An Efficient Electric Vehicle Path-Planner That Considers the Waiting Time

Using graph relabeling and alternative paths generation

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Outline

Advantages of EV over conventional vehicles

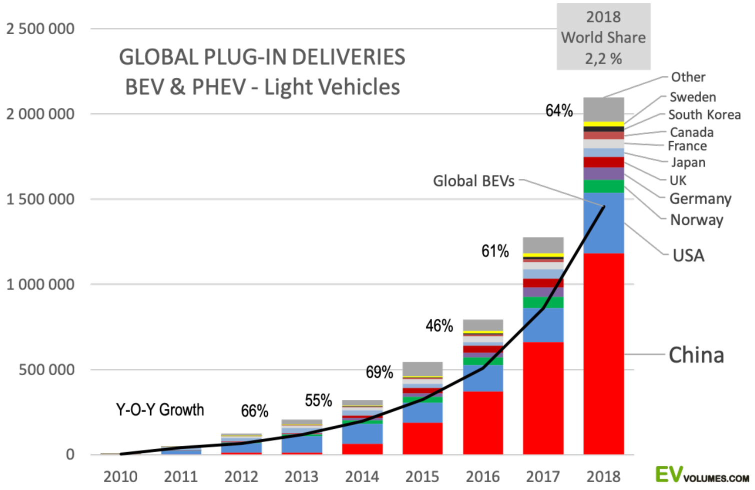
Less pollution

Less noisy

Cheaper in the long run

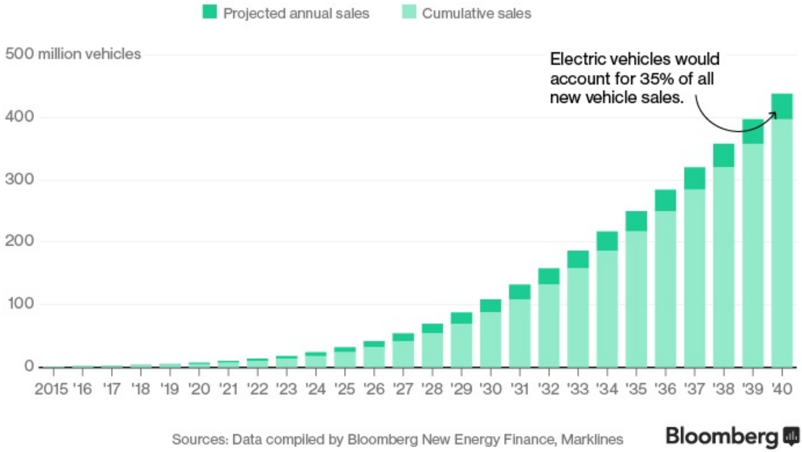
Less maintenance

Global EV market 2010–2018[1]



[1] http://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/

EV sales forecast[2]



[2] Bloomberg, February 25th, 2016, https://www.bloomberg.com/features/2016-ev-oil-crisis/

Comparison between a conventional vehicle and an EV

	Honda Civic	Nissan Leaf
Price (C$)[3]	17 890 $	42 298 $
Range	750 km	363 km
Refueling/Charging time	3 min	30 min
Gas/L3 Charging stations[4]	2924	225

[3] Starting price for the 2019 model. Excluding governmental subsidies for green vehicles

[4] In Québec province, Canada, in 2018

Research problem

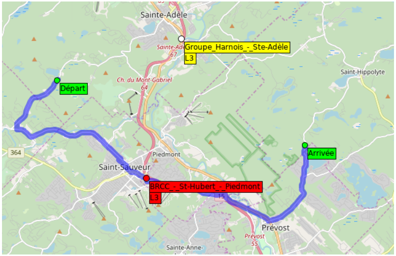
- The number of EV is increasing;
- Many paths need recharges to be feasible.

Objective

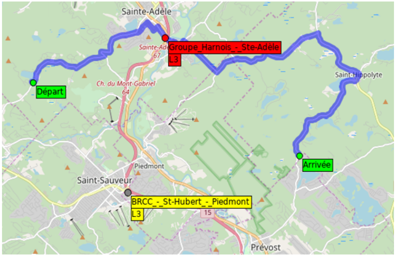
The objective is to have an EV planner that:

1. considers intermediate recharges at charging stations;
2. **considers the expected occupancy and waiting time at the stations.**

Real world example of the impact of the consideration of waiting time



Monday noon



Tuesday noon

Related Work

EVRP-MRUA[5]

- EV Routing Problem with Mid-Route Recharging and Uncertain Availability.
- Deliver mulitple packages in an optimal order (similar to the TSP).
- Minimize the cost for the operator and the global time to deliver the packages.

