7. Vehicle Platooning II

金力 Li Jin
li.jin@sjtu.edu.cn
上海交通大学密西根学院
Shanghai Jiao Tong University UM Joint Institute

Recap

- Background
  - Signalized & unsignalized intersections
  - Connected & autonomous vehicles
  - Vehicle-to-infrastructure connectivity
- Control in nominal setting
  - Centralized approach
  - Decentralized approach
  - Hierarchical control
  - **HW2**
- Control in face of disruptions
  - How to address latency
  - How to address packet loss
  - How to address malicious attacks

Outline

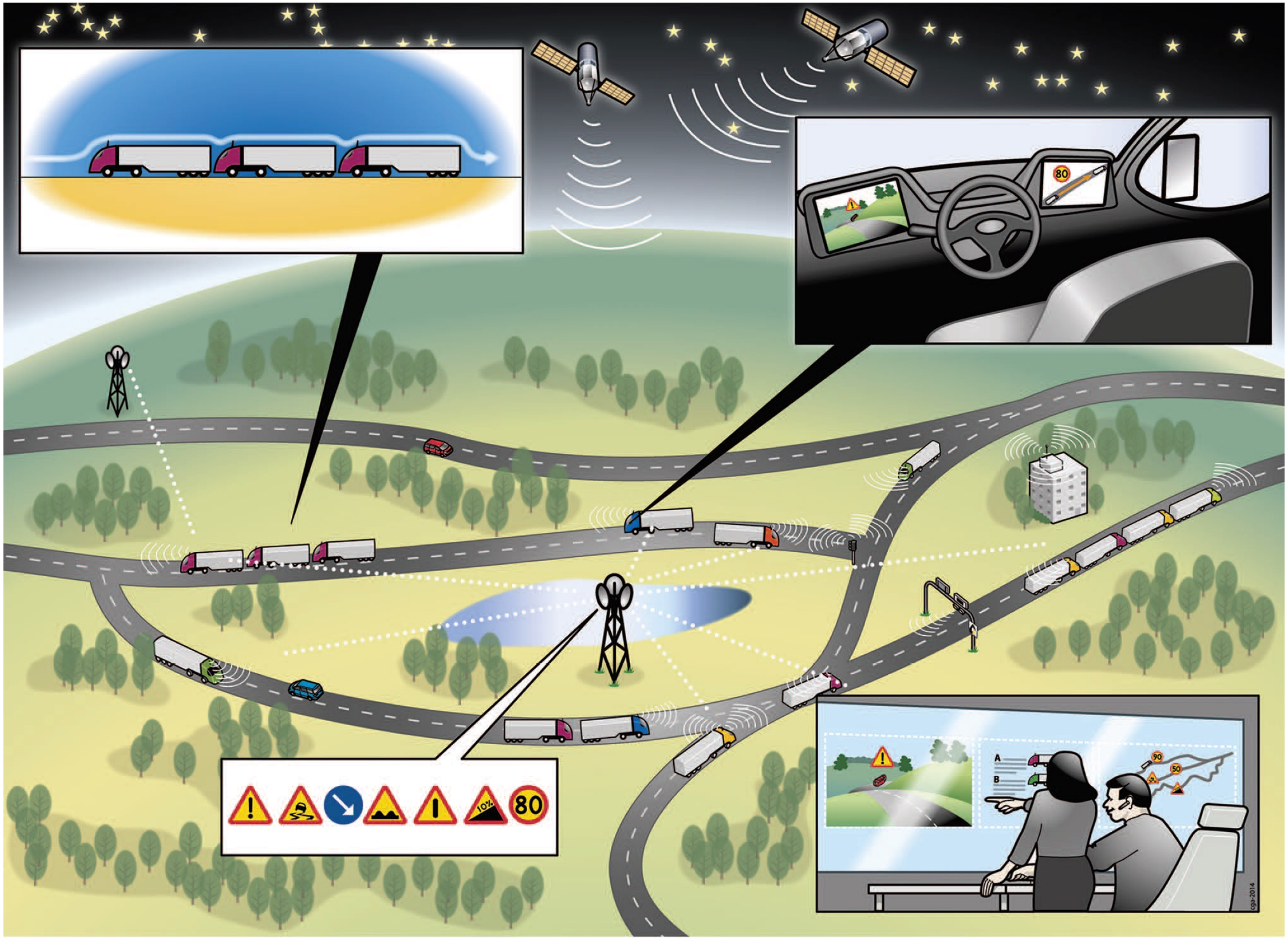
- Macroscopic decisions for platooning
- Link level: headway regulation
  - Hybrid fluid model
  - Analysis
  - Design
- Junction level: cooperative scheduling
  - Static approach
  - Dynamic approach
- Network level: cooperative routing
  - Problem formulation
  - Fundamental tradeoff

Macroscopic decisions for platooning

Platooning is more than CACC

- For two vehicles to form a platoon, they have to
    1. travel on fully or partially overlapping routes -> cooperative route planning
    2. arrive at the overlapping section at the same time -> cooperative scheduling
- Furthermore, platoons are not traveling on empty roads
    - Other vehicles on the road may influence the formation and movement of platoons.
    - Platoons may induce a non-trivial impact on neighboring traffic (“moving bottleneck”).
- All the above requires macroscopic (i.e. system-level) analysis and design!

A hierarchical decision-making framework



A hierarchical decision-making framework

- High level: global (network) planning
  - Schedule trips
  - Plan routes
  - Done by transportation authority or fleet manager
- Middle level: local (link & junction) coordination
  - Headway regulation
  - Coordinated time of arrival
  - Done by road-side unit (control tower)
- Low level: CACC (vehicle)
  - Joining & leaving maneuvers
  - Vehicle following
  - Done by onboard computer driver

