Urban Electric Vehicle Fleets: Strategic and Operational Management

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ACKNOWLEDGEMENTS

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Motivation – Urban Electric Mobility

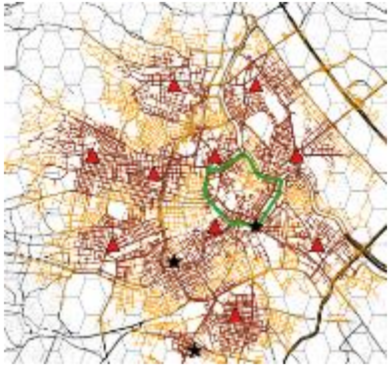
- **No local emissions**
- **Technological advances**
  - Extended range
  - Cost-efficiency
- **However**
  - High initial cost
  - Still limited range
  - Time-consuming recharging

- **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

Charging Station Location for Taxi Cabs

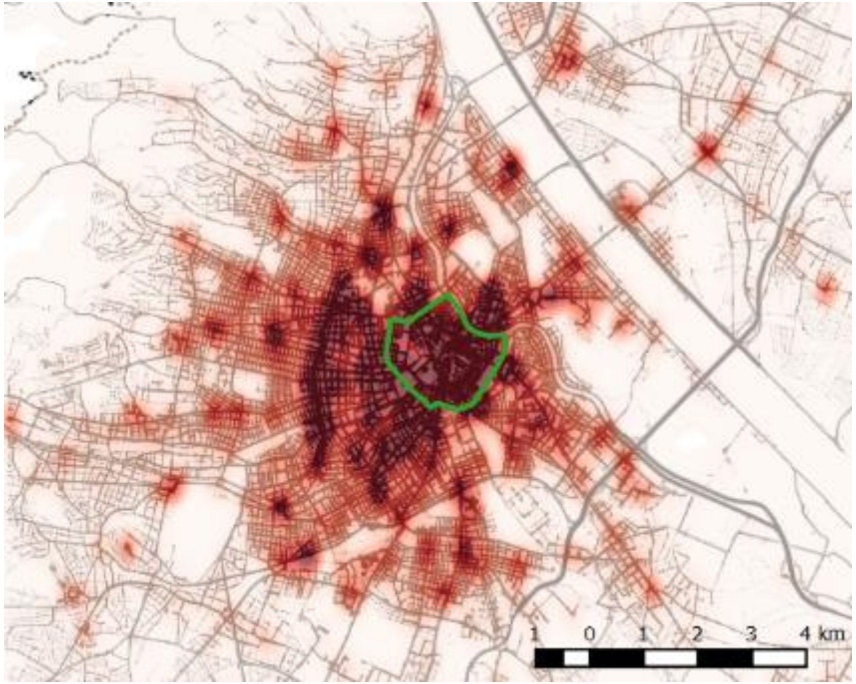
- **Decision support system for placing fast charging stations for electric taxi cabs**
- **Support decision makers to implement an electric taxi cab service**
- **Trade-of between budget and coverage of charging demand and road network**



Charging Station Location for Taxi Cabs

- **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

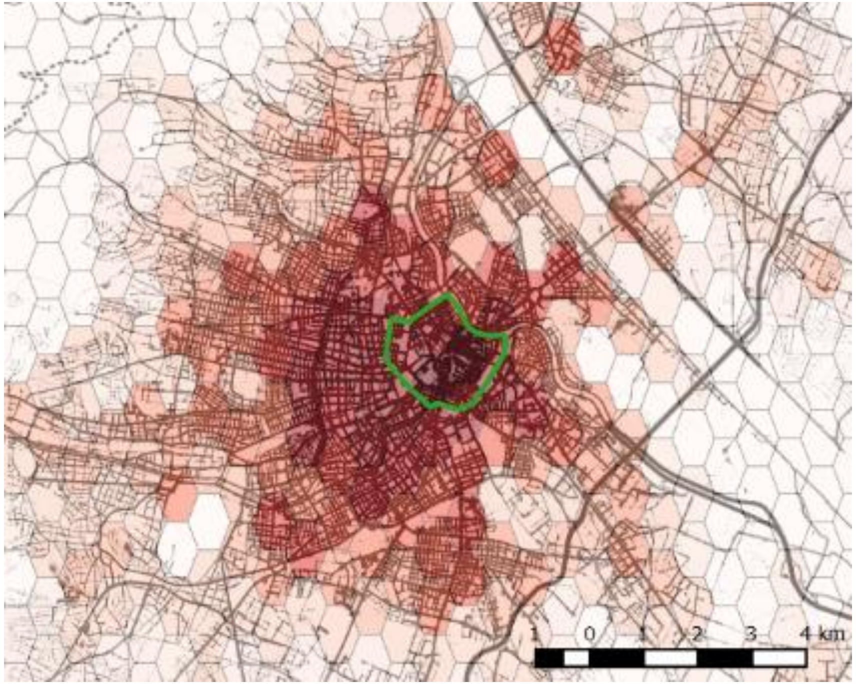
- **Goal: Locating fast-charging stations in regions with high density and high overall coverage**



Charging Station Location for Taxi Cabs

- Select regions for location of fast-charging stations
- Final exact locations require negotiations

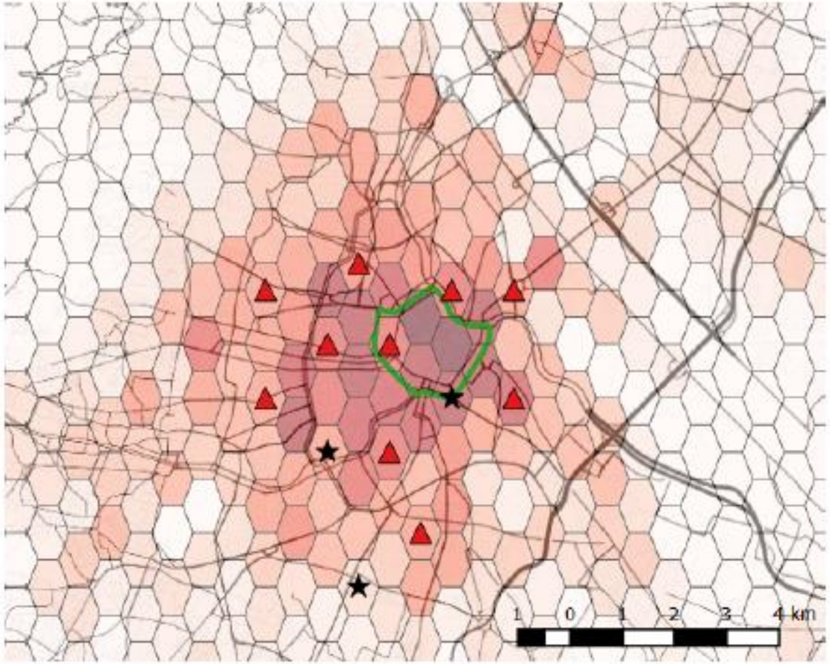
- Sum up the charging demand occurring in hexagons with diameter of 1km



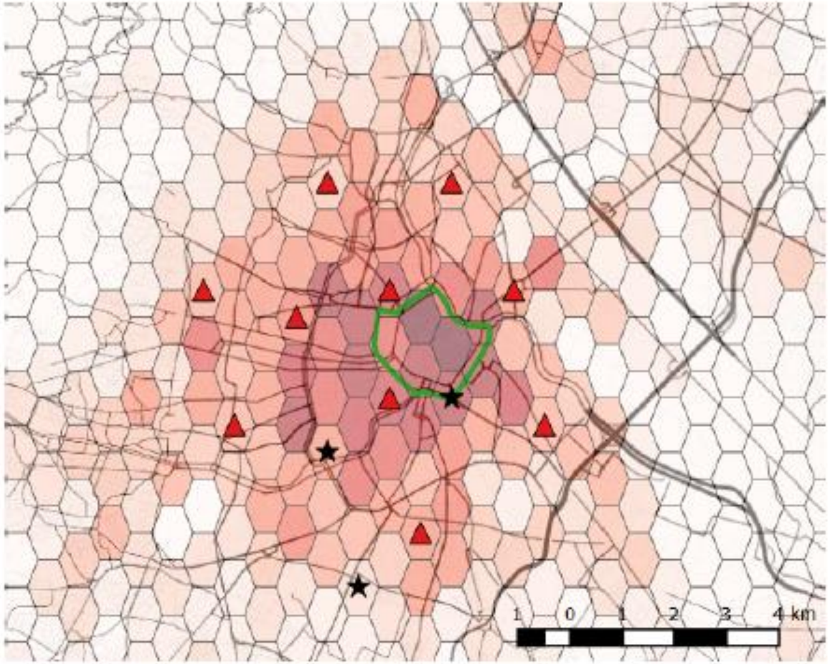
- **Computing optimal regions for installing charging stations**

