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A novel approach for global environmental performance evaluation of electric batteries for hybrid vehicles

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A B S T R A C T

The automotive product is increasingly restricted by environmental regulations, including reducing emissions of CO_2 and pollutants in exhaust pipes of vehicles. One solution implemented in the automotive industry are plug-in hybrid electric vehicles (PHEV) that use an electric traction battery. To help vehicle manufacturers in their choice of traction battery from an environmental point of view, a simulation method of environmental impacts generated by the use phase is proposed in this paper. This method takes into account the possible usages of the vehicle and potential developments of electric mix, with the formulation of a constraint satisfaction problem (CSP) solved using constraint programming (CP) techniques. The sensitivity of five parameters is investigated: the electricity mix used to charge the battery, the battery mass, electric consumptions, the autonomy in "all-electric mode", and the share of total travel in "all-electric mode". Power grid is the most differentiating parameter for global warming and PHEV generates less impact if less used in "all-electric mode" on a high carbon intensity power grid. Lastly, CSP acausal modeling makes it possible to process different simulations with the same model.

1. Introduction

The transport sector is one of the main sources of carbon dioxide (CO_2) emissions. To fight against global warming, the European Union has regulated the passenger vehicle CO_2 emission rates, the main greenhouse gas emitted by road transport (European Parliament Council, 2009).

Car makers have responded by seeking solutions to reduce vehicle fuel consumption, including the integration of lightweight materials (composite, aluminum), and the electrification of powertrains. The latter consists in substituting the thermal energy for electrical energy. This substitution can be partial: it is called hybrid vehicles (HEV - Hybrid Electric Vehicle) or hybrid electric plug-in (PHEV - Plug-in Hybrid Electric Vehicle). It can also be total: it is called electric vehicles (BEV - Battery Electric Vehicle). In both cases, it is necessary to be able to store electrical energy in the vehicle. To do so, the use of electric batteries is the current chosen solution of automakers.

In this paper, a methodological approach for the environmental assessment of traction batteries for PHEV or BEV is proposed. The overall objective is to guide design choices during the upstream phases of design in a car maker. However, during the innovation phase, the battery is not fully developed. In addition, the design of batteries is controlled by the battery manufacturers; the car maker defines the design specifications that match with the use he intends to make. The design specifications should answer to a specific use of the vehicle that is controlled by the car manufacturer. Currently, environmental evaluations of batteries are using discrete models of life cycle assessment (LCA): one LCA model parameterization gives one result. For more results, parameterization must be changed, so using LCA during the specification phase or the supplier selection phase would necessitate considerable time.

So an approach has been implemented that helps car makers to simulate the use of an electric battery in order to evaluate its environmental impact and to choose the appropriate battery for its adequate use. The approach is based on the development of a

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specific tool: EcoBatt. A special feature of this research is the Constraint Programming (CP) algorithms for solving constraint satisfaction problems (CSPs) representing the scenario of the use phase. CP and CSPs still found little use for solving ecodesign problems (Larroude et al., 2011; Tchertchian et al., 2013) whereas it is more widespread in preliminary design (Chenouard et al., 2009; Meyer and Yvars, 2012). CSPs in EcoBatt aim to use continuous models of LCA and to simulate multiple usage scenarios of several battery technologies. The purpose of this approach is to simulate the potential environmental impacts generated by multiple usage scenarios, and to deduct environmental optimization scenarios, without developing a model per scenario. The general idea of this article is to show the ability of the tool to simulate different usages of a traction battery with the same CSP model.

In Section 2, the use of electric batteries in the automotive sector is discussed and the chosen performance indicators are introduced. In Section 3, CSP and constraint programming (CP) are briefly presented. In Section 4, the methodological proposal for modeling and simulating the use stage of a traction battery is described. In Section 5, this method is applied to a Li-ion battery to validate and show the potential of the proposed method. Finally, in Section 6, the results are discussed and the paper is concluded with some perspectives.

2. The electric battery and its use in the automotive context

2.1. Environmental issues raised by the use of batteries in a PHEV

As regards the energy use, it is considered what is called the process Well-to-Wheels (WtW), itself decomposed into Well-to-Tank (WtT) and Tank-to-Wheels (TtW). WtT represents all the production processes of energy carrier from the primary energies to making it available to the end user. To illustrate the WtT, let's take the example of electricity. The first step of the WtT is to recognize environmental impacts from the extraction of primary resources (coal, uranium, natural gas …). In the second step, these primary resources are transformed into energy carrier (electricity) with the appropriate equipment (coal-fired, nuclear, wind turbine, etc.). The energy carrier is distributed to end users in the third step (power grid, charging station); this also includes online losses of the routing to the final consumer.

