Electric Energy and Power Consumption by Light-Duty Plug-In Electric Vehicles

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PEVs are here. . .

Chevy Volt

Starting at $32,780 = $40,280 (MSRP) − $7,500 (tax credit)

Nissan Leaf

Starting at $26,220 = $33,720 (MSRP) − $7,500 (tax credit)

Increased availability in late Spring 2011 with full market rollout through 2012.

Other manufacturers that plan to launch PEVs between 2011 and 2013: Toyota, Ford, Honda, Tesla, Mitsubishi, Chrysler, BYD, etc.

Motivation

Forecasts:

- ~1,000,000 within 5-10 years (in US, optimistic scenario)
- "coastal" effect
- heavy concentrations in large urban areas

Benefits:

- In the U.S. in 2009:
  - 94% of transportation energy was obtained from petroleum
  - 63% of the crude oil was imported
- Environmental reasons
- Could provide ancillary services to the electric power system (e.g., regulation)

Outline

For the "average" light-duty[1] PEV, estimate:

1. daily electric *energy* consumption (uncontrolled)
2. daily electric *power*(t) consumption (uncontrolled)
3. daily electric *power*(t) consumption (controlled by aggregator)

Also:

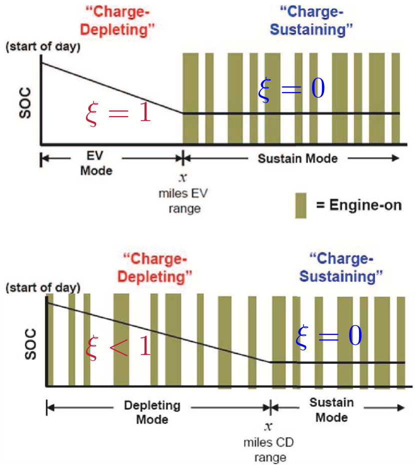
4. propose an operating framework for aggregators of PEVs—scheduling & dispatch algorithms

[1] Cars and light trucks, including minivans, SUVs, and trucks with gross vehicle weight less than 8500 pounds. LDV travel accounts for:

- 92% of the highway vehicle miles traveled
- 76% of the energy consumed by highway travel modes
- 74% of the carbon dioxide emissions from on-road sources

PEV operation

The tractive energy per mile that is provided by the battery in charge-depleting mode (h_e) is a fraction (ξ) of total tractive energy per mile (h_{tr}): $h_e = \xi h_{tr}$.



Source: M. Duoba, 2005
Argonne National Lab

Previous estimates of PEV load

Examples of (unrealistic) assumptions made:

- All PEVs have the same all-electric range
- All PEVs are driven only in all-electric mode
- All PEVs have the same amount of energy in their battery packs
- All PEVs fully exhaust their electric energy every day
- All PEVs are driven every day
- Charging frequency is once per day

So,

- Detailed vehicle travel patterns are not taken into account
- Power consumption is (crudely) extracted from energy calculations assuming, e.g., that all PEVs commence charging at 5 pm or 10 pm

National Household Travel Survey (NHTS)

The 2009 NHTS collects information on the travel behavior of a national representative sample of U.S. households, such as mode of transportation, trip origin and purpose, and trip distance. The survey consists of 150,147 households and 294,408 Light-Duty Vehicles (LDVs).

Data Example from the 2009 NHTS

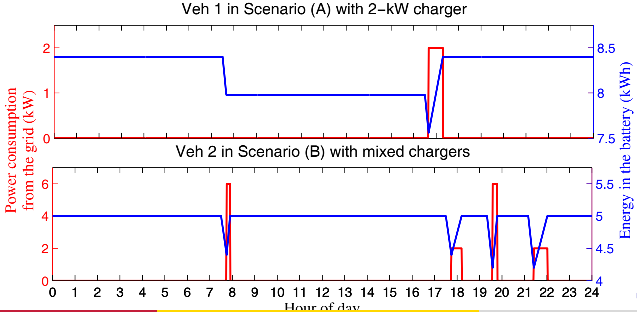
Vehicle	Type	Origin/purpose	Start time	Destination/purpose	End time	Trip miles
Veh1	Car	Home	07:30	Work	07:40	2
		Work	16:30	Home	16:40	2
Veh2	SUV	Home	07:30	Work	07:45	3
		Work	17:30	Home	17:45	3
		Home	19:20	Shopping	19:35	4
		Shopping	21:10	Home	21:25	4