[5]Nicholas Kullman, Justin Goodson, Jorge E. Mendoza. Dynamic Electric Vehicle Routing with Mid-route Recharging and Uncertain Availability. ODYSSEUS 2018, Jun 2018, Cagliari, Italy.

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Adaptive Routing and Recharging Policies for EV[6]

- Single EV going from a departure to an arrival node.
- Considers expected waiting time and EV stations availability uncertainty.
- Availability of EV station assumed to be known only when arriving.
- Every node is a station. Time complexity of $\mathcal{O}(n^4)$.

[5] Nicholas Kullman, Justin Goodson, Jorge E. Mendoza. Dynamic Electric Vehicle Routing with Mid-route Recharging and Uncertain Availability. ODYSSEUS 2018, Jun 2018, Cagliari, Italy.

[6] Timothy M Sweda, Irina S Dolinskaya, and Diego Klabjan. 2017. Adaptive Routing and Recharging Policies for Electric Vehicles. Transportation Science 51, 4 (2017), 1326–1348.

Formalism

Road Network

The **network** is a tuple (V, E, λ, μ, S), where (V, E) is a digraph. More specifically:

- V is the set of locations considered on the map (nodes);
- E is the set of road segments (edges);
- $\lambda\colon E \to \mathbb{R}^+$ gives the length (in m) of the edges;
- $\mu\colon E \to \mathbb{R}^+$ gives the expected speed (in m/s) at the edges;
- S is the set of charging stations (we assume that $S \subseteq V$).

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EV Planning Problem (EVPP)

An **EVPP** is defined by a tuple $(M, \rho, \alpha, \omega)$, where

- M is the road map;
- $\rho \in \mathbb{R}^+$ is the EV range;
- $\alpha, \omega \in V$ are the departure and arrival nodes.

EVPP Solution

Solution

A **solution** to an EVPP $(M, \rho, \alpha, \omega)$ is a tuple (P, Q), where

- $P \subseteq V$ is the sequence of nodes to traverse in the solution;
- $Q \subseteq P$ contains the stations where to charge (and α, ω);
- $\forall i, \mathrm{dg}(Q_i, Q_{i+1}) \leq \rho$, where dg is the graph distance.

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Optimal Solution

An **optimal solution** is a solution (P, Q) minimizing:

$$Z(P, Q) = \mathrm{DT}(P) + \mathrm{CT}(Q) + \mathrm{WT}(Q),$$

where DT, CT and WT are the expected driving, charging and waiting time.

Base algorithm

Algorithm Base planner

```
Compute the matrix D and the optimal path between every pair of stations
Construct the s-graph containing every charging station
for each request (α, ω, ρ) do
    Run Dijkstra from α on the original graph
    Run Dijkstra from ω on the reversed original graph
    Add α and ω to the s-graph and add edges with length ≤ ρ
    Run the A* algorithm on the s-graph from α to ω to find the sequence Q
    Find the sequence P from Q using all computed paths
end for
```

The time complexity for each request is $\mathcal{O}(|V| \log |V| + |E|)$.
This planner can be extended to:

- Consider partial initial EV charge;
- Consider the regenerative braking of EVs;
- Consider partial recharge and the non-linear charging curve.

The idea

- Consider historic data of stations occupancy;
- Relabel the graph to account for these data.

A priori known data

For every station s, the time-dependent probability of occupancy is given by:

$$\begin{aligned} f_s \colon \{Monday, \ldots, Sunday\} \times \{0..23\} &\to [0, 1] \\ (d, h) &\mapsto \mathbb{P}(s \text{ is occupied} \mid \text{Day} = d \wedge \text{Hour} = h). \end{aligned}$$

and the time-dependent expected waiting-time when occupied is given by:

$$g_s \colon \{Monday, \ldots, Sunday\} \times \{0..23\} \to \mathbb{R}^+$$

Time-dependent graph relabeling

Labeling considering the waiting time

Let $e = (u, v) \in E$. We define the time-dependent labeling to be

$$\xi \colon E \times \{Monday, \ldots, Sunday\} \times \{0..23\} \to \mathbb{R}^+$$

$$\xi(e, d, h) = \begin{cases} \lambda(e) & \text{if } u \notin S \\ \lambda(e) + f_u(d, h) \cdot g_u(d, h) \cdot \mu(e) & \text{if } u \in S \end{cases}$$

