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A multi-dimensional well-to-wheels analysis of passenger vehicles in different regions: Primary energy consumption, CO_2 emissions, and economic cost ☆

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HIGHLIGHTS

- Well-to-wheels analysis considering: petroleum energy use, CO_2 emissions, and cost.
- Analysis covers 5 regions: Brazil, China, France, Italy, and the United States.
- Several fuel pathways: gasoline, diesel, natural gas, biofuels, and electricity.
- WTT stage based on thermoeconomics using exergy to account for primary resources.
- TTW stage including a variety of drive cycles to capture real-world vehicle usage.

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ABSTRACT

This paper proposes an exergy-based well-to-wheels analysis to compare different passenger vehicles, based on three key indicators: petroleum energy use, CO_2 emissions, and economic cost. A set of fuel pathways, including petroleum-based fuels, compressed natural gas, biofuels, and electricity are considered in five representative national energy mixes, namely Brazil, China, France, Italy, and the United States of America. Results show no fundamental difference in the fossil fuel pathways among the five scenarios considered. Compressed natural gas vehicles and electric vehicles can completely displace oil consumption in the personal transportation sector. Compressed natural gas vehicles also reduce CO_2 emissions by over 20% compared to gasoline vehicles. Emissions from electric vehicles greatly vary depending on the electricity mix. In low-carbon electricity mixes electric vehicles reach almost-zero CO_2 emissions, while the use of biofuels leads to the lowest CO_2 emissions in carbon-intensive electricity generation mixes, where vehicles running on E85 could reduce CO_2 emission by over 50% compared to gasoline vehicles. Hybrid electric vehicles show the lowest overall economic cost, due to improved efficiency and low cost of petroleum-based fuels. Vehicles running on electricity are characterized by significantly higher capital cost and lower operating costs. Thus, different electricity generation costs impact minimally the overall cost. These results can be used to inform decision-makers regarding the multi-dimensional impact of passenger vehicles, including environmental impact, economic cost, and depletion of primary energy resources, with particular focus on petroleum.

1. Introduction

The transportation sector is responsible for almost a third of the global energy consumption [1] and a significant portion of greenhouse gases and pollutants emissions [2]. The sector has been dominated by oil for over a century, creating what *de facto* is an oil monopoly in transportation fuel markets. Recently, environmental concerns and geo-political issues related to oil procurement have spurred an interest in developing solutions to reduce vehicle fuel consumption and tailpipe emissions, and exploring the use of alternative fuels. In the quest to transition transportation towards a sustainable future, a comprehensive and accurate analysis is required to inform and educate automotive original equipment manufacturers, policy makers, and consumers, and to provide a

☆ The views and opinions expressed in this paper are those of the authors alone.

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common framework to compare different vehicles and fuel pathways.

This study follows a so-called well-to-wheels (WTW) approach, a subclass of life cycle assessment (LCA) specifically developed for the study of automotive fuels production and use [3]. WTW studies evaluate the embodied resource consumption (*i.e.* all the resources consumed in the activities related to a process), including direct and indirect consumptions related to fuel production and vehicle operations. Well-to-wheels analyses evaluate different transportation options (the combination of a vehicle and a fuel pathway) in terms of primary energy resources consumption and emissions.[1] WTW analyses are divided in two stages: the fuel production is studied in the well-to-tank (WTT) stage, and the vehicle operation is analyzed in the tank-to-wheel (TTW) stage. WTW neglect vehicle production and disposal, which are captures in automotive LCA studies [5]. Fig. 1 compares LCA and WTW studies, identifying the boundaries considered in the two approaches.

1.1. Objectives of this work

Well-to-wheels studies can be used as a tool to evaluate and compare the energy consumption, economic cost, and environmental impact of different passenger vehicles. The objective of this paper is to propose an exergy-based WTW analysis to compare a set of eight passenger vehicles, powered using one or a combination of the following fuels: gasoline, diesel, ethanol, natural gas, and electricity. The comparison is based on three indicators: (1) primary energy consumption, with particular focus on the ability of displacing oil of different personal transportation technologies; (2) CO_2 emissions; and (3) economic cost. Five representative countries have been chosen to represent different energy mixes: Brazil, China, France, Italy, and the United States of America. Each country shows peculiar energy mix characteristics [6]: Brazil largely relies on hydropower for electricity generation and makes extensive use of ethanol-blended automotive fuels; China electricity generation mix is dominated by coal; in France almost 75% of the electricity is generated using nuclear power plants; Italy uses a mix of renewable sources and fossil-based power plants, dominated by natural gas combined cycles; the U.S. electricity generation sector is characterized by a balanced mix of nuclear power, renewables, and fossil-based plants, including significant shares of both coal and natural gas.

