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Equilibrium scheduling of vehicle-to-grid technology using activity based modelling

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ABSTRACT

Vehicle-to-grid (V2G) is a technology which can reduce the cost for power distribution network operators by storing electricity in the batteries of electric-drive vehicles and retrieving it when energy demands increase during the course of a day. Participants of V2G are reimbursed for offering their vehicles which can lead to changes in trip schedules when V2G payments are high and travelers are sensitive to the payments. However, prior studies have ignored the effects of V2G on travelers' schedules. This research gap is addressed with a bi-level V2G market equilibrium model where the lower level model determines the equilibrium activity patterns as a result of upper level pricing and linear approximated AC flow distribution decisions. An algorithm is proposed for the model and illustrated on a simple telecommuting example where travelers can work from home and offer their vehicle charge capacity to the power provider. The model is then applied to the same case study from Lam and Yin (2001) to first replicate the lower level equilibrium problem as a special case when no V2G is present, and then to show the potential effects of the V2G policy to decrease locational marginal prices for a distribution network operator. The proposed algorithm for the V2G policy resulted in a substantial 20% increase in social welfare over the benchmark equilibrium without V2G.

1. Introduction

In recent years there has been increasing public interest in electric-drive-vehicles (EDVs) with growing federal and provincial government subsidies for purchasing them. As an example, the Obama Administration in the United States proposed in 2011 to put a total of 1.2 million electric vehicles on roads by 2015 (US DOE, 2011). As EDV market penetration goes up, the quintessential electric load diagram could change substantially to bring new challenges to power providers. However, new technological advances are under way to tackle unprecedented electricity loads. The "smart grid" enables new technologies to be integrated with the grid such as application of Distributed Energy Resources (DER) that include solar energy, wind power, and V2G. DER management can be performed by a Distribution Network Operator (DNO) who is responsible for distributing electricity from the transmission grid to homes and businesses. Studies on DER management by a DNO can be found in Morais et al. (2010), Connolly et al. (2010), and Varkani et al. (2011).

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Nomenclature

Variables

$V_i(t)$	utility value of activity i at time t
$\mu_{rs}(t)$	travel time from r to s when departing at time t
V_s	systematic utility of zone s
V_{si}	systematic utility of activity i in zone s
ε_{si}	random utility component which represents the unobservable factors of the utility
$q_r(t)$	cost of charging in zone s at time t
$\lambda_k(t)$	the locational marginal price at bus k and time t
P_{rst}	marginal choice probability that destination s is chosen from origin r at time t
$N_r(t)$	number of electric-drive travelers available in each zone r at each time segment $t > 0$
$\mathcal{M}_r^c(t)$	number of electric-drive travelers available in each zone r with a charge level c at time t
$d_{rs}(t)$	aggregate departure flow at time t from origin r to destination s
$z_p^{rs}(t)$	travel time on path p when travelers depart from r to s at time t via path p
$f_p^{rs}(t)$	flow of travelers who depart from r to s at time t via path p
$v_a(t)$	traffic volume inflow of link a at time t
$u_a(t)$	denote traffic volume outflow of link a at time t
$u_{apt}^{rs}(\tau)$	traffic inflow on link a at time τ of OD pair rs travelers departing at time t via path p
$\delta_{apt}^{rs}(\tau)$	binary indicator equal to 1 if the traffic flow of OD pair rs departing at time t via path p arrives at link a at time τ
g_{kt}	total electricity generation of bus k at time t
$h_{km,t}$	electricity flow from bus k to bus m at time t
v_{kt}	V2G energy provided by EDVs to bus k at time t
l_{kt}	charging load of EDVs at bus k and time t
$\hat{l}_{kt}$	regular power load at bus k and time t
$\overline{w}_r^c(t)$	number of vehicles that are charged from a state-of-charge c to the state-of-charge $c+1$
$\underline{w}_r^c(t)$	number of vehicles that are discharged from a state-of-charge c to the state-of-charge $c-1$

Sets

$\mathcal{N}$	set of zones
$\mathcal{A}$	set of links
K	set of power buses
L	set of transmission lines of the grid
S	choice set of activity and destination combinations
$A(r)$	set of links whose head node is zone r
$B(r)$	set of links whose tail node is zone r

Parameters

α	travel time (from r to s) disutility parameter
β	utility (or disutility) of charging costs (or benefits)
U_{km}	thermal limit of power flow
LG_k	lower bound of bus k power generation
UG_k	upper bound of bus k power generation
T	total number of times segments
Δ	duration of each time segment
s_a	capacity of link $a \in \mathcal{A}$ measured in vehicles per hour
τ_0	free flow travel time measured in minutes
C_a	required energy to for traveling link $a \in \mathcal{A}$
$N_r(0)$	Total number of travelers living in zone r

In particular, the electric power grid and the transportation system can be viewed as complementary systems for better managing power and energy. Coupled together, the two systems can induce better use of available energy storage. Currently, the power grid in the United States has no storage except for its 2.2% capacity in pumped storage (Energy Information Administration, 2000). As a solution, generators are turned on and off (on a minute-by-minute basis) so that power generation roughly matches the fluctuating electricity load. The light electric vehicle fleet, on the other hand, has storage which is used only 5% of the time for driving and left idle for the remaining 95% (Pearre et al., 2011). The increasing number of EDVs