Optimal Charging of Vehicle-to-Grid Fleets via PDE Aggregation Techniques

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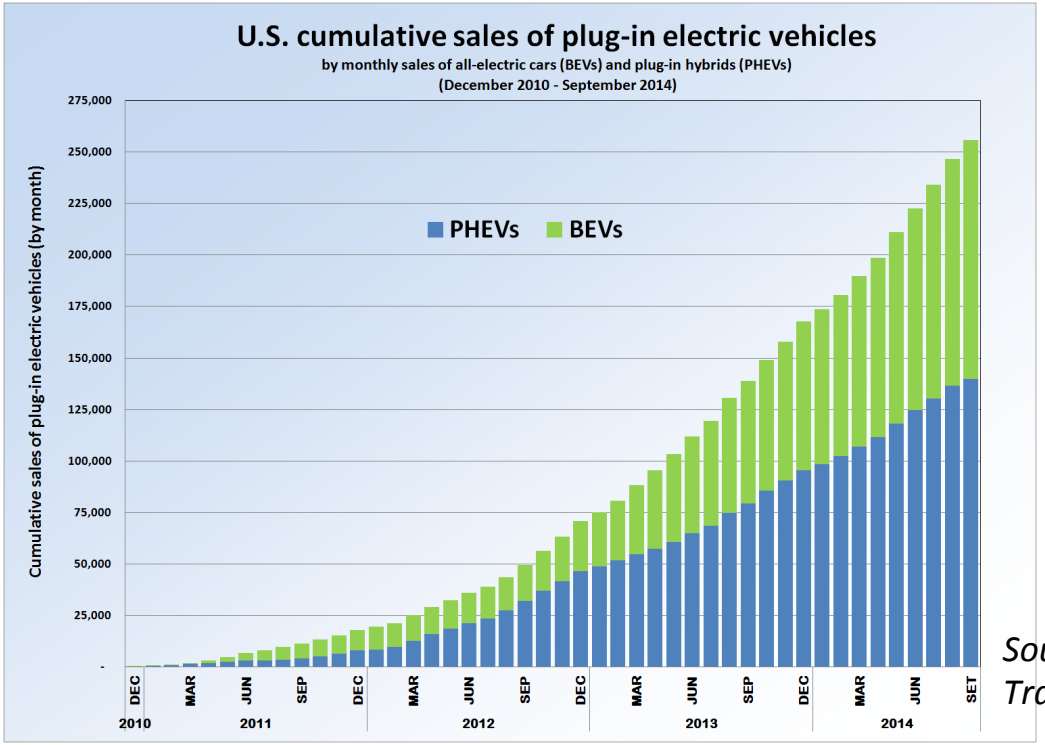
Introduction

Why are “EVs”, “Vehicle to Grid (V2G)”, hot topics?

