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Conventional, hybrid and electric vehicles for Australian driving conditions – Part 1: Technical and financial analysis

R. Sharma [a], C. Manzie [b,*], M. Bessede [b], M.J. Brear [b], R.H. Crawford [c]

[a] School of Information Technology and Electrical Engineering, The University of Queensland, Australia
[b] Department of Mechanical Engineering, The University of Melbourne, Australia
[c] Faculty of Architecture, Building and Planning, The University of Melbourne, Australia

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ABSTRACT

This paper is the first of a two part study which quantifies the economic and greenhouse performance of conventional, hybrid and fully electric passenger vehicles operating in Australian driving conditions. This first study focuses on the total cost of vehicle ownership. Two vehicle sizes are considered, Class-E and Class-B, which bracket the large majority of passenger vehicles on Australian roads.

Simulation models of baseline production, conventional vehicles are first developed. These models are then systematically altered to obtain the fuel and/or electricity consumption of equivalent mild hybrid, parallel hybrid, plug-in hybrid and fully electric vehicles. The total operating cost of each vehicle is then calculated, and the vehicle production costs are estimated by decomposing the vehicles into their major constituent parts. This enables the total cost of vehicle ownership to be estimated, taking particular account of variations in fuel, electricity and battery prices.

1. Introduction

Increasing the degree of passenger vehicle electrification has the potential to reduce greenhouse gas emissions, improve urban air quality and reduce consumption of liquid fuels simultaneously. However, partial or total vehicle electrification typically comes at a purchase price premium, with other considerations such as vehicle range and charging times for fully electric vehicles also potential purchase disincentives (Boulanger et al., 2011). Offsetting the higher purchase price, partially or fully electrified vehicles reduce running costs by reducing or eliminating the on-board consumption of liquid fuels. However, for consumers the choice is often not clear as to which vehicle configuration is the most economic over the duration of its ownership, thus necessitating a lifetime cost-analysis for the different vehicle configurations. Worldwide, there is recognition of the uncertainty in life cycle costs as reflected in studies performed for American (Brooker et al., 2010; O'Keefe et al., 2010; Simpson, 2006; Becker et al., 2009; Lee and Lovellette, 2011) and European driving conditions (Douglas and Stewart, 2011; van den Bulk and Hein, 2009). The combination of Australian energy production and driving characteristics mean outcomes of these studies may not be directly transferrable in either economic or environmental terms.

Recognition of this need has resulted in some studies being undertaken. The topics investigated include an estimation of the uptake of the different vehicle configurations in the Australian state of Victoria (Kinghorn and Kua, 2011) and assessment of the economic viability and potential greenhouse gas savings of plug-in hybrid electric vehicles in the Australian state of New South Wales (Feeney, 2009). However, these studies do not develop or utilize explicit vehicle powertrain simulation

* Corresponding author.
E-mail address: manziec@unimelb.edu.au (C. Manzie).

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models. In addition, the vehicle configurations are not decomposed into constituent parts to enable high fidelity component-wise cost estimation.

The benefits of vehicle electrification can be examined in two related problems. On one hand, the cost of vehicle ownership is of importance to the consumer, while greenhouse gas emissions are relevant to the community. This paper addresses the former by estimating the total cost of ownership for different vehicle types under a range of possible scenarios, while a companion paper (Sharma et al., in press) addresses the latter. Together these two works attempt a systematic assessment of vehicles with increasingly electric powertrains for Australian driving conditions.

The total costs of ownership (TCO) are calculated by estimating the purchase price, lifetime running costs and the resale values, and is coupled with a net-present-value (NPV) analysis to account for depreciation. To conduct these studies, the base vehicles are selected to be commercially available Class-B and Class-E sedans with internal combustion engines. Class-E sedans constitute 15–20% of the new car sales in Australia (Federal Chamber of Automotive Industries, 2011), and are heavily represented by two makes with very similar specifications and pricing: the Ford Falcon and the Holden Commodore, representing around 33% and 47% of vehicle sales in this class over the past 3 years respectively. The 4-L, 6-cylinder, 1800 kg Ford Falcon is selected as the base vehicle in this study as detailed experimental data over the legislative drive cycle was available to the authors.

