Spring 2025

12 Emerging Topic II: Autonomous vehicles

CIVIL-477 Transportation network modeling & analysis

École polytechnique fédérale de Lausanne

Overview

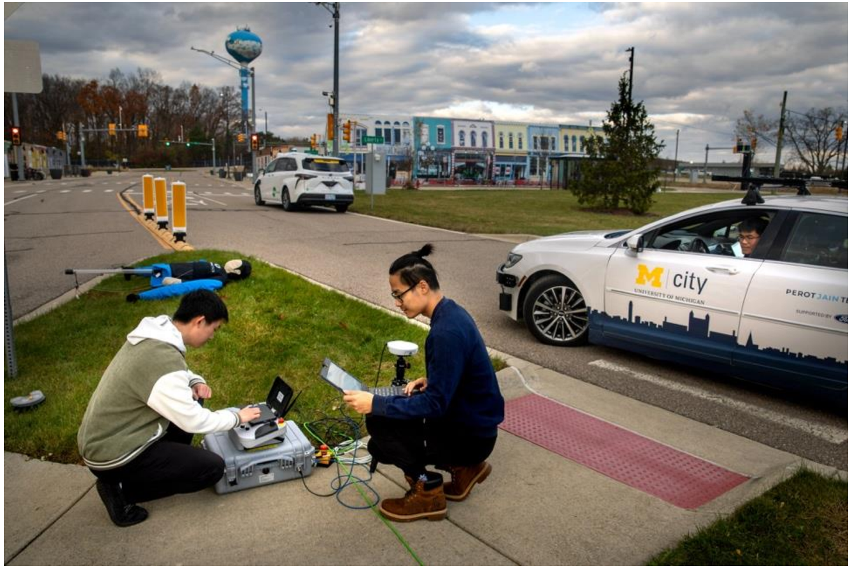
- History and state-of-art of autonomous driving
  - Earliest developments
    - 1961 Remote-control lunar rover developed at Stanford
    - 1977 Semi-autonomous car developed at Tsukuba Mechanical Engineering Laboratory
    - 1980-1990 VaMoRs (Visual Autonomous Mobile Robot System) with a full vision system developed at Bundeswehr University Munich

Stanford Cart

VaMoRs

Overview

- History and state-of-art of autonomous driving
  - Recent advances
    - 2015 Tesla Autopilot: Adaptive cruise control for highway driving
    - 2015 MCity: AV test field by University of Michigan



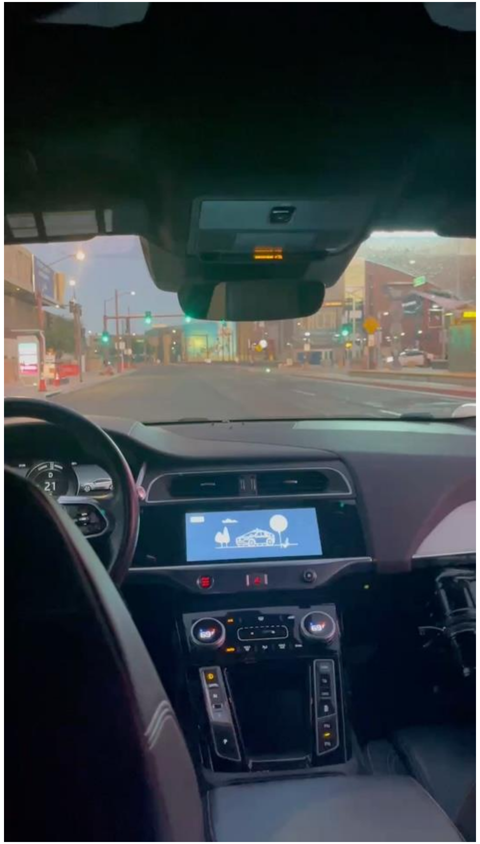
M City, Michigan

Overview

- History and state-of-art of autonomous driving
  - Recent advances
    - 2017 Waymo: Robotaxi with a backup driver
    - 2018-2020 Launch of several robotaxi and robodelivery services in US cities

Waymo

Nuro



Waymo in Pheonix

Overview

- History and state-of-art of autonomous driving
  - Levels of automation

- Adaptive cruise control
- Lane-keeping

- Traffic jam pilot

Mercedes-Benz HONDA AUDI

0	1	2	3	4	5
NO AUTOMATION	DRIVER ASSISTANCE	PARTIAL AUTOMATION	CONDITIONAL AUTOMATION	HIGH AUTOMATION	FULL AUTOMATION
Manual control. The human performs all driving task (steering, acceleration, braking etc).	The vehicle features a single automated system (e.g. it monitors speed through cruise).	ADAS. The vehicle can perform steering and acceleration. The human still monitors all tasks and can take control at any time.	Environmental dectection capabilities. The vehicle can perform most driving tasks, but human override is still required.	The vehicle performs all driving tasks under specific circumstances. Geofencing is required. Human override is still an option.	The vehicle performs all driving tasks under all conditions. Zero human attention or interaction is required.

The human monitors the driving environment (levels 0–2) | The automated system monitors the driving enviroment (levels 3–5)

Overview

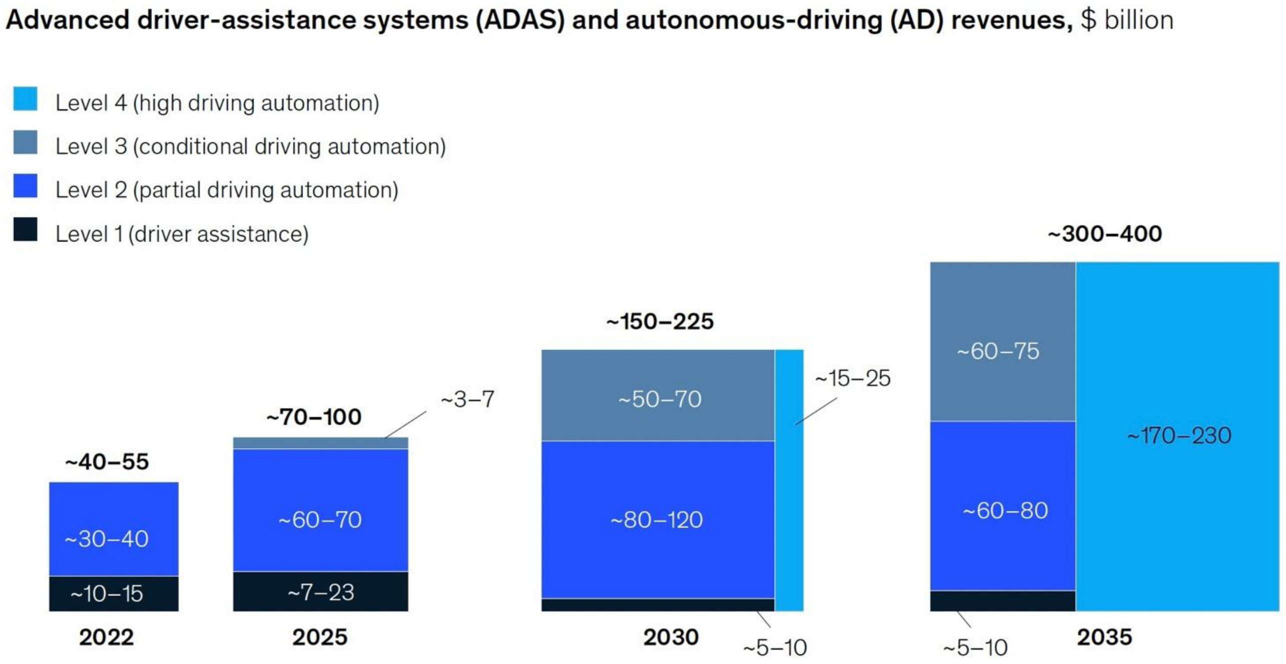
- History and state-of-art of autonomous driving
  - Levels of automation

