Autonomous Vehicles

Impacts from a traffic wide perspective

Prof. Francesc Soriguera

BIT
Barcelona Innovative Transport

UNIVERSITAT POLITÈCNICA
DE CATALUNYA
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Autonomous vehicle (AV)

- Vehicle centric research
- Technology development is considered as the final goal

⇒ Impacts in traffic performance of 50 years technological development?

⇒ Autonomous vehicles will represent a ”change of paradigm” in traffic?

- Objectives of the presentation:
  - *Describe the impacts of autonomous mobility from a traffic wide perspective*
  - *Highlight the importance of traffic management in the era if AVs*

SAE **J3016**™ LEVELS OF DRIVING AUTOMATION™

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	SAE LEVEL 0™	**SAE LEVEL 1™**	**SAE LEVEL 2™**	**SAE LEVEL 3™**	**SAE LEVEL 4™**	**SAE LEVEL 5™**
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	

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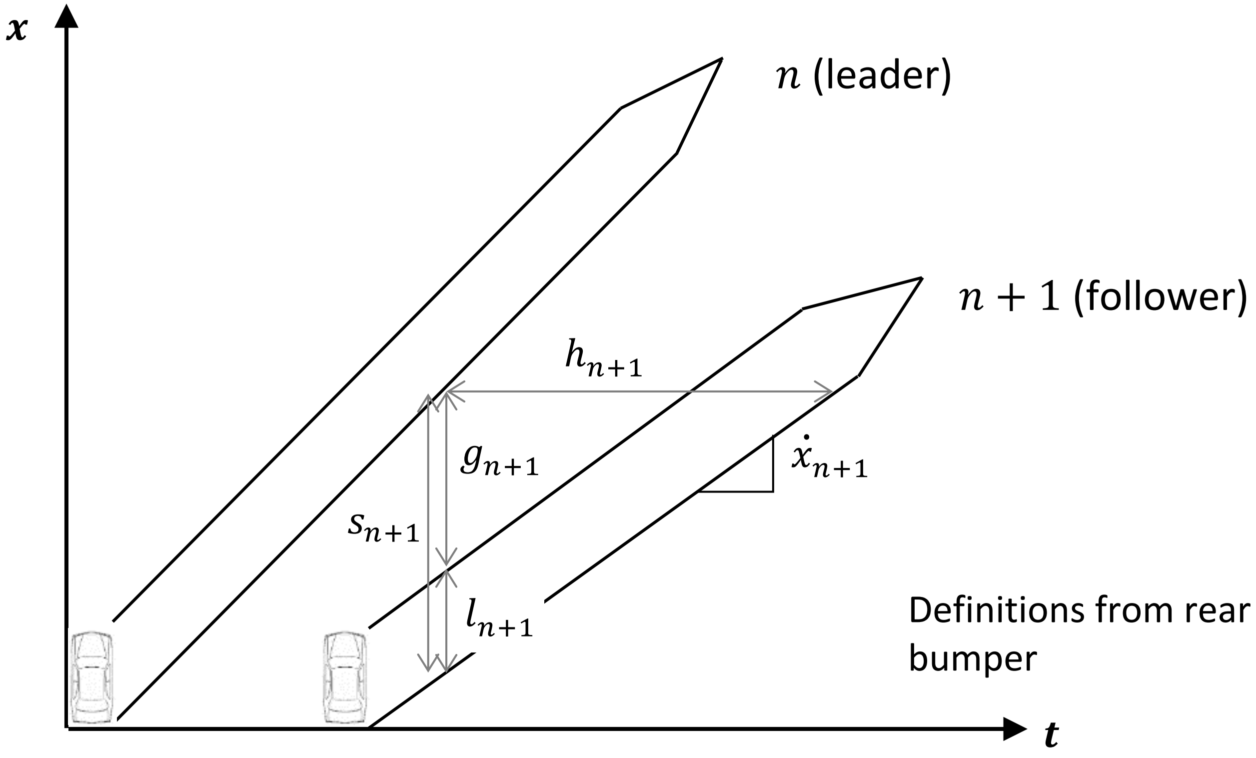
	These are driver support features			**These are automated driving features**		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/ acceleration support to the driver	These features provide steering **AND** brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering **OR** • adaptive cruise control	• lane centering **AND** • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

Contents

- Basics of car-following theory
- Traffic management in the era of AVs
    - CAVs as traffic actuators
    - CAVs platooning
- Safety impact of AVs
- Security in CAV platooning
- Pollutant emission impact of CAV platooning
- Other AV impacts in mobility
    - AVs route planning
    - AVs opportunities and threats as on-demand transportation

Basics of car-following theory

Basics of car-following theory



Definitions from rear bumper

s = spacing [space]

g = space gap [space]

l = vehicle length [space]

h = headway [time]

$$s_{n+1}(t) = l_{n+1} + g_{n+1}(t)$$

$$h_{n+1}(t) = \frac{s_{n+1}(t)}{\dot{x}_{n+1}(t)}$$

q = flow [veh/time]

k = density [veh/space]

$$q = \frac{1}{\bar{h}}$$

$$k = \frac{1}{\bar{s}}$$

Traffic management in the era of AVs

AVs: the end of traffic congestion?

Self-driving cars could be the answer to congested roads

November 21, 2014 3.49pm GMT

Nose-to-tail driving would be the norm if computers drove the cars. Danny Lawson/PA

ROAD RUSH

How self-driving cars will ease traffic congestion

PETER CHENEY

The Globe and Mail

Published Thursday, Dec. 12, 2013 5:00AM EST

Last updated Thursday, Dec. 12, 2013 5:26PM EST

WHY SELF-DRIVING CARS COULD CUT DOWN COMMUTER CONGESTION

By David Nield — March 8, 2015

https://www.youtube.com/watch?v=ftouPdU1-Bo

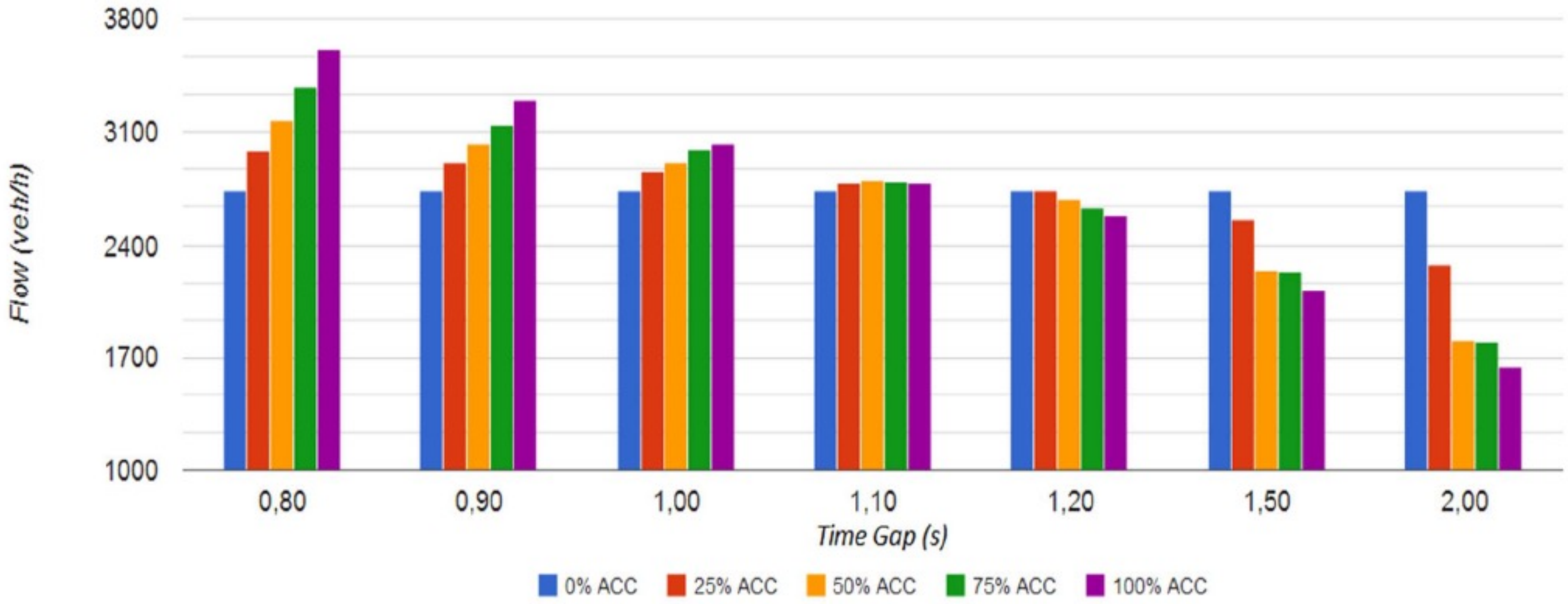
AVs by itself will NOT improve traffic conditions

- AV development focus on comfort and safety => Conservative parameters
  - *ACC with long gaps and sluggish accelerations*
  - *Conservative lane-changing and merge assistants*

  ¿Would you be willing to accept short gaps or strong accelerations (longitudinal and lateral) in your ACC vehicle?

- Uncoordinated behavior (e.g. car following, route guidance, lane assignment)
  - *Non cooperative car-following => may lead to unstable traffic behavior*
  - *Inefficient lane assignment*
  - *Uncoordinated route advice*

ACC – time gap implications



From: Ntousakis, I.A., Nikolos, I.K., Papageorgiou, M.: On microscopic modelling of adaptive cruise control systems. *4th Intern. Symposium of Transport Simulation (ISTS'14)*, 1-4 June 2014, Corsica, France. Published in *Transportation Research Procedia* 6 (2015), pp. 111-127.

→ AVs can be detrimental in terms of traffic efficiency

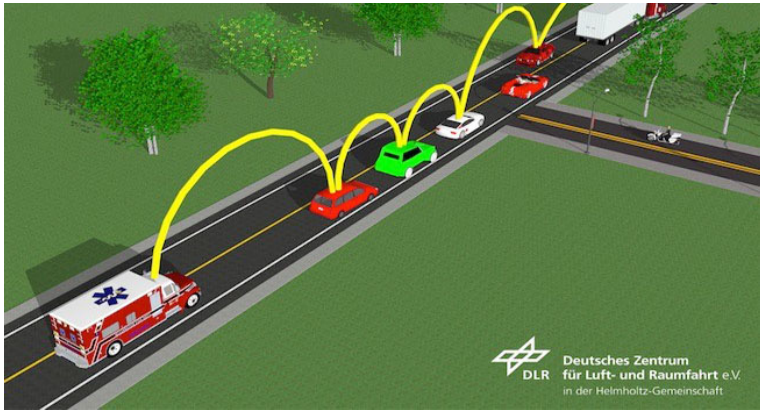
Traffic management in the era of AVs

- Traffic management will remain vital in the era of AVs.
- Concepts and strategies need to be adapted to AVs => **Research in progress**

- Huge potential of **Connected** Autonomous Vehicles (CAVs)
  - *Sensors => vehicle based*
  - *Communications => wireless. V2V, V2I, I2V*
  - *Computation => massively distributed*
  - *Control & actuator devices => in the vehicle*

AVs traffic management and coordination

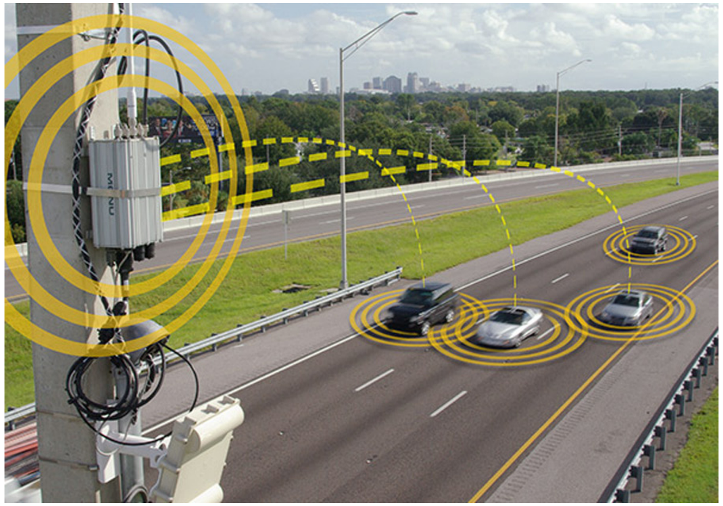
1. CAVs as actuators of traditional traffic management strategies
2. CAVs platooning => longitudinal coordination (locally)
    - *CAVs lane management in multi-lane facilities*
3. Coordinated route planning (network level)



CAVs as traffic actuators

CAVs as traffic actuators

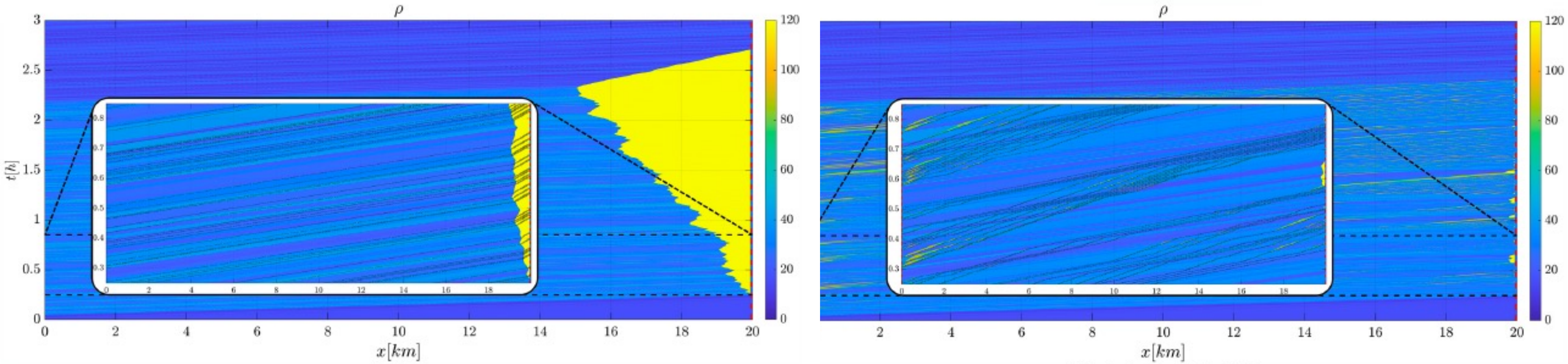
- Traditional traffic management strategies
  - *Dynamic speed limits*
  - *Main trunk traffic metering*
  - *Ecodriving*
  - *Cooperative lane-changing*



- CAVs may act as *Lagrangian* controllers => moving with traffic
- Effective even with low penetration rates of CAVs (e.g. 15%)

E.g. CAVs acting as traffic control devices

- Main trunk metering to prevent congestion at a stationary bottleneck. Platoon trajectories are shown by dotted black lines in the simulation run.



