Algorithms for Extending Battery Life in Electric Vehicles

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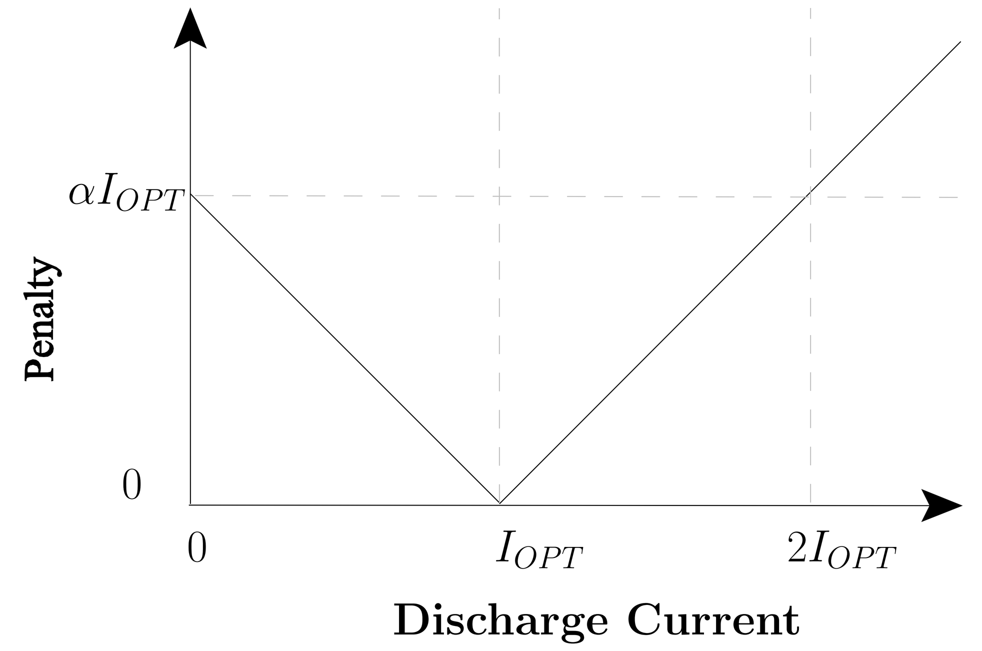
The Problem

The battery is a key component in any Electric Vehicle (EV). In this work we focus on improving the battery's *life*, which is greatly affected by the method of use. Each battery is a pack of cells series connected in parallel designed to be discharged and charged with specific optimal currents, whereby other currents, i.e. higher or lower, may have negative effects on the life of the battery. We refer to these negative effects as penalties that are aggregate over time and propose a discharge method to minimize them. The common discharge method is very simple but far from optimal. In this method the power demand is supplied using all the cells series where the current from each is the same. The method we propose is an advanced switching algorithm that for each power demand selects the cells' series and controls the discharge current from each, based on understanding the electrochemical properties of the individual cells.

Penalty Function

Each battery's chemistry is designed to be discharged in a specific current, while higher or lower currents have negative effects on it . Moreover, an optimal discharge current exists, denoted I_{OPT}, for each battery and depends on the its specific chemistry. Based on these insights, we propose a penalty function that maps each discharge current to a numeric value reflecting its detrimental affect on the battery's life. We assume the following linear penalty function.



Mathematical Model

The problem where all the power demands are known in advance can be described as the following mathematical model using the notation:

- I_{OPT}: the optimal discharge current.
- d_j: the j power demand.
- s_i: the i cells series.
- C: the initial capacity of all cells series.
- C_j^i: the capacity of s_i before d_j.
- I_j^i: the discharge current of s_i for d_j.

$$\min \sum_{i=1}^{n}\sum_{j=1}^{m} Penalty(I_j^i)$$

$$\text{s.t.} \quad \sum_{i=1}^{n} I_j^i \le C \qquad \forall j = 1\ldots m$$

$$\sum_{j=1}^{m} I_j^i = d_i \qquad \forall i = 1\ldots n$$

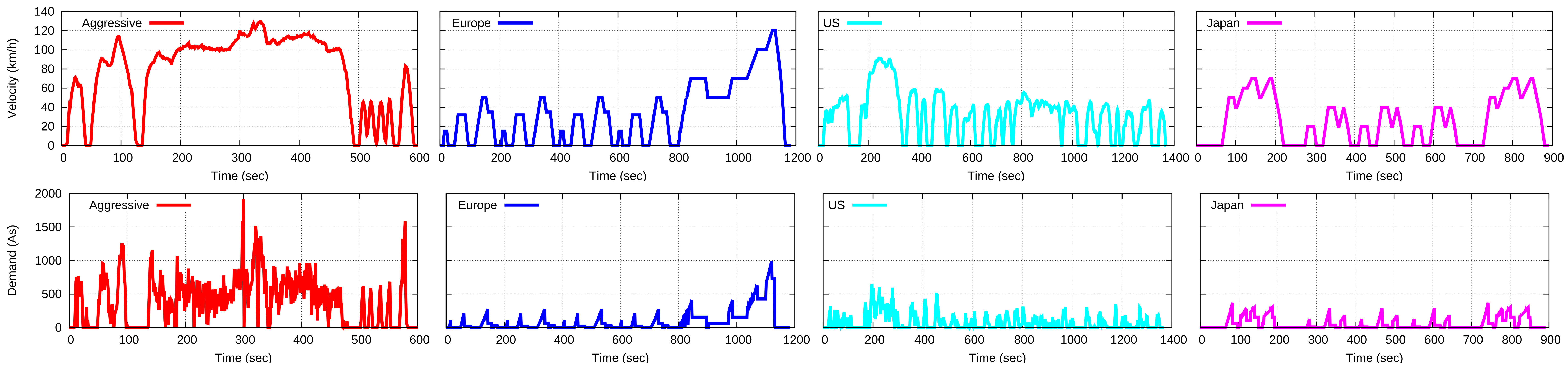
$$0 \le I_j^i, \;\; I_j^i \in R \quad \forall i = 1\ldots n, \;\; j = 1\ldots m$$

