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Fuel economy analysis of conventional and hybrid heavy vehicle combinations over real-world operating routes

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ABSTRACT

This research evaluates the fuel economy of conventional and hybrid heavy vehicle combinations. The evaluation takes into account four heavy vehicle combinations with different total weights and three parallel hybrid configurations, which were developed for the tractor powertrain. The simulation models of conventional diesel powered and parallel hybrid vehicle combinations were developed in the Autonomie vehicle simulation software. Simulations were carried out in real-world operating routes that had been measured from popular truck routes in southern Finland. According to the simulations results, for one ton of additional weight to the total weight of the vehicle combination, the fuel consumption increases by 0.65–0.95 l/100 km depending on the operating route. The payload specific fuel consumption (the amount of fuel consumed per payload ton-kilometer) decreases on average 17% when total combination weight increases from 40 t to 60 t. The decrease is 23% when going from 40 t to 76 t and 28% when going from 40 t to 90 t. According to the simulation results, the fuel economy of a heavy vehicle combination can be improved by up to 6% by hybridization. The simulation results also indicate that the hybridization is more beneficial in operating routes which have more hill climbing.

Introduction

Improving the fuel economy of heavy vehicle combinations (HVC) is becoming more and more interesting because these vehicles consume a lot of fossil fuels, the demand for the road freight transportation is increasing, and the fuel costs have been steadily increasing (Grenzeback et al., 2013; Frey and Kuo, 2007). In 2010, the energy consumption share of Class 7–8 Trucks was about 17% of total transportation energy consumption in the United States (Davis et al., 2012). Class 7–8 trucks include all heavy-duty trucks, and most of the tractor-trailer trucks are included in Class 8 (NAS, 2010). Several non-electrification technologies have been studied over the years to increase the fuel economy of heavy-duty trucks and HVCs (NAS, 2010; Ogburn et al., 2008). Alternative fuels have also been seen as a solution to decrease fuel consumption and emissions (Zhao et al., 2013b; Krail and Kühn, 2012). Most of the research has been focused on the powertrain, aerodynamics, rolling resistance and lightweight materials (NAS, 2010; Hill et al., 2009a). The energy efficiency of the diesel engine technology has improved, especially with respect to the reduction in the pollutant emissions of heavy-duty trucks (Saricks et al., 2003). However, a large portion of the energy losses of a HVC still originates from the heat losses in the engine, and the fuel economy has not notably increased in the past 30 years (Ogburn et al., 2008). Over the years, the increasingly stringent pollutant emission regulations and the higher power consumption of auxiliary and electronic devices have created additional

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challenges in improving the fuel economy. One way to decrease the energy intensity, which corresponds to the load specific fuel consumption, is to adopt higher weights for the combinations (Ruzzenenti and Basosi, 2009). In fact, there is more and more interest for longer and heavier vehicles in Northern Europe in order to increase the energy and operating efficiency of road transport sector (Bark et al., 2012; Vierth and Haraldsson, 2012; Leduc, 2009). In Finland and Sweden, where freight transport distances can be quite long and population density is low, higher HVC weights are more accepted than in other European countries (Hill et al., 2009a). For further increasing the fuel economy, even higher weights than 60 t have been tested with experimental vehicle combinations in Sweden (Skogforsk, 2014; Bark et al., 2012; Vierth and Haraldsson, 2012), and in Finland 76 t HVCs were accepted in October 2013 (LVM, 2013). There is an ongoing political debate over the use of heavier and longer heavy vehicles among the European Union (EU) member countries. Research studies have been carried out by EU member countries and European Commission to evaluate the impacts of these vehicles especially in economic and technical terms e.g. (Vierth and Haraldsson, 2012; Rijkswaterstaat, 2011; Christidis and Leduc, 2009; Leduc, 2009). Although the research results indicate mostly positive impacts, more research is needed to be able to draw long-term conclusions about large-scale introduction of heavier combinations. One particular political issue is the possible competition against freight transportation in railways.

