Cost-effective and Eco-friendly

Plug-In Hybrid Electric Vehicle Charging Management

Eleftheria (Ria) Kontou PhD, University of Florida, ekontou@ufl.edu;

Yafeng Yin PhD, University of Florida; Ying-en Ge PhD, Shanghai Maritime University

INTRODUCTION

Why is PHEV technology promising?

1. potential for reduction of dependency on oil and fuel prices
2. potential for reducing carbon dioxide emissions
3. prompt deployment, no need for additional infrastructure installation

Benefits of PHEV technology depend on:

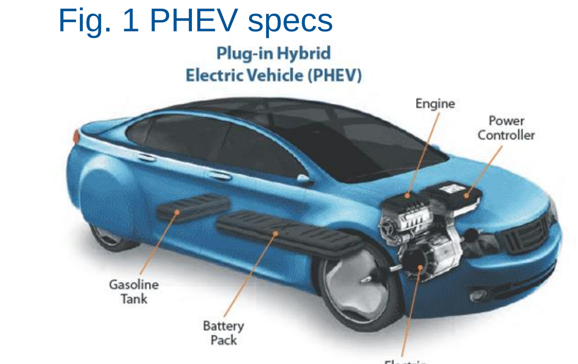
1. PHEV design (all-electric driving range)
2. market penetration (spatial & temporal variability)
3. charging infrastructure availability (spatial variability)
4. generation source of charging electricity (temporal & spatial variability)

PHEV SPECS & CHARGING

PHEVs operating in two modes:

Charge-depleting mode; powered by electricity
Charge-sustaining mode; fueled with gasoline

Fig. 1 PHEV specs



Union of Concerned Scientists (2012)

Charging behavior and control

Uncontrolled charging hypotheses

- only at home Kang and Recker (2009)
- home & workplace/public Weiller (2011); Clement et al. (2009)
- last-minute home Kelly et al. (2012)

Table 1 U.S. best-selling PHEV specs

Specifications	Chevy Volt
Electric driving range (mi)	[24, 53]
MPG-equivalent	Combined 106

Department of Energy (2016)

Controlled charging objectives and methods

- unit commitment modeling; min generation costs Clement et al. (2009); Sioshansi (2012); Weis et al. (2015)
- scheduling charge during low demand grid util. Ahn et al. (2012)
- maximize electrified miles from daily trips Rotering and Ilic (2011)
- minimize drivers cost of recharging Zhang and Markel (2016)

RESEARCH MOTIVATION

Centralized PHEV charging control benefits

Optimized PHEV charging control can help towards:

- control demand surge
- utility grid reliability
- control emissions from recharging

This study explores two optimal PHEV charging management schemes:

1. Cost-effective: minimize PHEV drivers cost from daily driving
   - drivers benefit, take advantage of hourly variation of elec. prices
2. Eco-friendly: minimize PHEV emissions from daily PHEV driving
   - min. externalities due to substantial difference between marginal electricity prices and hourly emission factors of electricity generation

CHARGING MANAGEMENT STRATEGIES

Cost-effective charging management

- minimize sum of cost of daily PHEV operation
  - cost of charging PHEV
  - cost of operating PHEV in charge-sustaining mode (gas consumption)

Eco-friendly charging management

- minimize emissions from daily PHEV operation
  - emissions from electricity generation realized while charging
  - tailpipe emissions from charge-sustaining PHEV operation

OPTIMIZATION FRAMEWORK

Mixed integer programming: 2 schemes – 2 obj. functions, same set of constraints

Constraints enhanced and modified from Sioshansi (2012)

Determine optimal hourly charging profiles and power loads (p_i^t, ${d_{CD}}_i^t$, a_i^t)

Cost-effective scheme obj.

$$\min z1 = \sum_t \sum_i \left(p_e^t \cdot n_e \cdot r_i^t + p_{g_i}/n_g \cdot d_{cs_i}^t\right)$$

Minimize sum of operational costs
- charging cost (electricity generation)
- gasoline consumption cost

Eco-friendly scheme obj.

$$\min z2 = \sum_t \sum_i \zeta\left(v_e^t \cdot n_e \cdot r_i^t + v_g/n_g \cdot d_{cs_i}^t\right)$$

Minimize sum of monetized emissions
- from electricity generation for charging
- from gas-fueled trip portion (tailpipe)

s.t.

