Modeling, Estimation and Control of Traffic Networks

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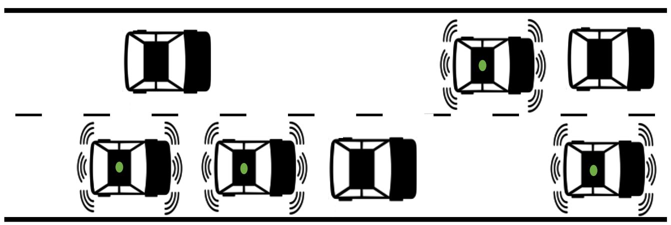
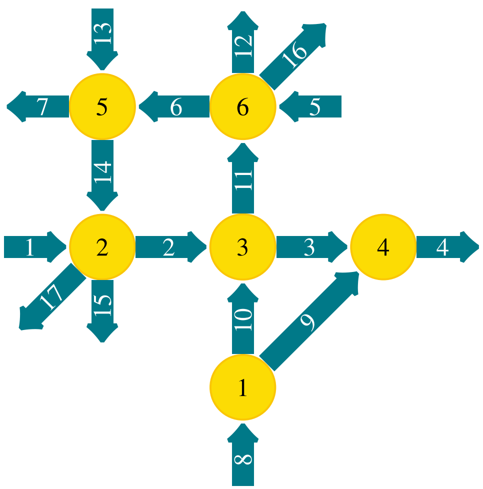
Traffic Management with Connected and Autonomous Vehicles
“Smart Vehicles”





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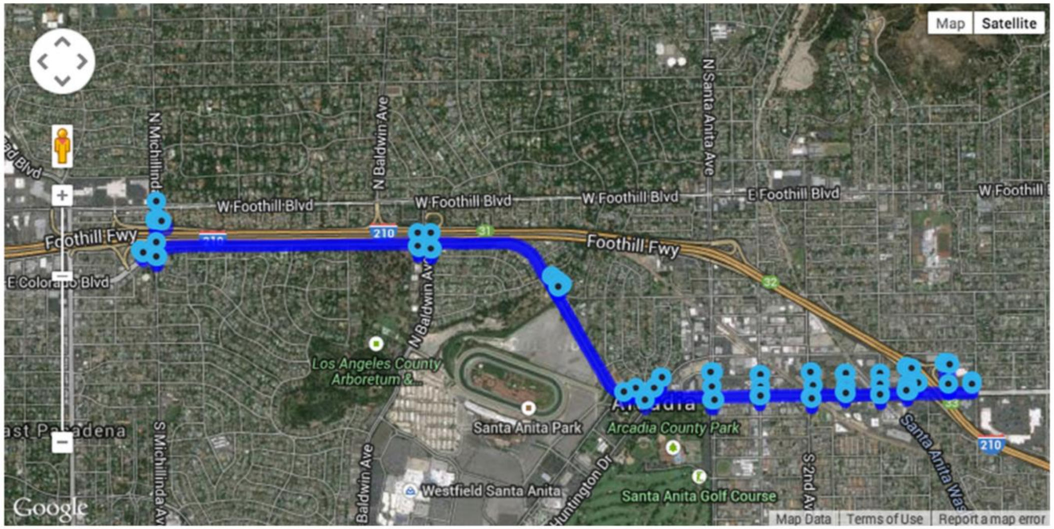
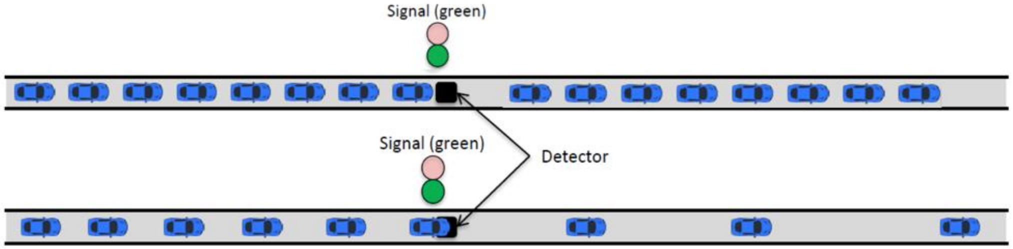
PATH – smart vehicle platooning

Reducing energy consumption

Increasing traffic capacity

Smart vehicle platoons can increase throughput in ***urban roads*** (30%- 50%) - Varaiya et al.