(b) Fixed controlled segment length (FS)

M. Cicic, C. Pasquale, S. Siri, S. Sacone, and K. H. Johansson, “Platoon-actuated decongestion,” Eur. J. Control, vol. 68, Nov. 2022, Art. no. 100687, doi:10.1016/j.ejcon.2022.100687.

CAVs platooning

CAVs platooning

- CAVs platooning => CAVs travelling in a coordinated way, with very short gaps, relatively high speeds and ensuring safety.
- California PATH Program (1990s); EU projects & truck manufacturers (2010s)

https://www.youtube.com/watch?v=h7tO-4FoKCo

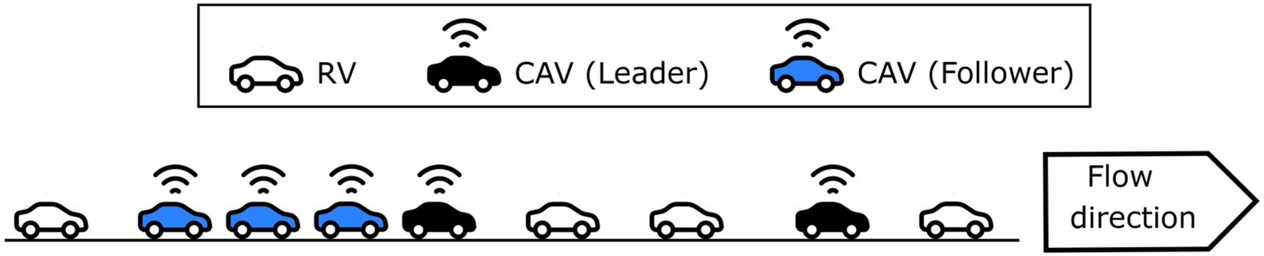
https://www.youtube.com/watch?v=lpuwG4A56r0

PATH Automated Vehicle Platoon Demo ‘97 on I-15 San Diego California PATH: Vehicle Highway Automation
YouTube: https://www.youtube.com/watch?v=h7tO-4FoKCo

SCANIA Trucks & Buses platooning experiments.
YouTube: https://www.youtube.com/watch?v=lpuwG4A56r0

Platooning: leader and followers

- Within a platoon there are two types of vehicles:
    - *Leader: the first vehicle of the platoon*
    - *Follower: the other vehicles*
- Followers use reduced gaps, as they have information of the preceding vehicle.
- Leader uses non-coordinated AV gaps, since it has no information of the preceding vehicle.



Platooning V2V communications

- AVs shared data: vehicle relative position, speed and acceleration/deceleration
- Limited communication range for each vehicle (typically 300m is considered)
- Information exchange flow topologies (IFTs):

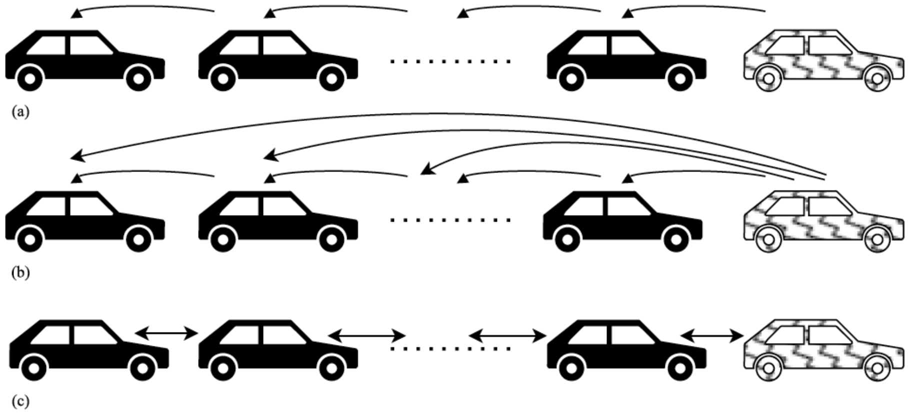
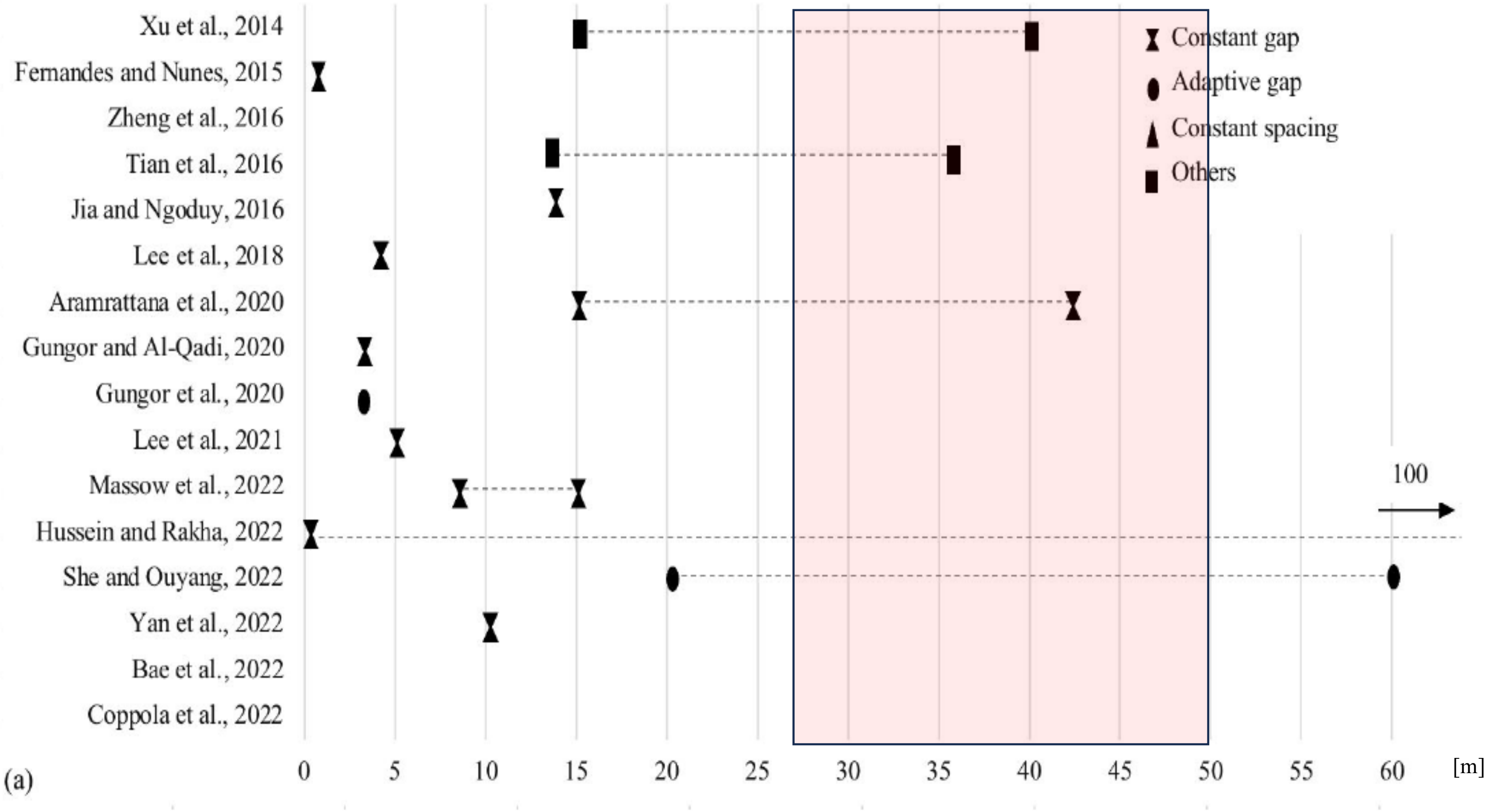


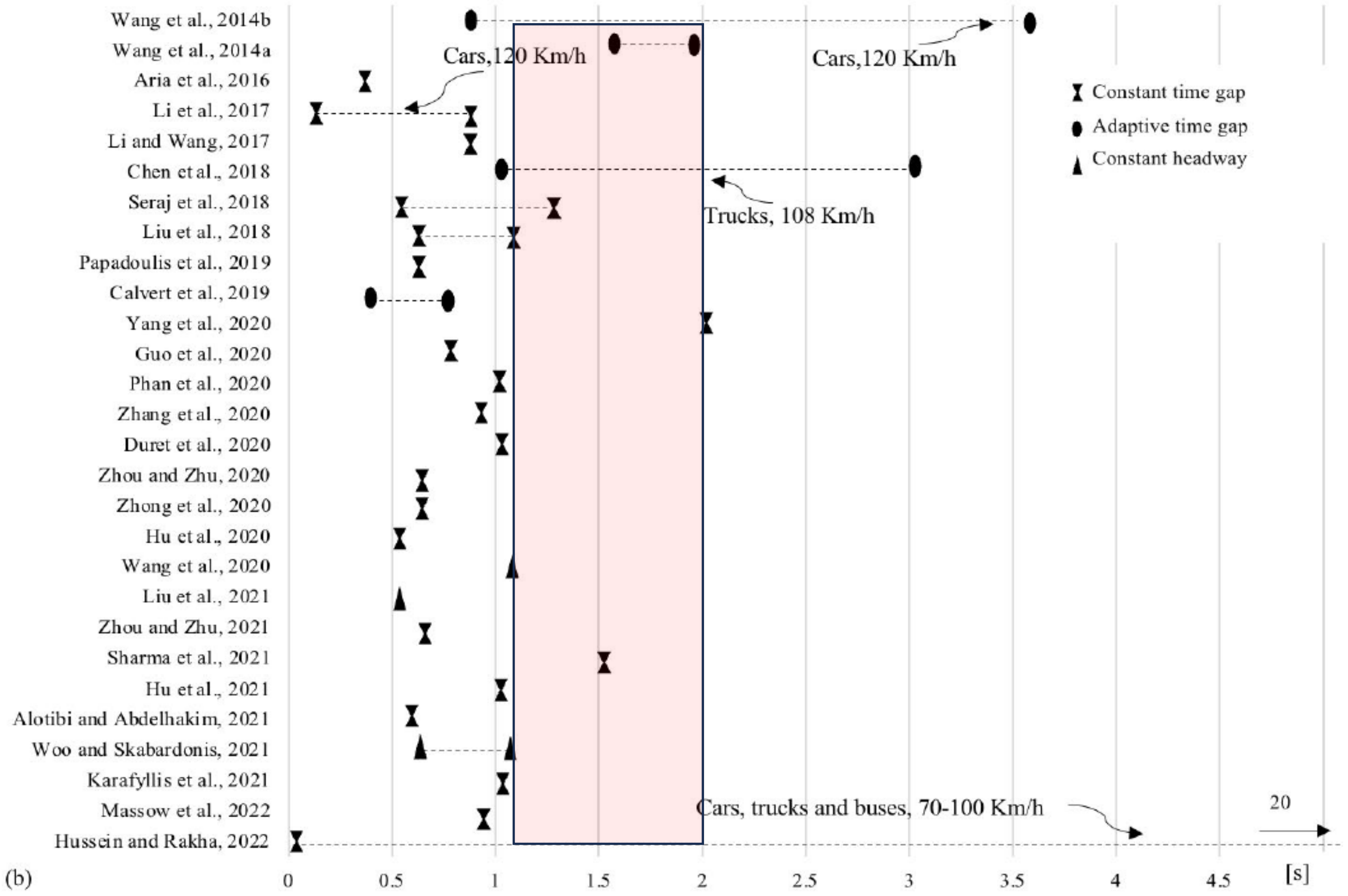
Fig. 7. Examples of IFTs (leader highlighted): (a) predecessor-following, (b) predecessor-leader-following, (c) bidirectional.

