Transportation Research Part C 88 (2018) 107–123

Contents lists available at ScienceDirect

Transportation Research Part C

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

Battery electric propulsion: An option for heavy-duty vehicles? Results from a Swiss case-study

Emir Çabukoglu, Gil Georges*, Lukas Küng, Giacomo Pareschi, Konstantinos Boulouchos

Aerothermochemistry and Combustion Systems Laboratory, ETH Zurich, Sonneggstrasse 3, 8092 Zurich, Switzerland
Swiss Competence Center for Energy Research on Efficient Technologies and Systems for Mobility, Zurich, Switzerland

ARTICLE INFO

Abbreviations:
BEV
Battery Electric Vehicle
CNG
Compressed Natural Gas
ENTSO-E
European Network of Transmission System Operators for Electricity
GTE
Goods Transport Survey
ICE
Internal Combustion Engine
LNG
Liquified Natural Gas
LSVA
Distance-specific Heavy-duty Vehicle Tax
MPW
Maximum Permissible Weight
PHEV
Plug-in Hybrid Electric Vehicle
pkm
Passenger-kilometer
SOC
State of Charge
tkm
Tonne-kilometer
vkm
Vehicle-kilometer
Mt
Megaton
WHVC
World Harmonized Vehicle Cycle

Keywords:
Road freight heavy-duty truck
Battery electric propulsion
Technology potential

ABSTRACT

Road freight is the most energy-intensive freight mode (per *tkm*) and runs almost exclusively on fossil fuels. Electrification could change that, but can batteries really power actual heavy-duty operations? This study introduces a data-driven, bottom-up approach to explore the technical limits of electrification using real data from the entire Swiss truck fleet. Full electrification increased the total Swiss electricity demand by about 5% (3 TW h per year) over its current level and avoid about 1 megaton of CO_2 per year (accounting for emissions of generation). Realizing this potential required (1) an allowance to exceed current maximum permissible weight regulations, (2) a high-capacity grid access for charging at the home-base (at least 50 kW) and (3) a supporting intra-day energy infrastructure (we explored battery swapping). Boosting the gravimetric energy density of the battery cells was generally beneficial, but only effective if the aforementioned conditions were met. Thus, right now, battery electric trucks are no drop-in replacements for their Diesel counterparts. To allow their wide-spread usage, the road-freight sector would have to transform well beyond the vehicle. The required changes are substantial, but not unthinkable. Therefore, we think electric trucks deserve further exploration, in particular regarding their costs, life-cycle impact, technological variants and comparison to competing technologies.

* Corresponding author at: Aerothermochemistry and Combustion Systems Laboratory, ETH Zurich, Sonneggstrasse 3, 8092 Zurich, Switzerland.
E-mail address: gil.georges@lav.mavt.ethz.ch (G. Georges).

https://doi.org/10.1016/j.trc.2018.01.013
Received 5 September 2017; Received in revised form 15 January 2018; Accepted 15 January 2018
Available online 04 February 2018

Annual transport performance
Switzerland

1. Introduction

1.1. Why truck electrification is hard but important

Heavy-duty road freight[1] are the most energy-intensive freight mode (in units energy per tkm) (EEA, 2008). Since Diesel fuels virtually the entire fleet, it is an important CO_2 emitter: trucks produce roughly 11% of the transportation CO_2 emissions of Switzerland (BAFU, 2017), and more than 16% worldwide (Kahn Ribeiro et al., 2007). Passenger cars produce the lion share of emissions, but electrification could change that in the coming decades. Meanwhile, recent studies expect the demand for road freight to grow roughly twice as fast: + 33% (in tkm) until 2040, compared to a "mere" + 18% for motorized individual mobility (in pkm) (ARE, 2017); internationally, the International Transport Forum even expects a + 160% growth (in tkm) until 2050 (ITF, 2017).

Not surprisingly, the International Energy Agency calls for rapid electrification of road freight (Teter, 2016). But the average Swiss heavy-duty vehicle is more than ten times heavier than the average car – in terms of curb weight, i.e. before adding any payload (Rohner, 2004). To achieve the same autonomy range, electric trucks must thus carry thousands of kilos of batteries, as opposed to hundreds in cars. To make matters worse, trucks generally drive much greater distances on a daily basis. From a purely technical perspective, this raises a fundamental question: are trucks electrifiable to a meaningful extent?

1.2. What has been done thus far (state of the art)

We found no empirical work specifically on the electrifiability of trucks, presumably due to the lack of commercial products; see Section 1.2.2. However, there is a rich body of literature for passenger cars; see Section 1.2.4. A number of studies approached the topic from a market angle; see Section 1.2.3. We found no previous analytical work on the technological potential; but methodologies similar to our own have been used in environmental impact assessment, namely concerning CO_2 and pollutant emissions; see Section 1.2.1.

1.2.1. Environmental impact assessment of current heavy-duty vehicles

There are two types of assessment methodologies: bottom-up and the top-down. The bottom-up approach assesses the impact of each vehicle individually and then it sums up; the top-down approach uses aggregated data, such as fuel sales and average emission factors. Cai et al. (2012) compared the two methods. They concluded that the bottom-up approach incurs a high uncertainty from factors such as fuel type, driving behavior and road conditions. However, it allows more sophisticated analyses, as it considers what kind of vehicle causes them.

McKinnon and Piecyk (2009) evaluated three different bottom-up methods against a top-down reference. The difference were the data sources: namely survey and counting station data for the distance, as well as survey, empirical and test-bench data on the fuel-consumption. The authors concluded that the survey-data was prone to under-reporting of trip distances; counting station data produced the most reliable estimates.

Despite their weaknesses, bottom-up methods remain the preferred impact assessment tool for freight transport (Cai et al., 2012). We found examples from Finland, China, Canada, Turkey and Spain: Liimatainen and Pöllänen (2010) determined trends of energy efficiency in Finnish road freight using an energy demand model and statistical data. Yang et al. (2015) used questionnaires, GPS devices and an energy demand model to track driving behavior and compute CO_2 emissions. Lukomskyj (2003) computed emissions in Alberta using traffic counts. Ozen (2013) and Burón et al. (2004) calculated emissions using COPERT, a modeling tool developed by the European Environment Agency (EEA).

1.2.2. Practical experience: commercially available electric truck products

There are too few heavy electric road vehicles to draw conclusions for the entire freight sector: In public transport, trolley buses have been commonplace in cities for a long time; more recently, plug-in electric and all-electric solutions have been tested in many countries, including Switzerland (such as ABB's electric bus in Geneva (ABB Communications, 2013)). In road freight, Siemens is currently testing its "eHighway" technology: direct-electric hybrid trucks, powered via overhead lines (Siemens, 2016).

Pure and independent electric freight vehicles remain exotic: at the time of writing we identified the Swiss E-Force One (E-FORCE ONE, 2017), EMOSS (EMOSS Full Electric Truck, 2017) and Terberg electric trucks (Terberg Yard/Port Tractor, 2017). Mercedes-Benz (Mercedes-Benz Urban eTruck, 2017) and recently Tesla (Tesla Semi, 2017) announced products.

1.2.3. Uptake of electric propulsion in heavy-duty vehicles

In its "commercial vehicles study" on the "future of German road freight and bus and coach travel up to the year 2040" (Adolf

[1] We follow the Swiss legal definition: any automobile road-vehicle (a) dedicated to the transport of goods for commercial purposes and (b) whose maximum permissible weight exceeds 3.5 metric tonnes (Muncrief and Sharpe, 2015).