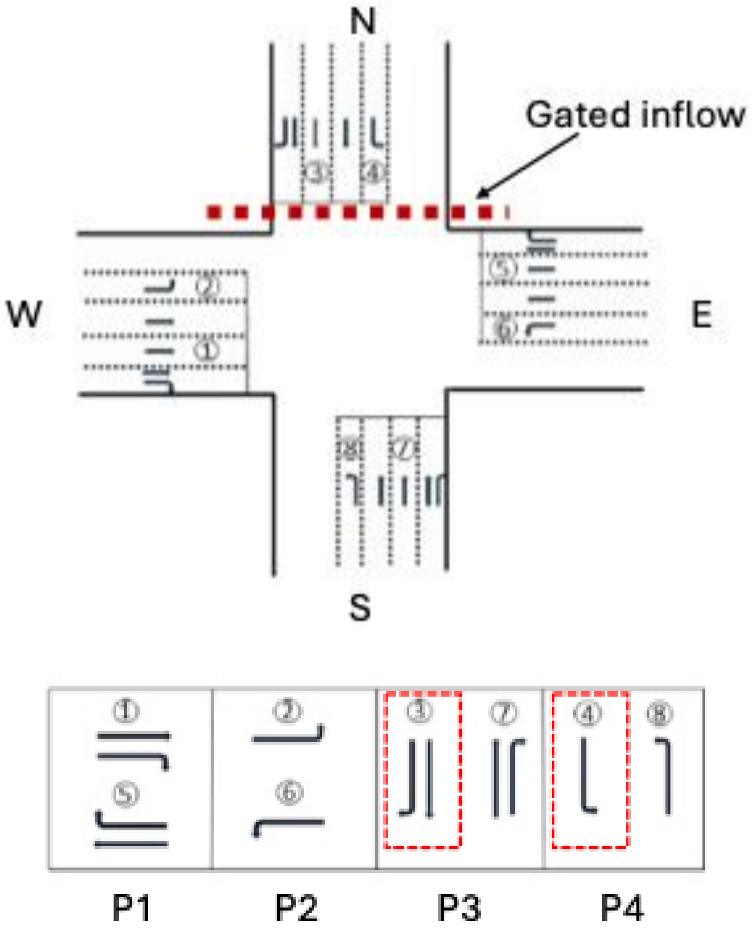
i) Prioritizes PT and serves the rest of traffic fairly, in normal conditions

