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How car material life-cycle emissions are considered in environmental rating methodologies? Suggestion of expedite models and discussion

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ABSTRACT

This paper reviews existing vehicle environmental rating methodologies worldwide and focuses on how these methodologies deal with alternative vehicle technologies (plug-in vehicles, hybrid vehicles, and fuel cell vehicles) and emissions of greenhouse gases (CO_2, N_2O, and CH_4) and pollutants (NO_x, VOC, CO, SO_x, PM_{10} and $PM_{2.5}$) derived from embodied materials life cycle. United States, Mexico, Europe and Australia have public access data and websites with top 10 rankings. The ways the scores are calculated for each vehicle have differences in what regards the considered boundaries for the emissions analysis. In Europe, there is still not a unique rating methodology or ranking system, e.g., Belgium, Germany and United Kingdom have their specific scoring schemes. Multilinear regression models were developed as an attempt to estimate the vehicle embodied emissions as a function of vehicle lifecycle mileage, electricity mix, vehicle mass, battery mass and fuel cell power to cope with different production regions and different alternative vehicle technologies. The regression models were validated against Volkswagen life cycle assessments (LCAs), and compared against American Council for an Energy Efficient Economy (ACEEE) – Green Book linear functions for material assessment and UK 12 material dataset for materials assessment. The developed models proved to be useful in applications related to rating methodologies using life-cycle concepts, with good reliability for comparisons considering the complexity of processes involved in vehicle materials life-cycle assessment.

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1. Introduction

Road passenger vehicle fleet has a significant impact on energy consumption and, consequently, due to the dominant internal combustion technology, in greenhouse gas (GHG) and pollutant emissions worldwide. In 2010, the transport sector consumed about 2200 million tons of oil equivalent (mtoe), constituting around 19% of the global energy supplies [1]. More than 60% of the oil consumed goes to the transportation sector. Road transport accounts for the bulk, around 76% of the total transportation energy consumption [1]. The light-duty vehicles (LDVs), including light trucks, light commercial vehicles, and minibuses, accounted for 52%, while trucks, including medium- and heavy-duty ones, accounted for 17% [1]. Due to this reality, both public transportation and more efficient light-duty vehicle technologies are being considered ([2–4]).

Concerning light-duty vehicles, several methods for informing car end users are accessible by means of an informative label at purchasing spots, or through websites dedicated to attributing scores and providing lists with the ranks of commercial available vehicles in each country. For example in Europe, first sale vehicles must have an environmental rating sticker, which among other parameters shows the CO_2 emission and the fuel consumption of the vehicle while in usage [5], see Fig. 1, as part of the action plan for the Directive 2012/27/EU. In United States it is mandatory that the car on sale has a label, which focuses on fuel economy, fuel costs and environmental impacts related to smog and GHG [6], see Fig. 2 An extensive review of existing labels worldwide can be found in Mahlia et al. [7]. The focus is usually on in-use CO_2 tailpipe emissions.

Despite the main methods used to raise awareness about consumers' purchasing decisions and encourage manufacturers to explore more efficient powertrains such as car labeling and environmental rankings, the main methodology used by the scientific community is life cycle assessment (LCA).

The LCA methodology was developed to evaluate the mass balance of inputs and outputs of systems and to organize and convert those inputs and outputs into environmental themes or categories relative to resource use, human health and ecological areas. The quantification of inputs and outputs of a system is called Life Cycle Inventory. The process of making an LCA can be divided into four phases according to ISO 14001:

- Phase 1: Definition of purpose, goal, functional unit and system boundaries.
- Phase 2: Inventory analysis, including data collection for all processes (input and output data) and allocation or system expansion between product and co-product.
- Phase 3: Evaluation of the environmental effects, including calculation of the LCA results through classification and characterization.
- Phase 4: Interpretation of the result and identification of significant issues.