Adding leader information to enhance stability

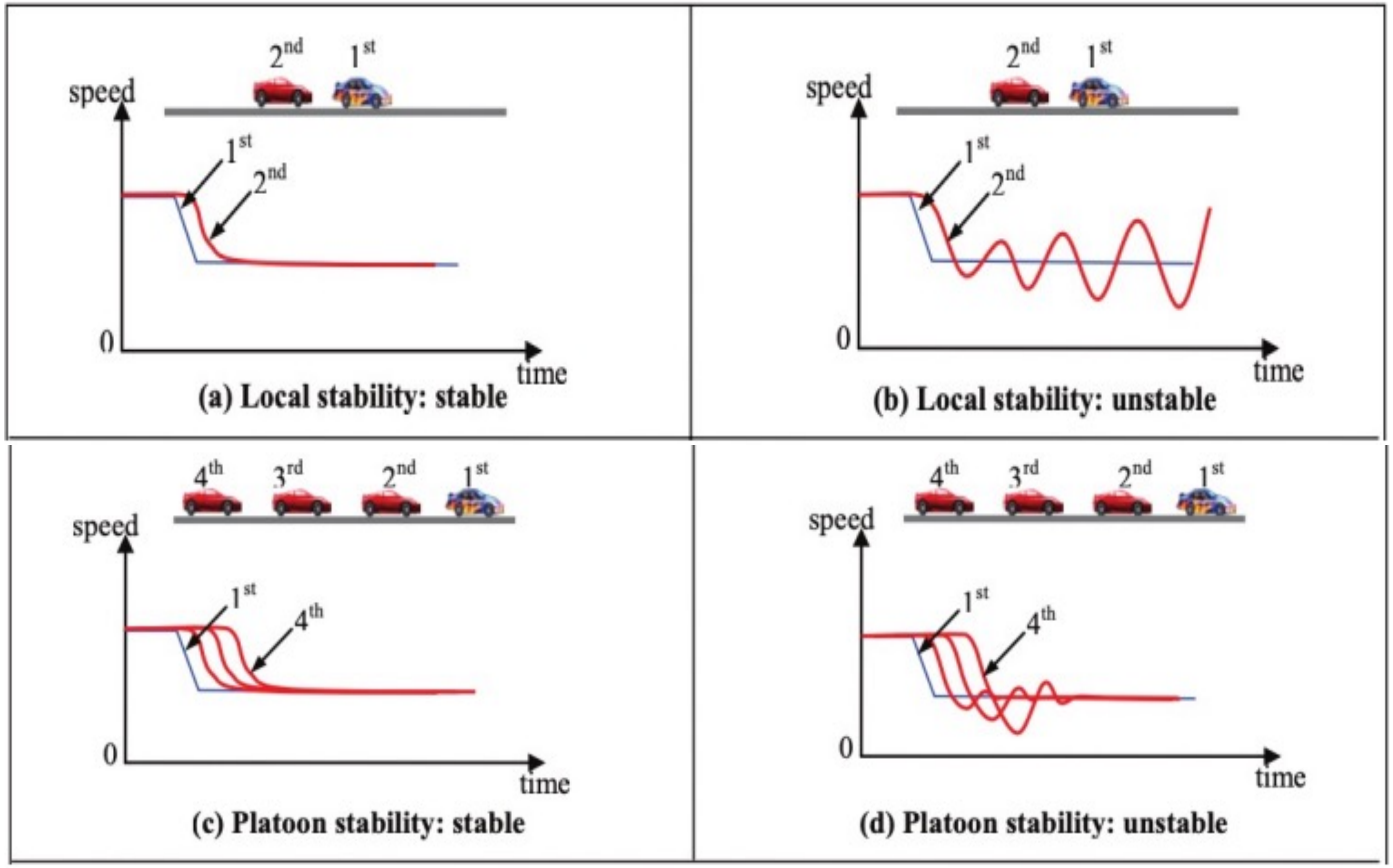
Platoon car-following rules => space based



Platoon car-following rules => time based



Platoon stability



(a) Local stability: stable

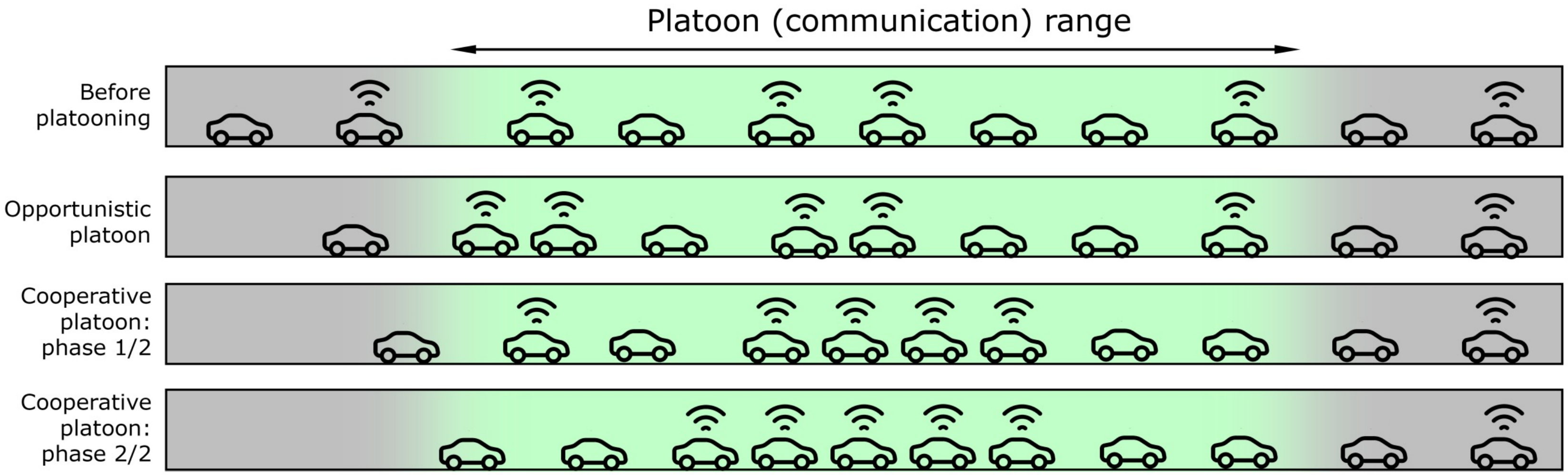
(b) Local stability: unstable

(c) Platoon stability: stable

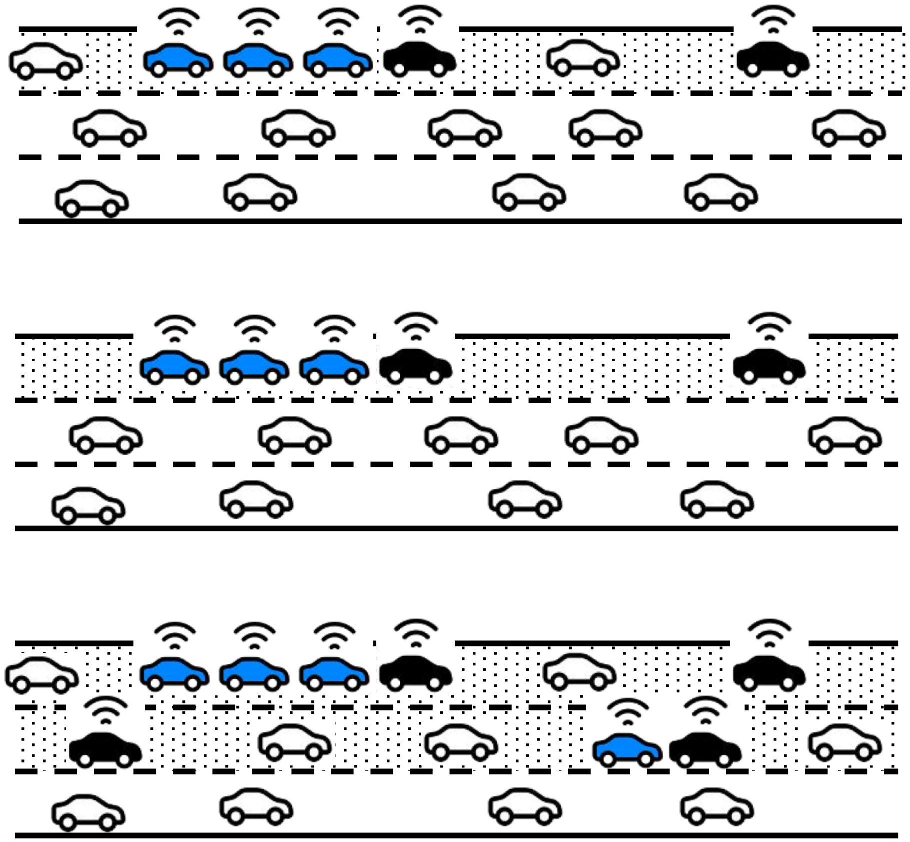
(d) Platoon stability: unstable

Platoon formation

- Opportunistic => Only consecutive CAVs form the platoon.
  - *Worst case; easy implementation.*
- Cooperative => All CAVs in the communication range aim to form the platoon.
  - *Best case; Difficult implementation.*



Platooning lane management



Mixed platooning lane — CAVs + RVs

General purpose lanes — RVs

Dedicated platooning lane — CAVs only

General purpose lanes — RVs

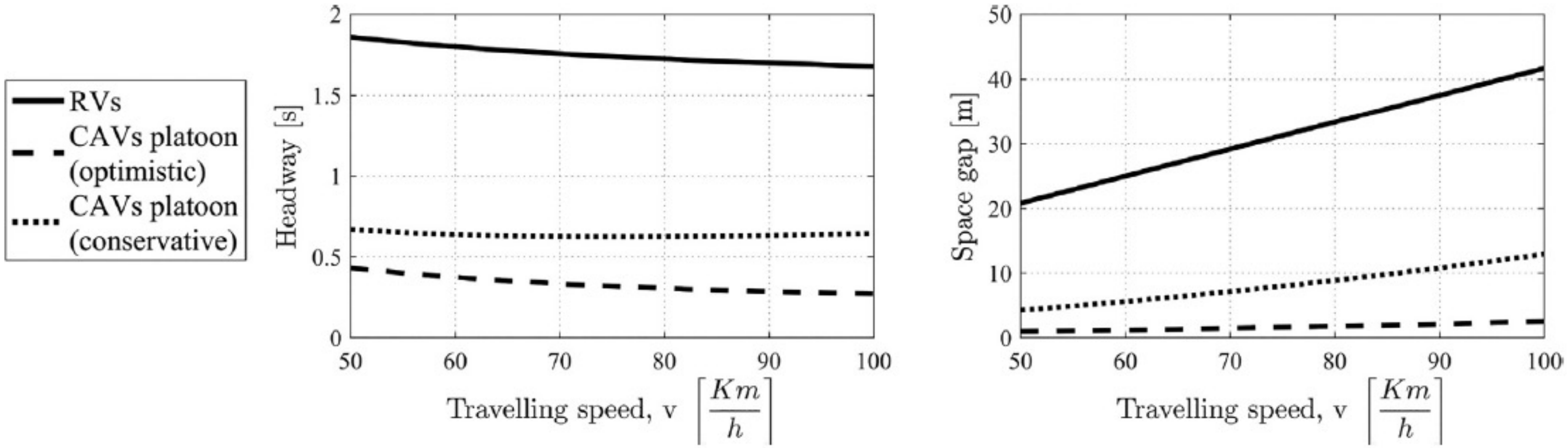
Two mixed platooning lanes — CAVs + RVs

General purpose lane — RVs

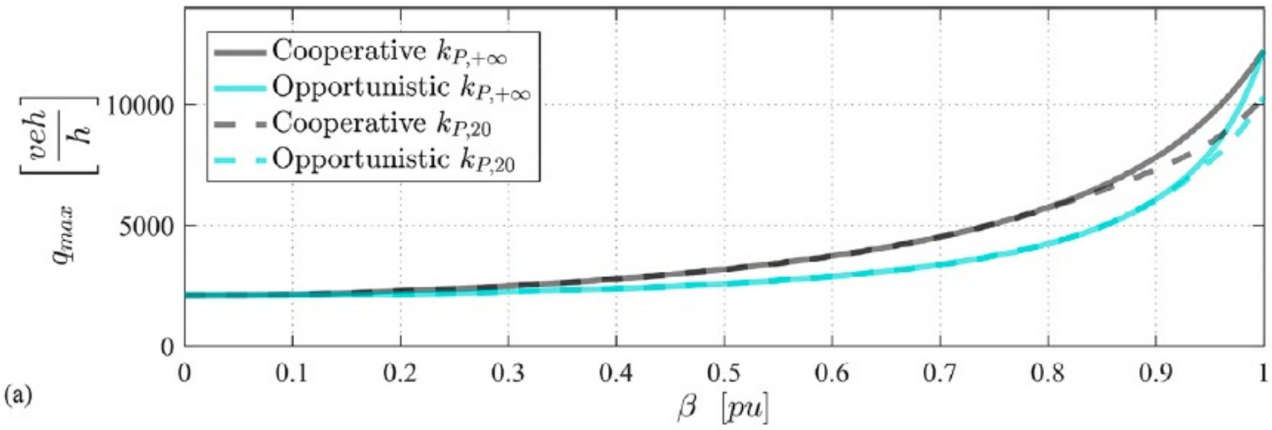
CRITERIA	TYPOLOGIES
Vehicle types	Homogeneous Heterogeneous
Platoon length	Limited Unlimited
Platoon formation policies	Opportunistic (on-the-fly) Cooperative Online, dynamic or in real time Offline, static or scheduled (truck platooning) Merging/split policies
Platoon car-following policies	Constant space-gap Constant time-gap Adaptive space-gap
Information flow topology	Predecesor - Follower Predecesor – Leader – Follower Bidirectional
Platoon lane Management	Mixed lanes (Leftmost, one – two) Dedicated (Leftmost)

An analytical analysis of a mixed platooning lane

Input	Value*	Units	Description
v_f	100	[Km/h]	Free flow speed.
β	0 to 1	[fraction on unit]	Penetration rate of CAVs in the mixed traffic platooning lane.
l_d	300	[m]	Platooning distance (i.e. communications range considered for platooning applications).
k_P	20	[vehicles]	Maximum allowed platoon length in units of vehicles.
t_R	1.5	[seconds]	Human drivers' average reaction time in car-following.
$\bar{l}$	5	[m]	Average vehicle length.
δ	0.001 - 0.1	[seconds]	Latency of vehicle to vehicle communications.
d_{max}	10	[m/s^2]	Maximum CAVs deceleration in emergency conditions. Defined positive.
γ	0.05 - 0.2	[fraction of unit]	Acceptable relative difference in the CAVs' max. deceleration (i.e. the minimum deceleration is $d_{max}(1-\gamma)$).
f_{min}	0.5	[m]	Safety margin in the space gap between CAVs in the platoon to account for measurement errors.