- Robotaxi (WAYMO, apollo)

0	1	2	3	4	5
NO AUTOMATION	DRIVER ASSISTANCE	PARTIAL AUTOMATION	CONDITIONAL AUTOMATION	HIGH AUTOMATION	FULL AUTOMATION
Manual control. The human performs all driving task (steering, acceleration, braking etc).	The vehicle features a single automated system (e.g. it monitors speed through cruise).	ADAS. The vehicle can perform steering and acceleration. The human still monitors all tasks and can take control at any time.	Environmental dectection capabilities. The vehicle can perform most driving tasks, but human override is still required.	The vehicle performs all driving tasks under specific circumstances. Geofencing is required. Human override is still an option.	The vehicle performs all driving tasks under all conditions. Zero human attention or interaction is required.
The human monitors the driving environment			The automated system monitors the driving enviroment		

Overview

- History and state-of-art of autonomous driving
  - $300-400 billion in revenue by 2035 (McKinsey, 2023)

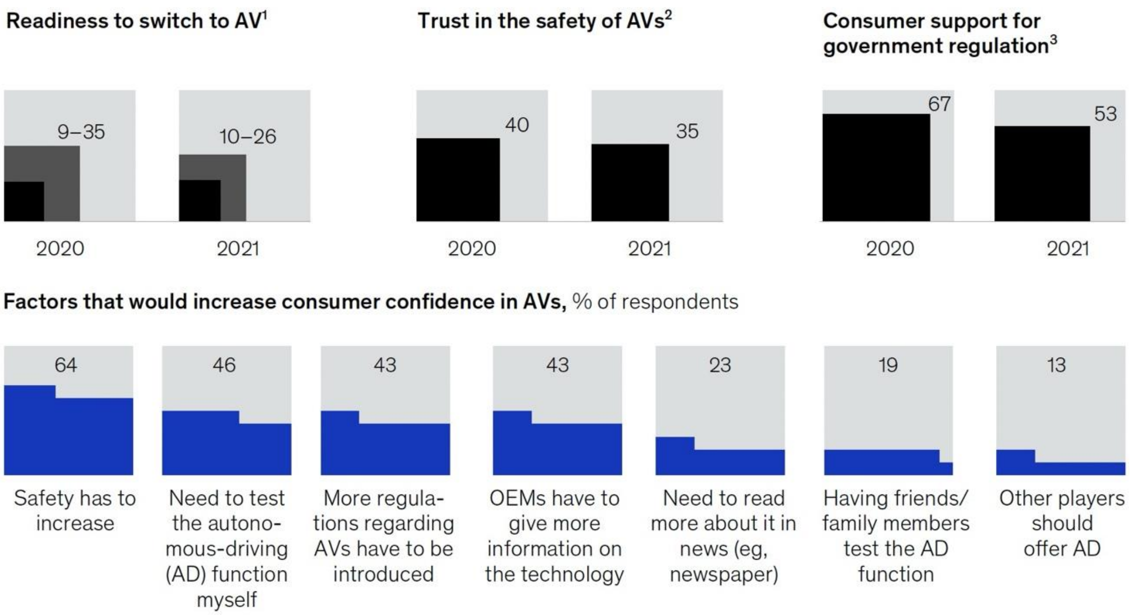


Source: McKinsey Center for Future Mobility

Overview

- Key factors and impacts on urban transportation systems
  - Mixed traffic of human-driven vehicles and AVs for a long time

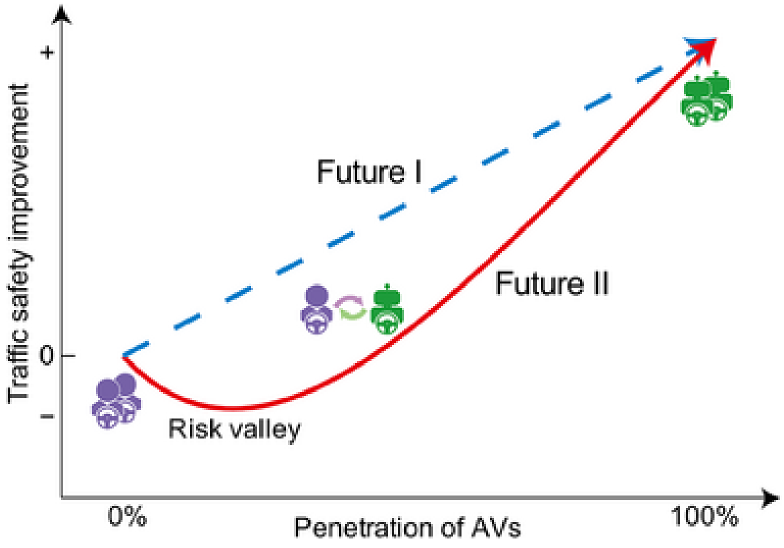
Indicators of consumer interest in owning fully autonomous vehicles (AVs), % of respondents



[1]Question: If the car maker of your choice offered a fully autonomous car, would you want to keep your old car or switch at the same costs? Answers included "I would definitely switch to a fully autonomous car" or "I would rather switch to a fully autonomous car."
[2]Responses to the statement: I would feel good with my family members driving in a fully autonomous car.
[3]Question: Do you think the government should legalize fully autonomous vehicles on all roads?
Source: McKinsey Center for Future Mobility ACES Consumer Survey, Dec 2021, n = 26,285