The LCA of a car can be composed by the fuel life cycle (well-to-wheel, WTW) and by the embodied materials life cycle. The last one is particularly important with the increasing electrified technologies. The vehicle embodied materials life cycle analysis potentially includes raw materials extraction, production, assembling, dismantling and recycling, and some components have a more significant impact than others; for instance, batteries and fuel cells have higher impact than internal combustion engine (ICE) or electrical motor due to the material in their constitution, considering for instance nickel metal hydride and lithium-ion materials for batteries and graphite, aluminum and carbon sheets for fuel cell stack [8]. This life cycle part can represent as much as 6–17% of the total GHG emissions ([8–13]) and is especially important for electrified technologies like pure electric vehicles (EVs), hybrid vehicles (HEVs), plug-in hybrid vehicles (PHEVs) and fuel cell-based vehicles (FCHEVs or FCPHEVs).

Materials life cycle may be assessed using for example Ecoinvent database in Simapro [14] or using GREET ([15,17]). While Simapro is a generic software that has life-cycle inventory databases and impact assessment methods, and follows the LCA four phases described above, therefore allowing it to assess life-cycle impact from different perspectives of a material or product, GREET is specific for light-duty vehicle life cycle ([18,15]). GREET stands for Greenhouse gas Regulated Emissions and Energy use in Transportation, and is basically an inventory dataset specific for the fuels that feed the cars “fuel cycle” and for the materials used in the cars itself “vehicle cycle”. It returns inventory values for GHG, energy consumption and criteria pollutants.

Hawkins et al. [16] provide an assessment of the completeness of the literature in describing the full life cycle of HEV, PHEV and EV vehicles, excluding hydrogen-based technologies: production of the vehicle itself; the in-use phase; production and distribution of the in-use phase energy consisting of transmission, and distribution of electricity or other fuels; and end of life. It reviews 51 studies including different scopes (vehicle production, battery production, electronics production, recycling, disposal, use patterns, electricity/fuel production, maintenance, electric grid, and dynamic grid), emissions (CO_2, NO_x, CO, SO_2, PM, N_2O, HC, VOC, and CH_4), impact categories (global warming potential – GWP, or greenhouse gas – GHG, acidification potential, eutrophication potential, human toxicity potential) and resource use (energy use, fuel use, metals use and water). An extensive review of hydrogen base technologies LCA studies and WTW studies can be found in Geerken et al. [19]. This covers 100 papers in the field, not including the PHEV technology. The LEM main report [20] and Lipman and Delucchi [21] have studied several vehicles and countries, including road infrastructure but also not including PHEV. A PHEV detailed analysis can be found in Elgowainy et al. [17] and reviewed in Lipman and Delucchi [21].

These review studies allow concluding that the majority of the research works focus on the fuel life cycle (well-to-wheel, WTW) part of the vehicle life cycle, on energy use and GHG or CO_2 equivalent emissions. Few studies report indicators such as acidification potential (AP), human toxicity potential (HTP) or eutrophication potential (EP). This way the comparison of the alternative vehicle technologies is made by means of an environmental category only, the climate change.

Despite the ISO 14040-series discouraging the use of single scores, they are useful to better compare the environmental performance of two or more products. For example the Ecoindicator 99 method (included in Simparo) considers 11 impact categories related to Human Health, Ecosystem Quality and Resources (see Fig. 3). The impacts are then normalized and weighted to give a single score function of the chosen perspective: hierarchist, egalitarian, or individualist. By nature the method can be dubious due to its inherent subjectivity, but can be extremely useful for comparison purposes.

Environmental scoring methodologies can be based on LCA principles but usually use monetized external damages for each pollutant [22] and usually global warming potential and air quality categories. Again they use single score indicators for comparing vehicles' environmental performances (see Fig. 5 as an example). Other methods used by manufacturers allow comparing only vehicles of the same model. For instance Ford Product Sustainability Index (PSI) allows comparing several Ford models and is based on life cycle assessment (LCA) principles, but chose 8 indicators to compare the sustainability of the vehicles, as shown in Fig. 4. It adds the social and economic dimensions to the products' sustainability.