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Congestion Pricing in a World of Fully-Automated Vehicles (AVs): Analyzing Traffic & Traveler Behaviors

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Long-term: AVs Add Much VKT

+10% from **longer urban trips** to more distant stores & such.

+5 to 15% from **mode shifts** away from transit & walk modes.

+10% from "driving" by **under-served populations** (elderly, infirm, & youth).

+10% from **empty driving** in **Shared AVs** (SAVs).

+10% from **shift away from airline** travel on trips < 800 km.

Perhaps +10% from **land use changes**? (sprawl)

→ **VKT/capita is likely to rise > 25%**

Central Question: Can **tolling strategies** keep traffic moving while improving social welfare?

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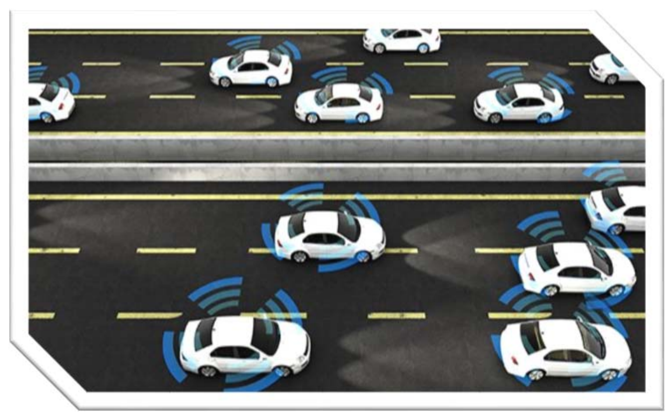
PART I
Real-time Pricing of AVs + HVs



2019 *Transp Research Record* paper with **Jooyong Lee**

Introduction

- **Automated driving** makes travel easier, adding VMT to congested networks. **Most regions need CP to keep moving**.
- **Human-driven + AV mixtures (HV vs. CACC)** & driver/vehicle behaviors will be key to traffic conditions, along with **toll levels + policies.**
- **Cooperative Adaptive Cruise Control** (CACC) = key automation technology used here, to **microscopically simulate** traffic flows (along with standard car-following choices for HVs).
- This work develops real-time **traffic-based** CP for mixtures of CACCs & HVs, to anticipate simple-**network outcomes** (for **fixed-demand with variable departure-time** examples).

Newell's Car-following Theory for HV Driving

- **HVs** use standard car-following on single-lane roadway (no passing permitted).
- If **distance to lead vehicle < min. stopping sight distance (SSD)**, HV is in **car-following mode**.
- Else, HV moves at **free-flow speed**.

$$\text{Recall that } \mathbf{SSD} = \boldsymbol{v}\,\boldsymbol{t_r} + \frac{\boldsymbol{v^2}}{\boldsymbol{2g(f_b + G)}}$$

where t_r = driver's response time (2 s assumed), g = 9.81 m/s^2, f_b = coef. of (emergency) braking friction (0.4 assumed), & G = roadway grade (0 % [flat roads] assumed here).

CACC Car-Following

Acquire & respond to info on instrumented **forward vehicles** within radio range.

$$a_{ref\_r} = a_{ld} + h(v_{ld} - v_{flw}) + (s_{flw} - s_{ref}), \ \text{(h=0.58)}$$

where a_{ld}= acceleration of the leader → Cooperative

v_{ld}= speed of the leader

v_{flw} = speed of the follower

s_{flw}= spacing between the leader & the follower

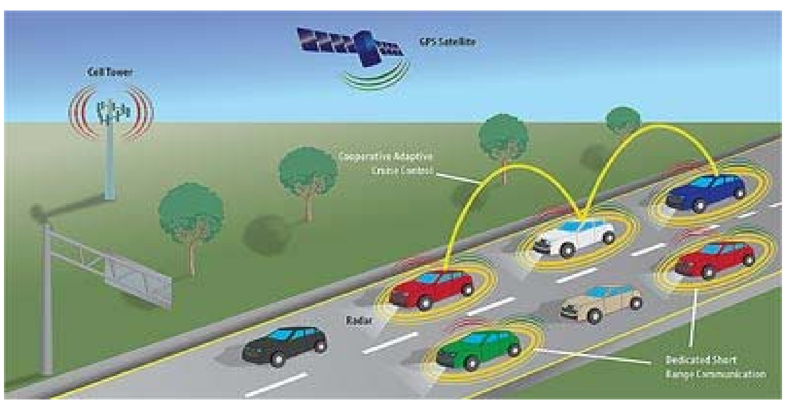
s_{ref}= reference spacing → Adaptive

$$a_{ref\_d} = k\,(v_{des} - v_{flw}), \ \text{(k=0.3)}$$

where v_{des} = desired speed

v_{flw} = current speed of the follower

→ Cruise Control

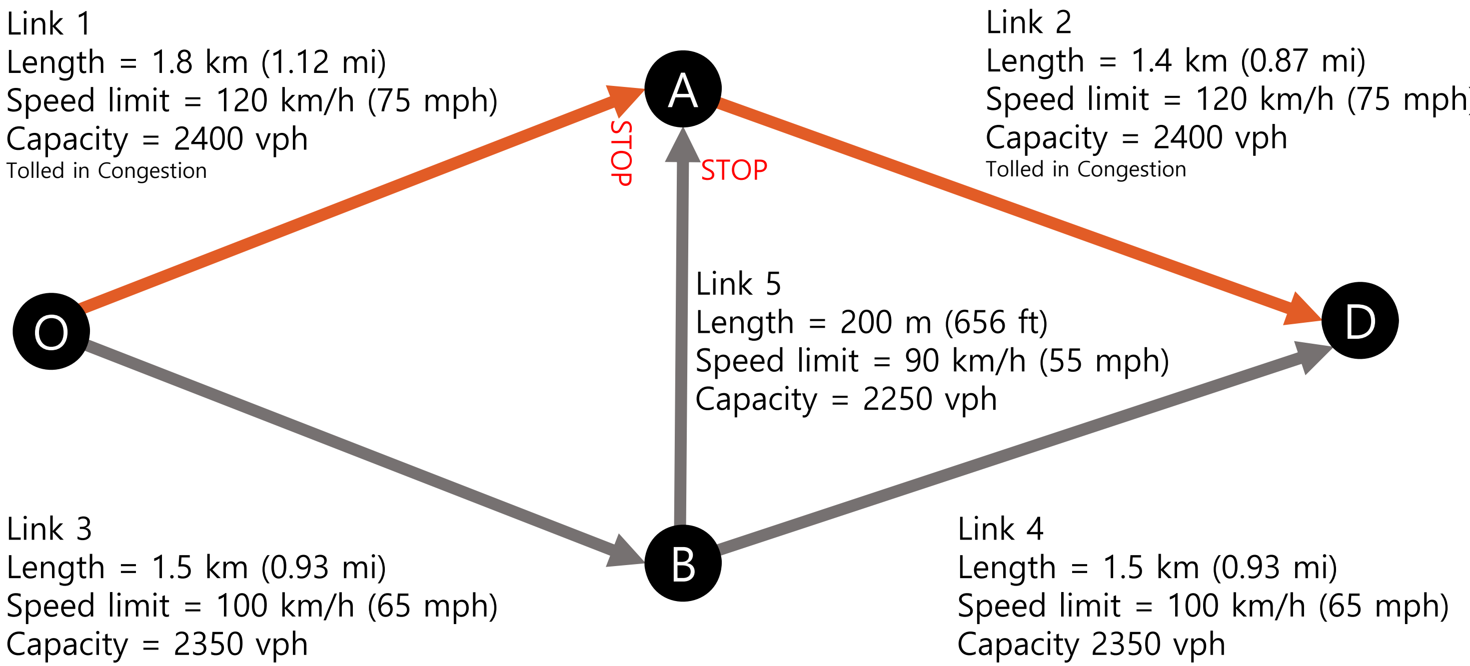


$$\therefore\ a_{flw} = \min(a_{ref\_r}, a_{ref\_d})$$

CAVs adjust speeds & positions for **safer & more efficient** driving.

