Integrating Autonomy into Traffic Systems: Scalable Control and Optimization

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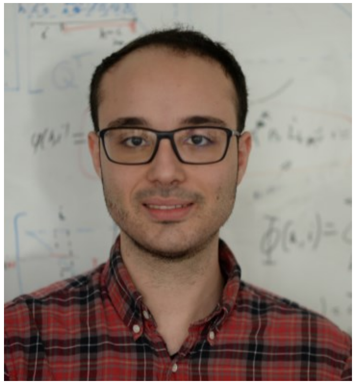

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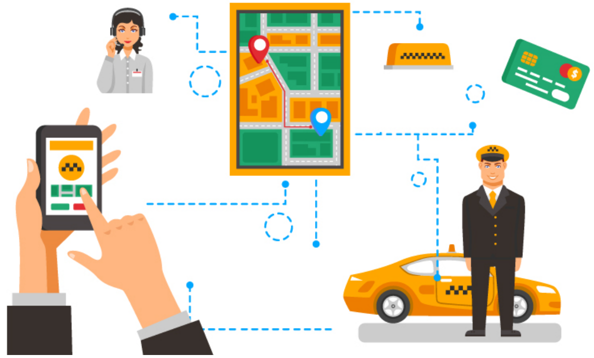
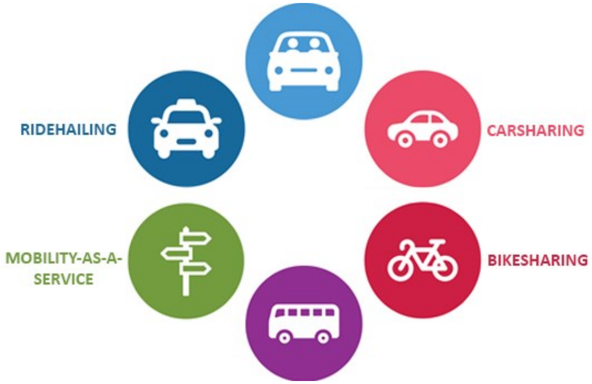
Autonomous Vehicles

- **Reduce traffic accidents**
  - 37,000 fatalities
  - 41% deaths of young adults (ages 15-24)
  - **94%** of serious crashes caused by human error

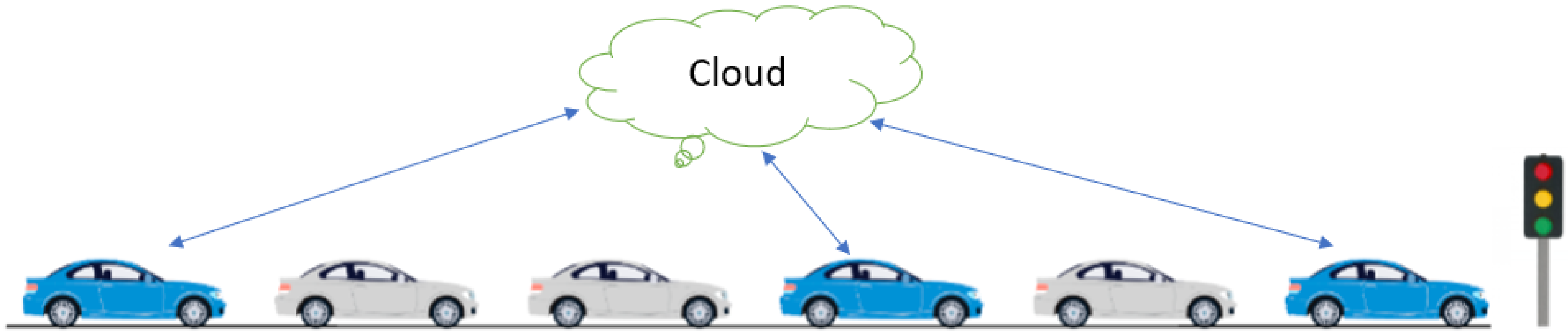
U.S. Census Bureau, 2017.

- **Ease traffic congestion**
  - **6.9 billion hours** wasted annually
  - Cost of traffic congestion is **$1740** per person annually in US/Europe.
- **Improve energy efficiency**
  - 28% of greenhouse gas emission is from transportation
- **New mobility patterns**: on-demand mobility, mobility as service etc.





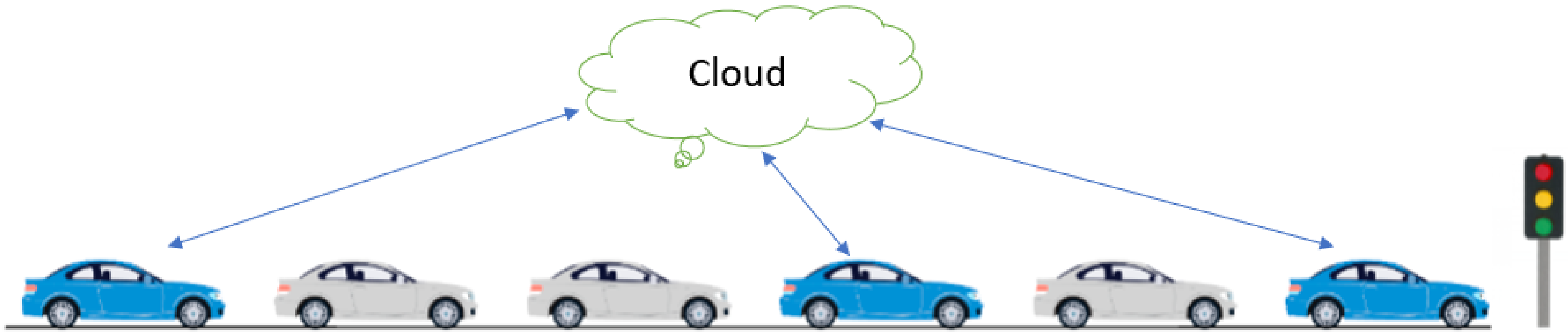
Mix-Autonomy Mobility



Mixed-autonomy mobility: a traffic condition where both autonomous vehicles and human-driven vehicles co-exist.

- **Q1:** How will **a small scale of autonomous vehicles** change traffic dynamics?
- **Q2:** How to integrate **a small scale of autonomous vehicles** to improve traffic performance?

Mix-Autonomy Mobility



- **Q1:** How will **a small scale of autonomous vehicles** change traffic dynamics?
- **Q2:** How to integrate **a small scale of autonomous vehicles** to improve traffic performance?

Theoretical evidence of the high potential of autonomous vehicles

Practical design via distributed control and scalable optimization

Benchmark Ring Road Experiment

Traffic jams

Sugiyama, et al.

