The 4th IEEE Conference on
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Power and Transport Nexus: Autonomous Electric Vehicle Fleet Operation and Optimization

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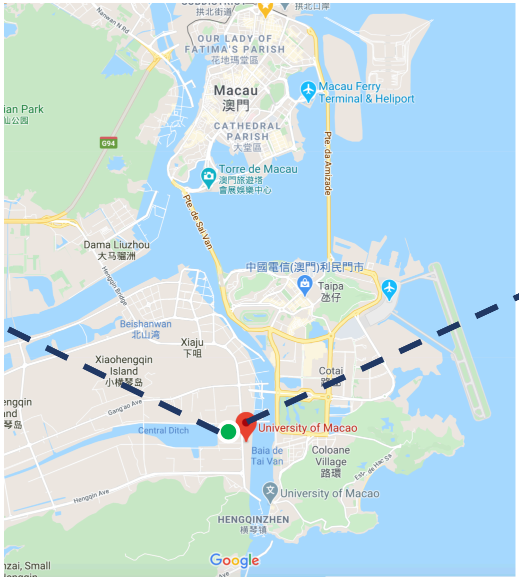

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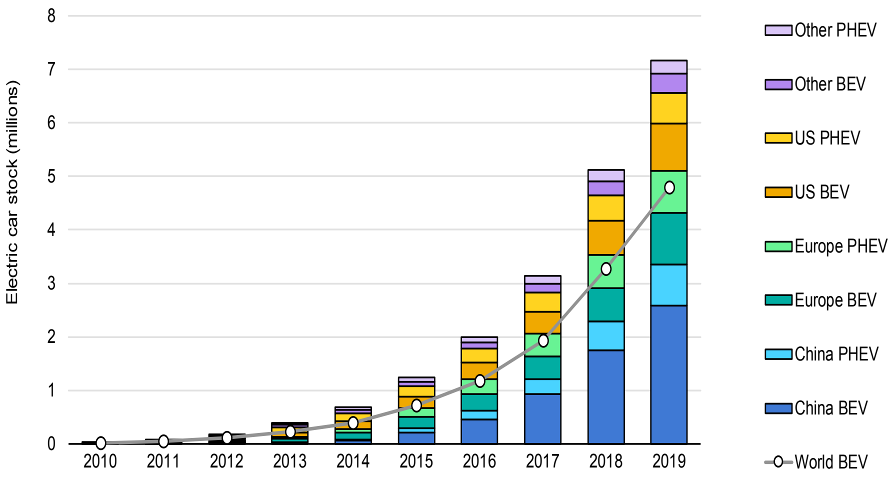
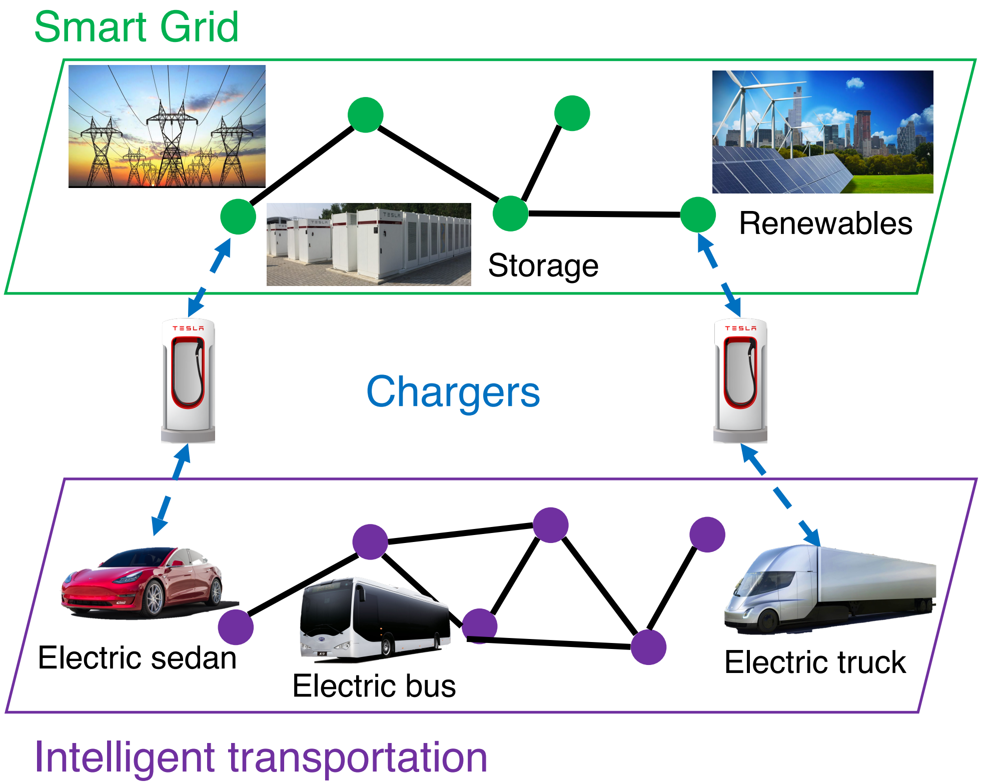
1. **H. Zhang**, Z. Hu, and Y. Song, "Power and Transport Nexus: Routing PEVs to Promote Renewable Generation Integration," **IEEE Transactions on Smart Grid**, vol. 11, no. 4, pp. 3291-3301, July 2020. DOI: 10.1109/TSG.2020.2967082
2. **H. Zhang**, C. J. R. Sheppard, T. E. Lipman, T. Zeng, and S. J. Moura, "Charging Infrastructure Demands of Shared-Use Autonomous Electric Vehicles in Urban Areas," **Transportation Research Part D: Transport and Environment**, vol. 78, p. 102210, 2020. DOI: 10.1016/j.trd.2019.102210
3. **H. Zhang**, C. J. R. Sheppard, T. E. Lipman, and S. J. Moura, "Joint Fleet Sizing and Charging System Planning for Autonomous Electric Vehicles," to appear in **IEEE Transactions on Intelligent Transportation Systems**, 2019. DOI: 10.1109/TITS.2019.2946152