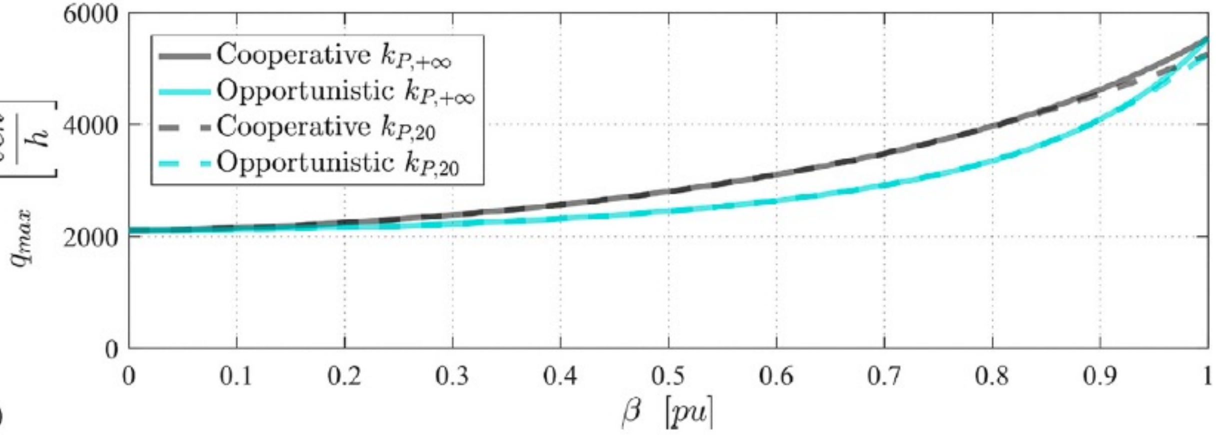
Capacity of a mixed platooning lane



(a)

Optimistic parameters

- *Latency = 0.001 [s]*
- *Differential braking = 0.05*



(b)

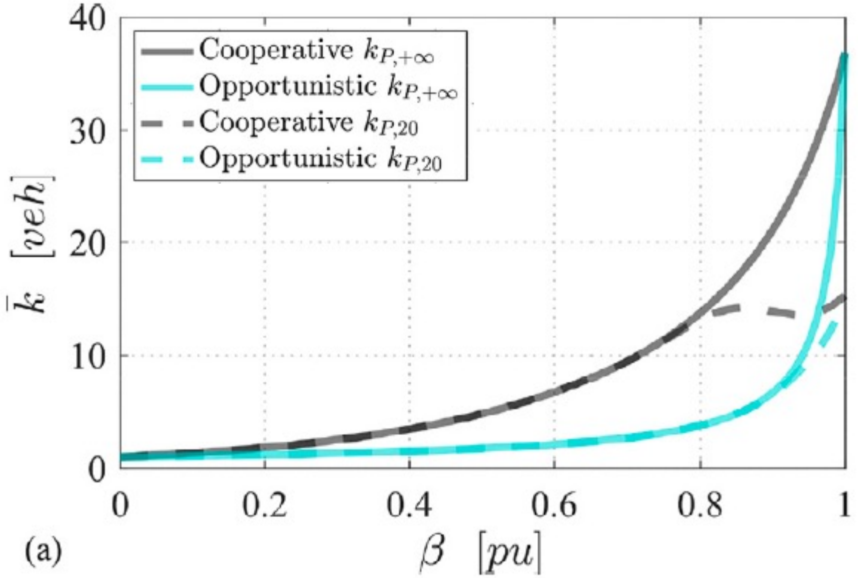
Conservative parameters

- *Latency = 0.1 [s]*
- *Differential braking = 0.2*

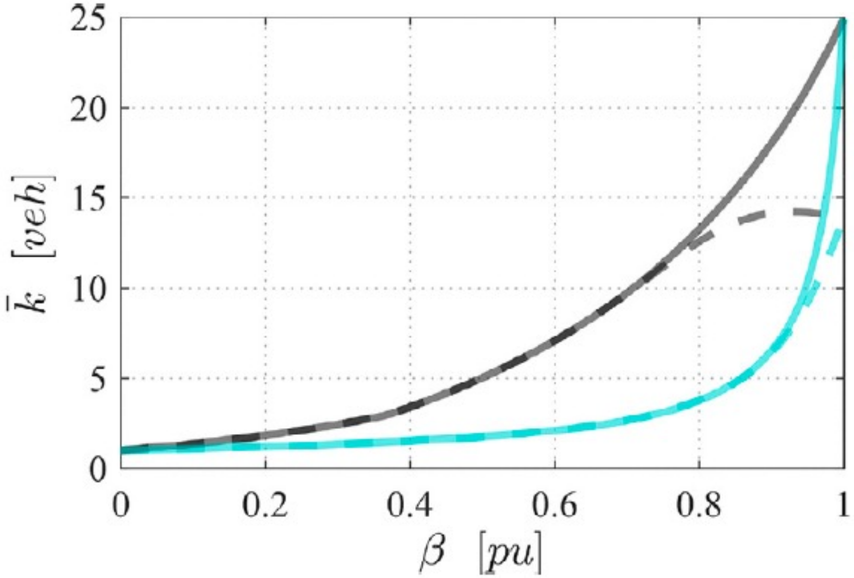
Avg. platoon length at capacity in a mixed lane

- Proportion of CAVs in the lane (β)
- Platoon length limitation of $k_p = 20$ [veh] is not binding for $\beta < 0.8$

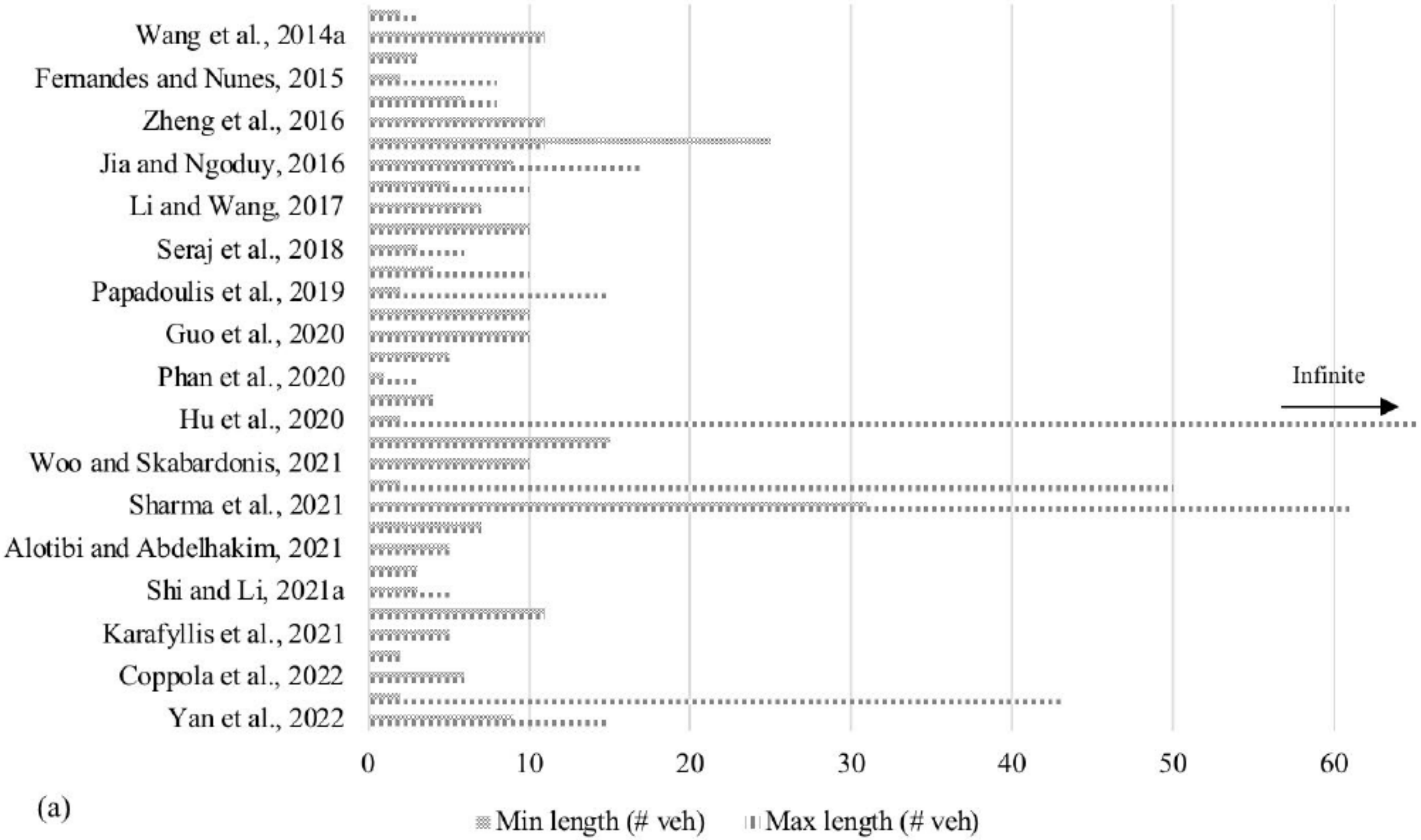
Optimistic



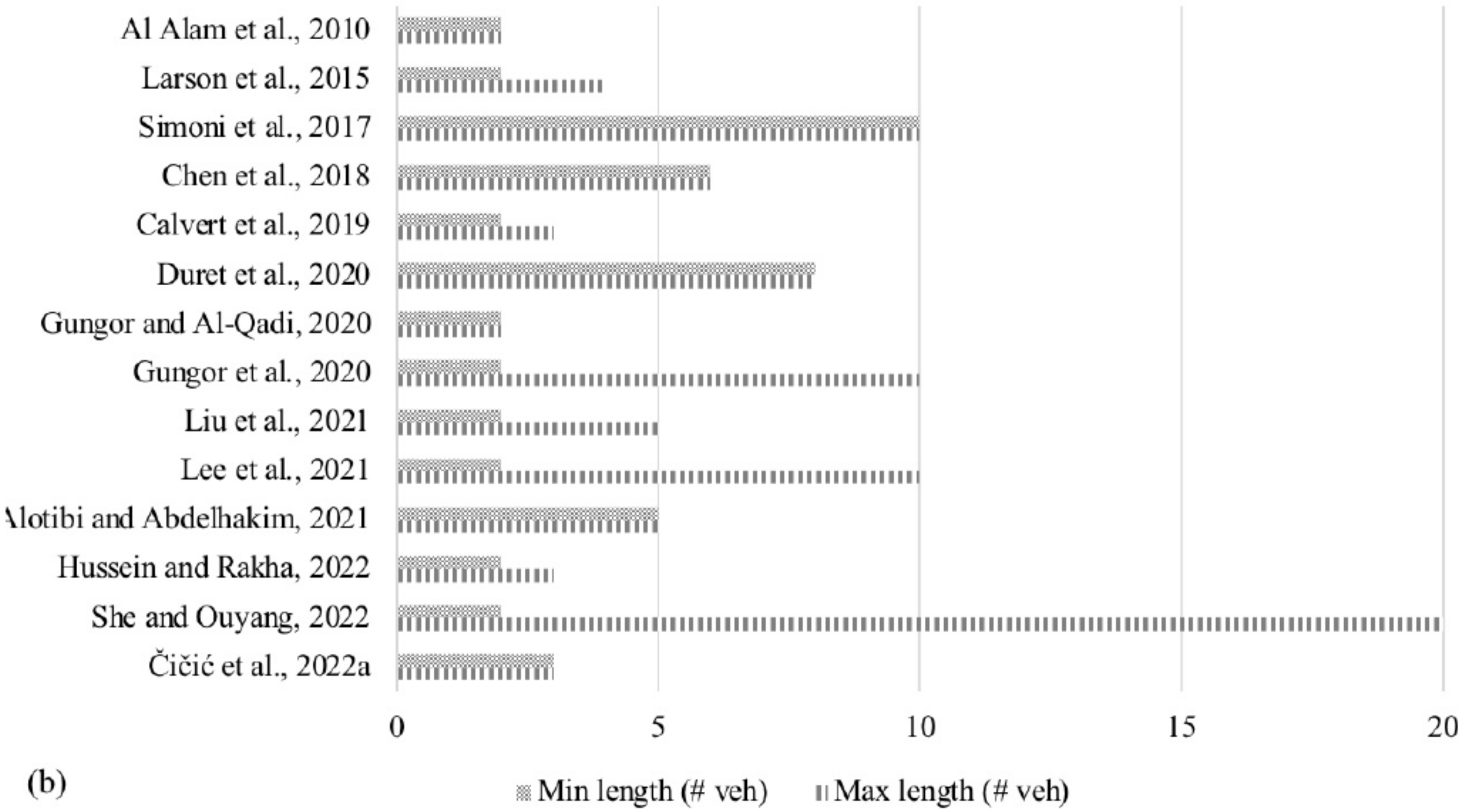
Conservative



Min. / Max. platoon length in car platooning

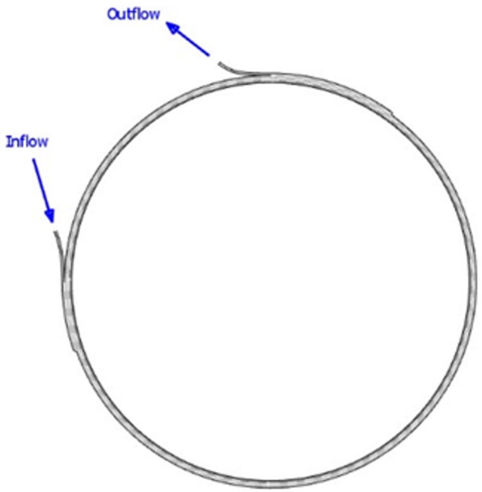


Min. / Max. platoon length in truck platooning



A simulation analysis of multi-lane platooning

- Default microsimulation car-following and lane changing algorithms based on the Gipps model (Gipps, 1981; Gipps, 1986a; Gipps 1986b)
- Ad hoc developed API with the platooning control algorithm