Link level: headway regulation

- Hybrid fluid model
- Analysis
- Design

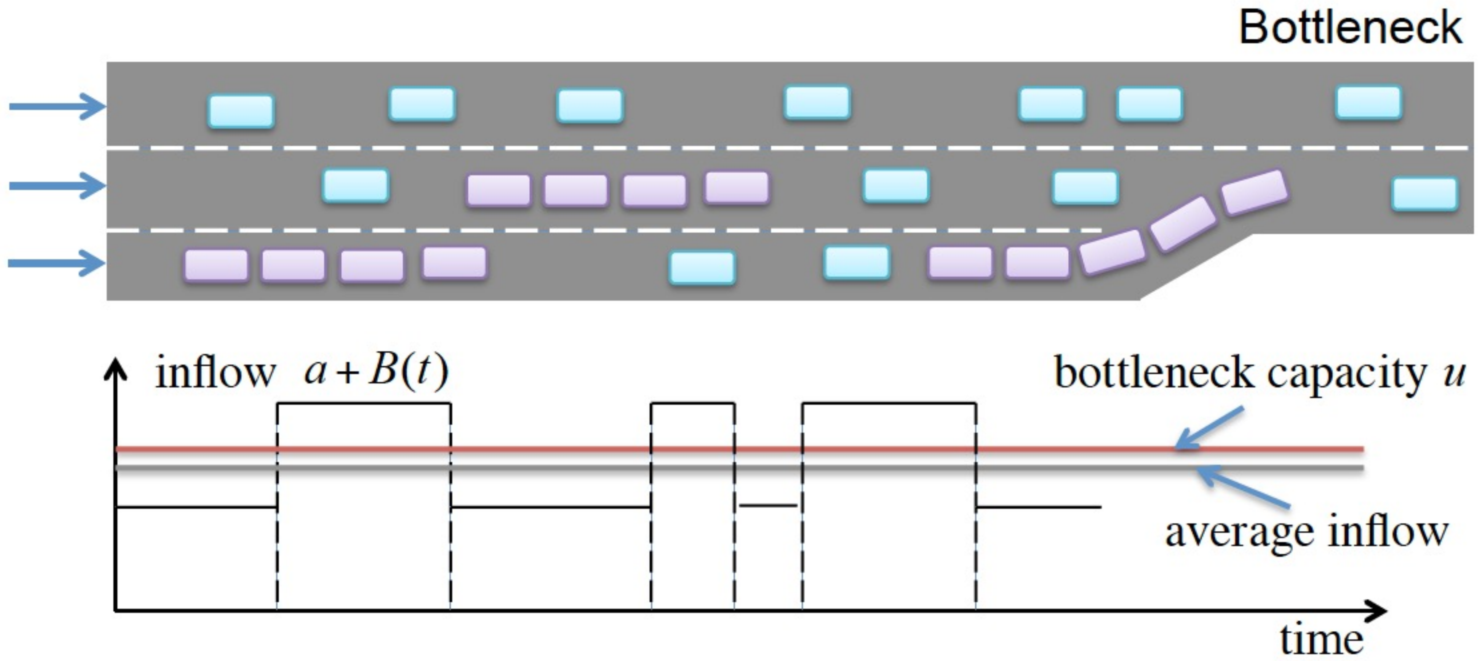
Main questions

Main questions:

- How to model macroscopic interaction between CAV platoons and background traffic?
- How to design platooning operations to improve highway performance?

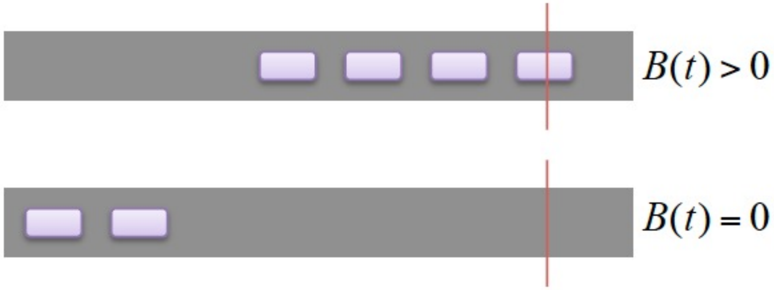
Platoons at bottlenecks

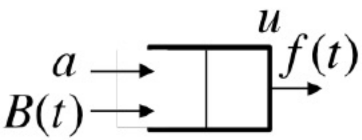
- CAV Platoons are less flexible than non-CAVs
- Platoons may lead to local congestion and disrupt local traffic flow



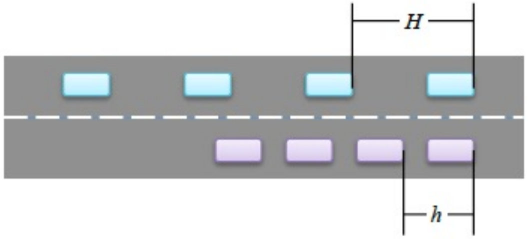
Hybrid fluid model

- Two classes of traffic
  - Background traffic: non-CAVs, constant inflow rate $a \in \mathbb{R}_{\geq 0}$
  - Platooned traffic: CAV platoons, switching inflow rate $B(t) \in \{0, b\}$





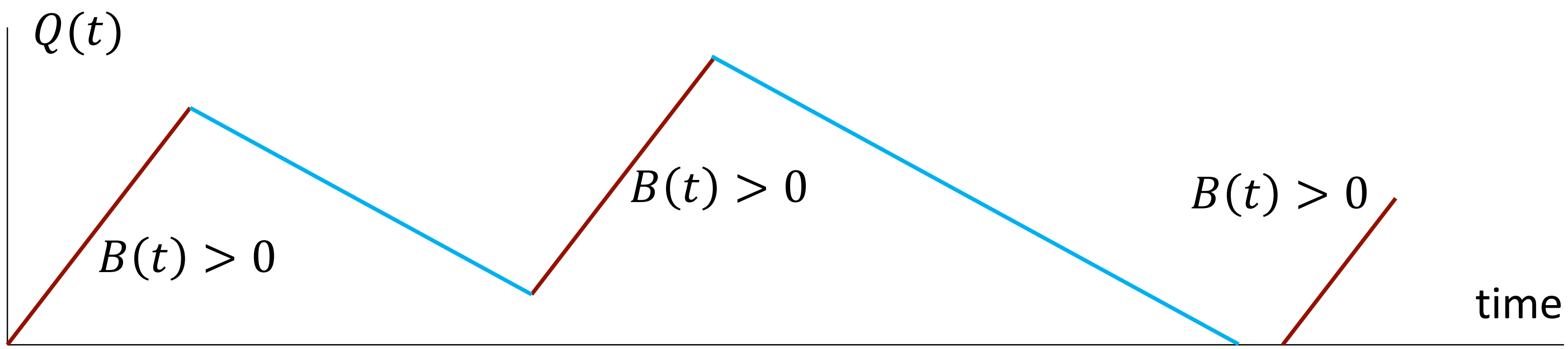
- Platoons are “condensed” traffic



Hybrid fluid model (HFM)

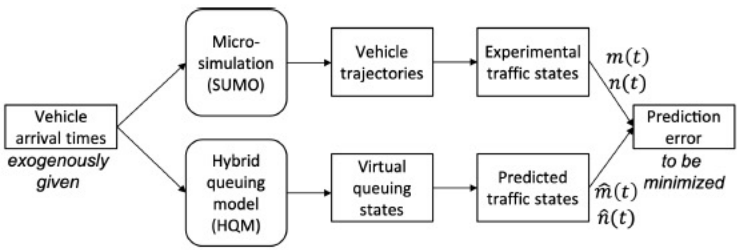
- Actual queue: $Q_a(t) \ + \ Q_b(t)$.
- Actual inow: $a \ + \ B(t)$.
- A platoon of n CAVs $\frac{h}{H}n$ non-CAVs
- Effective queue: $Q(t) \ = \ Q_a(t) \ + \frac{h}{H}Q_b(t)$.
- Effective inflow: $R(t) \ = \ a \ + \frac{h}{H}B(t)$.
- Queuing dynamics:

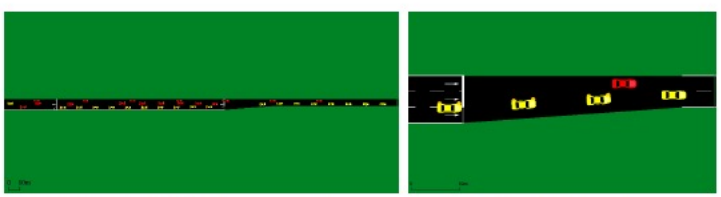
$\dot{Q}(t) = \ a \ + \frac{h}{H}B(t) - f\ (t)$ (a stochastic process)



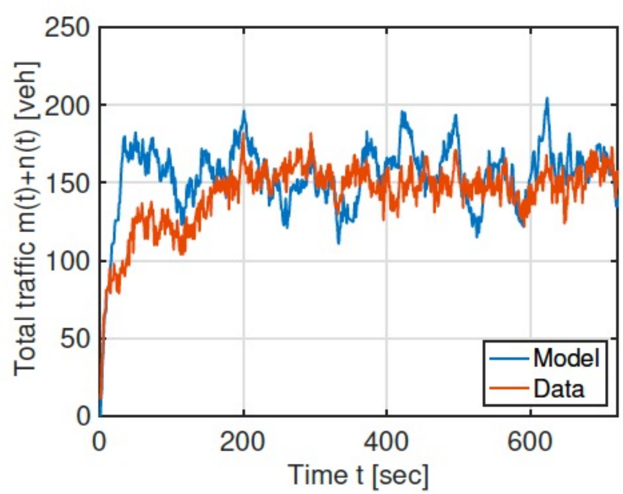
Model validation

- Very important! Wrong model + good math = nothing.
- Essential task: show consistency between model and reality
  - Reality = intuition, actual data, simulation, experiments…
  - Consistency needs quantification: prediction error





(a) Part of highway section. (b) Bottleneck.



- Su, l … g on
  Mix…

Model validation

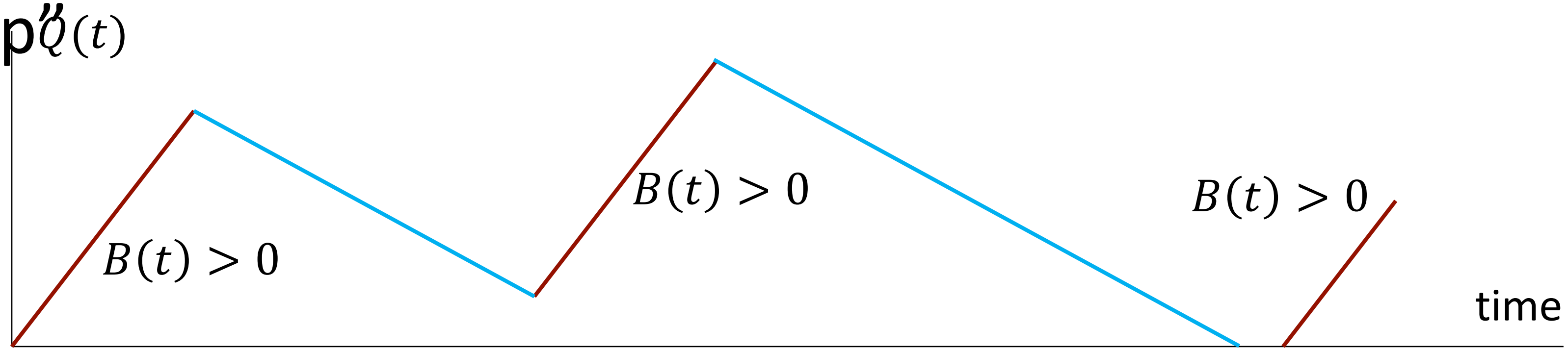
- Something philosophical

All models are wrong, but some are useful

- Statistical or scientific models always fall short of the complexities of reality but can still be of use.
  - Vehicle dynamic model
  - Vehicle kinematic model
  - Intersection model
  - Hybrid queuing model
- Modeling is both science and art
  - We need models for analysis & design
  - But we cannot include every complexity
  - A tradeoff is needed

George E. P. Box

- Intuitively, the HFM is stable if $Q(t)$ does not "blow up"



- Since $Q(t)$ is stochastic, we can only specify stability in a probabilistic sense:

$$\limsup_{t\to\infty} \frac{1}{t}\int_{s=0}^{t} \mathrm{E}[Q^p(s)]ds \le Z$$

- $\mathrm{E}[Q^p(s)]$ is called the pth moment.

Theoretical results*

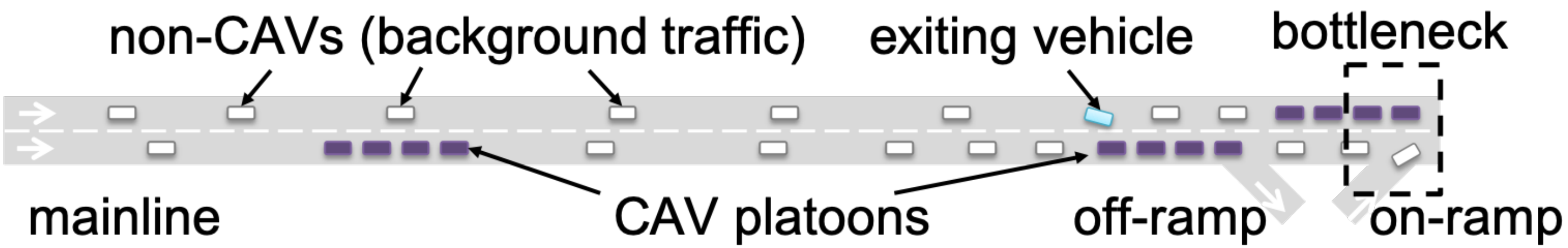
Theorem

- $Q(t)$ is stable if and only if average inflow < capacity.
- $Q(t)$ converges to a unique steady-state distribution that can be analytically computed -> q & $Var(q)$
- Proof idea: construct a switched Lyapunov function for the HFM, and apply a drift condition.

