Increased Plan Stability in Cooperative Electric Vehicles Path-Planning (CEVPP)

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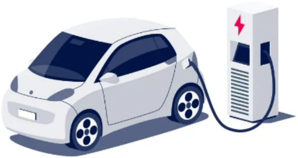
Outline

Electrical vehicles and path-planing

EVs are becoming increasingly widespread :

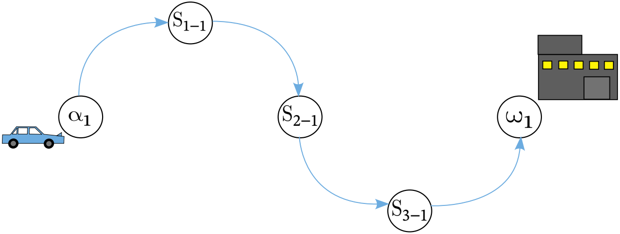
- ↑ Environmental concerns ;
- ↑ Battery range ;
- ↑ EV availibility and options ;
- ↑ Charging stations availability ;



Planning trips is challenging for long journey :

- You need to stop for recharging ;
- Unpredictable waiting times ;
- Unbalanced occupation amongst charging stations.

The CEVPP Problem definition – Example



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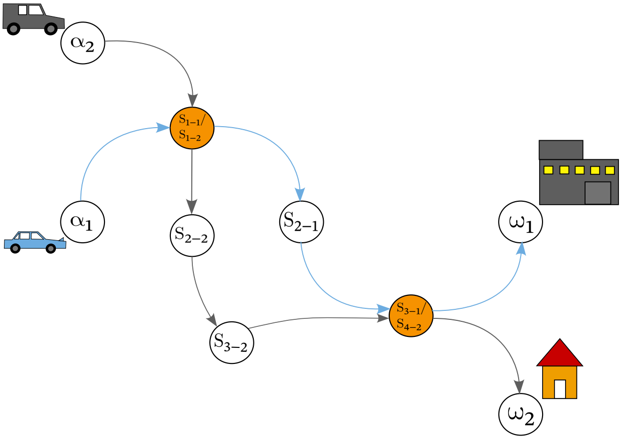
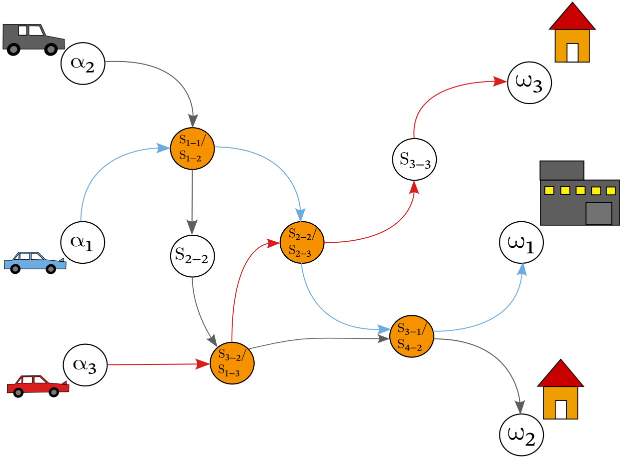


The CEVPP Problem definition – Example



The CEVPP Problem definition

- MAPF problem with **soft collision**.
- EV drivers can send a planning request to a centralized planner.
- New EVs can enter the planning problem at any time.
- Replanning triggers
  - N new requests arrived to the planner OR
  - T minutes elapsed since the last replanning.
- *Commitment constraint* : Agents already on their way to a station cannot have their station changed.
- Global planner ignores agents that are on the segment toward their destination.

The CEVPP Problem definition

Objective

At the i[th] replanning, find global plan $\pi^{(i)} = \left[\pi_1^{(i)}, \pi_2^{(i)}, \ldots, \pi_k^{(i)}\right]$ that :

- Minimizes total (travel + charge + wait) time for all agents (in minutes).
- $Z(\pi^{(i)}) = \frac{1}{k_i} \sum_{j=1}^{k} \left(C(\pi_j) - C^\star(\pi_j)\right)^2$.
- $C^\star(\pi_j)$: best possible optimal plan cost for the j^{th} agent, i.e., :
  - geographically the shortest-path ;
  - no waiting time.
- Optimal solution is $\pi^* = \arg\min_{\pi^{(i)} \in \Pi^i} Z(\pi^{(i)})$

CEVPP – Formalisation

CEVPP instance

A **CEVPP instance** is a tuple (M, R) where :

- M is a road network ;
- R is a list of EV requests in chronological order.