Simulation methodology

Use NHTS travel pattern and virtually convert vehicles to PEVs, using reasonable probability distributions:

- assign tractive energy (h_{tr}) according to vehicle type
- assign degree of drivetrain electrification ($0 < \xi \leq 1$)
- assign charge-depleting range (d)
- assign charger type (kW rating)

Then, run Monte-Carlo simulations:



Daily electric energy consumption per PEV

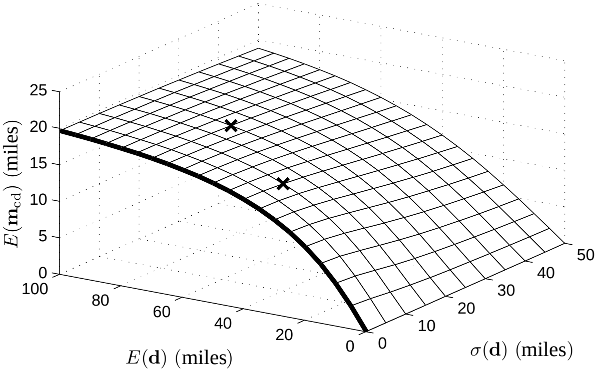
	$E(\mathbf{h}_{\text{tr}})$ kWh/mile	$E(\mathbf{m}_{\text{cd}})$ miles		$E(\boldsymbol{\epsilon})$ kWh		$\sigma(\boldsymbol{\epsilon})$ kWh	
		$f_{d,1}$	$f_{d,2}$	$f_{d,1}$	$f_{d,2}$	$f_{d,1}$	$f_{d,2}$
Urban weekday	0.28	14.70	17.89	4.16	5.06	5.36	7.31
Urban weekend	0.28	11.41	14.10	3.23	3.99	4.98	6.92
Rural weekday	0.31	15.70	20.24	4.88	6.29	6.43	9.10
Rural weekend	0.31	11.92	15.29	3.70	4.75	5.87	8.28

h_{tr} = tractive energy
m_{cd} = miles driven in charge-depleting mode
ϵ = daily electric energy consumption (at the wall outlet)
$f_{d,1}$ and $f_{d,2}$ = probability distributions for the charge-depleting range.
$f_{d,1}$ has mean value 40 mi. $f_{d,2}$ has mean value 70 mi.

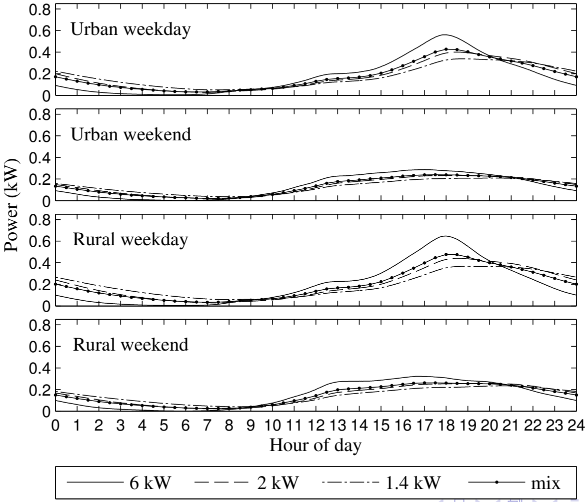
Impacts of battery size on electricity consumption

$$E(\boldsymbol{\epsilon}) = \frac{1}{\eta} E(\boldsymbol{\xi}) E(\mathbf{h}_{\mathsf{tr}}) E(\mathbf{m}_{\mathsf{cd}})$$ where $\eta =$ wall-to-wheels efficiency