The base Class-B sedan chosen was the 1.6 L, turbocharged four-cylinder diesel, 1100 kg Ford Fiesta ECOnetic, as this represents one of the highest fuel economy vehicles in Australia, and this car size accounts for 35–40% of Australian passenger vehicle sales (Federal Chamber of Automotive Industries, 2011). These two vehicle classes bracket the large majority of vehicles on road, and so trends in their electrification can be used to infer similar trends in vehicles of intermediate size.

The total cost of ownership for different vehicle configurations is evaluated under scenarios which include possible variations in the fuel and electricity prices to establish the most cost effective vehicle type. Furthermore, since there is significant uncertainty in the price of the batteries, different costing scenarios which favour or penalise vehicle electrification are presented and analysed. A cost-equivalence analysis is also conducted to establish different combinations of the fuel, electricity and battery prices that result in cost parity of the conventional vehicle with its electric variants within the first 3–5 years of owning a particular electric or hybrid vehicle type.

2. Modelling energy usage

The objective of this section is to estimate the fuel and electricity usage for different vehicle types. This is accomplished in two steps. In the first step, commercially available conventional vehicles are chosen as the base vehicles and their simulation models are developed and validated using legislative drive cycles. These conventional vehicle simulation models are sequentially altered to obtain simulation models of the electric variants of the conventional vehicles with comparable performance.

The simulation models are developed using PSAT (Powertrain System Analysis Toolkit). Upon validation of the modelling procedure, the components of the Class-E internal combustion engine vehicle (the 'conventional vehicle', CV) model are altered to develop models with increasing levels of electrification to successively obtain mild, parallel, series and plug-in hybrid electric vehicles as well as a full battery electric vehicle (BEV). In addition, a BEV variant of the Class-B vehicle is also modelled.

2.1. Modelling and validation of conventional vehicles

The PSAT library does not contain a component-based model of a 2010 internal combustion engine based Ford Falcon vehicle, and consequently one was created using the Ford Taurus as the base vehicle with only minor changes required to meet the Falcon specifications. These included modifying the component files corresponding to the engine (including the engine fuel consumption map and the physical characteristics of the Falcon engine) and the gearbox (the 2010 Falcon models use a ZF 6HP26 six speed automatic gearbox). Additional minor modifications are also required including electrical accessories load, exhaust after-treatment power and the equivalence ratio. All other components in the existing model were of minor difference to the Falcon vehicle for which transient dynamometer test results were available.

In Australia, the legislative fuel consumption and emissions requirements are tested by operating the vehicles over the New European Drive Cycle (NEDC). The Class-E CV model was simulated over the NEDC and the transient simulation responses are compared against the experimental data obtained from Ford of Australia, with both datasets presented in Fig. 1. The simulated responses for both engine torque and instantaneous fuel consumption exhibit some high frequency dynamics that are not present in the experimental data, possibly due to a combination of the gear change strategies or experimental sampling rate. The lower initial fuel consumption is due to the absence of a cold start model in the PSAT simulation. This leads to roughly 5% lower cumulative fuel consumption, however there is good general agreement between the experimental and simulated data. The simulated fuel consumption over the cycle is 9.4 L/100 km, which is close to the reported consumption of 9.9 L/100 km, and indicates the simulation model is sufficiently accurate for the financial analysis in this paper.

A similar approach was used to develop a Class-B CV model, whereby existing components close to the ECOnetic specifications are selected and modified slightly to meet the available power, fuel economy and emissions specifications. In particular, the Ford Focus PSAT model components apart from the engine are chosen and the parameters in their initialization