# Analysis on Battery Charging Behavior of Electric Vehicles

Toshiyuki Yamamoto, Xiao-Hui Sun
and Takayuki Morikawa

Nagoya University

# Outline

- Introduction
- Battery charging behavior
  - Within trip
  - At home
- Conclusions



# Battery electric vehicles and Plug-in hybrid vehicle in Japan

i-MiEV
2009


Leaf
2010

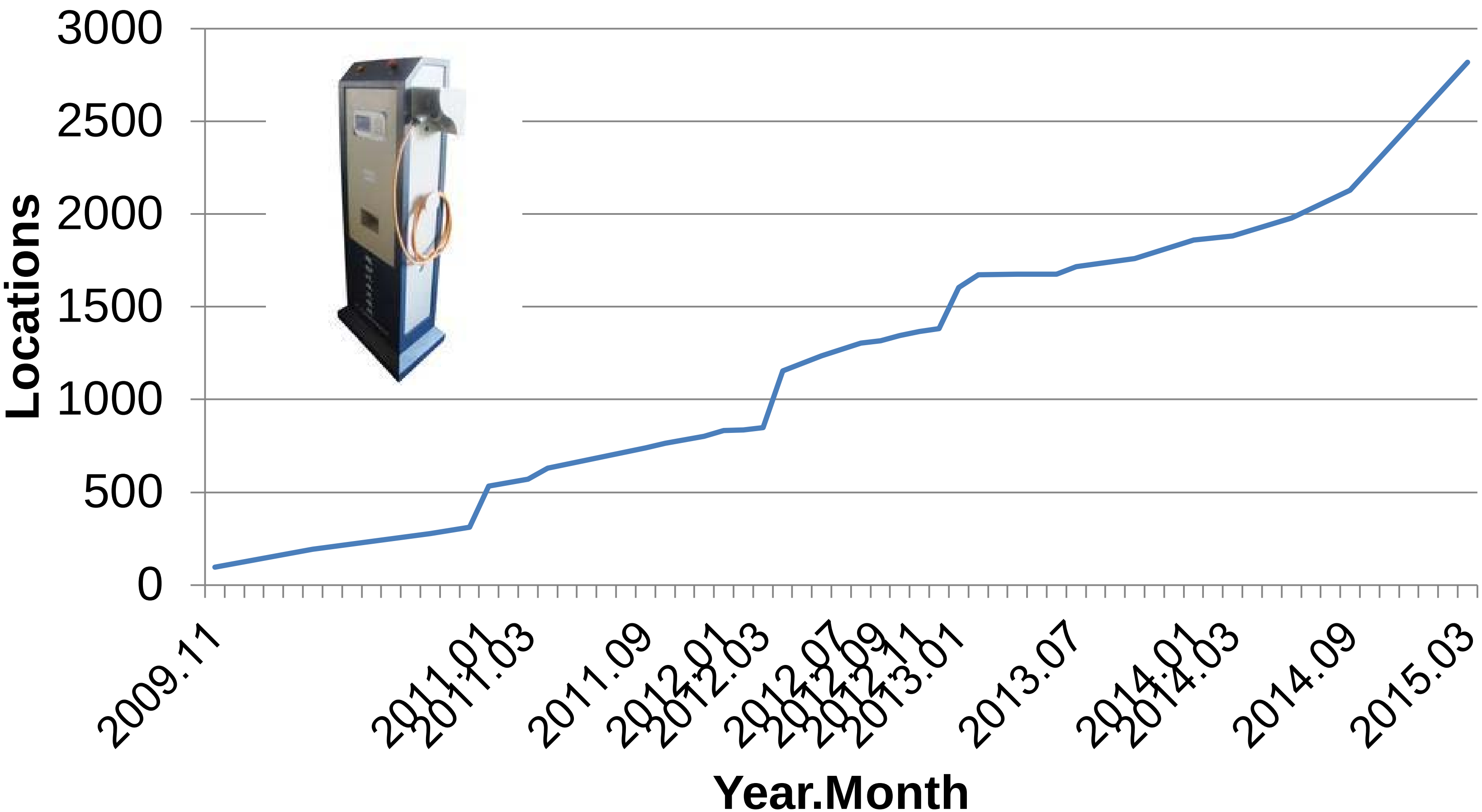
Prius plug-in hybrid
2012

More energy efficient, but
more electricity dependent

# Charging types

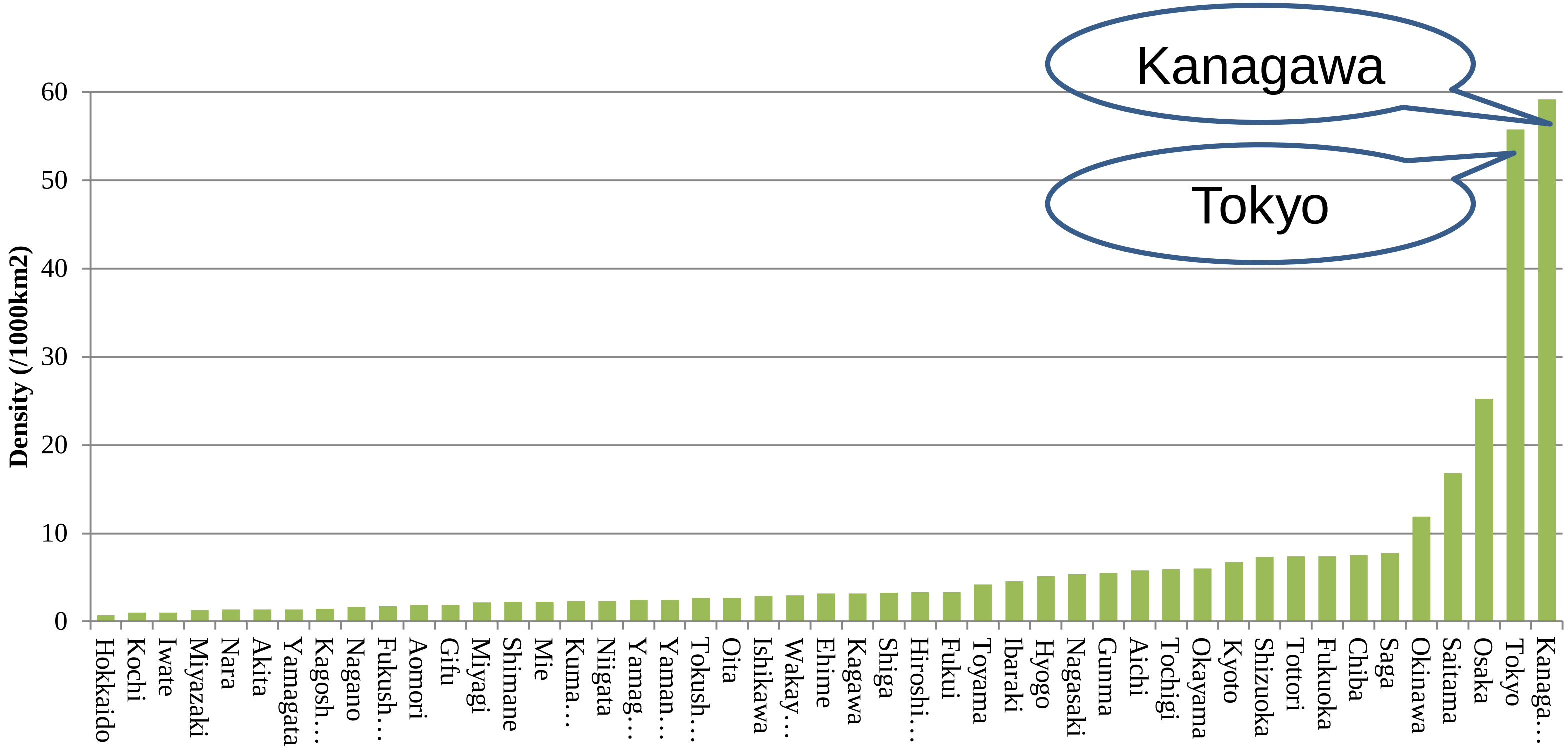
| **Level 1** | | **Level 2** | | **Level 3** |
|---|---|---|---|---|
| 120V (SAE J1772) | *100V (Japan)* | 240V (SAE J1772) | *200V (Japan)* | >=480V (CHAdeMO technology) |
| Normal charging (aka slow charging) requires several hours to completely charge a fully depleted battery and can be performed at home | | | | Fast charging (aka quick or rapid charging) provides an 80% charge in 30 minutes |

# Fast charger deployment in Japan




Source: CHAdeMO Association

# Fast charger density




Charging stations are located:

Workplaces & leisure places (47.3%)
Car sales shops (40.4%)
Parking lots (4.8%)
Motorways (2.8%)
Convenience stores (2.5%)
Gas stations (2.2%)

# Battery charging within trip

- Sun, X.-H., Yamamoto, T. and Morikawa, T.: Stochastic frontier analysis of excess access to mid-trip battery electric vehicle fast charging. Transportation Research Part D, Vol. 34, pp. 83-94, 2015. DOI:10.1016/j.trd.2014.10.006

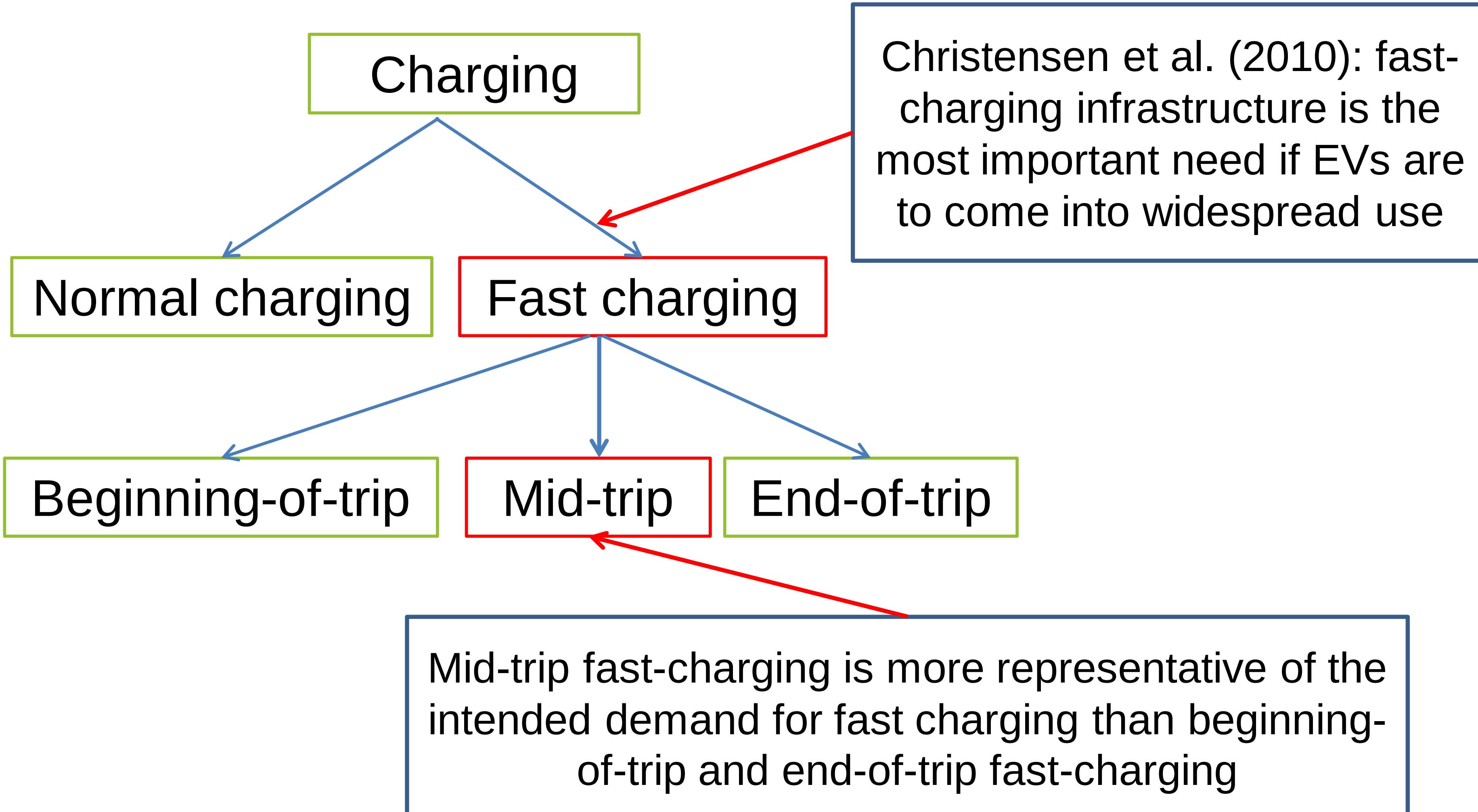
# Trade-off between battery size and fast charger density

How to optimize battery size & fast charger deployment?

- Drivers charge battery before empty
- Charging behavior should be understood

# Charging behavior of battery usage

➢ Focus of this study: Mid-trip fast charging

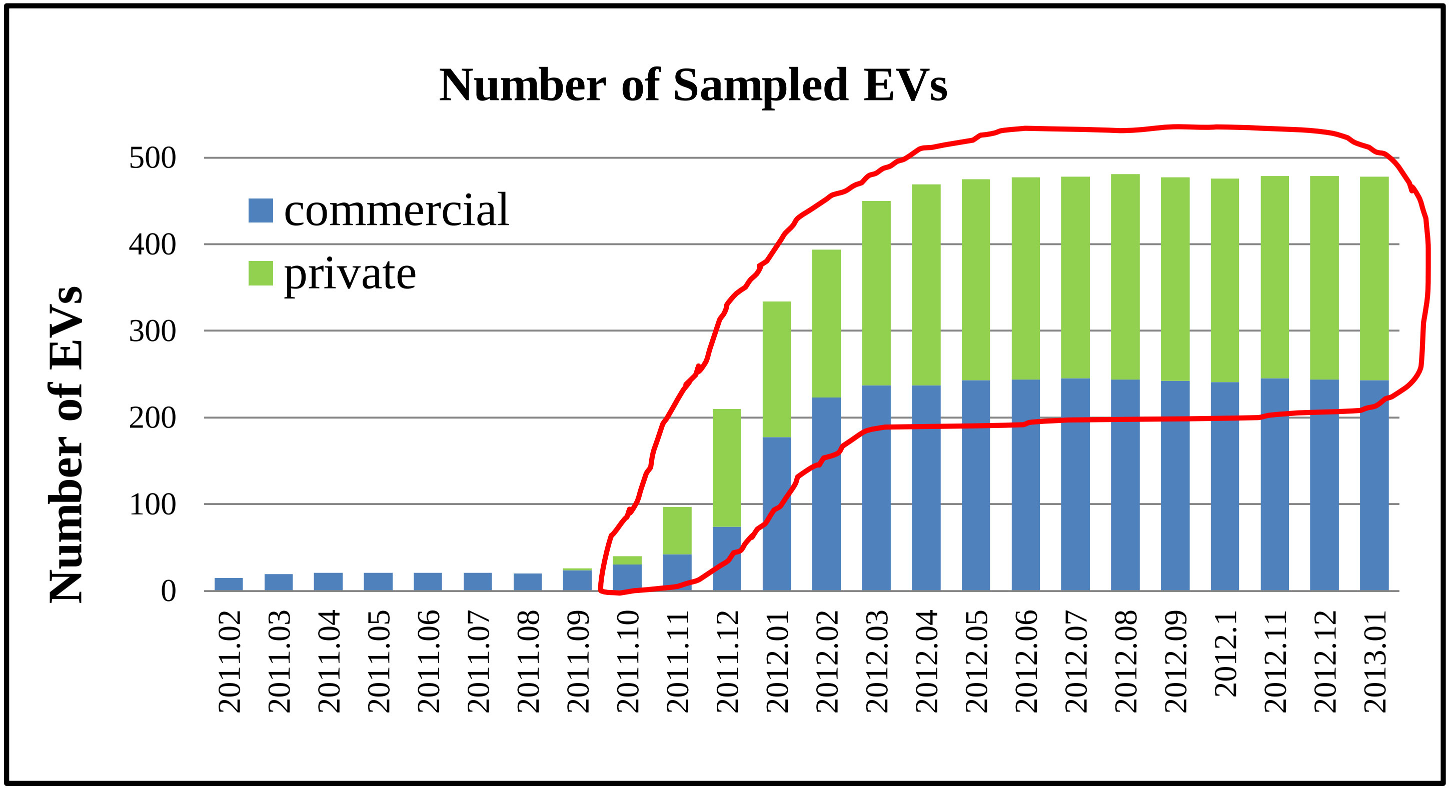


# Data

- Investigator: Japan Automobile Research Institute
- Sample: 252 company cars & 247 private cars
- Survey period: 2 years (2011.2-2013.1)
- Survey area: 42 out of 47 prefectures in Japan

- **Built-in data logger with GPS & communication unit**: clock time, location, vehicle state (driving, normal charging, fast charging), odometer reading, use of air-conditioner & heater, state of charge

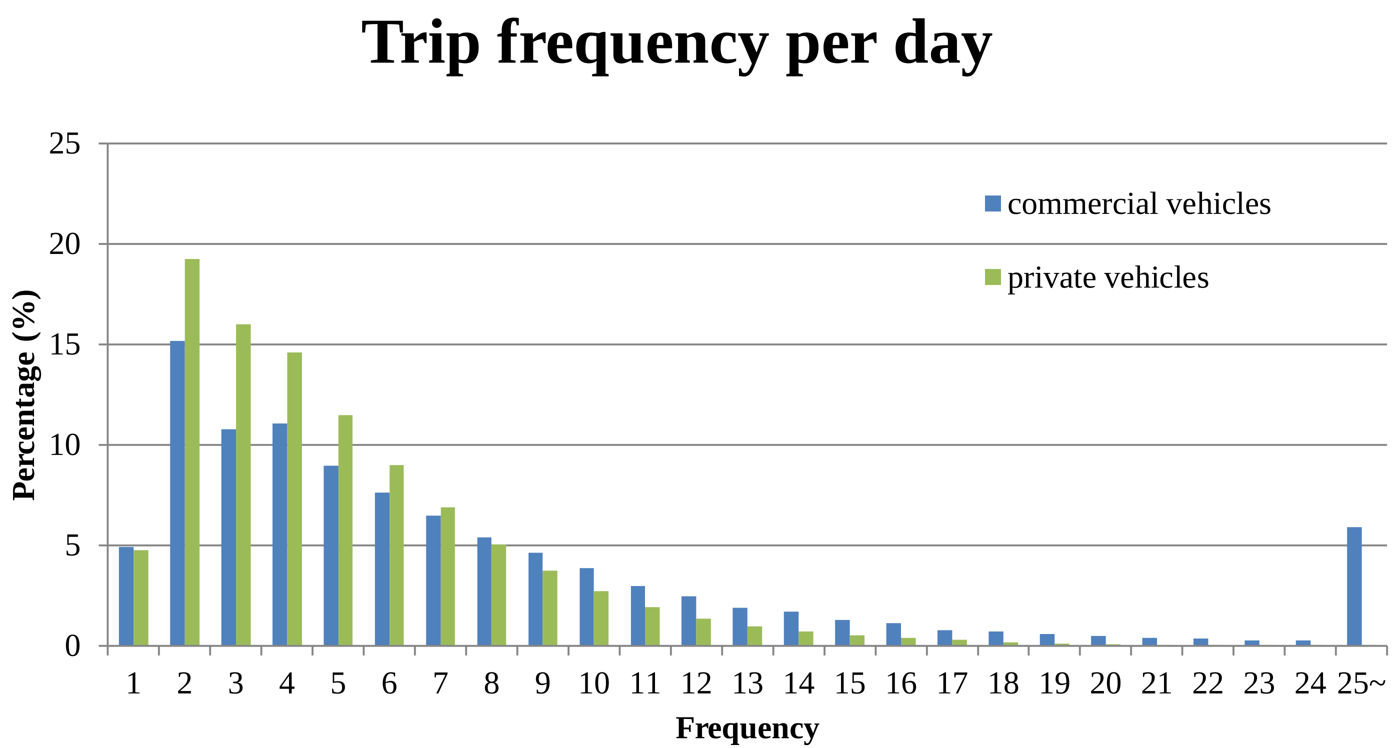
# Field trial and data profiles




- commercial vehicles: vehicles owned by fleets, include business vehicles and government vehicles
- private vehicles: vehicles owned by households

| Battery Capacity | 10.5&16 kWh |
|---|---|
| Max. Driving Mileage | 120&180 km |

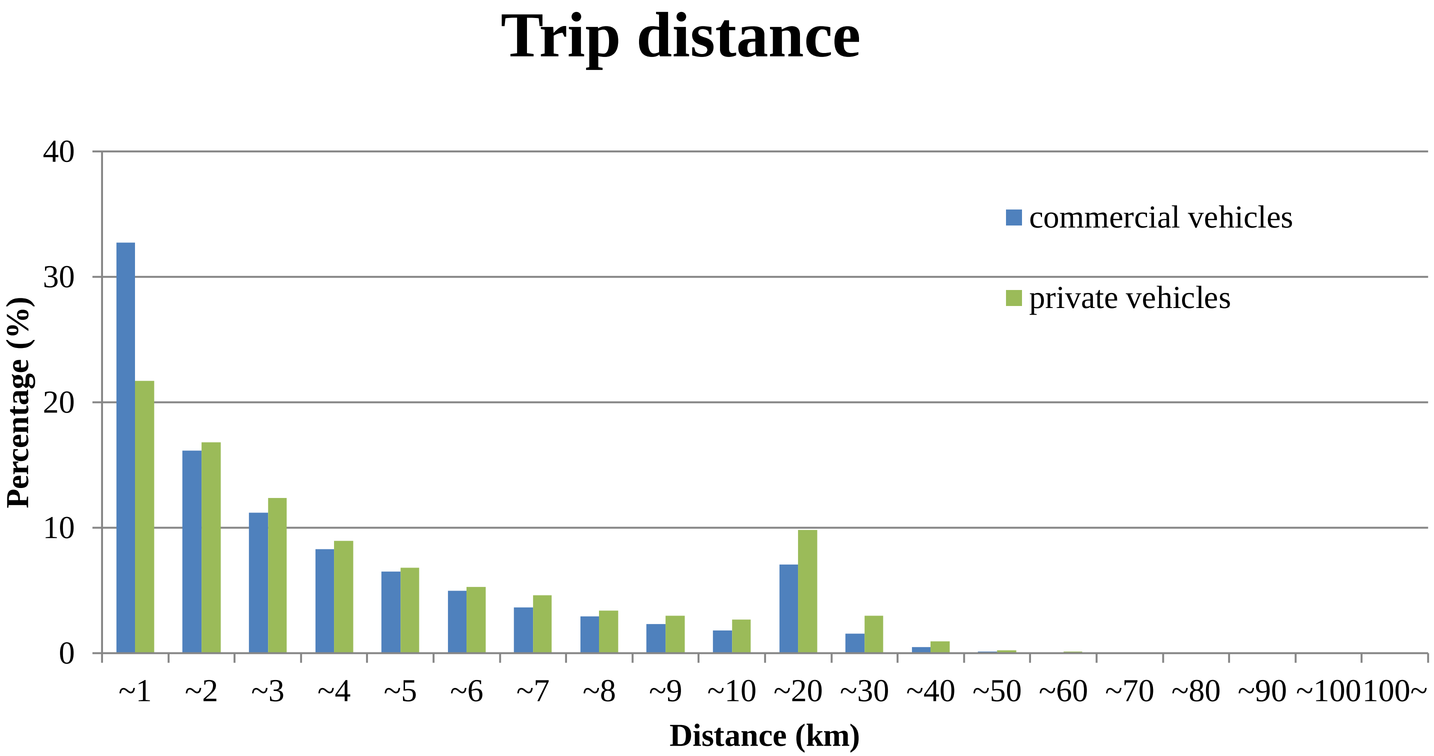
# Field trial and data profiles




Average trip frequency per day:
Commercial vehicles: 8.7
Private vehicles: 5.0

* Trip: travel distance between engine starting and engine stopping

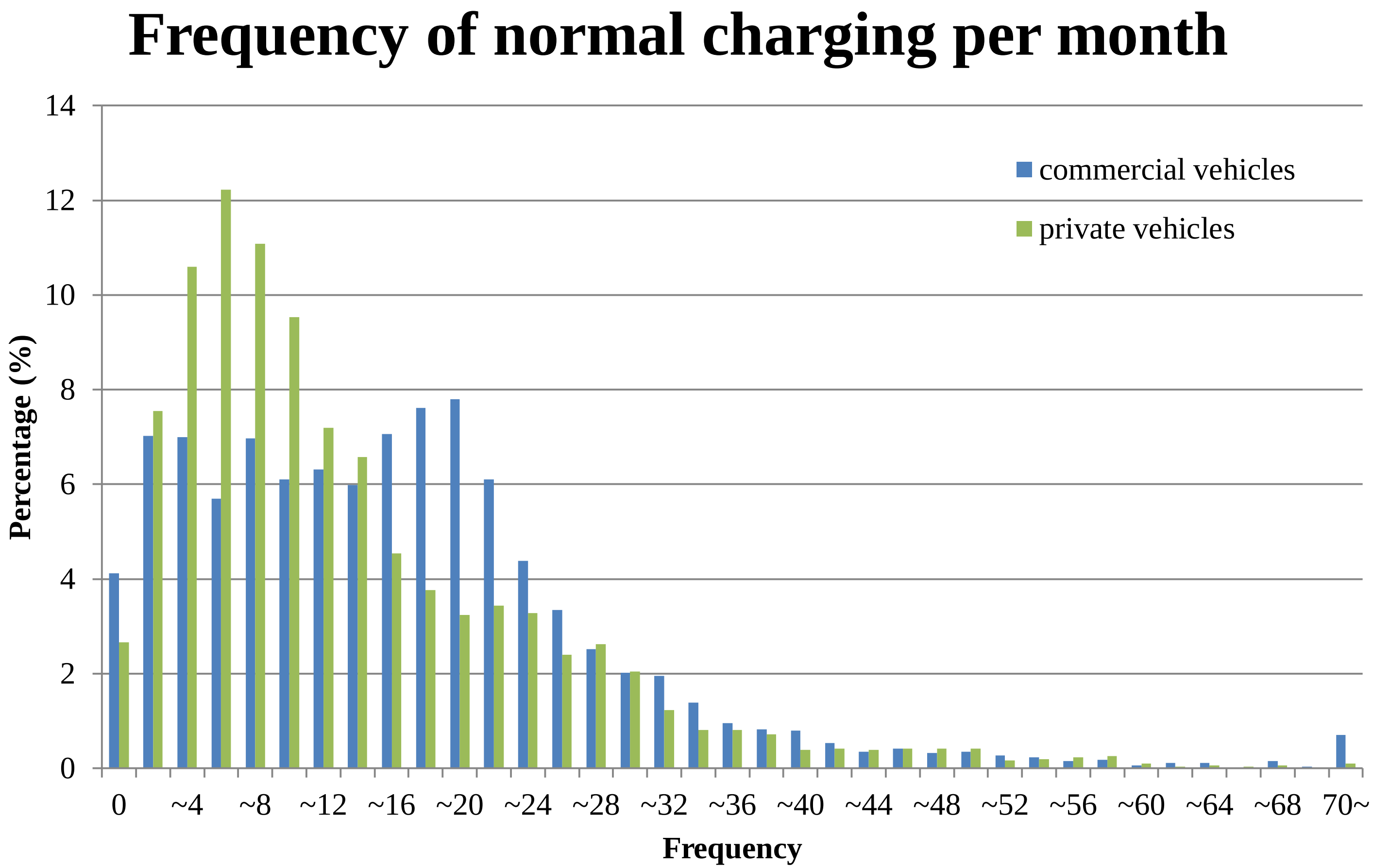
# Field trial and data profiles




Average trip distance:
Commercial vehicles: 4.5km
Private vehicles: 5.9km

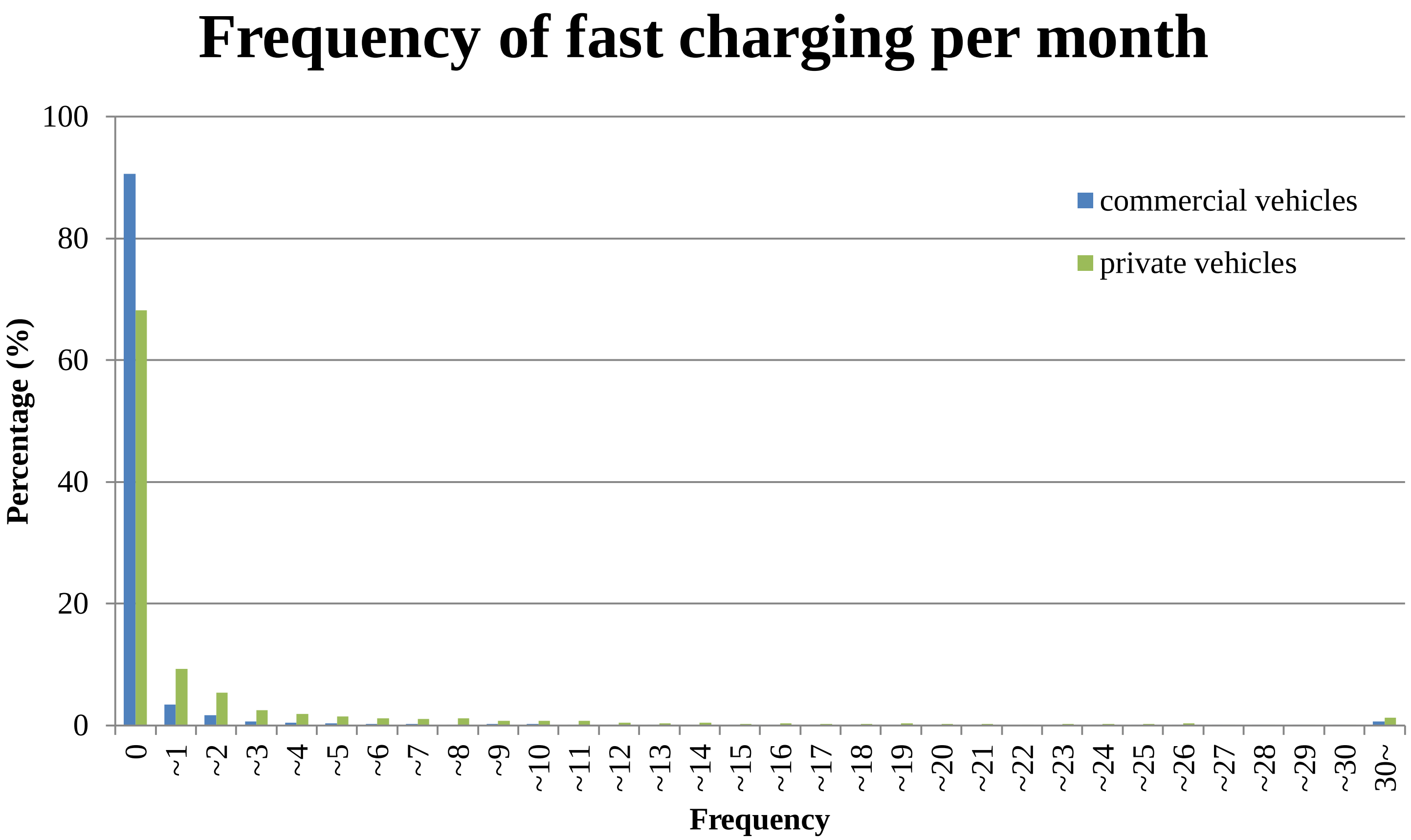
* Trip: travel distance between engine starting and engine stopping

# Field trial and data profiles



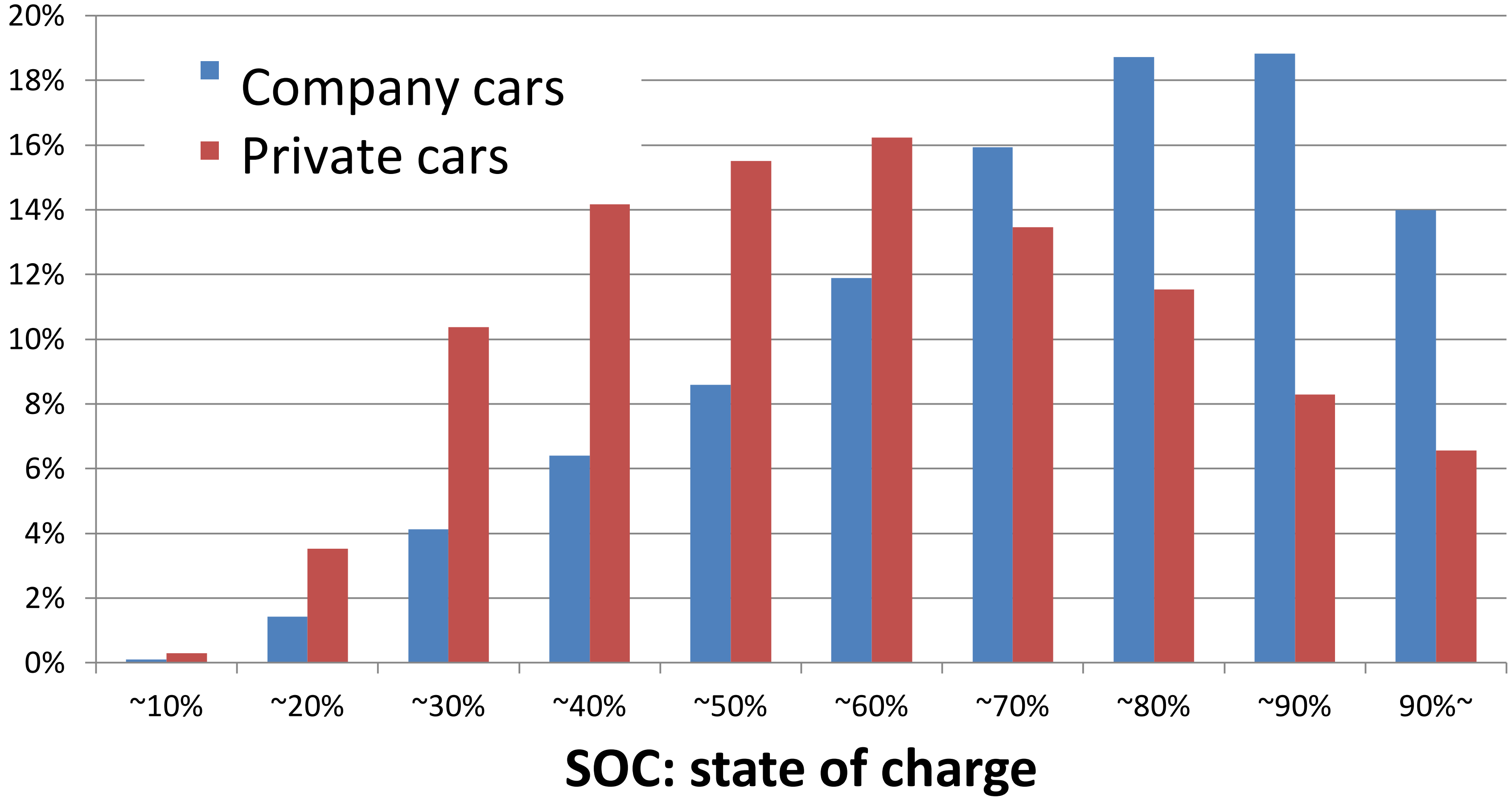

Average frequency of normal charging per month:
Commercial vehicles: 16.2
Private vehicles: 13.1

# Field trial and data profiles



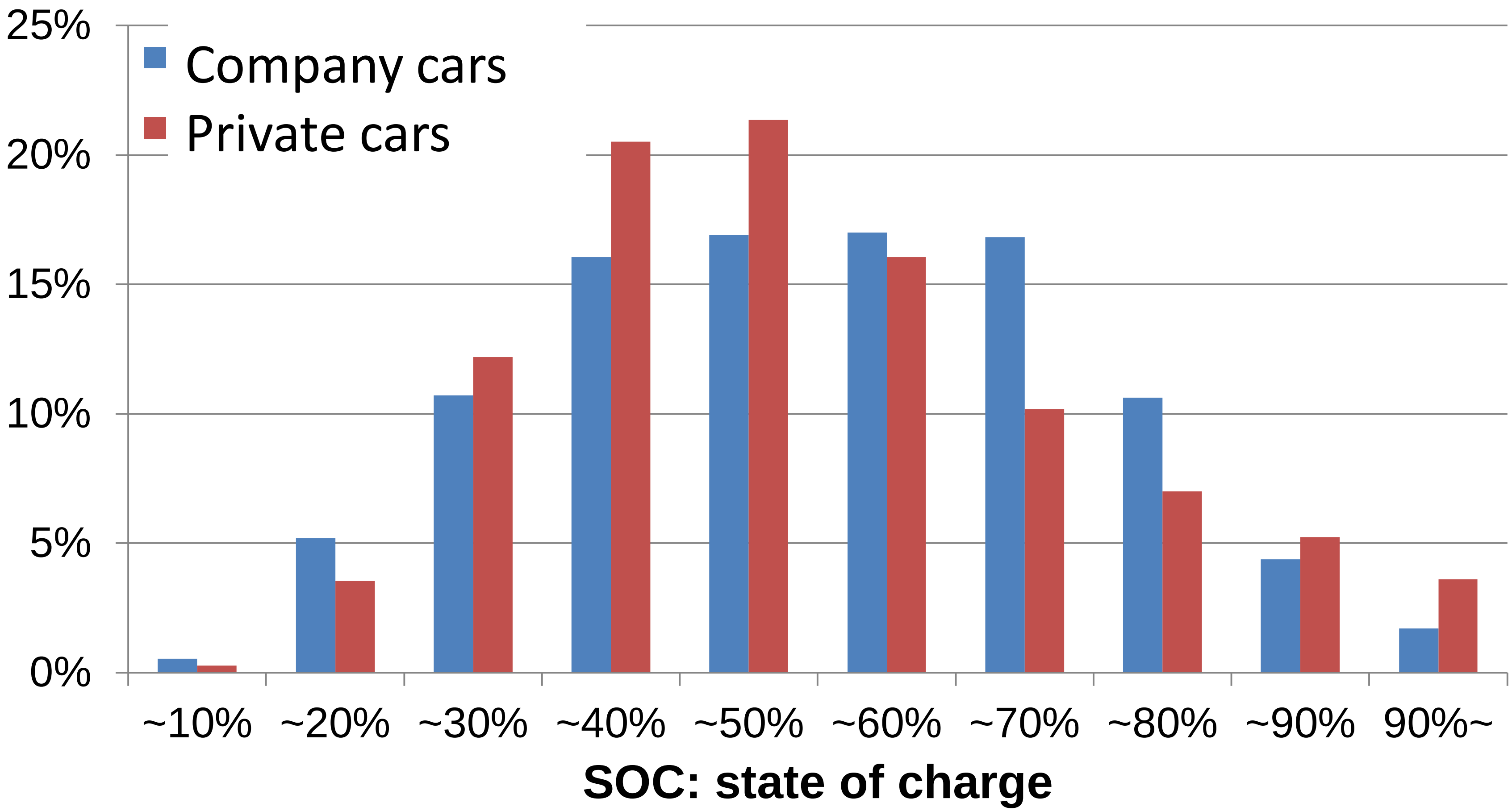

Average frequency of fast charging per month:
Commercial vehicles: 0.8
Private vehicles: 2.3

# Distribution of SOC at normal charge




Company cars are charged at the end of the working hours regardless of SOC

# Distribution of SOC at fast charge




Battery capacity is not fully utilized

# Stochastic frontier model of SOC at fast charging within trip

- Driver avoids running out of power

**Actual remaining electricity to start charging** ≥ **Subjective minimum electricity**

- Inefficiency is added to minimum electricity

**Actual remaining electricity** = **Subjective minimum electricity** + **Inefficiency**

- Stochastic cost frontier model is applied

# Charging behavior of battery usage

## ➢ Methodology

✓ Motivating phenomenon: An EV will be stranded without charge if there are no charging stations within the range provided by the remaining charge

The minimum required electricity to prevent being stranded ← $RE_0 \leq RE_1$ → The actual remaining electricity when a fast-charging begins

✓ Data characteristics: Unbalanced panel data

- 140 vehicles, 2011.2-2013.1

✓ User characteristics: heterogeneity

- Personality: risk-adverse, adventurer
- Perception: station availability, electricity consumption

**Random parameters stochastic frontier model**

# Charging behavior of battery usage

- Random parameters stochastic frontier model

$$y_{it} = \alpha + w_i + \beta' x_{it} + v_{it} + u_{it}$$

$y_{it}$: remaining electricity when a fast-charging begins

$w_i$: random vehicle specific effect

$$w_i \sim N[0, \sigma_w^2]$$

$v_{it}$: Symmetric random error

$$v_{it} \sim N[0, \sigma_v^2]$$

$u_{it}$: One-sided random error

$$u_{it} = |U_{it}|, U_{it} \sim N[0, \sigma_u^2]$$

$u_{it}$: Inefficiency in fast charging

*i* : EV
*t* : trial period

# Charging behavior of battery usage

## ➢ Model specification

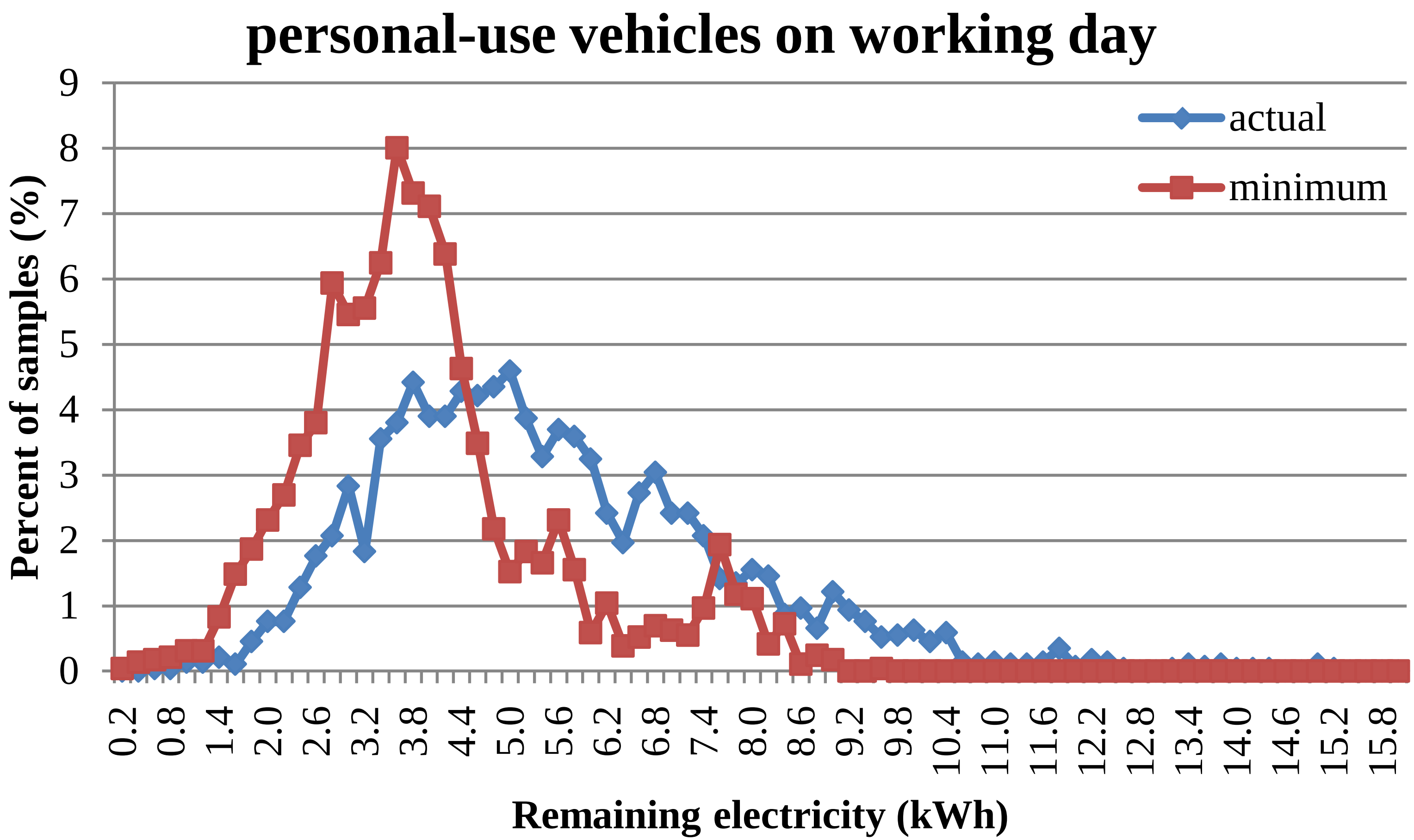
| | | |
|---|---|---|
| **Dependent variable** | Remaining electricity | —— |
| **Independent variables** | Number of Charging stations | TEPCO's experience (2009) |
| | Familiarity with whole charging station network | Dingemans & Sperling & Kitamura (1986) |
| | Usage of Air-conditioning or heater | 109Wh/km (both off), 186Wh/km (both on) |
| | Battery capacity | —— |
| | Travel patterns | Kitamura & Sperling (1987) |
| | Speed | Yao & Yang & Song, et al (2013) |
| | Price for fast-charging | Plummer & Haining & Sheppard (1998) |
| | Latter half of trial | Dingemans & Sperling & Kitamura (1986) |
| | Electricity company | Stations exclusively for members |

# Charging behavior of battery usage

| Variable | Commercial vehicles | | | | Private vehicles | | | |
|---|---|---|---|---|---|---|---|---|
| | Working days | | Non-working days | | Working days | | Non-working days | |
| | coefficient | *t*-stat | coefficient | *t*-stat | coefficient | *t*-stat | coefficient | *t*-stat |
| Constant (E[$\alpha$]) | 3.687** | 6.96 | 33.815 | 1.01 | 3.778** | 27.17 | 3.667** | 18.04 |
| Number of charging stations 1 | — | — | -3.954 | -0.88 | — | — | — | — |
| Number of charging stations 2 | -0.051 | -0.71 | — | — | — | — | -0.074** | -3.18 |
| Number of charging stations 3 | — | — | — | — | -0.001 | -0.75 | — | — |
| Tokyo & Kanagawa | -0.151 | -0.31 | -30.761 | -0.92 | 0.089 | 0.93 | -0.036 | -0.21 |
| Osaka & Saitama | 1.397** | 3.01 | -32.762 | -0.97 | -0.047 | -0.33 | -0.345 | -1.63 |
| Familiarity | -0.066 | -0.31 | -0.098 | -0.09 | -0.262** | -4.30 | 0.269** | 3.26 |
| Air-conditioning or heater | -0.037 | -0.31 | 0.143 | 0.35 | -0.141** | -3.37 | 0.039 | 0.46 |
| High-capacity battery | 2.153** | 9.97 | 0.623 | 1.59 | 2.147** | 23.83 | 2.390** | 21.47 |
| Number of trips | 0.048* | 2.54 | 0.028 | 0.41 | -0.020* | -2.35 | 0.011 | 0.81 |
| VMT | -0.004* | -2.25 | 0.001 | 0.15 | 0.002** | 3.24 | 0.002* | 2.15 |
| Speed (0,20] | -0.107 | -0.39 | 0.435 | 0.27 | 0.020 | 0.21 | 0.210 | 1.68 |
| Speed (40~) | -0.107 | -0.46 | 0.434 | 0.36 | -0.214 | -1.51 | 0.017 | 0.13 |
| Free | 0.152 | 0.78 | 0.172 | 0.31 | 0.013 | 0.17 | 0.026 | 0.29 |
| Paid | — | — | — | — | -0.256* | -2.55 | -0.175 | -1.19 |
| Latter half | 0.375* | 2.33 | 0.421 | 0.55 | 0.223** | 4.53 | -0.113 | -1.52 |
| Electricity | 1.202** | 4.06 | — | — | — | — | — | — |
| Log likelihood function | -2357.871 | | -609.274 | | -4713.811 | | -2493.885 | |
| Std(*u*), Std(*v*), Std(*w*) | 2.083,1.191,1.209 | | 1.975,1.121,2.787 | | 1.633,1.093,1.282 | | 1.971,0.955,1.257 | |
| Observations | 1187 | | 317 | | 2575 | | 1325 | |
| Unbalanced panels | 33 | | 10 | | 89 | | 85 | |

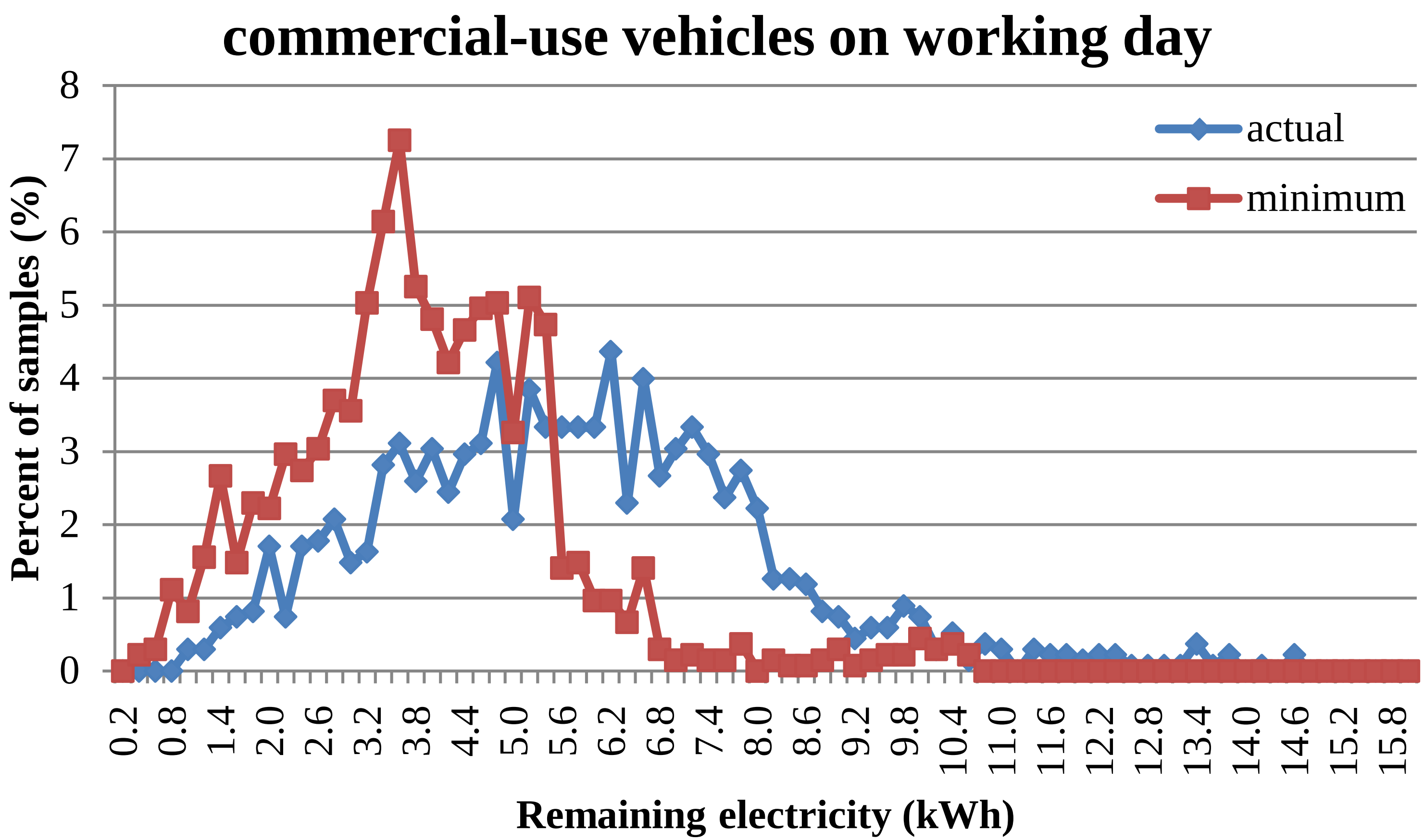
**, * significance at 1%, 5% level

# Distribution of subjective minimum and actual remaining charge




- Subjective minimum remaining charge has peak at 3.6kWh
- 1.5kWh of average inefficiency is estimated

# Distribution of subjective minimum and actual remaining charge




- Same peak of minimum remaining charge
- Larger (1.8kWh) average inefficiency is estimated

# Battery charging at home

- Analysis on charge timing choice behavior of plug-in hybrid vehicles in Toyota City, Japan
  - This is a part of the results obtained by joint research with Toyota Motor Corporation

# Smart Melit（Smart Mobility & Energy Life in Toyota City）project

- Toyota City, Japan
- 67 new houses, some with plug-in hybrid Prius
- HEMS（Home Energy Management System）
- DRP (demand response point) system

# Smart house


Visualization by HEMS (home energy management system)

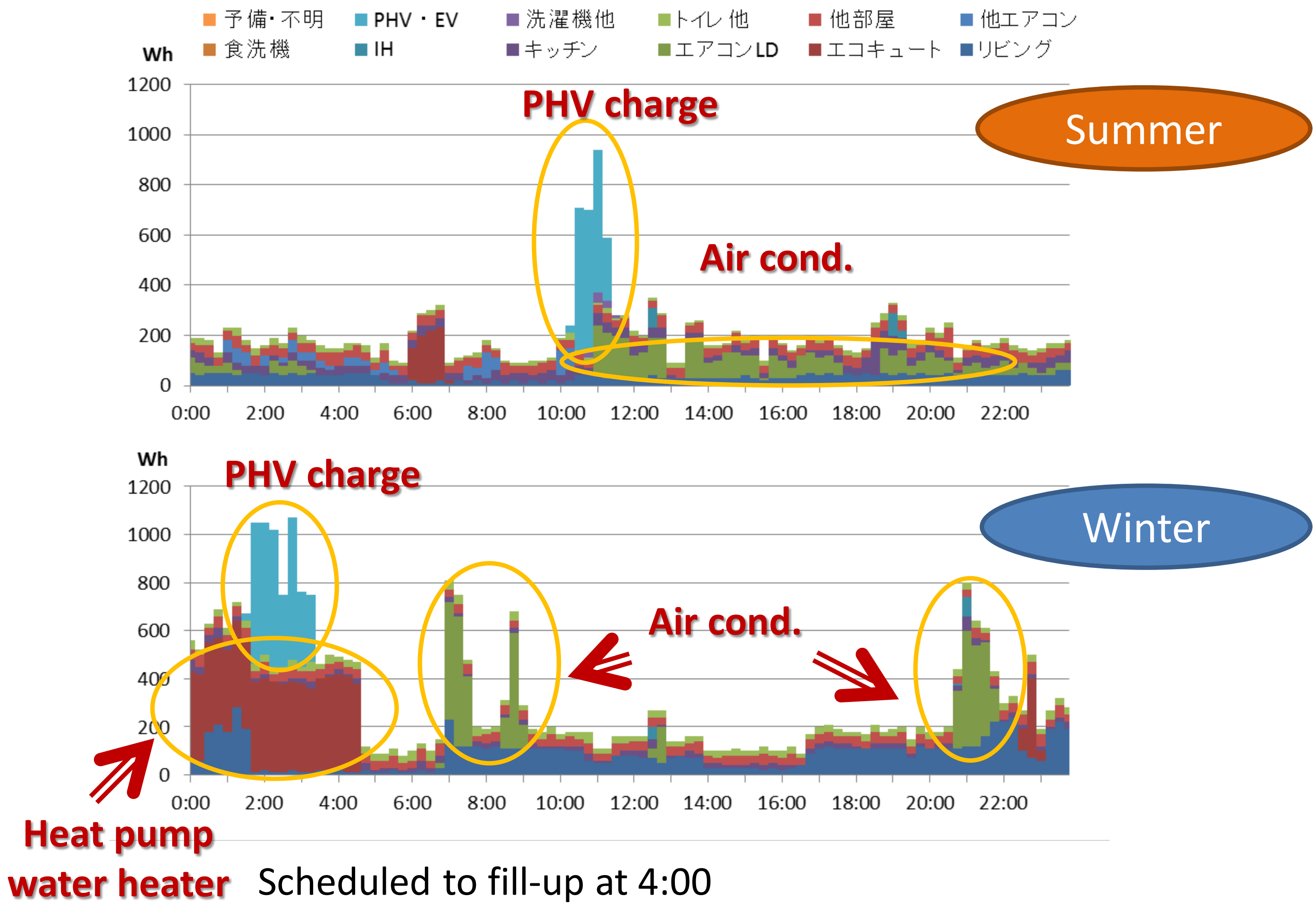

DRP (demand response point) portal


PHV charger

PHV


PHV charging monitor

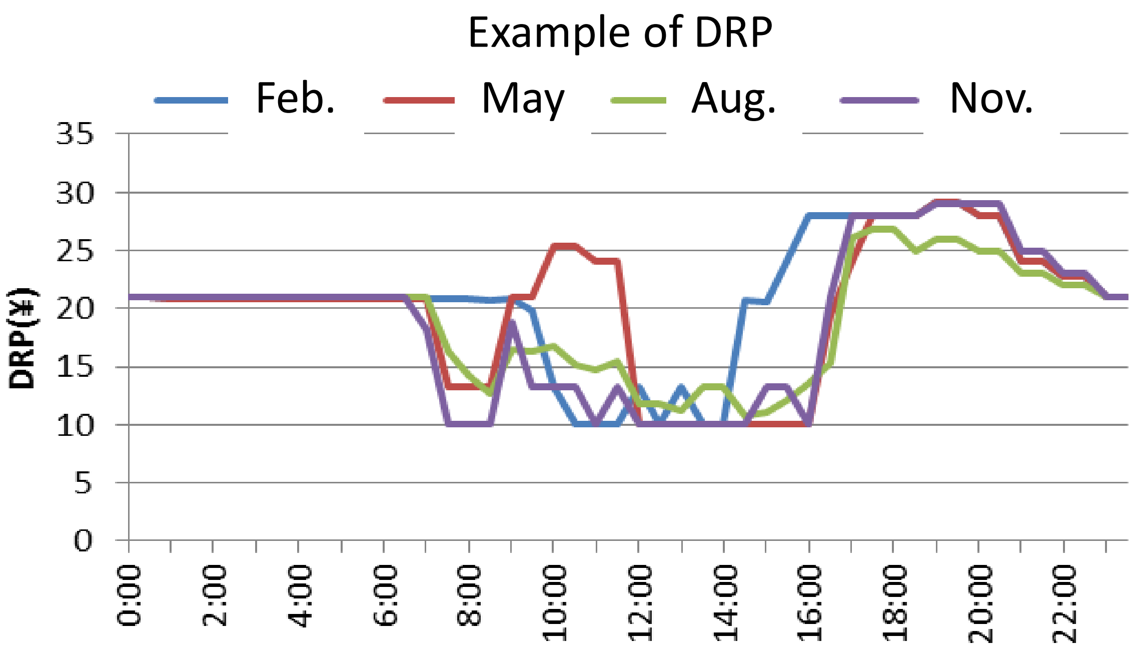
# Example of electricity demand curve



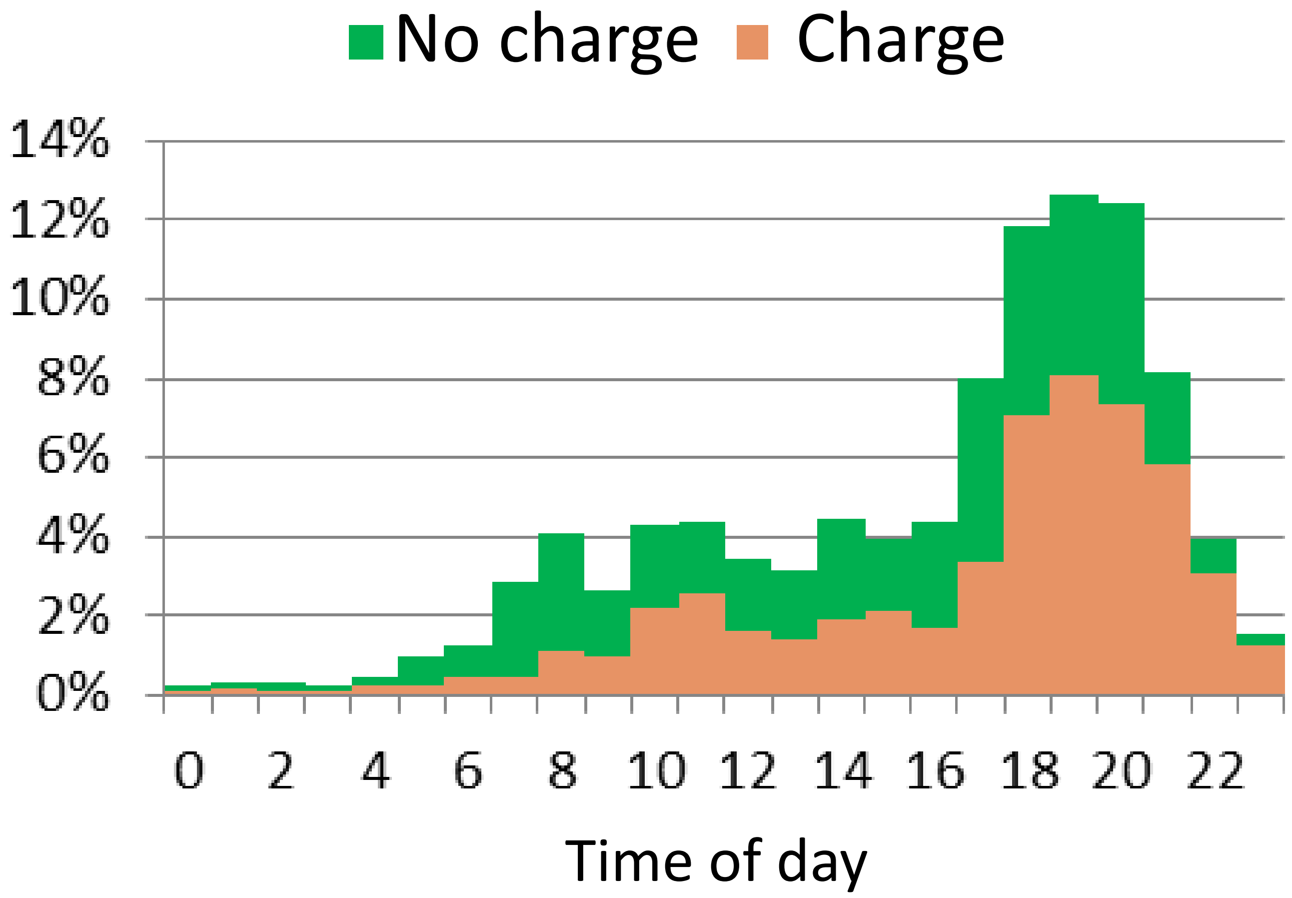

Scheduled to fill-up at 4:00

# DRP (demand response point)

- Peak pricing by point system
- Low at daytime (solar energy) & high at evening (more activity at home)



# Distribution of returning home timing

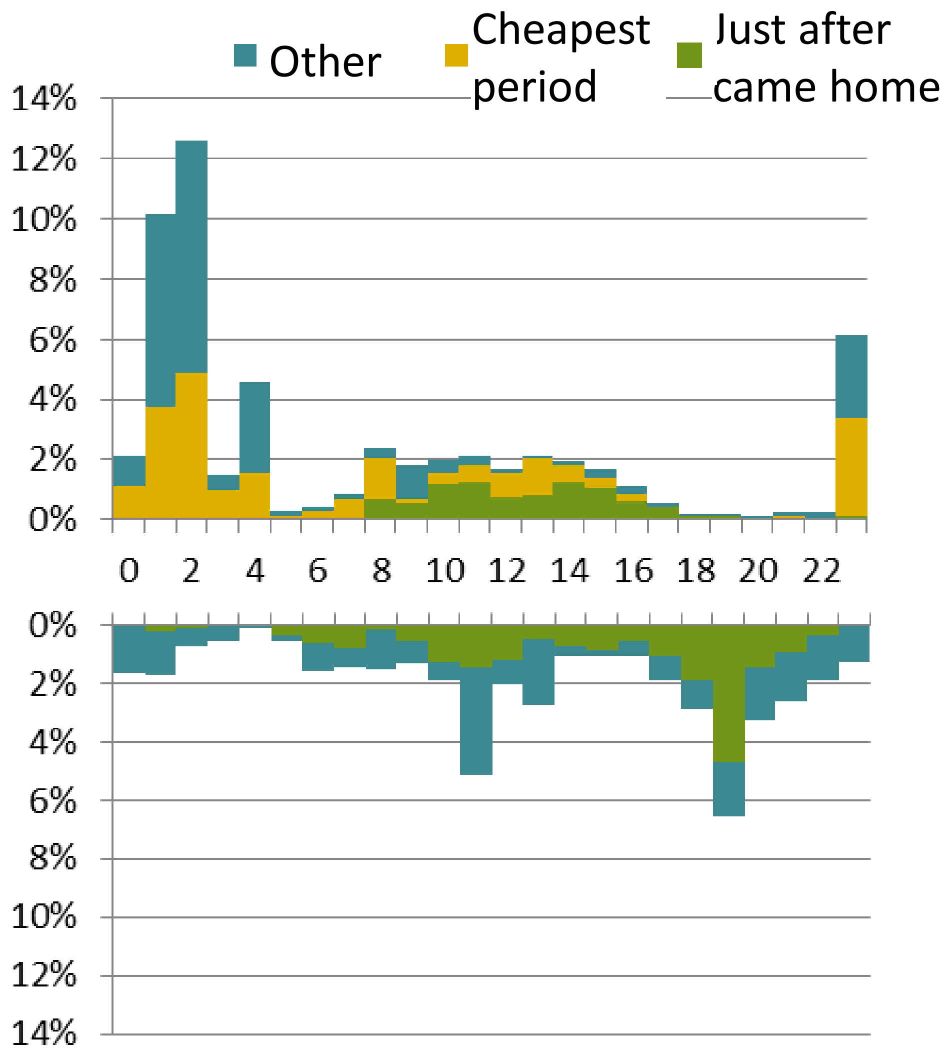



Many cars return home at 18 to 20 o’clock, which potentially cause peak demand

# Charging time is shifted by demand response point system

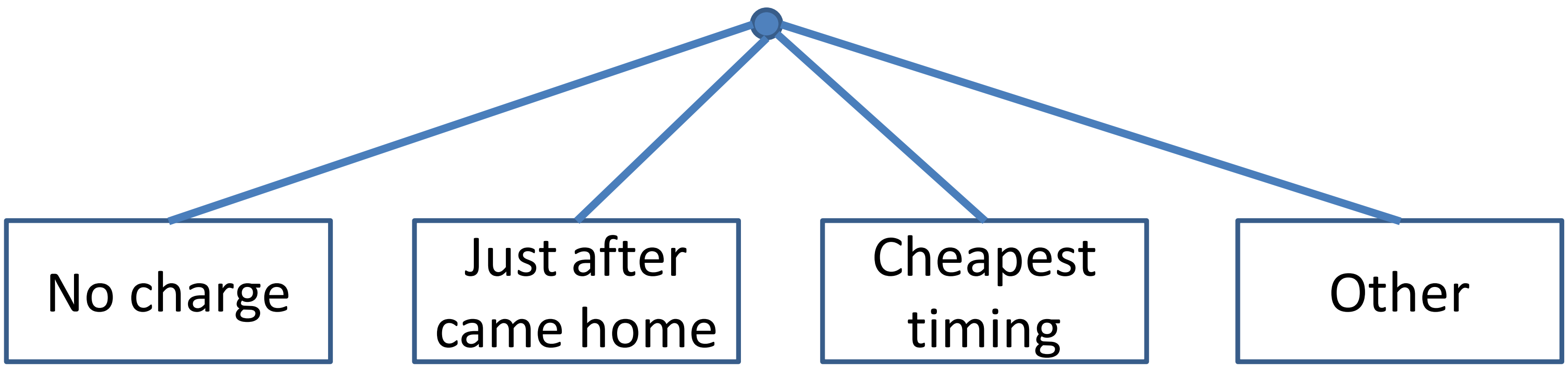
With demand response point

W/O demand response point



# Charge timing choice model

- Multinomial logit model




Cheapest timing before the next vehicle use

Didn’t change the setting of on-timer previously set, or by mistake

  - 12 Prius plug-in hybrid vehicles
  - 2011/10/1 to 2012/10/31
  - 4615 cases

# Charge timing choice model

| Alternative | Variable | Coef. | |
|---|---|---|---|
| No charge | Constant | 1.34 | ** |
| | Drive distance (<24 km) | -0.10 | ** |
| | Long distance dummy (>24 km) | -0.38 | ** |
| Just after came home | **Price** for energy conscious person | -0.044 | ** |
| | **Price** for energy unconscious person | -0.065 | ** |
| | Return home at daytime (9-16) | 0.70 | ** |
| Cheapest time | Constant | -0.69 | ** |
| | **Price** for energy conscious person | -0.016 | ** |
| | **Price** for energy unconscious person | 0.001 | |
| | Housewife dummy | 0.66 | ** |
| | Return home at evening (17-23) | 1.41 | ** |
| Other | Constant | -0.96 | ** |
| | Return home at evening (17-23) | 0.65 | ** |
| | Same as the last charge dummy | 2.21 | ** |
| **Log-likelihood (0)** | | -5774 | |
| **Log-likelihood at convergence** | | -4415 | |
| **Adjusted rho-square** | | 0.233 | |

** 1%, * 5%

# Sensitivity of the estimated model

Base case: High energy conscious male driver returned home in evening after 10 km drive

| Electricity price | No charge | Just after came home | Cheapest timing | Other |
|---|---|---|---|---|
| No DRP (20.9 JPY) | 35% | 47% | | 18% |
| Evening price 20.9 -> 28 JPY | 36% | **8%** | **38%** | 19% |
| + Midnight price 20.9 -> 10 JPY | 34% | **7%** | **42%** | 18% |

Charge timing is easier to change than the timing of air conditioner usage, etc.

# Conclusions

- Battery capacity is not fully utilized, and measures to improve efficiency are needed
- Battery charging at home causes significant electricity demand, but the timing can be controlled by peak pricing