1955 >10,000 papers for traffic control **2008** 2020

Setting:

22 human drivers

Instructions:

drive at 30 km/h /following its preceding vehicle

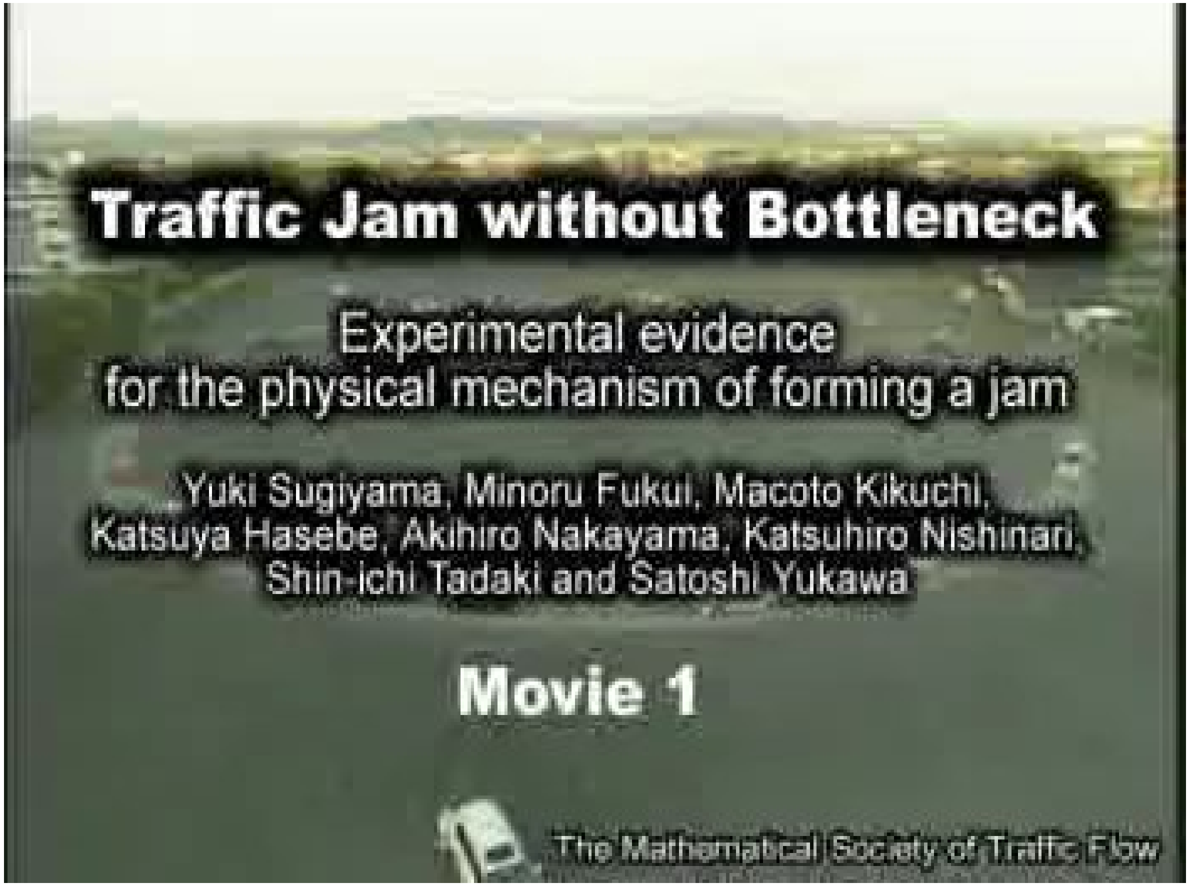
Environment

Single lane

No traffic lights,

No stop signs,

No lane changes.



Video credits: NewScientist.com

Benchmark Ring Road Experiment

Traffic jams

Sugiyama, et al. **Stern, et al.**

1955 >10,000 papers for traffic control 2008 **2018** 2020

Setting:

21 human drivers

+ 1 AV

Instructions:

drive at 30km/h /following its preceding vehicle

Environment

Single lane

No traffic lights,

No stop signs,

No lane changes.

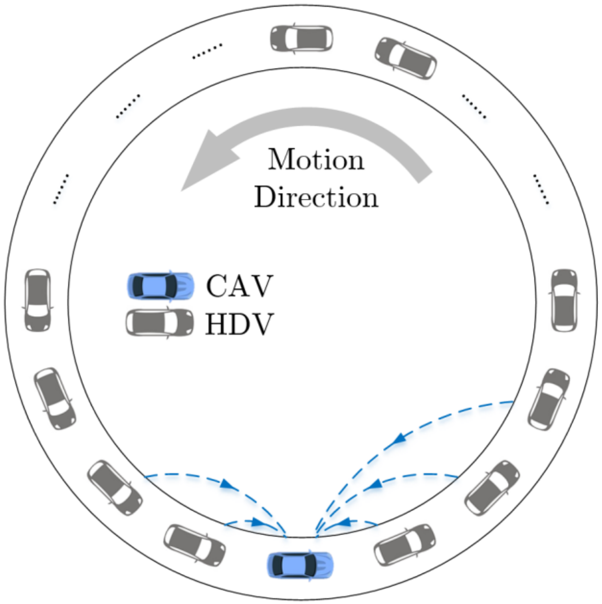
Dissipation of stop-and-go traffic waves via control of a single autonomous vehicle

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN RUTGERS TEMPLE UNIVERSITY THE UNIVERSITY OF ARIZONA

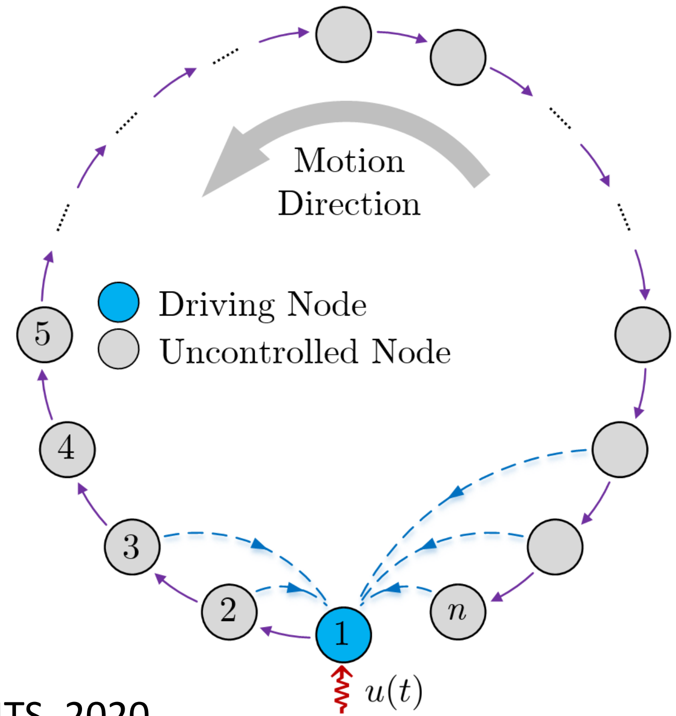
Theoretical Evidence in mixed traffic

❑ Theoretical Evidence & Controller design

- Why does it work?
- Does it work in other setups (e.g., different number of HDVs, different human-driver behavior, open straight road scenario)?



Sparse network control

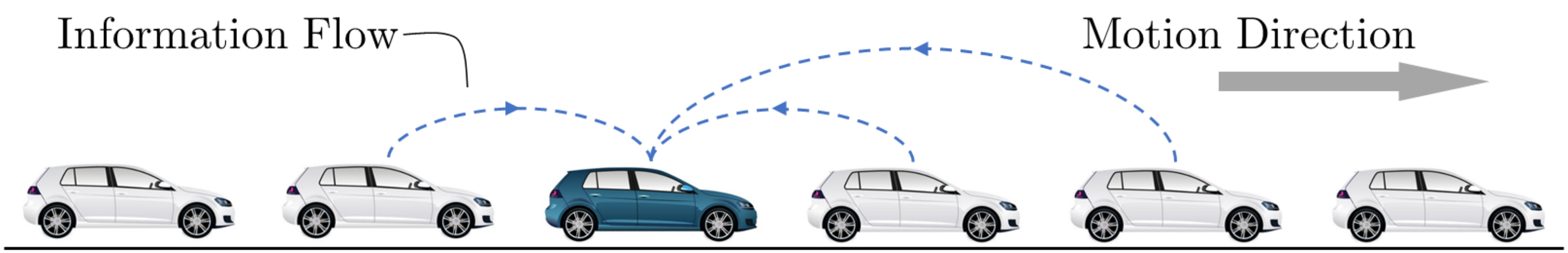


Zheng, Wang, & Li, IEEE IoT, 2019; Wang, & **Zheng**, et al., IEEE TITS, 2020

Scalable Control & Optimization

❑ Theoretical Evidence & Controller design

- ➢ How to design distributed controllers with limited communication?
- ➢ How to scale up the computation efficiency?