Motivation

- Synergy of smart grid and intelligent transportation is a key feature of future smart cities

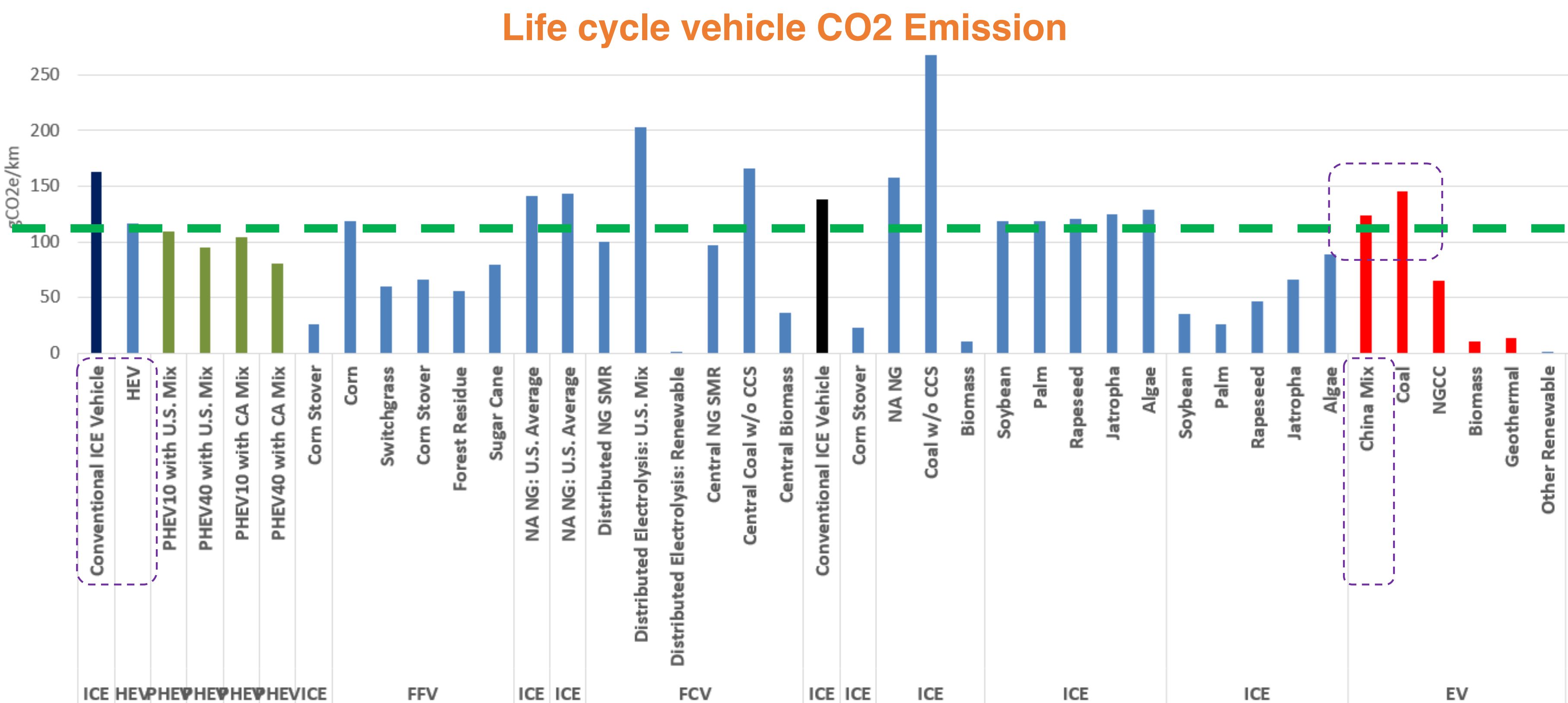
EV stock has hit 7.1M globally, and 3.3M in China by the end of 2019





Motivation

- EVs are not clean without renewables



Motivation

- EVs may still emit more even with high penetration of renewables

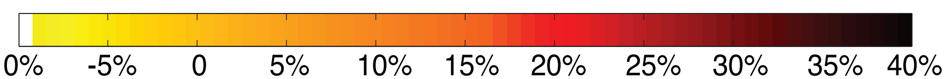
Vehicle emission with high penetration of wind power in Jing-Jin-Tang

a CO_2 reductions

	Wind level 0%	10%	20%	30%	40%
ICEVs	0%	10%	19%	25%	29%
Uncontrolled EVs	-3.4%	6%	12%	17%	20%
Controlled EVs	-2.7%	8%	18%	26%	31%

b NO_x reductions

	Wind level 0%	10%	20%	30%	40%
ICEVs	0%	5%	9%	12%	14%
Uncontrolled EVs	11%	15%	18%	20%	22%
Controlled EVs	11%	16%	21%	24%	27%



*X. Chen, H. Zhang, Z. Xu, C. P. Nielsen, M. B. McElroy, and J. Lv, "Impacts of Fleet Types and Charging Modes for Electric Vehicles on Emissions under Different Penetrations of Wind Power," Nature Energy, vol. 3, pp. 413-421, 2018.

Motivation

- Commercialization of autonomous vehicles is right around the corner!
- Future autonomous vehicles are more likely to be electric!