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

$$
\begin{aligned}
\max \sum_{i \in H} c_i x_i & & \\
\text{subject to} \quad \sum_{i \in H \setminus \overline{H}} y_i &\le R & \\
y_i &= 1 & \forall i \in \overline{H} \\
x_i &\le w_0 y_i + \sum_{j \in N_i} w_1 y_j & \forall i \in H \\
0 \le x_i &\le M & \forall i \in H \\
y_i &\in \{0, 1\} & \forall i \in H
\end{aligned}
$$

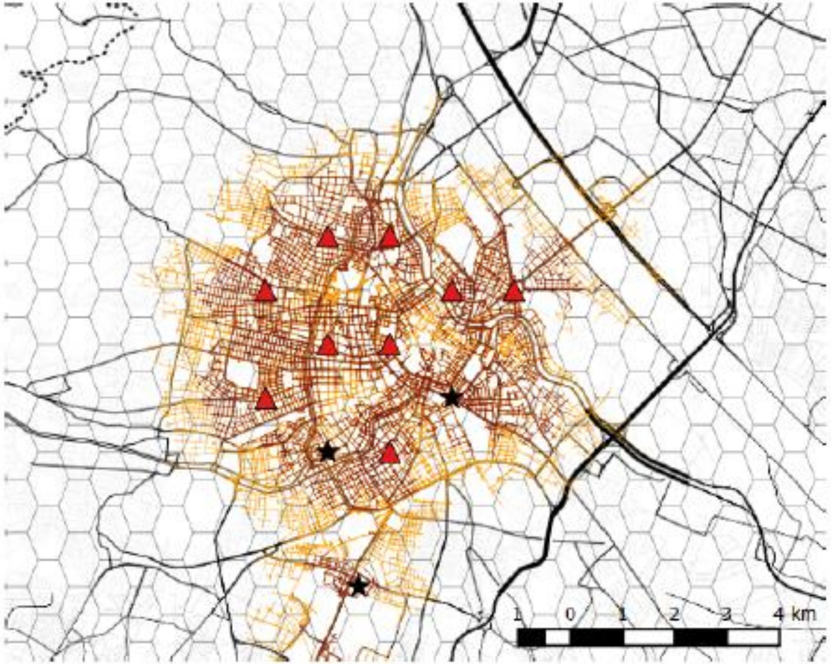


(c) $R = 10, w_1 = 0.5$

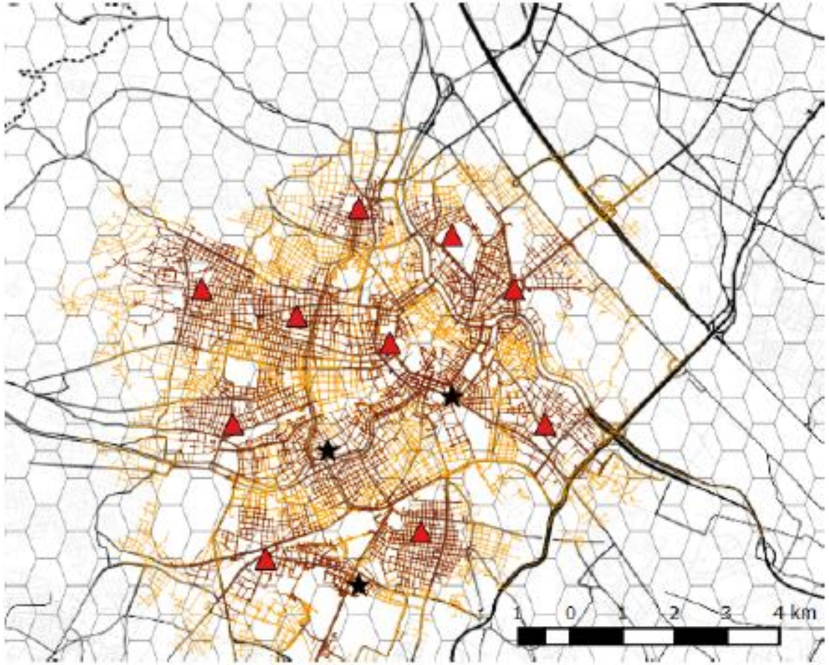


(d) $R = 10, w_1 = 1$

Isochrones



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



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

Percentage of network length (%)			
		Travel time $\leq$ 5 min	Travel time $\leq$ 8 min
R	w_1	[Min., Max.]	[Min., Max.]
5	0.5	[9, 10]	[21, 24]
5	1	[11, 13]	[28, 31]
10	0.5	[16, 17]	[31, 35]
10	1	[18, 20]	[38, 43]
20	0.5	[28, 30]	[49, 53]
20	1	[30, 35]	[68, 73]
30	0.5	[40, 42]	[70, 75]
30	1	[41, 47]	[93, 99]

Strategic Planning – Fleet Management

Strategic 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)

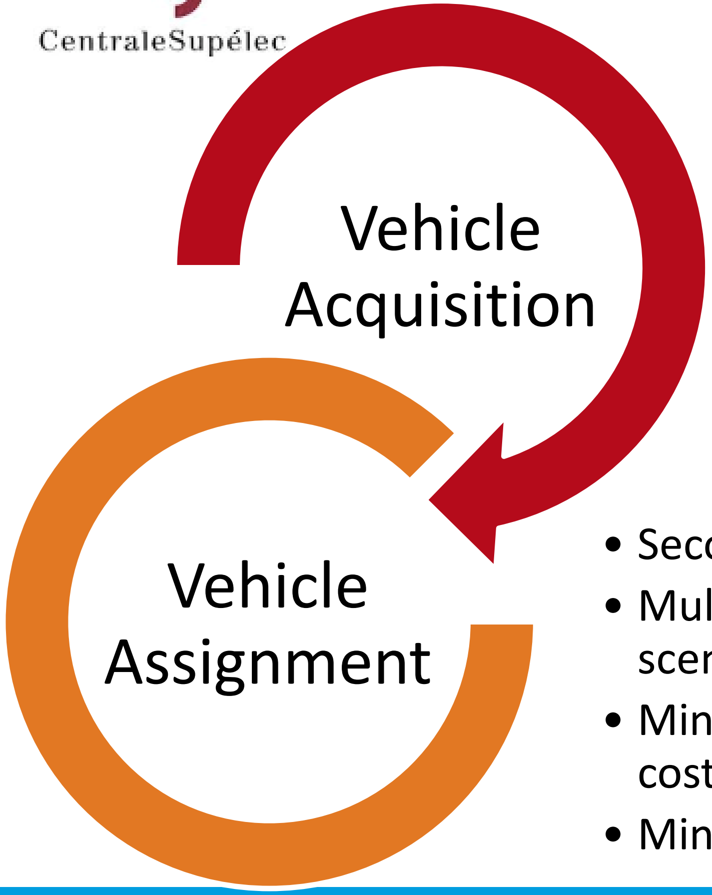
- Goal: decision making tool supporting fleet managers in strategic planning (once or twice a year)
- Medium term scenarios about development of mobility needs, vehicle characteristics and infrastructure