- Furieri, L., **Zheng**, Y., Papachristodoulou, A., & Kamgarpour, M. (2020). Sparsity invariance for convex design of distributed controllers. IEEE Transactions on Control of Network Systems. (***Best Student Paper Finalist***, ECC 2019)
- **Zheng**, Y., Fantuzzi, G., Papachristodoulou, A., Goulart, P., & Wynn, A. (2020). Chordal decomposition in operator-splitting methods for sparse semidefinite programs. ***Mathematical Programming***, *180*(1), 489-532.

Today's talk

Integrating Autonomy into Traffic Systems

Part 1: Theoretic potential of autonomy in traffic

- Stabilizability of mixed traffic flow;
- Autonomous vehicles as mobile actuators in traffic networks;
- Leading Cruise Control (LCC)

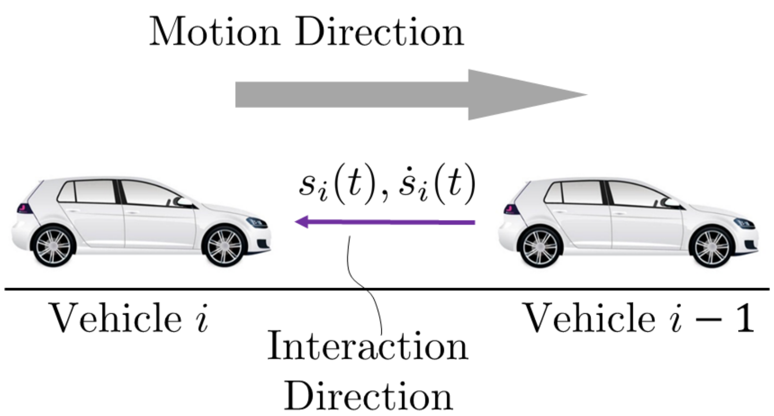
Part 2: Practical design via control & optimization

- Convex design of distributed control over traffic network;
- Scalable optimization for large-scale convex problems;

Mixed-autonomy ring road

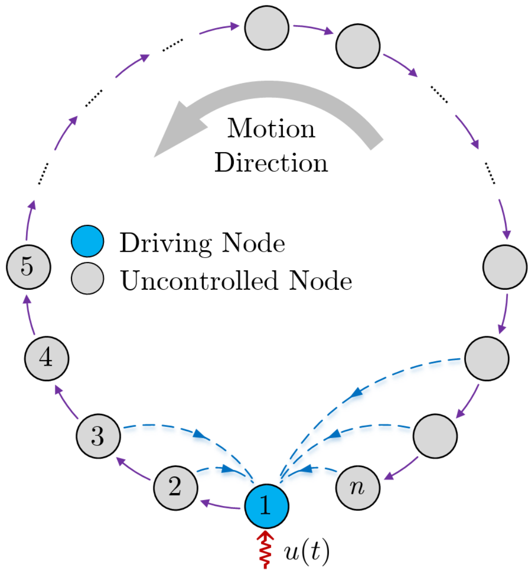
❑ System modeling

1. Human drivers → car-following dynamics

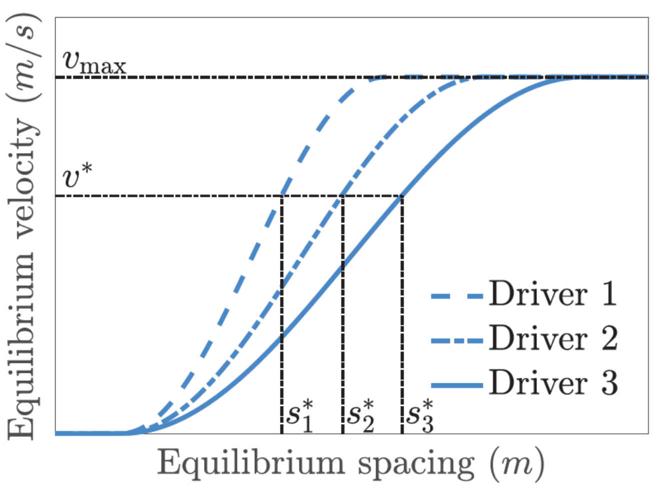


$$\dot{v}_i(t) = F_i(s_i(t), \dot{s}_i(t), v_i(t))$$

- $v_i(t)$: Velocity of vehicle i
- $s_i(t)$: Spacing between vehicle i and vehicle $i-1$



$$0 = F_i(s_i(t), 0, v_i(t))$$



Dirk Helbing, 2001; Orosz, Wilson, and Stepan, 2010.

Large spacing ↔ Large velocity

Mixed-autonomy ring road

❑ System modeling

2. Autonomous vehicle → direct control

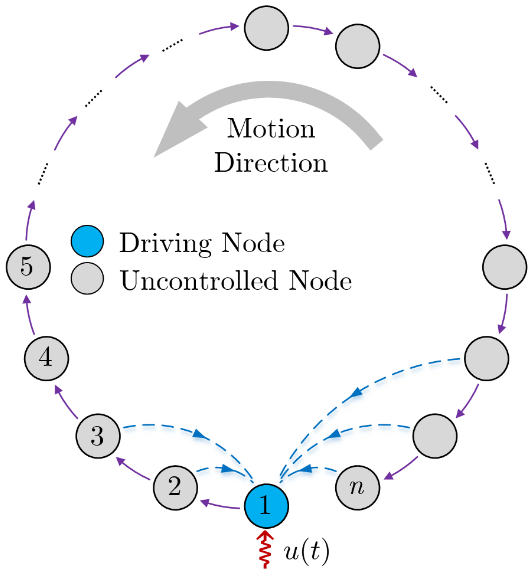
$$\begin{cases} \dot{s}_1(t) &= v_n(t) - v_1(t) \\ \dot{v}_1(t) &= u_1(t) \end{cases}$$

3. Assuming an equilibrium traffic state $v^*(t)$

$$\dot{x}(t) = Ax(t) + Bu(t),$$

where the system matrices have the following structure

$$A = \begin{bmatrix} C_1 & 0 & \dots & \dots & 0 & C_2 \\ A_2 & A_1 & 0 & \dots & \dots & 0 \\ 0 & A_2 & A_1 & 0 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \dots & 0 & A_2 & A_1 & 0 \\ 0 & \dots & \dots & 0 & A_2 & A_1 \end{bmatrix}, B = \begin{bmatrix} \boxed{\begin{matrix} 0 \\ 1 \end{matrix}} \\ 0 \\ \vdots \\ 0 \end{bmatrix},$$