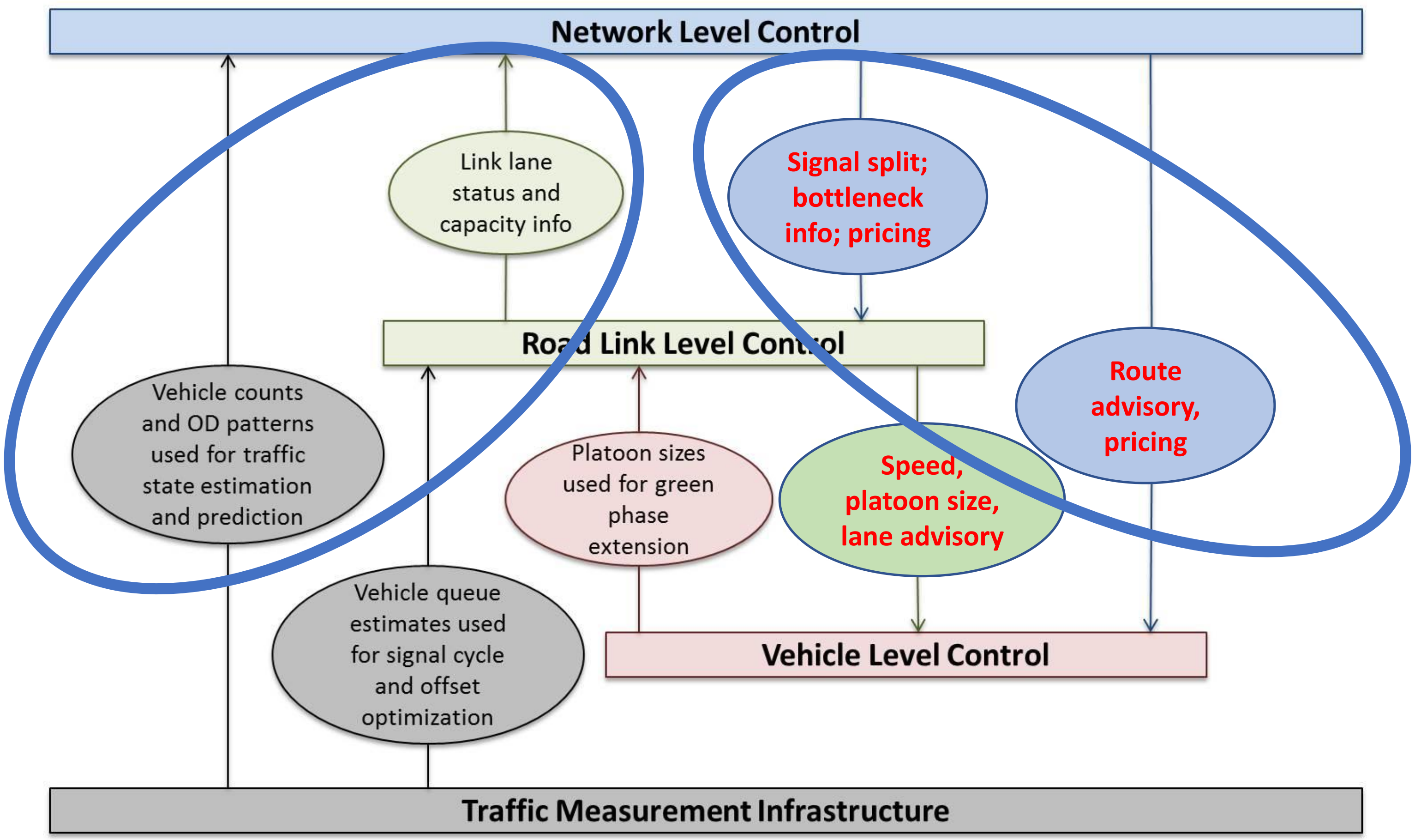




J. Lioris, et al. 2017.

- Platooning can decrease vehicle headway
- It can also increase saturation flow rates at intersections by 50%
- Roadway capacity can be increased by 50%