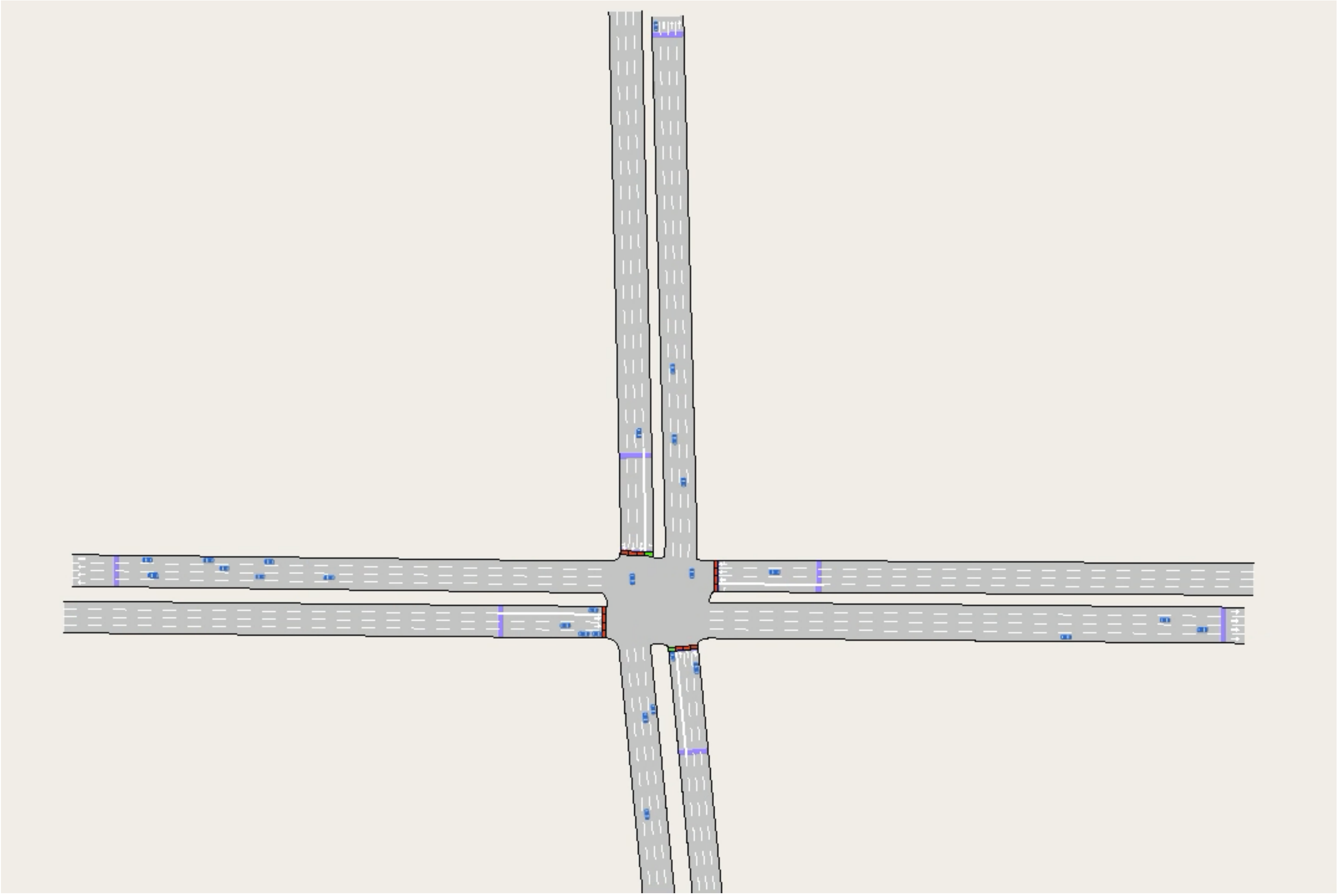
ii) Can act as a Gating (perimeter) controller when needed?