Three-lane highway with a circular configuration $(L = 1.5\ km)$, 1 on/off-ramp

Exit ratio $\alpha = 0.1$

Inflow, $f(t) = 300 \div 1100$ veh/h

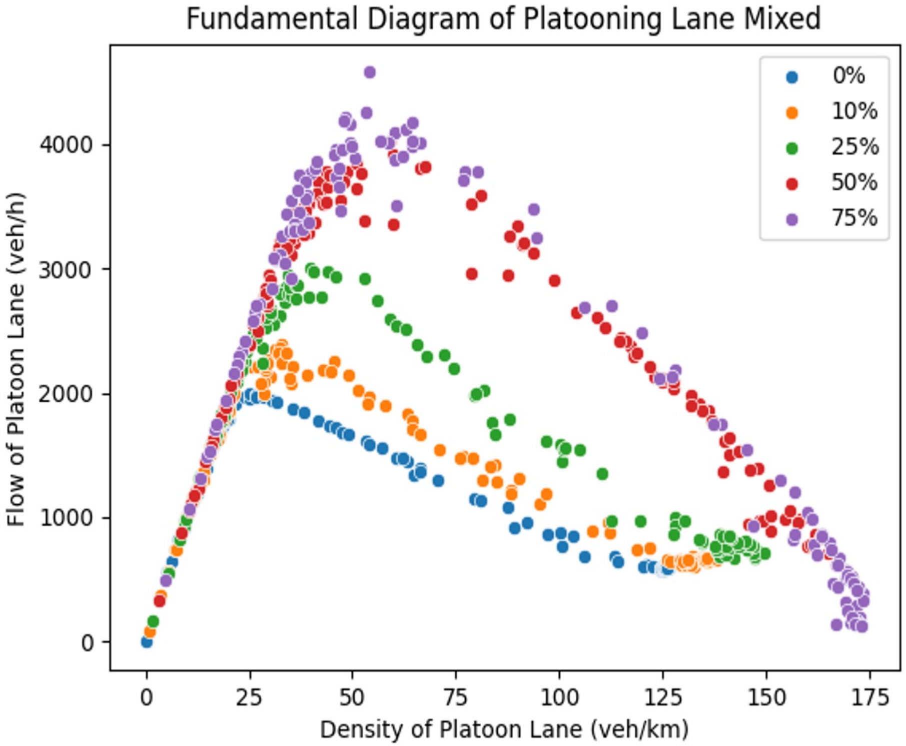
Platooning simulation algorithm

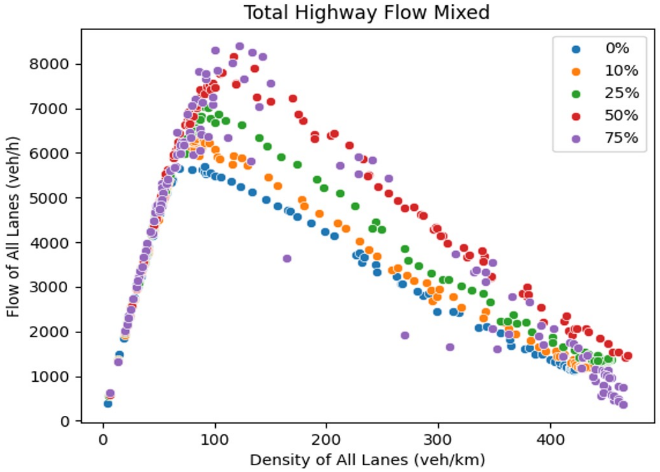
- CAV enters into simulation
  - *CAVs enter the simulation using Gipps car-following like all normal vehicles*
- Enters platoon lane
  - *If the CAV does not need to exit yet, lane changes left until the platoon lane. With default cooperation and safety behavioural parameters considered*
- Forms platoon until exiting
  - *If the CAV has nearby platoons in front, it will try to join the group, or be joined from behind. It can also merge into an existing platoon.*
- Leaves platoon lane and simulation
  - *Once the CAV needs to leave, lane changes out of the platoon to the off ramp.*

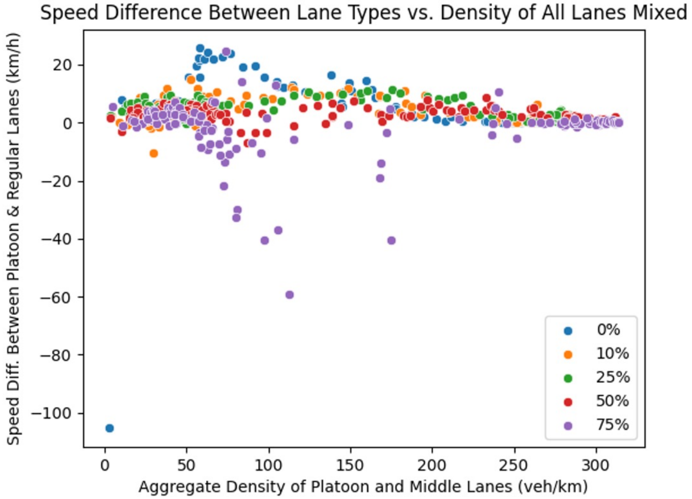
Platooning lane management scenarios

CAVs penetration rate	0%, 10%, 25%, 50%, 75%, 100% *Note that CAV penetration rate in the platooning lane will be higher*
One Mixed Platooning Lane	1 Platoon Lane, Left most lane, Regular Vehicles allowed *CAVs platooning desirability management*
One Dedicated Platooning Lane	1 Platoon Lane, Left most lane, CAVs only *Speed-limit management strategy*
Double Mixed Platooning Lane	2 Platoon Lanes, Left and middle lanes, Regular Vehicles allowed in all lanes
100% CAV	All lanes available for platooning, Lane changing is AIMSUN controlled