A network system with only one controllable node

Mixed-autonomy ring road

❑ Theoretical evidence 1: Unstable behavior

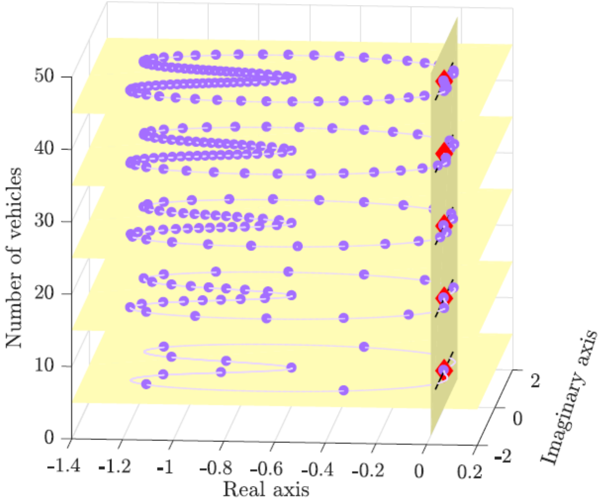
$$\dot{x}(t) = \hat{A}x(t)$$

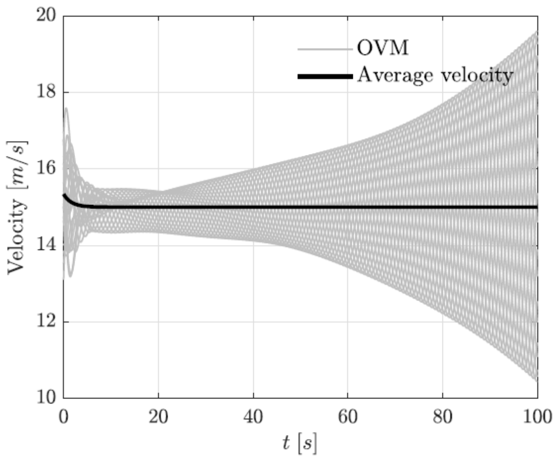
(Informal) The traffic system in a ring-road can be unstable if drivers' sensitivity to speed and spacing errors is small (e.g. Cui et al., 2017)

$$\boxed{\alpha + 2\beta} < \text{Constant}$$

Sensitivity to speed and spacing errors

Slow response to spacing; To catch up, it drives to a large velocity → **Oscillation**





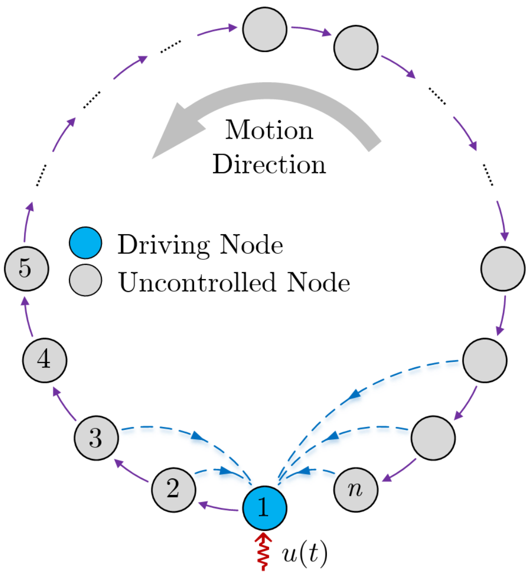
Mixed-autonomy ring road

❑ Theoretical evidence 2: Fundamental change of dynamics

$$\dot{x}(t) = \hat{A}x(t)$$

Theorem (zheng *et al.*, 2019)**: The mixed traffic system in the ring-road setup is not controllable, but stabilizable.**

1. **Independent of the number of human-driven vehicles**
2. **Independent of car-following dynamics**
3. **Offer a strong control-theoretic support for the potential of autonomy in mixed traffic**



Integrating autonomy is a fundamental change of traffic dynamics (more control freedom)!

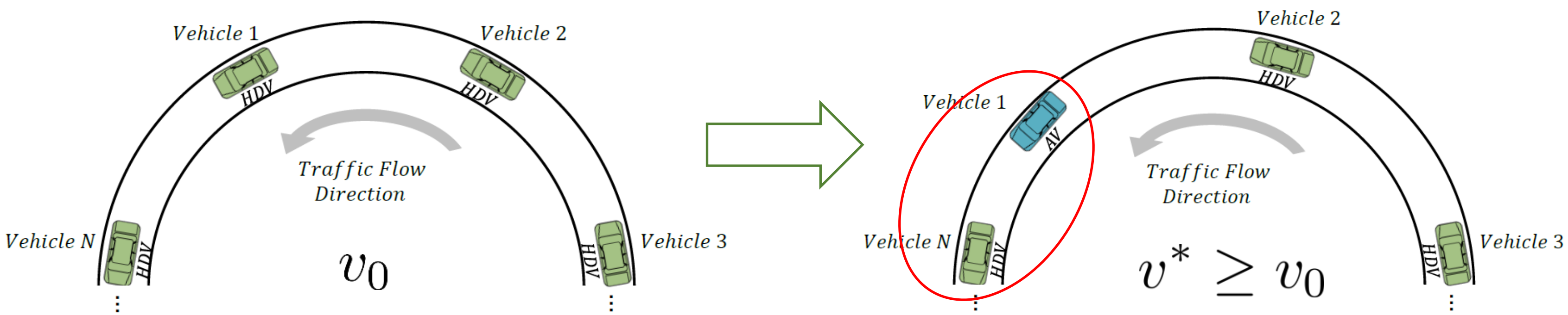
Zheng, Wang, & Li, IEEE IoT, 2019

Mixed-autonomy ring road

❑ Theoretical evidence 3: Beyond stabilization/increase traffic speed

Theorem (zheng *et al.*, 2019)**: The global traffic velocity can be increased to a larger value:**

$$0 \leq v^* < v_{\max}$$



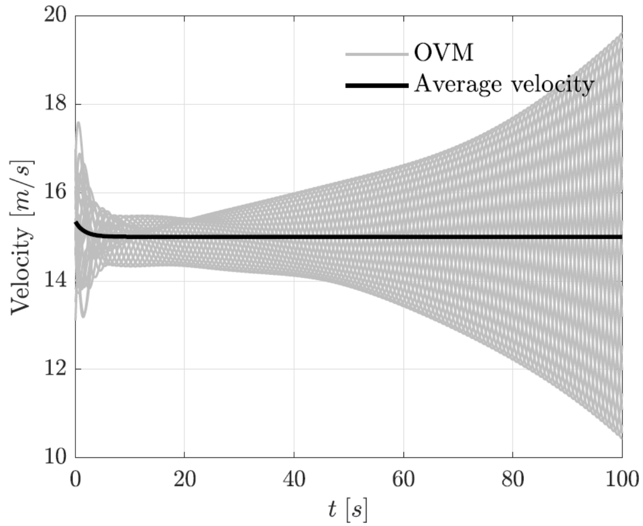
❑ Physical interpretation

✓ The AV can change its own spacing to influence other HDVs' spacing, and thus change traffic velocity v^*.