Auction-based intersection control

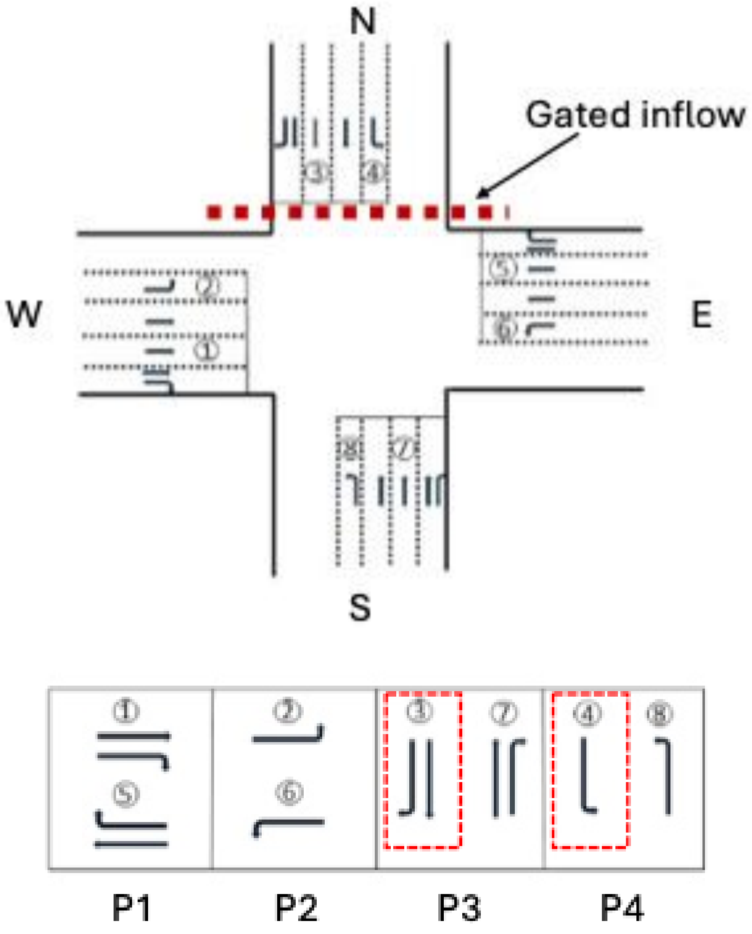
from priority to hybrid functionality



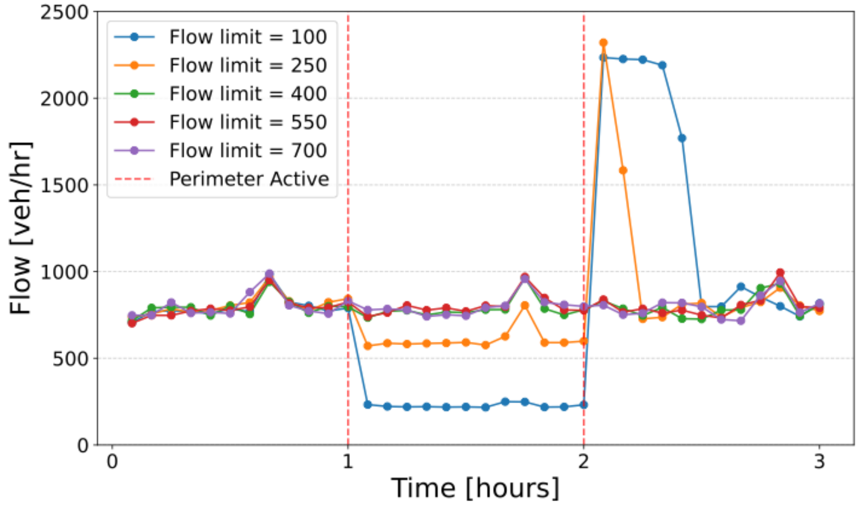


Auction-based intersection control

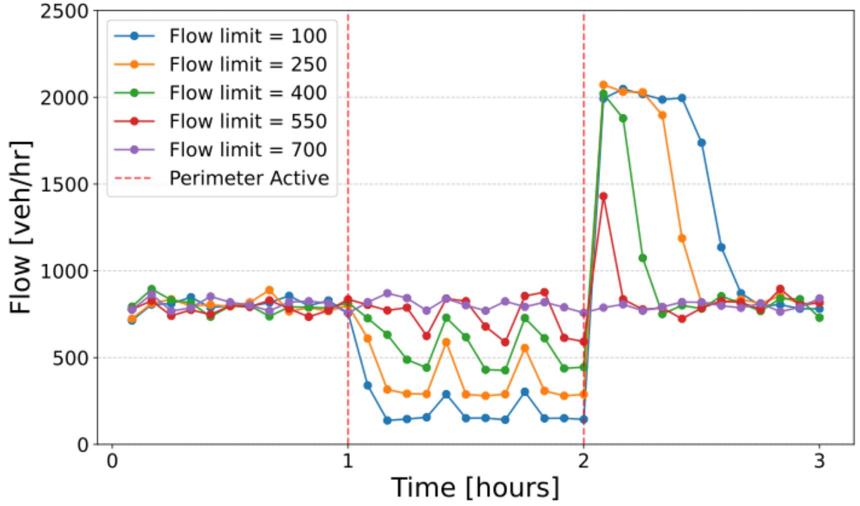
from priority to hybrid functionality



Volume-based



Auction-based



04

Auction-based traffic management II

CAV Platooning

Auction-based platooning management

Platooning:

- Helps reduce emissions (particularly for trucks, air drag)
- Can work in combination with traffic light signals (green duration proportional to platoon size and vice versa)
- More and more feasible thanks to V2X communication (some pilots running in NL, for instance)

Auction-based platooning management

However:

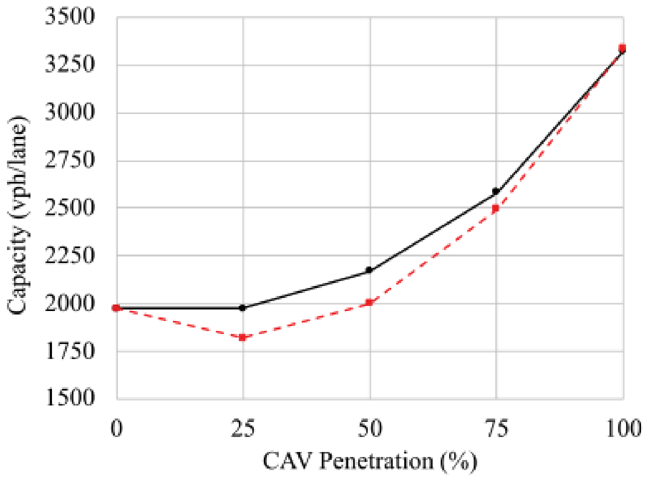


Fig. 4. Capacity for varying market penetrations of CAVs.

Auction-based platooning management

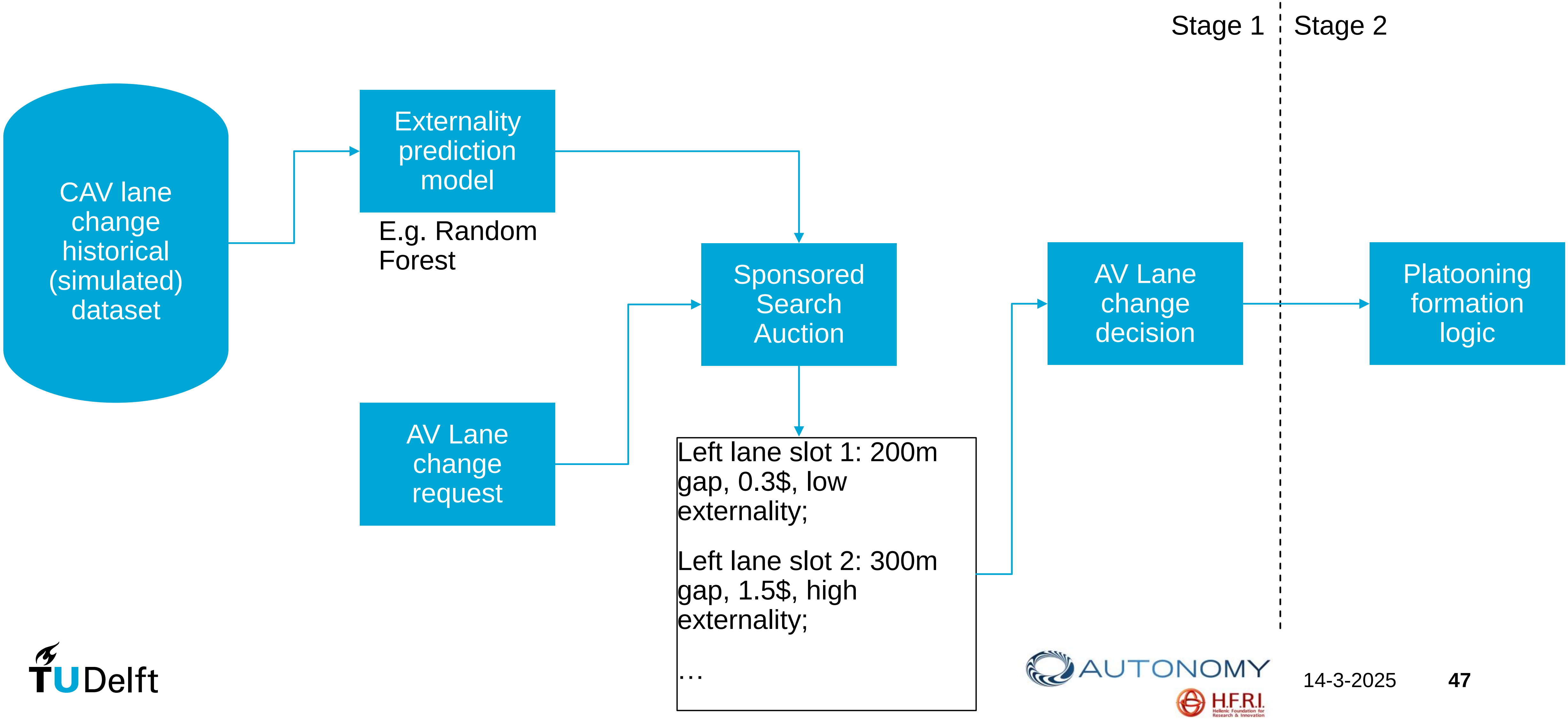
Could we use an auction mechanism to take lane-change decisions for platooning vehicles, so that