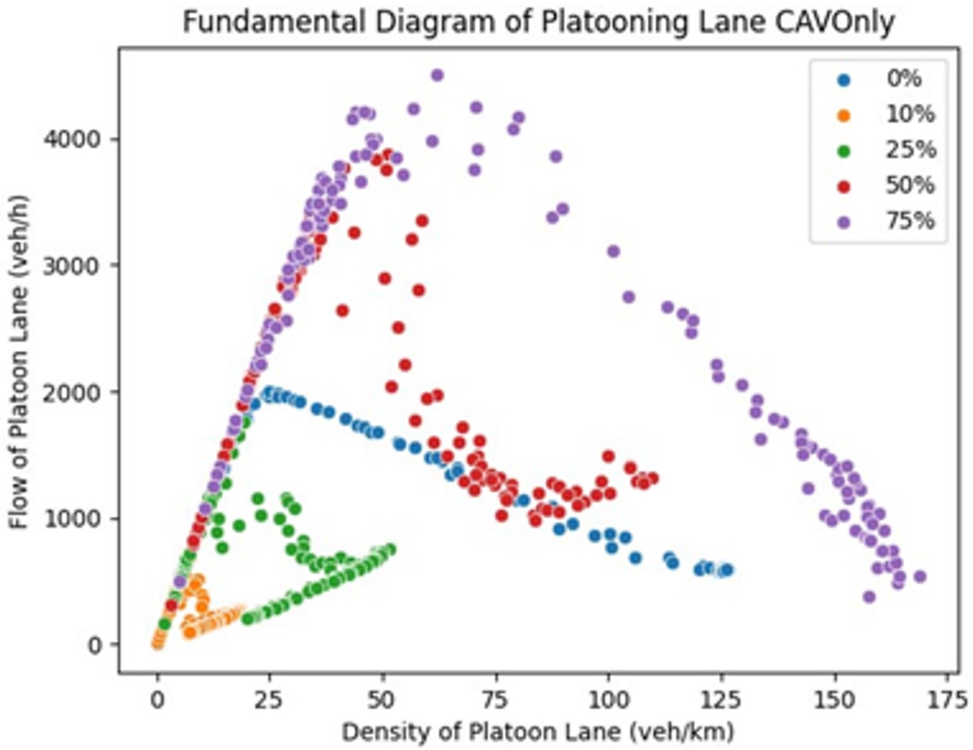
One mixed platooning lane

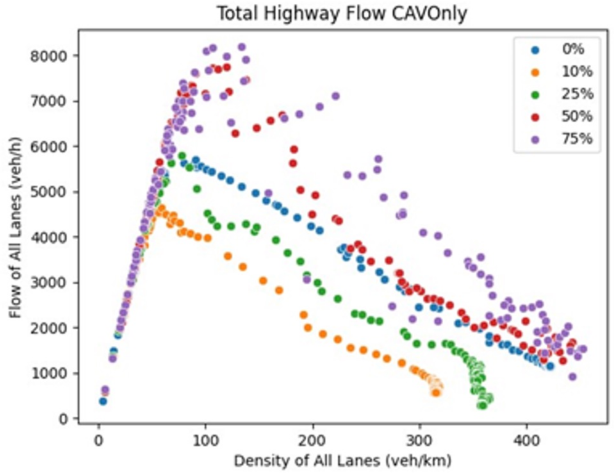


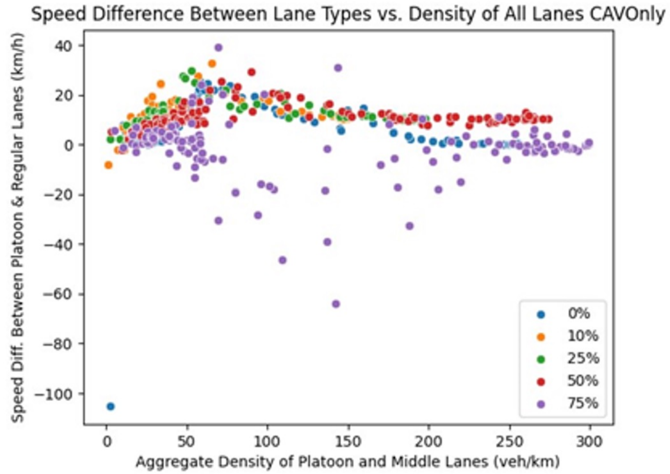




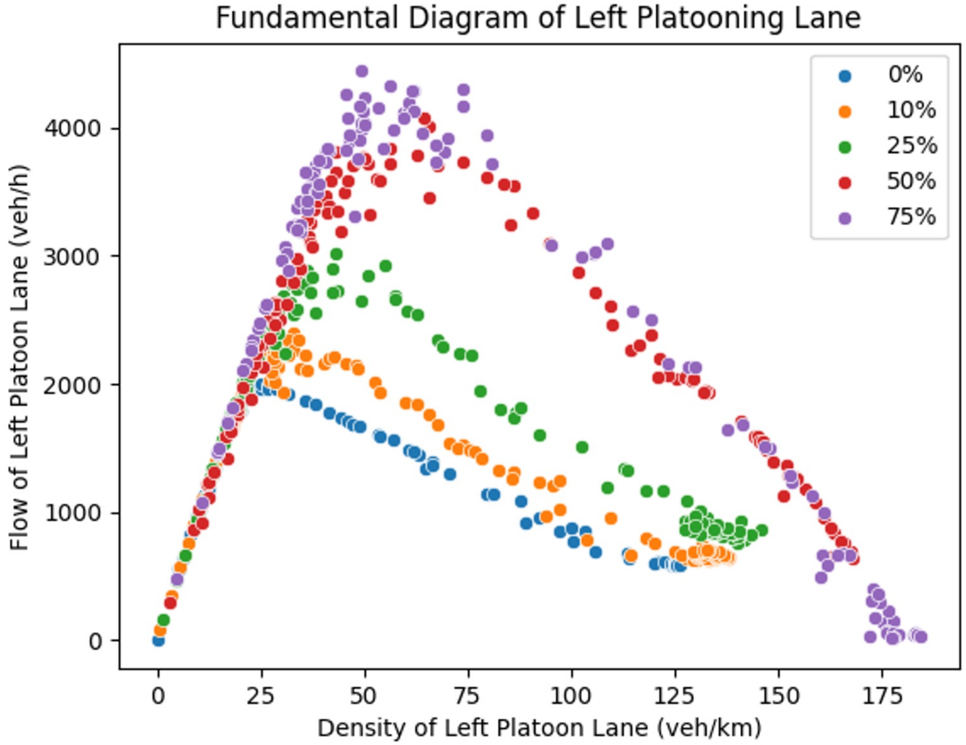
One dedicated platooning lane

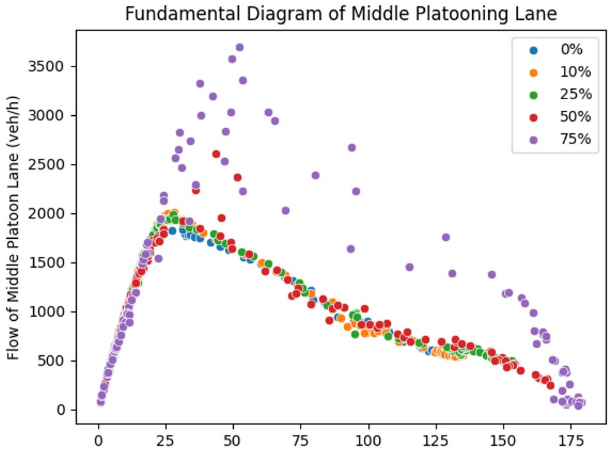

Fundamental Diagram of Platooning Lane CAVOnly

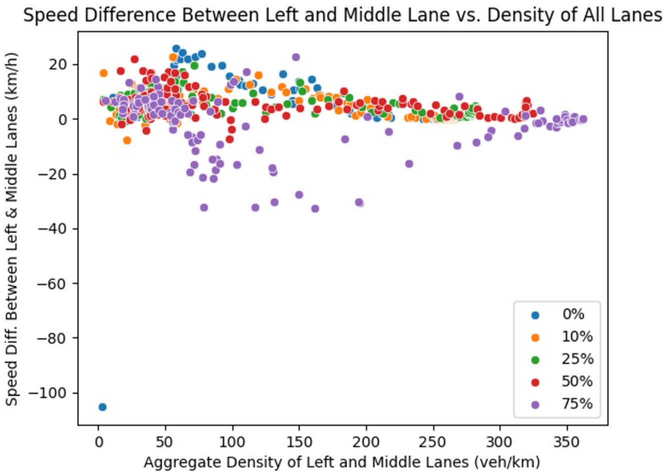

Total Highway Flow CAVOnly


Speed Difference Between Lane Types vs. Density of All Lanes CAVOnly

Double mixed platooning lane

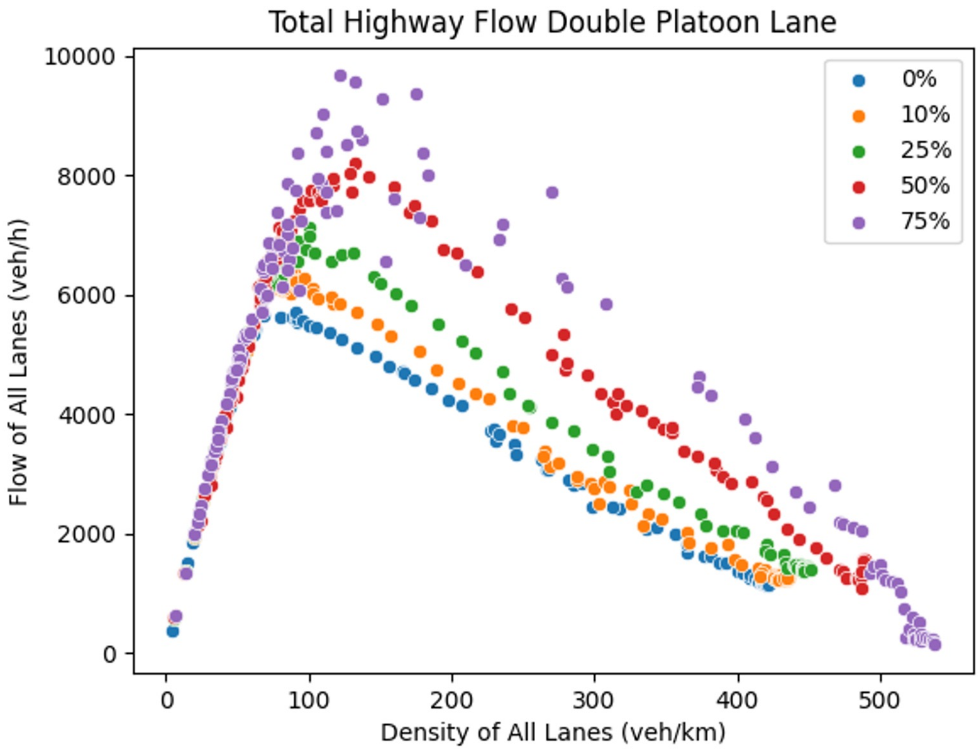

Fundamental Diagram of Left Platooning Lane

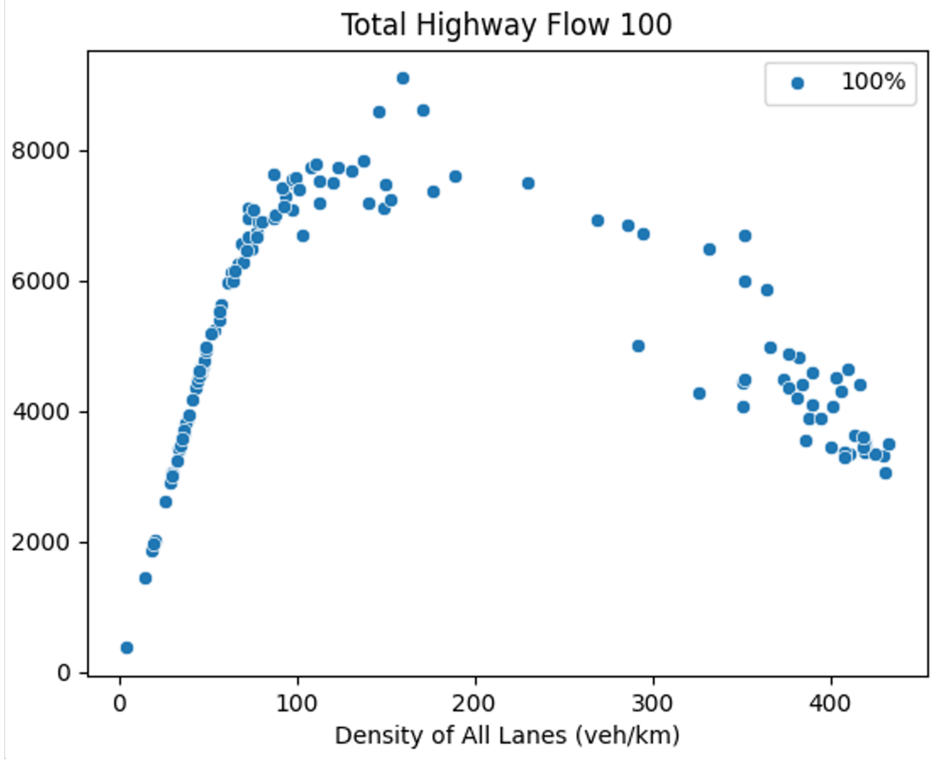

Fundamental Diagram of Middle Platooning Lane


Speed Difference Between Left and Middle Lane vs. Density of All Lanes

Double mixed platooning lane

100% CAV penetration rate





Conclusions on managing platooning lanes

- Dedicate lanes need physical infrastructure or a different policy
- Mixed platooning lanes significantly improve highway capacity
  - *Mixed Platoon lanes function well until a threshold in CAV penetration rate*
  - *Regular vehicles help to fill in the gaps of underutilized lane space*
  - *In the simulated scenario (3 lane, specific platooning parameters), the CAV penetration rate threshold for one mixed platooning lane is approx. 50%.*
- High CAV penetration rates require two (or more) platooning lanes to improve lane flow
- CAVs need platooning management to improve traffic flow
- Further research: Lane specific infrastructure, platoon lane management, non-lane based CAVs platooning management

Safety impacts of AVs

Surrogate safety indicators

- Surrogate safety indicators are frequently used to analyze safety.

Surrogate indicator	Definition	Calculation	Threshold
Time to collision, (TTC)	Time left until vehicles collide if they maintain constant their current speeds.	$TTC = \frac{gap_f}{v_f - v_l} = \frac{gap_f}{\Delta v_f}$	> 1.5 to 4 [s]
Modified time to collision, (MTTC)	Time left until vehicles collide if they maintain constant their current accelerations.	$MTTC = \frac{\Delta v_f \pm \sqrt{{\Delta v_f}^2 + 2\Delta a_f gap_f}}{\Delta a_f}$	> 1.5 to 2.5 [s]
Deceleration rate to avoid the crash, (DRAC)	Minimum braking rate required to prevent a collision.	$DRAC = \frac{{\Delta v_f}^2}{gap_f}$	< 3.4 [m/s^2]
Post encroachment time, (PET)	Time difference between a vehicle leaving the area of encroachment and a conflicting vehicle entering the same area.	Surrogate measure to identify conflicts linked to lateral maneuvers	> 5 [s]
Time-exposed time to collision, (TET)	Sum of cases in which the TTC is lower than its chosen threshold	Larger values lead to higher collision risks. Thus, safe conditions are characterized by low TET values.	

Safety impacts of AVs

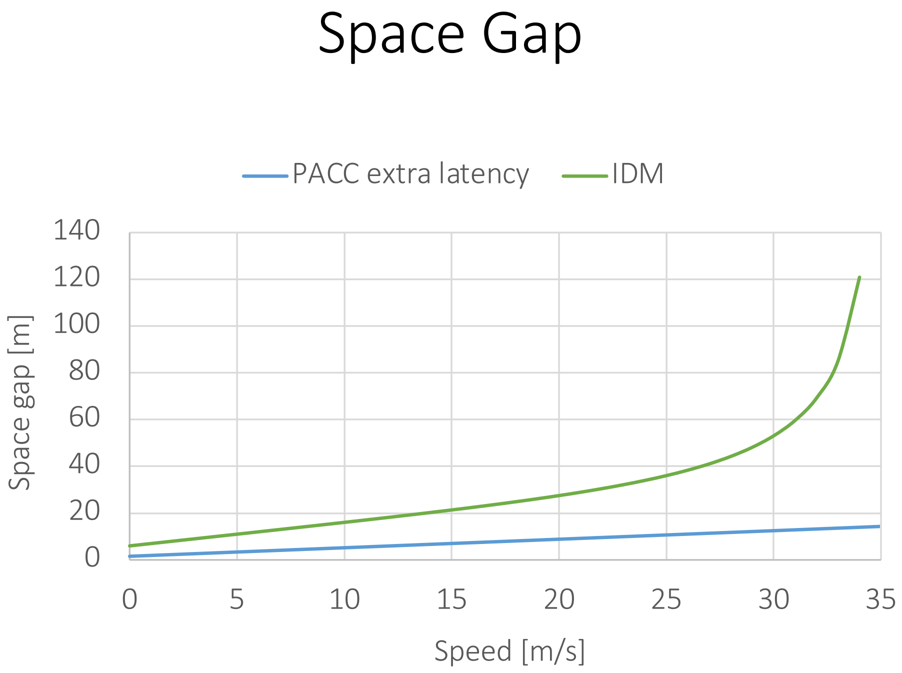
- The increase in the penetration rate of CAVs leads to a gradual decline of the global TET values.
- The decline rate is larger for high flows, except for low penetration rates of CAVs (e.g., < 25%), in which TET could even slightly increase (< 5%).
  - *The average number of lane changes of HDVs increases with the presence of AVs until a 30% penetration rate is reached.*
- For a penetration rate of 50% of CAVs, TET reductions between 15% and 85% have been observed depending on the prevailing flows.
- Insignificant extra benefits were achieved from the CAV penetration rate of 75% onwards.

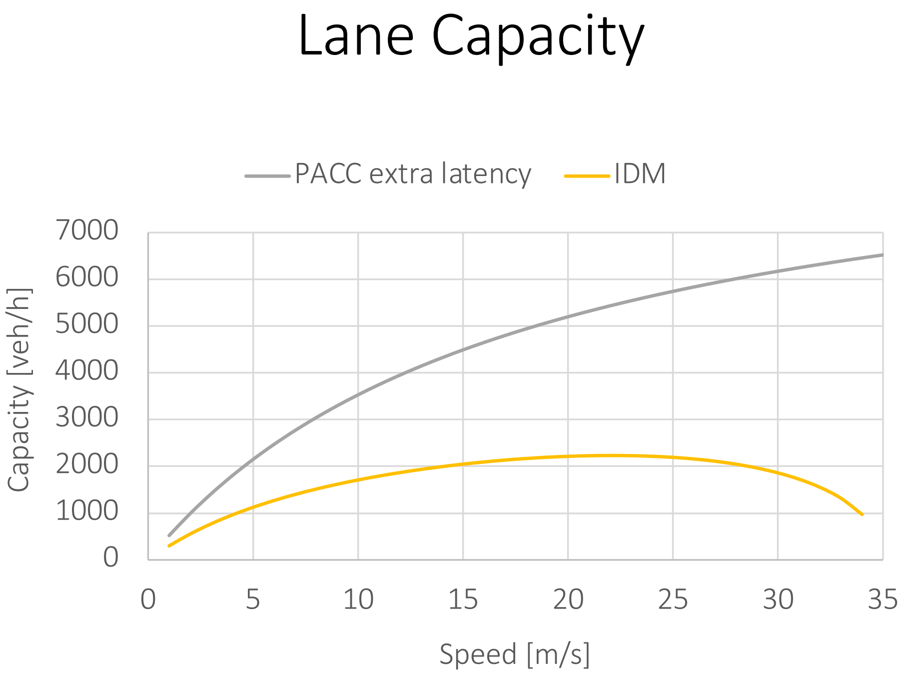
Safety in CAVs platooning (i)

- Collision analysis of a line of vehicles travelling at a given speed, v_{max}, and with their stationary car-following space gap.
- CAVs in platooning mode. Emergency analysis in case of:
  - *Do nothing*
  - *Coordinated emergency response*
- HDVs travelling according to the IDM – Intelligent Driver Model car-following

Variable	Values used [Units]	Description
g_{min}	1.54 [m]	Minimum gap between vehicles when stopped.
a_{max}	1 [m/s^2]	Acceleration threshold for a comfortable acceleration process of the vehicles.
a_{min}	–1 [m/s^2]	Acceleration threshold for a comfortable braking of the vehicles.
j_{min}	–0.9 [m/s^3]	Jerk threshold for comfortable braking of the vehicles.
a_{min_e}	–9.8 [m/s^2]	CAVs maximum deceleration in emergency conditions.
	–7.2 [m/s^2]	HDVs maximum deceleration in emergency conditions.
j_{min_e}	–20 [m/s^3]	CAVs maximum braking jerk in emergency conditions.
	–11.3 [m/s^3]	RVs maximum braking jerk in emergency conditions.
v_{max}	15 - 30 [m/s]	Maximum travelling speed of the CAV platoon. Range used in the different scenarios analyzed.
δ	0.1 [s]	Latency of communications between CAVs. It is also assumed that platoon followers adapt their acceleration every δ time units.
α	0.2 [-]	Differential braking parameter. Maximum deviation of braking capabilities between different CAVs that will be accepted in technical revisions. [Dimensionless]. Expressed as a fraction of a_{min_e}.
δ^*	0.3 - 0.5 [s]	Extended latency to account for platoon stability. Depends on v_{max} and α. Range resulting from $v_{max} = 15 - 30$ [m/s].
T	1.5, 1 [s]	Reaction time for HDVs, (Follower 1, and rest).
β	4 [-]	Fundamental diagram shape parameter in the IDM [Dimensionless].

