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Scenario analysis of lightweight and electric-drive vehicle market penetration in the long-term and impact on the light-duty vehicle fleet

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HIGHLIGHTS

- Japanese passenger light-duty vehicle fleet between 2012 and 2050 is assessed.
- A new vehicle market model and a vehicle stock turnover model are combined.
- Internal combustion engine and hybrid electric vehicles dominate the Base scenario.
- Fuel cell hybrid electric vehicles dominate when low cost is prioritized.
- Shift to battery electric vehicles occurs when low CO_2 emissions are prioritized.

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ABSTRACT

Electric-drive vehicles, including hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles, fuel cell electric vehicles and fuel cell hybrid electric vehicles, are emerging as less polluting alternatives to internal combustion engine vehicles. Therefore, it is important to assess their penetration in the vehicle market in the future. A 'two-step' approach is used to estimate the optimum market penetration of lightweight and electric-drive vehicles in the long-term and the impact on the light-duty vehicle fleet, focusing on Japan. First, an optimization model is used to estimate the vehicle market composition in 2050. Then, a vehicle stock turnover model is used to estimate light-duty vehicle fleet energy and material consumption, CO_2 emissions and cost. Internal combustion engine vehicles and hybrid electric vehicles dominate in the Base scenario. Fuel cell hybrid electric vehicles dominate when low cost is prioritized. Shift to battery electric vehicles occurs when low CO_2 emissions are prioritized. CO_2 emissions are reduced 56.9% between 2012 and 2050 in the Base scenario. Lightweight mini-sized battery electric vehicle diffusion has the largest CO_2 emissions reductions, 87.3% compared to the 2050 baseline value; with the net cash flow peaking at 10.2 billion USD/year in 2035 and becoming negative after 2044.

1. Introduction

1.1. Motivation

Transport sector accounts for 23% of the world CO_2 emissions from fuel combustion [1]; with road transport representing about three quarters of the transport sector CO_2 emissions [2]. Light-duty vehicles (LDVs) play a significant role in transport energy consumption and CO_2 emissions. For instance, LDVs accounted for 52% of global transport energy consumption and 41% of total transport emissions in 2010 [3]. Perspectives for the future are more critical. Global LDV stock is expected to grow from around 850 million vehicles in 2013 to more than 2 billion vehicles in 2050, causing CO_2 emissions to increase if no action is taken [4]. In that sense, a paradigm shift in mobility is required [5].

Along with travel demand reduction and modal shift, electric-drive vehicles (EDVs)[1] are necessary to reduce global CO_2 emissions and meet sustainability targets [6]. For instance, mass deployment of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles

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[1] Electric drive vehicles (EDVs) include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), fuel cell vehicles (FCVs) and fuel cell hybrid electric vehicles (FCHEVs).

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Nomenclature

α_1	model parameter 1
α_2	model parameter 2
β	optimum new vehicle market share
β_{Max}	maximum affordable vehicle market share
β_{Size}	market share projection for each size class
Δ_y	half of the cycle diffusion span
a	vehicle age
a_0	median vehicle service life
AFV	alternative fuel vehicle
b	diffusion rate
BEV	battery electric vehicle
c_{cap}	vehicle capital cost
c_{ene}	energy price
c_{OM}	vehicle annual O&M cost
Conv	conventional glider
CRF	capital recovery factor
E	fleet energy consumption
EDV	electric-drive vehicle
EF	CO_2 emission factor
ETP	Energy Technology Perspectives
EV	electric vehicle
F	survival fraction
FC	vehicle fuel consumption
$FC_{St,n}$	fuel consumption standard for new vehicle sales in weight class n for gasoline vehicles
$FC_{St,s}$	standard for new vehicle sales average fuel consumption for gasoline vehicles
FCV	fuel cell vehicle
FCHEV	fuel cell hybrid electric vehicle
FRP	fiber reinforced polymer
g	vehicle CO_2 emissions
G	fleet CO_2 emissions
$g_{St,s}$	CO_2 emissions target for new vehicles
GAMS	General Algebraic Modeling System
GHG	greenhouse gas
HEV	hybrid electric vehicle
i	glider type
I	number of glider types
I_n	number of glider types in vehicle weight class n
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
j	vehicle size class
J	number of vehicle size classes
Jn	number of vehicle size classes in vehicle weight class n
k	powertrain type
K	number of powertrain types
Kn	number of powertrain types that use gasoline
$K_{g,n}$	number of powertrain types that use gasoline in vehicle weight class n
l	vehicle attribute
L	number of vehicle attributes
LDV	light-duty vehicle
LEAP	Long-range Energy Alternatives Planning System
m	material content in a vehicle
M	annual traveled distance
Min	material consumption
MLIT	Ministry of Land, Transport, Infrastructure and Tourism
MOE	Ministry of Environment
MS	market share
MS0	market share in the baseline year
n	vehicle weight class
N	vehicle stock
O&M	operating and maintenance
PAMVEC	Parametric Model of Vehicle Energy Consumption
PHEV	plug-in hybrid electric vehicle
s	vehicle score
S	vehicle sales
SMR	steam methane reforming
t	vehicle type
Tz	number of vehicles that use the fuel z
TTW	tank to wheel
v	vintage
V	number of vintages considered
w	weighting coefficient
WTW	well to wheel
x	material type
y	calendar year
y_0	inflexion point in technology diffusion curve
z	fuel type
Z	new vehicle sales overall score
ZEV	zero emission vehicle

(PHEVs) powered with low-carbon electricity have great potential to reduce fossil fuel use in transportation [7]. Similarly, fuel cell vehicles (FCVs) can provide the same mobility service as internal combustion engine vehicles (ICEVs) with very low CO_2 emissions [8]. Additionally, EDVs can contribute to enhance energy security [9], improve urban air quality [10], and reduce noise levels [6].

Reduction of greenhouse gas (GHG) and air pollutant emissions in road transportation is a major motivation for powertrain electrification [11]. Additionally, EDVs can act as flexible energy storage resources and provide ancillary services [12]; which is an additional motivation for EDV adoption. Strategies considered in previous studies include using BEVs and PHEVs to provide regulating-and reserve power (RRP) services [13]; coupling BEVs to power distribution networks [14]; and coupling BEVs and renewable power generation in power distribution networks [15]. These studies conclude that vehicle to grid (V2G) strategies can provide benefits to both the user and the infrastructure.

Nevertheless, there are several barriers that prevent EDV diffusion. In the case of hybrid electric vehicles (HEVs), barriers include low gasoline and diesel prices, low consumer risk tolerance and high purchase price [16]. Barriers for PHEV and BEV adoption include negative perceptions regarding safety and resilience, resistance to change, non-conformity with available models, lack of awareness of financial incentives, inappropriate taxation and fuel economy policies, lack of signaling for charging stations and usage-related incentives, low battery energy density, lack of charging infrastructure, and high investment required to develop the charging infrastructure [17]. In the case of FCVs, barriers include lack of hydrogen infrastructure, hydrogen production from fossil fuels, inability of FCVs to be recharged at home, high system cost and concerns about hydrogen safety [18].

Despite of the barriers, the combined global stock of PHEVs, BEVs and FCVs reached 1.26 million vehicles in 2015, driven by ambitious targets and policies in several countries that lowered vehicle costs, increased vehicle driving range and reduced consumer barriers [6]. In the case of HEVs, market penetration is more mature. For instance, Toyota's cumulative HEV sales in the world topped 2.7 million vehicles in 2010 [19]. Technology improvement, infrastructure development and cost reduction can lower the barriers for EDV diffusion. Additionally, changes in the motivation of