Traffic Operating System (TOS)
NSF – CPS (Horowitz, Arcak Varaiya)



Effect of *Smart Vehicles* on the traffic network systems

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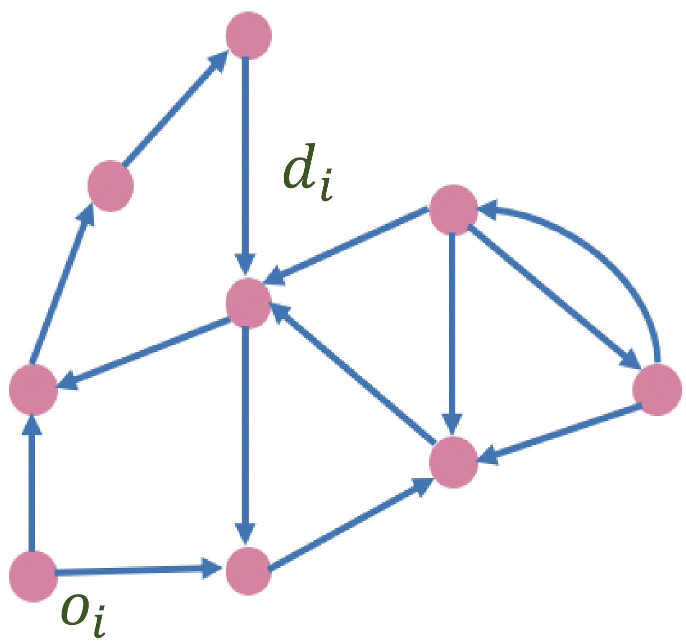
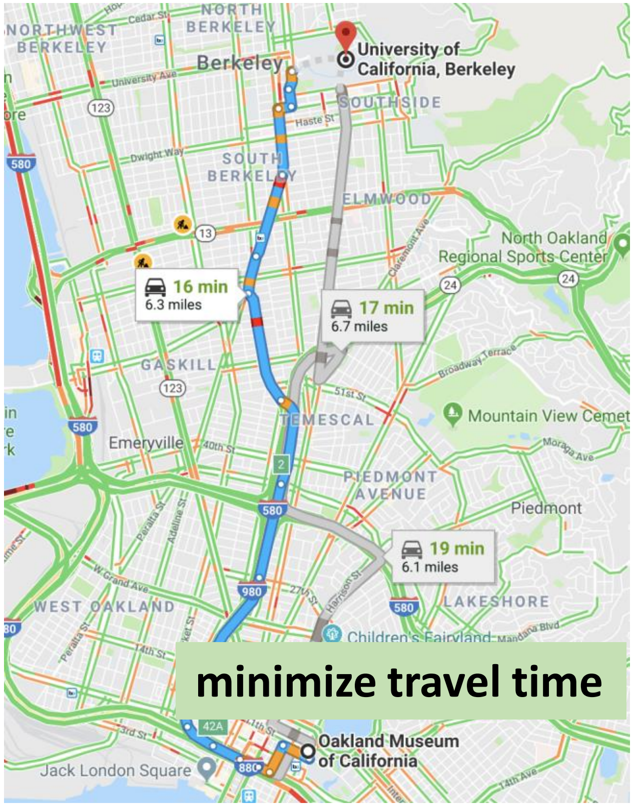
Smart Vehicle Gradual Deployment

