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Motivation – Urban Electric Mobility

- No local emissions
- Technological advances
  - Extended range
  - Cost-efficiency
- However
  - High initial cost
  - Still limited range
  - Time-consuming recharging
Main challenge:
- Limited range and long recharging times

Strategic decisions:
- Location of charging stations
- Long-term fleet mix

Operational decisions:
- Vehicle allocation
- Tour planning
Strategic Planning – Location of Charging Stations
◆ Decision support system for placing fast charging stations for electric taxi cabs
◆ Support decision makers to implement an electric taxi cab service
◆ Trade-off between budget and coverage of charging demand and road network
• GPS data from 800 taxis over one year (2014)
• Density map start/end locations
  • High demand in inner districts
  • High probability to start/end trip in high demand areas

• Goal: Locating fast-charging stations in regions with high density and high overall coverage
- Select regions for location of fast-charging stations
- Final exact locations require negotiations
- Sum up the charging demand occurring in hexagons with diameter of 1km
Computing optimal regions for installing charging stations

MIP Model
- Maximise covered trips
- Include existing infrastructure
- Hexagons and their neighbours are covered with configurable weights

\[
\begin{align*}
\max & \sum_{i \in H} c_i x_i \\
\text{subject to} & \sum_{i \in H \setminus \overline{H}} y_i \leq R \\
& y_i = 1 & \forall i \in \overline{H} \\
& x_i \leq w_0 y_i + \sum_{j \in N_i} w_1 y_j & \forall i \in H \\
& 0 \leq x_i \leq M & \forall i \in H \\
& y_i \in \{0, 1\} & \forall i \in H
\end{align*}
\]
(c) $R = 10, w_1 = 0.5$

(d) $R = 10, w_1 = 1$
(c) $R = 10, w_1 = 0.5$

(d) $R = 10, w_1 = 1$
### Percentage of network length (%)

<table>
<thead>
<tr>
<th>$R$</th>
<th>$w_1$</th>
<th>Travel time $\leq 5$ min [Min., Max.]</th>
<th>Travel time $\leq 8$ min [Min., Max.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.5</td>
<td>[9, 10]</td>
<td>[21, 24]</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>[11, 13]</td>
<td>[28, 31]</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>[16, 17]</td>
<td>[31, 35]</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>[18, 20]</td>
<td>[38, 43]</td>
</tr>
<tr>
<td>20</td>
<td>0.5</td>
<td>[28, 30]</td>
<td>[49, 53]</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>[30, 35]</td>
<td>[68, 73]</td>
</tr>
<tr>
<td>30</td>
<td>0.5</td>
<td>[40, 42]</td>
<td>[70, 75]</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>[41, 47]</td>
<td>[93, 99]</td>
</tr>
</tbody>
</table>
Strategic Planning – Fleet Management
- Long-term strategic decisions regarding fleet composition
- Consideration of vehicle pools
- Securing the satisfaction of daily mobility needs
- Incorporation of modal alternatives (e.g. public transport, bicycle)

- Goal: decision making tool supporting fleet managers in strategic planning (once or twice a year)
- Medium term scenarios about development of mobility needs, vehicle characteristics and infrastructure
- **Vehicles**
  - Existing vehicles
  - Vehicles to be acquired
  - Acquisition and salvage cost
  - Maintenance cost

- **Mobility demand**
  - Representative daily trips per time period (month, quarter)
  - Trip cost and emissions depending on vehicle type
  - Trip cost and emissions for rented vehicles

- **Possible alternative modes of transport**
A Flexible Modeling Framework

Vehicle Acquisition
- First stage decisions
- Minimization of time dependent cost and expected distance dependent cost
- Minimization of expected emissions

Vehicle Assignment
- Second stage decisions
- Multiple representative single-day scenarios per time period
- Minimization of distance dependent cost
- Minimization of emissions
Iterative method starting from a solution using the initial fleet
Buying and reselling decisions of single vehicles in the fleet are evaluated and, if the cost and emissions are smaller than the best solutions already found, they are added as a new candidate for the next iteration
Fleet composition (start):
- 7 conventional vehicles

Solution 1 (final):
- +4 BEV
- +4 PHEV

Solution 2 (final):
- +3 BEV
- +2 PHEV
Operational Planning
Problem Definition

Hybrid Heterogeneous Electric Vehicle Routing Problem with Time Windows and recharging stations

◆ 3 vehicle classes
  ◆ Internal Combustion Engine Vehicles (ICEV)
  ◆ Battery Electric Vehicles (BEV)
  ◆ Plug-in Hybrid Electric Vehicles (PHEV)

◆ Problem Setting
  ◆ single depot (d)
  ◆ customers (C)
  ◆ recharging stations (F)
  ◆ different cost for using energy or fossil fuel
- **Internal Combustion Engine Vehicles** => VRPTW
  - well researched topic

- **Battery Electric Vehicles** => E-VRPTW(PR)
  - visits to additional nodes (recharging stations) for recharging
  - partial recharging (PR)
    - no recharge to maximum capacity required
    - additional decision on the amount recharged per visit

Routing Problems
**Plug-in Hybrid Electric Vehicles**

- visits to additional nodes (recharging stations) for recharging
- partial recharging assumed as well
- decision when to use
  - pure electric engine
  - Internal combustion engine