- **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**

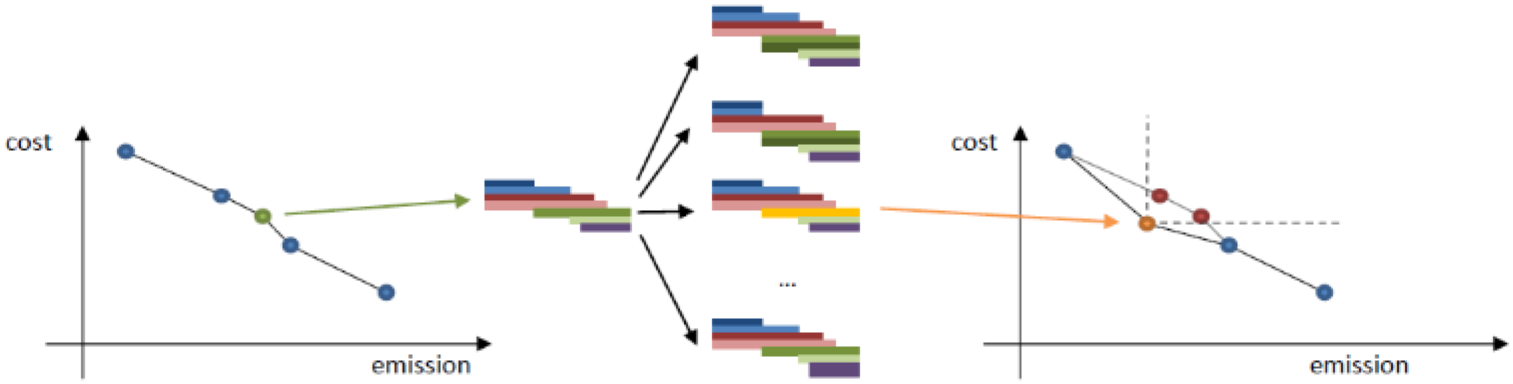
A Flexible Modeling Framework



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

- 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

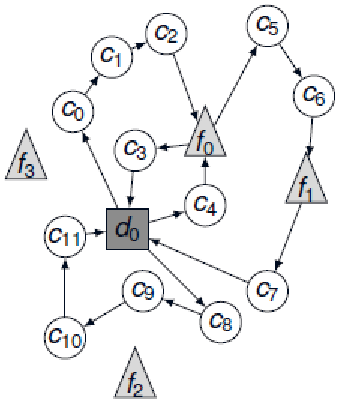


Example: Corridor Vienna-Graz

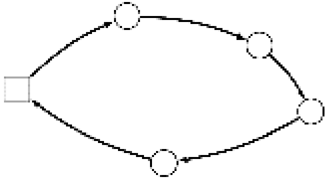
- **Fleet composition (start):**
  - 7 conventional vehicles
- **Solution 1 (final):**
  - +4 BEV
  - +4 PHEV
- **Solution 2 (final):**
  - +3 BEV
  - +2 PHEV

Operational Planning

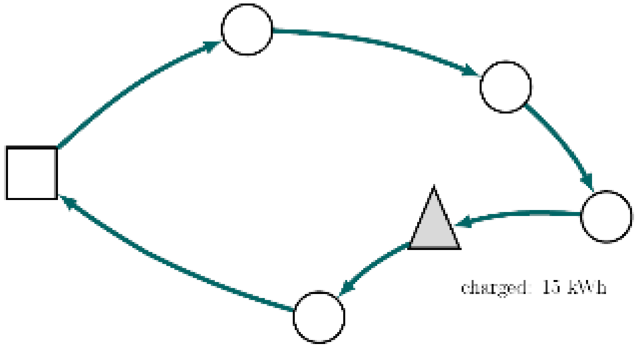
- **3 vehicle classes**
  - Internal Combustion Engine Vehicles (ICEV)
  - Battery Electric Vehicles (BEV)
  - Plug-in Hybrid Electric Vehicles (PHEV)
- **Problem Setting**
  - single depot (d)
  - customers (C)
  - recharging stations (F)
  - different cost for using energy or fossil fuel



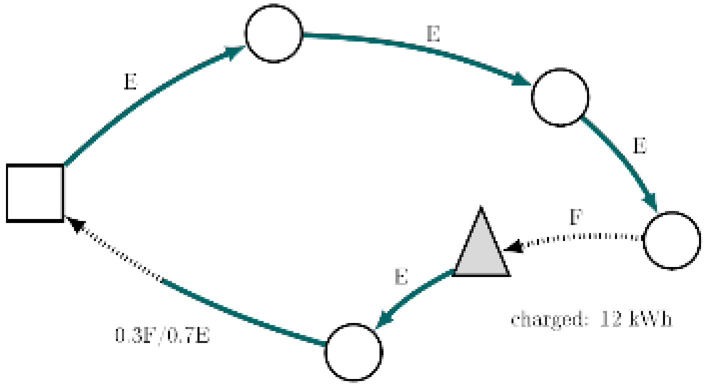
- **Internal Combustion Engine Vehicles => VRPTW**
  - well researched topic



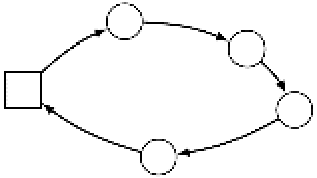
- **Battery Electric Vehicles => E-VRPTW(PR)**
  - visits to additional nodes (recharging stations) for recharging
  - partial recharging (PR)
    - no recharge to maximum capacity required
    - additional decision on the amount recharged per visit



- **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

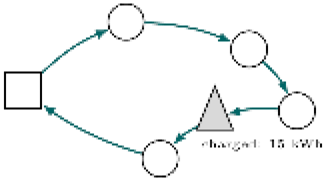


ICEV



itinerary

BEV

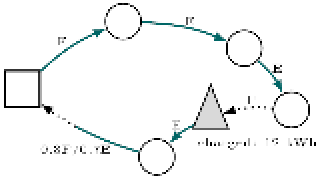


itinerary

RS visits

charge in RS

PHEV



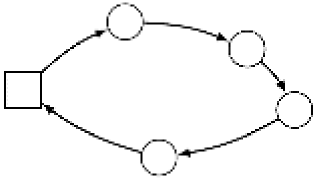
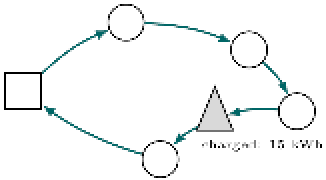
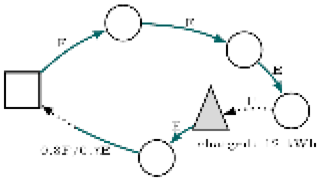
itinerary

RS visits

charge in RS

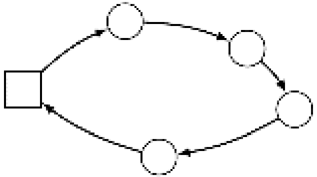
mode selection

(RS .. recharging station)

ICEV	BEV	PHEV
		
itinerary	itinerary	itinerary
	RS visits	RS visits
	charge in RS	charge in RS
		mode selection

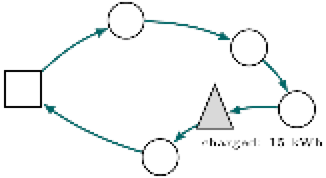
(RS .. recharging station)