Vehicle Electrification

Their number grows…



Source: Electric Drive Transportation Association

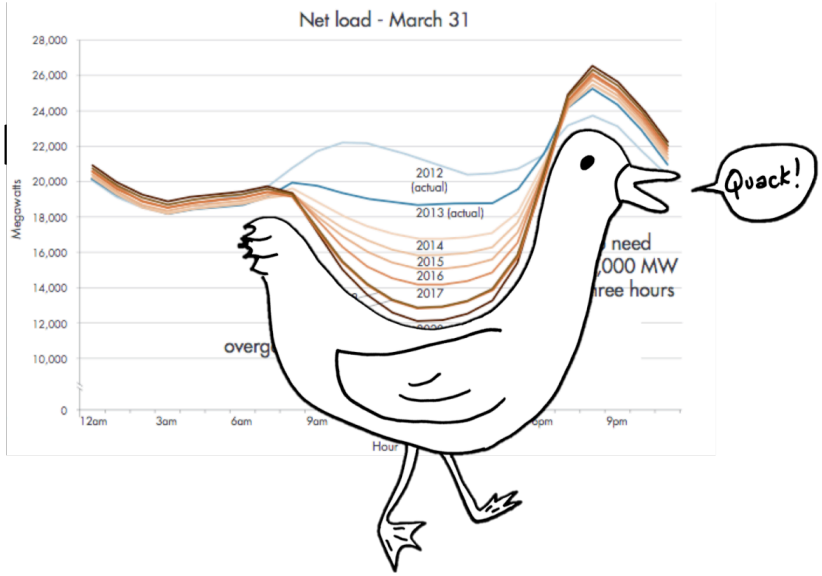
Introduction

Why are “EVs”, “Vehicle to Grid (V2G)”, hot topics?

Vehicle Electrification

<u>If not controlled</u>, represents an additional risk for Grid Resilience

- Additional loads during peak hours
- Extra investment in grid infrastructure



Axsen, J., & Kurani, K. S. (2010). *Transportation Research Part D: Transport and Environment*, *15*(4), 212-219.

Hadley S. Oak Ridge, *TN: Oak Ridge National Laboratory*; 2006.

Introduction

Why are "EVs", "Vehicle to Grid (V2G)", hot topics?

Vehicle Grid Integration

<u>If controlled</u>, represents a great opportunity for

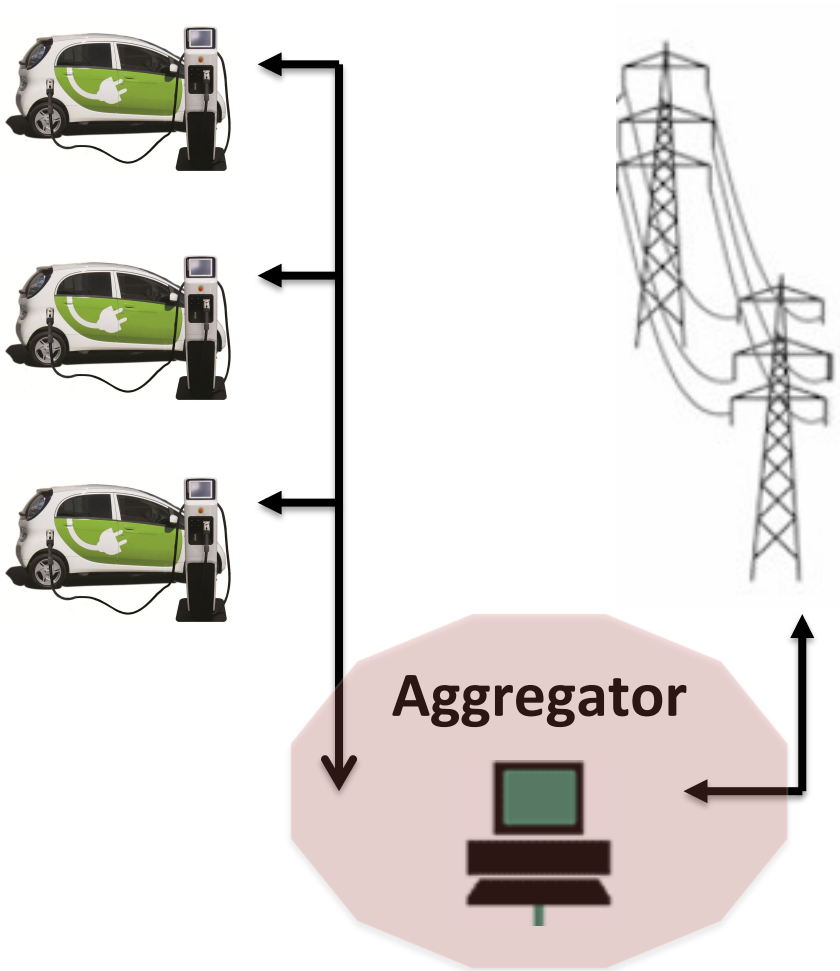
- Demand Response
- Storage
- …

US personal vehicles are parked 96% of time!

