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Vehicle energy efficiency evaluation from well-to-wheel lifecycle perspective

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ABSTRACT

Given a fundamental role of automobiles in human society, evaluation of vehicle energy efficiency is of utmost importance. Various reports have been published hitherto concerning well-to-wheel (WTW) fuel consumption at the vehicle operation phase. On the other hand, WTW energy consumption at other lifecycle phases has been scarcely integrated in the assessment of vehicle energy efficiency. Particularly, WTW energy consumption for material structure is significantly associated with fuel economy. As such, this paper firstly analyzes the lifecycle WTW vehicle energy efficiency from the perspective of both material structures at the manufacture phase and fuel consumption at the operation phase for conventional vehicle (CV), electric vehicle (EV), hybrid vehicle (HV) and fuel cell vehicle (FCV). Then, an expected transition of vehicle weight and energy consumption arising from material structural shift through the replacement of steel with aluminum is evaluated. Finally, the overall vehicle energy efficiency in Japan in 2020–2050 is projected. It is discovered that the inclusion of energy consumption for material structure has a significant impact on the determination of the vehicle energy efficiency, particularly for new generation vehicles. WTW analysis at the multiple lifecycle phases may be of use in establishing more comprehensive principles of vehicle energy efficiency.

1. Introduction

In last decades, the increase of global energy demand has raised alarming security of energy supply and environmental sustainable issues. Among the intensive energy sectors a transportation sector in 2013 contributes to 27.8% of global primary energy consumption (Agency for Natural Resources and Energy, 2016). Particularly, automobiles are fundamental to the human society and improvement of vehicle energy efficiency has been widely accepted as a strategy of dealing with energy-related issues (Zahabi et al., 2014).

The mitigation of energy consumption in the transport sector has been achieved through the identification of potential factors influencing on vehicle energy efficiency from a bottom-up approach (Ruzzenenti and Basosi, 2009). This can be of use to customers in selecting the proper vehicle model and to makers in determining reasonable marketing strategies for different regions (Fetene et al., 2017). Potential factors are categorized into two groups: local environment and driving patterns. In the local environment, earlier studies identified potential factors which affect the fuel consumption of cars from the physical perspectives including road grade (Wang et al., 2008), road width (Hu et al., 2012; Yao et al., 2007), temperature (Alvarez and Weilenmann, 2012) and from the social perspectives including traffic congestion information (Fotouhi et al., 2014), traffic design (Hallmark et al., 2002; Vàrhelyi, 2002). In the driving patterns, peculiarities of speed and acceleration were identified to be potential factors (El-Shawarby et al., 2005).

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Although fuel consumption arising from drivers' behavior is sometimes discussed in the discipline of energy conservation for the mitigation of environmental burdens (Oikonomou et al., 2009), its inclusion in vehicle energy efficiency would deliver overarching principles covering a various sustainable issues (Moriarty and Honnery, 2012). Particularly, the term "eco-driving" is highly associated with driving patterns for accomplishment of environmentally benign behavior (Smith, 1999). Several research works were published concerning integration of local environment with driving patterns (Brundell-Freij and Ericsson, 2005; Ma et al., 2015). These aforementioned research works basically have been conducted on a basis of empirical method in the real world (Huo et al., 2012). Other than the empirical method, a mathematical method has been also employed by theoretically executing a parametric analysis (Wang et al., 2008). In the mathematical method new parameters are integrated in the main five resistant forces comprising of loss of gravity, rolling resistance, aerodynamic resistance, inertial acceleration forces, cornering loss (Ehsani et al., 2016; Burgess and Choi, 2003; Pérez-Martínez et al., 2011), which may be of use in revealing the sensitivity of fuel efficiency (Oh et al., 2014).

In contrast to the bottom-up approach of identifying potential factors affecting vehicle energy efficiency, top down approach plays an important role on monitoring the trend of economy-wide vehicle energy efficiency. Economy-wide vehicle energy efficiency has been widely evaluated in the form of energy intensity, in which energy consumption per a unit of passenger with a unit of traveled distance is focused in the automobile mode (Dalla Chiara and Pellicelli, 2016). Chronological trend of vehicle energy intensity has been evaluated in the multi-nations (Eom and Schipper, 2010, Lipscy and Schipper, 2013) and at the regional level (Chung et al., 2013). Other research works attempted to propose several indicators including fuel economy (Ruzzenenti and Basosi, 2009) and carbon emission intensity (Lipscy and Schipper, 2013) in comparison with energy intensity and to aggregate them for the provision of composite energy efficiency index (Cui and Li, 2014). Economy-wide transport exergy efficiency was also developed for the measurement of energy efficiency (Utlu and Hepbasli, 2006; Saidur et al., 2007; Zhang et al., 2011). It must be noted that the most of aforementioned research works focus on the economy-wide energy efficiency of various transportation means and the difference of automobile types in the economy-wide energy efficiency has been scarcely analyzed hitherto.