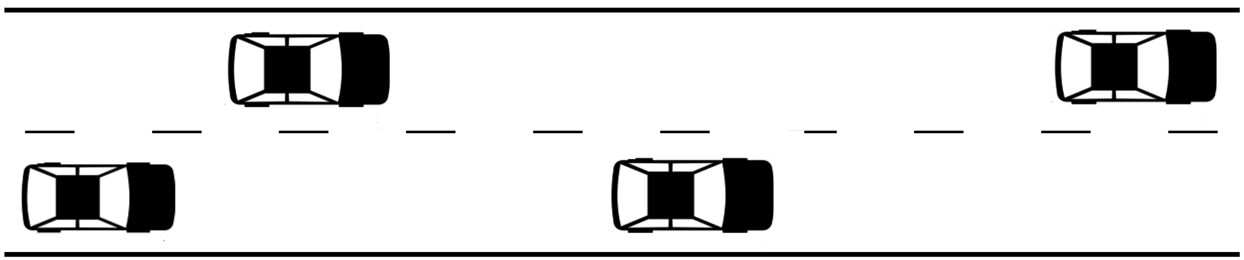
- **Can increases in roadway capacity translate into increases in traffic network throughput?**





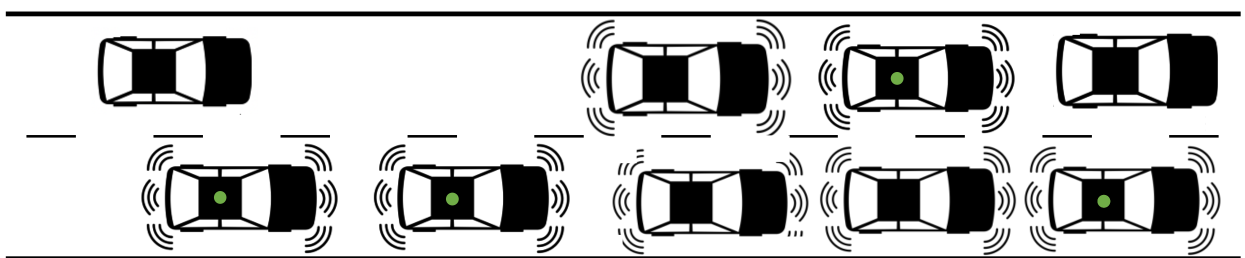
- **Vehicles select their routes *selfishly*.**

Does replacing a fraction of vehicles with smart vehicles *improve* the social delay of the network?