(A. Langton and N. Crisostomo, *California Public Utilities Commission, Tech. Rep*, 2013)

How can we model and control PEV loads during this available time?

EV aggregator



Vehicle-To-Grid (V2G):
Cars communicate with the Grid
Can "sell" energy

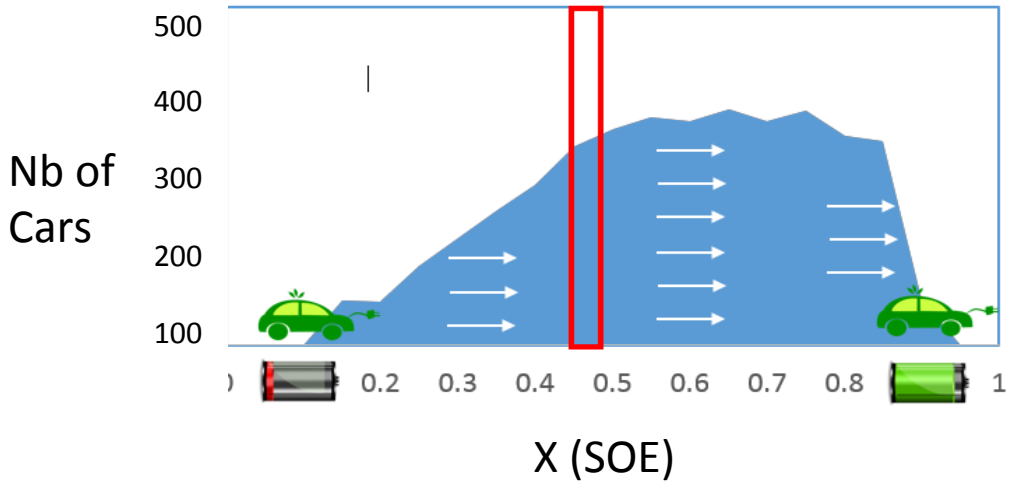
Aggregator:
Single PEV~ 5-20 kW
The aggregator collectively charges, discharges cars.
The aggregator may participate in the electricity market

Challenge: Controlling large population of EVs

- **Participate in the electricity market**
- **Satisfy drivers and needs for mobility**
- **Be profitable for the aggregator**

PDE aggregation model

Fleet of EVs



u(x,t): number of cars, which are plugged-in and charging at time t and SOE x.

Charging dynamics of vehicle i:

$$\dot{x}_i(t) = \frac{\eta^m(x_i)}{E_{\max}} P_i(t), \qquad i = 1, \cdots, N,$$

$$m = \begin{cases} 1 & \text{if } P_i(t) \geq 0, \\ -1 & \text{if } P_i(t) < 0, \end{cases}$$

X_i: State of Energy (SOE)
η: Conversion efficiency
E_{max}: battery energy capacity

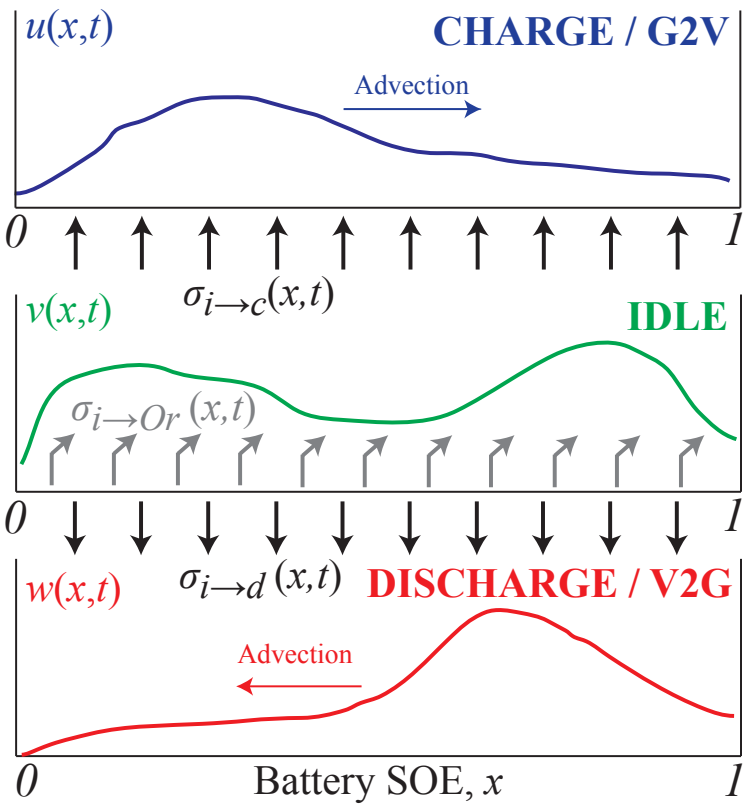
Cars charge at rate $\frac{\eta^m(x_i)}{E_{\max}} P_i(t)$.