Picture: Waymo autonomous car (Alphabet)

- 10 m miles on public roads, 7 b simulation miles, from 2009 to 2018
- 25 k virtual self-driving cars travel 8 million miles per day
- Autonomous taxi service launched in May 2018

County	Time to ban ICEV
Norway	2025
Germany	2030
India	2030
Ireland	2030
Israel	2030
Netherlands	2030
Scotland	2032
France	2040
UK	2040
China	Actively studying

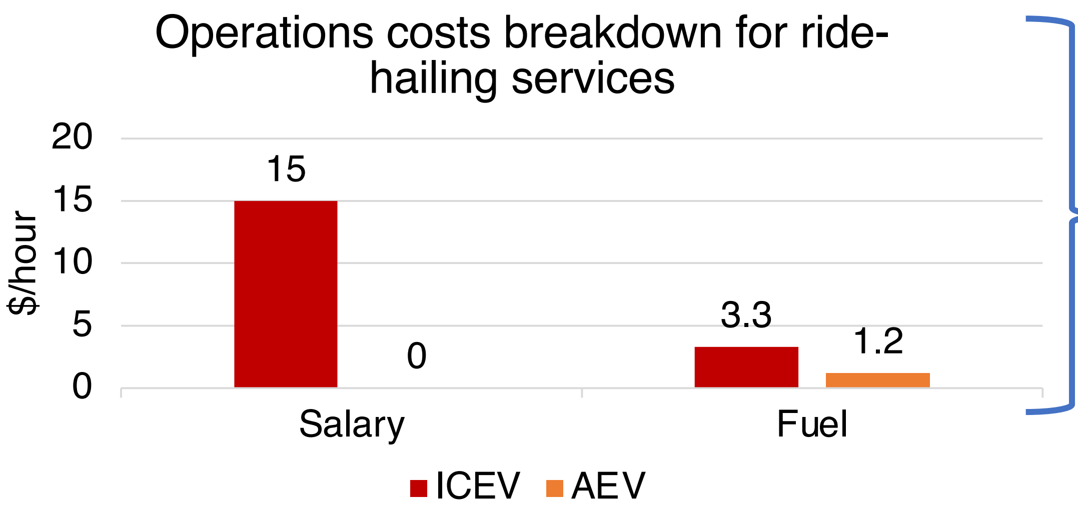
ICEVs are losing the market

Motivation

- Autonomous EVs in University of Macau

Motivation

- Autonomous EVs will strength power & transportation nexus!
  - Fuel cost is the major operation cost (time is not expensive)
  - Scheduled driving & parking behaviors (no driver to make decisions)



Autonomous EVs have stronger motivation to detour for cheaper energy

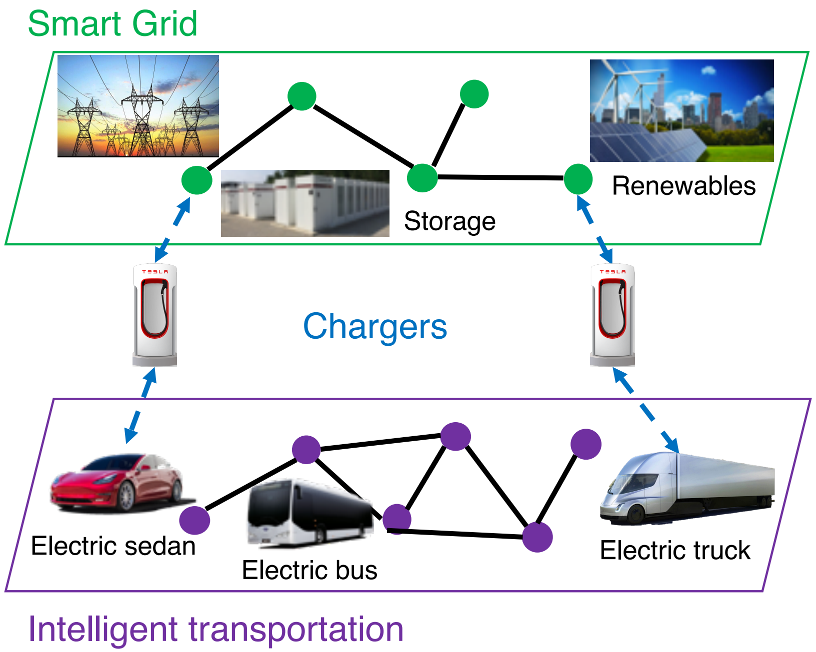
Note: fuel efficiency 0.32 kWh/mile for AEVs, and 30 mi/gallon for ICEVs; gas price 3.3 $/gallon; average driving speed 30 mile/hour.

Intercity scenario: Routing EVs to promote renewable generation

- Problem statement: Strategic EV fleet routing & charging on coupled power & transportation networks

  - With power network: EVs may detour to consume cheaper electricity – choose cost-minimizing paths

  - Without power network: EVs try to save time - choose the shortest paths

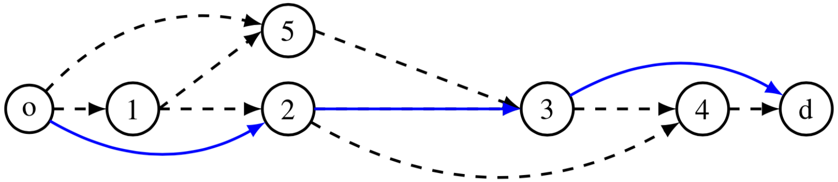


Intercity scenario: Routing EVs to promote renewable generation

- Optimize AEV flow to minimize operational costs (quadratic)

$$\min_{\boldsymbol{g},\hat{\boldsymbol{\Lambda}}_g^{\text{arc}}} \ \frac{1}{2}\boldsymbol{g}^\top \boldsymbol{Q}\boldsymbol{g} + \boldsymbol{c}^\top \boldsymbol{g} + c^{\text{t}}\left(\frac{1}{v} + \frac{\eta}{p^{\text{spot}}}\right)\sum_{g\in\mathcal{G}} \boldsymbol{L}^\top \hat{\boldsymbol{\Lambda}}_g^{\text{arc}}$$

- Constraints
  - AC power flow (Second order cone)
  - Coupled constraints (Linear)
  - Driving range (expanded network) (Linear)



$$\boldsymbol{A}\hat{\boldsymbol{\Lambda}}_g^{\text{arc}} = \boldsymbol{\lambda}_g^{\text{OD}}, \quad \forall g \in \mathcal{G}$$
$$\hat{\boldsymbol{\Lambda}}_g^{\text{arc}} \geq 0, \quad \forall g \in \mathcal{G}$$

