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Applying Multi-Criteria Decision Analysis to the Life-Cycle Assessment of vehicles

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A B S T R A C T

This article presents a methodology to classify light-duty vehicles according to their environmental impacts. The classification is based on Life-Cycle Impact Assessment indicators and vehicle operation indicators, which are aggregated using a Multi-Criteria Decision Analysis (MCDA) method. In contrast with most literature combining Life-Cycle Assessment (LCA) and MCDA, vehicles are not compared directly; they are compared to pre-established profiles defining a set of classes. These profiles are established relatively to the impacts of the country's light-duty fleet. The ELECTRE TRI method is chosen for MCDA classification, thus avoiding complete substitutability among criteria and allowing for imprecision in the data. MCDA typically incorporates the subjective values of decision makers, namely through criteria weighting. To obtain conclusions that are not contingent on a given weight vector, we consider a space of weight vectors defined by constraints with a clear rationale and obtain all the possible results compatible with those constraints. The methodology is applied to classify six vehicles available in Portugal with different powertrains: Gasoline and Diesel Internal Combustion Engine Vehicles, Plug-in Hybrid Electric Vehicles (10 and 40-mile battery range) and Battery Electric Vehicle. The discussion suggests how this methodology might be useful for a decision-making entity that wishes to classify vehicles according to their environmental impacts.

1. Introduction

Vehicles are one of the main causes of air pollution in urban areas, mostly due to fossil fuel combustion during vehicle operation. Many countries have established measures to control air pollution from transport, such as limiting vehicle speed and banning older vehicles (e.g. older than EURO 1) from city centers. The dependence of the transportation sector on fossil fuel imports is also a political concern in many countries, such as Portugal. Aiming to promote the reduction of pollution and oil imports, the European Union (EU) Directive 2009/28/EC (European Comission, 2009) set a target of 10% share of energy from renewable sources in transportation by 2020. Electric vehicles are being promoted (e.g., by tax incentives) since they can have an important role in achieving this target due to their use of electricity, if it is generated with a large share of renewable sources. In countries such as Portugal, another important benefit can be the reduction of oil imports.

The assessment of the environmental impacts of vehicles is an important component of the decision-making process of policy makers and consumers. A meaningful assessment of alternative vehicles, especially when these are based on different technologies, should address multiple dimensions of environmental performance and include impacts over all stages of the vehicle life-cycle using a Life-Cycle Assessment (LCA) (Arena et al., 2013). Indeed, several studies have assessed the environmental performance of new vehicles both at product or company level using a life-cycle

Acronyms: AC, Acidification; AD, Abiotic Depletion; BEV, Battery Electric Vehicle; EUT, Eutrophication; FC, Fuel Consumption (primary energy); FU, Functional Unit (FU); GW, Global Warming; HEV, Hybrid Electric Vehicle; LCA, Life-Cycle Assessment; LCIA, Life-Cycle Impact Assessment; MCDA, Multi-Criteria Decision Analysis; OLD, Ozone Layer Depletion; PHEV, Plug-in Hybrid Electric Vehicles; PM, Particulate Matter; PO, Photochemical Oxidation.

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approach (Liu et al., 2015; Ma et al., 2012; Nanaki and Koroneos, 2013; Ou et al., 2012; Samaras and Meisterling, 2008; Smith, 2010; Van Vliet et al., 2011; Yagcitekin et al., 2013). Most of these studies assess the environmental impacts of conventional and alternative powertrains, such as electric or hybrid, in different locations, e.g. China (Liu et al., 2015; Ou et al., 2012), Greece (Nanaki and Koroneos, 2013), Turkey (Yagcitekin et al., 2013) and the UK (Ma et al., 2012). These studies highlight the importance of LCA to avoid burden shifting, i.e., reducing a negative impact at one part of the system but increasing the same impact elsewhere. However, these studies usually focus on few environmental impact categories (indicators), such as Global Warming (GW), not accounting for many other potentially relevant impacts (Hawkins et al., 2012). In particular, few studies covered impacts specifically associated with the operation phase, in which lie the main differences between new and conventional vehicle alternatives, despite the importance of this phase with regard to air pollution in urban areas.

The need to consider multiple environmental impacts suggests the use of Multi-Criteria Decision Analysis (MCDA). MCDA has been defined as a “collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter” (Belton and Stewart, 2002, p. 2). Tsoukiàs (2007) presents MCDA as a process encompassing the activities of representing the problem situation (describing the purpose of the process and the actors concerned), choosing a problem formulation model (stating the problem situation in a formal way), building an evaluation model (specifying alternatives to be evaluated and how they are evaluated), and applying this model to derive recommendations (translating the results to the current language of the client actors).