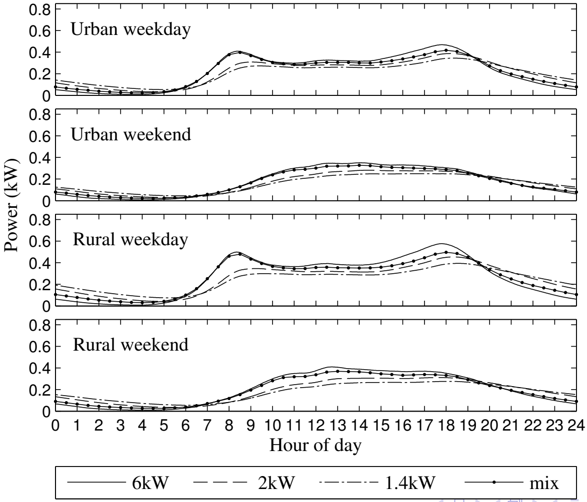
$$f_{m_{\mathsf{cd}}}(x) = f_m(x) \int_x^{\infty} f_d(v)\, dv + f_d(x) \int_x^{\infty} f_m(u)\, du$$



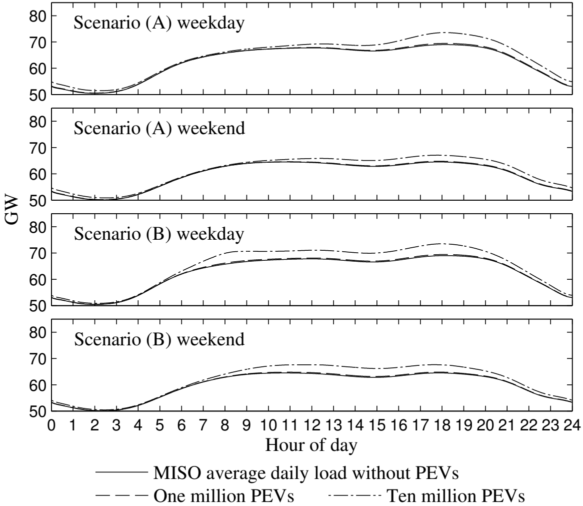
Power consumption — opportunistic charging at home only



Power consumption — opportunistic charging at any location (home, shopping mall, work, etc.)



Power consumption — superimposed on MISO load curve



PEV control by aggregators

- Aggregators will coordinate charging of a PEV fleet:
  - meet commitments to the ISO
  - meet commitments to PEV owners
- Could be:
  - existing, knowledgeable utility organizations
  - entities with little or no experience in interfacing with the bulk power grid

PEV products and services

- Scheduled Energy
- Regulation
- Reserves
- Emergency Load Curtailment
- Balancing Energy
- Dynamic Pricing