Large-scale (may drive on any path)

- Path flow constraints

$$\hat{\boldsymbol{F}}_g^{\text{arc}} = \boldsymbol{B}_g \boldsymbol{F}_g^{\text{path}},$$
$$\boldsymbol{F}_g^{\text{path}} \geq 0.$$

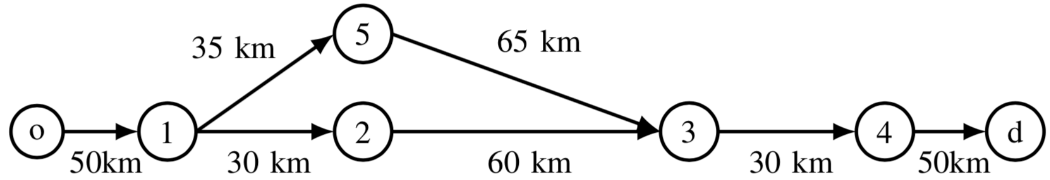
Require EVs only choose limited paths

Intercity scenario: Routing EVs to promote renewable generation

- Incorporate EV range constraints by an expanded transport network

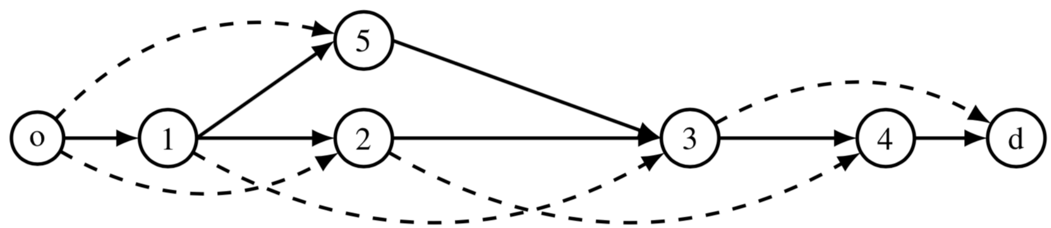
$$\boldsymbol{A}\boldsymbol{\Lambda}_g = \boldsymbol{\lambda}_g^{\mathrm{od}}, \qquad \forall g \in \mathcal{G},$$

$$\boldsymbol{\Lambda}_g \geq 0, \qquad \forall g \in \mathcal{G},$$



(a) The original network $G(\mathcal{I}, \mathcal{A})$

Remark: The expanded network can be determined *a priori* & offline; its cardinality is limited by (I-1)I/2



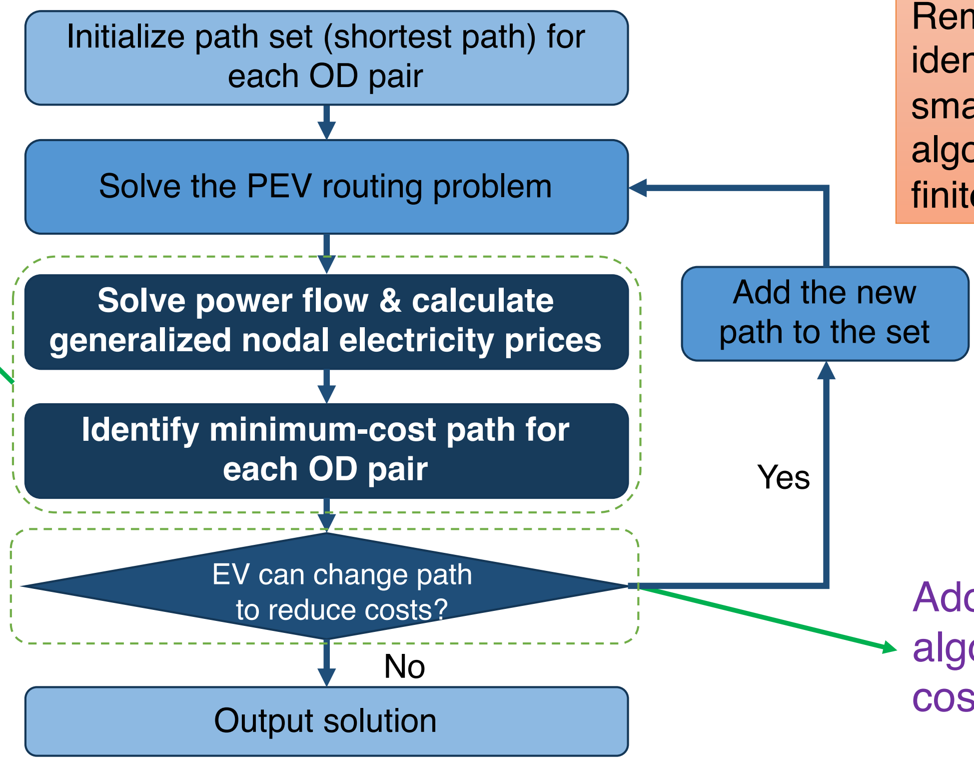
(b) The expanded network $G(\mathcal{I}, \hat{\mathcal{A}})$ (driving range 100 km)

Intercity scenario: Routing EVs to promote renewable generation

- Iterative algorithm based on generalized locational marginal prices

Remark: The scale of the identified path set is much smaller than arc set; The algorithm converges in a finite number of iterations

Adopt generalized nodal electricity prices to estimate total driving costs (time & electricity)