Reference : Van Arem et al., 2006

Network Assumptions



$\boldsymbol{Route_1}$ = OAD $\boldsymbol{Route_2}$ = OBAD $\boldsymbol{Route_3}$ = OBD

- **3 routes** connect single OD pair. Route lengths, capacities & speed limits differ.
- **Links 1 & 2 = tolled**. So Route 1 = fully tolled, & Route 2 = partly tolled.
- **Node A = stop-controlled intersection → Delays** at Node A.
- Simulated for **1 hour of heavy traffic** → **Delays** in Node O due to heavy traffic.

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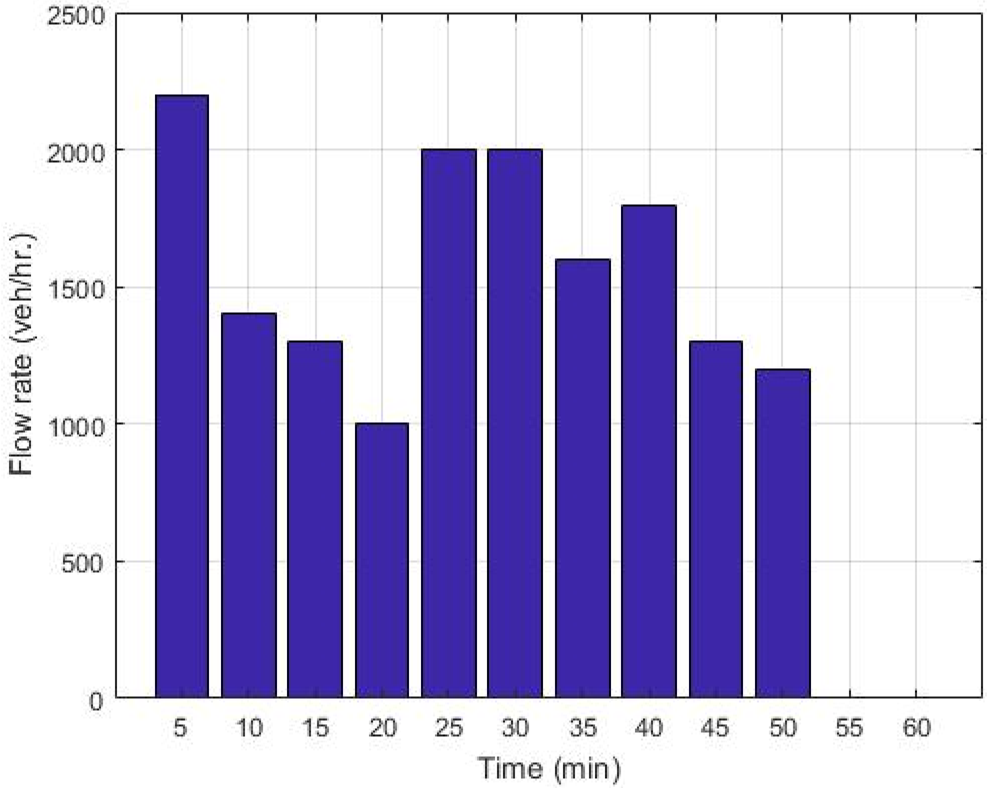
Desired Departure Time Assumptions
(but travelers can delay trips to avoid tolls)



Demand levels every 5 minutes, vary from 2200 veh/hr for 5 min, to 1400, 1300, 1000, 2000, 2000, 1600, 1800, 1300, & 1200 veh/hr.

Other Assumptions

- Network starts **empty**, & vehicles wait to enter at Node O if another vehicle has arrived first & is still occupying this node.

- **BPR function** for **running times** along each link:

$$t_i = t_{ff}\left(1 + \alpha\left(\frac{q_i}{c_i}\right)^{\beta}\right), \alpha = 0.84, \beta = 5.5$$

where t_{ff} = free-flow travel time = link length/speed limit, q_i = flow of link *i*, & c_i = capacity of link *i*

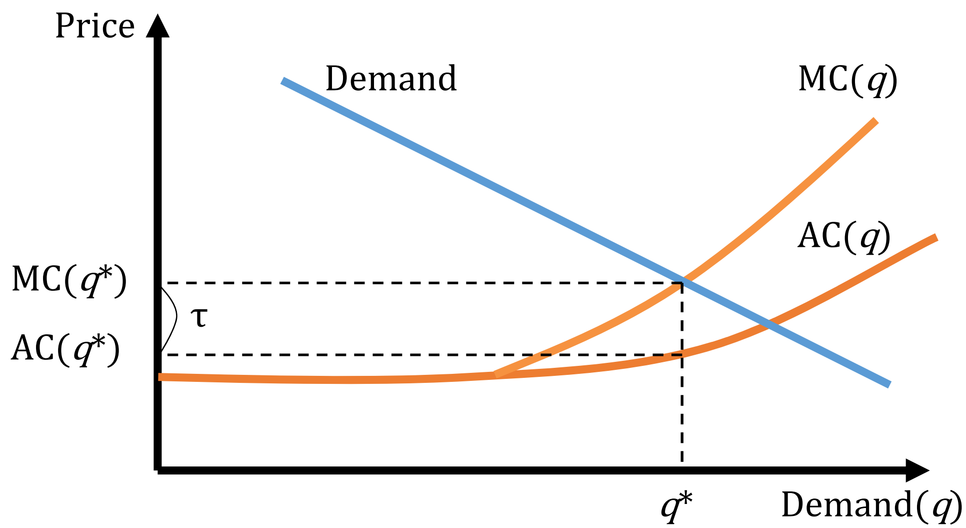
- **Total travel time** = **running time + intersection delay + network entry** wait time (if initial links are backed up).

- Travelers have **full information on current tolls & travel times** (thanks to **navigation apps**).

Values of Travel Time

- **CACC owners** are more tech-savvy, & likely have **higher VOTT** than HV drivers, on average.
- Thus, **50%** of HVs assumed to have **VOTT1 = $15/hr &** **50% VOTT2 = $7/hr**, while 64% of **CACCs** travel with **VOTT1** & just **36%** have **VOTT2.**
- **Route Choice minimizes generalized cost** to each traveler = VOTT*route travel Time + route Tolls

Marginal Social Cost Tolling



$$\mathrm{AC}(q) = \mathrm{VOTT} * \mathrm{t} = \mathrm{VOTT} * \frac{d}{v} = \frac{\mathrm{VOTT}}{v}$$

$$\mathrm{TC}(q) = q\frac{\mathrm{VOTT}}{v}$$

$$\mathrm{MC}(q) = \frac{d\mathrm{TC}(q)}{dq} = \frac{\mathrm{VOTT}}{v} - \frac{q\mathrm{VOTT}}{v^2}\frac{dv}{dq} = \mathrm{AC}(q) - \frac{q\mathrm{VOTT}}{v^2}\frac{dv}{dq}$$

$$\tau = \mathrm{MC}(q) - \mathrm{AC}(q) = -\frac{q\,\mathrm{VOTT}}{v^2}\frac{dv}{dq} = -\frac{\mathrm{VOTT}}{v}\underline{\left(\frac{q}{v}\frac{dv}{dq}\right)} \geq 0$$

Traffic stream model required

M. Li (2002) *Transp Research Part B*

Marginal Congestion Cost

- Greenshield's speed-density assumptions used here, to simplify marginal social cost (congestion toll) calculations:

$$q = v_f\left(1 - \frac{k}{k_j}\right)k$$

Final Toll Calculations

$$\tau_{\boldsymbol{i}} = -\frac{VOTT}{v}\left(\frac{q}{v}\frac{dv}{dq}\right) = -\frac{VOTT}{v}\left(\frac{v_f - v}{2v - v_f}\right)$$ (for link *i* assuming Greenshield's model, so $v < v_f/2$)

q = q_1+q_2 (where q_j = flow by those with $VOTT_j$)

$$\text{Thus, } \tau_{\boldsymbol{i}} = \sum_{\boldsymbol{j}=1}^{2}\left\{-\frac{VOTT_{\boldsymbol{j}}}{v_{\boldsymbol{j}}}\left(\frac{v_f - v_{\boldsymbol{j}}}{2v_{\boldsymbol{j}} - v_f}\right)\right\}$$ for link *i*

Notes: Reactive tolling used here, based on prior 5 minute period's traffic conditions.