i) Lane-changes that cause a lot of negative externalities are less desirable (higher bid)

ii) Platoon formation is as effective and efficient as possible

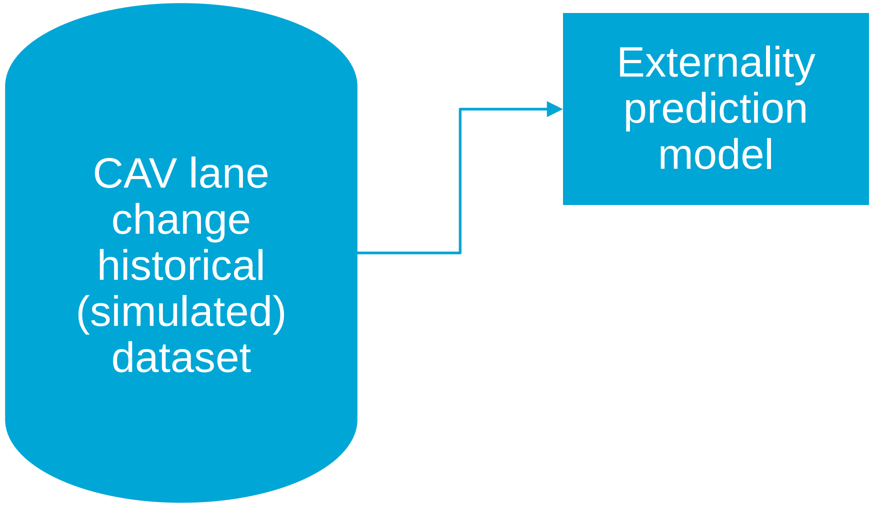
Auction-based platooning management

our idea (current research, collaboration NTUA x TUD)