Overview

- Key factors and impacts on urban transportation systems
  - Mixed traffic of human-driven vehicles and AVs for a long time
  - Road safety is expected to improve with a wide adaption of AVs
    - 94% of highway deaths are attributed to human errors
    - First reported pedestrian killed by Uber AV in 2018



Overview

- Key factors and impacts on urban transportation systems
  - Mixed traffic of human-driven vehicles and AVs for a long time
  - Road safety is expected to improve with a wide adaption of AVs
  - Private “driving” will become less stressful and more enjoyable
    - Provide mobility solution to those who cannot drive
  - Private vehicle ownership will possibly be replaced by a subscription of AV service
    - e.g., Tesla’s vision of cybercab city

Overview

- Influences on traffic congestion

  - Induce more vehicle trips due to cost saving and enhanced mobility
  - More cruising traffic due to self-parking

  https://www.youtube.com/watch?v=nvbZK6Yf5PA

  - Smooth traffic flow and prevent ”phantom congestion”
  - Increase road capacity by reducing car following gap
  - Enable adaptive traffic control and management

  https://www.youtube.com/watch?v=Suugn-p5C1M

Outline

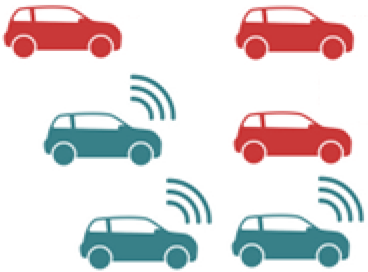
- Traffic dynamics
  - Road capacity enhancement
- Route control
  - System optimum (SO) and fleet optimum (FO)
- Dedicated infrastructures
  - AV lane and AV zone

Link capacity with AVs

- From microscopic behaviors to macroscopic modeling

Reaction time ⇨ **Min car-following distance**

0.5-1.5 sec **< 0.1 sec**

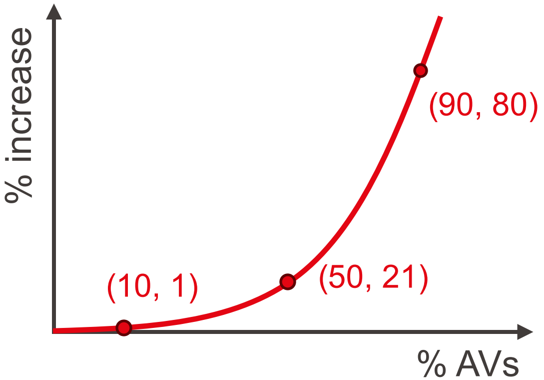


2-3 sec

0.5-1 sec

< 0.5 sec

⇨ **Road capacity**



Link capacity with AVs

- Revised BPR function
  - Link travel time

$$t = t_0 \left[1 + 0.15 \left(\frac{x}{s} \right)^4 \right]$$

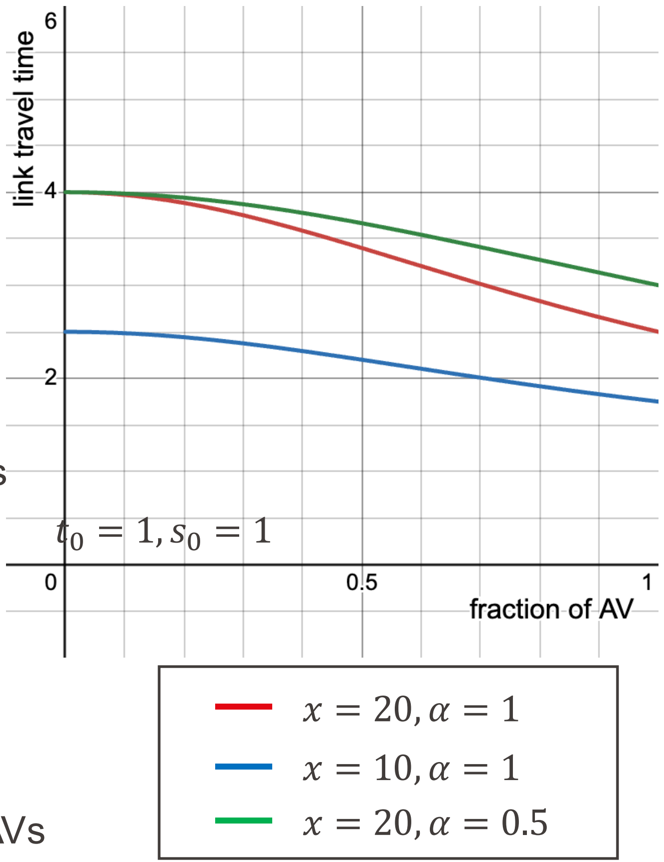
    - t_0: free-flow link travel time
  - Total link flow

$$x = x_{HV} + x_{AV}$$

    - x_{HV}, x_{AV}: link flow of human-driven (HV) vehicles and AVs
  - Link capacity

$$s = s_0(1 + \alpha r^2)$$

    - s_0: base link capacity (all HVs)
    - $r = x_{AV}/x$: fraction of AVs
    - $\alpha = s_{AV}/s_0 - 1$: capacity improvement with all AVs



Link capacity with AVs

- Equilibrium conditions

$$(\mathbf{f}^*)^T(\mathbf{c}^* - \Lambda^T\mu^*) = 0$$ **Complementary condition of path flows**

$$\mathbf{c}^* - \Lambda^T\mu^* \geq \mathbf{0}$$ **Min path cost**

$$\Lambda\mathbf{f}^* = \mathbf{q}$$ **Demand flow conservation**

$$\mathbf{f}^* \geq \mathbf{0}$$ **Path flow feasibility**

  - Demand flow $\mathbf{q} = [\mathbf{q}_{HV}, \mathbf{q}_{AV}]$
  - Path flow $\mathbf{f} = [\mathbf{f}_{HV}, \mathbf{f}_{AV}]$

- ***Q: Which traffic assignment extension this problem belong to?***

Link capacity with AVs

- Equilibrium conditions

$(\mathbf{f}^*)^T(\mathbf{c}^* - \Lambda^T\mu^*) = 0$	**Complementary condition of path flows**
$\mathbf{c}^* - \Lambda^T\mu^* \geq \mathbf{0}$	**Min path cost**
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  - Demand flow $\mathbf{q} = [\mathbf{q}_{HV}, \mathbf{q}_{AV}]$
  - Path flow $\mathbf{f} = [\mathbf{f}_{HV}, \mathbf{f}_{AV}]$

- ***Q: Which traffic assignment extension this problem belong to?***
  - Heterogenous users

$$t_a^{HV}(x_a^{HV}, x_a^{AV}) = t_a^{AV}(x_a^{AV}, x_a^{HV}) = t_0\left[1 + 0.15\left(\frac{x_a^{AV} + x_a^{HV}}{s_a(x_a^{AV}, x_a^{HV})}\right)^4\right]$$