Each of 6 scenarios run 100 times: Toll vs. No toll, %CACCs = 0%, 50%, & 100%

Results: Speeds & Times

- Rising CACC penetration rate **improves travel speeds** of all scenarios, so **congestion-based tolls fall as CACC use rises**.
- Tolling policy delivers **higher speeds along Route 1 (fully tolled),** but lower speeds on Routes 2 (partly tolled) & 3 (non-tolled).
- Not-tolled scenarios have almost similar travel time among routes. When tolled, Route 1 delivers shortest travel times.

Average result across 100 Iterations		0% CACCs			50% CACCs			100% CACCs		
		Route 1	Route 2	Route 3	Route 1	Route 2	Route 3	Route 1	Route 2	Route 3
Tolled Scenarios	Average Toll ($/mi)	5.95 $/mi		-	4.04		-	1.55		-
	Travel Speed (mi/hr)	33.02 mph	23.46 mph	20.66 mph	37.11	26.92	23.96	47.12	36.89	32.12
	Travel time (min)	3.61 min	4.92 min	5.41 min	3.22	4.29	4.67	2.53	3.13	3.48
Not-tolled Scenarios	Travel Speed (mi/hr)	31.1 mph	28.2	27.0	34.7	31.8	31.3	45.2	42.4	38.5
	Travel time (min)	3.84 min	4.09	4.14	3.44	3.64	3.57	2.64	2.72	2.90

Results: Route Choices & Tolls

- **Dynamic change** in route choice & toll rate observed
- Route 1 demand rises with %CACCs, while Route 3's falls.

Time Point in Simulation (secs)	0% CACCs				50% CACCs				100% CACCs			
	Route 1 veh. (#)	Route 2 veh. (#)	Route 3 veh. (#)	Toll ($/mi)	Route 1 veh. (#)	Route 2 veh. (#)	Route 3 veh. (#)	Toll ($/mi)	Route 1 veh. (#)	Route 2 veh. (#)	Route 3 veh. (#)	Toll ($/mi)
300	125	0	1	0 $/mi	132	0	0	0	150	0	1	0
600	2	3	124	13.21	1	14	117	15.31	6	28	120	6.99
900	44	10	102	3.65	27	45	68	3.07	63	11	34	0.00
1200	1	62	23	15.66	0	37	44	8.06	44	0	29	0.00
1500	49	7	93	0	70	3	82	0	83	1	77	0
1800	15	38	87	6.68	13	41	89	3.38	1	69	78	3.69
2100	67	2	96	0	78	3	86	0	79	10	70	0
2400	0	35	90	22.15	0	46	89	9.14	0	70	72	3.44
2700	49	9	97	1.03	45	11	65	0.00	56	1	44	0.00
3000	0	70	35	14.24	0	62	33	4.10	63	0	48	0.00
3300	0	0	0	0	0	0	0	0	0	0	0	0
3600	0	0	0	0	0	0	0	0	0	0	0	0
Average (#)	29.33	19.67	62.33	6.39	30.50	21.83	56.08	3.59	45.42	15.83	47.75	1.17
Percent (%)	26.3	17.7	56.0		27.4	19.6	50.4		40.8	14.2	42.9	

VOTT & Route Choice

- **VOTT affects Route choice:** VOTT1 drivers ($15/hr) choose Route 1 more than VOTT2 driver ($7/hr).
- **CACC penetration rate affects Route choice:** More drivers select Route 1 when CACC penetration rate increases.
- **Tolling strategy affects Route choice:** Drivers in Not-tolled scenario choose Route 1 more (no toll); & Fewer drivers in Route 1 when tolled → travel speed rises.

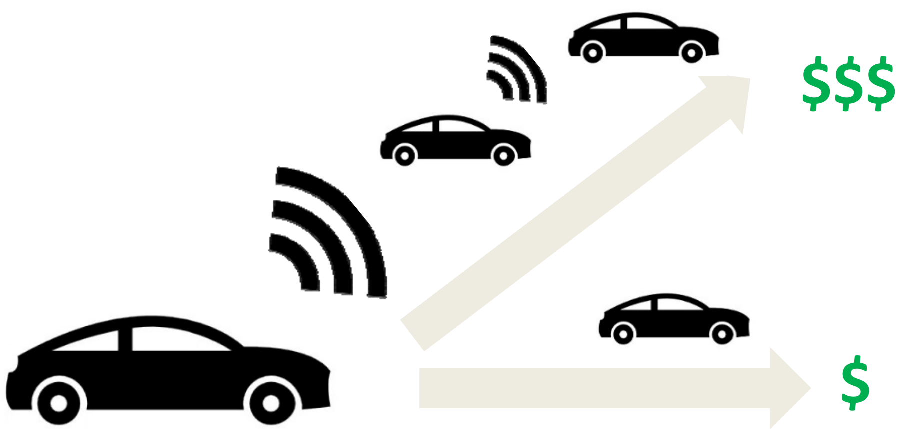
Average value from 100 Iterations		CACC 0%			CACC 50%			CACC 100%		
		Route 1 (%)	Route 2 (%)	Route 3 (%)	Route 1 (%)	Route 2 (%)	Route 3 (%)	Route 1 (%)	Route 2 (%)	Route 3 (%)
Tolled Scenario	VOTT1 ($15/hr)	13.21 (26.88)	10.19 (20.74)	25.74 (52.38)	16.59 (29.25)	11.13 (19.62)	29 (51.13)	22.92 (36.11)	13.62 (21.46)	26.93 (42.43)
	VOTT2 ($7/hr)	12.07 (23.73)	10.56 (20.76)	28.23 (55.51)	12.71 (29.36)	8.45 (19.52)	22.12 (51.12)	14.67 (40.17)	6.66 (18.22)	15.2 (41.61)
Not-tolled Scenario	VOTT1 ($15/hr)	18.99 (38.93)	1.97 (4.04)	27.82 (57.03)	24.00 (44.94)	3.63 (6.79)	25.77 (48.27)	35.83 (56.51)	1.95 (3.07)	25.62 (40.42)
	VOTT2 ($7/hr)	19.38 (37.84)	1.42 (2.77)	30.42 (59.39)	20.22 (43.38)	3.39 (7.28)	22.99 (49.34)	19.39 (52.98)	2.1 (5.74)	15.11 (41.28)

Travel Times, Revenues, & Net Benefits

- **Route 1's travel time falls** with this tolling strategy, while **Route 2 & Route 3's travel times rise**, as expected.
- Route 2 & Route 3's travel time increases can be compensated by **revenues earned from toll users**. (Credit-based congestion pricing!)
- **Net social benefits are positive** when tolling strategy is applied to the network. NSB falls as **%CACC** rises!
- **CACC improves the network**, since it lowers congestion & thus tolls!
- However, **tolling still improves the network** conditions, since NSB remains positive with higher %CACCs.
- As expected, higher VOTT drivers tend to choose tolled routes more.
- **+$675/hr net benefits for 0% CACC case** can be used to improve Routes 2 & 3.