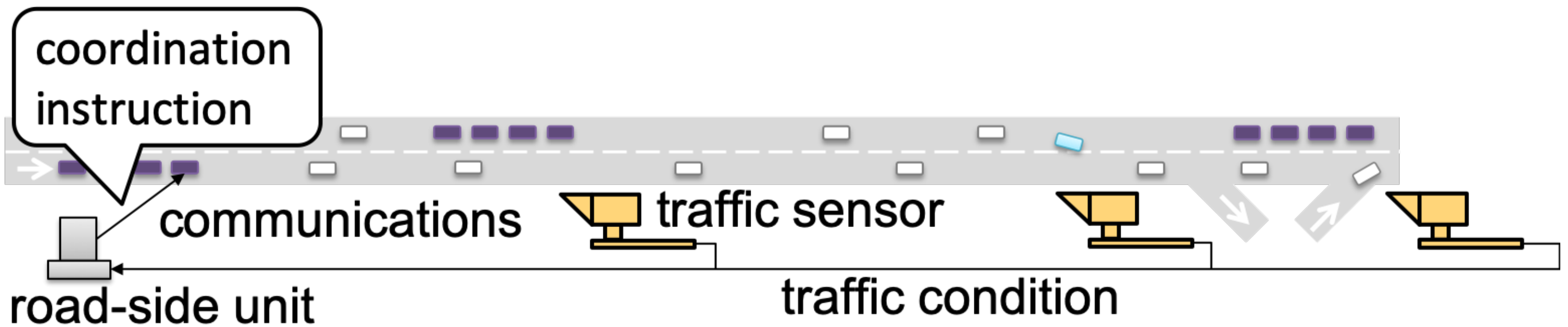
- Jin, L., Čičić, M., Amin, S. and Johansson, K.H., 2018, April. Modeling the impact of vehicle platooning on highway congestion: A fluid queuing approach. In *Proceedings of the 21st International Conference on Hybrid Systems: Computation and Control (HSCC, part of CPS Week)* (pp. 237-246). ACM.

Local congestion

- We should avoid clustering platoons!
- Uncontrolled:



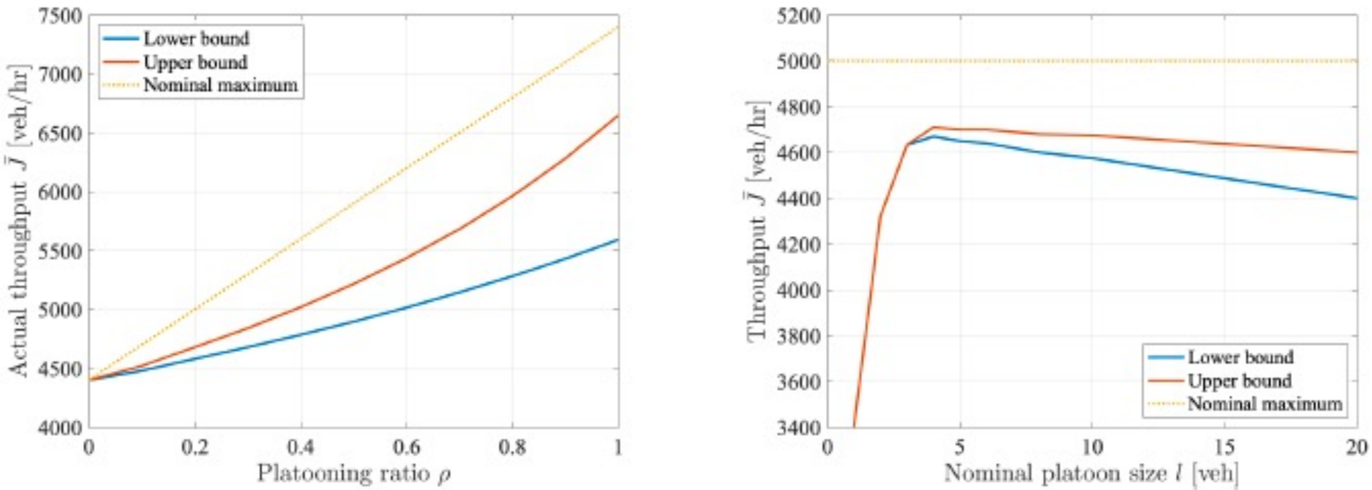
- Controlled:



Theoretical results*

Theorem

- The throughput of uncontrolled system can be analytically computed

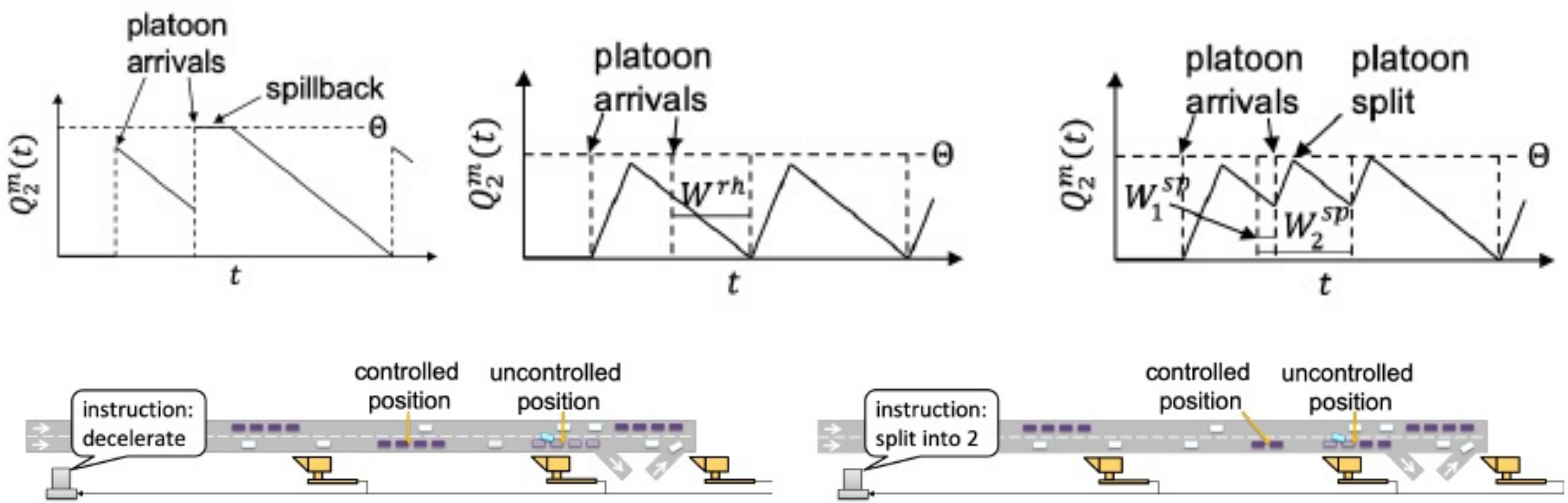


(a) Throughput vs. fraction. (b) Throughput vs. platoon size.

- Jin, L.*, Čičić, M., Johansson, K.H. and Amin, S. Analysis and design of vehicle platooning operations on mixed-traffic highways. *IEEE Transactions on Automatic Control*, accepted.

