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Assessing life cycle impacts and the risk and uncertainty of alternative bus technologies

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ABSTRACT

Low-emission alternative bus technologies are of increasing interest to bus fleet operators due to the reduced environmental impact and potential for lower operating costs. However, with uncertainty regarding the total cost of ownership of new technologies and life cycle impacts beyond the typical well-to-wheel boundary, stakeholders may not have the necessary specific tools or evidence to evaluate life cycle impacts. The aim of this paper is to develop a novel framework to assist decision-makers in assessing the uncertainty of the life cycle impacts of alternative bus technologies. The Technology Impact Forecasting methodology was employed, integrating a life cycle model, to investigate whole life cycle impacts in an exploratory assessment environment, allowing for the analysis and trade-off evaluations of alternative drivetrain technologies and operational scenarios. This research provides a comprehensive novel framework for addressing uncertainty in whole life cycle costs and GHG emissions for the manufacture, use, maintenance and infrastructure phases of diesel and battery electric buses. Eleven scenarios are assessed in the framework, evaluating combinations of battery technologies, well-to-tank pathways, charging infrastructure and auxiliary demands. For every battery electric bus scenario, there is an 80% confidence that life cycle GHG emissions are mitigated by 10–58% compared to the baseline diesel bus, but life cycle costs are 129–247% higher. Opportunity charged electric buses employing a lithium-titanate battery are the most effective scenario for mitigating GHG emissions per additional cost of the new technology to the operator. The framework highlights a key trade-off between dependence on battery capacity and high-power charging infrastructure for battery electric bus technologies. The framework enables stakeholders to make technology adoption and resource allocation decisions based on the risk of a scenario and provides a level of confidence in a technologies' ability to mitigate whole life cycle impacts.

1. Introduction

1.1. Background

The 2015 Paris Agreement signalled a global commitment to mitigate the effects of climate change caused by anthropogenic greenhouse gas (GHG) emissions [1]. The EU has also committed to reducing GHG emissions by 80–95% by 2050 compared to 1990 levels [2]. The transport sector is responsible for ~25% of EU GHG emissions [3], and as part of measures to address this emissions standards have been introduced for heavy duty vehicles, e.g. Euro VI legislation [4]. For large operators of heavy duty vehicles, such as bus fleets, the need to conform to environmental legislation is steering interest towards low emission vehicles. However, market penetration of alternative technologies, e.g. battery-electric buses (BEB), is hindered by higher acquisition costs compared to conventional diesel vehicles [5–7]. There are also concerns about the total cost of ownership (TCO) with uncertainty regarding additional infrastructure, maintenance routines and the sensitivity to energy costs [5–10].

Stakeholders seeking to employ alternative driveline technologies need to evaluate both economic and environmental effects. However, the many factors in a vehicle life cycle lead to high levels of variation in whole life cycle impacts reported in literature, both for a specific technology and when comparing multiple technologies (Figs. 1 and 2). Although a decreasing trend can be observed in whole life cycle GHG emissions with increased electrification, there is wide variation in the results, and there is no clear trend for whole life cycle costs versus technology type. Such variation leads to uncertainty when comparing alternative technologies. To assist in this complex decision-making process, there is a need for a rapid assessment environment to evaluate

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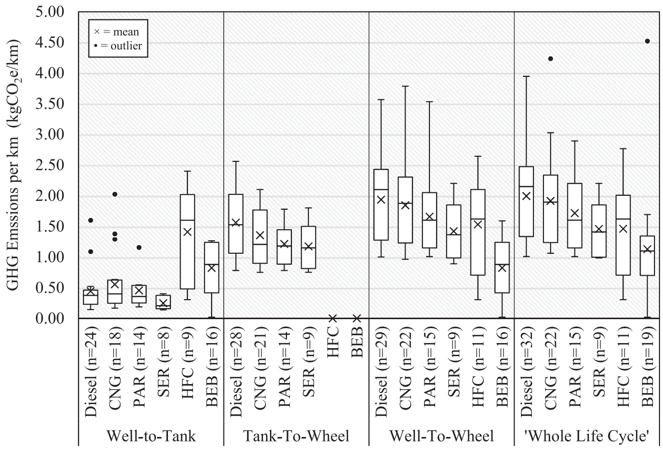

Fig. 1. Box and whisker plots of GHG emissions of key life cycle phases for 6 of the most common drivetrain technologies evaluated in literature: diesel, compressed natural gas (CNG), parallel hybrid (PAR), series hybrid (SER), hydrogen fuel cell (HFC) and a battery electric bus (BEB) technologies. Sources: [7,9,11–23] converted to a functional unit of 1 vehicle-km. 'Whole Life Cycle' refers to the entire system boundary considered by each cited source. Table 1 provides descriptions of the Well-to-Tank, Tank-to-Wheel and Well-to-Wheel terms. See Supplementary material for data.