$$\frac{\partial u}{\partial t}(x,t) = -\frac{\partial}{\partial x}[q_c(x,t)u(x,t)] + \sigma_{i\to c}(x,t).$$

External flows

PDE aggregation model

Fleet of EVs = 3 states



$$\frac{\partial u}{\partial t}(x,t) = -\frac{\partial}{\partial x}[q_c(x,t)u(x,t)] + \sigma_{i\to c}(x,t),$$

$$\frac{\partial v}{\partial t}(x,t) = -\sigma_{i\to or}(x,t) - \sigma_{i\to c}(x,t) - \sigma_{i\to d}(x,t),$$

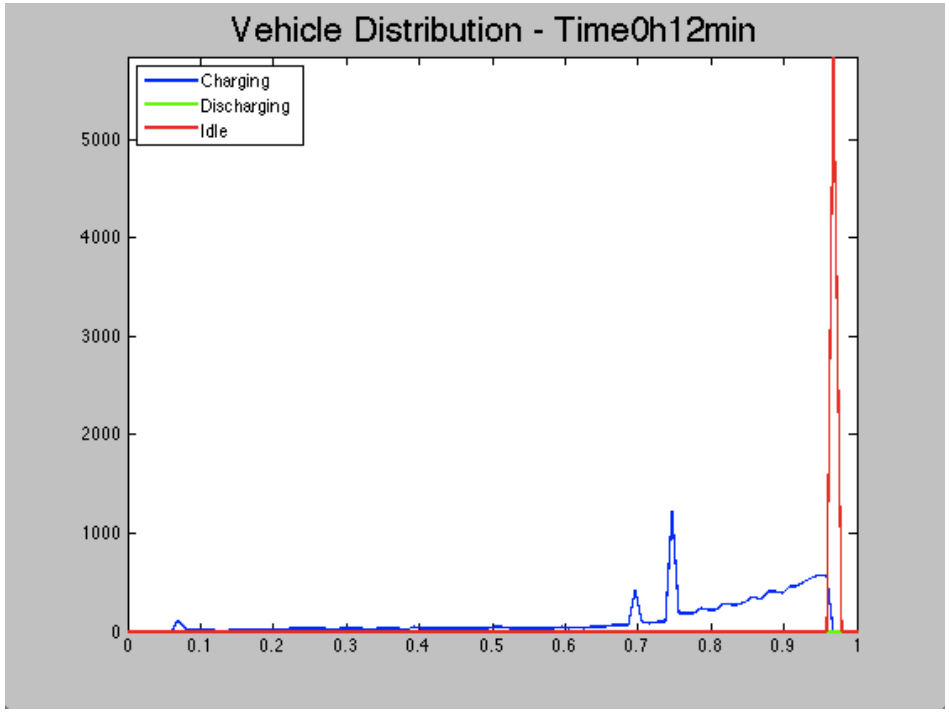
$$\frac{\partial w}{\partial t}(x,t) = \frac{\partial}{\partial x}[q_d(x,t)w(x,t)] + \sigma_{i\to d}(x,t).$$

System of 3 coupled PDEs

PDE aggregation model

EVs stop charging at 97% SOC.