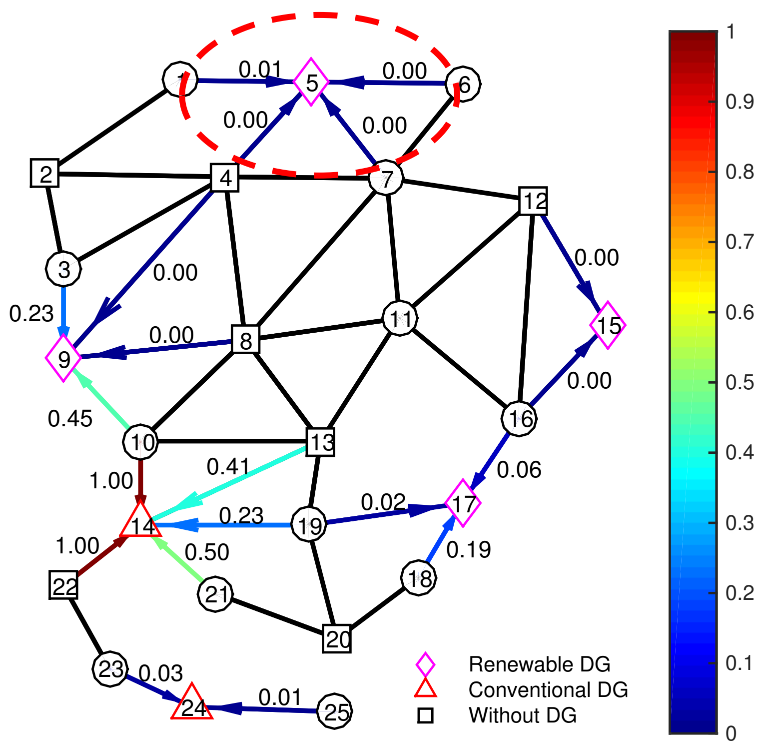


Adopt shortest path algorithm to identify cost-minimizing paths

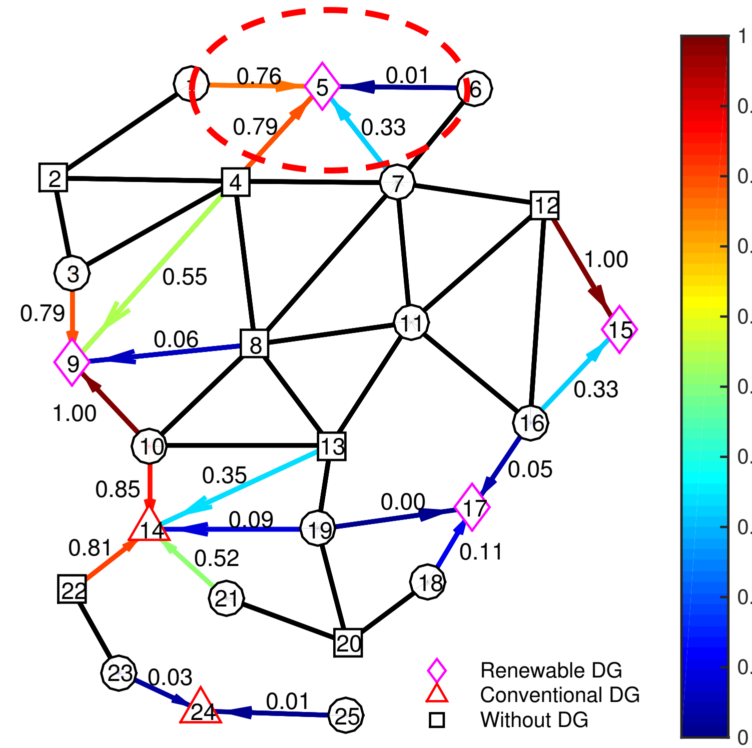
*F. He, Y. Yin, and S. Lawphongpanich, Transp. Res. Part B Methodol., 2014.

Intercity scenario: Routing EVs to promote renewable generation

- Results – distribution of AEV traffic flow



Traffic flow distribution (before routing)



Traffic flow distribution (after routing)

Intercity scenario: Routing EVs to promote renewable generation

- Results – operation costs (assume one driver in one car)

Significant operation costs reduction (-20%) with mild detour

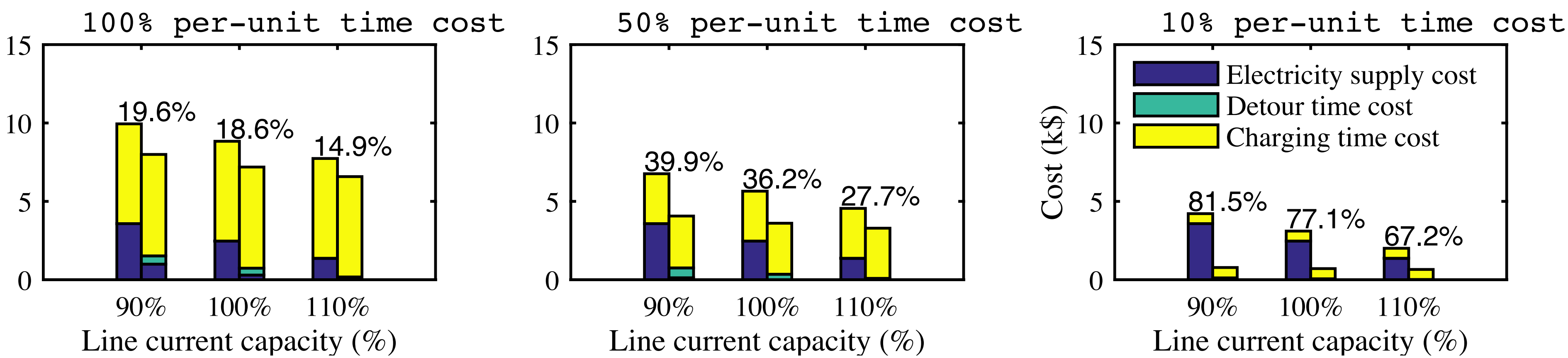
Case	Power generation and purchase (MWh)			Fueling costs (k$/h)				
	Electricity purchase	Conventional DG	Renewable DG	Electricity	Emission	Charging time	Detour time	Total
1	10.37	6.05	94.65	2.37	0.099	6.36	0	8.83
2	1.14	0.86	113.98	0.29	0.012	6.45	0.44	7.19
3	105.37	5.45	–	15.58	0.66	6.36	0	22.61
4	110.21	0.64	–	15.53	0.66	6.36	0.004	22.56

Much cleaner energy consumption considering power-transport nexus

Case	Electricity purchase (MWh)	Conventional DG (MWh)	Renewable DG (MWh)				Average renewable power curtailment (%)
		Bus 5	Bus 9	Bus 10	Bus 11	Bus 13	
1	10.36	6.05	21.51	24.11	21.75	27.27	21.13
2	1.14	0.86	27.69	30.0	26.28	30.0	5.03

Intercity scenario: Routing EVs to promote renewable generation

- Benefits of routing EVs are more obvious when
  - More congested power network
  - Lower per-unit driving time cost (autonomous vehicles!)