PART II

Regional Congestion Pricing in a World of Personal + Shared AVs



2019 *Transp Research Part C* paper

with **Michele Simoni**, **Murthy Gurumurthy** & **Joschka Bischoff**

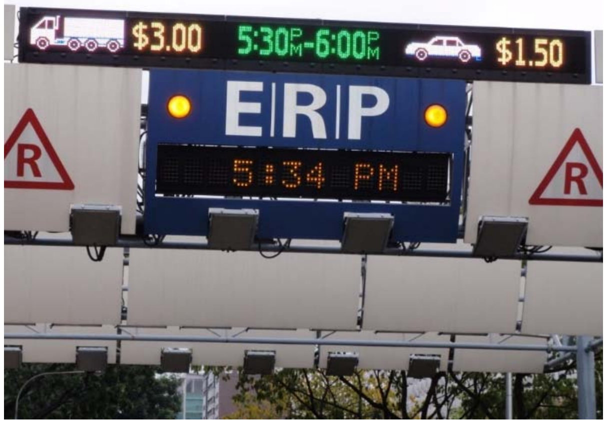
LONG-TERM expectations of **privately owned + shared AVs** (AVs + SAVs)

→

BENEFITS in road safety, accessibility, electrification of vehicles + higher link capacities **may be mostly offset by Rising Congestion?**

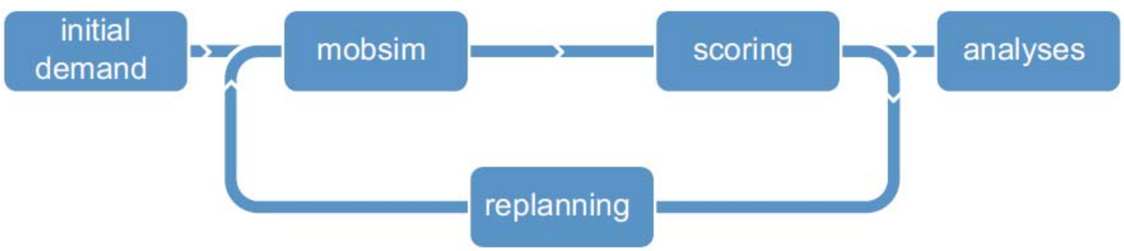
→

OPPORTUNITY: Smart system management with congestion pricing (traditional & advanced strategies)



Agent-based Austin Simulation

- MATSim model from ETH Zurich + TU Berlin
- Activity-based (using people's daily plans)
- Dynamic traffic assignment
- Endogenous mode, departure time, & route choices



Agent 1: Home→Leisure →Shopping→Home

Agent 2: Home→Education →Leisure→Home

Agent 3: Home → Work → Home

Scenarios Evaluated

Base Scenario: No AVs

- 5% sample from 1M population
- Car, transit, + walk/bike modes
- High car access (90% of travelers)

Private AV-Oriented Scenario

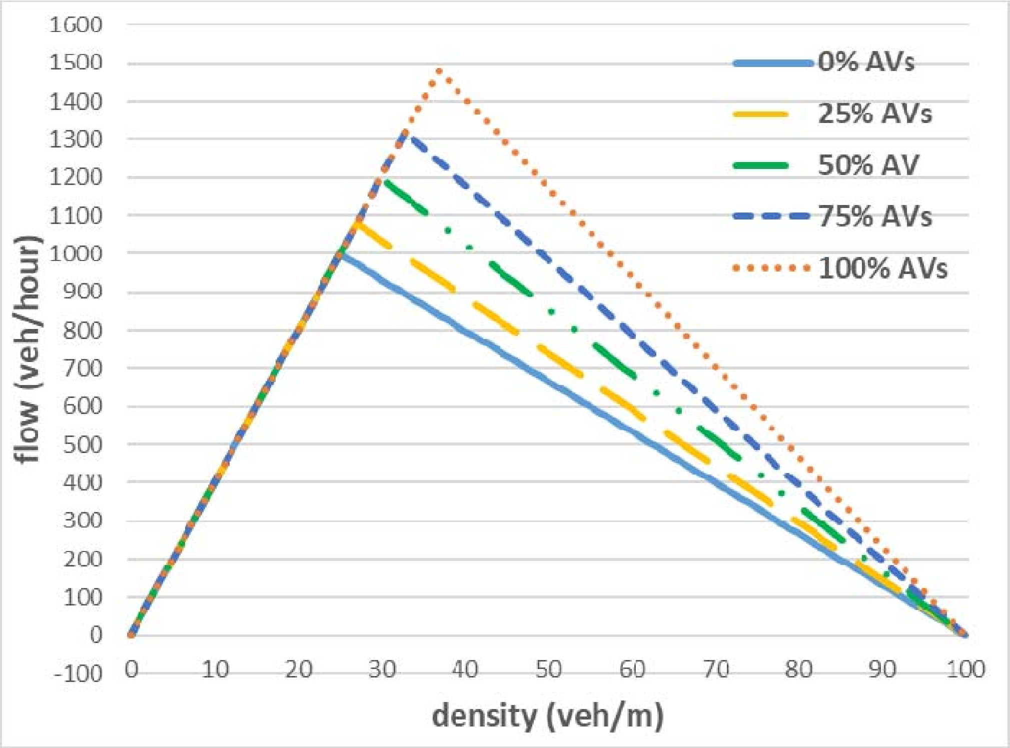
- 90% of travelers now own AVs
- AVs travel similar to cars, but lower cost
- Just 1 SAV for every 50 agents, function similar to current taxis

SAV-Oriented Scenario

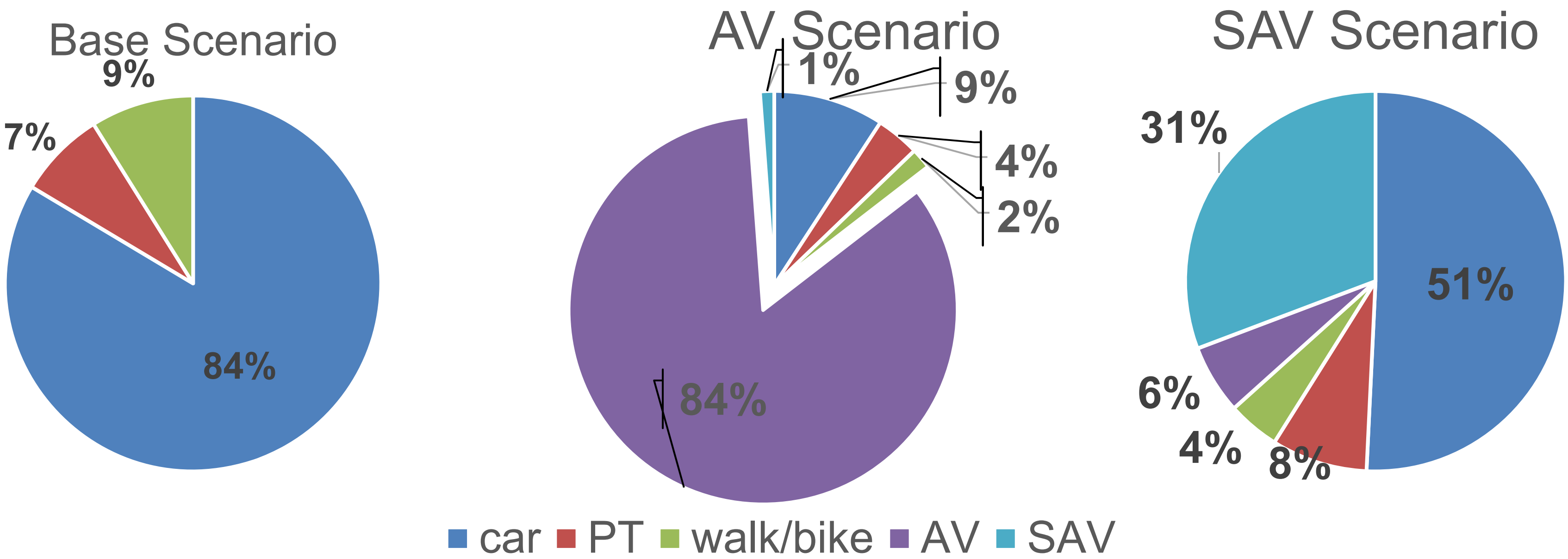
- Low car ownership (10% of travelers)
- Large fleet: 1 SAV for every 10 agents
- 50% lower SAV fares