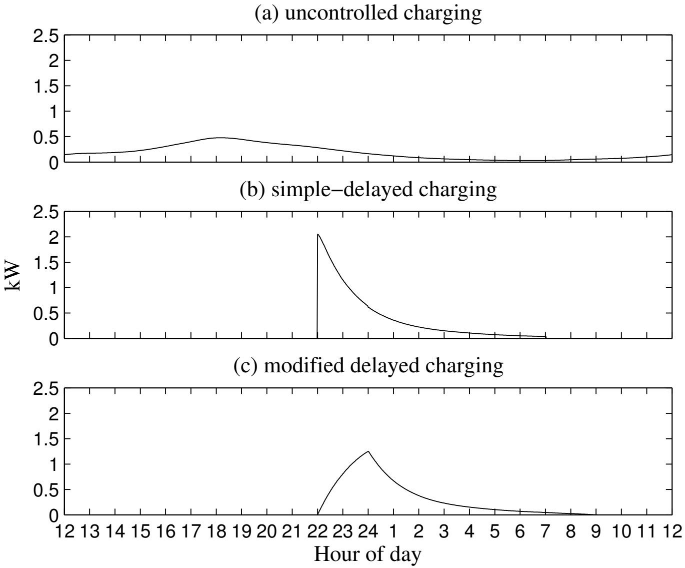
Assumptions about our aggregator

- wishes to maximize its energy trading-related profits
- retail customers pay fixed rate
- controls $N = N_1 + N_2$ PEVs
- risk-averse: purchases part of its energy with long-term bilateral contracts (N_1)
- participates in the day-ahead markets (N_2)
- the split N_1/N_2 is pre-determined (somehow)

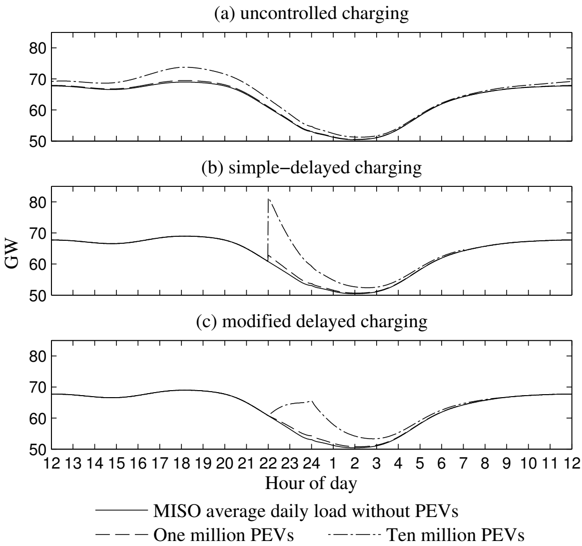
Objectives

1. Set forth algorithms that aggregators can use to *schedule* and *dispatch* the PEV load so that their energy cost is reduced (and ideally minimized).
    - Need information about the forecasted charging demand for the coming day.
    - The proposed scheduling algorithm can be applied for negotiating long-term bilateral contracts, based on the offered electricity price (especially if this price is time-varying); or for participating in the day-ahead market, based on the forecasted electricity price.
2. Identify impact of aggregated PEV load on the power system.

Various power consumption curves

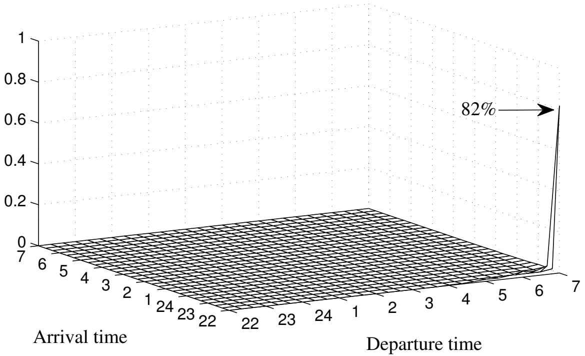


Impact on MISO load curve

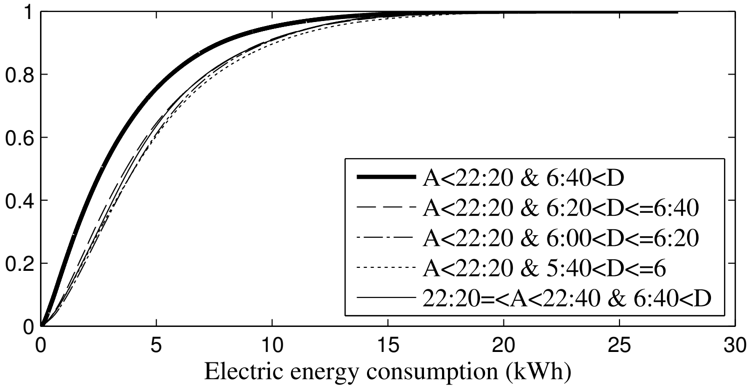


Scheduling

- Aggregator maintains database of PEV travel pattern statistics
- $n(l, j, s, e)$: number of PEVs with charging duration l, charger type j, arrival slot s, and departure slot e