f_l^r

regular vehicle flow

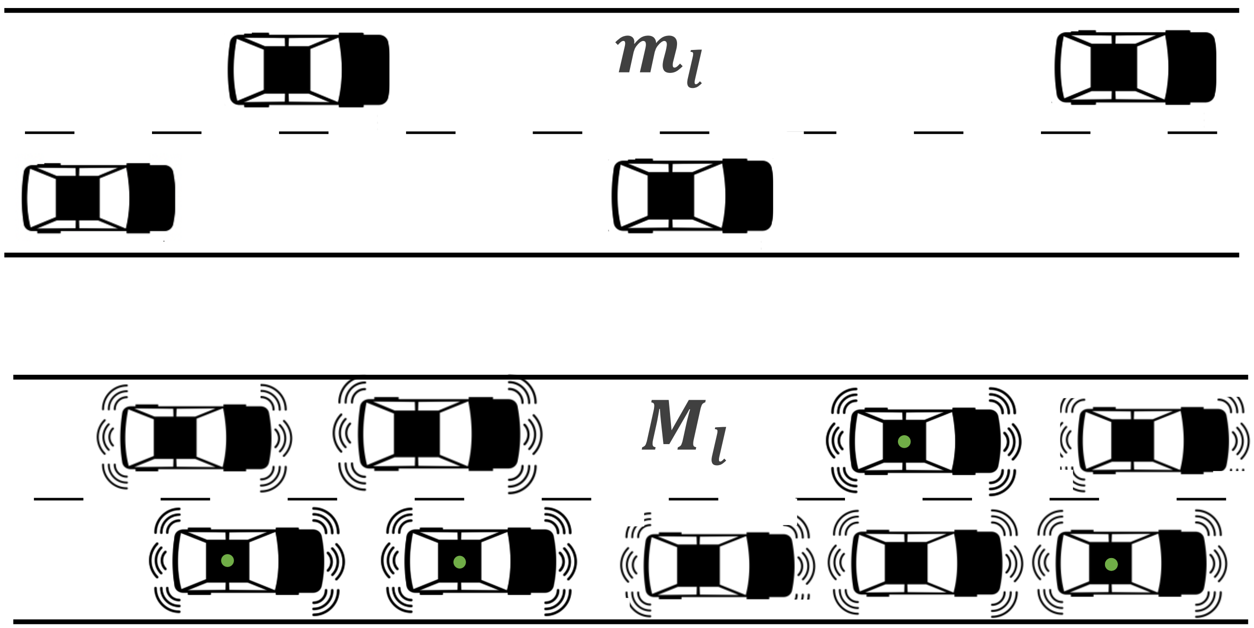


$f_l^r + f_l^s$

mixed vehicle flow

$$\alpha_l := \frac{f_l^s}{f_l^s + f_l^r}$$ Autonomy fraction on link l

Assume that smart vehicles *increase* road capacity



m_l

regular vehicle capacity

M_l

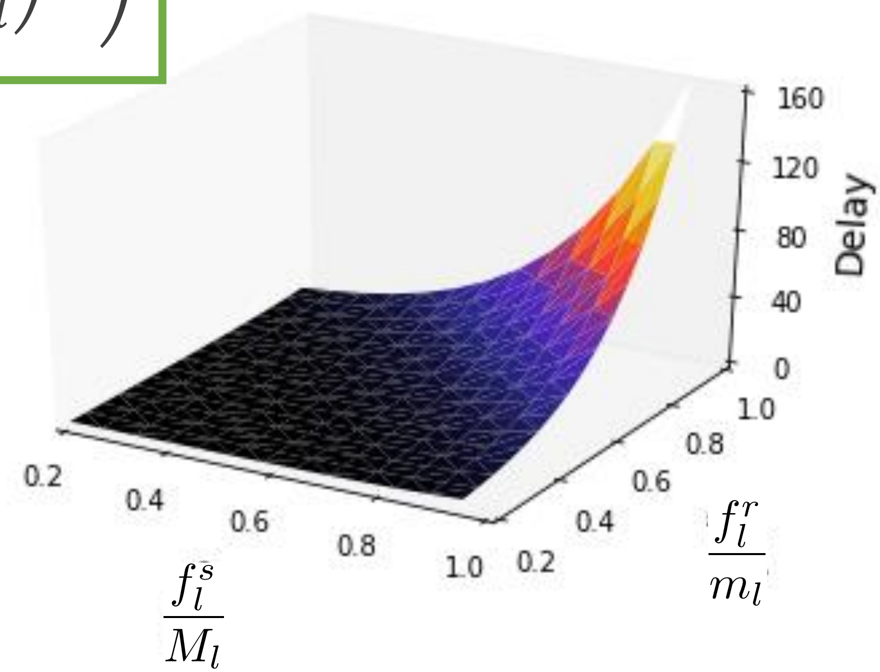
smart vehicle capacity

$\mu := \frac{m_l}{M_l}$ degree of capacity asymmetry of link l

Mixed Traffic Delay Characterization

BPR link delay function

$$e_l(f_l^r, f_l^s) = a_l\left(1 + \gamma_l\left(\frac{f_l^s}{M_l} + \frac{f_l^r}{m_l}\right)^{\beta_l}\right)$$



