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Life cycle energy optimisation: A proposed methodology for integrating environmental considerations early in the vehicle engineering design process

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ABSTRACT

To enable the consideration of life cycle environmental impacts in the early stages of vehicle design, a methodology using the proxy of life cycle energy is proposed in this paper. The trade-offs in energy between vehicle production, operational performance and end-of-life are formulated as a mathematical problem, and simultaneously balanced with other transport-related functionalities, and may be optimised. The methodology is illustrated through an example design study, which is deliberately kept simple in order to emphasise the conceptual idea. The obtained optimisation results demonstrate that there is a unique driving-scenario-specific design solution, which meets functional requirements with a minimum life cycle energy cost. The results also suggest that a use-phase focussed design may result in a solution, which is sub-optimal from a life cycle point-of-view.

1. Introduction

A major challenge in vehicle design today is to simultaneously meet the transport needs of society while minimising energy use and its associated environmental impacts. Efforts to reduce the environmental impacts of transport vehicles have been increasing over the past few decades. However, this challenge cannot be met by further extrapolating existing vehicle technologies alone. New step-changing solutions are needed. Finding new solutions, however, requires balancing a large number of economic, environmental and technical parameters. These parameters interact with each other in often quite complex and conflicting ways. The aim of this current work is to propose a new conceptual approach in which these trade-off considerations can be balanced so as to enable the emergence of new vehicle designs that have significantly lower environmental impacts.

1.1. Targeting vehicle architecture to reduce environmental impacts

Much of the effort to improve the environmental performance of vehicles has focussed on reducing the significant energy consumption during the use phase of the vehicle's life cycle (Nemry et al., 2008; Hawkins et al., 2013; Castro et al., 2003; Schweimer

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and Levin, 2000). In the case of cars, for example, the use phase contributes in the order of 80–90% of the life cycle energy demand, with production contributing 5–10% and end-of-life less than 5% (Nemry et al., 2008; McAuley, 2003; MacLean and Lave, 1998; Mayyas et al., 2012a). Mostly a combination of three basic strategies have been followed (Samaras and Meisterling, 2008) that are illustrated with the help of Fig. 1 (a) improving transport efficiency (i.e. reducing vehicle movement, $W_{Transport}$), (b) improving engine efficiency (i.e. increasing $E_{Transmission}/E_{Fuel}$), or by (c) switching to energy sources that have less environmental impacts (e.g. bio-based fuels or clean electricity, E_{Fuel}) (European Environment Agency, 2007; Sweeting and Winfield, 2012). These strategies, however, target only part of the total energy-use picture for a vehicle system over its life cycle (González Palencia et al., 2012). The overall energy profile of a vehicle is determined not only by the efficiency of the energy supply and conversion through the fuel, motor, transmission and operation, but also by the efficiency of the vehicle architecture over its complete life cycle.

Potentially large gains are achievable from rethinking the vehicle architecture (i.e. the designed structure of the vehicle and its complex emergent attributes) with a life cycle perspective. During the use phase, significant energy is required to overcome the dynamic losses (from aerodynamic drag, acceleration inertia, rolling resistance) of the vehicle itself, $E_{Loss,V}$. These account for approximately 50–80% of the fuel consumption depending on the vehicle and drive-cycle considered (Nemry et al., 2008; Koffler and Rohde-Brandenburger, 2010). The corresponding energy demands are intrinsic to the vehicle system's architecture, as a function of its material, structure and form, and have knock-on implications for the upstream energy supply. The vehicle architecture, as such, also offers an important starting point for reducing energy consumption and so environmental impacts (Knittel, 2011). However, changes to the vehicle architecture for use-phase gains must be balanced against their effect on production and end-of-life impacts.