Contributions

Theoretical and ***empirical*** contributions:

1. Prove the problem is strongly NP-hard, even if all the power demands are known in advance.
2. Prove it is hard to approximate within an additive gap of $\Omega(m)$ from the optimum.
3. Propose an online algorithm with an additive gap of $1.5m$ - independent of the number of demands in the sequence and of the initial capacity of the batteries.
4. Provide a lower bound of 1.5 for the competitive ratio of any online algorithm.
5. Propose greedy and heuristic algorithms.
6. Evaluate the proposed algorithms using simulations of known driving cycles and compare their performances to those of the common naive algorithm.

Simulation Data - Driving Cycles

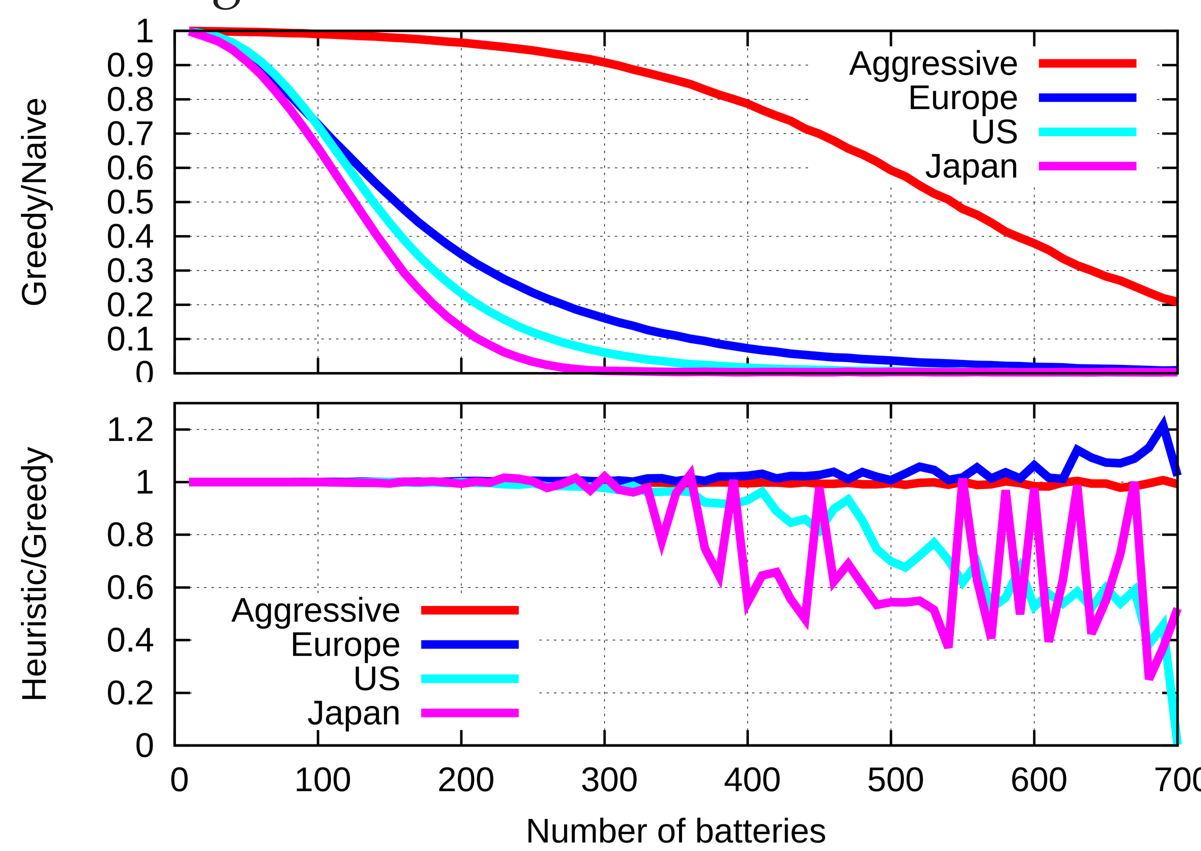


We evaluated our algorithms using simulations on standard testing driving cycles for measuring fossil fuel emission and consumption of vehicles. The driving cycles, which consisted of velocity-time measurements in one second intervals, were translated into energy-time data, assuming a vehicle weighs 1.5 tons and a $360V$ battery pack. Negative energy values, i.e. energy that was generated by slowing the EV, was ignored as charging is not part of the scope of this paper. Notice the x-axis may differ from one plot to another as the duration of the driving cycles are different.

The driving cycles we used:
Aggressive - aggressive driving in USA.
Europe - urban and highway driving in Europe.
US - urban driving in the USA.
Japan - urban driving in Japan.

Empirical Results

The total achieved penalty comparing the naive algorithm. The lower the value the better.



Using the algorithms the penalty can be significantly reduced and almost avoided as the number of batteries increase. The heuristic algorithm outperformed the greedy only in the urban driving cycles where the demands were not too high.