Recent developments in MCDA applications to LCA have highlighted that the use of MCDA contributes to support environmental decisions consistent with the values of the decision-maker (Kiker et al., 2005) by aggregating complex information and being able to cope with qualitative and quantitative data in a transparent way (Jeswani et al., 2010). MCDA is particularly useful in environmental decision making because it can compare alternatives regarding technical information, stakeholder values and non-monetary factors (Huang et al., 2011). Using MCDA it is possible to incorporate multiple perspectives in an assessment, namely in the final weighting phase (Rogers and Seager, 2009; Soares et al., 2006).

MCDA and LCA complement each other well (Geldermann and Rentz, 2005; Hermann et al., 2007; Myllyviita et al., 2012; Seppälä et al., 2002), but there are still relatively few studies combining these methods. Examples in the transportation sector include studies on transportation systems (Bouwman and Moll, 2002), vehicle fuels (Mohamadabadi et al., 2009; Rogers and Seager, 2009; Tan et al., 2004; Zhou, 2007), biofuel pathways (Narayanan et al., 2007; Perimenis et al., 2011), and road maintenance strategies (Elghali et al., 2006). All these authors use MCDA methods that rank the alternatives, such as weighted sums and additive value functions (Bouwman and Moll, 2002; Elghali et al., 2006; Zhou, 2007), the Analytic Hierarchy Process (Narayanan et al., 2007), PROMETHEE and SMAA-LCIA (Mohamadabadi et al., 2009; Prado-Lopez et al., 2014; Rogers and Seager, 2009), compromise programming (Tan et al., 2004), or a custom-built method in the case of Perimenis et al. (2011).

In this article we contribute to this literature complementing it in a number of ways. We propose and apply a methodology to classify light-duty vehicles available in Portugal according to their environmental impacts. Vehicles with different powertrains (Gasoline and Diesel vehicles, Plug-in Hybrid Electric vehicles and Battery Electric vehicle) are used as diverse examples. Thus, unlike other works (Mohamadabadi et al., 2009; Rogers and Seager, 2009; Tan et al., 2004; Zhou, 2007), we are assessing specific existing vehicles rather than fuels.

In Portugal, as in many European countries, vehicles are classified for taxation purposes, but the classes are defined based only on use phase CO_2 emission ranges. This article aims to address not only GW impacts but also other indicators, some considering the whole life-cycle of the vehicle and others focused on the use phase.

In terms of MCDA formulation, this work deals with a sorting problem (Roy, 1996; Zopounidis and Doumpos, 2002): the vehicles are to be sorted (classified) according to a predefined set of classes, taking into account a set of environmental impact indicators. Such classes are in this case ordered from the highest to the lowest environmental impact. The aim of obtaining an absolute evaluation of each alternative distinguishes this work from most literature on the combined use of LCA and MCDA, which uses relative evaluation methods that aim at selecting one alternative, or ranking the alternatives, rather than assigning them to performance classes. Let us also note that a different type of classification might be performed, namely using a classification matrix (Dangelico and Pontrandolfo, 2010).

Among several possible sorting methods (Zopounidis and Doumpos, 2002), this work uses ELECTRE TRI (Yu, 1992), which is a classic sorting method within the ELECTRE family (Figueira et al., 2005; Roy, 1991). In contrast with methods referred to above such as weighted sums, ELECTRE methods have several important characteristics: they can work with any type of scales, the criteria weights are scale-independent, they allow for imprecision in performance indicators and they deny full substitutability (it is a so-called non-compensatory method) (Figueira et al., 2005; Infante et al., 2013; Khalili and Duecker, 2013). The latter characteristic means that in ELECTRE, if the decision maker wishes so, a very poor performance on one indicator cannot be compensated by a very good performance on another indicator. As far as the authors are aware, this work is the first one applying ELECTRE TRI in a combined LCA and MCDA methodology.

This work also differs from most literature on the way criteria (in this research, environmental indicators) weights are dealt with. Indeed, besides the analyst's methodological choices at each stage of the process, MCDA introduces subjectivity explicitly through the incorporation of criteria weighting (Rowley et al., 2012). Rather than selecting precise criteria weight vectors or a small number of variants, which is the most common choice in the literature (e.g., Santoyo-Castelazo and Azapagic, 2014) (an exception is Rogers and Seager, 2009), we consider a space of weight vectors defined by constraints with a clear rationale and obtain all the possible results compatible with those constraints. The constraints are such that they can be easily understood and accepted by decision makers, since they do not involve value judgment that could be considered unwarranted.

The details on the methodology are presented next in Section 2. Section 3 presents various scenarios of stakeholder preferences and the respective results, aiming at obtaining conclusions that are robust, i.e., not contingent on precise criteria weights. The results are discussed in the concluding section, suggesting how the methodology proposed in this article might be useful for a decision-making entity that wishes to classify vehicles according to their environmental impacts. Although the methodology is illustrated for only six vehicles and considering the Portuguese context, it is applicable to other vehicles and regions.

2. Material and methods

The conceptual framework for this work is presented in Fig. 1 and is further detailed in Sections 2.1–2.3. Section 2.1 provides detailed information about the light-duty vehicles that were