TtW is to convert the energy carrier in the final energy, i.e. in the present case into mechanical energy to propel the vehicle. While in the case of an electric power, no impact is associated with this step, a vehicle such as hybrid vehicle plug-in, which uses the combustion of a fossil fuel, emits carbon dioxide and other pollutants (nitrogen oxides, carbon monoxide, sulfur dioxide, hydrocarbons and particles of matter). These emissions have an impact on the environment and must also be taken into account.

PHEV batteries are loaded onto the power grid of the country of use. The all-electric mode, also known as “zero emission vehicle” mode (ZEV), allows the driver to drive without the thermal engine. When converting electrical energy into mechanical energy, there is no material emission. In contrast, production of energy carrier is a source of environmental impacts, and is different from one country to another, for example Polish, Portuguese and French electric mixes in Faria et al. (2013), or one year to another, for example current and 2030 electric mixes in Girardi et al. (2015), or 2050 in Tagliaferri et al. (2016). It depends on the electricity mix adopted by countries whose primary energy can be coal, natural gas, uranium, renewable, etc. Therefore, different electric mixes must be taken into account; in this paper, the French (FR) and the average Europe of 27 (EU-27) electric mixes are used.

The use of auxiliary systems may increase the power consumption of the vehicle. It can be estimated for example that the use of air conditioning in a BEV can decrease its autonomy by 33% (Lee et al., 2013). The BEV potential overconsumption of energy has been modeled and tested with air conditioning.

Battery manufacturing is not neutral on the environment. Current technologies solicit a large number of rare and precious metals. Nordelöf et al. (2014) note in fact that the manufacturing of cells, and in particular the processing of the active ingredients, is the most energy-intensive phase in the battery manufacturing process. Although this research focuses on the modeling of the use phase and its optimization, manufacturing step is taken into account.

Finally, battery end of life is still poorly controlled: the valuation process is poorly understood. However studies have shown the potential for environmental benefits generated by recycling, especially on energy consumption (Dunn et al., 2012). Similarly to manufacturing, the end of life is taken into account in this paper.

2.2. Specifications for the environmental evaluation of batteries

It is thus assumed that, under certain conditions such as recharging batteries on a low-carbon power grid, the electrification of powertrains can cause the reduction of the environmental impacts of the use stage (through actions focused on consumption and vehicle emissions) over the impacts of vehicle manufacturing phase that increase in proportion. In other words, the existence of a risk of a transfer of pollution should not be underestimated.

The main objectives of the paper lie in the development of a decision support method for avoiding the transfers of pollution. It should help to guide the traction battery design choices during the upstream development phases. Several uses of batteries should be compared from an environmental point of view, taking into account changes in electrical mix, and the anticipated uses of the vehicle.

The method is based on a life cycle approach and on multiple criteria. This is however devoted to the proposal of an advanced modeling of the use phase. The end of life stage is also considered, and the manufacturing step is based on a simplifying assumption. The environmental impact indicators used in this article are described in Table 1:

The method is designed based on a literature review of environmental assessments of batteries from which the influential parameters are deducted. From these data, a model is proposed and tested. This model is based on the process WtW. Environmental impacts from WtT and TtW of both fuel and electricity are related to the mass of the battery. Moreover, the ZEV mode ratio over the life cycle is based on an equation.

3. Modeling and solving with constraint satisfaction problems

In this section, CSP and classical CP algorithms used within Ibex C++ library (IBEX library homepage, 2014) are explained.

A CSP is formalized as follows (Rossi et al., 2006): this is a triple (X, D, C) such that:

- $X = \{x_1, x_2, \ldots, x_n\}$ is a finite set of variables of the problem;
- $D = \{d_1, d_2, \ldots, d_n\}$ is a finite set of domains of variation for variables in X such that:

$$\forall i \in \{1, \ldots, n\}, x_i \in d_i \quad (1)$$

- $C = \{c_1, c_2, \ldots, c_p\}$ is a finite set of p constraints of the problem. A constraint is defined as any relation that restricts values of variables. It can be any type of mathematical relationships (equation, inequality, etc.) as well as explicit relations between variable values like tuples in a database.