Link capacity with AVs

- Symmetry of link interactions

  For $k \in \{HV, AV\}$,

$$\frac{\partial t_a}{\partial x_a^k} = \frac{\partial}{\partial x_a^k}\left\{t_0\left[1 + 0.15\left(\frac{x_a^{AV} + x_a^{HV}}{s_a}\right)^4\right]\right\}$$

$$= 0.6t_0\left(\frac{x_a}{s_a}\right)^3 \frac{\partial}{\partial x_a^k}\left(\frac{x_a^{AV} + x_a^{HV}}{s_a}\right)$$

$$= 0.6t_0\left(\frac{x_a}{s_a}\right)^3 \frac{1}{s_a^2}\left[s_a - (x_a^{AV} + x_a^{HV})\frac{\partial s_a}{\partial x_a^k}\right]$$

- Jacobian matrix of link costs $\nabla\mathbf{t}(\mathbf{x})$ is symmetric iff $\nabla\mathbf{s}(\mathbf{x})$ is symmetric
- ***Q: Does this symmetry condition hold?***

Link capacity with AVs

- Symmetry of link interactions

For $k \in \{HV, AV\}$,

$$\frac{\partial s_a}{\partial x_a^k} = \frac{\partial}{\partial x_a^k}\left\{s_{0,a}\left[1 + \alpha\left(\frac{x_a^{AV}}{x_a}\right)^2\right]\right\} = 2\alpha s_{0,a}\frac{\partial}{\partial x_a^k}\left(\frac{x_a^{AV}}{x_a}\right)$$

$$\frac{\partial s_a}{\partial x_a^{HV}} = \frac{2\alpha s_{0,a}}{x_a^2}\left(-x_a^{AV}\right)$$

$$\frac{\partial s_a}{\partial x_a^{AV}} = \frac{2\alpha s_{0,a}}{x_a^2}\left(x_a - x_a^{AV}\right) = \frac{2\alpha s_{0,a}}{x_a^2}\left(x_a^{HV}\right)$$

- Jacobian matrix of link costs $\nabla\mathbf{t}(\mathbf{x})$ is asymmetric because $\nabla\mathbf{s}(\mathbf{x})$ is asymmetric

Link capacity with AVs

- Symmetry of link interactions

For $k \in \{HV, AV\}$,

$$\frac{\partial s_a}{\partial x_a^k} = \frac{\partial}{\partial x_a^k}\left\{s_{0,a}\left[1+\alpha\left(\frac{x_a^{AV}}{x_a}\right)^2\right]\right\} = 2\alpha s_{0,a}\frac{\partial}{\partial x_a^k}\left(\frac{x_a^{AV}}{x_a}\right)$$

$$\frac{\partial s_a}{\partial x_a^{HV}} = \frac{2\alpha s_{0,a}}{x_a^2}\left(-x_a^{AV}\right)$$

*** Link capacity increases with x_a^{AV} but decreases with x_a^{HV}**

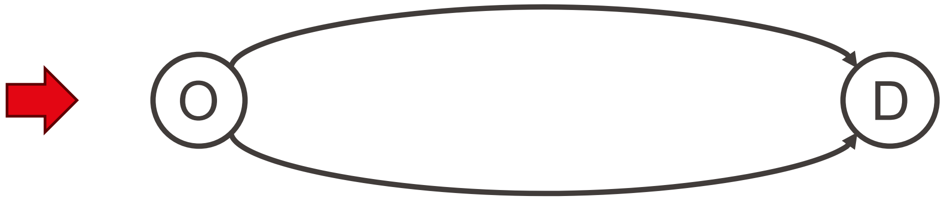
$$\frac{\partial s_a}{\partial x_a^{AV}} = \frac{2\alpha s_{0,a}}{x_a^2}\left(x_a - x_a^{AV}\right) = \frac{2\alpha s_{0,a}}{x_a^2}\left(x_a^{HV}\right)$$

- Jacobian matrix of link costs $\nabla \mathbf{t}(\mathbf{x})$ is not only asymmetric but also non-monotone
  - there may exist multiple equilibria $[\mathbf{f}_{HV}^*, \mathbf{f}_{AV}^*]$

Link capacity with AVs

- Case study
  - A network with single OD and two parallel links

$$q_{HV} = 1$$
$$q_{AV} = 1$$



- Link travel time
  - $t_0 = 1$

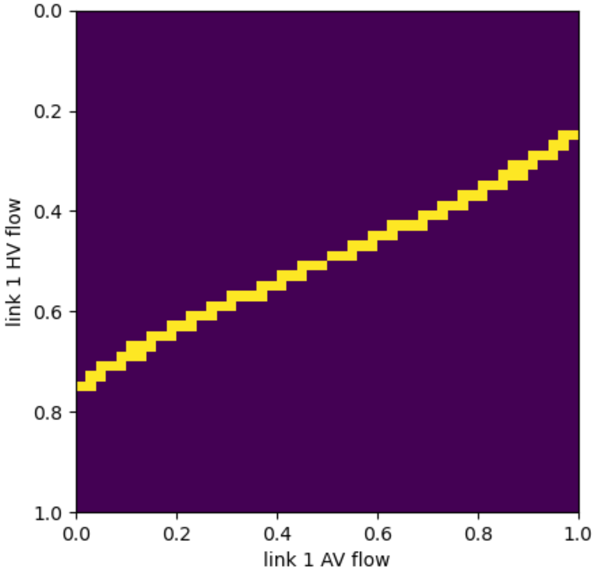
$$t_a = 1 + 0.15\left(\frac{x_a^{HV} + x_a^{AV}}{s_a}\right)^4$$

- Link capacity
  - $s_0 = \alpha = 1$

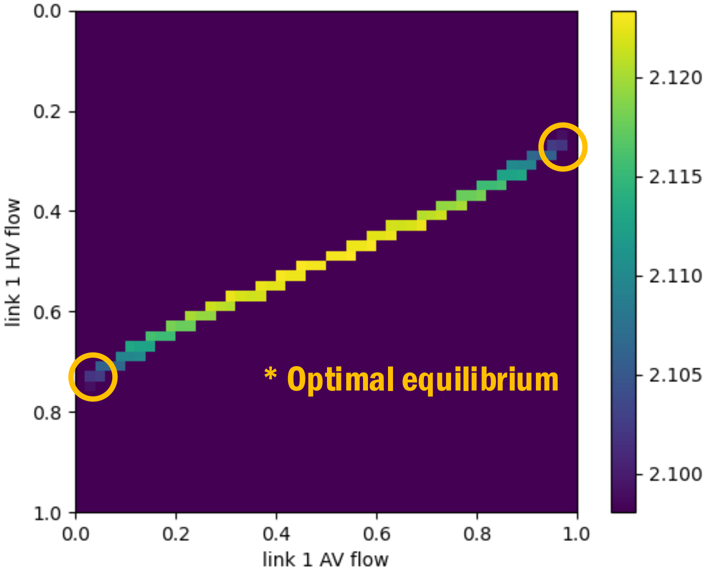
$$s_a = 1 + \left(\frac{x_a^{AV}}{x_a^{HV} + x_a^{AV}}\right)^2$$