Zheng, Wang, & Li, IEEE IoT, 2019

Numerical Experiments with Nonlinear Dynamics

Unstable traffic system

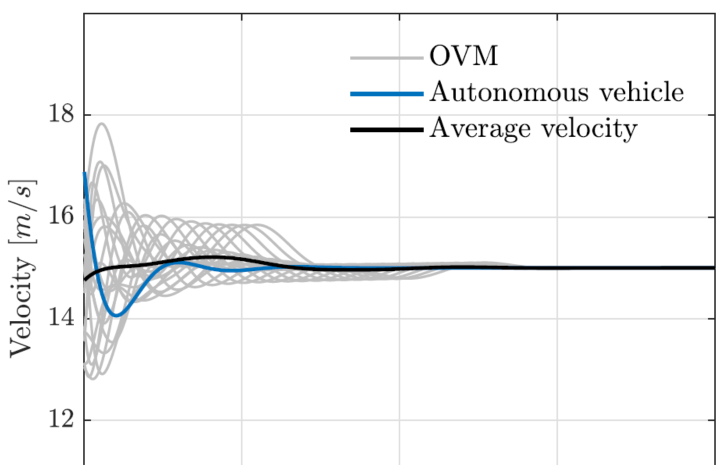


OVM: Optimal Velocity Model

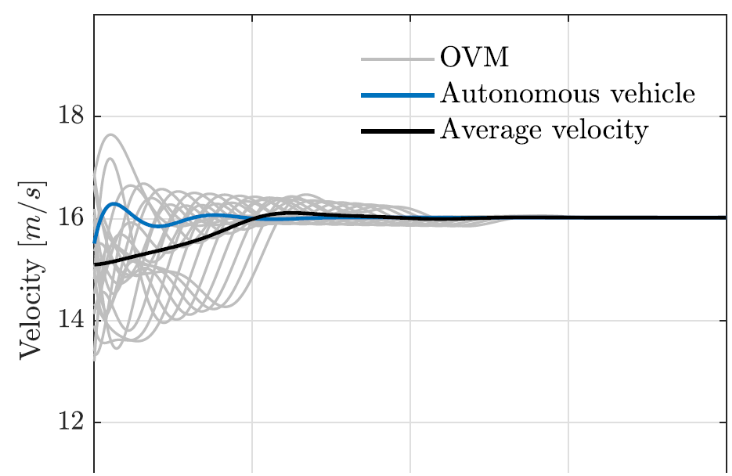
$$F_i = \alpha(V(s_i(t)) - v_i(t)) + \beta \dot{s}_i(t)$$

$$V(s) = \begin{cases} 0, & s \le s_{\mathrm{st}}, \\ f_v(s), & s_{\mathrm{st}} < s < s_{\mathrm{go}}, \\ v_{\max}, & s \ge s_{\mathrm{go}}, \end{cases}$$

$$f_v(s) = \frac{v_{\max}}{2}\left(1 - \cos(\pi \frac{s - s_{\mathrm{st}}}{s_{\mathrm{go}} - s_{\mathrm{st}}})\right).$$



Stabilize the traffic flow

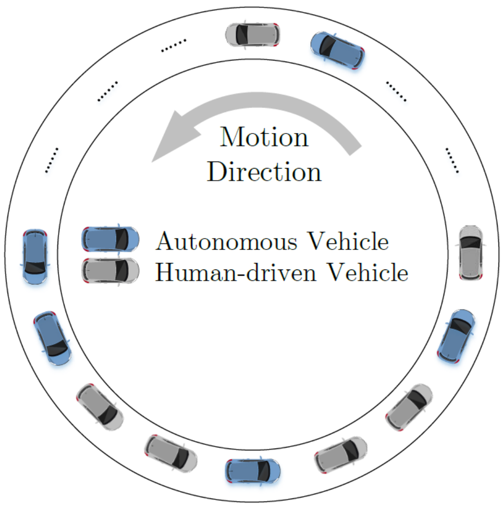


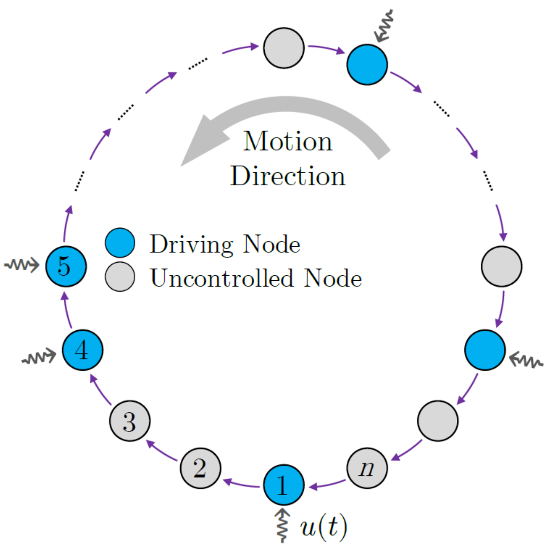
Increase the traffic speed

The existence of **5% AVs** (1 out of 20) can bring **6% improvement** on traffic velocity

Integrating Autonomy: Multiple AVs

Main question: How to coordinate multiple autonomous vehicles in traffic flow? Is platooning the optimal choice?