This study adds to and extends existing well-to-wheels studies in several ways:

- the WTW comparison framework is based on three key indicators (cost, CO_2 emissions, and petroleum use) that reflect current energy policy issues;
- a common approach is used for evaluating a set of eight passenger vehicles, powered using fossil fuels, biofuels, and electricity. In particular, a compressed natural gas vehicle model developed and experimentally validated at *The Ohio State University – Center for Automotive Research* is used;
- the study includes five different regions, characterized by peculiar energy mixes;
- the WTT stage is based on a formal thermoeconomic analysis, which uses exergy to account for the consumption of primary resources and to allocate it over multiple products[2];
- the TTW analysis is performed on a variety of transient driving cycles to capture different driving conditions and better estimate real vehicle usage;
- the TTW analysis is based on detailed vehicle models rather than on aggregate data, allowing for future parametric analysis to capture the effect of different technology improvements or changes in vehicle use and design.

The rest of this paper is structured as follows: Section 2 presents an overview of the *state-of-the-art* of well-to-wheels studies. Section 3 reports on the well-to-tank analysis proposed, which includes a formalized exergy analysis to properly capture the impact of the production of transportation fuels from different primary energy sources. AVL Cruise, a commercially available software, is used to perform the tank-to-wheels analysis over a set of six driving cycles, as reported in Section 4. The results of the complete well-to-wheels analysis are reported in Section 5. An economic analysis is presented in Section 6, that allows computing the lifetime cost of the alternative transportation solutions. Moreover, a sensitivity analysis to evaluate the impact of oil price is proposed in the section. A multi-objective discussion on final results, including economic cost, CO_2 emissions, and the ability to displace oil for the alternative options considered is presented in Section 7. Concluding remarks and proposed direction for future research are reported in Section 8.

2. Review of the *state-of-the-art*

Many variations of WTW studies have been proposed in the literature to capture different aspects of the fuel life-cycle of transportation fuels in different regions of the world. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) fuel-cycle model developed by the U.S. Argonne National Laboratory is currently the most widely adopted software to perform WTW studies.[3] Developed in 1996, the model has been constantly updated and has been adopted in several studies (*e.g.* [8–15]). As described by Wang [3], the GREET model estimates the full fuel-cycle energy use and greenhouse gases (GHG) emissions associated with various transportation fuels for light-duty vehicles.

General Motors and Argonne National Laboratory proposed in 2001 a WTW analysis for the U.S. market which includes a set of 75 different fuel pathways and 15 vehicle powertrains, aimed at informing public and private decision makers on the impact of diverse fuel/vehicle systems [16]. GREET was used for the WTT tank stage, while proprietary GM models were used to compute TTW energy consumption and emissions. In 2002 Wang extended the WTW literature to include fuel cell vehicles [8].

Williamson and Emadi [9] proposed in 2005 a well-to-wheels comparison study of hybrid electric and fuel cell vehicles. The WTT stage relies on GREET, while ADVISOR is used to calculate TTW efficiencies.[4] The benchmark vehicle chosen for the analysis is a SUV tested under standard urban and highway driving conditions (using two driving cycles: the Urban Dynamometer Driving Schedule and the Highway Fuel Economic Driving Schedule, respectively).

Elgowainy et al. [10] investigated WTW energy efficiency and GHG emissions of plug-in hybrid electric vehicles (PHEV) using the GREET model and the Powertrain Systems Analysis Tool (PSAT) for the WTT and TTW stages, respectively. A key factor to evaluate the environmental impact of a PHEV is the primary energy used for the production of electricity used to charge the vehicle batteries.

[1] Primary energy should be used to designate those sources that only involve extraction or capture, with or without separation from contiguous material, cleaning or grading, before the energy embodied in that source can be converted into heat or mechanical work [4].

[2] Exergy can be defined as "*the amount of useful work extractable from a generic system when it is brought to equilibrium with its reference environment through a series of reversible processes in which the system can only interact with such environment*" [7].

[3] For more information on GREET refer to: https://greet.es.anl.gov/.

[4] ADVISOR is a vehicle simulator implemented in the MATLAB/Simulink environment developed by the U.S. National Renewable Energy Laboratory to perform rapid analysis of the performance and fuel economy of light and heavy-duty vehicles.