COMMUNITY-AWARE CHARGING STATION NETWORK DESIGN
FOR PROMOTING LIVABILITY
REDUCING CONGESTION, EMISSIONS, IMPROVING ACCESSIBILITY, AND PROMOTING WALKING, BICYCLING, AND USE OF PUBLIC TRANSPORTATION
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PROJECT SPONSOR:
TRANSPORTATION RESEARCH CENTER FOR LIVABLE COMMUNITIES (TRCLC)
WESTERN MICHIGAN UNIVERSITY
Models for EV Charging Station Network Design
- Develop models and methods - “charging station network design”
  - Determine number, location, size, and charging levels of stations
- Assess impact on traffic flows (reduced congestion), improve livability metrics (reduced noise, greenhouse emission, increase walkability)
- Consider user choices/behaviors (e.g., range anxiety, trip distributions) as well as preferences of charging station operators (cost of location, electricity, utilizations and revenues)

Target Adoption by SEMCOG & Other Planning Agencies
- Ensure models can work with routine and available datasets and planning requirements
- Collaborate to pilot models in few communities
- Account for potential integration into larger planning projects
- Contribute to development of a practical tool kit for agencies
Current Literature & Studies

Current Literature

Traffic Demand Pattern (Arrival Times and Dwell Times; Weekdays)

Fraction of arrivals as a function of destination and time

EVSE power requirements, as determined from dwell times and next trip average distance.

<table>
<thead>
<tr>
<th>Charging location</th>
<th>Dwell time (hours)</th>
<th>Next trip avg distance (miles)</th>
<th>Energy required (kWh)</th>
<th>Power required (kW)</th>
<th>EVSE type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home</td>
<td>10.0</td>
<td>9.8</td>
<td>3.3</td>
<td>0.3</td>
<td>Level 1</td>
</tr>
<tr>
<td>Work</td>
<td>5.6</td>
<td>11.4</td>
<td>3.8</td>
<td>0.7</td>
<td>Level 1</td>
</tr>
<tr>
<td>School</td>
<td>3.2</td>
<td>8.5</td>
<td>2.8</td>
<td>0.9</td>
<td>Level 1</td>
</tr>
<tr>
<td>Medical</td>
<td>1.1</td>
<td>8.4</td>
<td>2.8</td>
<td>2.6</td>
<td>Level 2</td>
</tr>
<tr>
<td>Shopping</td>
<td>0.5</td>
<td>6.7</td>
<td>2.2</td>
<td>4.9</td>
<td>Level 2</td>
</tr>
<tr>
<td>Social</td>
<td>1.8</td>
<td>9.0</td>
<td>3.0</td>
<td>1.6</td>
<td>Level 1 or 2</td>
</tr>
<tr>
<td>Family</td>
<td>1.0</td>
<td>7.7</td>
<td>2.6</td>
<td>2.5</td>
<td>Level 2</td>
</tr>
<tr>
<td>Transport</td>
<td>0.3</td>
<td>7.0</td>
<td>2.3</td>
<td>8.3</td>
<td>Level 2</td>
</tr>
<tr>
<td>Meals</td>
<td>0.7</td>
<td>7.0</td>
<td>2.3</td>
<td>3.3</td>
<td>Level 2</td>
</tr>
</tbody>
</table>

EVSE power requirements, as determined from dwell times and next trip average distance

Source: Brooker, R. Paul, and Nan Qin. "Identification of potential locations of electric vehicle supply equipment." Journal of Power Sources 299 (2015): 76-84. – [LINK](Data Source: NHTS - Trip distances, Destination types and Destination dwell times)
EV likelihood of charging by time of day and destination
a) Nissan Leaf: 80 mile range; b) GM VOLT: 40 mile range

Source: Brooker, R. Paul, and Nan Qin. "Identification of potential locations of electric vehicle supply equipment." Journal of Power Sources 299 (2015): 76-84. – [LINK](Data Source: NHTS - Trip distances, Destination types and Destination dwell times)
State of Charge at the Time of Arrival