$$s_i^{t+1} = s_i^t + r_i^{t+1} - {d_{CD}}_i^{t+1}, \forall i,t$$
$$S^- \le s_i^t, \forall i,t$$
$$s_i^t \le S^+, \forall i,t$$

constraints tracking PHEV battery state-of-charge

$$r_i^t = P_i^t \cdot \left(l_i^t \cdot \frac{p_i^t}{n_e}\right), \forall i,t$$

kWh charged based on charging availability and level

$$d_{CD_i}^t + d_{CS_i}^t = d_i^t, \forall i,t$$
$$d_{CS_i}^t \le d_i^t \cdot (1 - a_i^t), \forall i,t$$
$$a_i^t \ge \frac{s_i^t - S^-}{S^+ - S^-}, \forall i,t$$

electricity-powered and gas fueled distance equations

$$\sum_i p_i^t \le C^t, \forall t$$

upper bound of electricity drawn from the grid (charging availability and level constraint)

$$d_{CS_{ij}}^t, d_{CD_{ij}}^t \ge 0, \forall i,t$$
$$p_i^t \ge 0, p_i^t \le v_i^t, \forall i,t$$
$$a_i^t \in \{0,1\}, \forall i,t$$

non-negativity & integrality constraints

DATASETS

Plug-in hybrid vehicle & charging characteristics

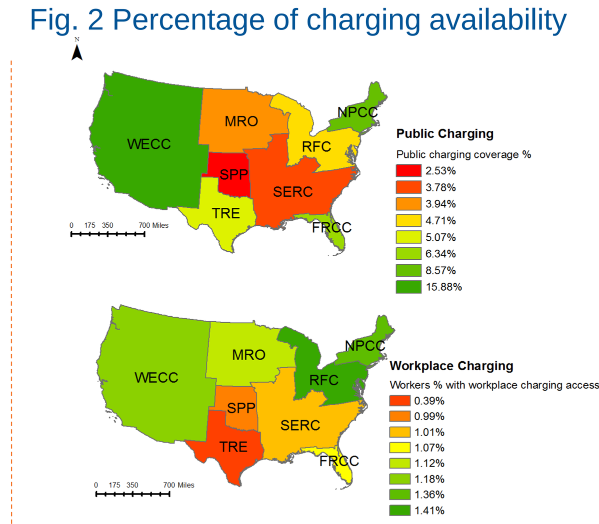
Table 2 Vehicle and charging characteristics — Department of Energy (2016)

Vehicle Specifications						
Type	Model	Battery Capacity (kWh)	Max SOC (mi)	Min SOC (mi)	Electricity Efficiency (kWh/mi)	Gasoline Economy (mpg)
Base:PHEV-50	Chevrolet Volt 2016	18.4	53	10.6	0.3	42
Sc1:PHEV-10		6.7	6	0	same	same
Sc2:PHEV-20		7.6	19	6	same	same

Charging Characteristics				
Destination	Type of charge	AC Input	Charge rate (kWh)	Charge rate (avg. miles)
Home	Level 1	120 V/ 10 A	1.2	4
Work	Level 2	240 V/ 40 A	7.2	24
Public	Level 2	208 V/ 80 A	19.2	64

Workplace & public charging

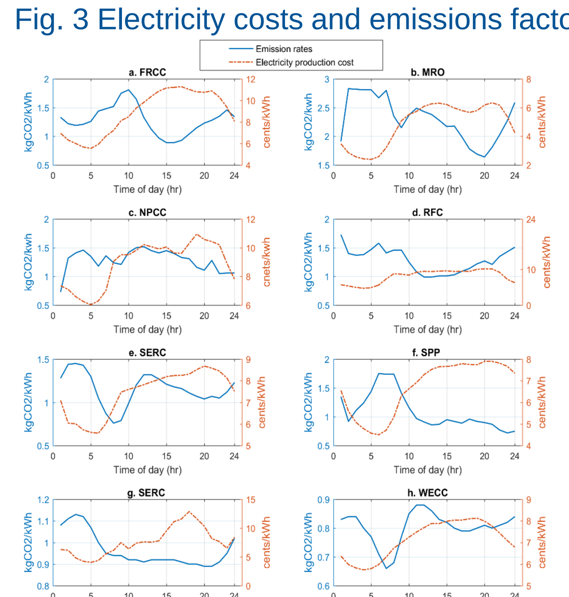
Fig. 2 Percentage of charging availability



North American Electric Reliability Corporation (2016); Department of Energy (2016); Office of Energy Efficiency and Renewable Energy (2016)

Spatial & hourly variability of marginal electricity generation costs ($/kWh) & emission factors (kgCO2-eq/kWh)