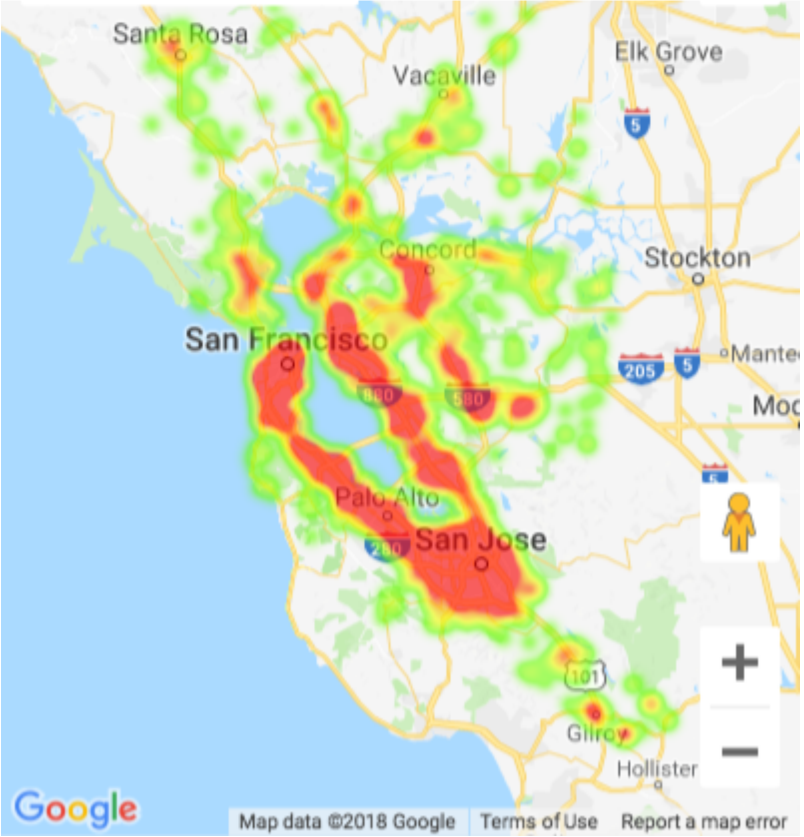


Open question: trade-off between delivery time & operational costs?

Intracity scenario: Shared-use autonomous EVs

- How shared-use autonomous EV compete with traditional vehicles?

- Objective
  - Fleet size
  - Charging infrastructure
- Constraints
  - Mobility demands
  - AEV driving range
- Technoeconomic analysis
  - Vehicle battery capacity
  - Rated power of chargers



Intracity scenario: Shared-use autonomous EVs

- Fleet sizing and charger planning based on data-driven approaches

BEAM simulation

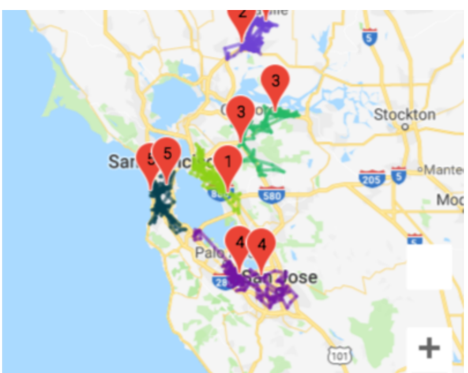
- Simulate the driving, parking & charging behaviors of AEVs
- Whenever an AEV's SoC drops below the given threshold, it gets charged

Record events

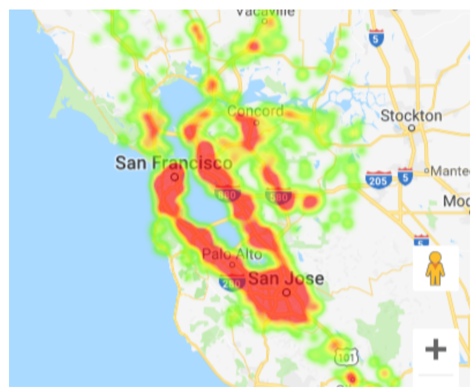
- Record when, where, & how many AEV charging demands that happen in the system

Planning

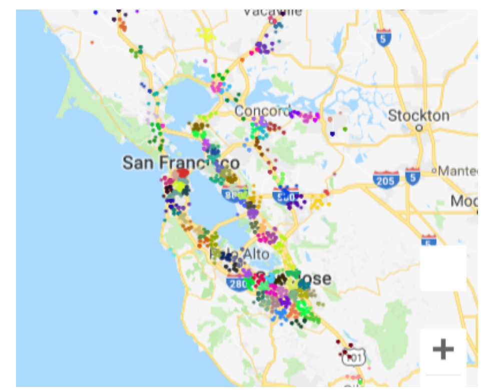
- Locate a number of charging stations to satisfy all the demands
- Subject to quality of service constraints