ICEV

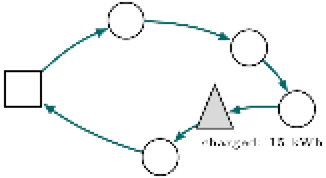


itinerary

BEV



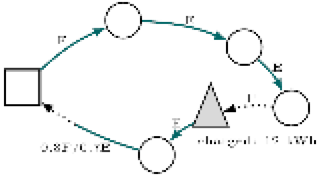
itinerary



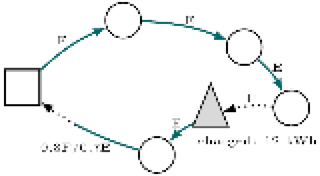
RS visits

charge in RS

PHEV



itinerary



RS visits

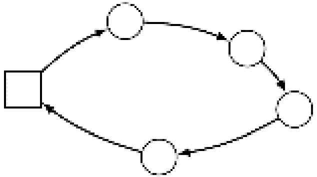
charge in RS

mode selection

Top Layer

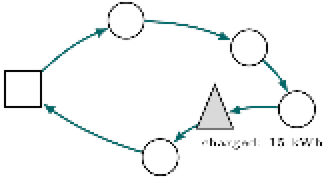
Methodology – Decision Layers

ICEV

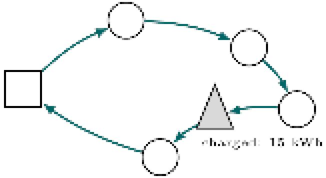


itinerary

BEV



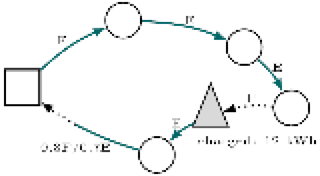
itinerary



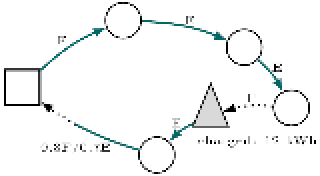
RS visits

charge in RS

PHEV



itinerary



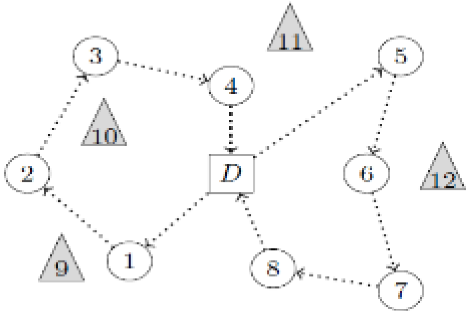
RS visits

charge in RS

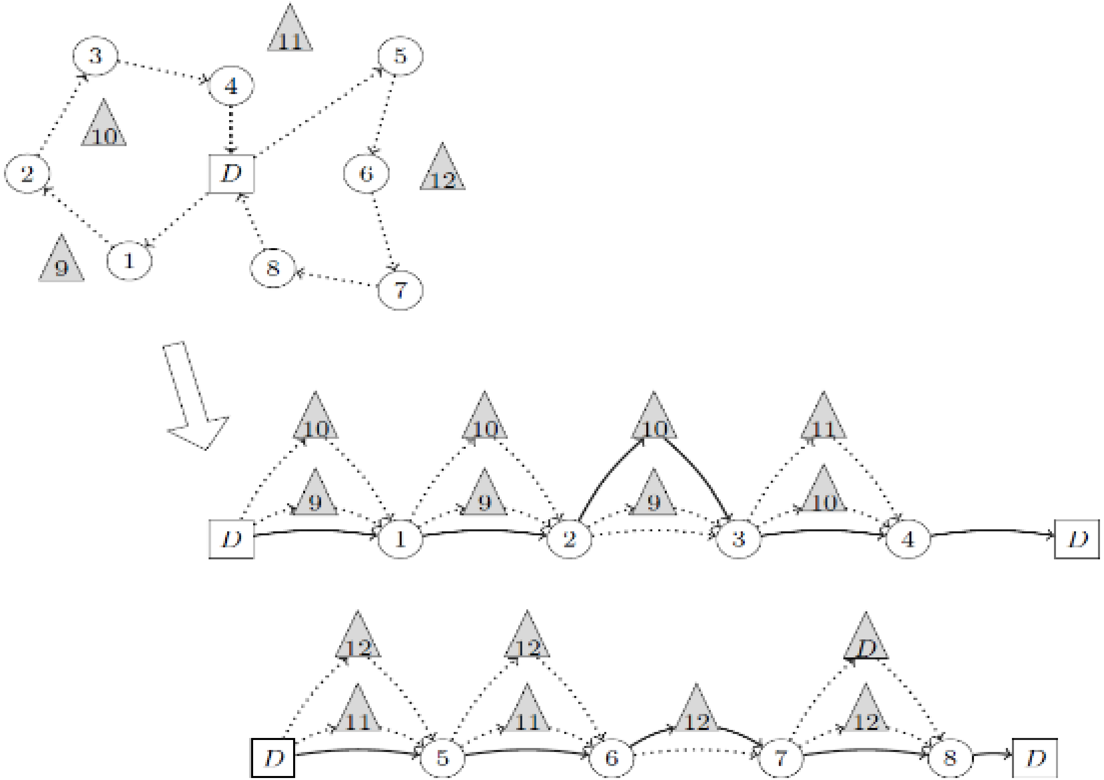
mode selection

Top Layer

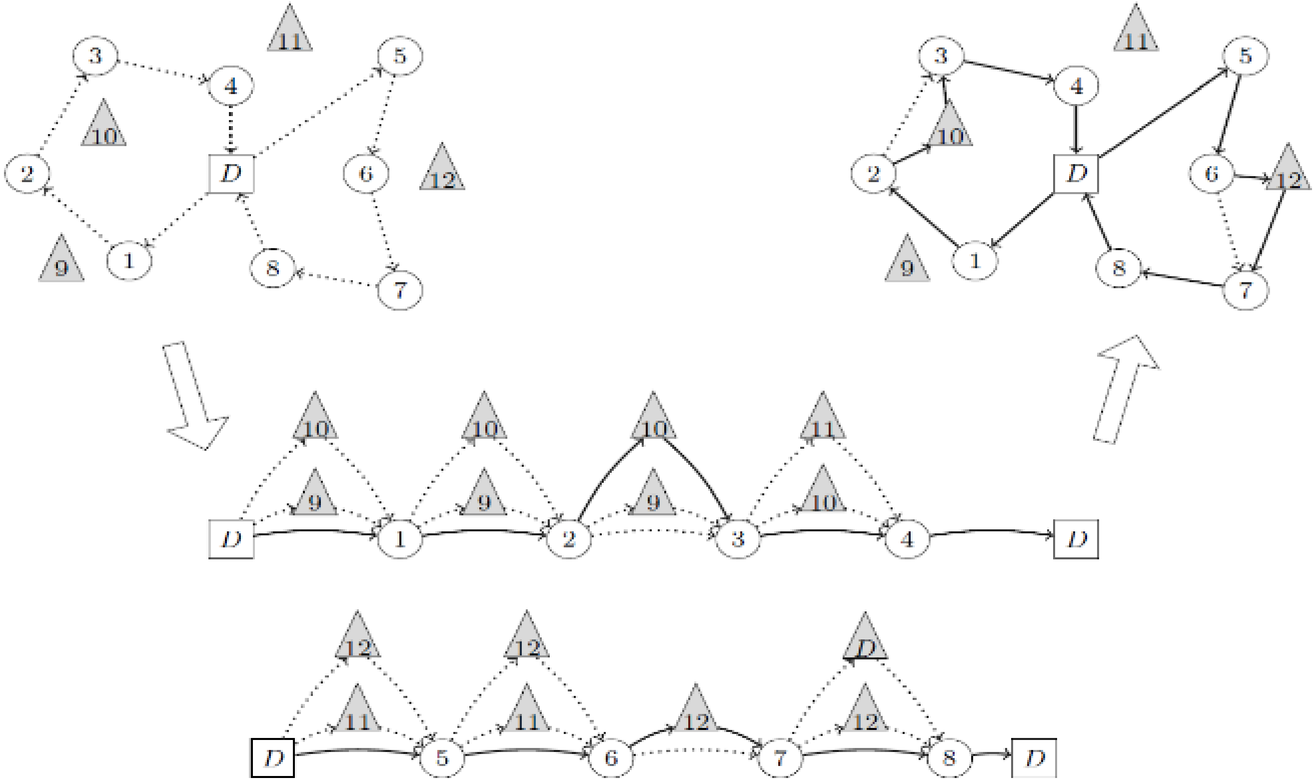
Implicit handling of Recharging Stations