EVs discharge (V2G) between 6pm and 9pm



Why is this model interesting?

- Computation doesn't depend on the number of cars
- Nice Parallel with TCLs
- Large number of analysis and control methods for PDEs

Optimal Charging of V2G fleets

(Validation of the model with V2Gsim)

$$\min_{\sigma_{i\to d},\sigma_{i\to c},Dep} C = \int_0^{T_{max}} C_{elec}(t) \int_0^1 q_c(x,t)u(x,t)\ dx\ dt,$$

subject to

$$\frac{\partial u}{\partial t}(x,t) = -\frac{\partial}{\partial x}[q_c(x,t)u(x,t)] + \sigma_{i\to c}(x,t),$$

$$\frac{\partial v}{\partial t}(x,t) = -\sigma_{i\to c}(x,t) - \sigma_{i\to d}(x,t) + Arr(x,t) - Dep(x,t),$$

$$\frac{\partial w}{\partial t}(x,t) = \frac{\partial}{\partial x}[q_d(x,t)w(x,t)] + \sigma_{i\to d}(x,t),$$

$$u(0,t) = 0,\ w(1,t) = 0,$$

$$u(x,0) = u_0(x),\ v(x,0) = v_0(x),\ w(x,0) = w_0(x),$$

$$-w(x,t) \le \sigma_{i\to d}(x,t) \le v(x,t),$$

$$-u(x,t) \le \sigma_{i\to c}(x,t) \le v(x,t),$$

$$u(x,t) = 0, \quad \forall\ x \ge X_{max},$$

$$v(x,t) = 0, \quad \forall\ x \le X_{min},$$

$$w(x,t) = 0, \quad \forall\ x \le X_{min}.$$

$$\int_0^1 q_d(x)w(x,t)dx \ge P^{des}(t), \quad \forall\ t.$$

$$\int_{X_{dep}}^1 Dep(x,t)\ dx = Dem(t), \quad \forall\ t.$$

$$\int_{X_{dep}}^1 (u+v+w)(x,T_{max})\ dx \ge N_{min}.$$

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Optimal Charging of V2G fleets

(Validation of the model with V2Gsim)

$$\min_{u,v,w,Dep} \Delta t \; \Delta x \sum_{n=0}^{N} \sum_{j=0}^{J} C_{elec}^{n} q_j^n w_j^n$$

subject to

$$[u+v+w]^{n+1} + \frac{Dep^{n+1}}{\Delta x} = M_c u^n + M_d w^n + \frac{Arr^{n+1}}{\Delta x}$$

$$u_0^n = 0, \quad v_J^n = 0,$$
$$u_j^0 = u_{0,j}(j\Delta x), \; v_j^0 = v_{0,j}(j\Delta x), \; w_j^0 = w_{0,j}(j\Delta x), \; \forall j,$$

$$u^n, v^n, w^n, Dep^n \geq 0,$$
$$u_j^n = 0 \; \forall \; j \geq X_{max} \cdot J$$
$$v_j^n = 0 \; \forall \; j \leq X_{min} \cdot J$$
$$w_j^n = 0 \; \forall \; j \leq X_{min} \cdot J$$

