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An integrated method to calculate an automobile's emissions throughout its life cycle

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ABSTRACT

Although studies can be found in the literature that present emissions inventories associated with different types of automobiles, distinct technologies or various stages of their life cycles, they do not enable us to compare the environmental impact of the complete life cycle of two vehicles. This is because there is no valid emissions inventory for all types of automobiles that covers all the life cycle stages (the cradle to grave approach). This paper proposes a method to estimate the principal types of emissions throughout a vehicle's life cycle based on primary data (weight, year of manufacture, engine technology, fuel type used, etc.). The proposed method requires neither sophisticated life cycle assessment software nor knowledge of specific information on individual vehicles. The proposal has been validated by analyzing three different gasoline and diesel-fueled internal combustion engine vehicles and by considering a life span of 100,000 km.

1. Objective

This paper presents a method to estimate the emissions of an internal combustion engine vehicle throughout its life cycle. Although studies exist in the literature those present emissions inventories associated with different types of automobiles [1–3], distinct technologies and energies [4–6] or various stages of their life cycles [7–9], they cannot be used to compare the environmental impact of the complete life cycle of two vehicles. This is because there is no valid emissions inventory for all types of automobiles that covers all the stages of their life cycles, often referred to as the cradle to grave approach.

Although the use stage of a vehicle may represent between 46% and 76% of the total energy consumed during its life cycle, and in spite of the fact that between 67% and 74% of greenhouse gas emissions[1] are generated during its use, depending on engine type (varying from hydrogen-powered fuel cell vehicles to internal combustion fueled with gasoline) [7], the manufacturing and end-of-life stages cannot be left out of the analysis, and have to be taken into account in the LCA (life cycle assessment). Since a vehicle's fundamental impact can be expressed in terms of emissions and energy consumption, the term “emissions” has been chosen to address the matter.

When two gasoline and diesel-fueled vehicles were previously compared in their use stage, in relation to fuel consumption per kilometer, the latter has been traditionally associated with lower emissions of pollutant gases (including CO_2), together with higher emissions of PM (particulate matter). However, with the advance of engine technology and increasingly stringent regulations (Euro and EPA standards [10,11]), differences in PM emissions have been practically eliminated since the Euro 5 standard, which is currently in force, limits PM emissions to 5 mg/km, while the EPA standard limits PM emissions to 20 mg/mile for both vehicle types.

Apart from differences in the use stage, what other differences can be found between different types of vehicles in the other stages of their life cycles? Which vehicle performs better at the end-of-life stage from an environmental perspective? What influence does the choice of one material or another have on the vehicle's final impact?

When a vehicle is manufactured, the effect of changes on the materials used in its components (e.g. the recent trend of increased plastics and aluminum content, and less iron and steel) on its total environmental impact have to be taken into account since these

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[1] For hydrogen-fueled engines, the greenhouse gas emissions generated during fuel production may represent up to 80% [7].

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changes affect not only emissions [12,13], but also the possible different end-of-life scenarios. It can, therefore, be stated that vehicle composition data are important since they will determine the vehicle's recyclability rate.

The emissions estimation method proposed herein allows the calculation of the emissions associated with a vehicle throughout its life cycle. It also enables a sensitivity analysis to estimate variations in emissions according to the mileage (in kilometers) covered, engine type, composition of vehicle components, and the end-of-life scenario.

The ultimate aim of this paper was to propose a method to estimate emissions from different types of internal combustion engine vehicles in order to determine which has the least environmental impact. To this end, it was necessary to find a way of complementing the existing data in the literature with additional data for the manufacturing and end-of-life stages in order to compare equivalent vehicles in both size and power terms.

Although for this paper only internal combustion engine technologies have been considered, it would be interesting to extend the method into the future to the rest of types of engines. The reason why this project considers initially the indicated technologies is due to the fact that nowadays internal combustion engines compose the greatest share of the market, and also because due to this it exists sufficient reference material available to define the proposed model.

2. Environmental impact of an automobile

Automobiles are involved in many different environmental problems, the best known of which is probably atmospheric pollution caused by engine emissions. Other existing problems are associated with the large amounts of materials and energy consumed in their manufacture and maintenance, the energy consumed and the emissions generated to extract and process fossil fuels, the liquids used as lubricants or coolants of engines, and those used to wash the vehicles, as well as the materials used to decontaminate them at the end of their life.