Link capacity with AVs

- Case study
  - Multiple equilibria with different total travel time



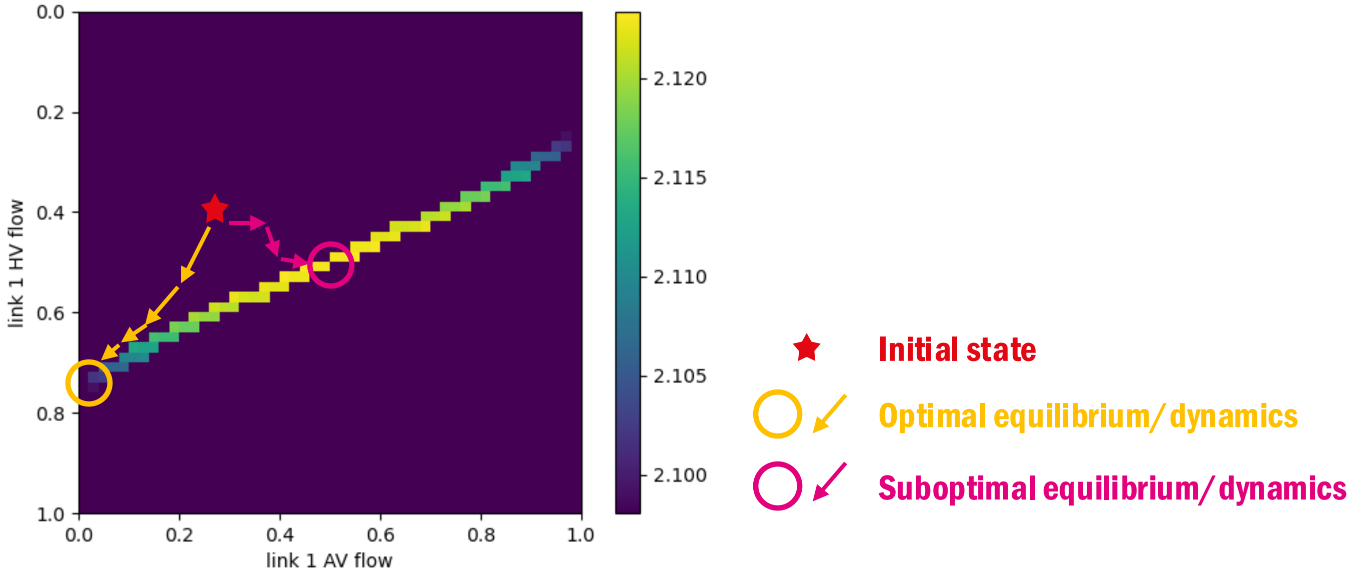
Equilibrium



Equilibrium total travel time

Link capacity with AVs

- Case study
  - Multiple equilibria with different total travel time
  - Induce optimal equilibrium via different day-to-day dynamics



Equilibrium total travel time

Questions?

Outline

- Traffic dynamics
  - Road capacity enhancement
- Route control
  - System optimum (SO) and fleet optimum (FO)
- Dedicated infrastructures
  - AV lane and AV zone

Routing of AVs

- Mixed traffic equilibrium with HVs and AVs
  - Different impacts on link travel time

$$t = t_0 \left[1 + 0.15 \left(\frac{x_{HV} + x_{AV}}{s} \right)^4 \right]$$

$$s = s_0 \left[1 + \alpha \left(\frac{x_{AV}}{x_{HV} + x_{AV}} \right)^2 \right]$$

  - Different routing principle
    - HV as UE travelers
      - choose route to min self travel time
    - AV as SO travelers
      - choose route to min total travel time

    - ***Q: How to model this traffic assignment problem?***

Routing of AVs

- Mixed traffic equilibrium with HVs and AVs
  - Different impacts on link travel time

$$t = t_0 \left[1 + 0.15 \left(\frac{x_{HV} + x_{AV}}{s} \right)^4 \right]$$

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  - Different routing principle
    - HV as UE travelers
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Routing of AVs

- Equilibrium conditions

For $k \in \{HV, AV\}$,

$$(\mathbf{f}_k^*)^T(\mathbf{c}_k^* - \Lambda^T \mu_k^*) = 0$$ **Complementary condition of path flows**

$$\mathbf{c}_k^* - \Lambda^T \mu_k^* \geq \mathbf{0}$$ **Min path cost**

$$\Lambda \mathbf{f}_k^* = \mathbf{q}_k$$ **Demand flow conservation**

$$\mathbf{f}_k^* \geq \mathbf{0}$$ **Path flow feasibility**

- Path cost for HVs $\mathbf{c}_{HV} = \Delta\mathbf{t}$
- Path cost for AVs $\mathbf{c}_{AV} = \Delta\mathbf{mt}$
  - marginal link travel time

$$mt(x) = \frac{\partial x t(x)}{\partial x} = t(x) + xt'(x) = t_0\left[1 + 0.75\left(\frac{x_{HV} + x_{AV}}{s}\right)^4\right]$$

Routing of AVs

- Optimal route control of AVs
  - The higher penetration rate of AVs and the control ratio, the closer the system approaches SO

- ***Q: Is it necessary to control all AVs to min total travel time?***

Routing of AVs

- Optimal route control of AVs
  - The higher penetration rate of AVs and the control ratio, the closer the system approaches SO
  - Key idea: Only control travel flows that contribute the most to congestion

LEADER:
Traffic manager

$$\min_{\tilde{\mathbf{q}}} \; TT(\mathbf{x}^*) + \gamma \|\tilde{\mathbf{q}}\|_1$$
$$s.t. \;\; 0 \leq \tilde{\mathbf{q}} \leq \mathbf{q}_{AV}$$

- $TT(\cdot)$: total travel time
- $\tilde{\mathbf{q}}$, $\mathbf{q}_{AV}$: controlled/AV demand
- γ: weight parameter

FOLLOWERS:
Travelers w/ and w/o control

$$\langle \mathbf{T}(\mathbf{x}^*), \mathbf{x} - \mathbf{x}^* \rangle \geq 0, \qquad \forall \mathbf{x} \in \Omega_{\mathbf{x}}(\tilde{\mathbf{q}})$$