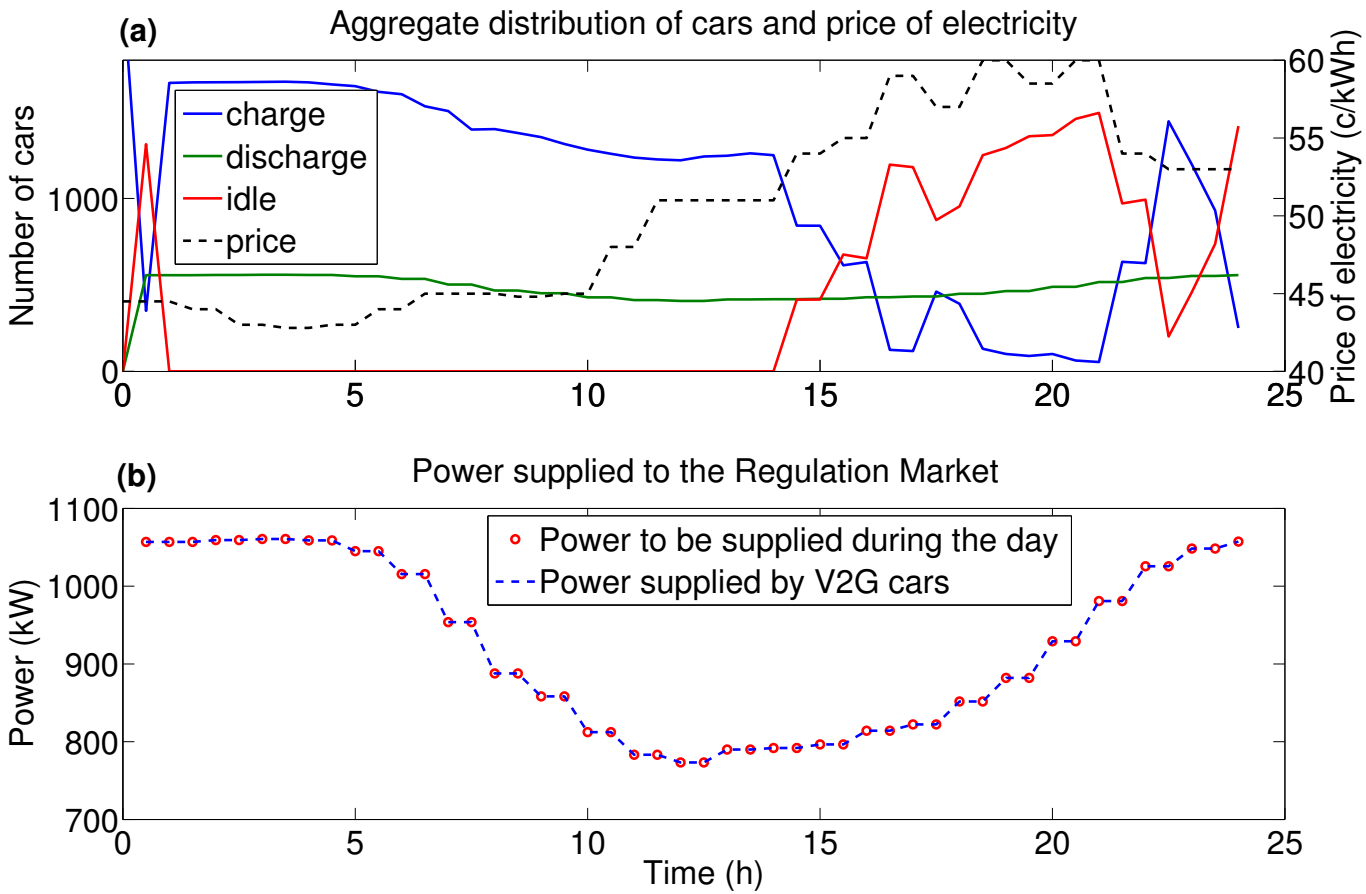
$$\Delta x \sum_{j=0}^{J} q_{d,j}^n w_j^n \geq P^{des,n}$$

$$\sum_{j=X_{dep} \cdot J}^{J} Dep_j^n = Dem^n$$

$$\Delta x \sum_{j=X_{dep} \cdot J}^{J} u_j^N + v_j^N + w_j^N \geq N_{min}$$

Optimal Charging of V2G fleets

Result :



Conclusion

Conclusion

- Model is well suited to handle large population of EVs
- We gave an example for using this model to control a EV fleet

Ongoing work

- Heterogeneity and stochasticity
- Grid constraints
- Different optimization objectives

Thank you!