Road Network

A **road network** M as a tuple (V, E, λ, μ, S), where :

- V : set of nodes (latitude, longitude) on a map ;
- E : set of road segments (edges) connecting exactly 2 nodes ;
- $\lambda\colon E \rightarrow \mathbb{R}^+$: travel distance of every road segment (in m) ;
- $\mu\colon E \rightarrow \mathbb{R}^+$: average speed on every edge (in m/s) ;
- $S \subseteq V$: set of all charging stations.

EV Request

Each agent has an associated **EV request**, a tuple $(\alpha, \omega, \rho, \tau)$, where :

- α : is the starting node ;
- ω : is the destination node ;
- ρ : is the range of the EV ;
- τ : is the departure time.

pcEVP solver

In previous work [1] the pcEVP solver has been proposed :

- Computes local plan successively with different insertion order.
- Tests $log(k!)$ randomized insertion permutations (non-optimal).
- Records charging stations occupancy in a reservation table -> waiting time.

Algorithm Permutations Cooperative EV Planner

procedure PCEVP($(M, R = \langle r_1, \ldots, r_k \rangle)$: CEVPP)
  $\mathcal{P} \leftarrow$ GETCONSIDEREDPERMUTATIONS(R)
  $C_{best} \leftarrow \infty$
  for all $\phi \in \mathcal{P}$ **do**
    $\pi \leftarrow \emptyset$
    $\mathcal{R} \leftarrow$ Empty Reservation Table
    for all $r_i \in \phi$ **do** ▷ In given order
      $\pi_i =$ MODIFIEDA*($M, r_i, \mathcal{R}$)
      UPDATERESERVATIONTABLE($\mathcal{R}, \pi$)
      $\pi \leftarrow \pi \cup \{\pi_i\}$
    if $C(\pi) < C_{best}$ **then**
      $\pi_{best} \leftarrow \pi$
      $C_{best} \leftarrow C(\pi)$
  Compute the global penalty $P(\pi_{best})$

1. Champagne Gareau, J. ; Lavoie, M.-A. ; Gosset, G. ; and Beaudry, E. 2024. Cooperative Electric Vehicles Planning. In Proceedings of the 23rd International Conference on Autonomous Agents and Multiagent Systems, AAMAS '24, 290–298. International Foundation for Autonomous Agents and Multiagent Systems. ISBN 9798400704864.

Motivation

- Individual plans can drastically change when replanification occurs.
- Agent could value plan stability (avoid major detours for marginal gains).

$$
\begin{array}{lccccccccc}
\pi_j^{(0)} = & A_1 & \rightarrow & B_1 & \rightarrow & C_1 & \rightarrow & D_1 & \rightarrow & E_1 \\
 & & & & & \downarrow & & \downarrow & & \\
\pi_j^{(1)} = & & & B_1 & \rightarrow & C_2 & \rightarrow & D_2 & \rightarrow & E_1 \\
 & & & & & \downarrow & & \downarrow & & \\
\pi_j^{(2)} = & & & B_1 & \rightarrow & C_1 & \rightarrow & D_3 & \rightarrow & E_1 \\
 & & & & & & & \downarrow & & \\
\pi_j^{(3)} = & & & & & C_1 & \rightarrow & D_4 & \rightarrow & E_1 \\
 & & & & & & & & & \\
\pi_j^{(4)} = & & & & & & & D_4 & \rightarrow & E_1
\end{array}
$$

Objective function extension

Proposed objective function

$$\bar{Z}(\pi^{(i)}) = \frac{1}{k_i} \sum_{j=1}^{k_i} \left[\left(C(\pi_j^{(i)}) - C^\star(\pi_j^{(i)}) \right)^2 + \delta^2(\pi_j^{(i)}) \right].$$