Implicit handling of Recharging Stations

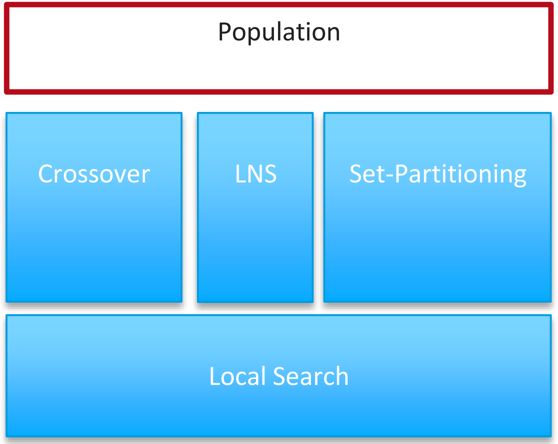


Implicit handling of Recharging Stations



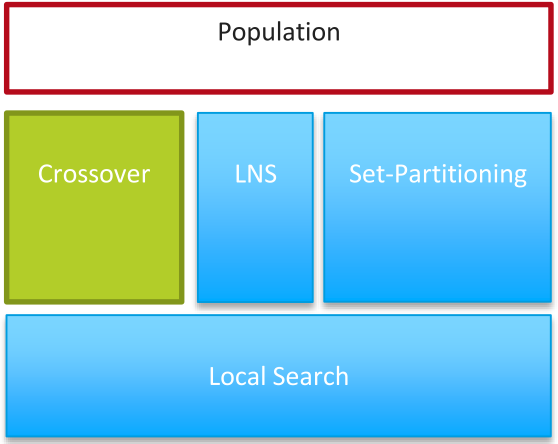
Heuristic Solver

- **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

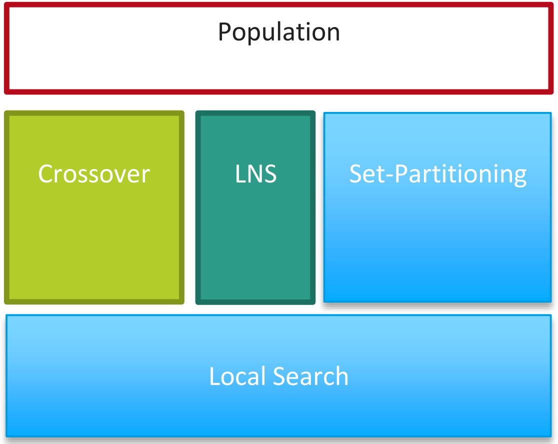


Crossover

- selecting a second Individual using Binary Tournament as well
- Ordered Crossover (OX) on the giant tours
- using split procedure for decoding

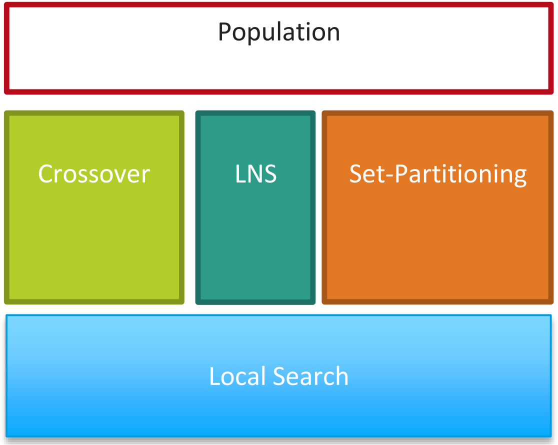


- **Large Neighbourhood Search**
  - set of destroy operators
  - random removal
  - similar (Shaw)
  - route removal
  - target
  - set of repair operators
  - greedy insertion
  - 2-regret insertion
  - random selection (roulette-wheel with equal probability)

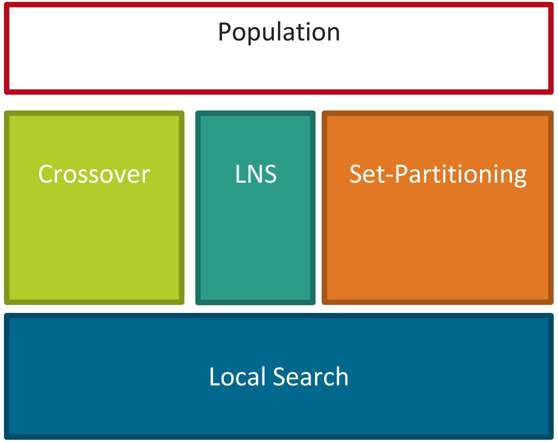


Set Partitioning

- pre-processed set of all 1-2 customer tours
- store promising complete tours (> 2 customers) throughout the search
- solve set partitioning problem

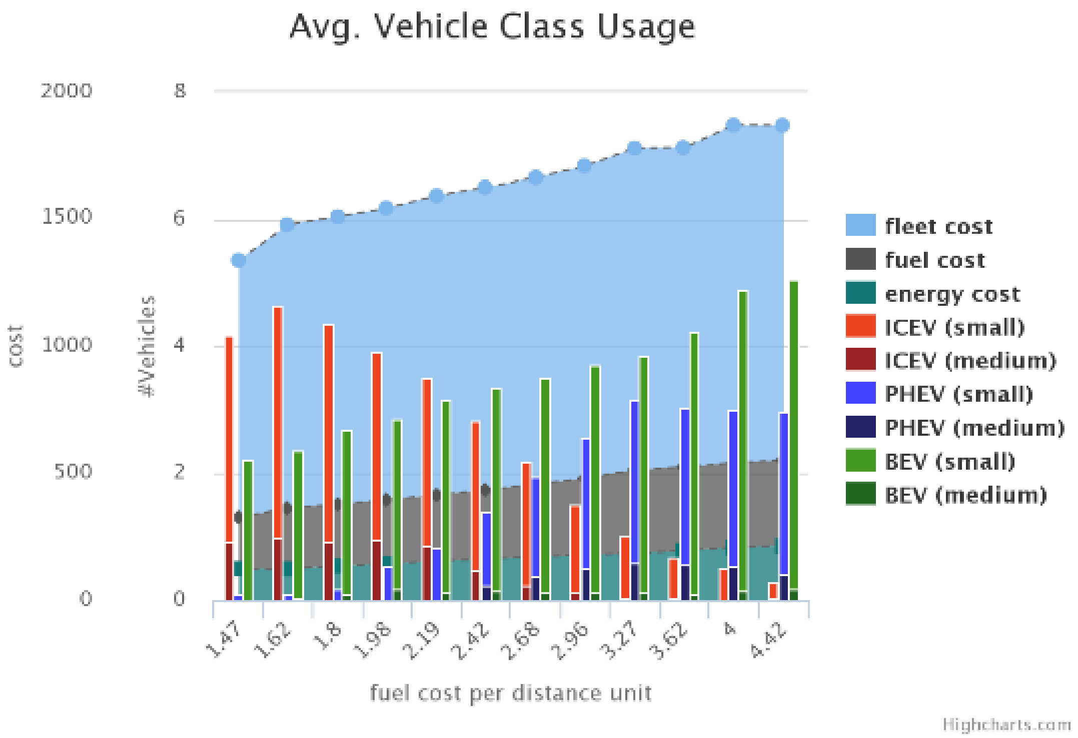


- **Local Search (Education)**
  - 2Opt, 2Opt*
  - Relocate (1-2), Swap (0-2)
  - also used as a heuristic repair step (multiply penalties by 10/100)