Theorem

We can attain maximal throughput and minimal delay by either (i) imposing a minimal headway between platoons or (ii) decomposing long platoons.

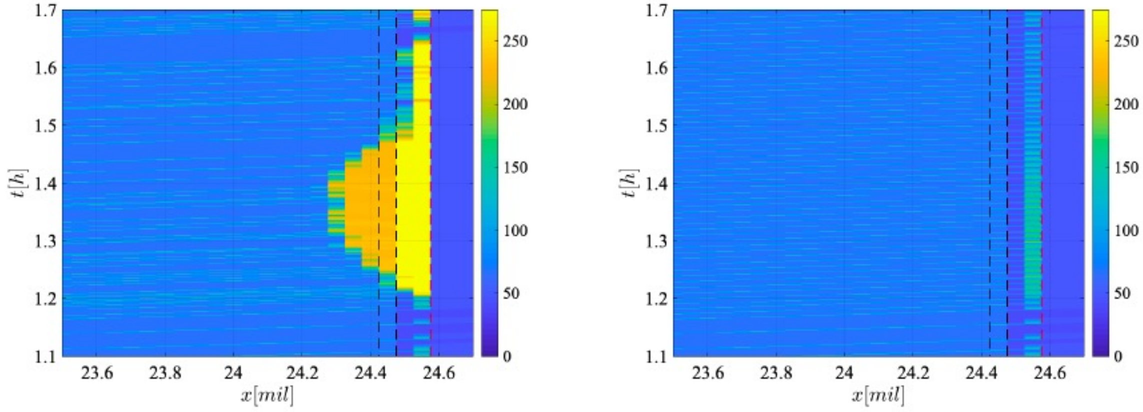


(a) Headway regulation.

(b) Platoon size management.

Validation

- Macroscopic simulation



(a) Without coordination.

(b) With coordination.

- Microscopic simulation

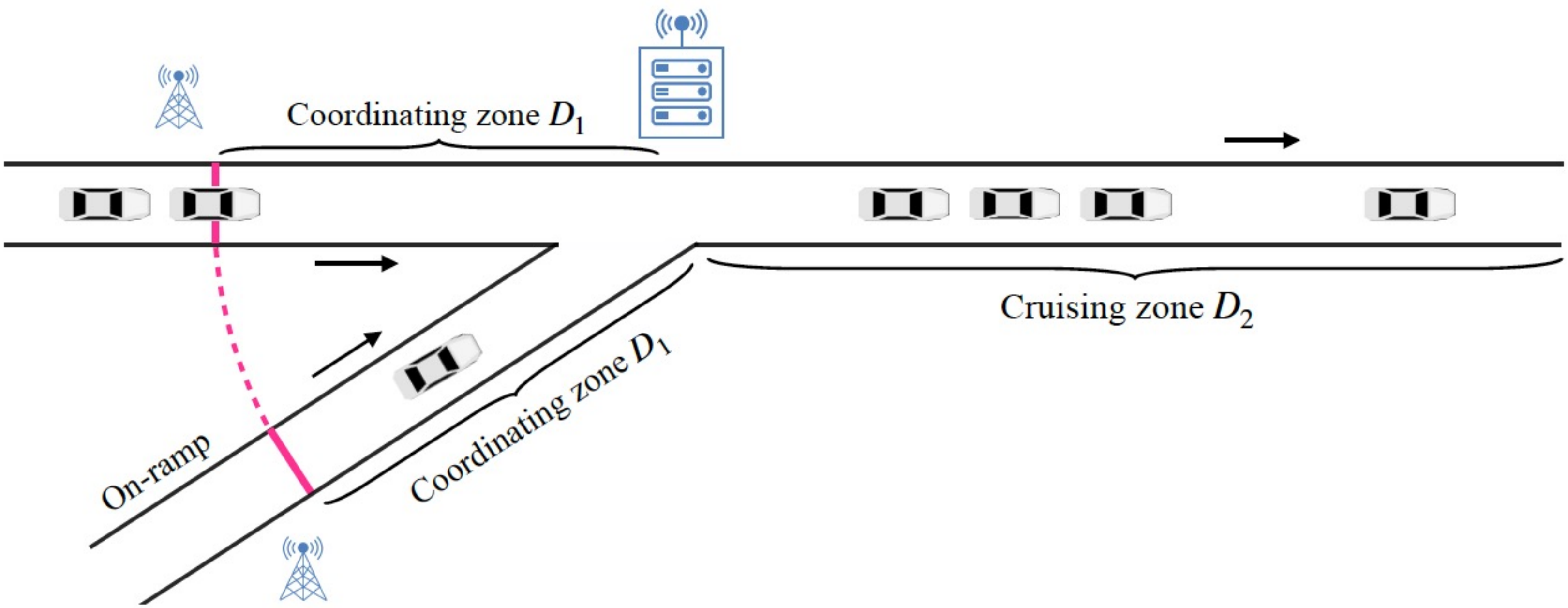
Strategy	VHT, CTM	Improvement (VHT)	Traverse time, SUMO [min]	Improvement [min]
No coordination	3471	0	36.26	0
Theoretically optimal	3466	5.3	33.27	2.99
Simulation optimal	3465	6.2	32.58	3.68

Junction level: cooperative scheduling

- Cooperative scheduling
- Static approach
- Dynamic approach

Cooperative scheduling

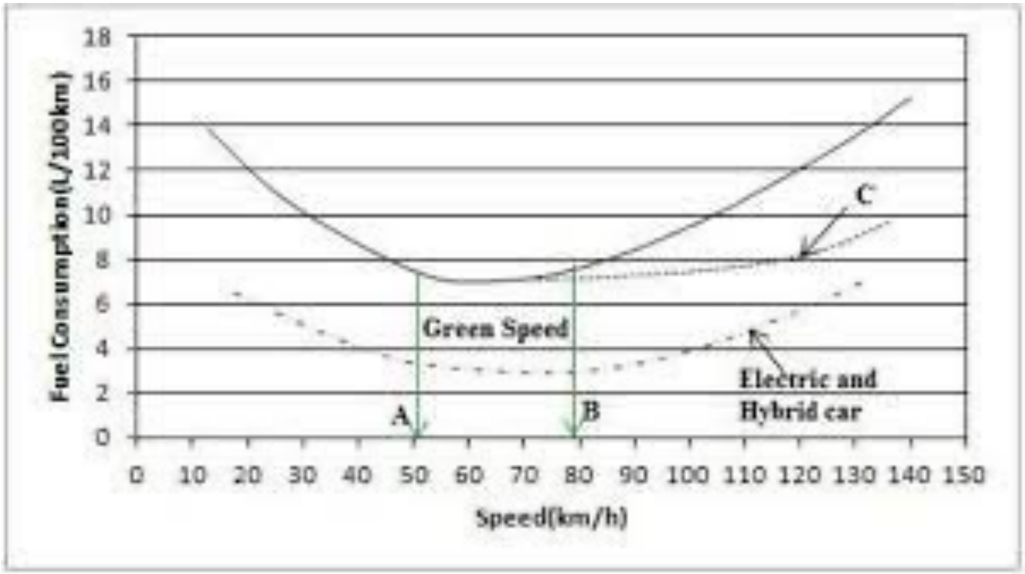
When a CAV enters coordinating zone, system operator instructs the CAV to merge with the leading CAV or CAV platoon or not