As various studies have pointed out [14–17], from a brief examination of an automobile's life cycle, it can be concluded that the use stage has a negative environmental impact, mainly due to the energy consumed in this stage, which is far greater than the amount consumed in other stages, even in the so-called low fuel-consumption vehicles [7].

However, when this impact is analyzed from the waste generation or global warming point of view (greenhouse gas emissions, such as CO_2, CH_4, and so on), the raw materials extraction and processing stage is considered to be the most polluting one.

When analyzing the environmental impact due to particulate matters, and NO_x and CO_2 emissions, the raw materials extraction and processing stage is usually found to be the most polluting one. However, the largest amount of water is consumed in the manufacturing stage [16,18].

The concern voiced by the automobile industry for its environmental impact has increased in recent years due to more and more increasing pressure placed by public administrations, and given increasingly stricter European, Asian and US regulations. Car manufacturers are, thus, under growing pressure to improve their environmental performance, and, that they are doubtlessly responding to this challenge. Since 1990, the reuse and recycling rates of materials in production cycles and the industry's global productivity have substantially risen [19]. Since 1970, PM and toxic gas emissions in the vehicle usage stage have been considerably reduced and the trend still moves in this direction.

As regards the treatment of vehicles at the end of their life, and as different studies have pointed out [20–24], each country has introduced comprehensive regulations to control the end-of-life stage of discarded vehicles.

3. Review of the state of the art

There are different qualitative (MET Matrix, checklists, etc.) and quantitative techniques (ecoindicators, life cycle assessment, etc.) available to analyze a product's environmental profile; i.e. to obtain a general perspective of its most important environmental aspects throughout its life cycle, which, in some techniques, describe them as environmental impacts. All the techniques are based on an analysis which includes all the stages of the product's life cycle. Its complexity, cost, time required to carry it out and amount of information needed is what distinguish one method from another.

LCA (life cycle assessment) is currently the most popular technique in the scientific community for analyzing a product's environmental load. According to the SETAC (Society of Environmental Toxicology and Chemistry), LCA can be defined as “an objective process for evaluating the environmental loads associated with a product, process or service” [25]. This involves identifying and quantifying the energy and materials used, as well as all the waste returned to the environment, with the objective of analyzing and assessing their environmental impact in order to adopt those measures that minimize negative effects and maximize positive ones.

From the literature review of methods or studies carried out to calculate the environmental impact of an automobile, surprisingly very few works include all the life cycle stages. Among them, these are noteworthy [2,7,8]. However, there are numerous studies that focus on only one stage, where the use stage predominates.

Regarding the studies that apply LCA to automobiles, the following are highlighted:

- Those that deal with LCA methods: authors like Lundqvist et al. [21], Hentges [26] and Saur et al. [27] consider specific aspects of LCA methods with a special emphasis placed on automobiles.
- LCA studies that focus on any vehicle component: Steele and Allen [28] made a simplified LCA of vehicle batteries. Other similar studies into batteries include [29–31]. It is also worth mentioning the work of Saur [32], who assessed five car fender designs. Keoleian et al. [33] and Joshi [34] made LCAs on alternative materials for fuel tanks.
- LCA studies that deal with materials: Gibson [35] compared components made of different materials to investigate the feasibility of using the lightest. Young and Vanderburg [36] analyzed an environment for applying LCA to materials in order to determine their extrinsic environmental properties. Other interesting studies have focused on one kind of raw material: e.g., diverse metals [12], magnesium [13,37], steel [38] and aluminum [39]. There are also studies that simultaneously compare different raw materials [3,40].
- LCA studies that focus on a specific life cycle stage: the most important ones are those that have analyzed the use stage because it is the most complex stage, there is considerable information available about it, and it accounts for most of the environmental impact throughout an automobile's life cycle [1,4,41–46]. Kirkpatrick et al. [47] analyzed the end-of-life stage and found only minor differences in the environmental impact when considering different end-of-life scenarios. Lave et al. [15] studied the manufacturing stage and Kaniut et al. [48] specified percentages of energy consumption and NO_x emissions for different automobile operating units in the manufacture stage.
- LCA studies that consider the complete life cycle: Sullivan and Hu [49] and Schweimer and Schuckert [50] were the first to