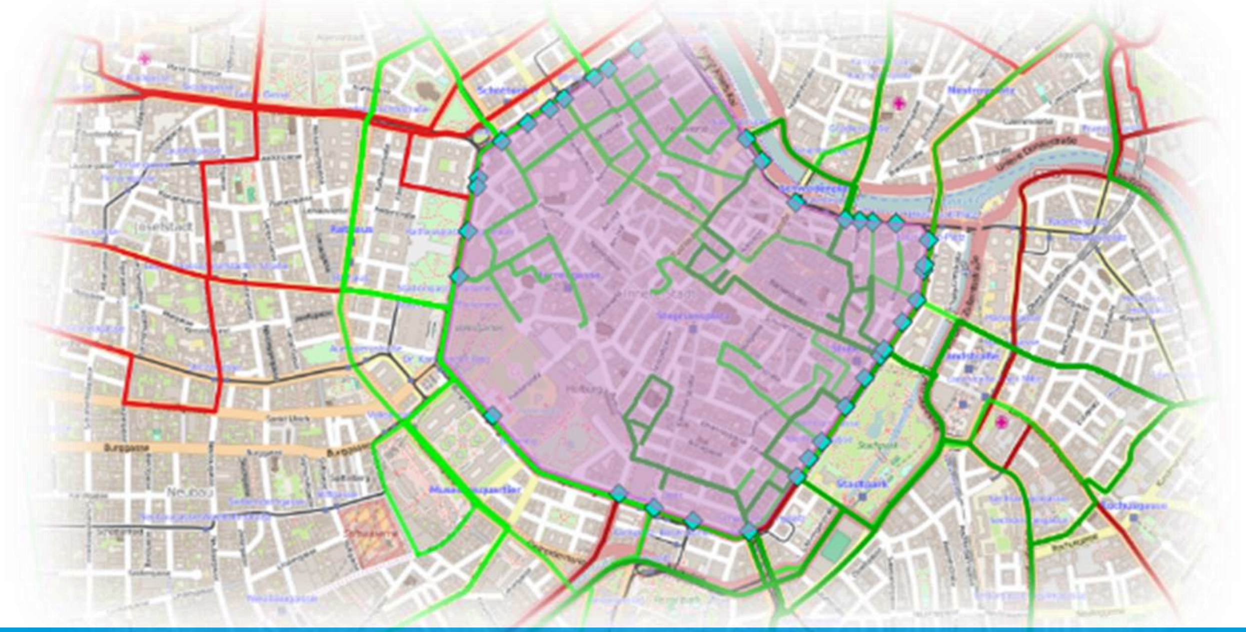


Experimental Results

- 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 …



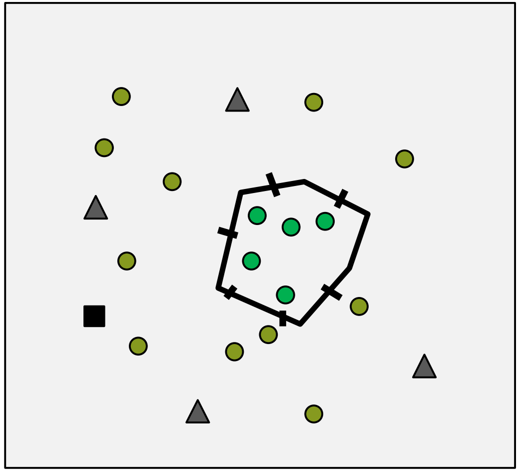
What is a City Center?

- **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**

$$u \in C_i, v \in C_j, i \neq j$$

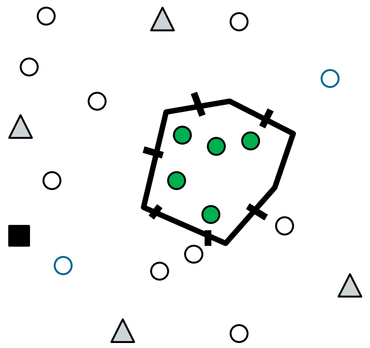
consists of an odd number of entry points

- **Not necessarily euclidian distances**



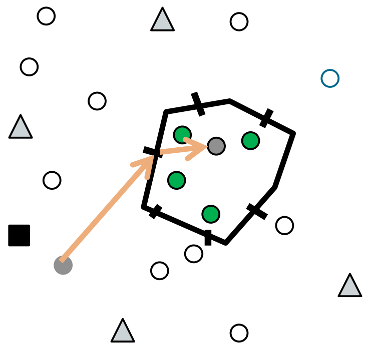
- Time restrictions
  - e.g. prohibited from 9-17h
- **Engine**
  - e.g. no internal combustion engines
- Vehicle type
  - e.g. only small vehicles / bikes
- **Penalization**
  - one time fee
  - per km cost

- **A leg is described by**
  - from / to node
  - all intermediate entry points used
  - distance / time / energy needed



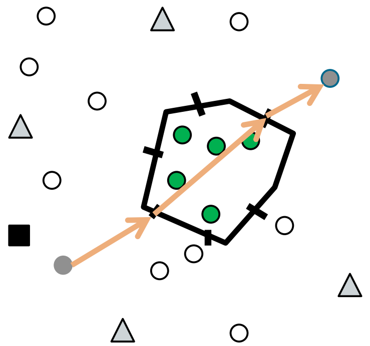
Additional Decision: Leg use

- **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**

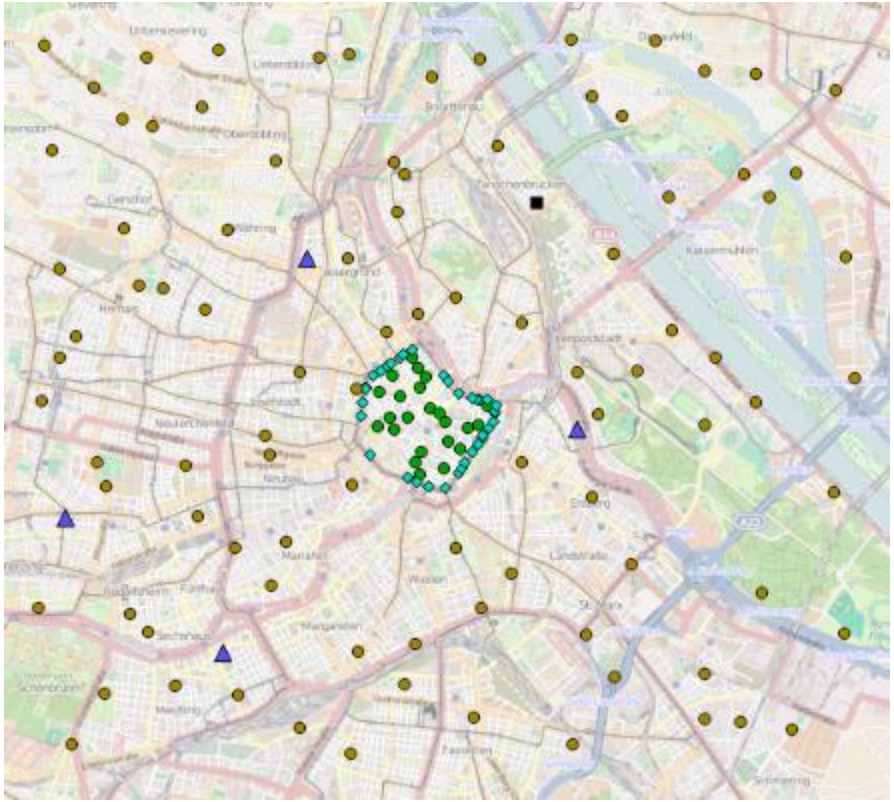
- **A leg is described by**
  - from / to node
  - all intermediate entry points used
  - distance / time / energy needed



- **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)