- $\mathbf{T}(\cdot)$: joint link cost function
- $\mathbf{x}^*, \mathbf{x}$: (equilibrium) link flow belong to $\Omega_{\mathbf{x}}$

Routing of AVs

- Optimal route control of AVs
  - The higher penetration rate of AVs and the control ratio, the closer the system approaches SO
  - Key idea: Only control travel flows that contribute the most to congestion

LEADER: Traffic manager

$$\min_{\tilde{\mathbf{q}}} \; TT(\mathbf{x}^*) + \gamma \left\| \tilde{\mathbf{q}} \right\|_1$$

$$s.t. \;\; 0 \leq \tilde{\mathbf{q}} \leq \mathbf{q}_{AV}$$

- $TT(\cdot)$: total travel time
- $\tilde{\mathbf{q}}$, $\mathbf{q}_{AV}$: controlled/AV demand
- γ: weight parameter

*** Balance total travel time saving and control intensity**

FOLLOWERS: Travelers w/ and w/o control

$$\langle \mathbf{T}(\mathbf{x}^*), \mathbf{x} - \mathbf{x}^* \rangle \geq 0, \qquad \forall \mathbf{x} \in \Omega_{\mathbf{x}}(\tilde{\mathbf{q}})$$

- $\mathbf{T}(\cdot)$: joint link cost function
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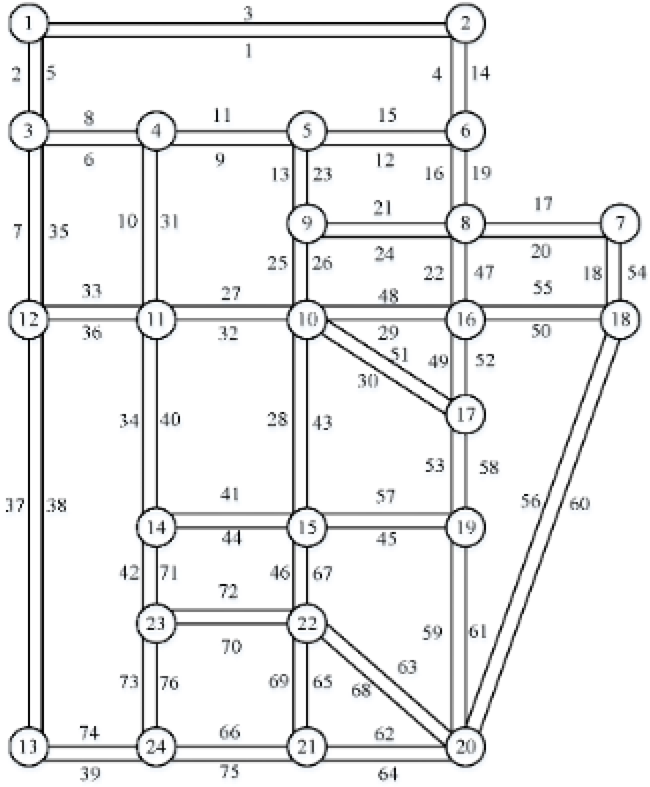
Routing of AVs

- Optimal route control of AVs
  - Sioux Falls network
    - 24 nodes, 76 links, 528 OD pairs
    - BPR function as link travel time
    - Uniform AV penetration rate

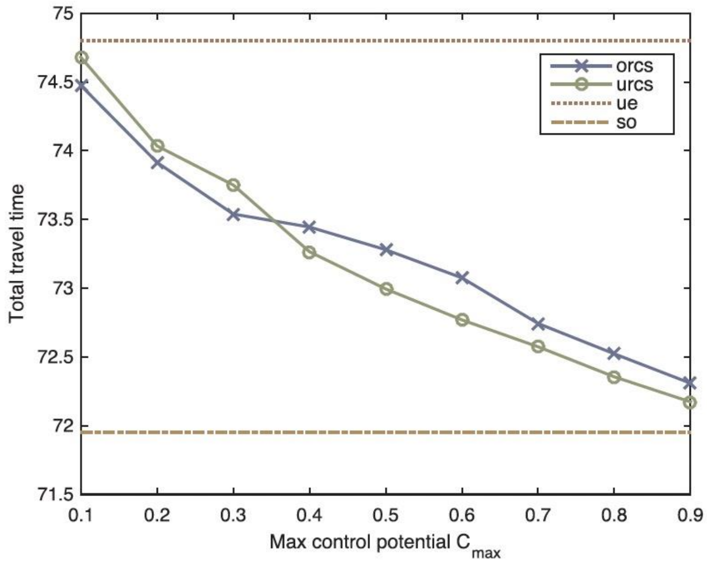
    - Test policy
      - Optimal route control scheme (ORCS)
    - Benchmark policy
      - Uniform route control scheme (URCS)
      - Same control ratio for all OD pairs



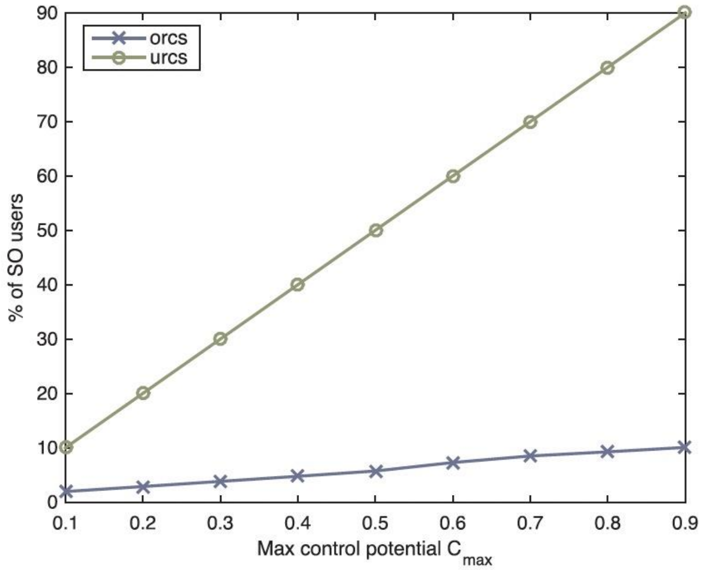
Zhang & Nie. Mitigating the impact of selfish routing: An optimal-ratio control scheme (ORCS) inspired by autonomous driving. TRC, 2018