Set function optimization

$$\max_{S} \quad J(S)$$

$$S \subseteq \Omega, |S| = k$$

$\Omega = \{1, 2, \ldots, n\}$: all the vehicles

$S = \{i_1, \ldots, i_k\} \subseteq \Omega$: k autonomous vehicles

Li, Wang, & **Zheng,** (2020), IEEE TITS, under review

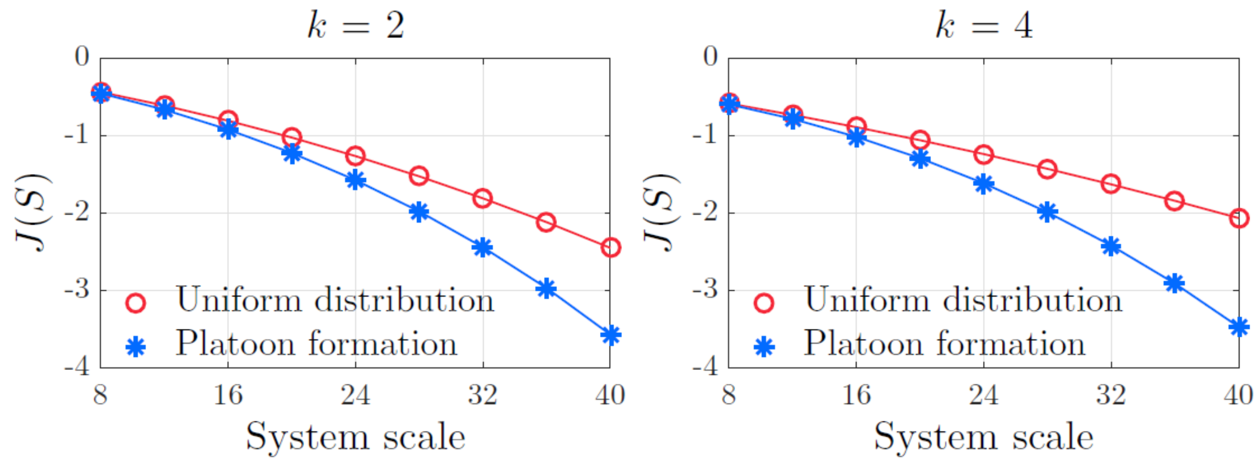
Integrating Autonomy: Multiple AVs

Set function optimization

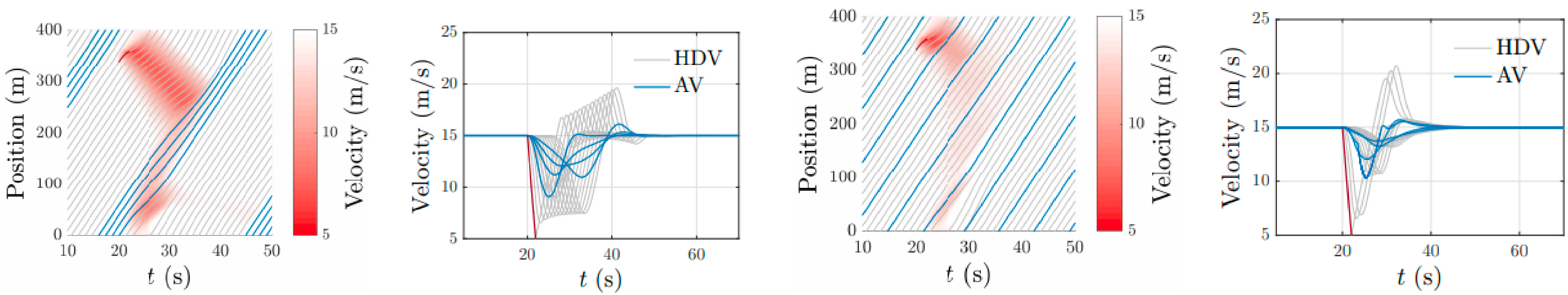
$$\max_{S} \quad J(S)$$

$$S \subseteq \Omega, |S| = k$$

Platooning is not always optimal



Simulation with Nonlinear Car-following Dynamics



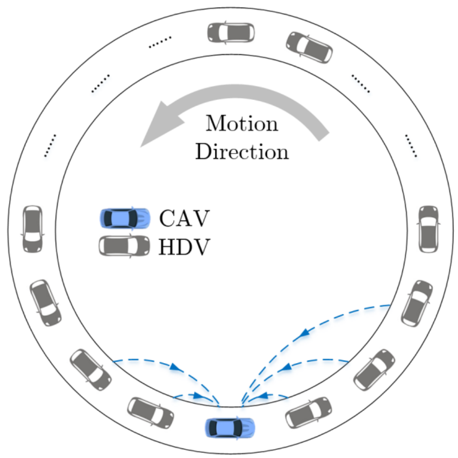
Platoon formation:
$S = \{9, 10, 11, 12\}$

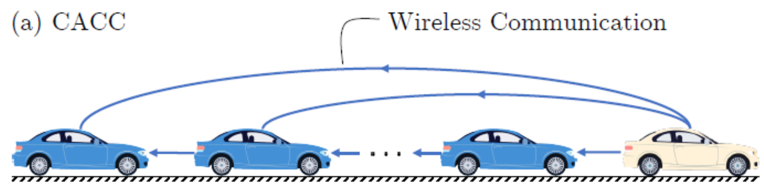
Li, Wang, & **Zheng,** (2020), IEEE TITS, under review

Uniform distribution:
$S = \{3, 8, 13, 18\}$

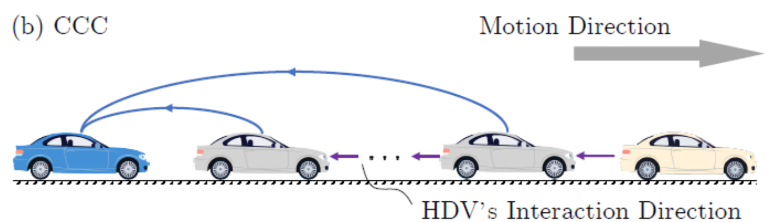
Integrating Autonomy in Open-straight road

Closed-ring road setup



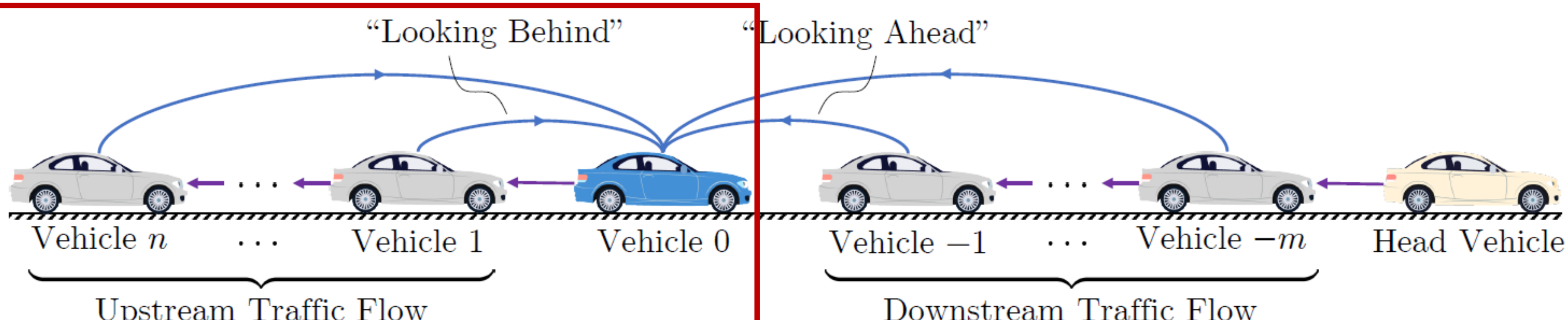


CACC: Fully-autonomous scenario



Connected Cruise Control: downstream traffic flow

➤ Leading Cruise Control

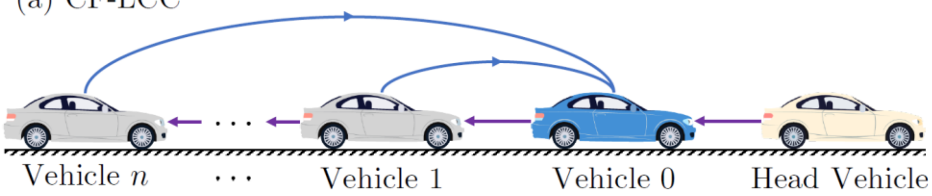


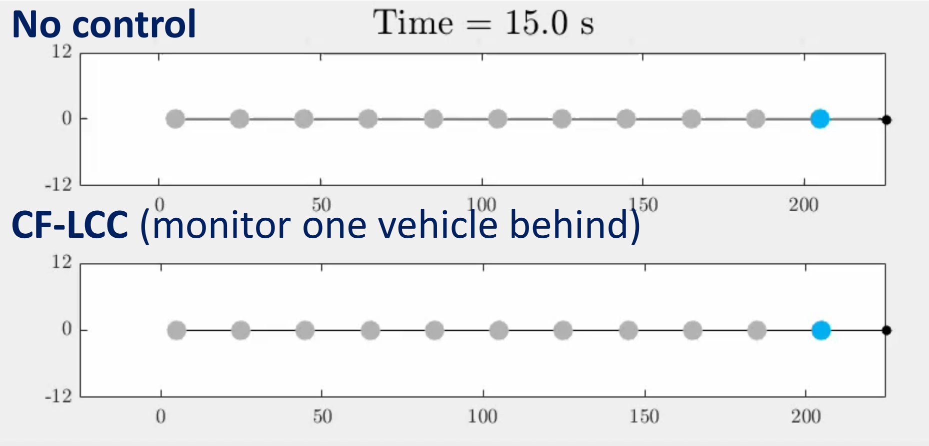
Lead the motion of the vehicles behind + **Adapt to the motion of the vehicles ahead**

Leading Cruise Control (LCC)