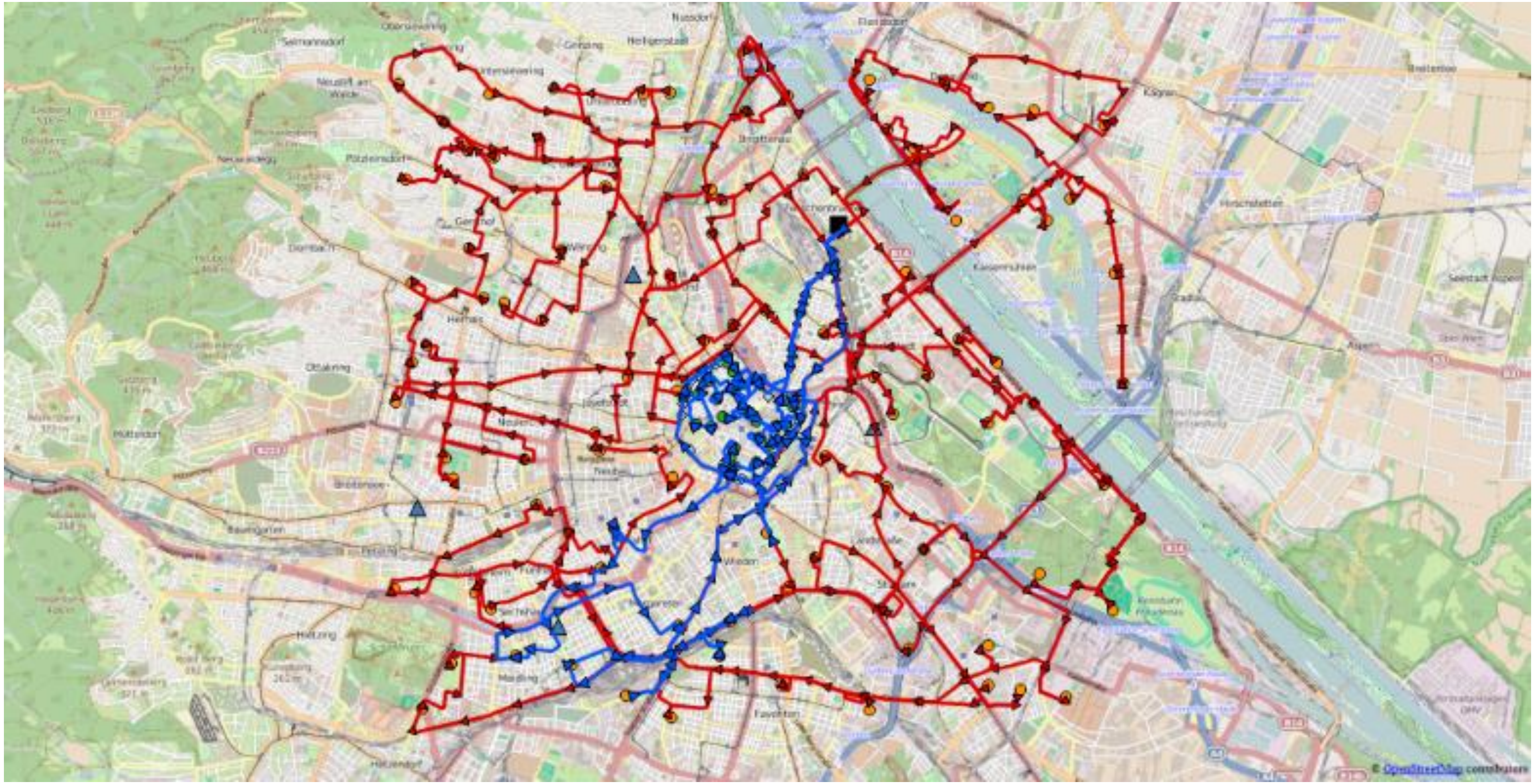
Experiments using a street graph

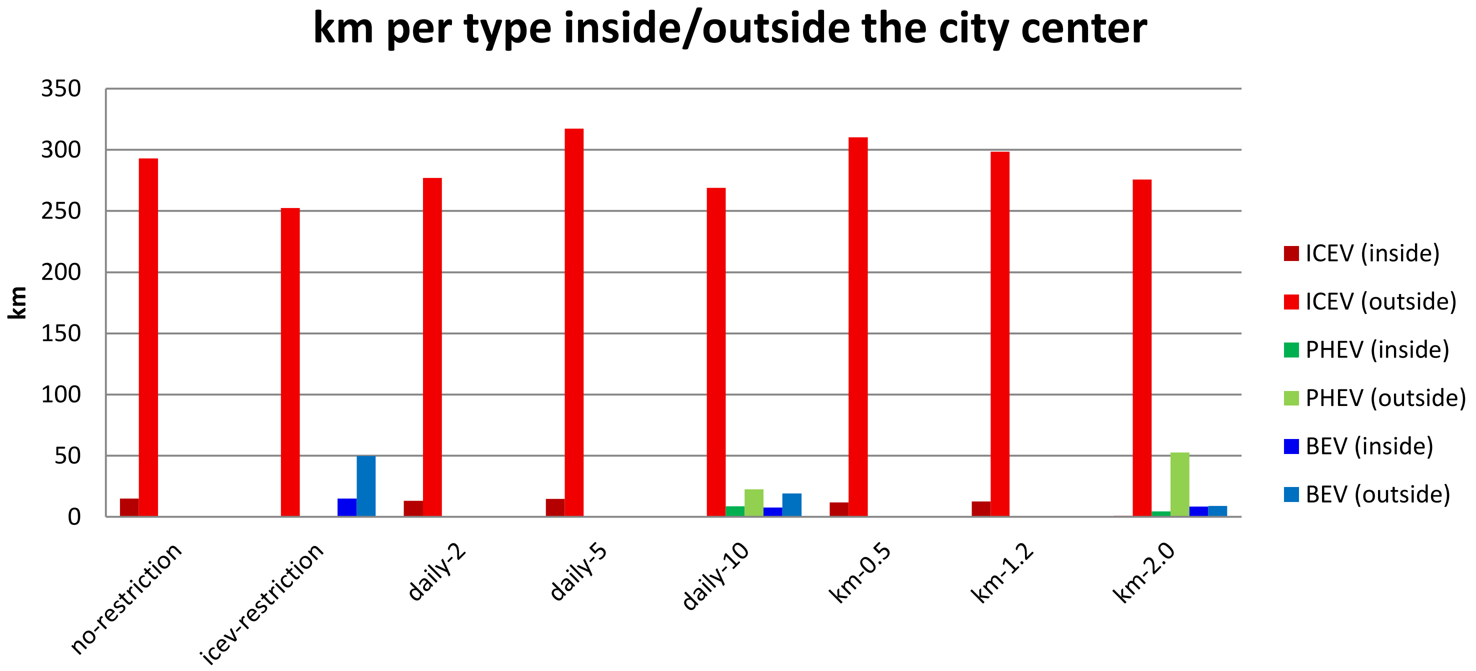
- **Vienna**
- **Random node locations**
  - 1 depot
  - 5 recharging stations
  - 116 customers
  - 35 entry points
- **Properties**
  - 8h planning horizon
  - random demand (1-20 units)
  - Time window (0.5-2h)
  - Optimistic recharging technology (16kWh in 0.6h)



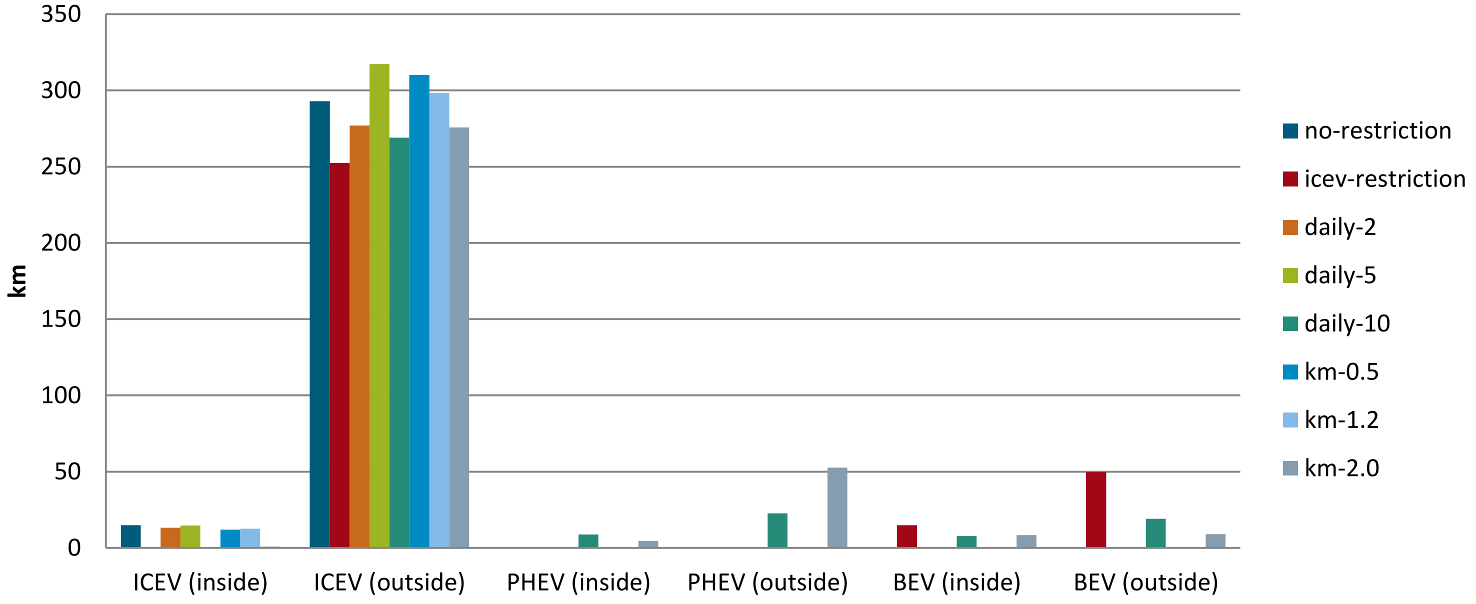
Experiments using a street graph

Example instance solution




km per type inside/outside the city center
350
300
250
200
150
100
50
0
km
no-restriction
icev-restriction
daily-2
daily-5
daily-10
km-0.5
km-1.2
km-2.0
ICEV (inside)
ICEV (outside)
PHEV (inside)
PHEV (outside)
BEV (inside)
BEV (outside)