Routing of AVs

- Optimal route control of AVs
  - Approach SO with 10% AVs being controlled



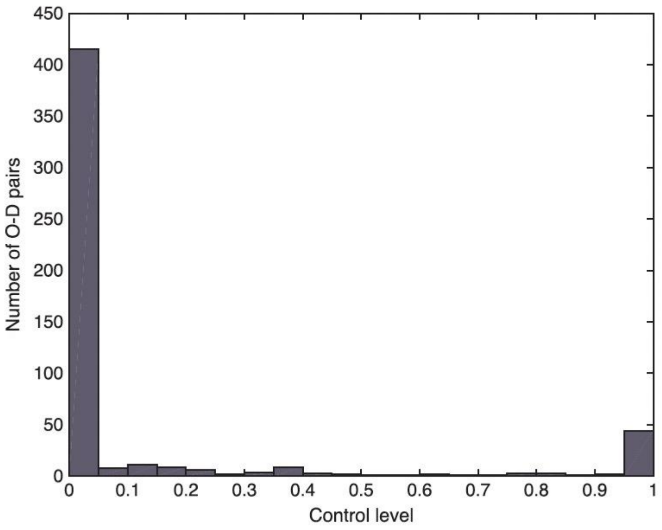
Total travel time vs AV penetration



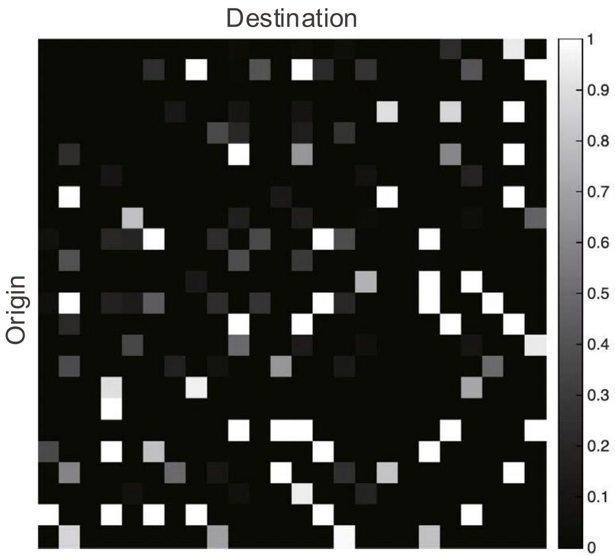
Control ratio vs AV penetration

Routing of AVs

- Optimal route control of AVs
  - Some OD pairs are selected and fully controlled, while the others are not controlled at all



Number of OD pairs vs control ratio



Control ratio by OD pair

Routing of AVs

- Optimal route control of AVs
  - What if AVs are not controlled by the traffic manager but the AV company
    - the goal is no longer min total travel time of all travelers but only AV users
  - Another mixed traffic equilibrium
    - HV as UE travelers
      - choose route to min self travel time
    - AV as fleet optimum (FO) travelers
      - choose route to min total travel time of AVs
      - path cost based on marginal link travel time wrt AV flow

$$mt_{AV}(x) = \frac{\partial x_{AV} t(x)}{\partial x_{AV}} = t(x) + x_{AV} t'(x)$$

$$= t_0 \left[1 + \left(0.15 + \frac{0.6 x_{AV}}{x_{HV} + x_{AV}} \right) \left(\frac{x_{HV} + x_{AV}}{s} \right)^4 \right]$$

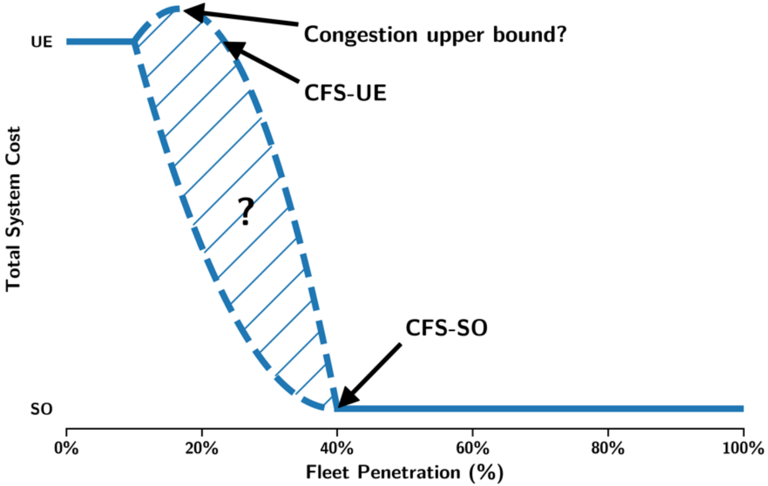
Routing of AVs

- Optimal route control of AVs
  - The higher penetration rate of AVs, the closer FO approaches SO

- ***Q: Does FO always lead to less congestion than UE?***

Routing of AVs

- Optimal route control of AVs
  - The higher penetration rate of AVs, the closer FO approaches SO
  - FO may result in more congestion when fleet penetration is low
    - Two Critical fleet sizes (CFS)
      - CFS-UE: largest fleet to maintain UE
      - CFS-SO: smallest fleet to induce SO



Total travel time vs fleet penetration

Battifarano & Qian. The impact of optimized fleets in transportation networks. TS, 2023

Questions?

Outline

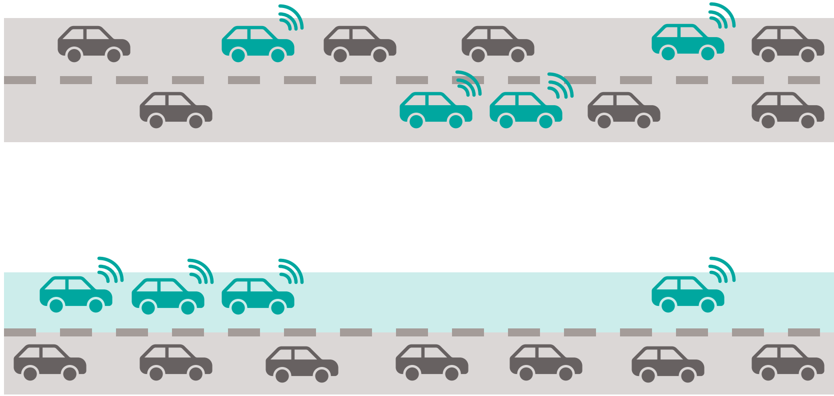
- Traffic dynamics
  - Road capacity enhancement
- Route control
  - System optimum (SO) and fleet optimum (FO)
- Dedicated infrastructures
  - AV lane and AV zone

Dedicated network for AVs

- What are AV lanes and AV zones, and why?
  - Roads and regions that only allow AVs to enter
  - Motivated by the higher driving efficiency of AVs

mixed traffic

separate traffic



- ***Q: How to model AV lanes and AV zones in traffic assignment?***

Dedicated network for AVs

- Mixed traffic equilibrium with HVs and AVs
  - Different impacts on link travel time
    - adjust link travel time function
  - Different routing principle
    - adjust definition of path cost
  - Different routing network
    - adjust accessible links and feasible paths