- The edge weight now depends on the time of arrival;
- We need to modify the graph search algorithm (e.g., Dijkstra/A*)[7];

[7] Daniel Delling and Dorothea Wagner. 2009. Time-dependent route planning. In Lecture Notes in Computer Science, Vol. 5868 LNCS. 207–230. https://doi.org/10. 1007/978-3-642-05465-5_8

Problem with previous technique

- The previous technique uses only *a priori* known data;
- Real-time occupancy can be much worse than what was expected;
- Assume we have access to real-time occupancy while driving;
- We can further reduce the waiting time by precomputing alternative paths.

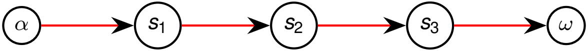
Two extreme cases

1. No alternative path;
2. A total policy π: State $\rightarrow$ Action (e.g., found using MDP)

We want a compromise between these two extreme cases.

The idea

Generate one alternative path for every station on the initial path.



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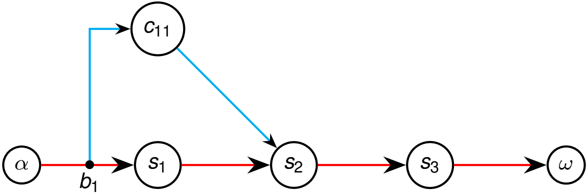

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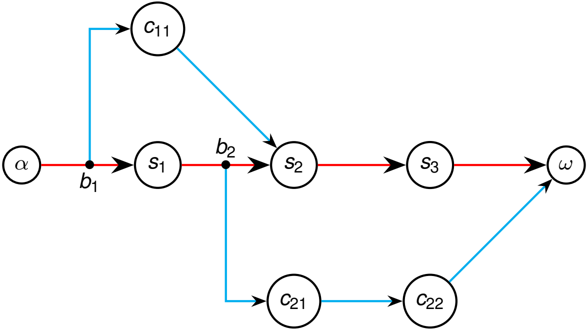


Generating the alternative paths

Algorithm Alternative path generation for station s_i

1: Assume $f_{s_i} \equiv 1$
2: Run the relabeled time-dependent planner
3: **if** new path is same as base path **then**
4:     **return**
5: **end if**
6: $b_i \leftarrow$ last common node in prefix of new path and base path
7: Set the new path as an alternative path on node b_i

After running this algorithm on every station, we obtain a partial policy

$$\pi : V \to V^2$$

$$\pi(x) = \begin{cases} (s_{i+1}, -) & \text{if } x = s_i \wedge \nexists b_{i+1} \\ (b_i, -) & \text{if } x = s_i \wedge \exists b_{i+1} \\ (s_i, c_{i1}) & \text{if } x = b_i \\ (c_{i,j+1}, -) & \text{if } x = c_{ij}, \end{cases}$$

Executing the policy

Algorithm Online plan execution

```
procedure EXECUTEPLAN(π)
    n ← α
    while n ≠ ω do
        (x, y) ← π(n)
        if y = − ∨ ¬occupied(x) then
            n ← x
        else
            n ← y
        end if
        Move EV to node n
    end while
end procedure
```

Test methodology

- The real map data come from the OpenStreetMap project.
- The territory used is the Province of Québec, Canada:
  - 2 923 013 nodes
  - 5 907 672 edges
- The charging stations data come from the Circuit Électrique:
  - 1318 charging stations (1178 L2 and 140 L3)
  - the f_s and g_s functions were generated from the data.
- 1000 requests:
  - EV range was generated uniformly between 90 and 550 km;
  - α and ω were chosen at random among all nodes;
  - Travel distance was between 200 and 1500 km.

