Power and Transport Nexus: Autonomous Electric Vehicle Fleet Operation and Optimization

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The 4th IEEE Conference on Energy Internet and Energy System Integration
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The 4th IEEE Conference on Energy Internet and Energy System Integration
Acknowledgement


The 4th IEEE Conference on Energy Internet and Energy System Integration
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

Smart Grid

Storage

Renewables

Chargers

Electric sedan

Electric bus

Electric truck

Intelligent transportation
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

<table>
<thead>
<tr>
<th>Wind level</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
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<td>19%</td>
<td>25%</td>
<td>29%</td>
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<td>6%</td>
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<td>8%</td>
<td>18%</td>
<td>26%</td>
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CO₂ reductions

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<th>Wind level</th>
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<td>5%</td>
<td>12%</td>
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<td>19%</td>
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<tr>
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<td>6%</td>
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<td>20%</td>
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NOₓ reductions

ICEVs
Uncontrolled EVs
Controlled EVs

Motivation

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

<table>
<thead>
<tr>
<th>County</th>
<th>Time to ban ICEV</th>
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<tbody>
<tr>
<td>Norway</td>
<td>2025</td>
</tr>
<tr>
<td>Germany</td>
<td>2030</td>
</tr>
<tr>
<td>India</td>
<td>2030</td>
</tr>
<tr>
<td>Ireland</td>
<td>2030</td>
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<td>2030</td>
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<td>Netherlands</td>
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<td>Scotland</td>
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<td>France</td>
<td>2040</td>
</tr>
<tr>
<td>UK</td>
<td>2040</td>
</tr>
<tr>
<td>China</td>
<td>Actively studying</td>
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</table>

ICEVs are losing the market

- 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

Picture: Waymo autonomous car (Alphabet)
Motivation

- Autonomous EVs in University of Macau
Motivation

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

![Operations costs breakdown for ride-hailing services](chart)

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)

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

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

\[
A \hat{\Lambda}_g^{\text{arc}} = \lambda_g^{\text{OD}}, \quad \forall g \in \mathcal{G}
\]
\[
\hat{\Lambda}_g^{\text{arc}} \geq 0, \quad \forall g \in \mathcal{G}
\]

- Path flow constraints

\[
F_g^{\text{arc}} = B_g F_g^{\text{path}},
\]
\[
F_g^{\text{path}} \geq 0.
\]
**Intercity scenario**: Routing EVs to promote renewable generation

- Incorporate EV range constraints by an expanded transport network

\[ A \Lambda_g = \lambda_{od}^g, \quad \forall g \in \mathcal{G}, \]
\[ \Lambda_g \geq 0, \quad \forall g \in \mathcal{G}, \]

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

(a) The original network \(G(I, A)\)

(b) The expanded network \(G(I, \hat{A})\) (driving range 100 km)
**Intercity scenario:** Routing EVs to promote renewable generation

- Iterative algorithm based on generalized locational marginal prices

  - Initialize path set (shortest path) for each OD pair
  - Solve the PEV routing problem
  - Solve power flow & calculate generalized nodal electricity prices
  - Identify minimum-cost path for each OD pair
  - EV can change path to reduce costs?
  - Add the new path to the set
  - Output solution

  *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)


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**Intercity scenario**: Routing EVs to promote renewable generation

- Results – distribution of AEV traffic flow

![Traffic flow distribution (before routing)](image1)

![Traffic flow distribution (after routing)](image2)

Traffic flow distribution (before routing)

Traffic flow distribution (after routing)

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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

<table>
<thead>
<tr>
<th>Case</th>
<th>Power generation and purchase (MWh)</th>
<th>Fueling costs (k$/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electricity purchase</td>
<td>Conventional DG</td>
</tr>
<tr>
<td>1</td>
<td>10.37</td>
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<td>2</td>
<td>1.14</td>
<td>0.86</td>
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<td>3</td>
<td>105.37</td>
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<tr>
<td>4</td>
<td>110.21</td>
<td>0.64</td>
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</tbody>
</table>

Much cleaner energy consumption considering power-transport nexus

<table>
<thead>
<tr>
<th>Case</th>
<th>Electricity purchase (MWh)</th>
<th>Conventional DG (MWh)</th>
<th>Renewable DG (MWh)</th>
<th>Average renewable power curtailment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(MWh)</td>
<td>Bus 5</td>
<td>Bus 9</td>
<td>Bus 10</td>
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<tr>
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<tr>
<td>2</td>
<td>1.14</td>
<td>0.86</td>
<td>27.69</td>
<td>30.00</td>
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</tbody>
</table>
**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!)

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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)](image1)

![Charging demands clusters](image2)
**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

![Graphs showing mileage for different ranges and charger powers](attachment:graphs.png)

*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

![Graphs showing charging demands per AEV under different cases](image_url)

**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

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**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
Thank you!

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