m_l: regular vehicle capacity

M_l: smart vehicle capacity

D. Lazar, et al.. 2017

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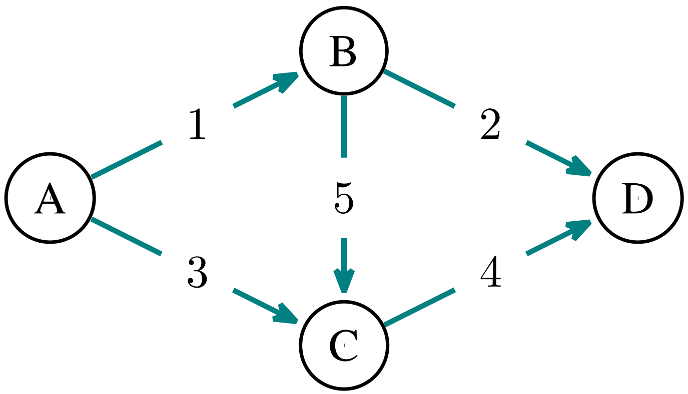
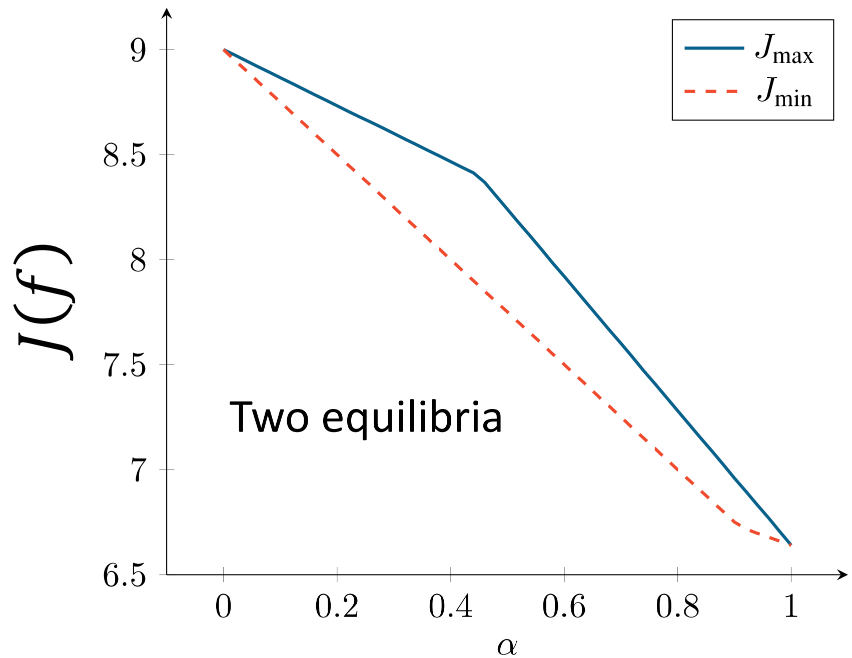
Mixed Traffic User Equilibrium

Social delay as a function of autonomy fraction



Single O/D pair – A/D



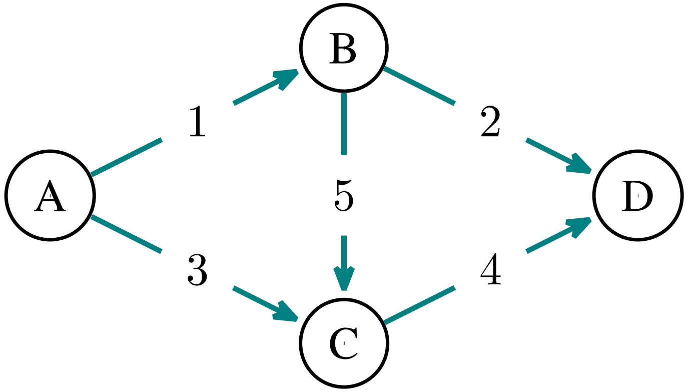
In this example, social delay decreases as the fraction of autonomous vehicles increases.