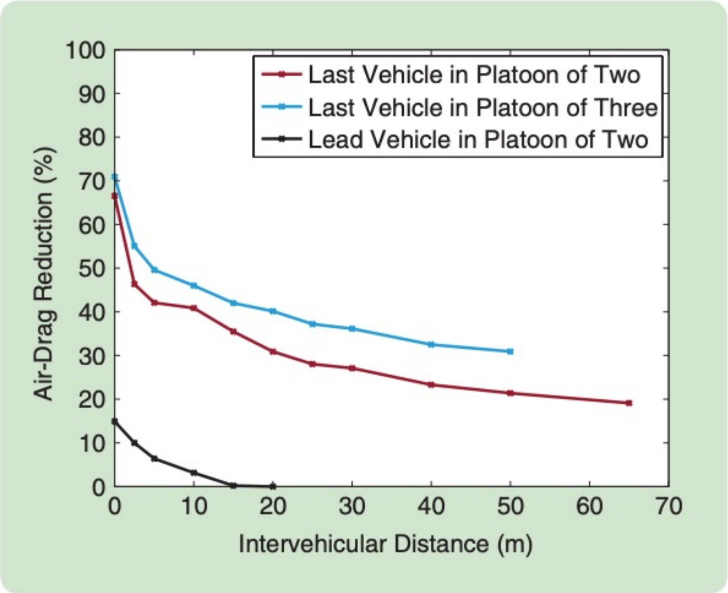


The Trade-off to Study

- Benefits of merging:
  - Fuel savings over cruising zone
  - Reduced travel time
- Cost of merging:
  - Increased fuel consumption due to acceleration
  - Lower chance of platooning with following CAVs
- State of the art: very limited methods for link/network level coordination
- Our approach:
- Two threshold-based coordination policies are proposed to minimize travel cost (time + fuel) in the link layer
  - Static approach: threshold for coordinating zone entering time, static optimization
  - Dynamic approach: threshold for actual headway upon CAV arrival, dynamic programming

To platoon or not to platoon?

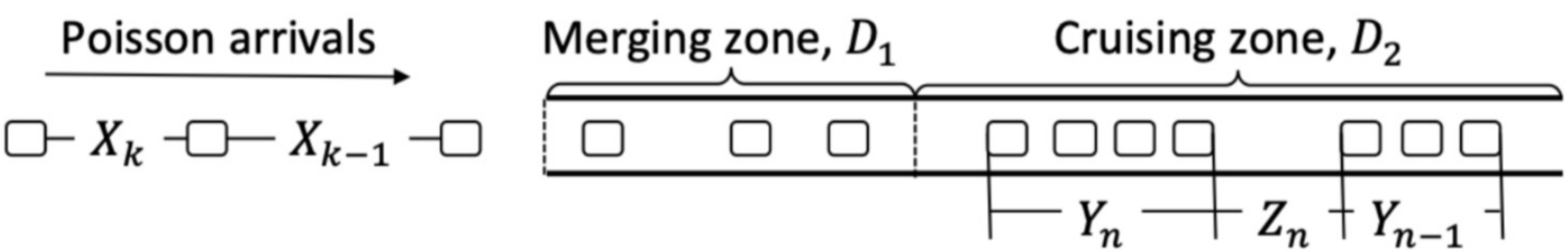




Static approach

Assumptions

- We assume the vehicle arrival is a Poisson process. The inter-arrival time X_k is independent and identically distributed, which follows the exponential distribution with parameter λ.
- Let r be the threshold for platooning. After the merging process, we assume the headway between platoon is $h_0 \approx 0$.
- Three ways to coordinate merging process: acceleration only, deceleration only and cooperation.



Static approach

- When operating platoons on the highway, we need to identify some essential characteristics, including
  - platoon size;
  - headway between platoons;
  - time reduction due to platooning.
- Note that all the results consider the process in the steady state.
- Main question: how does the decision variable r affect platoon characteristics?

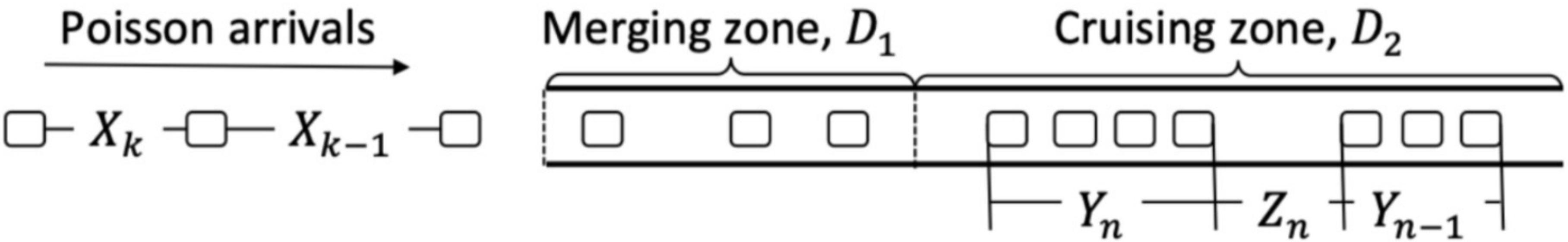
Reference: Xiong, X., Xiao, E. and Jin, L., 2019, December. Analysis of a stochastic model for coordinated platooning of heavy-duty vehicles. In 2019 IEEE 58th Conference on Decision and Control (CDC) (pp. 3170-3175). IEEE.

Static approach*

Proposition

In the steady state, the number of vehicles in a platoon Y follows the probability mass function (PMF):

$$P_Y(y) = e^{-\lambda r}\left(1 - e^{-\lambda r}\right)^{y-1}, \qquad y = 1, 2, 3, \ldots$$



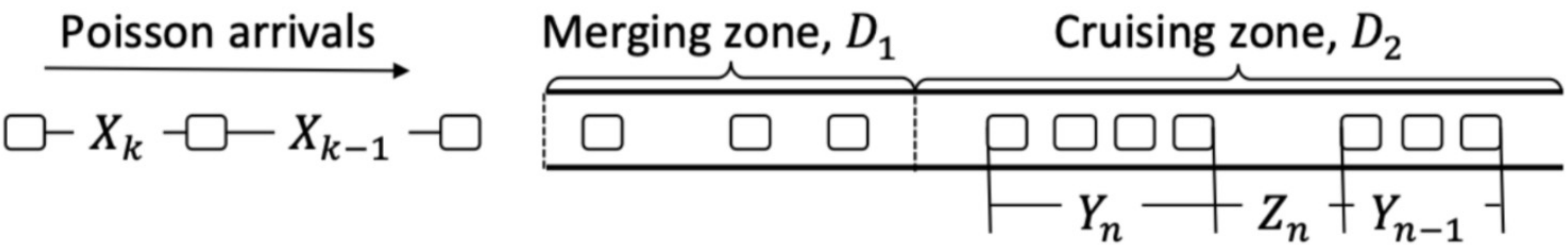
Interpretation: platoon size distribution decreases exponentially.