Where δ penalizes plan modificiation at the ith replanning compared to the previous iteration (i-1)th :

$$\delta(\pi_j^{(i)}) = \begin{cases} \phi_j \sum_{k=1}^{k_j^{(i)}} r_j^k \left[\pi_{j,k}^{(i)} \neq \pi_{j,k}^{(i-1)} \right] & \text{if } i > 0, \\ 0 & \text{otherwise.} \end{cases}$$

- $[P]$ is the Iverson bracket : $[P] = \begin{cases} 1 & \text{if } P \text{ is true,} \\ 0 & \text{otherwise,} \end{cases}$
- Each agent has 2 parameters :
  - ϕ_j controls the importance of the plan stability for the jth EV.
  - r_j controls a geometric decay so later plan modification yield lesser penality.

Evaluation - Experimental setup

- pcEVP variants :
  - Planner using Z -> original planner.
  - Planner using $\bar{Z}$ -> proposed planner ϕ=15, r=1.0 for all agents
- Evaluation metrics :
  - Penalty $Z(\pi) = \frac{1}{k}\sum_{i=1}^{k}(C(\pi_i) - C^{\star}(\pi_i))^2$ of the returned solutions (in minutes).
  - Cumulated changes ($\mathbb{S}$) in global plan.
- using g++ v13.2.
- 4.2 GHz Intel Core i5-7600k CPU with 32 GB of RAM.
- Execution timeout value : 15 minutes per CEVPP instance.
- Running times not reported : proposed extension for pcEVP does not significantly impact execution duration.

Evaluation - Experimental setup

The $\mathbb{S}$ metric

The $\mathbb{S}$ metric used to measure the obtained plan stability is defined as follows :

$$\mathbb{S}(\pi^{(0)}, \pi^{(1)}, \dots, \pi^{(m)}) = \sum_{i=1}^{m} \frac{1}{n_i} \sum_{j=1}^{n_i} \sum_{k=1}^{k_j^{(i)}} \left[\pi_{j,k}^{(i)} \neq \pi_{j,k}^{(i-1)} \right].$$

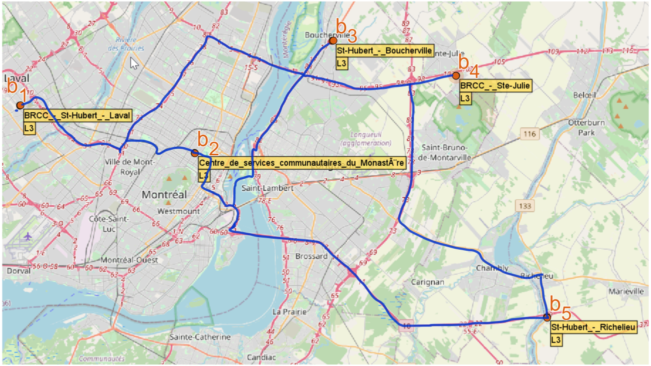
- $\mathbb{S}$: averaged amount of changes cumulated over all replanning event ;
- n_i : amount of EV at the i^{th} replanification ;
- $k_j^{(i)}$: amount of stations for local plan j^{th} at the i^{th} replanning.
- $\pi_{j,k}^{(i)}$: k^{th} station used by j^{th} EV for local plan at the i^{th} replanning.

⚠ When a local plan has a different length between i^{th} and $(i-1)^{th}$, the difference is also counted.