Recharging probability as a function of state of charge at the time of arrival

Source: Brooker, R., Qin, N., 2015. Identification of potential locations of electric vehicle supply equipment.
Current Literature & Studies …

- **Average Dwell Time at Final Destination**

![Bar chart showing average dwell time as a function of activity]

**Source:** Brooker, R., Qin, N., 2015. Identification of potential locations of electric vehicle supply equipment.
Arrival Pattern in Weekdays and Weekends

The expected breakdown of vehicle arrival percentages for weekdays (left) and weekends (right)

Source: Brooker, R., Qin, N., 2015. Identification of potential locations of electric vehicle supply equipment.
Current Literature & Studies …

- EV Market Penetration

Cumulative 2010-2014 BEV market share (left) and PHEV market share (right) across the U.S.

Willingness of Walking Distance of Drivers (USA)

Distance decay function for walking trips to different destination types

### Willingness of Walking Distance of Drivers (USA)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Category</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Season</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Winter (Dec-Feb)</td>
<td>1.88</td>
</tr>
<tr>
<td></td>
<td>Spring (Mar-May)</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>Summer (Jun-Aug)</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td>Autumn (Sep-Nov)</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>Region</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Northeast</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>Midwest</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>1.65</td>
</tr>
<tr>
<td><strong>Community</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Town and County</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>Suburban</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>Urban</td>
<td>1.78</td>
</tr>
</tbody>
</table>

*Estimated parameter for distance decay function for different factors and their categories*

Willingness of Walking Distance of Drivers (Netherlands)

Maximum distance car drivers are willing to walk per trip purpose


- Studied joint behavior of travel and parking of drivers through a time-dependent network equilibrium model.
- Travel demand, walking distance, parking capacity and parking fee are the most important factors in determining parking behavior.


- Examined the impact of public charging infrastructure on gasoline consumption of plug-in hybrid EVs.
- Public charging infrastructure benefits PHEVs with small batteries the most and reduces energy consumption of PHEVs by 30% compared to charging stations installed at homes.

- Studied the economic, environmental and technical factors that may affect charging behavior of EV drivers and in turn the electricity load on the grid.
- Charging infrastructure and battery performance are the most important factors in charging pattern of EV drivers.

Study 4: Panter, J., Desousa, C., Ogilvie, D., 2013. Incorporating walking or cycling into car journeys to and from work: The role of individual, workplace and environmental characteristics.

- Examined the individual, workplace and environmental factors that could increase the share of walking and biking activities in travelling to and from work.
- People who do not have access to parking at work and who have the most supportive environment are more likely willing to walk and bike.
- Providing limited or non-free parking at work and provide free off-site parking may encourage people to walk and bike more.
Current Literature & Studies …

- **Study 5:** Dong, J., Liu, C., Lin, Z., 2014. Charging infrastructure planning for promoting battery electric vehicles: An activity-based approach using multiday travel data.
  - Applied a genetic algorithm to find the optimal locations of charging stations for EVs considering the daily travel activity and charging behavior constraints.
  - Installing public charging stations will significantly increase EV adoption.

- **Study 6:** Capar, I., Kuby, M., Leon, V., Tsai, Y., 2013. An arc cover-path-cover formulation and strategic analysis of alternative-fuel station locations.
  - Presented a more computationally efficient model for flow-refueling location model.
  - Provided insights for managerial concerns such as OD demand forecasting uncertainty, robustness of optimal locations in regard to vehicle driving ranges.
WSU Solution Methodology

OD Pairs based on Household Survey

Estimation of potential arrival pattern for parking locations (NHTS) and final destinations

Driver Behavioral Characteristics

Willingness of drivers to adopt EVs and change to routes with potential charging stations

Distribution of final destination of drivers

Estimation of dwell time / required hours of charge

Uncertainty

Operational Constraints

Pass thru / community traffic, Budget, range anxiety, drivers with disabilities, charging rates, practical space restrictions