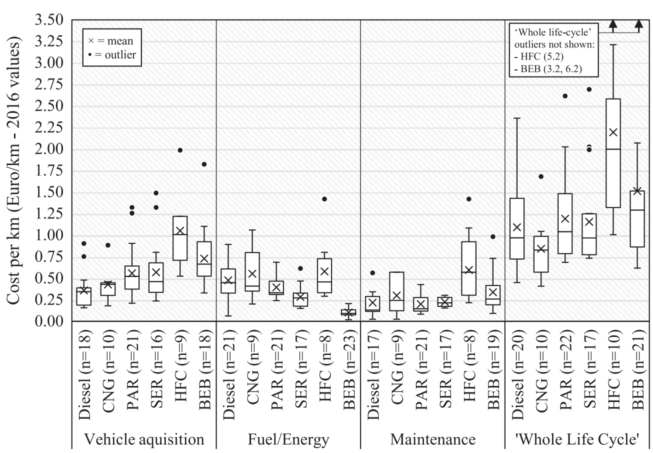

Fig. 2. Box and whisker plots of costs (converted to 2016 equivalent values) of key life cycle phases for 6 of the most common drivetrain technologies evaluated in literature: diesel, compressed natural gas (CNG), parallel hybrid (PAR), series hybrid (SER), hydrogen fuel cell (HFC) and a battery electric bus (BEB) technologies. Sources: [5–9,15,21,24,25]. 'Whole Life Cycle' refers to the entire system boundary considered by each cited source. Table 1 provides descriptions of the Well-to-Tank, Tank-to-Wheel and Well-to-Wheel terms. See Supplementary material for data.

whole life cycle environmental and economic impacts of alternative bus driveline technologies (and varying operational conditions) and to quantify the potential uncertainty and assess key sensitivities of the vehicle life cycle.

1.2. Aim and focus of paper

*The aim of this paper is to develop a novel framework to assist decision-makers in assessing the uncertainty of the life cycle impacts of alternative bus technologies***.** This paper focuses on conventional Euro VI diesel and theoretical battery electric bus technologies. A BEB provides a good case study; in terms of the degree of vehicle electrification, conventional diesel and battery-electric vehicles are on contrasting ends of the scale [30]. Some knowledge of alternative propulsion systems is assumed and will not be covered in this paper, as many review studies cover these topics extensively, e.g. [7,31–35]. Note that the concepts of risk and uncertainty can differ depending on the field of research e.g. economics [36]. In the context of this paper, uncertainty is a state of limited knowledge, where possible states or outcomes can be quantified by assigning probabilities to these states or outcomes [37]. Risk is therefore the quantified probability of an outcome occurring [37].

1.3. Life cycle modelling of bus technologies

Life cycle analysis (LCA) methods (Table 1) are typically used to compare alternative technologies. There are three common types of LCA: process-based, economic input-output (EIO-LCA) and a combination of the two, hybrid-LCA. Process-based LCA considers the inputs (energy, materials, etc.) and resultant outputs (emissions, waste, products, etc.) of each unit process over a product's life cycle i.e. a bottom-up approach [38]. EIO-LCA uses monetary transactions between economic sectors to characterise the product's supply chain, including all direct and indirect impacts i.e. a top-down approach [39]. EIO-LCA has the potential for use in a design process, but a hybrid-LCA approach is recommended if more precision is required [40]. Although hybrid-LCAs can still include truncation errors inherent in EIO-LCAs, they can yield a more complete set of results than a single modelling approach [41].

In the context of buses, lack of available component data (e.g. bill of materials) is often cited as a reason why bottom-up studies don't consider the manufacturing phase in life-cycle modelling studies [14,15]. Hybrid-LCAs can provide the additional fidelity of process-based methods for key sections of a product's life cycle, e.g. the WTW phase [28], with EIO-LCA methods covering the product's raw material extraction and fabrication. Previous work has tended to use EIO-LCA data for standard components [21,42], while process based LCA has been combined with EIO-LCA results to quantify the impacts from the addition or replacement of specific items, e.g. battery [9,17]. The literature review highlighted the following key findings/recommendations regarding the set up a hybrid-LCA bus model:

- The use of aggregated process-based WTT inventories from literature or model databases [43,44] is prevalent in many studies, where

Table 1
Life cycle analysis terminology.

Term	Description
Life cycle analysis (LCA)	A methodology which addresses the potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use and end-of-life treatment [26,27].
Well-to-wheels (WTW) analysis	The dominant LCA approach for comparing alternative vehicle technologies. Widely used for policy support in road transport [28]. Focuses on the processes of the energy carrier (i.e. diesel or electricity) used to propel the vehicle during operation. Comprises the well-to-tank (WTT) and tank-to-wheel (TTW) phases.
Well-to-tank (WTT) analysis	Comprises the recovery or production of the feedstock for the energy carrier and subsequent energy conversion, delivery/transmission and storage.
Tank-to-wheels (TTW) analysis	Comprises the on-board energy conversion to drive the vehicle based on the lifetime distance travelled, fuel energy required and vehicle efficiency [29].