Dedicated network for AVs

- Optimal design of AV infrastructure

LEADER:
Network designer

$$\min_{\mathbf{z}} \; TT(\mathbf{x}^*) + \gamma g(\mathbf{z})$$
$$s.t. \; \mathbf{z} \in Z$$

- $TT(\cdot)$: total travel time
- $g(\cdot)$: construction cost
- γ: weight parameter
- Z: set of feasible designs

*** Balance total travel time saving and construction cost**

FOLLOWERS:
HVs and AVs

$$\langle \mathbf{t}(\mathbf{x}^*), \mathbf{x} - \mathbf{x}^* \rangle \geq 0, \qquad \forall \mathbf{x} \in \Omega_{\mathbf{x}}(\mathbf{z})$$

- $\mathbf{t}(\cdot)$: joint link cost function
- $\mathbf{x}^*, \mathbf{x}$: (equilibrium) link flow belong to $\Omega_{\mathbf{x}}$

*** Feasible link flows correspond to different AV network designs**

- ***Q: What is the key challenge solving this problem?***

Dedicated network for AVs

- Optimal design of AV infrastructure

LEADER:
Network designer

$$\min_{\mathbf{z}} \; TT(\mathbf{x}^*) + \gamma g(\mathbf{z})$$

$$s.t. \;\; \mathbf{z} \in Z$$

- $TT(\cdot)$: total travel time
- $g(\cdot)$: construction cost
- γ: weight parameter
- Z: set of feasible designs

*** Balance total travel time saving and construction cost**

FOLLOWERS:
HVs and AVs

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- $\mathbf{t}(\cdot)$: joint link cost function
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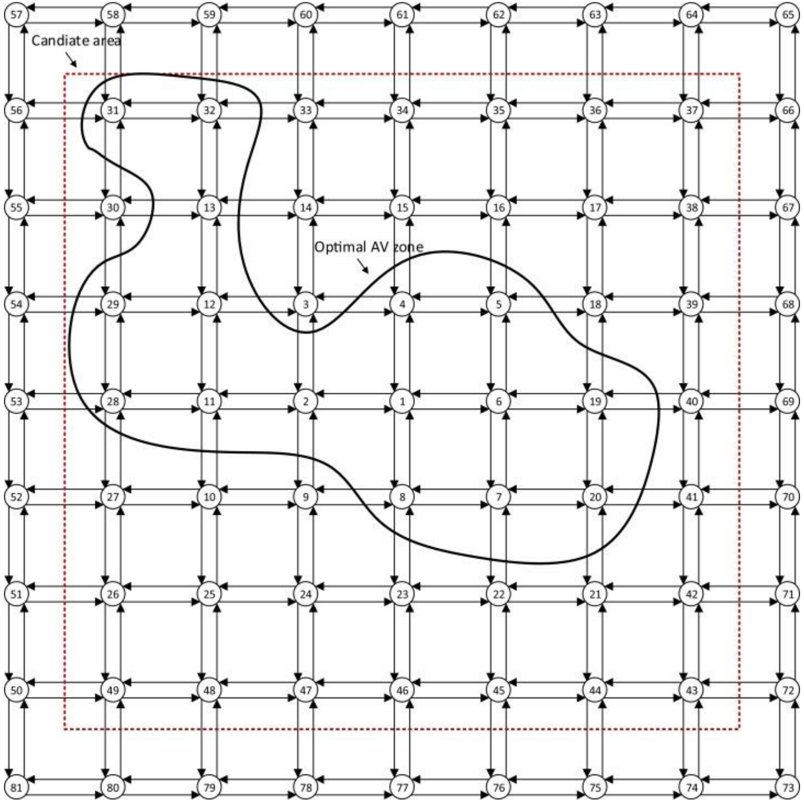
*** Feasible link flows correspond to different AV network designs**

- ***Q: What is overlooked in this formulation?***

Dedicated network for AVs

- Optimal design of AV infrastructure
  - Hypothetical grid network



Candidate zone

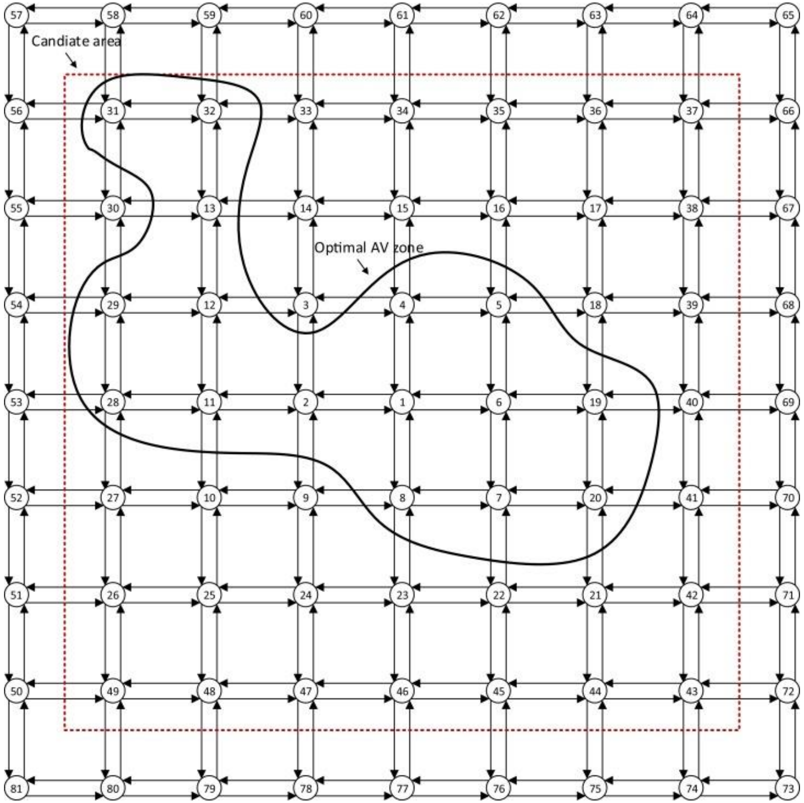
Optimal zone

Chen, et al. Optimal design of autonomous vehicle zones in transportation networks." TRB, 2017.

Dedicated network for AVs

- Optimal design of AV infrastructure
  - Hypothetical grid network

	w/o AV zone (10^6 min)	w/ AV zone (10^6 min)	
Total travel time	4.17	3.28	21%
TT inside AV zone	0.47	0.20	57%
TT outside AV zone	3.70	3.08	17%



Questions?