The powertrain electrification by hybridization is another way to improve the fuel economy of HVCs. The main advantage of the hybrid technology is the possibility to increase the powertrain operating efficiency and to regenerate braking energy into an on-board energy storage. Even if the operation of HVCs is typically over a long-distance and consists mostly of constant speed driving, a significant amount of braking energy can be regenerated because of the road elevation changes. As the diesel engines in heavy vehicles already operate in high efficiency regions, not a lot of improvement is expected to the powertrain efficiency (Zhao et al., 2013a). Besides traction power, the regenerated energy can be used to power the electric auxiliary devices, which can easily operate in higher voltages than the typical 24 V due to the high voltage battery in the hybrid system (Hill et al., 2009a). Despite the increasing interest towards hybrid and electric vehicles in the passenger vehicle markets and for hybrid and electric buses (Lajunen, 2014), only some commercial hybrid or electric heavy-duty truck applications have been developed e.g. (Volvo FE Hybrid, 2014; Arts, 2012; Walkowicz et al., 2012). Sometimes, solutions that are more radical have been suggested for the electrification of heavy-duty vehicles e.g. an electrified Highway (Grünjes and Birkner, 2012). Research has been previously done for determining the potential to reduce fuel consumption and CO_2 emissions of heavy-duty trucks by hybridization e.g. (Zhao et al., 2013a; NAS, 2010; Cooper et al., 2009; Delorme et al., 2009). The results of these recent studies show that the fuel consumption could be improved between 3% and 10% depending on the operation and the hybrid system configuration. Taking into account how much the HVCs consume energy in total, even small improvements in fuel economy can be considered valuable. Most of the previously done research lacks detail in the hybrid system dimensioning, and often the simulations have not been carried out in real-world driving cycles.

In this research, the impact of higher weights and hybridization on the fuel consumption of HVCs has been studied by modeling and simulation. Four different HVCs were defined with specific tractor and trailer structures. The pre-transmission parallel hybrid was chosen as the hybrid configuration for the tractor because according to the many previous studies e.g. (Zhao et al., 2013a; Delorme et al., 2009) it is the best suited and probably most affordable solution for heavy-duty trucks. In the pre-transmission parallel hybrid configuration, the electric motor is located between the engine and the transmission, thus before the transmission. The simulation models were developed in the Autonomie vehicle simulation software, which offers a proven simulation environment for heavy vehicle evaluations (Vijayagopal and Rousseau, 2011; Rousseau et al., 2010). The HVCs were simulated in different types of measured real-world operating routes. The research scope does not include any safety concerns related to the heavier and longer vehicle combinations, and the impact on road wear is excluded. The possible impacts on the other freight transportation modes (e.g. railways) are also not in the scope of the paper.

Description of heavy vehicle combinations

Combination structures

Heavy vehicle combinations in Europe are defined by the European Modular System (EMS), which is based on two different types of load-carrier combinations; swap bodies and semi-trailers (Bark et al., 2012; Åkerman and Jonsson, 2007). Fig. 1 presents the typical HVCs that are used in Europe. Finland and Sweden are the only European countries that allow the heaviest and longest vehicle combinations up to 60 t (~132,000 lbs) and lengths of 25.25 m. In the beginning of October 2013, the Finnish government accepted even higher weights up to 76 t (~167,000 lbs) for HVCs (LVM, 2013). In Sweden, there has been a test for 90 t (198,000 lbs) vehicle combination for timber transportation (Skogforsk, 2014).

HVCs take many forms in the United States and many states have different limitations for the maximum length and weight. The U.S. Federal maximum weight is 80,000 lbs (36,287 kg) but 22 states allow higher weights (Ogburn et al., 2008). The vehicle combinations considered in this research are based on the European combinations, and specifically on the vehicle combinations that are used in Finland. Table 1 describes the four different vehicle combinations, which were considered in this research. The link is considered to have three axles instead of two, as it is presented in Fig. 1. An example of the 76 t combination for timber transportation is shown in Fig. 2. It is foreseen that there could be some limitations for the operation of heavier and longer vehicle combinations e.g. the weight bearing capacity of bridges and structural strength of forest roads.