**Assumption**
- use of electric energy is always better
Methodology – Decision Layers

ICEV

- itinerary

BEV

- itinerary
- RS visits
- charge in RS

PHEV

- itinerary
- RS visits
- charge in RS
- mode selection

(RS .. recharging station)
Methodology – Decision Layers

ICEV

BEV

PHEV

itinerary

itinerary

itinerary

RS visits

charge in RS

charge in RS

mode selection

(RS .. recharging station)
Methodology – Decision Layers

ICEV
- itinerary
- RS visits
- charge in RS

BEV
- itinerary
- charge in RS

PHEV
- itinerary
- charge in RS
- mode selection

Top Layer
Methodology – Decision Layers

<table>
<thead>
<tr>
<th>ICEV</th>
<th>BEV</th>
<th>PHEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>itinerary</td>
<td>itinerary</td>
<td>itinerary</td>
</tr>
<tr>
<td></td>
<td>RS visits</td>
<td>RS visits</td>
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<tr>
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<tr>
<td></td>
<td></td>
<td>mode selection</td>
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</table>
Implicit handling of Recharging Stations
Implicit handling of Recharging Stations
Implicit handling of Recharging Stations
• Population-based Metaheuristic (Hybrid Genetic Algorithm)
• Chromosome consists of
  - giant tour without route delimiter (and recharging stations)
  - full solution (list of complete tours)
• Individual is selected using binary tournament selection
• Penalization
  - load capacity and time-window relaxation
Crossover
- selecting a second Individual using Binary Tournament as well
- Ordered Crossover (OX) on the giant tours
- using split procedure for decoding
Large Neighbourhood Search
- set of destroy operators
- random removal
- similar (Shaw)
- route removal
- target
- set of repair operators
- greedy insertion
- 2-regret insertion
- random selection (roulette-wheel with equal probability)
◆ Set Partitioning
  - pre-processed set of all 1-2 customer tours
  - store promising complete tours (> 2 customers) throughout the search
  - solve set partitioning problem
**Local Search (Education)**

- 2Opt, 2Opt*
- Relocate (1-2), Swap (0-2)
- also used as a heuristic repair step (multiply penalties by 10/100)
- higher fuel prices => more electric vehicles
- lower fixed cost still a major advantage of ICEVs
Daily fee for entering a controlled area
- London, Singapore, Stockholm, Milan ...
A City Center (CC) is an Area

With a finite number of entry points (crossing streets)

Partitions the set of customers into

- Inside $C_1$ (green)
- Outside $C_2$

Any path between $u$ and $v$

\[ u \in C_i, \ v \in C_j, \ i \neq j \]

consists of an odd number of entry points

- Not necessarily euclidian distances
- **Time restrictions**
  - e.g. prohibited from 9-17h

- **Engine**
  - e.g. no internal combustion engines

- **Vehicle type**
  - e.g. only small vehicles / bikes

- **Penalization**
  - one time fee
  - per km cost
A leg is described by
- from / to node
- all intermediate entry points used
- distance / time / energy needed
A leg is described by:
- from / to node
- all intermediate entry points used
- distance / time / energy needed

Required to travel between inside and outside nodes.
A leg is described by
- from / to node
- all intermediate entry points used
- distance / time / energy needed

Travel between inside and outside nodes
Also between outside / outside (inside / inside)
- shortcut through the city center
- drive around the center (i.e., avoiding low speed limits)
Experiments using a street graph

- **Vienna**
- **Random node locations**
  - 1 depot
  - 5 recharging stations
  - 116 customers
  - 35 entry points
- **Properties**
  - 8h planning horizon
  - random demand (1-20 units)
  - Time window (0.5-2h)
  - Optimistic recharging technology (16kWh in 0.6h)
Experiments using a street graph

Example instance solution
Experiments using a street graph

Results

km per type inside/outside the city center

- ICEV (inside)
- ICEV (outside)
- PHEV (inside)
- PHEV (outside)
- BEV (inside)
- BEV (outside)
Experiments using a street graph

Results

km per type inside/outside the city center

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- BEV (outside)

km

km per type inside/outside the city center

- no-restriction
- icev-restriction
- daily-2
- daily-5
- daily-10
- km-0.5
- km-1.2
- km-2.0
Experiments using artificial data

- Artificial instances based on classical Solomon / Schneider instances
- Adaptations from the original values
  - orig ../ original values of the instance
  - ref ... BEV-L (base fleet configuration)
  - distance
    \[
    \frac{\text{orig.battery}}{\text{orig.consumption}} \div \frac{\text{ref.battery}}{\text{ref.consumption}}
    \]
  - time
    - time window length of the depot node equals 8h
  - recharging rate
    - as the original

- Fleet-configuration based on Fraunhofer study (Plötz et al. 2013)
  - small / medium / large - sized vehicles
  - utility cost also includes driver wage (18€/h)
  - battery-size and consumption rate normalized relative to the largest vehicle
  - capacity assumed 50/75/100% of the original value
Experiments using artificial data - Results

km per type inside/outside the city center
Experiments using artificial data - Results

km per type inside/outside the city center

- ICEV (inside)
- ICEV (outside)
- PHEV (inside)
- PHEV (outside)
- BEV (inside)
- BEV (outside)

km per type inside/outside the city center

- no-restriction
- icev-restriction
- daily-2
- daily-5
- km-0.5
- km-1.2
- km-2.0
Big difference between street graph and artificial instances

- Artificial instances are designed for BEVs
  - Distances scale might be too beneficial for BEVs
  - Recharging rates still artificial
- Vienna city center is rather small
  - Per km cost do not have a large enough impact
  - Additional cost of heavier PHEVs (fixed + variable) are larger than a high daily fee
  - Close depot location favors BEVs instead of PHEVs
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