Travel Demand & Traffic Efficiency Changes

- **New, high-service modes:** No AV parking costs + SAVs dynamically dispatched (door to door)
- **50% lower VOTT** for Drivers
- **Non-linear rise in link capacities** for mixed (HV + AV flows)



Mode Split & VMT Results



	Base Scenario	AV-oriented Scenario	SAV-oriented Scenario
Total Weekday VMT	2.8M mi/day	**3.0M mi/day**	**3.3 M mi/day**
VMT by Empty SAVs	0	< 0.1M mi/day	0.3 M miles/day
Total Travel Delay (veh-hours per weekday)	437,887	**459,781**	**523,594**

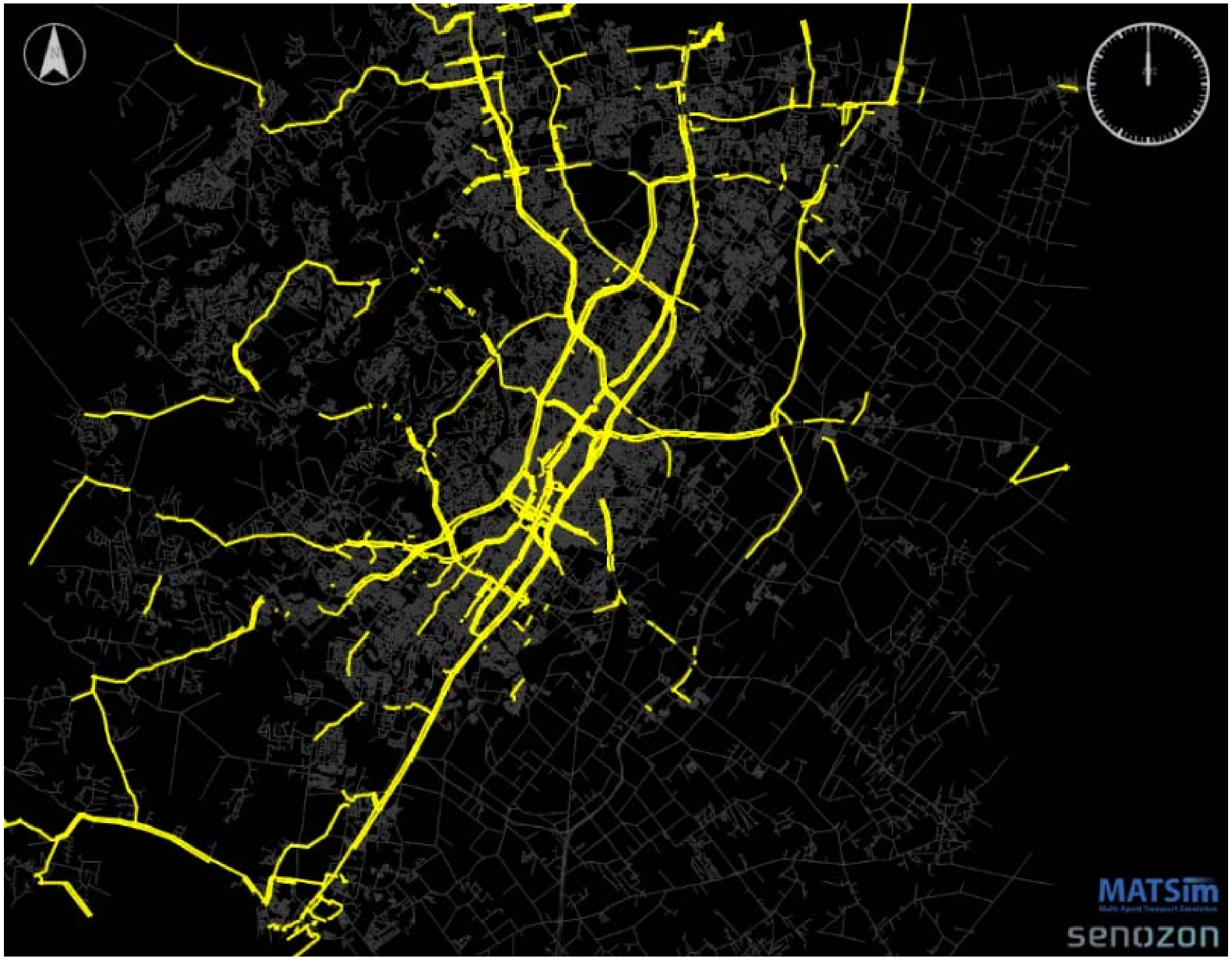
Simple Tolling Strategies

1. Congestion-based

- Toll **most congested links** (v/c > 0.9)
- Simply **$0.10 to $0.20** each, during **peak** periods
- **Just 4%** of Austin's **network**

2. Distance-based

- Simply **$0.10 per VMT**
- Over **entire day**



Advanced CP Strategies

3. Marginal Cost Pricing (MCP): Each link's toll varies dynamically based on fundamental diagram for traffic flow…

$$delay, d = \left[\left(\frac{l}{v_B} - \frac{l}{v_A}\right) \cdot n\right] \quad \rightarrow \quad toll = \tau = max\left\{0; \frac{d \cdot VOTT}{\Delta n}\right\}$$

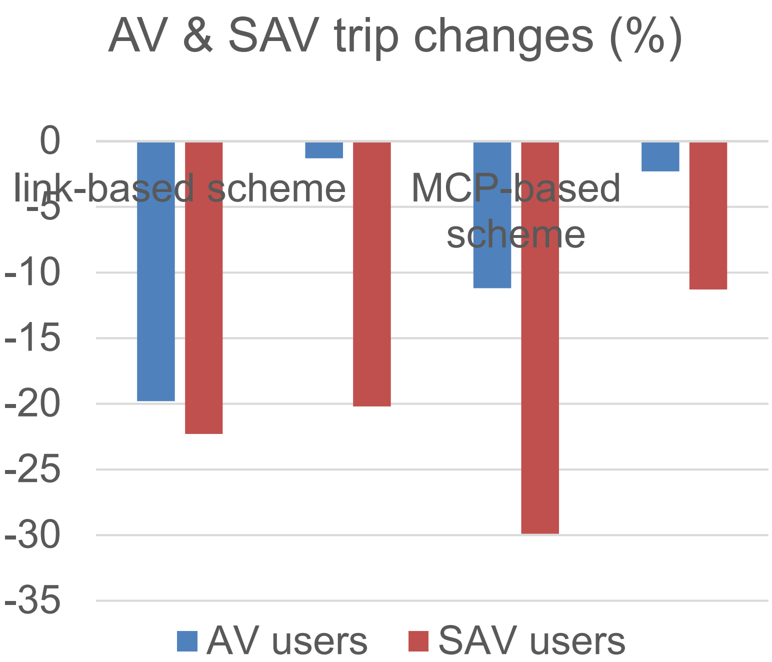
where v = average speed, n = #vehicles & $VOTT$ = (average) value of travel time