Scheduling — CDF of daily VMT for several combinations of arrival and departure times



Scheduling algorithm

1: Input: τ_k for $1 \leq k \leq K$, and $n(l, j, s, e)$ for $1 \leq s < e \leq K$, $0 \leq l \leq e - s \leq K$ and $1 \leq j \leq J$.
2: **for** $k = 1$ **to** K **do**
3: $\mathcal{P}_k \leftarrow 0$
4: **end for**
5: **for** $s = 1$ **to** K **do**
6: **for** $e = s + 1$ **to** K **do**
7: Rank the price τ_k for $s < k \leq e$ from lowest to highest. The ranking function is denoted by $R_{s+1,e}(\tau_k)$, and takes the values $\{1, \ldots, e - s\}$. If different time slots have equal τ_k, they are ranked according to the index k from low to high.
8: **for** $m = 1$ **to** $e - s$ **do**
9: Compute the power which should be purchased for the time slot with the m^{th} cheapest price among time slots $s + 1$ to e, which is

$$\chi_m \leftarrow \sum_{j=1}^{J} c_j \sum_{l=m}^{e-s} n(l, j, s, e) \, .$$

10: **end for**
11: **for** $k = s + 1$ **to** e **do**
12: Update the charging power $\mathcal{P}_k$ for time slot k:

$$\mathcal{P}_k \leftarrow \mathcal{P}_k + \chi_{R_{s+1,e}(\tau_k)} \, .$$

13: **end for**
14: **end for**
15: **end for**
16: **return** $\mathcal{P}_k$

Scheduling algorithm (what it really does)

Given the price variation, τ_k, solve the following linear program, where $p_{i,k} =$ power consumption of PEV i at time slot k:

$$\min_{p_{i,k}} \Delta T \sum_{i=1}^{N_x} \sum_{k=1}^{K} \tau_k p_{i,k}$$

$$\text{subject to } \sum_{k=1}^{K} p_{i,k} = p_i l_i, \text{ for all } i$$

$$0 \leq p_{i,k} \leq p_i, \text{ for all } i, k$$

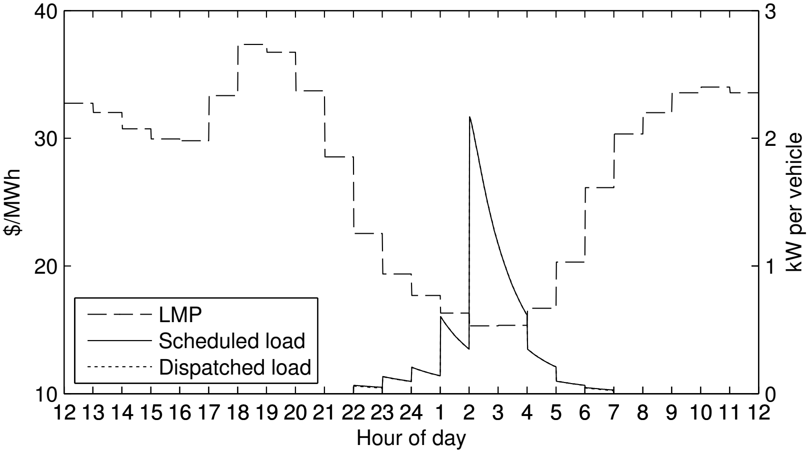
$$p_{i,k} = 0 \text{ for } k \leq s_i \text{ and } k > e_i, \text{ for all } i$$

The solution that is produced is (for all i)