$$\alpha_l := \frac{f_l^s}{f_l^s + f_l^r}$$

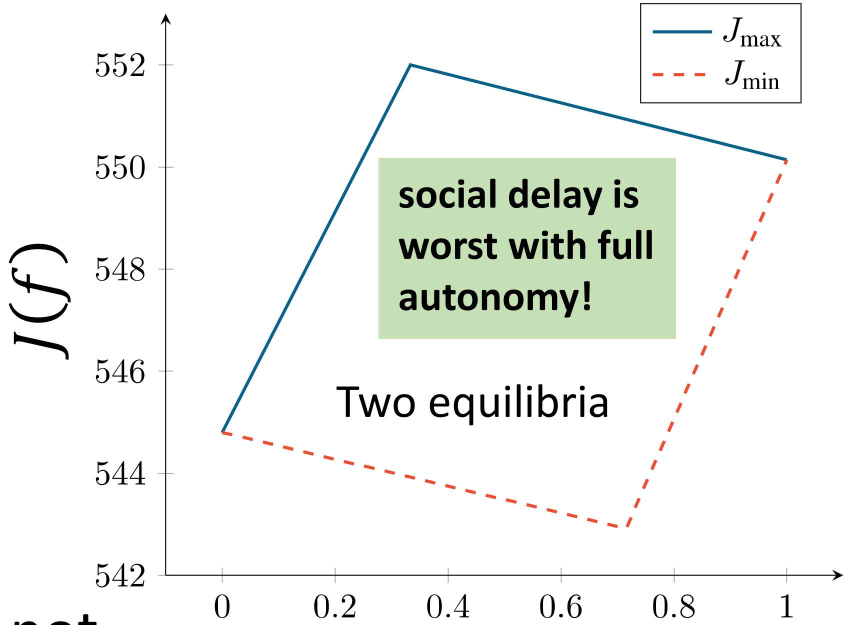
Mehr et al. CDC 2018

Mixed Traffic User Equilibrium

Social delay as a function of autonomy fraction



Single O/D pair – A/D



$$\alpha_l := \frac{f_l^s}{f_l^s + f_l^r}$$

In this example, social delay does not decrease monotonically as the fraction of autonomous vehicles increases.

Braess' paradox

Mehr et al. CDC 2018

Homogenous Networks with a Single O/D Pair

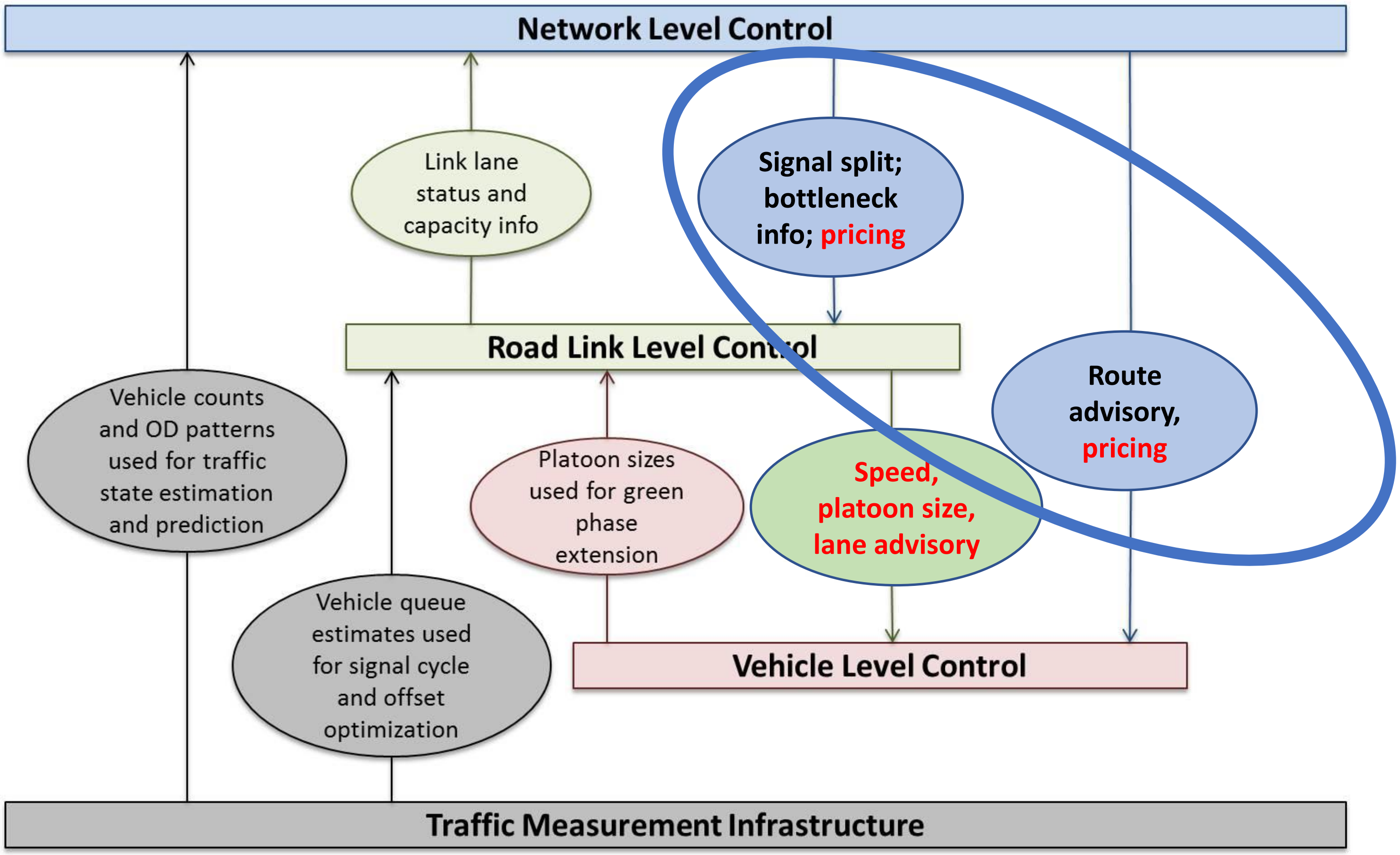
Theorem : Given a network $G = (N, L, W)$ with an **homogenous degree of capacity asymmetry $\boldsymbol{\mu}$**, for any demand $r \geq 0$, we have:

For a fixed $0 \leq \alpha \leq 1$, the social delay $J(f)$ is **unique** for all equilibrium flow vectors f.

The social network delay $J(.)$ is a **continuous** and **non-increasing** function of the **autonomy fraction $\boldsymbol{\alpha}$**.

Increasing the fraction of smart vehicles will enhance network performance when their impact is uniform throughout all roadways.

Traffic Operating System (TOS)



Pricing Traffic Networks with Mixed Autonomy

Use road tolling as a network traffic management scheme

Pricing Traffic Networks with Mixed Autonomy

- Vehicles select their routes ***selfishly***.

- User equilibria do not always yield the lowest social delay.

- Use ***road tolling*** as a network traffic management scheme so that:

  user equilibria will yield the lowest social delay.

Mehr, et al. ACC 2019

Differentiating tolling achieves a minimum social delay

Theorem : Given a network $G = (N, L, W)$ with an **homogenous degree of capacity asymmetry** $\boldsymbol{\mu}$

Let f^* be the optimal flow vector that achieves the **minimum** social delay J^*

$$f^* = \arg\left[\min_f \sum_{p \in \mathcal{P}} f_p e_p(f)\right]$$

There exists a differential **tolling scheme** such that all induced Wardrop **cost** equilibria attain the **minimum** social delay J^*

Mehr, et al. ACC 2019

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Optimal differentiated **tolling scheme**

$$\tau_l^r = (f_l^{r*} + f_l^{s*})\left(\frac{\partial}{\partial f_l^r} e_l(f_l^r, f_l^s)\right)\Big|_{f_l^*}$$

$$\tau_l^s = (f_l^{r*} + f_l^{s*})\left(\frac{\partial}{\partial f_l^s} e_l(f_l^r, f_l^s)\right)\Big|_{f_l^*}$$

Details: **ThB02** **Traffic Control**, Franklin 2

14:50-15:10, Paper ThB02.5

Pricing Traffic Networks with Mixed Vehicle Autonomy

by Negar Mehr and Roberto Horowitz

Summary

- Traffic systems exhibit very interesting complex behavior
- Sensing is key! – currently not sufficient sensing is available
- We can deploy sophisticated traffic estimation and management techniques
- Smart (autonomous and connected) vehicles can make traffic network management even more challenging
- Pricing can be an effective traffic management technique

Acknowledgements

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- CALTRANS
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