Static approach*

Proposition

- In the steady state, the headways Z between a platoon has the expected value

$$\mathrm{E}[Z] = \frac{e^{\lambda r}}{\lambda}$$

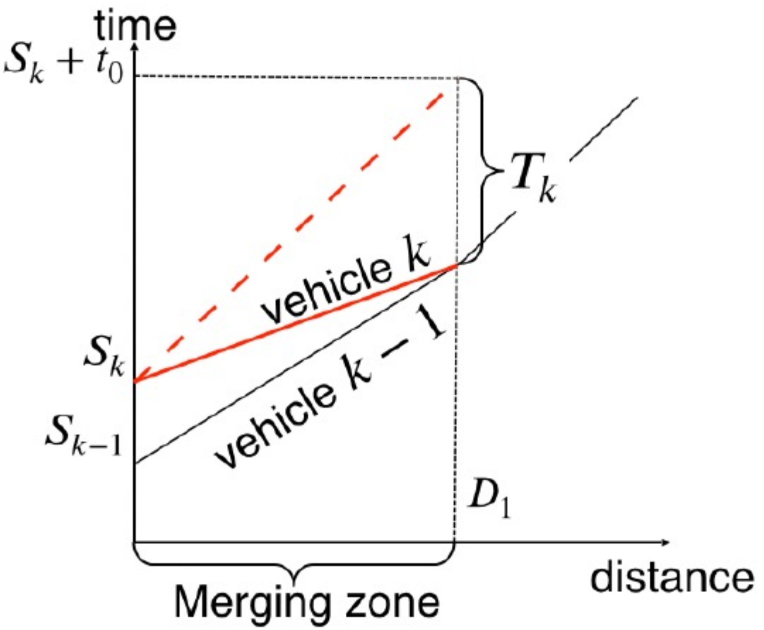


- Interpretation: headway exponentially increases with threshold.

Static approach*

- Time reduction due to platooning
  - the nominal traverse time t_0, which is identical for all vehicles,
  - the increment $-T_k \leq 0$ due to acceleration for merging.
- The time at which the kth vehicle leaves the merging zone is $S_k + t_0 - T_k$.
- **Proposition**

$$\mathrm{E}[T_k] = \frac{1}{\lambda} e^{\lambda r} - r - \frac{1}{\lambda}$$



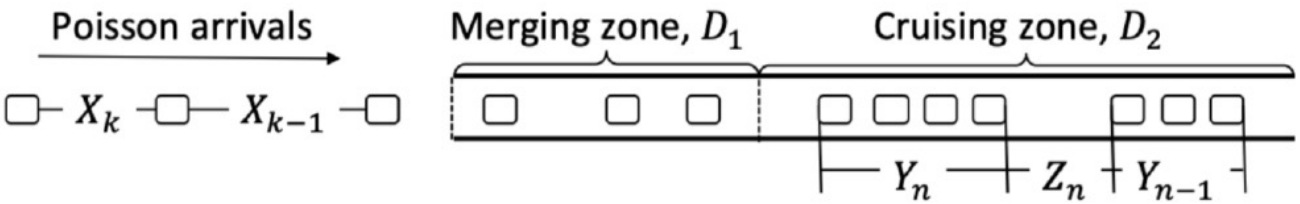
Static approach

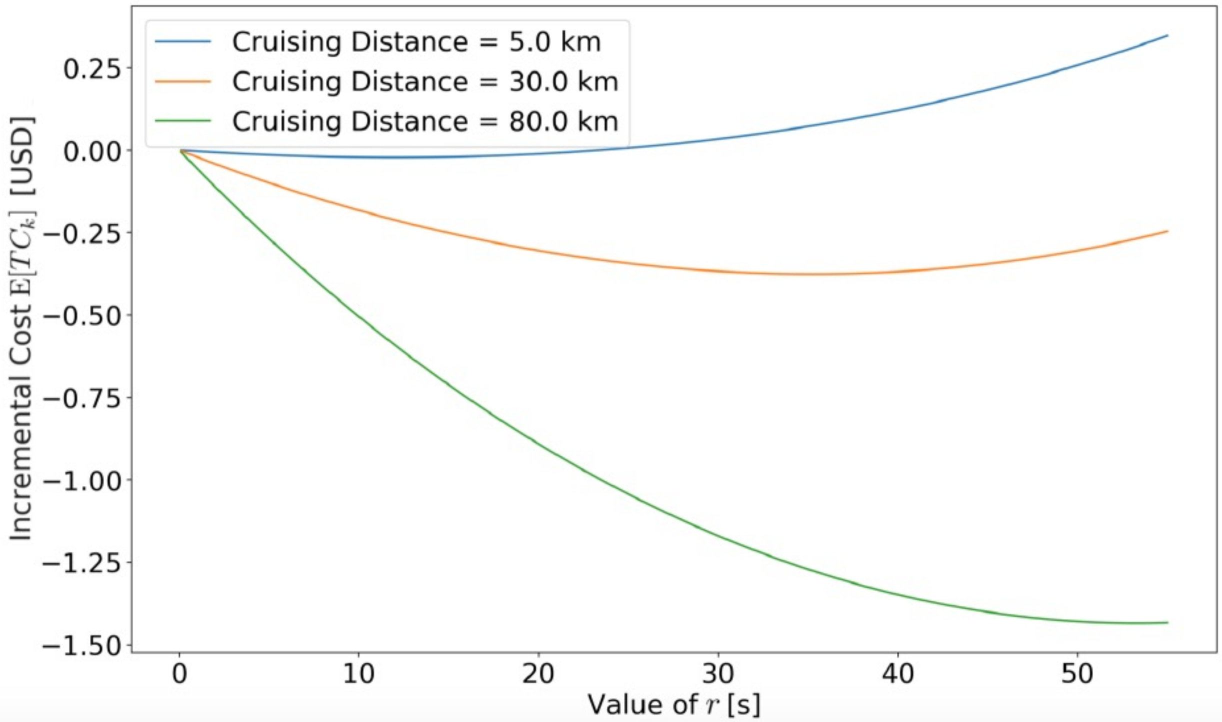
- Optimizing Platooning Threshold
- The benefits of platooning include two parts: reducing travel time and fuel consumption.
- The total cost TC_k is the incremental total cost instead of absolute value.
- We divide the cost of platooning into three parts: time reduction Tk, increased fuel F_1 during merging and fuel reduction F_2 after merging. The total cost TC_k can be expressed as:

$$TC_k = -w_1 T_k + w_2 \Delta F_1 - w_2 \Delta F_2,$$

- w_1 is value of time (VOT) and w_2 is fuel price.