Safety in CAVs platooning (ii)





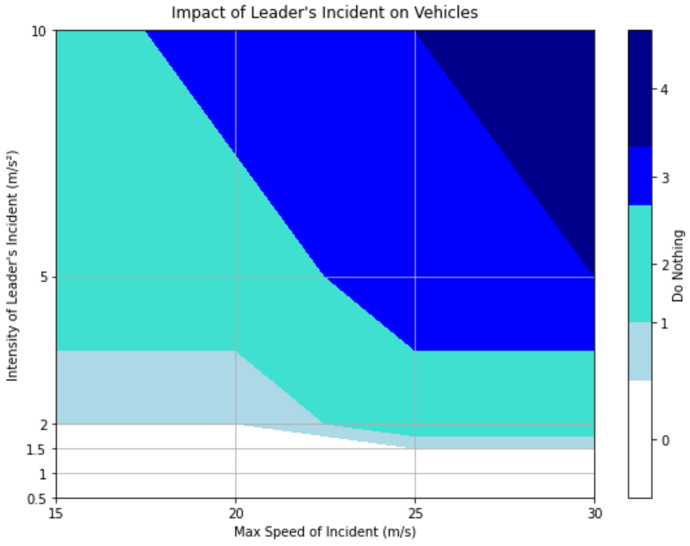
Safety in CAVs platooning (iii)

- Abscissa represents different speeds [m/s] when emergency conditions are detected. Ordinate represent various severities of the incident experienced by the leader $* \, g$ [m/s^2]

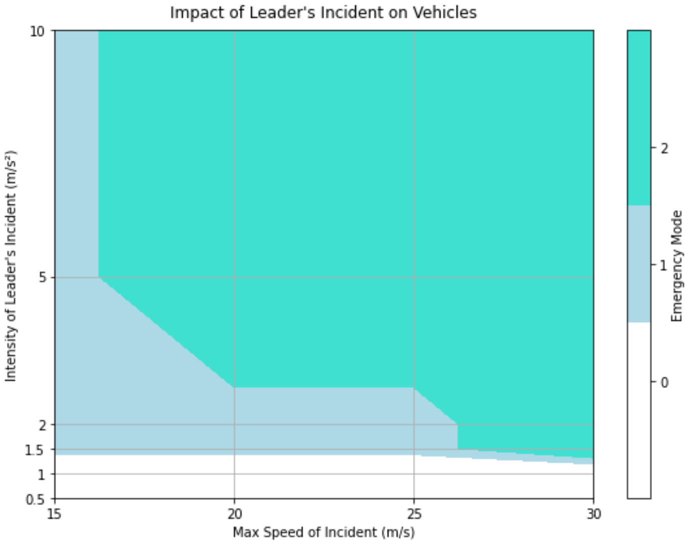
Crash number in CAVs

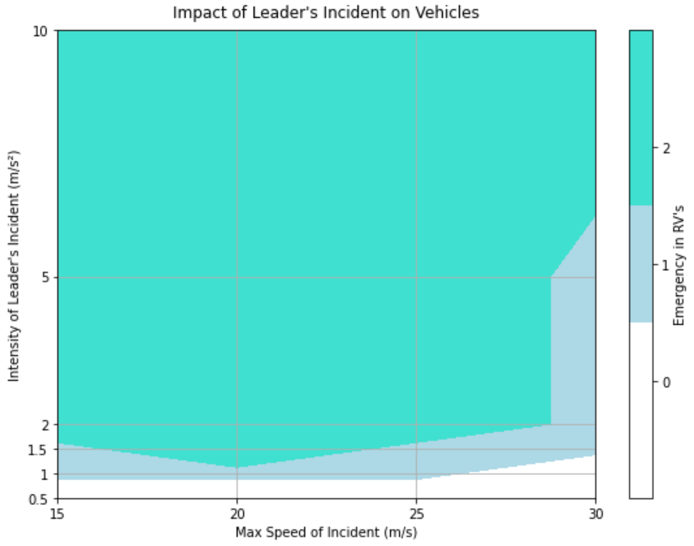
Crash number in RVs

Do-nothing mode



Emergency mode



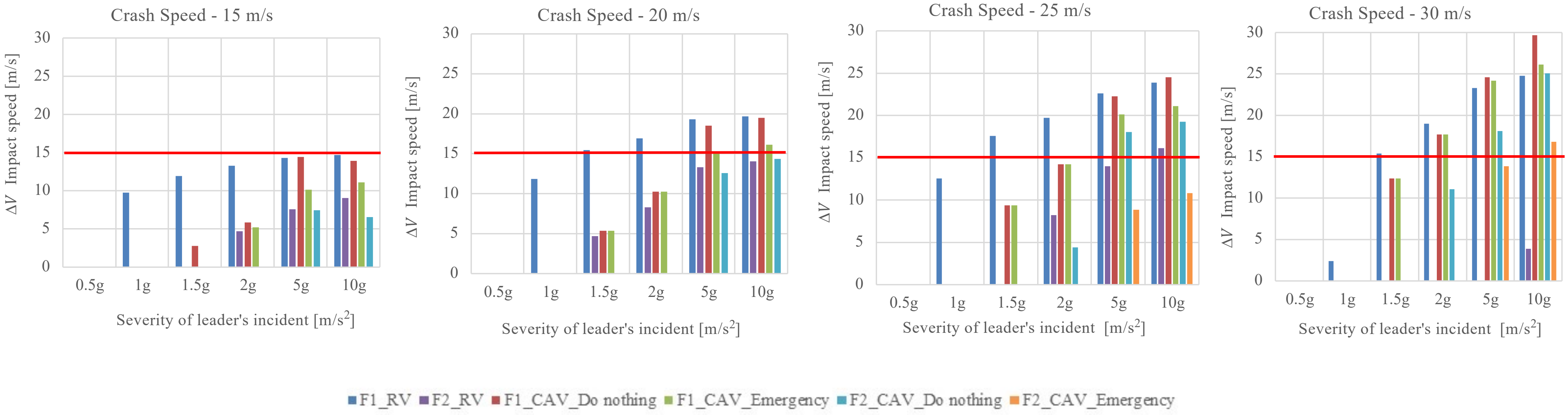


Safety in CAVs platooning (iv)

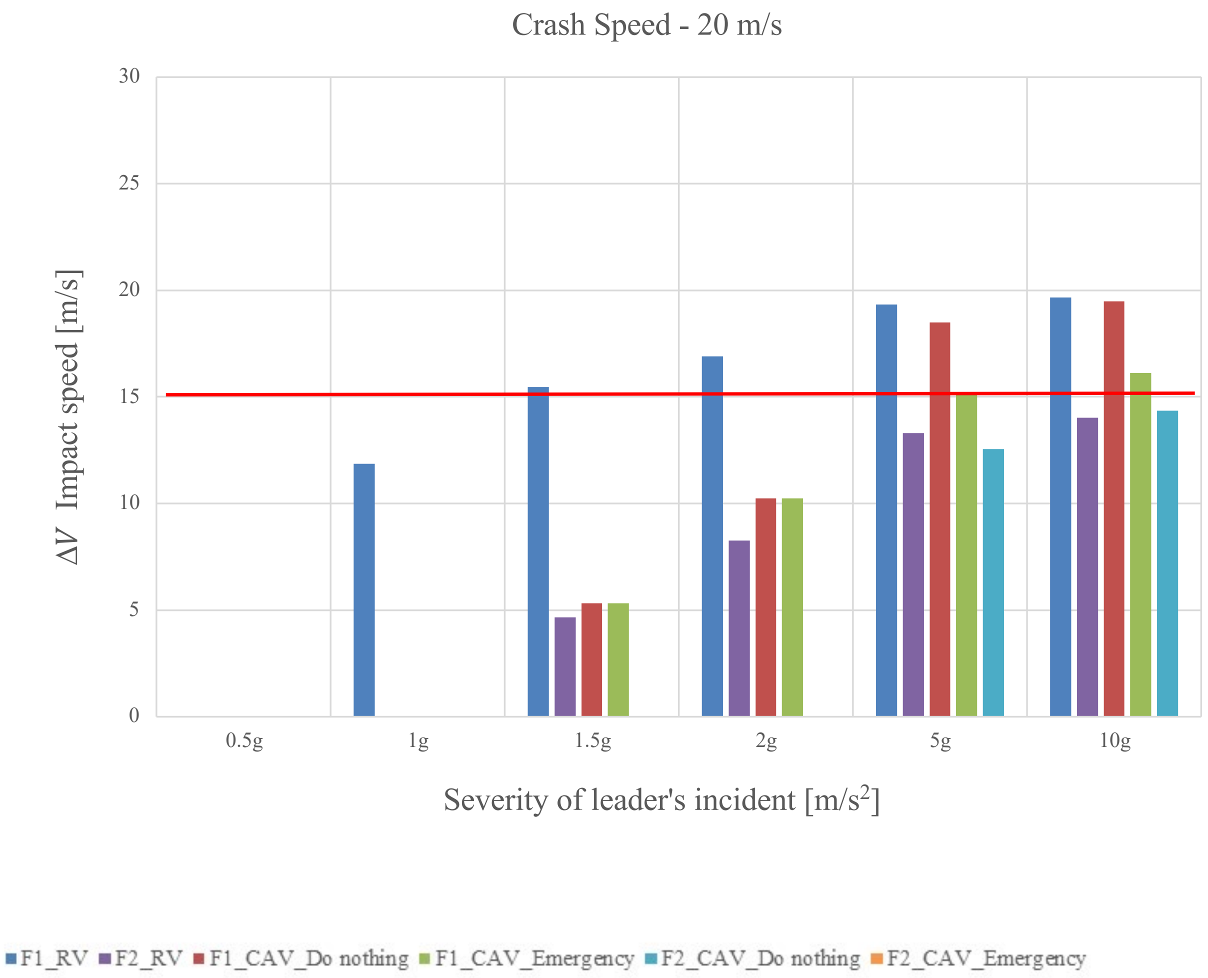
Impact speed analysis – Delta V (ΔV):

- Δv_i, the relative speed between the vehicles at the impact.

$$\Delta v_i = |v_i - v_{i-1}|$$



Where F1,F2... are follower number


Crash Speed - 20 m/s
ΔV Impact speed [m/s]
30
25
20
15
10
5
0
0.5g
1g
1.5g
2g
5g
10g
Severity of leader's incident [m/s²]
F1_RV
F2_RV
F1_CAV_Do nothing
F1_CAV_Emergency
F2_CAV_Do nothing
F2_CAV_Emergency

Other safety impacts CAVs platooning (i)

- An increase in the penetration rate of CAVs lengthens the duration of the lane-change preparation for HDVs:
  - *It is not easy for the drivers to find the gap to perform the maneuver safely*
  - *Increased risk of a rear-end collision between the HDV and its follower*
  - *Reduction in the overall traffic speed*
  - *Unsuccessful lane changes mostly involving women and elderly people*
  - *Performed lane changes of HDVs are more aggressive than in traditional environments*
- CAVs platooning (specially in the rightmost or middle lanes) could eventually cause congestion in on-ramps and even favor collisions during the merge.

Other safety impacts CAVs platooning (ii)

- Information transmission delays between CAVs can have an alarmingly negative impact on vehicle safety, implying potential chain collisions.
- For penetration rates of CAVs>15%, setting exclusive lanes reduces overall crash risks. The heavier the vehicles in the traffic stream, the higher the benefits.
- Space gaps > 30 m reassure drivers and facilitate smooth cut-in maneuvers while reducing collisions (when a HDV on an on-ramp must merge into a platoon).

Conclusions:

- In general, increasing penetration rates of CAVs in mixed traffic, the longitudinal safety improves, while the lateral safety worsens.
- There is a trade-off between ensuring safety and increasing traffic throughput.

Security in CAV platooning

Security in CAVs platooning

- Cyberattacks could result in serious disturbances.
  - *Lead to extremely small space gaps between vehicles, abrupt accelerations/decelerations, and even rear-end collisions.*
- Measures against cyberattacks must be implemented:
  - *Leaders play a key role in ensuring safety and efficiency of CACC-vehicle platoons. It must be especially ensured that leaders are not compromised.*
  - *Real-time mechanism combining statistical learning with kinematic laws to detect anomalies. Detects more than 92% of anomalies with less than 13% false alarms.*
  - *Combine different communication technologies to improve security*
- Difficulty of combining higher data privacy standards with a high communication security level.

Emission impact of CAV platooning

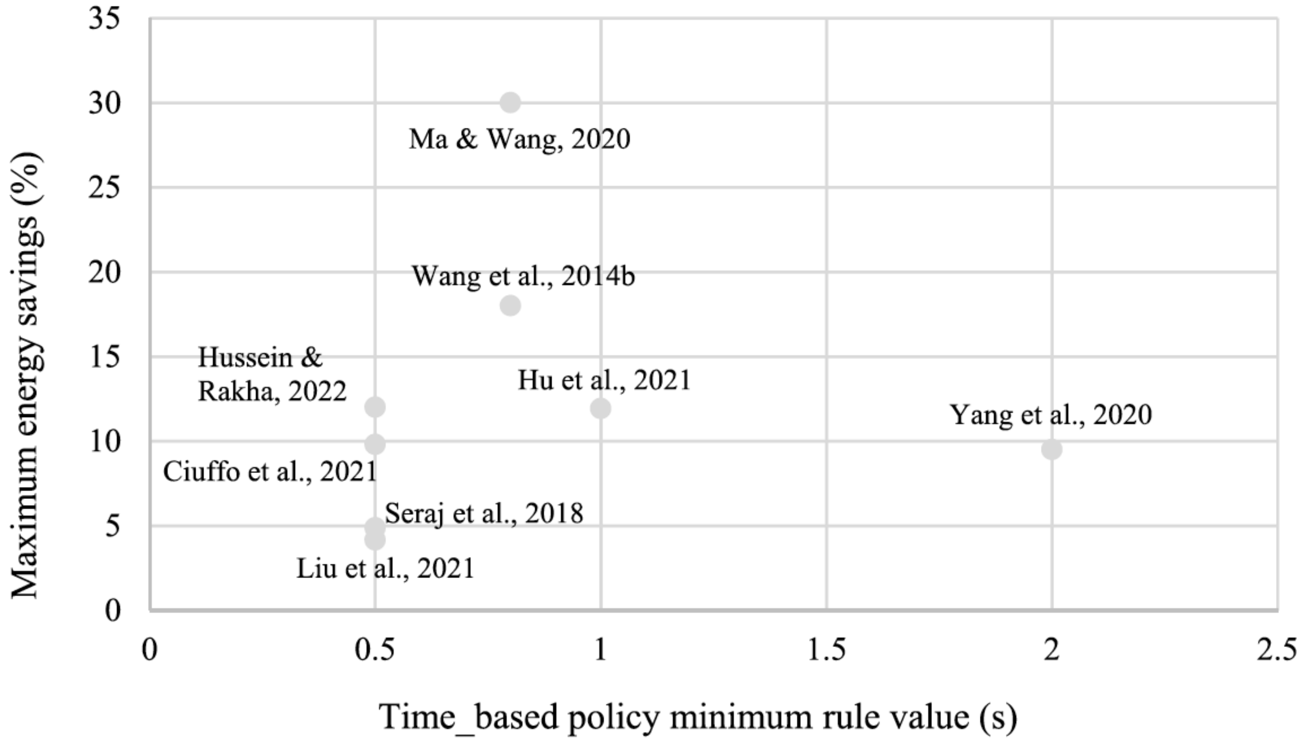
Emissions impact of CAVs platooning (i)

- Emissions are proportional to fuel consumption.
- Reduction of fuel consumption was one of the primary goals of platooning (particularly of truck platooning) even before AVs appeared on scene
- Platooning driving lowers the aerodynamic air drag, which in some contexts can represent well over 50% of vehicle traction energy demand.
- On the one hand:
  - *Savings are higher for longer platoons (benefiting the followers far more than the leader)*
  - *Savings are higher for small inter-vehicle distances, and especially if vehicles are big, i.e., trucks*
  - *Other factors such as the travelling speed are not so influential*

Emissions impact of CAVs platooning (ii)

- On the other hand, smaller gaps are prone to instabilities.
  - *In current ACC systems, the tractive energy consumption of the followers is usually larger than that of the leader*
  - *Frequent acceleration / deceleration process resulting from instable behavior penalizes energy efficiency and contributes to pollutant emissions*
  - *Mixing short and long time gap settings in ACC systems leads to higher savings than maintaining short time gaps.*
- Perfectly aligned trucks driving with small inter-vehicle distances in order to reduce the air drag, accelerate the damage accumulation in the pavement structure, thus penalizing the lifecycle emissions.