Beam simulation



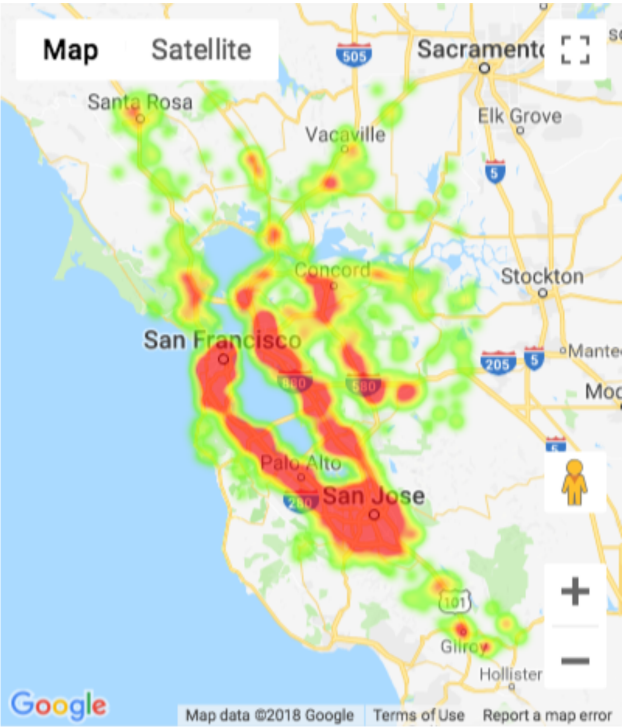
Charging demands



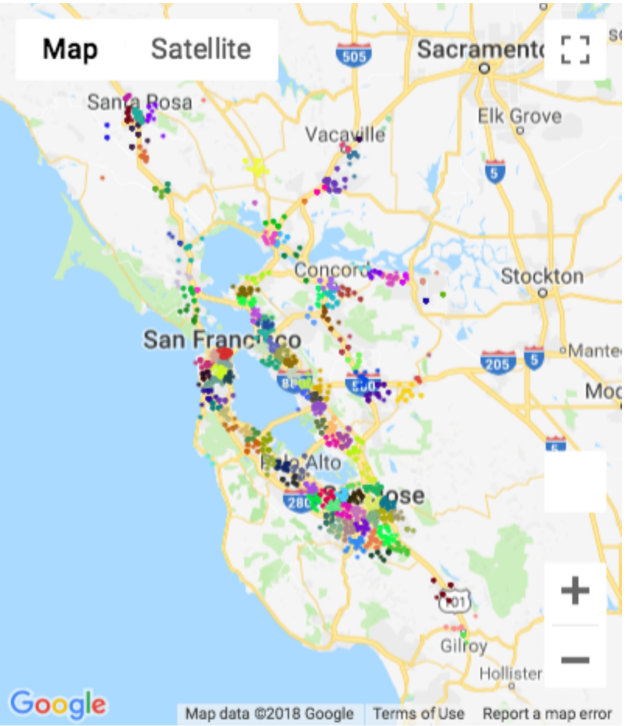
Charging station planning

Intracity scenario: Shared-use autonomous EVs

- Fleet size: 7,000 (original); 4,406 (AV); 4,510 (AEV, 50kW, 50 kWh)
  - 320k trips/day, 3 mile/trip, 30 miles/hour



EV charging demands (heatmap)



Charging demands clusters

Intracity scenario: Shared-use autonomous EVs

- Longer driving range & higher charger power will improve vehicle utilization, but not significantly
  - AEVs will not circulate on roads without passengers

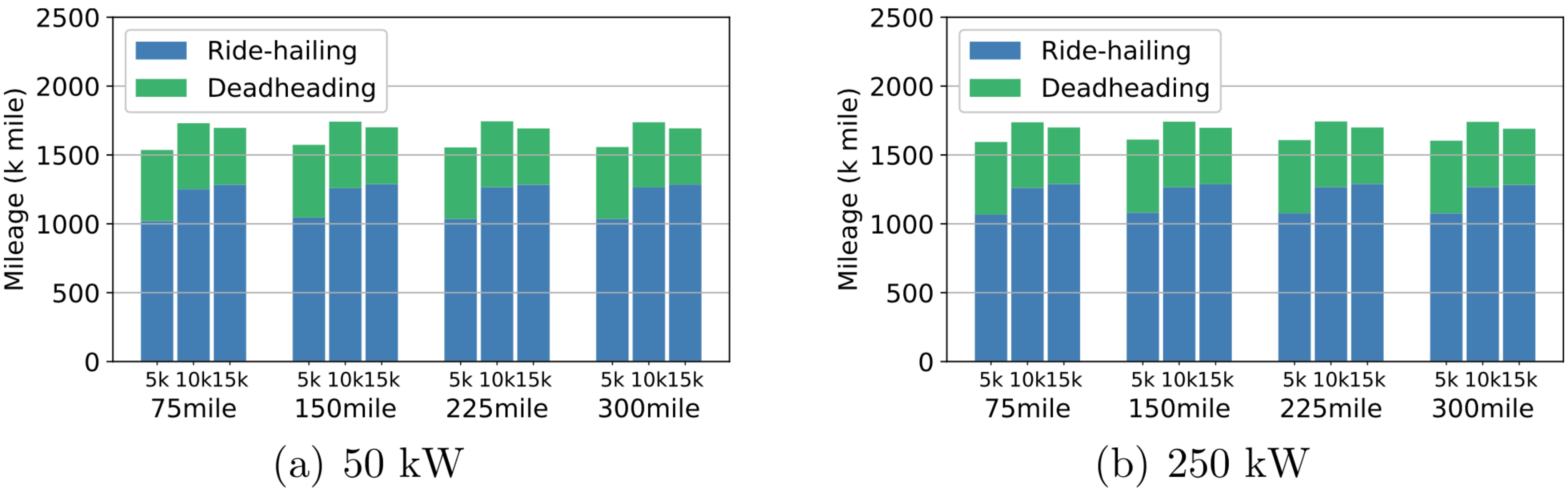
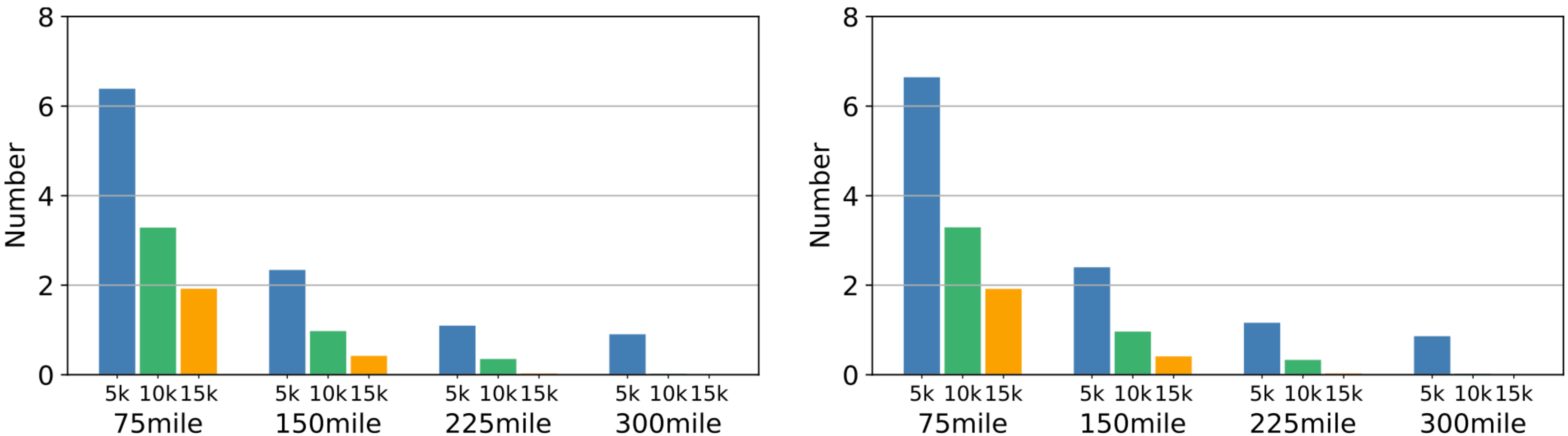