Results: Table showing the results obtained for real data

Parameters		Baseline		Relabeling			Alternative Paths		
SN	PM	WT min	TT min	WT min	WR %	TTR min	WT min	WR %	TTR min
R140	× 1	10.2	350.1	3.3	-67.5	-6.2	2.2	-78.8	-7.2
R140	× 2	22.7	362.5	6.0	-73.6	-15.5	4.1	-82.0	-17.2
R140	× 3	37.5	377.3	7.7	-79.3	-28.3	7.2	-80.9	-28.7
R140	Rand	51.3	391.2	10.9	-78.7	-38.5	9.8	-80.9	-39.5
R1318	× 1	19.4	356.0	2.2	-88.6	-16.7	1.7	-91.5	-17.3
R1318	× 2	37.5	374.0	4.0	-89.3	-32.8	3.0	-92.0	-33.7
R1318	× 3	50.5	387.1	6.5	-87.1	-43.1	4.7	-90.6	-44.8
R1318	Rand	62.0	398.6	6.9	-88.8	-53.3	6.0	-90.4	-54.2

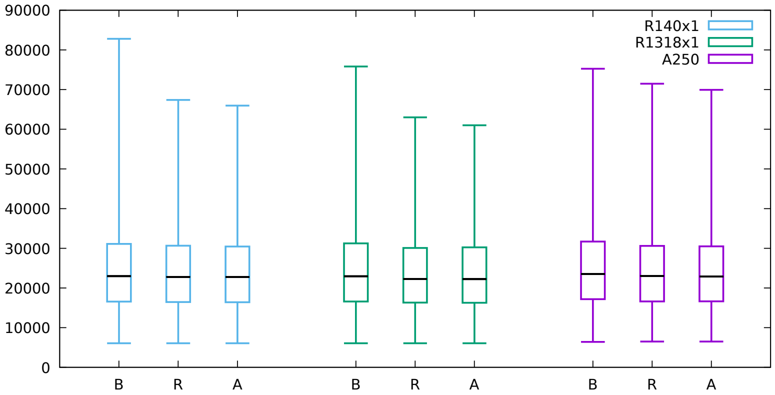
SN: Station Network; **PM**: Probability Modifier;**TTR**: Total time reduction (vs Baseline)

Results: Table showing the results obtained for artificial data

Parameters		Baseline		Relabeling			Alternative Paths		
SN	PM	WT min	TT min	WT min	WR %	TTR min	WT min	WR %	TTR min
A250	Rand	29.3	368.2	12.0	-59.0	-13.9	10.3	-64.8	-15.1
A500	Rand	28.9	363.4	9.4	-67.6	-16.5	8.3	-71.2	-17.3
A1000	Rand	28.7	362.5	7.4	-74.2	-18.7	6.5	-77.3	-19.4
A2000	Rand	27.1	359.9	4.9	-81.9	-19.9	3.8	-86.0	-20.9

SN: Station Network; **PM**: Probability Modifier;**TTR**: Total time reduction (vs Baseline)

Results: Box plots showing the five number summary of the total time



B: Baseline; **R**: Relabeling; **A**: Alternative paths.

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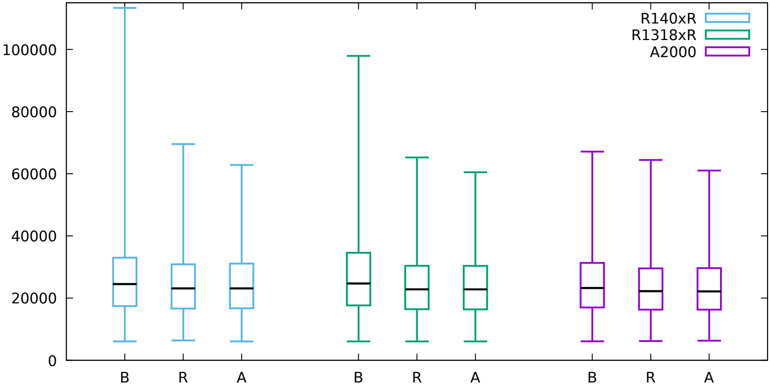

B: Baseline; **R**: Relabeling; **A**: Alternative paths.

Conclusion

- The waiting time can have a significant impact in EV planning.
- We proposed two techniques:
  - a dynamic time-dependent graph relabeling;
  - an alternative path generation mechanism to account for worse than expected occupancy.
- Both techniques have a negligible computation overhead over the base planner.
- Our techniques decreased by more than 3/4 the waiting time in our simulations, representing a 17.3 minutes saving on average.

Acknowledgements

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