Stochastic Mathematical Model

Locations of potential locations, size, type, estimation of impact on pollution and coverage of potential demand

Maximizes livability indices and adoption of EVs / charging stations
**WSU Solution Methodology**

**Data Collection:**
- Total Arriving Cars
- Arrival and Departure Pattern
- EV Market Share
- Charging Away From Home Preference
- State of Charge
- Dwell Time at Final Destination
- Walking Distance Preference

**Pre-processing:**
Demand Generation (in Python)

**Sample Average Approximation:**
Generating appropriate number of scenarios to represent uncertainty for the two-stage stochastic programming model (in R)

**Post-processing:**
Accessibility and Walking Distance analysis after selecting optimal locations of charging stations (in Python)

**Stochastic Optimization**
(Python-Gurobi Interface)
**WSU Solution Methodology**

- **Notations**
  
  \[ P: \text{Set of parking lots} \]
  \[ S: \text{Set of potential charging stations} \]
  \[ L: \text{Set of number of charging stations in each location} \]
  \[ \Gamma: \text{Set of arrival and departure times} \]
  \[ T: \text{Set of time periods} \]
  \[ W: \text{Set of scenarios} \]

- **Fixed Model Parameters**
  
  \[ p: \text{Maximum number of locations for installing charging stations} \]

- **Scenario Dependent Parameters**
  
  \[ d_{\gamma(t),p,s}(w): \text{Demand with arrival and departure time of } \gamma(t) \]
  \[ \text{that is attracted from parking } p \text{ to station } s \text{ in scenario } w. \]
  \[ d_{u_{s,s'}}(w): \text{Demand that can choose both station } s \text{ and stations } s' \text{ for charging in scenario } w. \]
First-Stage Decision Variables

\( x_s : 1 \) if location \( s \) is selected for installing charging stations.

\( z_{l,s} : 1 \) if \( l \) charging station is installed in location \( s \).

Second-Stage Decision Variables

\( y_{\gamma(t),p,s}(w) : \) Captured demand with arrival and departure time of \( \gamma(t) \) that is attracted from parking \( p \) to station \( s \) in scenario \( w \).

\( c_{s,s'}(w) : 1 \) if both station \( s \) and stations \( s' \) are selected for installing charging stations in scenario \( w \).
First-Stage Model

\[ Max \ f(x, z) = E[\varphi(x, z, w)] \]

\[ \sum_{s \in S} x_s = p \]

\[ \sum_{l \in L} z_{l,s} \leq 1 \quad \forall s \in S \]

\[ z_{l,s} \leq x_s \quad \forall l \in L, s \in S \]

\[ x_s, z_{l,s} \in \{0,1\} \quad \forall l \in L, s \in S \]
WSU Solution Methodology

Second-Stage Model

\[ \varphi(x,z,w) = \text{Max} \sum_{\gamma(t) \in \Gamma, p \in P, s \in S} y_{\gamma(t),p,s}(w) - \sum_{s,s'} c_{s,s'} \ast du_{s,s'} \]

\[ \sum_{\gamma(t) \in \Gamma, p \in P, s \in S} y_{\gamma(t),p,s}(w) \leq z_{l,s} \quad \forall s \in S, t \in T \]

\[ y_{\gamma(t),p,s}(w) \leq d_{\gamma(t),p,s}(w) \quad \forall \gamma(t) \in \Gamma, p \in P, s \in S, t \in T \]

\[ c_{s,s'} \leq x_s \quad \forall s, s' \in S \]

\[ c_{s,s'} \leq x_{s'} \quad \forall s, s' \in S \]

\[ c_{s,s'} \geq x_s + x_{s'} - 1 \quad \forall s, s' \in S \]

\[ y_{\gamma(t),p,s}(w) \geq 0 \quad \forall \gamma(t) \in \Gamma, p \in P, s \in S, t \in T, c_{s,s'} \in \{0,1\} \quad \forall s, s' \in S \]
Case Study and Results

Results from synthetic networks

<table>
<thead>
<tr>
<th></th>
<th>Small Network</th>
<th>Large Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Final Destinations</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Number of Parking Lots</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Number of Potential Charging Locations</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Charging Capacity</td>
<td>2 packs with 4 outlets</td>
<td>2 packs with 10 outlets</td>
</tr>
</tbody>
</table>

Sample Average Approximation to find optimal number of scenarios to generate.