Subsequently, energy consumption is a core of analysis on energy efficiency and well to wheel (WTW) analysis has been widely employed for comprehensively understanding of vehicle energy consumption. WTW is comprised of well to tank (WTT) as well as tank to wheel (TTW). In the WTW analysis of conventional vehicles, various types of fuel has been focused including ethanol blended gasoline (Zhang and Sarathy, 2016) and octane gasoline (Hao et al., 2016). Not only conventional vehicles, new generation vehicles have been also considered. Hawkins and colleagues conduct the comparative analysis between hybrid and electric vehicles (Hawkins et al., 2012) and between conventional and electric vehicles (Hawkins et al., 2013). Particularly, for electric vehicles the external impact of electricity configuration on its efficiency in the WTT analysis is evaluated as well (Held and Baumann, 2011; Casals et al., 2016). Additionally, WTW energy efficiency of fuel cell vehicles has been also assessed (Larsson et al., 2015; Hwang et al., 2013) by considering the hydrogen transforming process (e.g. Colella et al., 2005).

Notwithstanding WTW analysis is highly associated with the concept of lifecycle assessment (Zhang and Sarathy, 2016), Fiori et al. pointed out that the main stream of modeling vehicle energy consumption focuses on simplified well to wheel analysis of fuel at the vehicle operation phase (Fiori et al., 2016). Overall lifecycle phase of vehicle is comprised of material extraction and processing, manufacturing and assembly, maintenance, end of life besides vehicle operation, which should be also included in the discussion of vehicle energy consumption (Chester and Horvath, 2009). Consideration of all phase lifecycle vehicle could deliver the comprehensive evaluation of vehicle environmental impacts (Facanha and Horvath, 2007). Particularly, Burnham et al. pointed out the significance of magnitude at the manufacturing phase (Burnham et al., 2006). Chester et al. created the life-cycle energy inventory of vehicle operation in U.S. including direct fuel consumption at the use phase and material production at the manufacturing phase (Chester et al., 2010). Sheinbaum-Pardo analyzed carbon emissions through steel production to be integrated in the assessment of automobile environmental impacts (Sheinbaum-Pardo, 2016). Sullivan et al. stated the importance of analyzing material structure at the manufacturing phase to provide an informative insight to automobile communities (Sullivan et al., 2013).

Material structure at the manufacturing phase has been a major interest of research. Light weight design of vehicle material structure could contributes to energy saving, environmental protection (Zhang et al., 2006; Belingardi and Koricho, 2014) and improvement of vehicle fuel economy (Xiong et al., 2018). Particularly, among the various approaches of light weight design including the utilization of innovative materials and material structure optimization (Zuo et al., 2011; Bai et al., 2017), the amount of steel utilized for automobiles has decreased with time at the macro level and aluminum is selected as a replacement of steel during last decades (Xu et al., 2017; Liedl et al., 2011).

In summary, although various reports working on the WTW analysis for fuel consumption at the operation phase have been reported, integration of other lifecycle stage is of utmost importance to establish the comprehensive principles of vehicle energy efficiency. Particularly, given the interaction of material structure with fuel economy, lifecycle energy consumption of material structure can be considered as a potential aspect to be included in the WTW analysis. Furthermore, it can be said that lifecycle energy consumption of material structure denotes WTW material consumption at the manufacture phase, since it can be traced back energy requirements for processing materials. Integration of WTW fuel consumption at the operation phase with WTW material structure at the manufacturing phase can be potentially employed as a new model of evaluating lifecycle WTW vehicle energy efficiency.

As such, the objective of this research is to analyze the lifecycle WTW vehicle efficiency from the perspective of both material structures at the manufacturing phase and fuel consumption at the vehicle operation phase for conventional vehicle, electric vehicle, hybrid vehicle and fuel cell vehicle, and then to project the overall lifecycle WTW vehicle energy efficiency in future on a basis of material structural shift.

This paper is structured as follows. The methodology of developing lifecycle WTW vehicle energy efficiency from the perspective of material structures and fuel consumption is presented in Section 2. Subsequently, the computed lifecycle WTW vehicle energy efficiency and its projection are analyzed in Section 3. Finally, Section 4 concludes this paper.