4. Travel Time-based Congestion Tolls: $\tau = \frac{\alpha\left(\sum_i^M d_i\right) \cdot VOTT}{\mathrm{D} \cdot r}$

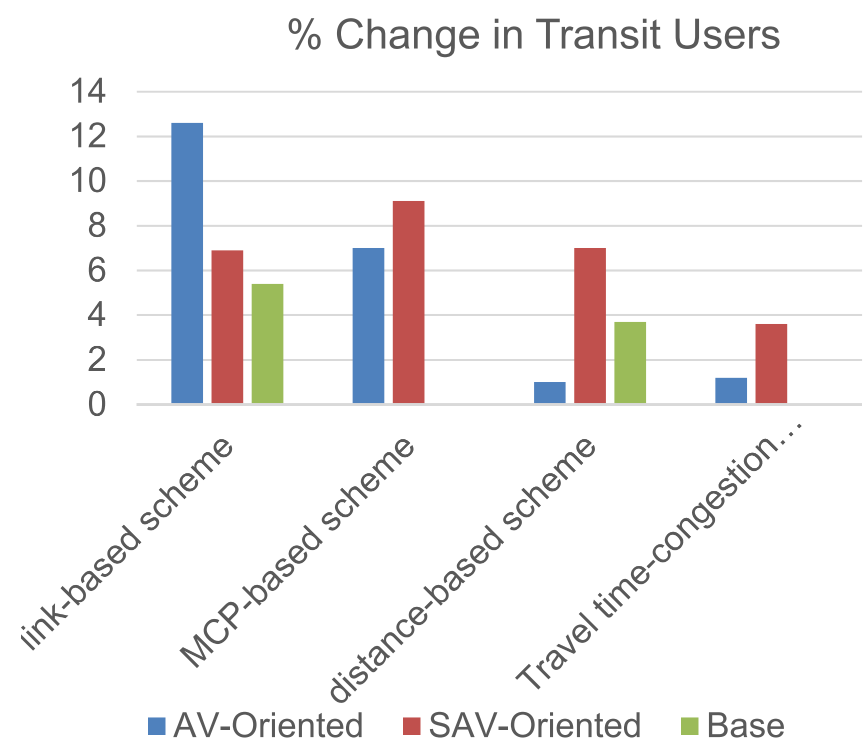
where D = # departures; r = average trip duration; $\alpha =$ parameter

Results: Mode Shifts

All tolling scenarios lower AV & SAV use…



Transit use rises, especially under simple link-based (v/c > 0.9) **tolling…**



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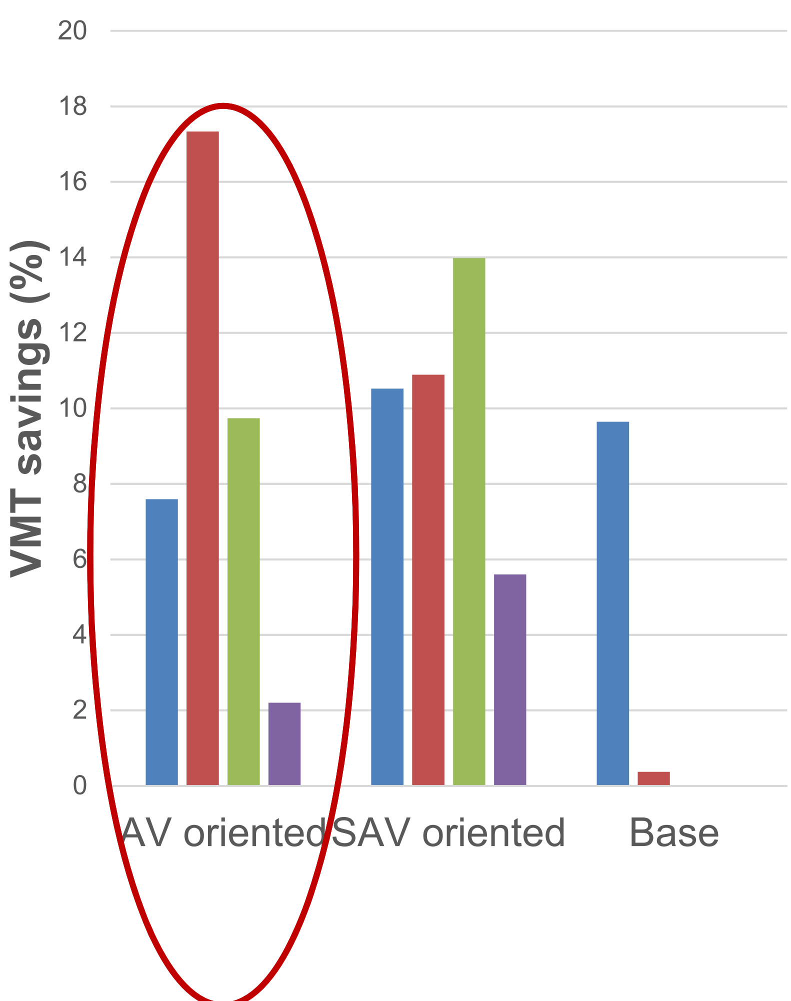
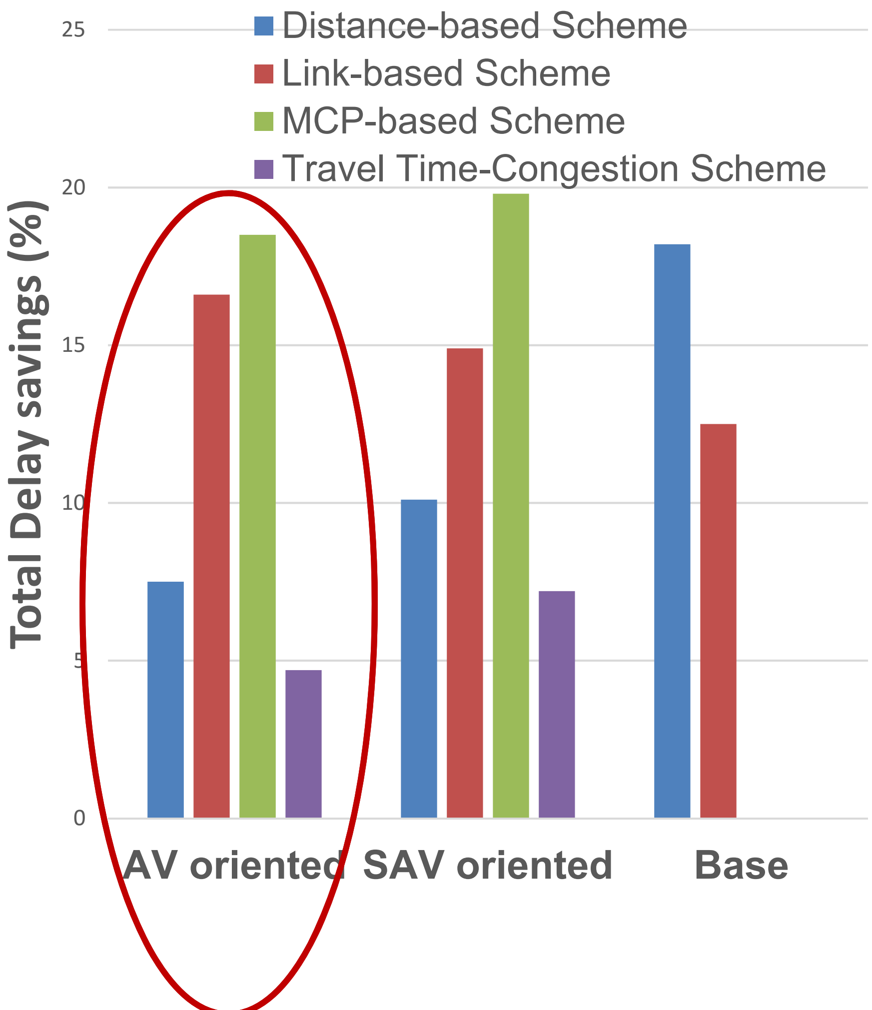
Results: Network Performance Changes





Results: Welfare Changes

- **Link-Based Scheme**: Total traveler welfare rises just +**0.5%** & +**0.7%** across scenarios.
- **Distance-Based Scheme**: Welfare up +**1.2%** & +**1.4%** in SAV & *No*-AV Scenarios, but falls **-1.2%** in the AV-Oriented Scenario (!).
- **MCP Tolling**: +**2.0%** & +**3.2%** in AV & SAV Scenarios
- **Travel-Time Congestion-based Tolling**: +**2.6%** & +**4.4%** in AV & SAV Scenarios **= BEST result**

Conclusions

- **Smart system management** exploits benefits of smart cars & navigation apps.
- **All CP strategies improve mode splits & traffic conditions.**
- But relatively **low welfare gains**, even after compensation → Importance of **thoughtful credit distribution.**
- **Dynamic CP schemes** are **best** (greatest improvements for lowest behavioral changes).
- Opportunities for **future research**: endogenous destination choice, explicit parking choice, & more advanced strategies.