1.2. The challenge of integrating environmental considerations

A redesign or rethink of the vehicle architecture offers a greater

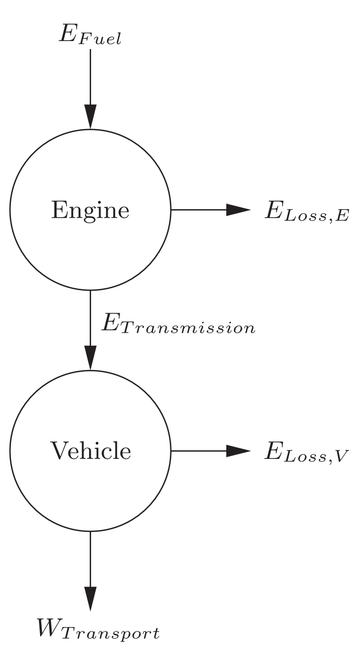

Fig. 1. Vehicle use-phase energy flow.

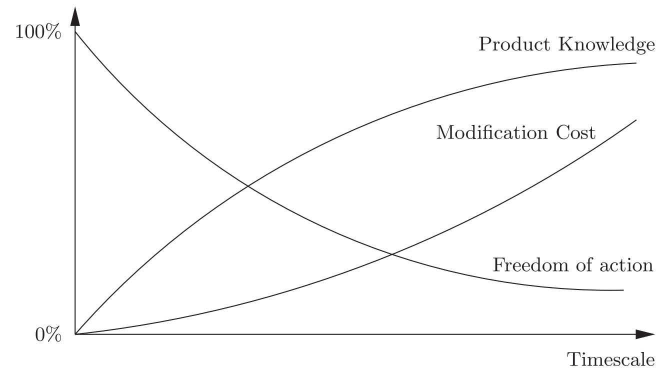

Fig. 2. The design paradox.

potential to reduce its environmental impacts than a repair or refinement of the existing architecture (as described by the Charter's 'four-step model' (Charter and Chick, 1997; Thompson and Sherwin, 2001)). However, modifying the existing architecture or designing radically new architectures to better incorporate these considerations presents a considerable challenge. Vehicle designers are faced with a design paradox (Lindahl and Sundin, 2013), as illustrated in Fig. 2, in which the freedom to design improved vehicle solutions early in the design process is accompanied by an inability to assess what these solutions will yield, while knowledge of the shortcomings in a vehicle design late in the design process is accompanied by an inability to make significant improvements. For established products such as vehicles, this paradox is mirrored in the conservative and late-stage nature of the conventional design process (Hodkinson and Fenton, 2000a; Minai et al., 2006). As the next generation of vehicles starts from the previous generation,[1] environmentally motivated changes to vehicle sub-systems may be characterised as repair or refine strategies of the existing architecture (Charter and Chick, 1997).

Modern vehicle architecture has being evolving gradually for more than 100 years through a traditional industrialised design process that is fundamentally top-down in nature (Minai et al., 2006). This means that the many functional requirements of the vehicle are decomposed into many levels of sub-functions, until a level is reached where the sub-functional task may be realised using available solutions, such as engines, chassis, etc. At this level, sub-functions are assumed to be independent of each other, and are designed separately. A concept solution is developed, refined and optimised for the sub-function in question. The sub-functional solutions or sub-solutions are then assembled to perform higher-level functional requirements.

At present, environmental considerations influence the design of technical sub-functional solutions through constraints (such as the prohibition of toxic materials (European Parliament and Council of the European Union, 2000)) or via a proxy (as in lightweight design (Hodkinson and Fenton, 2000b; Ermolaeva et al., 2004)). Furthermore, the environmental impacts of alternative solutions are assessed through life cycle assessment (International Organization for Standardisation, 14040 and International Organization for Standardisation, 14044) and this can be used as part of a down-selection process (Poulikidou et al., 2015). However, such eco-design methods have not been directly integrated into numerical optimisations, which often take place over thousands of

[1] There are cases such as the Chevrolet Volt, Nissan Leaf, BMW i3, Toyota Prius, Volkswagen XL1 that have a higher degree of originality but these are the exceptions that prove the rule.