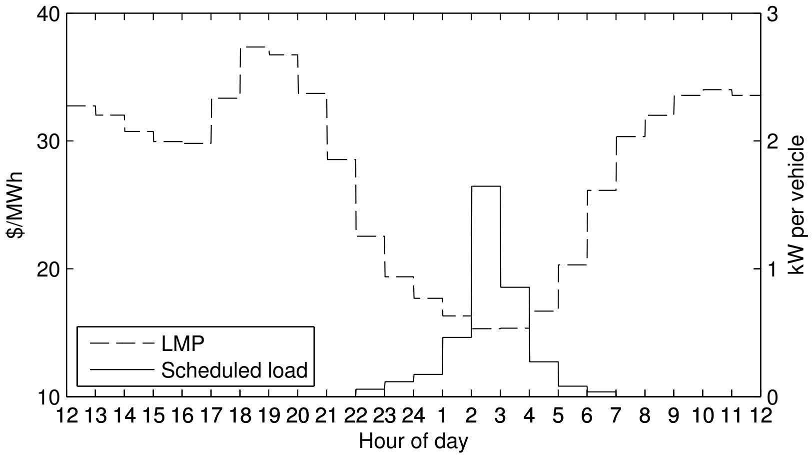
$$p_{i,k} = p_i, \text{ for } k \text{ such that } R_{s_i+1,e_i}(\tau_k) \leq l_i, \text{ and}$$

$$p_{i,k} = 0, \text{ otherwise.}$$

LMP and PEV scheduled load



LMP and flattened PEV scheduled load



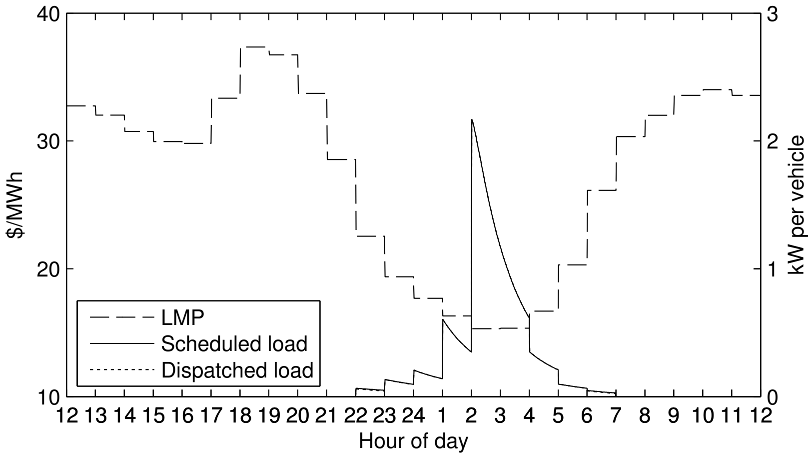
Interesting remarks

- Is this the only minimum cost solution?
- Is this load profile "good" from a power system standpoint?
- How much can we deviate from the flat power(t) hourly energy purchase commitments?
- What about the hourly step changes?
- Wouldn't PEV load affect the LMP?
- Could aggregators bid price-sensitive load curves?
- Are current market mechanisms adequate to enable the proper integration of PEVs to the power system?

Dispatch algorithm

Input: $\mathcal{P}_k$ for $k = 1, \ldots, K$, and p_i for $i = 1, \ldots, N_x$.
loop
  if PEV i arrives at home and gets plugged in **then**
    Receive $\{\mathcal{E}_i, s_i, e_i\}$. Calculate l_i.
    Rank the time slots $\{k : s_i + 1 \leq k \leq e_i$ and $\mathcal{P}_k > 0\}$ according to τ_k, from lowest to highest. The rank of slot k is denoted by $R_{s_i+1,e_i}(\tau_k)$. $\{\mathcal{P}_k \leq 0$ corresponds to the case where the purchased power at time slot k has been exhausted.$\}$
    $\mathcal{H}_i \leftarrow \{k : R_{s_i+1,e_i}(\tau_k) \leq l_i\}$.
    $\mathcal{P}_k \leftarrow \mathcal{P}_k - p_i$, for all $k \in \mathcal{H}_i$.
  end if
end loop

Dispatch (simulation results)



Thank you! Questions?

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