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PART III
Value of Dynamic Ride-Sharing in SAVs: Opportunities for Congestion Pricing

2019 *Transp Research Record* article
with K. **Murthy Gurumurthy & Michele Simoni**

DRS: Dynamic Ride-Sharing

- **SAVs** can **increase congestion via empty VMT & added demand** (from new motorists & longer trips, mode shift, etc.)

But…

- SAVs can also **raise average vehicle occupancy (AVO) & lower VMT** (through DRS) **& lower emissions & energy use** (via smaller vehicles, DRS + keeping engines warm)
- Smart cars enable **smarter system management**.
- **What's the net result on congestion?**

Fleet Size + Fare Assumptions

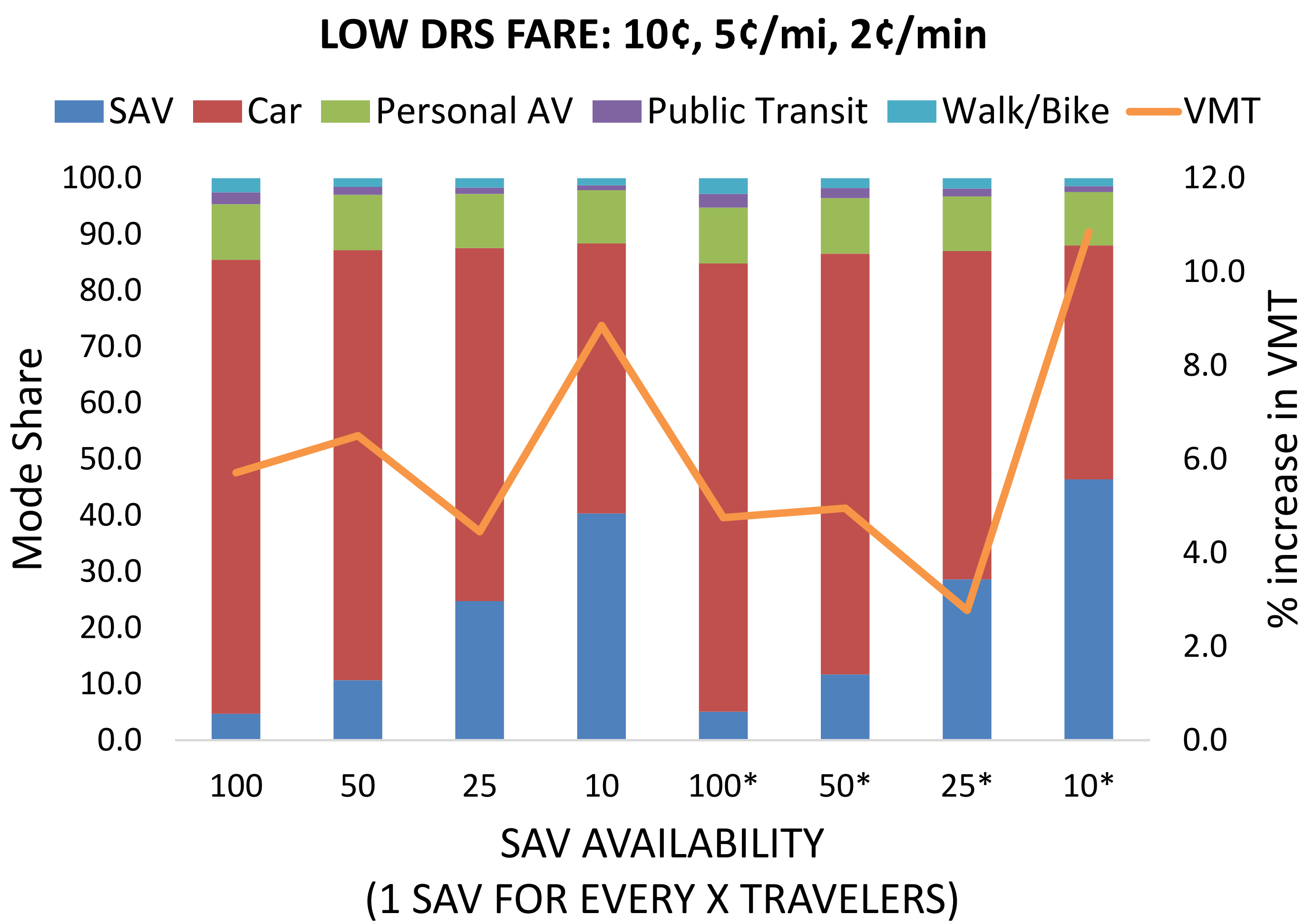
- **4** fleet sizes: **1 SAV** per **10**, **25**, **50** & **100** travelers
- DRS & SAV Pricing to **mimic ride-pooling apps**
- **Solo** travel in SAV costs **2x** a **shared ride.**

DRS Pricing	**Fixed Cost for Pickup**	**+ Distance-based Cost**	**+ Time-based Cost**
High Fare	**25¢**	**20¢ per mi**	**5¢ per min**
Medium Fare	**15¢**	**10¢**	**3¢**
Low Fare	**10¢**	**5¢**	**2¢**

Congestion Pricing (CP) Simulations

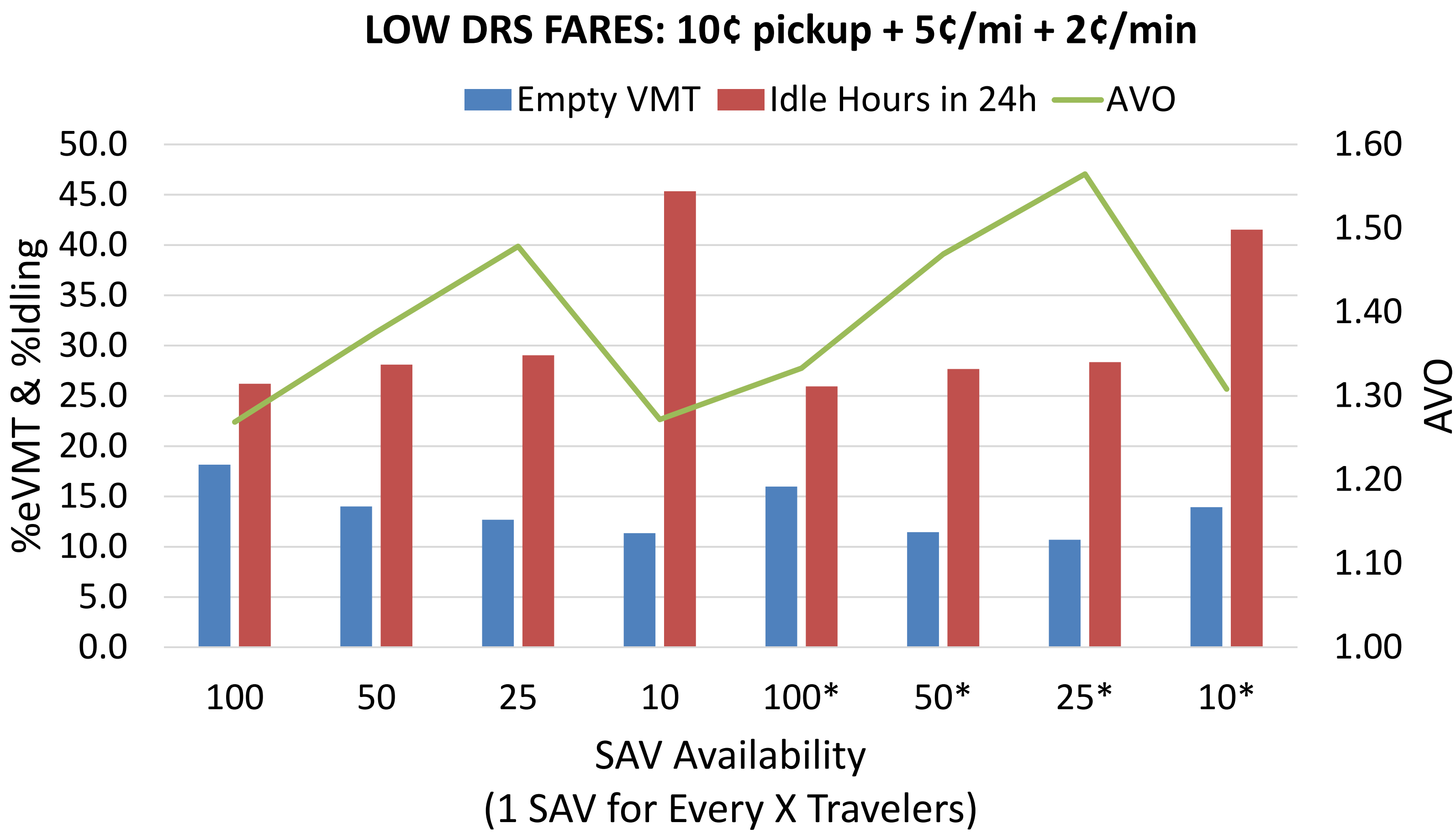
- **Austin key congested corridors selected** for CP.
- **Peak-period tolling** peaks (**7-9 am** & **5-7 pm**).
- **CP Tolls based on travel times**: **5¢ per min.**
- **MATSim** DTA code modified for SAVs + DRS + CP.
- Horl's heuristic **DRS** code with 2 settings:
  - **SAV Under-supply**: **High** ratio of **# requests** to available SAVs (low-cost **DRS** paths calculated)
  - **SAV Over-supply**: **Low** ratio (requests matched **instantly** to nearest SAV)