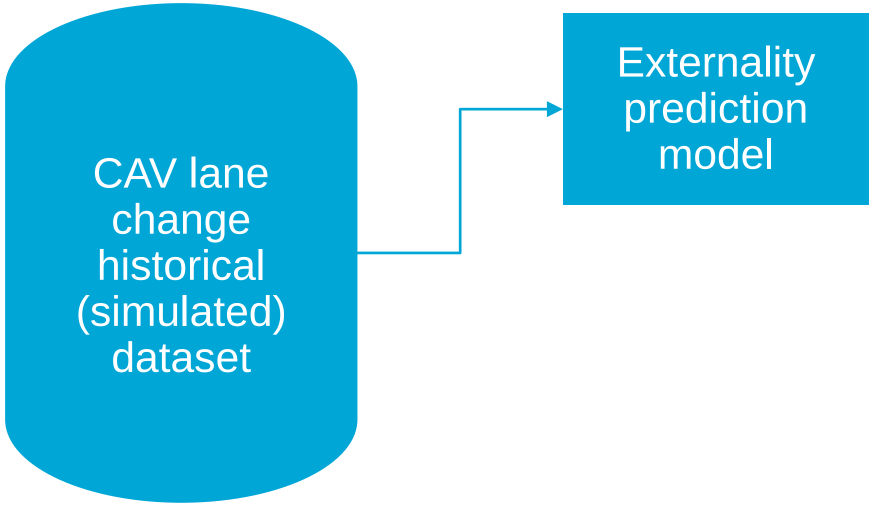
Auction-based platooning management

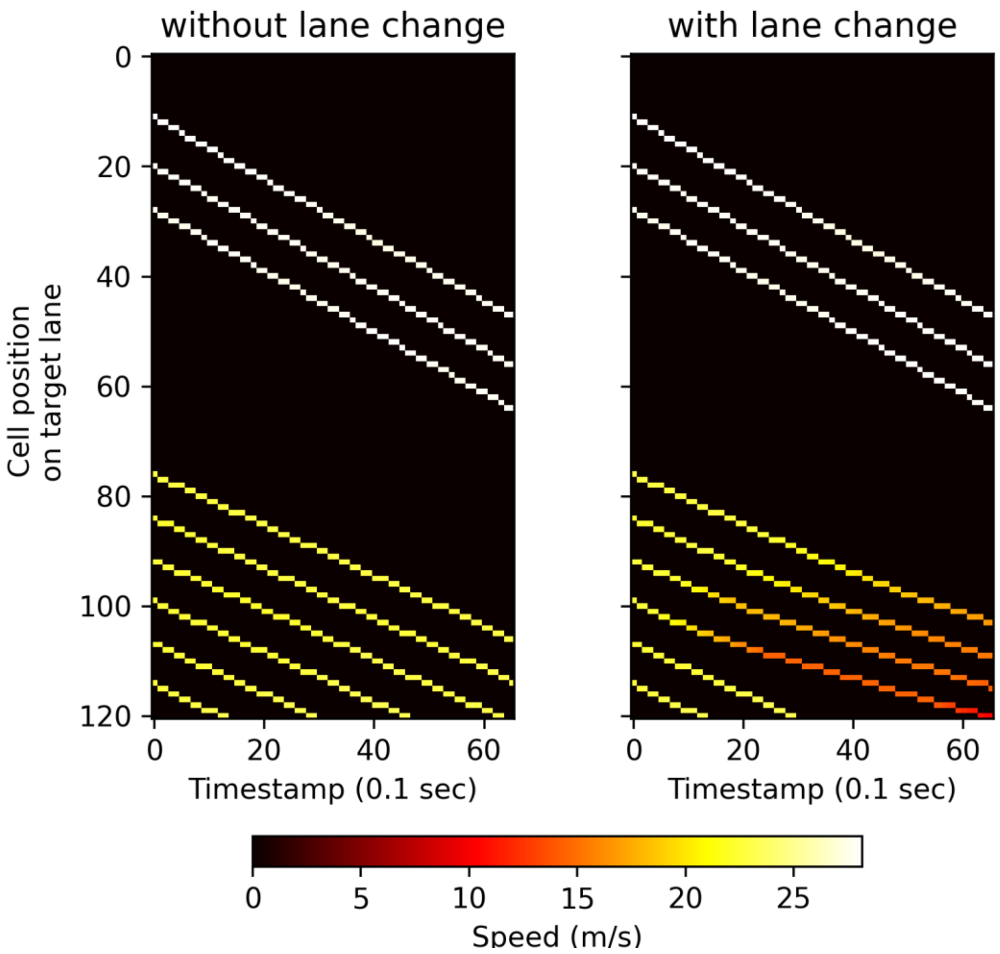
Preliminary results



Auction-based platooning management

Preliminary results





Wrap-up

- Auctions are a flexible computational framework
  - Shopping, traffic management, platooning, …
- Well versed for edge computing, V2X comm heavy scenarios
  - Quick (if approximate) solutions, good performance *in silico*
- More work needed!
  - Barely scratched the surface of what’s feasible
  - Challenging road to market (need lots of cooperation between stakeholders, be it municipality, road authority, payment backend, …)
  - Suboptimal/approximate auction solutions’ impact needs more investigation (particularly: what happens to incentive compatibility?)

Thank you!

Q&A

14-3-2025

References

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Auction-based intersection control (NTUA)	• https://www.sciencedirect.com/science/article/pii/S0378437122008160
Expressing priority in auction-based control	• https://research.tudelft.nl/files/239334470/Transportation_Research_Board_TRB_2025_Revised_5_.pdf
Dynamic perimeter control	• https://ieeexplore.ieee.org/abstract/document/10241647