km per type inside/outside the city center

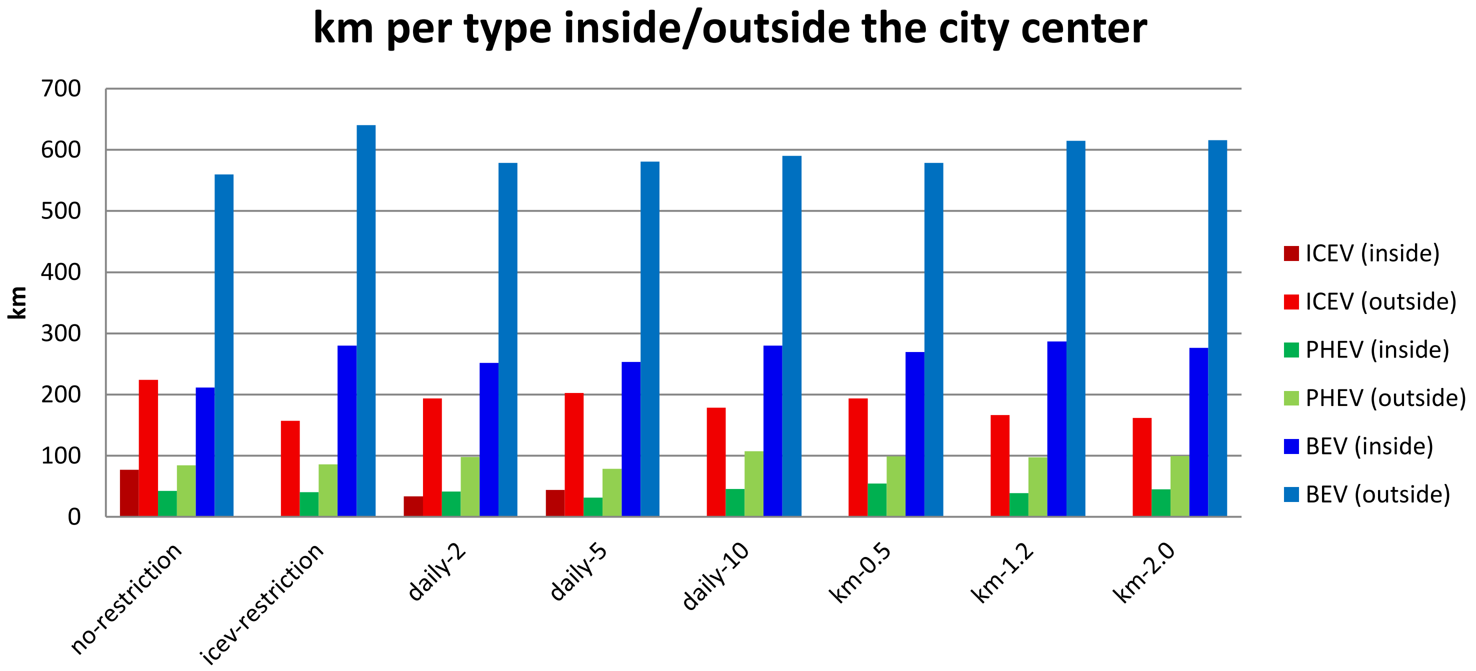


Experiments using artificial data

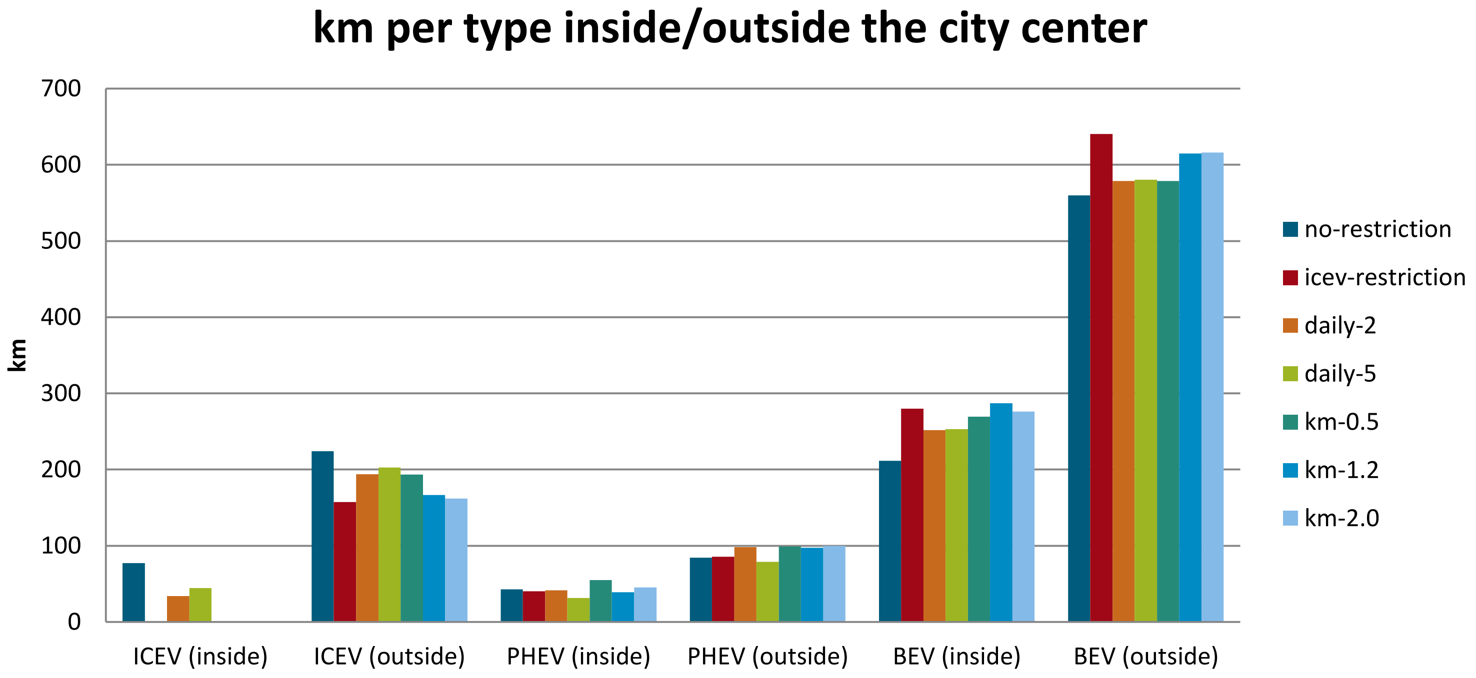
- **Artificial instances based on classical Solomon / Schneider instances**
- **Adaptations from the original values**
  - orig .. original values of the instance
    ref … BEV-L (base fleet configuration)
  - distance
    - $\frac{orig.battery/_{orig.consumption}}{ref.battery/_{ref.consumption}}$
  - 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



Experiments using artificial data - Results



- **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

- **Main challenge:**
  - Limited range and long recharging times
- **Strategic decisions:**
  - Location of charging stations
  - Long-term fleet mix
- **Operational decisions:**
  - Vehicle allocation
  - Tour planning

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