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Modeling light-duty plug-in electric vehicles for national energy and transportation planning[☆]

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HIGHLIGHTS

- We model plug-in electric vehicles (PEVs) for long-term national planning studies.
- Realistic travel patterns are used to estimate the vehicles' energy consumption.
- National energy and transportation system interdependencies are considered.
- Case studies illustrate optimum investments in energy and transportation sectors.
- PEVs synergistically with renewable energy can aggressively reduce GHG emissions.

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ABSTRACT

This paper sets forth a family of models of light-duty plug-in electric vehicle (PEV) fleets, appropriate for conducting long-term national-level planning studies of the energy and transportation sectors in an integrated manner. Using one of the proposed models, three case studies on the evolution of the U.S. energy and transportation infrastructures are performed, where portfolios of optimum investments over a 40-year horizon are identified, and interdependencies between the two sectors are highlighted. The results indicate that with a gradual but aggressive introduction of PEVs coupled with investments in renewable energy, the total cost from the energy and transportation systems can be reduced by 5%, and that overall emissions from electricity generation and light-duty vehicle (LDV) tailpipes can be reduced by 10% over the 40-year horizon. The annual gasoline consumption from LDVs can be reduced by 66% by the end of the planning horizon, but an additional 800 TWh of annual electricity demand will be introduced. In addition, various scenarios of greenhouse gas (GHG) emissions reductions are investigated. It is found that GHG emissions can be significantly reduced with only a marginal cost increment, by shifting electricity generation from coal to renewable sources.

1. Introduction

In the United States, the two largest consumers of energy are the electricity and transportation sectors. To power the electric grid, approximately 40 quadrillion BTU (Quads) of energy are absorbed annually, obtained from a mix of primary energy sources such as coal, natural gas, and uranium, whereas transportation uses approximately 27 Quads, mostly extracted from petroleum (Lawrence Livermore National Laboratory, 2009). Notably, as of today there is very little interdependence between the two sectors, since petroleum provides but a fraction of the overall electricity in the U.S., and the power grid provides very little energy for transportation purposes. However, this is bound to change in the U.S. and other nations with the electrification of the transportation sector, which will involve the introduction of potentially millions of plug-in electric vehicles (PEVs)—either plug-in hybrid electric vehicles (PHEVs) or pure battery electric vehicles (EVs)—and the electrification of rail transport.

In this study, we focus on the electrification of light-duty vehicles (LDVs), which are defined as cars and light trucks, including minivans, sport utility vehicles, and trucks with gross vehicle weight less than 8500 pounds (U.S. Energy Information Administration). They account for the majority of highway vehicle mileage, energy consumed by highway travel modes, and carbon dioxide emissions from on-road sources. It should be noted that electric high-speed rail (HSR) has grown rapidly around the world in recent years. In the U.S., various HSR projects are in the planning stage, mainly for passenger transportation (Campos and de Rus, 2009). However, the ratios of energy consumption and emissions of rail transport over those of LDVs are small (approximately 3–4%) (U.S. Dept. of Transportation,

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Nomenclature

a_v	equivalent all-electric range of a plug-in electric vehicle (PEV) of technology type v
$costVehInv_v(\mathbf{t})$	investment cost (in today's U.S. dollars) per light-duty vehicle (LDV) of technology type v at time $\mathbf{t}\in\mathcal{T}_{\text{LDV}}$
$d_i^{E\_LDV}(\mathbf{t})$	total demand for energy from LDVs at node i ($i\in\mathcal{N}_{\text{elec}}$ or $i\in\mathcal{N}_{\text{gas}}$) over time interval $\mathbf{t}$ ($\mathbf{t}\in\mathcal{T}_{\text{elec}}$ or $\mathbf{t}\in\mathcal{T}_{\text{gas}}$). For electricity, this refers to demand from the high-voltage transmission system, and is measured in GWh; for gasoline, it is measured in millions of gallons (i.e., not energy per se, but quantity of the corresponding energy carrier)
$d_j^{LDV}(\mathbf{t})$	demand for LDVs (i.e., number of LDVs needed) at node $j\in\mathcal{N}_{\text{LDV}}$ at time $\mathbf{t}\in\mathcal{T}_{\text{LDV}}$
d_v	charge-depleting range (CDR) of a PEV of technology type v
$e_{\text{elec}}(d_v,\xi_v)$	average daily electric energy demand (from the high-voltage transmission system) per PEV of CDR d_v and fuel displacement factor (FDF) ξ_v, in kWh
$e_{\text{gas}}(d_v,\xi_v)$	average daily gasoline demand per LDV of CDR d_v and FDF ξ_v, in gallons; also represents gasoline demand of conventional and hybrid LDVs, which have $d_v=0$
$e_{j,v}(\mathbf{t})$	average energy demand per LDV of technology type v at node $j\in\mathcal{N}_{\text{LDV}}$ over time interval $\mathbf{t}$ ($\mathbf{t}\in\mathcal{T}_{\text{elec}}$ or $\mathbf{t}\in\mathcal{T}_{\text{gas}}$)
f_x	probability density function (PDF) of continuous random variable x, or probability mass function (PMF) of discrete random variable x
$f_{x\mid y}$	conditional PDF (or PMF) of random variable x given y
G	vehicle group, according to annual mileage
$h_{\text{tr},v}$	tractive energy per mile at the wheels for a vehicle of technology type v
$\mathrm{I}[\cdot]$	indicator function that equals to 1, if the condition in the bracket holds, or 0, otherwise
m	a vehicle's mileage on a given day
$m_{\text{cd}}(m,d_v)$	mileage in charge-depleting mode for a PEV of CDR d_v that traveled m miles on a given day
$m_{\text{cd}}^{\text{avg}}(d_v)$	average (per PEV of CDR d_v) daily mileage in charge-depleting mode
$m_{\text{cs}}(m,d_v)$	mileage in charge-sustaining mode for a PEV of CDR d_v that traveled m miles on a given day
$m_{\text{cs}}^{\text{avg}}(d_v)$	average (per PEV of CDR d_v) daily mileage in charge-sustaining mode
M	a vehicle's annual mileage
MPG_v	fuel economy (miles per gallon) for vehicle of technology type v (excluding pure electric vehicles). For hybrid electric vehicles, this represents the fuel economy in charge-sustaining mode
$\mathcal{N}_{\text{elec}}$	set of electricity network nodes
$\mathcal{N}_{\text{gas}}$	set of gasoline network nodes
$\mathcal{N}_{\text{LDV}}$	set of LDV network nodes
$\mathcal{N}_{\text{LDV}}^i$	subset of $\mathcal{N}_{\text{LDV}}$ containing nodes that create an energy demand at node i ($i\in\mathcal{N}_{\text{elec}}$ or $i\in\mathcal{N}_{\text{gas}}$)
r	real discount rate
$\mathbf{t}$	vector that defines time for subsystem s, $\mathbf{t}=[t_1,\ t_2,\ \ldots,t_{z_s}]\in\mathcal{T}_s$. The dimension of the vector (z_s) varies among subsystems
$\mathcal{T}_{\text{elec}}$	domain of time for the electricity subsystem
$\mathcal{T}_{\text{gas}}$	domain of time for the gasoline subsystem
$\mathcal{T}_{\text{LDV}}$	domain of time for the LDV subsystem
$\mathcal{T}_s$	domain of time for subsystem s. The domain is divided into z_s levels of time scales of increasing granularity, i.e., $\mathcal{T}_s=[1,\ \ldots,\ T_1]\times[1,\ \ldots,\ T_2]\times[1,\ \ldots,\ T_{z_s}]$, where z_s can vary among subsystems. For example, in this study, for the natural gas subsystem, time is divided into "years" and "months;" for the electricity subsystem, simulation time is divided into "years," "months," and three subdivisions of a month (see Appendix A)
v	vehicle technology type, $v\in\mathcal{V}$
$vehCum_{j,v}(\mathbf{t})$	cumulative number of LDVs of technology type v at node $j\in\mathcal{N}_{\text{LDV}}$ at time $\mathbf{t}\in\mathcal{T}_{\text{LDV}}$
$vehInit_{j,v}(\mathbf{t})$	number of remaining LDVs of technology type v at node $j\in\mathcal{N}_{\text{LDV}}$ at time $\mathbf{t}\in\mathcal{T}_{\text{LDV}}$ from the initially existing ones, decreasing monotonically over time
$vehInv_{j,v}(\mathbf{t})$	investment (number) in new LDVs (i.e., new LDVs produced) of technology type v at node $j\in\mathcal{N}_{\text{LDV}}$ at time $\mathbf{t}\in\mathcal{T}_{\text{LDV}}$
$vehLife_v(\mathbf{t})$	lifetime (years) of an LDV of technology type v produced at time $\mathbf{t}\in\mathcal{T}_{\text{LDV}}$
$\mathcal{V}$	set of LDV technologies, including conventional gasoline vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, and pure electric vehicles
η_v	energy conversion efficiency for PEVs of technology type v, from high-voltage electricity to kinetic energy at the wheels
ξ_v	fuel displacement factor (FDF) in charge-depleting mode for PEVs of technology type v, which represents the fraction of tractive energy obtained from the battery pack in charge-depleting mode

Bureau of Transportation Statistics; U.S. Dept. of Transportation, Bureau of Transportation Statistics, 2010).

A major consequence of LDV fleet electrification will be the reduction of our dependence on petroleum, which is an insecure and unsustainable energy source, with a corresponding increase of our dependence on the electric grid and its primary energy sources, including renewable resources such as hydro, wind, and solar energy. The case studies in this paper indicate that with an aggressive electrification of the LDV fleet, through the introduction of PEV technology, the annual gasoline consumption by LDVs can be reduced by 66% by the end of the planning horizon. Meanwhile, up to 800 TWh of additional annual electricity demand will be introduced, which accounts for approximately one-fifth of today's total annual U.S. electricity consumption. Hence, further investments will be necessary in the electric grid to support this additional load, and the operational costs of the electricity sector will change according to the mix of generation technologies adopted. On the other hand, the investment costs in the transportation sector are expected to be higher than the ones that would be incurred by conventional gasoline vehicles. However, the *total* system cost will be reduced. For example, the case studies in this paper (see Section 5) show that the combined cost from the energy and transportation systems can be reduced by 5% (in terms of present value), which amounts to savings of 1 trillion dollars over the next 40 years. Moreover, emissions from vehicle tailpipes will shift to power plants, thus affecting the net emissions of the two sectors. The studies also show that the overall greenhouse gas (GHG) emissions from electricity generation and LDV tailpipes can be reduced by 10% over the next 40 years. The total GHG emissions over the next 40 years can be further reduced by 30% at an

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