Fig. 6. Total vehicle miles travelled under different cases.

Intracity scenario: Shared-use autonomous EVs

- Daytime charging demands significantly reduces with the increase of battery size (note that total electricity consumption will increase)
- Higher power charger marginally increases charging demands



(a) 50 kW (b) 250 kW

Fig. 9. Charging demands per AEV under different cases.

Intracity scenario: Shared-use autonomous EVs

- Large batteries are uneconomic for AEVs (OK with frequent charging)
- Higher power charging marginally increases total ride-hailing cost

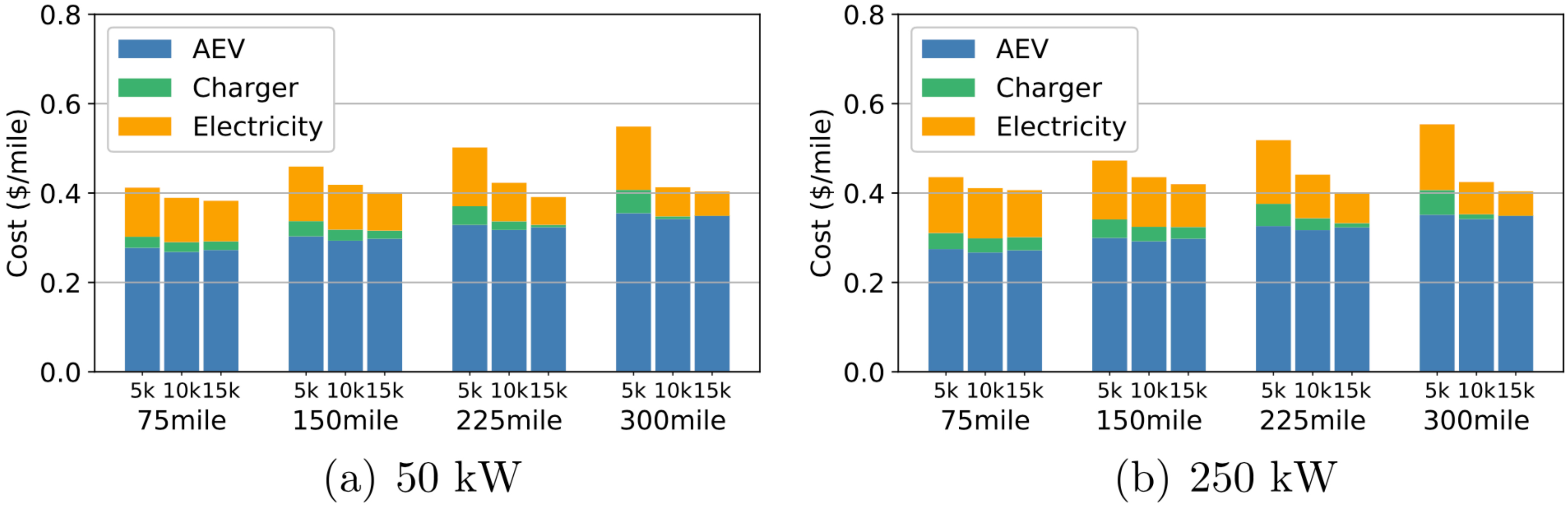


Fig. 15. Cost per ride-hailing mileage analysis under different cases.

Conclusion

- Synergy between power and transportation system is a major feature for future smart cities
- Autonomous driving further strengthens power-transport synergy

- Routing EVs can help enhance power system efficiency & promote renewable generation integration, especially when
  - The power network face serious congestion issues
  - The detour time cost of driver is low (or even driverless)

- Conclusions on range anxiety and charger power for EVs in cities shall be revised for autonomous EVs
  - Moderate EV battery and charger level are sufficient

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Thank you!

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