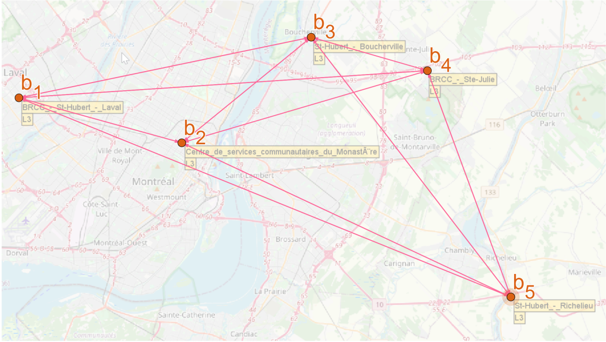
Evaluation - Testing instances

- Map data : Québec road network extracted from OpenStreetMap
  - 4 416 080 vertices ;
  - 8 797 051 edges.
- Charging stations data : *Electric Circuit*.
  - 347 L2 stations ;
  - 1816 L3 stations.
- Replaning triggers : 10 new requests or 20 minutes since last replanning.
- Batch of 8 to 128 EV requests.
  - EV range ρ, sampled uniformly 100-550 km ;
  - Departure time τ, sampled uniformly 0-4 hours ;
  - Departure α and arrival ω, sampled from a 100 km cluster. Travel distance is at least 200km ;
  - Optimal local plan has a least 2 stops.

Evaluation - Map and station data



Evaluation - Map and station data



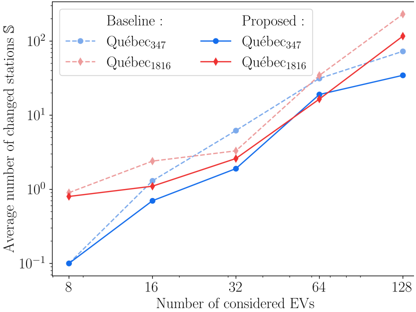
Average cumulated changes through plannification process.

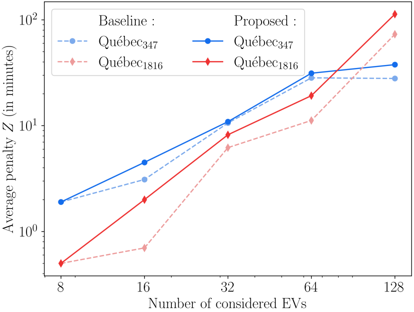
Test characteristics **Network**	 **#EVs**	Baseline $\mathbb{S}$ (# changes)	Stability-aware $\mathbb{S}$ (# changes)	Change $\mathbb{S}$ (%)
Québec_{347}	8	0.1	0.1	0.00
Québec_{347}	16	1.3	0.7	-46.15
Québec_{347}	32	6.2	1.9	-69.35
Québec_{347}	64	31.3	19.0	-39.30
Québec_{347}	128	72.7	34.5	-52.54
Québec_{1816}	8	0.9	0.8	-11.11
Québec_{1816}	16	2.4	1.1	-54.17
Québec_{1816}	32	3.3	2.6	-21.21
Québec_{1816}	64	34.4	16.5	-52.03
Québec_{1816}	128	230.5	116.5	-49.46

Average cumulated changes through planning process.

Test characteristics		Baseline	Stability-aware	Change
Network	**#EVs**	**Z**(π) (min)	**Z**(π) (min)	**Z**(π) (min)
Québec$_{347}$	8	1.9	1.9	0.0
Québec$_{347}$	16	3.1	4.5	1.4
Québec$_{347}$	32	10.6	10.9	0.3
Québec$_{347}$	64	28.3	31.3	3.0
Québec$_{347}$	128	27.9	37.7	9.8
Québec$_{1816}$	8	0.5	0.5	0.0
Québec$_{1816}$	16	0.7	2.0	1.3
Québec$_{1816}$	32	6.2	8.2	2.0
Québec$_{1816}$	64	11.2	19.2	8.0
Québec$_{1816}$	128	73.0	113.0	40.0

Visual representation of both metrics





Take away

- We proposed an improved objective function for pcEVP that considers plan stability when replanning occurs.
- The proposed method generated steadier plans (with 39.53% less cumulated changes on average) while causing a relatively small increase of the penalty in most cases.
- The CEVPP extension improved predictability in end-users' trips.
- Future works :
  - **Stability** Empirically evaluate the effect of the variation of ϕ and r (which were fixed in the current tests) on the considered metrics and the impact of non uniform parameters between agents (to accomodate the preferences of the different agents).
  - **Search** : Adapt M* algorithm for soft collision. M* is a global optimal search with heuristic for MAPF.

Acknowledgments

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