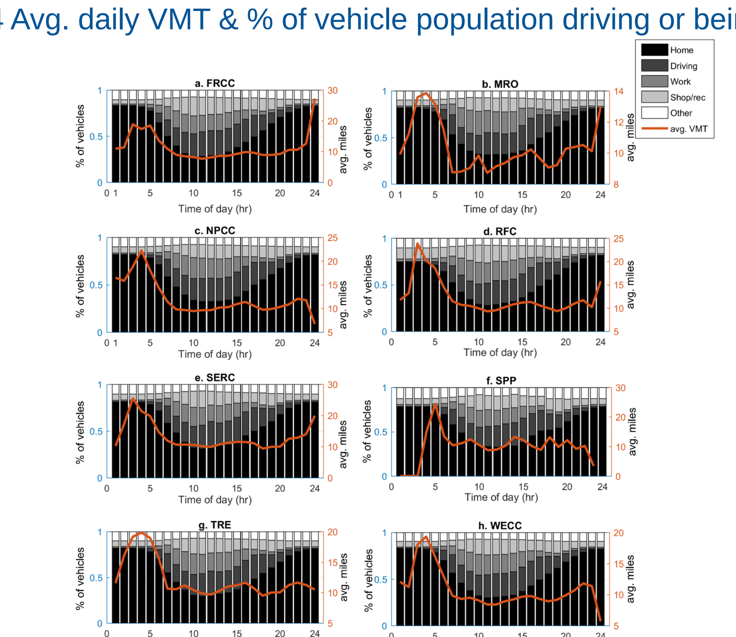
Fig. 3 Electricity costs and emissions factors



from Graff Zivin et al. (2014)

Heterogeneous daily driving/activity patterns

Fig. 4 Avg. daily VMT & % of vehicle population driving or being idle

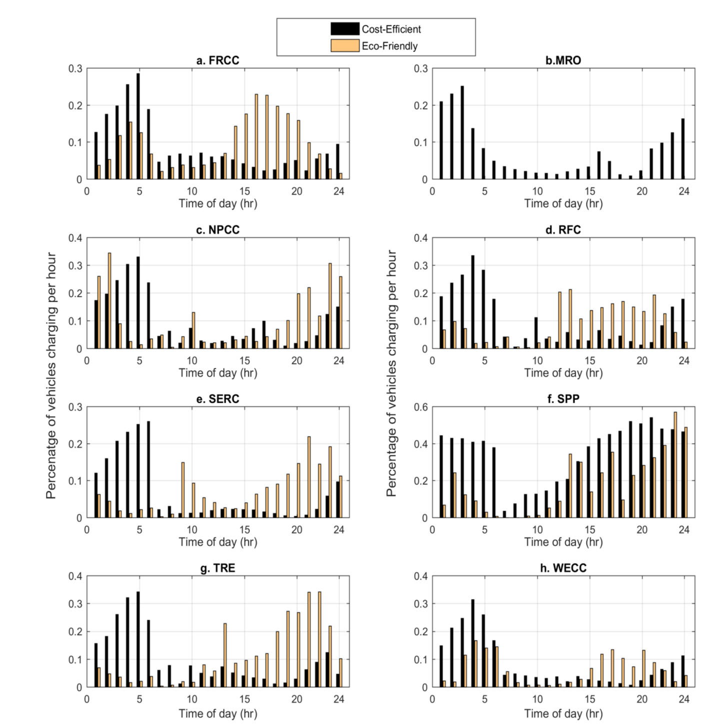


Department of Transportation (2009)

RESULTS

Optimal charging profiles under cost-effective and eco-friendly schemes

Fig. 6 Optimal charging profiles percentages resulting from the cost-effective and eco-friendly charging management schemes



Key findings

a) great difference in charging schedules

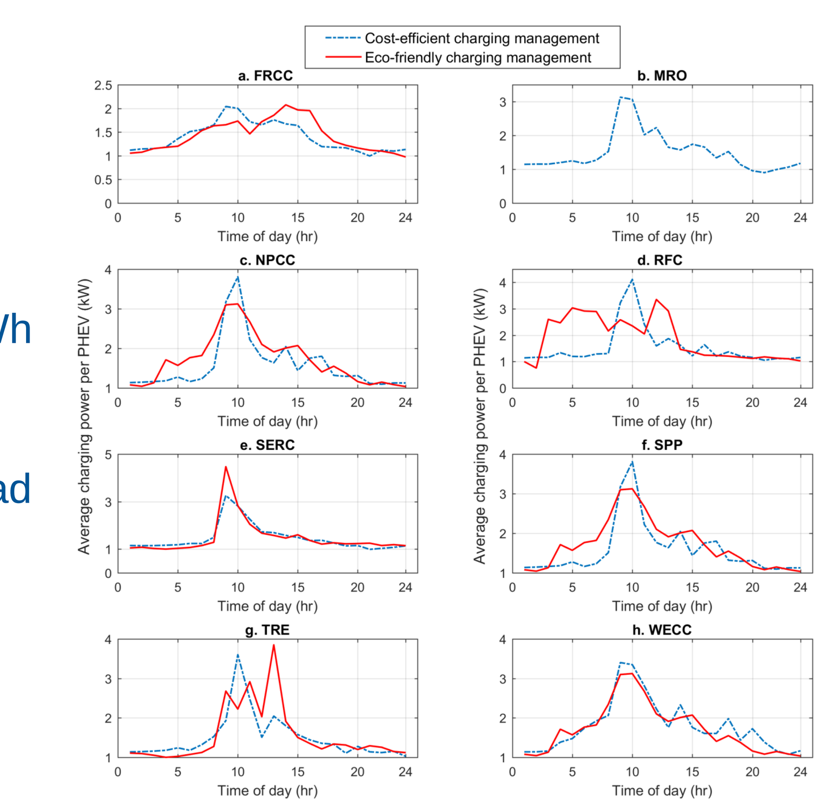
b) % charging ↑ when at home

c) daytime out-of-home charging ≤ 10%

d) MRO region eco-friendly scheme: no-charging

e) cost-effective control: greater % of PHEVS charging at lower avg. power

Fig. 7 Avg. hourly power load profiles per each NERC region



Key findings

a) avg. charging energy 8pm-5am 1.2kWh

b) spikes during day time (workplace charge)

c) NPCC, SERC, SPP, WECC similar load trends (both schemes)

d) FRCC and TRE shifted eco-friendly load later in the afternoon

Alternate scenario results

- Diverse range impact on daily electrified VMT, under 2 control charging schemes
- Workplace & public charging availability impact on % of vehicles charging per hour

Fig. 8 Daily mileage electrification for NERC regions

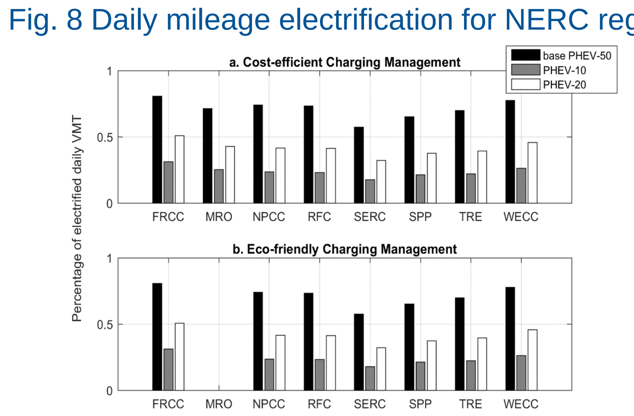
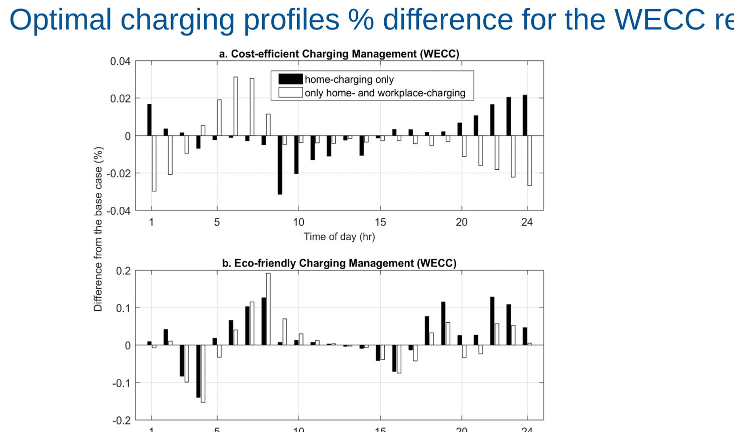


Fig. 9 Optimal charging profiles % difference for the WECC region



CONCLUSIONS

Cost-effective and eco-friendly controlled charging schemes

- very different resulting charging profiles
- optimal cost-effective charging occurs early morning hours
- optimal eco-friendly charging in the afternoon and evening

Scenarios findings

- Eco-friendly scheme
  - greater load spikes during the day
  - impacted by absence of public charging
- Cost-effective scheme
  - workplace charge absence leads to increasing charging at night

Charging control more cost-effective and environmentally friendly when range increases.