Special case 1: car-following LCC

(a) CF-LCC

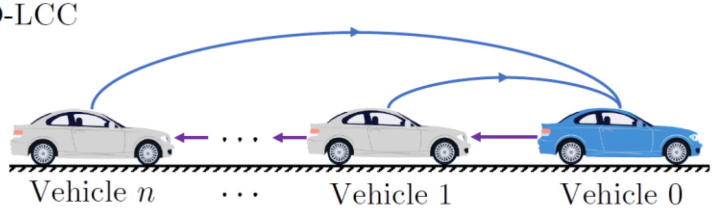


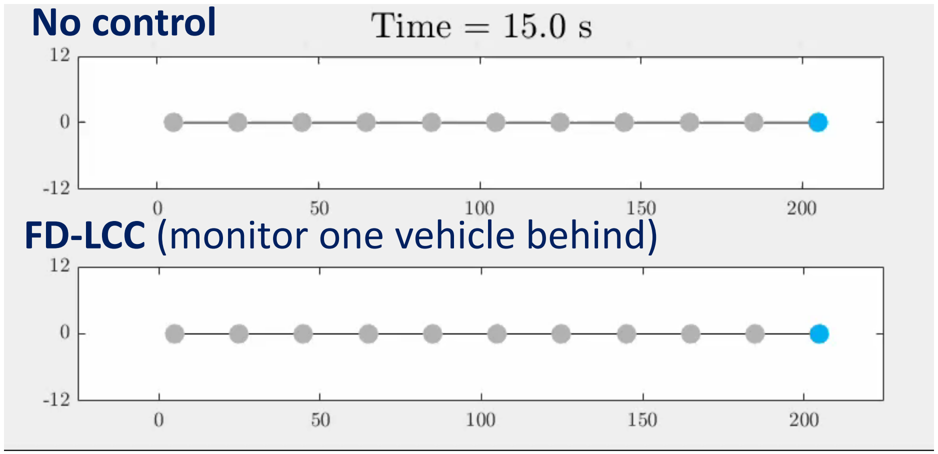


Reduce velocity perturbations by 28%

Special case 2: free driving LCC

(b) FD-LCC





Reduce velocity perturbations by 35%

1. **The motion after AV is controllable (leading motion behind)**
2. **String stability can be improved (attenuating perturbation ahead)**

Wang, J., **Zheng, Y.**, Chen, C., Xu, Q., & Li, K. (2020). Leading Cruise Control in Mixed Traffic Flow. arXiv:2007.11753.

Today's talk

Integrating Autonomy into Traffic Systems

Part 1: Theoretic potential of autonomy in traffic

- Stabilizability of mixed traffic flow;
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- Leading Cruise Control (LCC)

Part 2: Practical design via control & optimization

- Convex design of distributed control over traffic network;
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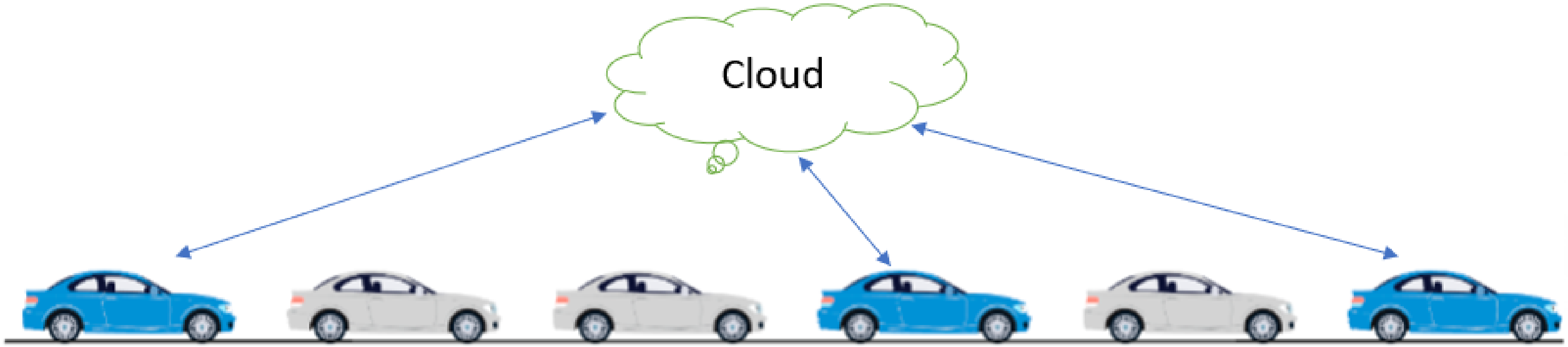
General Procedure



Control Problem Formulation

↓

Convex reformulation as LMI or SDP

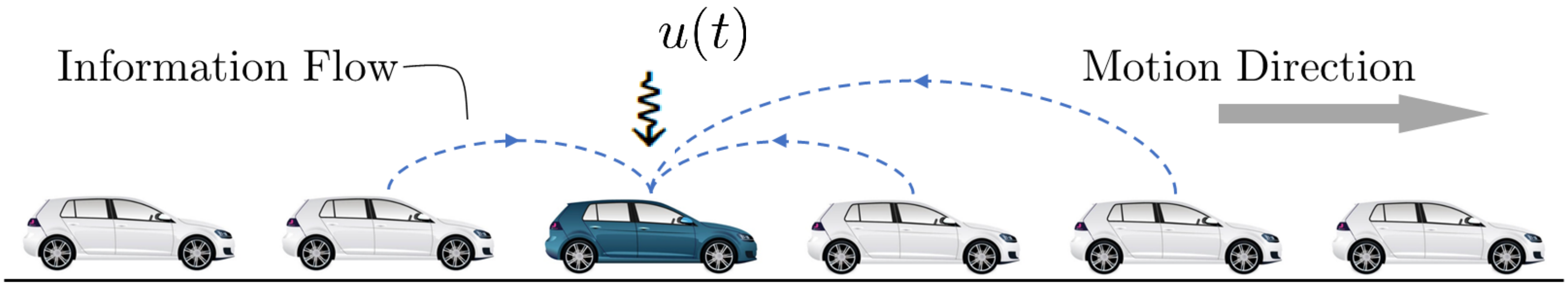
↓

Numerical solution

Challenge 1: How to handle info. constraints (recover convexity)

Challenge 2: How to deal with large-scale problems (Scalability)

Problem formulation: distributed controller



$$\min_{K} \quad J(K)$$ → System performance (e.g., speed oscillation)

$$\text{subject to} \quad K \in \mathcal{C}_{\text{stab}},$$ → Stable controller

$$K \in \text{Sparse}(S)$$ → Distributed controller

- This is **a non-convex optimization problem**
- The presence of the sparsity constraint makes the problem **challenging** (NP-hard in general).

Previous work on distributed control

❑ 90's: Feasibility & Stabilization

1) **Structural controllability:** Glover & Silverman, TAC 1976; Wang & Davison, TAC 1973; Davison, Automatica 1977; Mayeda and Yamada, SICON 1979, etc.
2) **Decentralized/distributed fixed mode:** Anderson & Clements, TAC 1981; Sezer & Šiljak, SCL 1981; Davison & Özgüner, Automatica 1983; etc.
3) **Decentralized stabilization & pole placement:** Davison & Chang, TAC 1995; Ravi et al, TAC 1995
4) **Early survey paper:** Sandell, Varaiya, Athans & Safonov, TAC 1978.

❑ Late 90's- Now: Performance enhancement via optimization

1) **Exact solutions for special classes of systems:** Quadratic Invariance (Rotkowitz & Lall, TAC 2005); Partially ordered sets (Shah & Parrilo, TAC 2013);
2) **Tractable convex approximation:** Dvijotham et al, TCNS 2015; Fazelnia et al, TAC 2016;
3) **Suboptimal solutions using iterative algorithms:** Fu, Fardad, & Jovanovic, TAC 2011;
4) **Structure regularization and system-level synthesis:** Jovanović & Dhingra, 2016; Wang et al., TAC 2019;

Recover
Convexity

A new framework based on Sparsity Invariance for convex design of distributed control

Unified framework for distributed control

Sparsity invariance (SI)

$$X \in \mathrm{Sparse}(R),\ Y \in \mathrm{Sparse}(T)$$
$$\Rightarrow$$
$$K = YX^{-1} \in \mathrm{Sparse}(S)$$

Recover
Convexity

A new framework based on Sparsity Invariance for convex design of distributed control

Static feedback

- Strictly better than the widely used **diagonal approximation strategy** (Geromel et al., 1994; Conte et al.,2012; Rubio et al., 2013; Han et al., 2017)

Dynamic feedback (past information + memory)

- Guaranteed to be optimal when a notion of **Quadratic Invariance (QI)** holds (Rotkowitz & Martins, 2012)
- Best known performance for non-QI cases

Furieri, **Zheng**, Karmgarpour & Papachristodoulou IEEE TCNS, 2020.

