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Techno-economic assessment of lightweight and zero emission vehicles deployment in the passenger car fleet of developing countries

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HIGHLIGHTS

- We developed a stock turnover model of the passenger car fleet.
- Lightweight and zero emission vehicles deployment in Colombia was studied.
- Battery electric and lightweight vehicles achieve the largest CO_2 reductions.
- Battery electric vehicles have the lowest cost for avoided CO_2.
- By 2050 gasoline remains the main fuel despite advanced vehicle deployment.

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ABSTRACT

The largest increment in the global light-duty vehicle fleet in the medium- and long-term will happen in developing countries. Advanced vehicles can outweigh increments in CO_2 emissions of a growing vehicle fleet; however, cost remains a barrier for their diffusion. A stock turnover model of the passenger car fleet was developed to estimate the potential of advanced vehicle deployment for CO_2 emissions reduction, and used in the case of Colombia. Vehicle types included internal combustion engine vehicles (ICEVs), battery electric vehicles (BEVs) and fuel cell hybrid electric vehicles (FCHEVs); using two glider types: conventional and lightweight materials-intensive. Five scenarios were considered: the base scenario that relies on conventional ICEVs, and four alternative scenarios targeting the penetration of (A) BEVs, (B) BEVs and lightweight vehicles, (C) FCHEVs, and (D) FCHEVs and lightweight vehicles. Deployment of BEVs and lightweight vehicles offers the largest cumulative well-to-wheel CO_2 emissions reductions, 22.01% compared to the base scenario; with cost of avoided CO_2 going from 930 USD/t-CO_2 avoided in 2020 to 31 USD/t-CO_2 avoided in 2050. Despite advanced vehicle deployment, gasoline will be the main fuel and iron and steel the main materials until 2050 in the Colombian passenger car fleet.

1. Introduction

Road passenger transportation poses a global challenge in terms of energy consumption, greenhouse gas (GHG) and local pollutant emissions. Characterized by high energy intensity and pervasiveness [1], road passenger transportation relies mostly on internal combustion engine vehicles (ICEVs) fueled with oil products, and represents a significant share of global energy demand. In the 'New Policies Scenario', the central scenario of the International Energy Agency (IEA)'s World Energy Outlook 2012 [2], by 2035 the passenger light-duty vehicle (LDV) stock is projected to duplicate its current size, reaching 1.7 billion vehicles and accounting for half of global transport oil demand. The largest increment in future global passenger LDV stock is projected in developing countries, where current vehicle ownership is low and expected to increase significantly, compared with modest increments in the developed world [3].

Though deployment of fuel saving measures in developing countries represents the fastest way to achieve energy savings in the global LDV fleet, characteristics such as long service lives for vehicles, low quality fuels, lack of infrastructure and low quality of roads prevent the actual diffusion of incremental fuel saving measures [4]. Considering LDV stock is expected to increase

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significantly in developing countries, where the potential for widespread of incremental fuel saving technologies for ICEVs is limited, the impact of leapfrogging to advanced vehicles using electric powertrains and lightweight materials is studied here as an option to reduce CO_2 emissions from passenger LDV fleet.

Substitution of steel-intensive ICEVs with advanced vehicles constitutes a simultaneous shift in fuels and automotive materials that will affect energy and material flows. Besides reducing fossil fuel consumption and GHG and pollutant emissions, deployment of alternative vehicles and fuels is necessary to achieve energy security, GHG emissions and urban air quality targets [5]. However, despite benefits of advanced vehicle deployment, there are barriers that might prevent it, particularly the increment in cost compared to conventional ICEVs.

In this research, the deployment of advanced vehicles was studied using a fleet perspective to capture the dynamic of the stock turnover, focusing on the effect on energy and material flows, CO_2 emissions and cost. Previous studies regarding the use of zero emission vehicles (ZEVs) and lightweight vehicles are extensive. Studies using a fleet perspective focused on the impact on energy consumption, GHG emissions and/or cost [6–11]. Other studies using a fleet perspective focused on energy and material flows without estimating the cost associated to the deployment of advanced vehicles [12–16].

In contrast, previous researches regarding cost estimation of advanced vehicles were mostly performed using a single vehicle approach [1,5,17,18]; or they did not consider vehicle fleet stock turnover [19]. Sun et al. [20] presented estimations for the cost of fuel cell vehicles (FCVs) and ICEVs using a single vehicle perspective, based on scenarios for FCVs penetration in the U.S.; however, fleet cost and the effect on energy and material flows were not considered. The IEA evaluated possible trajectories of the global LDV fleet using MoMo, a model that allows the assessment of energy consumption, material requirements, GHG and pollutant emissions and cost [21]; however, due to the significance of developing countries, the IEA recommended more work on a regional scale [22]. This research evaluates simultaneously the effect of advanced vehicle deployment on energy and material flows, CO_2 emissions and cost in the context of developing countries at national scale, using a fleet perspective and modeling stock turnover; something not found in the literature reviewed.