Results: Mode Splits + VMT



* with congestion pricing

%eVMT, %Idling, & AVO



* with congestion pricing

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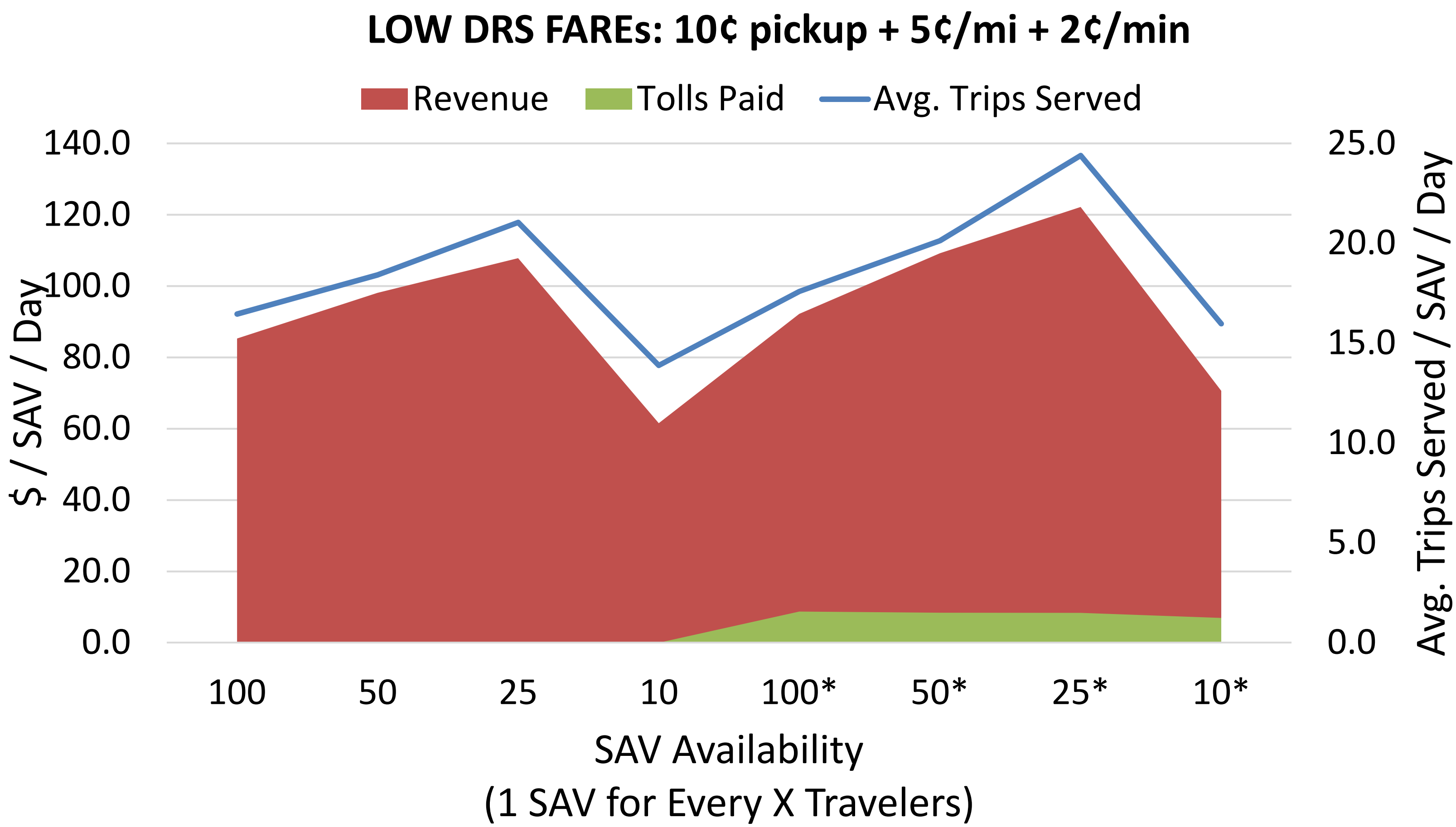
Profits + Tolls + Trips/day/SAV



* with congestion pricing

Conclusions

- **AVs & SAVs** will bring benefits but also much **VMT**, especially with large fleet sizes or AV ownership levels.
- As expected, **CP moderates** VMT + congestion.
- But **truly dynamic pricing can be harmful** & needs much smoothing via demand anticipation.
- **DRS** is helpful, but may be popular in US only at **competitive fares.**
- Both large & small SAV fleet sizes (1:10 & 1:100 persons) deliver **low DRS use** (due to excess supply of vehicles & inadequate matching, respectively).
- **Fleet profits ≈ $113**/SAV/day, even with **low fares.**
- Targeted analysis needed if goal is to **maximize AVO.**

Paper References

- Lee, J., & Kockelman, K. 2019. **Development of Traffic-based Congestion Pricing & Its Application to Automated Vehicles**. *Transportation Research Record: Journal of the Transportation Research Board* 2673 (6): 536-547 .
- Simoni, M.D., Kockelman, K., Gurumurthy, K.M. & Bischoff, J. 2019. **Congestion Pricing in a World of Self-Driving Vehicles: An Analysis of Different Strategies in Alternative Future Scenarios**. *Transportation Research Part C: Emerging Technologies* 98: 167-185.
- Gurumurthy, K.M., Kockelman, K. & Simoni, M.D. 2019. **Benefits & Costs of Ride-Sharing in Shared Automated Vehicles Across Austin, Texas: Opportunities For Congestion Pricing**. *Transportation Research Record: Journal of the Transportation Research Board* 2673 (6): 548-556.

Thank you!

Questions & Suggestions?

30+ CAV papers & reports at www.caee.utexas.edu prof/kockelman