SAA result for case $p = 1$ (top left), $p = 2$ (top right), $p = 3$ (bottom left) and $p = 4$ (bottom right) and $(M,N') = (20,1000)$
Case Study and Results

Results from synthetic networks

Optimal locations (blue) of charging stations in small network for cases of $p = 2$ (left) and $p = 3$ (right) when market share is 1% for BEV and 2% for PHEV.

Optimal locations (blue) of charging stations in large network for cases of $p = 1$ (left) and $p = 2$ (right) when market share is 2% for BEV and 5% for PHEV.
Case Study and Results

Results from synthetic networks

<table>
<thead>
<tr>
<th></th>
<th>Market Share (BEV :1%, PHEV 2%)</th>
<th>Market Share (BEV:0.05%, PHEV 0.4%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Chargers</td>
<td>Access</td>
<td>Walking Distance</td>
</tr>
<tr>
<td>P = 1</td>
<td>8</td>
<td>1%</td>
</tr>
<tr>
<td>P = 2</td>
<td>12</td>
<td>1%</td>
</tr>
</tbody>
</table>

Access to charging stations and walking distances in small network.

<table>
<thead>
<tr>
<th></th>
<th>Market Share (BEV :1%, PHEV 2%)</th>
<th>Market Share (BEV :2%, PHEV 5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Chargers</td>
<td>Access</td>
<td>Walking Distance</td>
</tr>
<tr>
<td>P = 1</td>
<td>10</td>
<td>1%</td>
</tr>
<tr>
<td>P = 2</td>
<td>20</td>
<td>1%</td>
</tr>
</tbody>
</table>

Access to charging stations and walking distances in large network.

- Negative values for walking imply that people are willing to walk less if we install charging stations at the optimal locations.
The AARP Public Policy Institute has developed the following categories that determine a community's strengths and weaknesses in terms of livability:

- Housing affordability as measured by housing cost burdens and the availability of subsidized housing
- Neighborhood quality as measured by safety metrics and vacancy rates, as well as proximity to grocery stores, parks, libraries, jobs, and so on
- Alternative transportation options that connect people to social activities, economic opportunities, and health care
- Environmental conditions, including air and water quality, as well as resiliency plans that incorporate disaster recovery and energy efficiency
- Health access, as measured by access to exercise options, health care availability, access to healthy food
- Civic engagement, including residents' ability to reduce social isolation through community engagement, measured by voting rates, number of cultural/arts institutions, and organizations, and access to the internet
- Employment opportunities
Increasing transportation options for people will improve livability.

<table>
<thead>
<tr>
<th>Impact</th>
<th>Urban Peak ($)</th>
<th>Urban Off-Peak ($)</th>
<th>Rural ($)</th>
<th>Average ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Congestion Restriction</td>
<td>0.2</td>
<td>0.05</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>Reduced Barrier</td>
<td>0.1</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Energy Conservation</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Pollution Reduction</td>
<td>0.1</td>
<td>0.05</td>
<td>0.01</td>
<td>0.044</td>
</tr>
</tbody>
</table>

Economic value of benefits of reduced motor vehicle travel per mile.


<table>
<thead>
<tr>
<th>Walking Level</th>
<th>Internal Benefits ($)</th>
<th>External Benefits ($)</th>
<th>2007 U.S. Dollars per mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.12</td>
<td>0.12</td>
<td>0.24</td>
</tr>
<tr>
<td>Medium</td>
<td>0.24</td>
<td>0.24</td>
<td>0.48</td>
</tr>
<tr>
<td>High</td>
<td>0.48</td>
<td>0.48</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Economic value of public health benefits from walking

Thank You!

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