The objective of this paper is to analyze the maximum potential for energy consumption and CO_2 emissions reduction achievable with advanced vehicle deployment using electric powertrains and lightweight materials, and the impact on energy and material flows, CO_2 emissions and fleet cost, in the context of developing countries. For that purpose, an accounting model of the passenger car fleet that considers energy and material flows, CO_2 emissions and fleet cost was developed. The model was used to study the particular case of the Colombian passenger car fleet between 2010 and 2050. The rest of this paper is organized as follows: methodology for passenger car fleet stock turnover modeling and cost estimation is described in Section 2, including the description of the Colombian passenger car fleet; results are presented and discussed in Section 3; and finally conclusions are presented in Section 4.

2. Methodology

2.1. Stock turnover model formulation

Energy and material flows for the passenger car fleet at national level, presented in Fig. 1, were modeled using a national scale bottom-up dynamic accounting model, which includes vehicle production, considering material production, part fabrication and vehicle assembly; on-road vehicle use; and vehicle disposal, limited to shredding. Automotive materials imports and exports are considered as materials, parts or assembled vehicles. The model was developed in Long-range Energy Alternatives Planning System (LEAP), a scenario-based, energy-environment modeling tool for the evaluation of energy systems at national/regional level [23]. The flowchart of the model is presented in Fig. 2.

Mathematical formulation of the model for the vehicle production, vehicle use and vehicle disposal modules can be found in [15]. Tank-to-wheel (TTW) energy consumption by the vehicle stock of type t and vintage v in the calendar year y is obtained as the product of the vehicle stock N, the average traveled distance for a vehicle in a year M, and the fuel consumption R, as shown in Eq. (1):

$$E_{TTW,t,y,v} = N_{t,y,v} M_{t,y,v} R_{t,y,v} \quad (1)$$

On-road vehicle stock for the vehicle type t and the vintage year v in the calendar year y is given by Eq. (2):

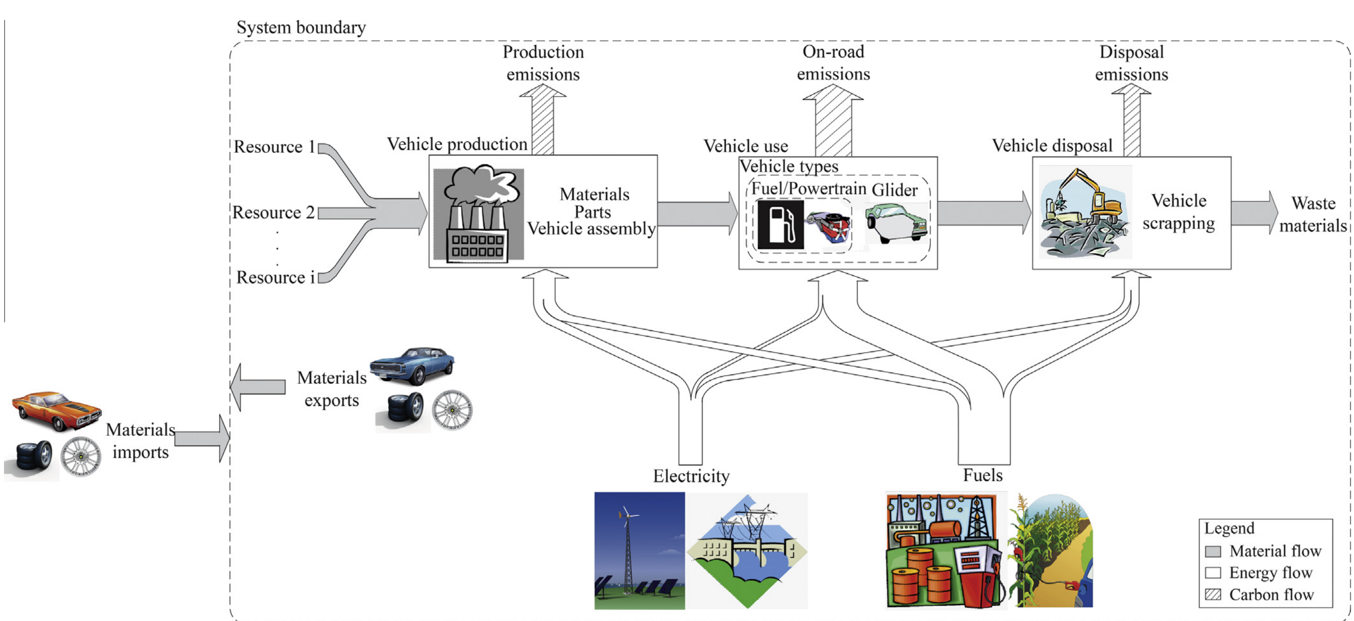

Fig. 1. Energy and materials flows in the system.