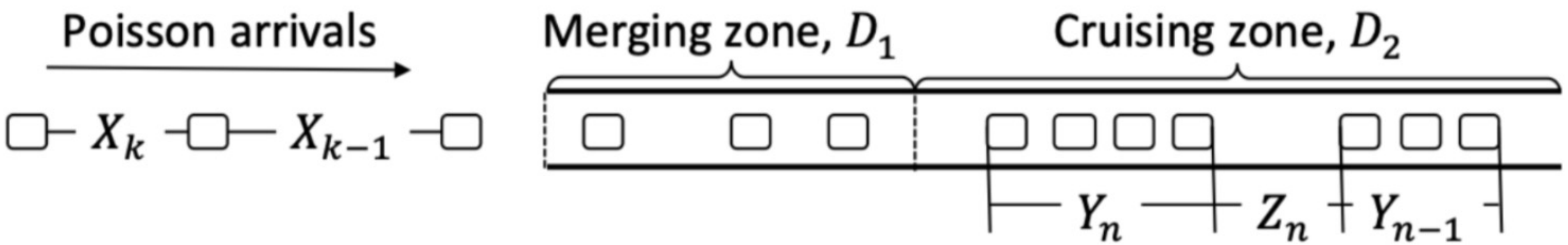
Static approach





Dynamic approach

- Previously we use inter-arrival time X_k as the decision variable, which would lead to consequent acceleration and high catch-up speed.
- We now use the time reduction of platooning Tk as the decision variable (platoon-size sensitive).
- The decision is made for an incoming CAV based on the position and speed of the CAV ahead when the incoming CAV enters the merging zone.



Dynamic approach

Dynamic programming formulation

- State S_k = predicted headway between CAVs k and $k-1$ at the junction.
- Action A_k = T_k , i.e. time reduction of CAV k.
- Reward R_k = - travel time cost - fuel cost for CAV k;
- State update equation: $S_k + 1 \ = \ X_k + 1 \ + \ A_k$.
- Objective: find the optimal policy to maximize accumulative rewards

$$\max \mathrm{E}\left[\sum_{k=0}^{\infty} \gamma^k R_k\right]$$

Dynamic approach

Dynamic programming formulation

- State S_k = predicted headway between CAVs k and $k-1$ at the junction.
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- State update equation: $S_{k+1} = X_{k+1} + A_k$.
- Objective: find the optimal policy to maximize accumulative rewards

$$\max \mathrm{E}\left[\sum_{k=0}^{\infty} \gamma^k R_k\right]$$

Dynamic approach*

Theorem

The optimal policy to the DP of coordinated platooning is such that

$$\mu^*(s) = \begin{cases} s & s \le \theta \\ c & s > \theta \end{cases}$$

where $\theta > 0$ and $c < 0$ are constants.

- Holds for general arrival processes.
- Interpretation:
  - If the predicted headway between two CAVs is less than a threshold, then merge;
  - Otherwise, the following CAV should slightly decelerate in anticipation of further subsequent CAVs to merge.
- Idea of proof: Bellman optimality equation*

Dynamic approach*

- The above theorem only states the structure of the optimal policy.
  - This significantly reduces computation time!

Headway Distribution		Bounded Value Iteration	Recursive Approximation	Refinement
Exponential	$\lambda e^{-\lambda x}$	9.6 h	0.9 h	< 1 s
Discrete random variable	$p_1 h_{c1} + p_2 h_{c2}$	37 s	10 s	——
Constant	h_c	29 s	8 s	——

Reference: Xiong, X., Sha, J. and Jin, L. Optimizing coordinated vehicle platooning: An analytical approach based on stochastic dynamic programming. *Transportation Research Part B: Methodological*, conditionally accepted.

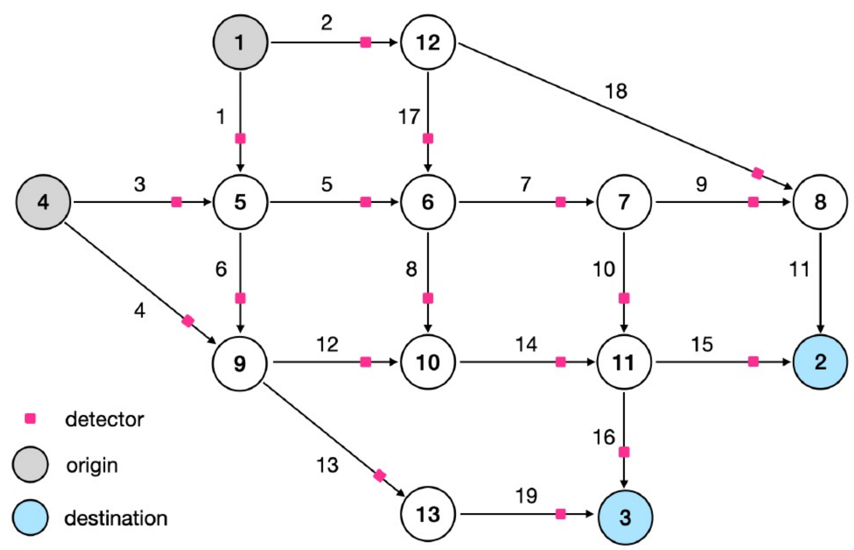
Network level: cooperative routing

- Problem formulation
- Fundamental tradeoff

Platooning Coordination in Networks

Coordinated platooning at junctions

- State: predicted headway and vehicle destinations;
- Action: time reduction and routing decisions.
- System-level coordination and cooperation
- Challenge: spatial-temporal correlations in networks



Fundamental tradeoff

- One the one hand, we want CAVs' routes to have as many overlapping legs as possible to maximize the chance of platooning.
- One the other hand, clustering all CAVs on a small number of legs may lead to congestion, which compromises non-CAV traffic.
- This tradeoff is very complex, and learning-based methods will be needed to approximately compute the optimal decisions.

Summary

- Macroscopic decisions for platooning
- Link level: headway regulation
  - Hybrid fluid model
  - Analysis
  - Design
- Junction level: trip coordination
  - Markov decision process
  - Optimal coordination policy
- Network level: cooperative routing
  - Problem formulation
  - Fundamental tradeoff

Next time

Analysis & design of intersection sequencing

- Modeling
- Analysis
- Design