Max. energy savings for different time gaps



Conclusions in CAVs platooning

- Early work on platooning aimed, explicitly or not, at ensuring that vehicles travelled at the shortest possible gap, while maintaining safety.
  - *Increase in infrastructure capacity and fuel savings*
- Current studies have highlighted the important role of platoon string stability
  - *Dangerous situations, inefficiencies in terms of flow and energy consumption*
- Because it is easier for a platoon to become string unstable if vehicles circulate at very small distances, it seems clear that there is a need to move towards adaptive car-following policies.
- The same reflection applies to the maximum allowable platoon length, which on average should not surpass 5-6 vehicles
  - *Longer platoons would increase the conflicts with the adjacent lanes.*

AVs route planning

AVs’ route planning

- AVs route planning conforms a “Traffic Assignment” problem (TA)
  - *Given the Origin – Destination, decide on which route to take*
- AVs might be rather “homogeneous” in the route selection

	Regular Vehicles	Autonomous Vehicles
Behavior	Different individuals behave differently based on their socio-economic characteristics and past experience	Personalization of route choice behavior will be limited, and similar options will be available for all AVs.
Choice set	Different individuals may have different route choice sets	Complete road network information for all AVs
Objective	Routing objective may differ across individuals	Routing objectives will be similar for all AVs

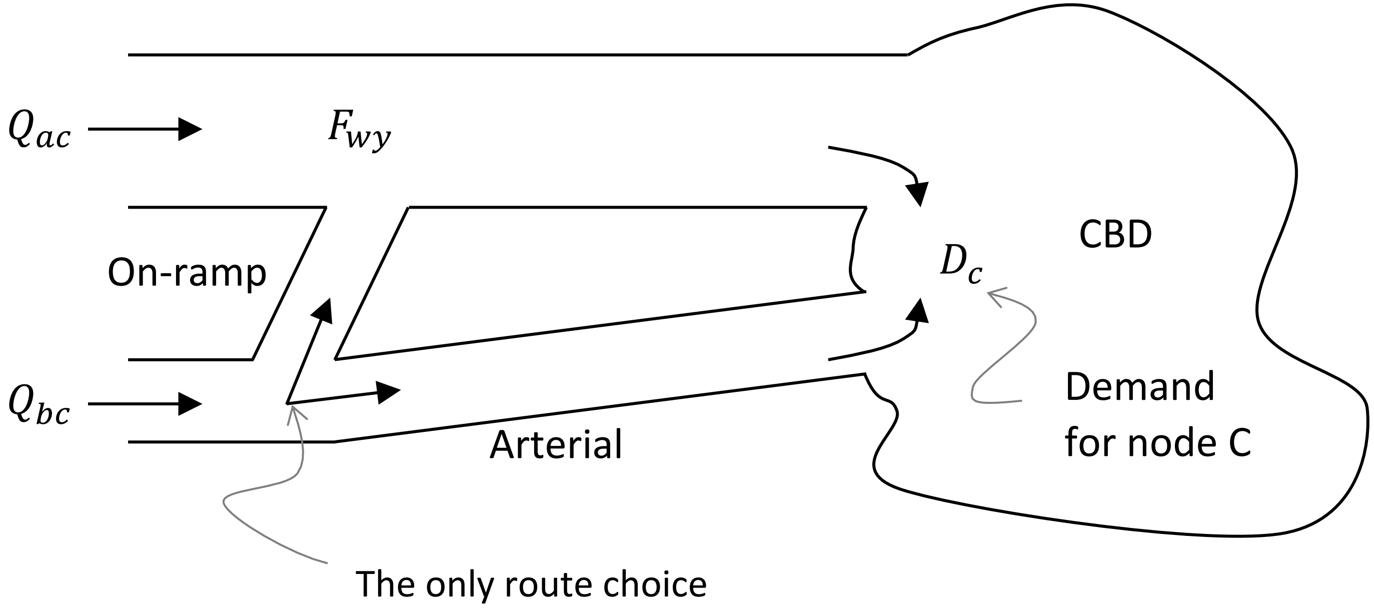
Wardrop’s principle of User Equilibrium (UE)

- Routing rule: AVs will try to minimize their own travel “cost” when traveling form origin to destination. AVs’ behavior is “selfish” (like that of individual drivers).
- Travel cost is a function of a number of attributes:
  - *Distance*
  - *Travel time*
  - *Tolls, Fares, Fuel, ………*
- AVs perfectly fulfill the conditions for Wardrop’s principle of UE:
  - *AVs have full information (route choice set and travel times),*
  - *AVs consistently make the correct route choice decision*
  - *AVs are identical in their behavior*

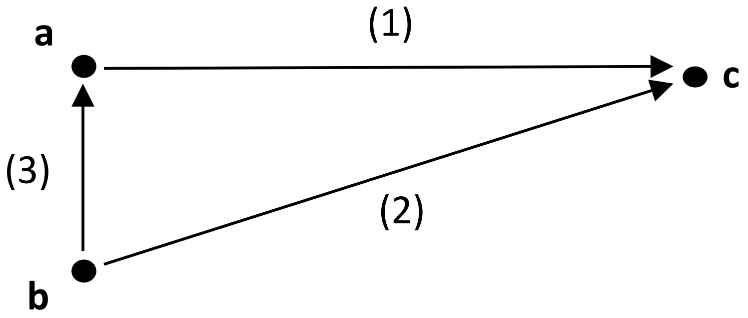
Then, User Equilibrium (UE) is reached

- Given the previous conditions, Wardrop’s first principle states that an equilibrium situation (UE) is reached where:
  - *For each O-D pair, the travel times on all used routes are equal, and less than or equal to those on any unused route*
  - *At UE, no user can improve his/her travel time by unilaterally switching routes*
- UE is generally sub-optimal.
  - *The total aggregated “cost” of all users is larger than the minimum possible*
- Wardrop’s second principle (System Optimal – SO):
  - *There exists a traffic assignment where the total system travel cost is minimum (that is, the average travel cost is minimum)*

An example: the Braess' paradox



The Braess' paradox: problem formulation

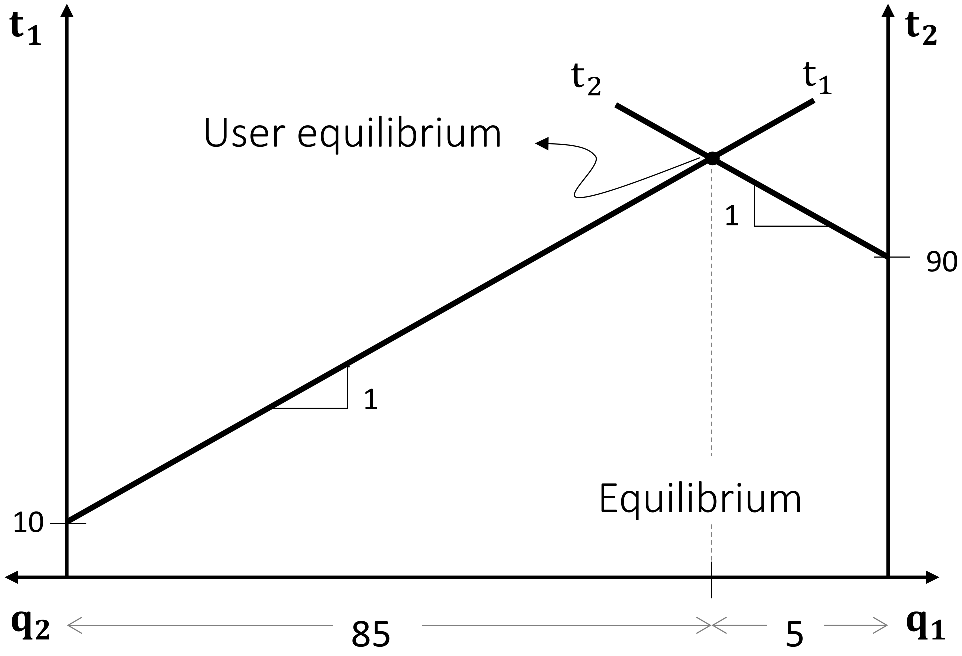


O \ D	c
a	$Q_{ac} = 80\ {}^{veh}/_{period}$
b	$Q_{bc} = 10\ {}^{veh}/_{period}$

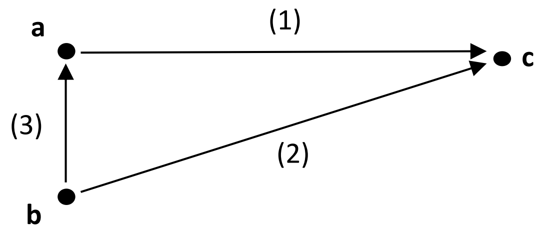
$t_1 = 10 + q_1$
$t_2 = 90 + q_2$ in some units of time
$t_3 = 0\ (ramp)$

$q_1, q_2, q_3 = ?$

The Braess’ paradox: graphical solution



The Braess' paradox: UE vs SO



$t_1 = 10 + q_1$
$t_2 = 90 + q_2$ in some units of time
$t_3 = 0\ (ramp)$

D O	c
a	$Q_{ac} = 80\ {}^{veh}/_{period}$
b	$Q_{bc} = 10\ {}^{veh}/_{period}$

	UE	SO
q_1	85	80
q_2	5	10
q_3	5	0

$$UE\ Total\ travel\ time = \sum_i q_i t_i = q_1 t_1 + q_2 t_2 = 85 \cdot 95 + 5 \cdot 95 = 8550\ {}^{veh.time}/_{period}$$

$$SO\ Total\ travel\ time = \sum_i q_i t_i = q_1 t_1 + q_2 t_2 = 80 \cdot 90 + 10 \cdot 100 = 8220\ {}^{veh.time}/_{period}$$

- Traffic management & control and coordinated AVs route assignment is needed to move from UE to SO.

Further complications in AVs’ routing

- AVs probably will use “static” route selection process
  - *Route selection based on real-time traffic information*
- Not considering future traffic evolution may lead to wrong route selection
  - *Specially, in rapid evolving traffic conditions (non-recurrent congestion)*
    - E.g. rapid congestion increase in alternative routes after an incident
- Difficulties in incorporating “dynamic” route selection
  - *Link travel times depend on traffic demand*
  - *Traffic demand depends on AVs route selection*
  - *If AVs penetration rate is high this leads to an unpredictable chaotic system (double guessing).*

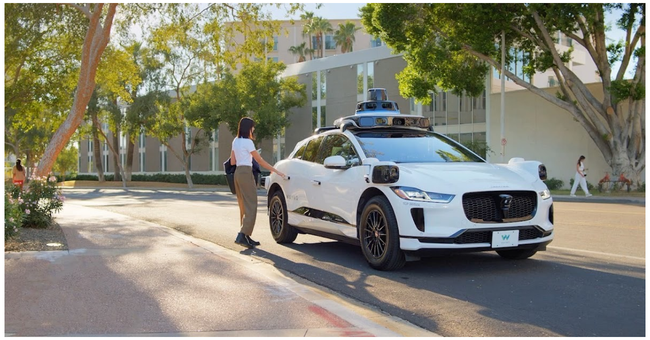
Conclusions on AVs’ route planning

- Simplistic AVs’ individual (i.e. selfish) route selection would lead to inefficient traffic assignment over the traffic network.
- Detrimental effects could be more significant if:
  - *AVs penetration rate is high*
  - *Traffic conditions evolve rapidly (e.g. incident conditions)*
- Coordinated AVs route selection is needed to achieve network efficiency
  - *Move from the inefficient user equilibrium to a system optimal assignment*
  - *Some AVs will be penalized for the benefit of the whole system (equity issues?)*
  - *Predict network loading and future travel times*
- **AVs are the actuators**. This is an opportunity to achieve system optimal.

AVs as on-demand transportation

AVs’ opportunities in on-demand transportation (i)

- RoboTaxis represent the first business opportunity for AVs.
  - *Enhanced vehicle sharing service => No access, much cheaper repositioning.*
  - *Eventually can be cheaper than taxi / ride hailing services => No driver*
- First implementations in several cities in the USA and China:
  - *US - Cruise (GM), Waymo (Google), Zoox (Amazon)*
  - *China - Pony.AI (partnering with Toyota + Guangzhou Automobile Group), WeRide*



AVs’ threats in on-demand transportation (ii)

- Still, very expensive deployment and operation. Cannot compete with more conventional ride-sharing services yet.
- Technology still not ready for commercial deployment
  - *Still rely on some remote human supervision to operate safely.*
  - *Several serious accidents (e.g. the state of California suspended Cruise’s operations there indefinitely)*
- Not an efficient mobility option in dense urban environments
  - *Still a car; a particularly inefficiently driven car.*
  - *May lead to an increase of the VKT (at least doubling, research points out)*
    - Dead-head miles before each pick-up.
    - Demand attracted from from public transportation, biking and walking.

Conclusions on AVs’ on-demand transportation

- When technologically ready and economically viable, AVs robotaxi deployment may bring an increase of urban traffic and congestion in dense urban areas.
- In dense urban areas, it remains essential to prioritize space-efficient modes of public transportation, walking and biking.
  - *Europe has lagged behind in the robotaxi competition, partly because giving priority to the deployment of autonomous vehicles in mass transit.*
- AVs ride-hail can be valuable to meet specific mobility needs, such as:
  - *Providing paratransit services to people with disabilities*
  - *Providing first and last mile connections to transit services in low density environments*
  - *Connecting late-night workers to jobs.*

Closing notes

- Traffic management and vehicular coordination are essential to achieve most of the benefits of the autonomous vehicle mobility.
- Without adequate traffic management, the progressive penetration of the AV in dense traffic environments will be detrimental in all mobility aspects (e.g. overall demand, congestion, energy consumption, emissions)
- The exception would be the traffic safety which is likely to increase for higher penetration rates of AVs.

Autonomous Vehicles

Impacts from a traffic wide perspective

Prof. Francesc Soriguera

Barcelona Innovative Transport

UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH