Applied Energy 157 (2015) 871–883

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework ☆

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HIGHLIGHTS

- We perform Life Cycle Assessment (LCA) of current and future passenger vehicles.
- We include gasoline, diesel and natural gas as well as battery and fuel cell cars.
- An integrated vehicle simulation framework guarantees consistency.
- Only electric cars with "clean" electricity and H_2 allow for pollution mitigation.
- Complete LCA is mandatory for environmental evaluation of vehicle technologies.

ARTICLE INFO

Article history:
Received 30 August 2014
Received in revised form 2 December 2014
Accepted 5 January 2015
Available online 7 February 2015

Keywords:
Life Cycle Assessment (LCA)
Passenger vehicles
Environmental performance
Vehicle modeling

ABSTRACT

This paper contains an evaluation of the environmental performance of a comprehensive set of current and future mid-size passenger vehicles. We present a comparative Life Cycle Assessment (LCA) based on a novel integrated vehicle simulation framework, which allows for consistency in vehicle parameter settings and consideration of future technological progress. Conventional and hybrid gasoline, diesel and natural gas cars as well as battery and fuel cell electric vehicles (BEV and FCV) are analyzed, taking into account electricity and hydrogen production chains from fossil, nuclear and renewable energy resources.

Our results show that a substantial mitigation of climate change can be obtained with electric passenger vehicles, provided that non-fossil energy resources are used for electricity and hydrogen production. However, in terms of other environmental burdens such as acidification, particulate matter formation, and toxicity, BEV may in some cases and FCV are likely to perform worse than modern fossil fueled cars as a consequence of emissions along vehicle and fuel production chains. Therefore, the electrification of road transportation should be accompanied by an integration of life cycle management in vehicle manufacturing chains as well as energy and transport policies in order to counter potential environmental drawbacks.

1. Introduction

Over the last 60 years, the global passenger vehicle fleet has annually grown by about 5%, reaching about 900 million vehicles in 2013 and consuming more than 20 million barrels of crude oil per day. This fleet is expected to increase up to 1.7 billion vehicles in 2035 [1]. Current passenger vehicles are predominantly fueled by crude-oil based fuels and therefore a substantial source of CO_2 emissions. In addition, these vehicles are important sources of air pollutants such as nitrogen oxides (NO_x), sulfur dioxide (SO_2) and particulate matter (PM), which are increasingly contributing to

☆ This paper is included in the Special Issue of Clean Transport edited by Prof. Anthony Roskilly, Dr. Roberto Palacin and Prof. Yan.

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http://dx.doi.org/10.1016/j.apenergy.2015.01.019
0306-2619/

Nomenclature

BEV	battery electric vehicle
BG	biomass gasification
BoP	balance of plant
CC	combined cycle (power plant)
CCS	carbon capture and storage
CG	coal gasification
CNG	compressed natural gas
EoL	end-of-life
EU	European Union
EU mix	average European (EU-27) electricity mix
EV	electric vehicles
FC	fuel cell
FCHEV	fuel cell hybrid electric vehicle
FCV	fuel cell vehicle
GHG	greenhouse gas
GWP	global warming potential
H_2	hydrogen
HEV	hybrid electric vehicle
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
-g	gasoline fueled
-d	diesel fueled
-cng	CNG fueled
IPCC	intergovernmental panel on climate change
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
Li-ion	lithium ion
my	meter*years
NEDC	new European driving cycle
NG	natural gas
NO_x	nitrogen oxides
PEM	proton exchange membrane
PHEV	plug-in hybrid electric vehicle
PM	particulate matter
PV	photovoltaic
SMR	steam methane reforming
SNG	synthetic natural gas
SO_2	sulfur dioxide
vkm	vehicle-kilometer
WLPT	worldwide harmonized light vehicles test procedure

human health impacts, especially in urban areas. Furthermore, security of future oil supply and its price stability are uncertain. Particularly for these reasons, several advanced vehicle and fuel technologies are currently being developed in order to reduce the environmental impacts of road passenger transport and the dependency on fossil resources.

However, the potential advantages of these new technologies from the environmental perspective need to be demonstrated taking into account the complete life cycle of the vehicles including their manufacturing, operation, and end-of-life (EoL), as well as the energy supply. For this purpose, a comprehensive Life Cycle Assessment (LCA) of a wide range of current and future passenger vehicle technologies and their energy supply chains with a focus on electric drivetrains has been carried out and is presented in this paper. The technology portfolio includes conventional internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), battery electric vehicles (BEV), and fuel cell hybrid electric vehicles (FCHEV). Gasoline, diesel, natural gas, electricity from different sources and hydrogen from several production pathways have been considered as fuels. The time frame of the analysis takes into account expected technology development during the upcoming 15 years (until 2030).

Several LCA studies comparing the environmental performance of conventional and hybrid ICE, battery electric, and fuel cell passenger vehicles have been published during the last couple of years [2–23]. However, none of these provide a consistent and complete life-cycle based evaluation of environmental burdens caused by current and future passenger vehicles: goal and scope are frequently not explicitly stated, evaluated technology portfolios are often incomplete, specific levels of technology development are not considered in appropriate ways, future time perspective is lacking, boundary conditions and assumptions on e.g. fuel consumption can be biased and result in unfair comparisons, outdated inventory data are partially used, and greenhouse gas (GHG) emissions are often the only environmental indicator reported [5,17,24]. This paper aims to overcome these shortcomings by applying a novel integrated vehicle simulation and modeling framework to quantitatively assess technical and environmental criteria of a wide range of conventional and electric powertrains, consistently taking into account future technology development.

The assessment does not include bio-, or agrofuels. The potential impacts of using biomass for vehicle fuel production on the environment and human health are subject of ongoing research; a large number of LCA studies for a lot of different feedstocks and fuels used in passenger vehicles has recently been published, e.g. in [25–35], showing large variations in terms of LCA results. Due to the intrinsic complexity in the LCA of biofuel chains with issues ranging from location specific aspects such as specific crop yields and water scarcity to controversial topics such as indirect land use as well as interaction with food markets, we consider a selection of "representative" biofuel chains for comparative use as impractical and therefore these fuels as being out of scope of our current assessment.

2. Methodology

Evaluating the environmental burdens associated with passenger vehicles requires consideration of their complete life cycles, since substantial burdens can be generated not only in vehicle use, but also in their production and in fuel supply chains. The distribution of these burdens will be very different depending on power train technologies and fuel production pathways. The current stage of technological maturity of drivetrain technologies differs: while ICEV have been introduced more than 100 years ago, BEV have only recently entered the market and FCV are about to enter. A balanced comparison therefore requires a consistent modeling framework for all parts of the life cycle of vehicles and boundary conditions appropriately reflecting realistic technological advancement.

2.1. Life Cycle Assessment (LCA)

Life Cycle Assessment includes compiling inventories of the environmentally relevant flows (i.e. emissions, natural resources, material and energy, waste) related to all processes involved in the production, use, and end-of-life of a product and based on these, quantifying the associated cumulative life-cycle burdens [36]. The LCA methodology applied for this analysis follows the international standards [37,38].