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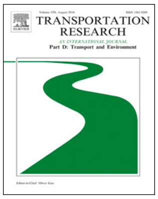

A study on opportune reduction in greenhouse gas emissions via adoption of electric drive vehicles in light duty vehicle fleets

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ABSTRACT

Electrified powertrain vehicles have the potential to bring about significant reductions in greenhouse gas (GHG) emissions in light-duty vehicle fleets as they replace conventional vehicles. Compared to electrified powertrains, a conventional vehicle (CV), whose driving power only comes from an internal combustion engine (ICE), is in many ways disadvantaged when in driven in conditions that involve frequent stops or idling. As a result, the amount of achievable reduction in GHG by replacing a CV with one that has an electrified powertrain can vary significantly depending on the driving patterns in which the vehicle is expected to be driven in. This work analyzes more than 65 thousand real-world trips from California household travel survey (CHTS) in order to highlight and quantify the differential benefit in opportune reduction of GHG emissions. Equivalent GHG emissions are estimated using a public-domain fuel economy simulations software for each trip if it was done on a mid-sized CV, a matching hybrid-electric vehicle (HEV), two different all-electric range (AER) plug-in hybrid electric vehicles (PHEVs), as well as a pure battery-electric vehicle (BEV). A clustering approach is used to discern sub-populations of vehicle samples in CHTS data set into four vehicle groups, ordered from least to most city-like driving patterns. Results show that replacing a CV in the group with city-like driving could reduce the GHG emissions by appreciably larger amounts (approx. two to three times) than in the group with less city-like driving.

1. Introduction

1.1. Overview

Electrified powertrain vehicles or electric drive vehicles (EDVs) are loosely defined as vehicles that can have a significant portion of the driving power coming from electric motors. According to US Department of Energy (US Department of Energy, 2011), EDVs include: (i) battery electric vehicles (BEVs), which have no internal combustion engine (ICE), (ii) hybrid electric vehicles (HEVs), which have ICE, motor and battery but no charging outlet, and (iii) plug-in hybrid electric vehicles (PHEVs), which have ICE, motor, battery and charging outlet that allows charging from grid electricity. Compared to conventional vehicles (CVs), EDVs have several important features that allow reduction in greenhouse gas (GHG) emissions during the use phase of the vehicle lifecycle. The features, which EDVs may have (depending on powertrain architecture), include:

- Ability to recover some of the driving energy via regenerative breaking (which CVs normally lose as heat to friction pads) during

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Nomenclature

E	electrical energy consumption in a given trip [kWh]
$\overset{\frown}{E}$	electrical energy consumption in a given trip if started at maximum charge level [kWh]
E_c	electrical energy [kWh] that gets reallocated (via first-order model Laberteaux and Hamza, 2017a) to equivalent gasoline
G	gasoline consumption in a given trip [gal]
$\breve{G}$	gasoline consumption in a given trip if started at maximum charge level [gal]
L	trip length [mile]
S_f	battery state of charge at the end of a trip [kWh]
$S_{\max}$	maximum charging limit for vehicle battery [kWh]
$S_{\min}$	discharge limit for vehicle battery [kWh]
S_c	battery state of charge after a daytime charging event [kWh]
S_l	anxiety limit for battery state of charge of BEVs [kWh]
S_o	battery state of charge at the beginning of a trip [kWh]
$\bar{c}$	average charging rate of a level-2 charger [kW]

Greek symbols

α_E	equivalent CO_2 for electric energy [g-CO_2/kWh]
α_G	equivalent CO_2 for gasoline [g-CO_2/gal]
β	PHEV Vehicle-specific constant for energy re-allocation [kWh/gal] via first-order model in Laberteaux and Hamza (2017a)
ϕ	fraction of battery swing for BEV anxiety limit
γ	vehicle GHG emissions [g-CO_2/mile]
λ	median GHG for a CHTS vehicle sample if its trips are driven on a CV [g-CO_2/mile]
ν	inter-quartile GHG value for a CHTS vehicle sample if its trips are driven on a CV [g-CO_2/mile]
τ	time gap between vehicle trips [h]
$\bar{\tau}$	threshold for duration of time gap between trips to allow a daytime charging event [h]
τ_o	logistics time for daytime charging events

Subscripts

a	index on the type of vehicle model
i	index on vehicle samples in CHTS data set
j	index on trips done by a vehicle sample in CHTS data set

Abbreviations

AER	All-Electric Range
BEV	Battery-Electric Vehicle
CDF	Cumulative Distribution Function
CHTS	California Household Travel Survey
CO_2	Carbon Dioxide
CV	Conventional Vehicle
DC	Direct Current
EDV	Electric Drive Vehicle
GHG	Greenhouse Gas
GPS	Global Positioning System
HEV	Hybrid-Electric Vehicle
HOV	High-Occupancy Vehicle
ICE	Internal Combustion Engine
LCA	Life-Cycle Analysis
PDF	Probability Density Function
PHEV	Plug-in Hybrid Electric Vehicle
SVC	Support Vector Clustering
W2W	Well to Wheels

breaking events.

- Ability to downsize/light-weight the ICE and/or motor and still attain good acceleration performance as the ICE and motor can both be providing driving power when needed for certain maneuvers.
- Decoupling the operating point of the ICE from driving power requirements, thus allowing the ICE to operate near or at its most efficient conditions most of the time, or get turned off completely.
- Running on lower carbon content energy source (electricity from grid with fraction of renewables and/or low carbon fuels in the generation mix).

It is notable that three of the GHG reduction features in EDVs mentioned (all but the lower carbon content energy source) are related to driving conditions that cause bad fuel economy for CVs: frequent braking/acceleration and ICE idling. It is thus understandable that city and highway window-sticker fuel economy ratings for CVs have a higher difference than EDVs (US Environmental Protection Agency, 2013a). It follows that replacing CV with EDV for vehicles whose driving is more resembling “city-like” patterns may achieve larger reduction in GHG. However, a complication is that real-world driving needs of the populace can often be a mix of different types of trips that do not necessarily match the standard dynamometer drive cycles (US Environmental Protection Agency, 2013b) used for window-sticker fuel economy ratings. Focus of this paper is not modeling and estimation of present-day GHG emissions, rather, the objective is to highlight opportunities for GHG reduction in hypothetical scenarios where a CV is replaced by an EDV in certain sub-populations of vehicles with certain driving characteristics. Towards that end, the research addresses two coupled questions:

(i) How big a fraction of the population of vehicles have significantly varying GHG reduction potential?
(ii) How much is the difference in GHG reduction when switching CV to EDV?