General Procedure

Control Problem Formulation

↓

Convex reformulation as LMI or SDP

↓

Numerical solution

Challenge 1: How to recover convexity

Sparsity Invariance

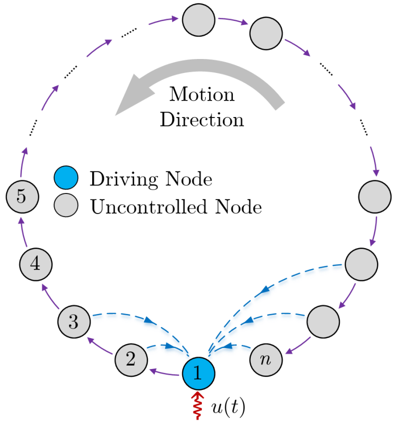
Challenge 2: How to deal large-scale problems (Scalability)

Sparsity Structure Matters

Sparsity Structure

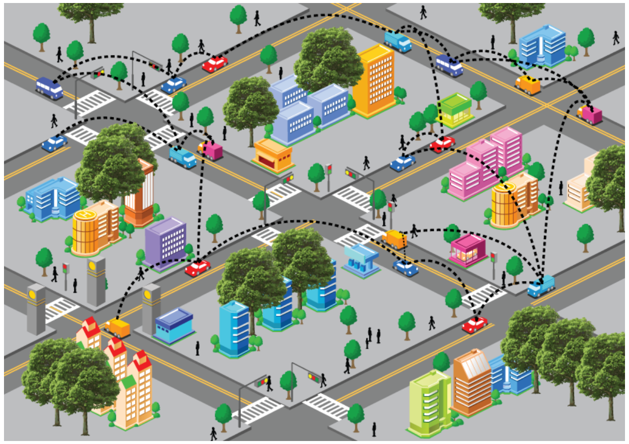
Sparsity structure appears in many places of real cyber-physical systems

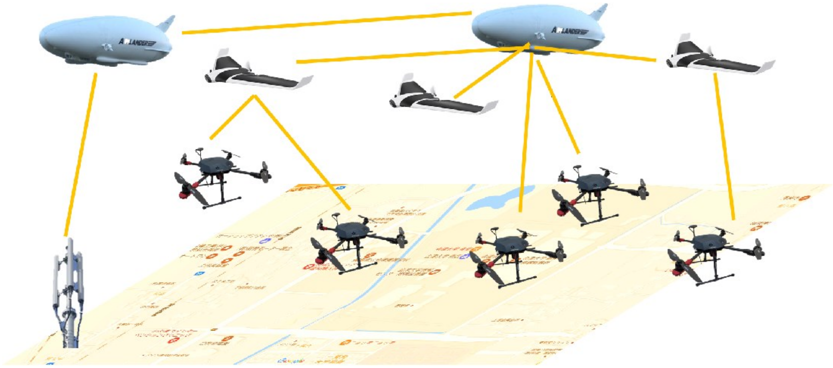
❑ System dynamics data



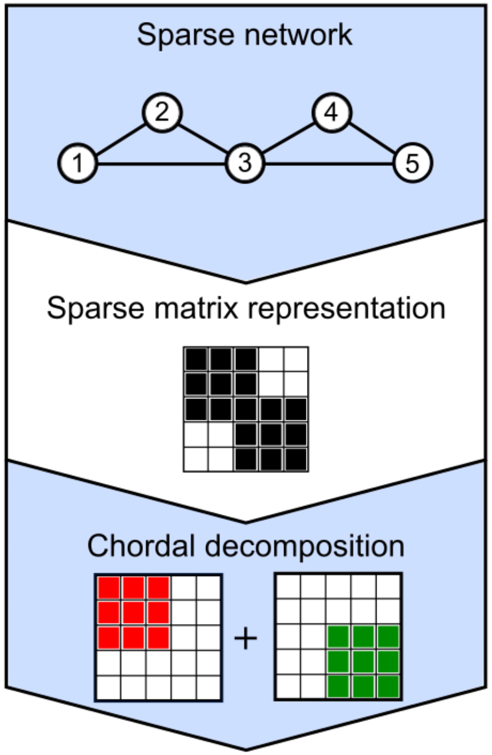
$$A = \begin{bmatrix} C_1 & 0 & \dots & \dots & 0 & C_2 \\ A_2 & A_1 & 0 & \dots & \dots & 0 \\ 0 & A_2 & A_1 & 0 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \dots & 0 & A_2 & A_1 & 0 \\ 0 & \dots & \dots & 0 & A_2 & A_1 \end{bmatrix}, B = \begin{bmatrix} 1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix},$$

❑ Sparse communication

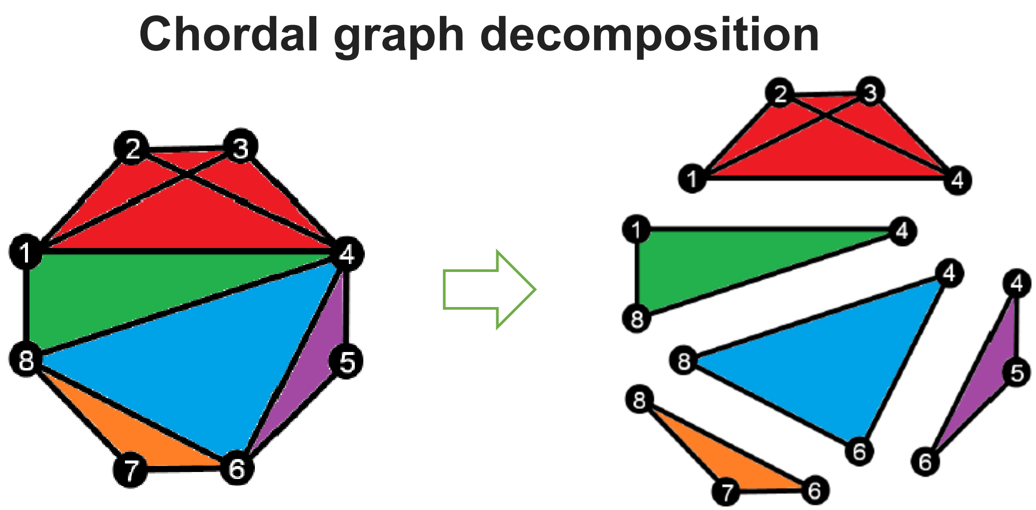




Graph Decomposition



Vandenberghe & Andersen (2015).



- This allows for the decomposition of a big positive semidefinite constraint
- Exploiting this decomposition → a new scalable algorithm for sparse SDP (**Zheng** et al. ***Math. Prog.,*** *2020*)

Conclusion

Two main takeaways

Theoretic potential of autonomy in traffic

- Mixed traffic systems is always **stabilizable**;
- Autonomous vehicles can not only **smooth traffic wave**, but also guide traffic velocity to **a higher value**;
- Autonomous vehicles can change traffic dynamics fundamentally (**Leading Cruise Control**)

Integrating Autonomy via Control and Optimization

- **Convexity** of distributed control: a new framework based on sparsity invariance
- **Scalability** of convex optimization: Sparsity-exploiting methods based on graph decomposition

References

Autonomous Vehicles in Mixed Traffic Flow

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Thank you for your attention!

More information; visit https://zhengy09.github.io/