

An Economic and In-Service Emissions Analysis of Conventional, Hybrid and Electric Vehicles for Australian Driving Conditions

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ABSTRACT

Hybrid and fully electric vehicles are becoming more common as a response to rising fuel prices and greenhouse considerations. While the benefits of electrification on urban air quality have been studied quite widely, financial assessments of the various alternative vehicle forms are less common, particularly for Australian driving conditions. The aim of this paper is therefore to identify the scenarios under which different vehicle configurations are attractive to the vehicle owner. A Class-E conventional vehicle is compared with full-electric, plug-in hybrid, parallel hybrid, series hybrid and mild hybrid electric vehicle configurations. A simulation model of a conventional internal combustion engine based large sized car is developed and validated against experimental data. The conventional vehicle model is then systematically altered to obtain its increasingly electric variants. The fuel consumption and greenhouse gas emissions are simulated on the legislative NEDC drive cycle and the more representative Australian Urban Drive Cycle (AUDC). The outcomes of these tests are used to estimate the total cost of ownership and in-service emissions, thus allowing the cost of emissions mitigation to be approximated for the different vehicles.

Different scenarios are considered for the pricing of energy and major powertrain components. This provides a baseline assessment based on current prices and projections, as well as 'electrification favorable' and 'electrification unfavorable' scenarios. The impact on vehicle emissions of significant penetration of renewable energy into the Australian electricity grid is also considered.

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INTRODUCTION

Vehicle electrification is currently viewed as a potential solution for more sustainable future transportation as it has the capability to reduce dependence on fuel consumption and also, depending upon the manner by which electricity is generated, mitigate greenhouse gas emissions.

From the consumer perspective, a major deterrent to choose an electric or hybrid electric vehicle over a conventional internal combustion engine based vehicle is the price premium [8], with reduced vehicle range also an important consideration. On the other hand, vehicle electrification typically reduces the vehicle running costs (through the reduced or no use of crude oil based fuels) which have the effect of offsetting the initial price premium to a certain extent. 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. Recent studies attempting to evaluate the lifetime cost of different options include [9], [19], [24], [7], [15] for US driving conditions and [11], [25] for European driving conditions.

The combination of Australian energy production and driving characteristics mean outcomes of these existing studies may not be directly transferrable. Recognition of this gap has resulted in some preliminary studies. These include an estimation of the uptake of the different vehicle configurations in the Australian state of Victoria [14], and assessment of the the economic viability and potential greenhouse gas savings of plug-in hybrid electric vehicles in the Australian state of New South Wales [12]. The major limitation of these studies is that the conclusions drawn are primarily based on the economic data which do not develop or utilize explicit vehicle powertrain simulation models that are essential to accurately establish the vehicle in-service

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

The aim of this paper is to evaluate the lifetime ownership costs of vehicles with increasingly electric powertrains for current and near-term Australian driving conditions, thus establishing the most cost effective vehicle configuration. To conduct these studies, a commercially available internal combustion engine based Class E sedan, the 4-litre, 6-cylinder, 1800kg Ford Falcon is selected as the base vehicle, given that this class of vehicle represents 15-20% of passenger vehicles sold annually in Australia [3], and detailed experimental data over the legislative drive cycle was available. Further, work that is yet to be published by the authors shows the relative economics of electrification is most favourable in vehicles of this size.

One of the main features of this work is the use of accurate powertrain simulation models to establish the vehicle fuel and electricity usage and consequently vehicle in-service costs. This is an improvement over several existing studies which heavily rely on the economic data and fail to capture the variations in the in-service costs with the variations in the powertrain configurations. The simulation models of the conventional vehicle and its electric variants are developed using Argonne National Laboratory's (ANL) Powertrain System Analysis Toolkit (PSAT) software using representative drive cycles to predict the fuel and electricity consumption of the modelled vehicles for Australian driving conditions. The fuel and electricity consumption are then utilized in the calculation of the vehicle running costs.

The total cost of ownership (TCO) is then calculated in net-present value terms by estimating the purchase price, lifetime running costs and the resale values. Different scenarios for both hardware and energy pricing are then considered, along with the impact on in-service emissions of moving to more renewable energy. These outputs are then used to determine the cost of mitigating the in-service greenhouse gas emissions for the various powertrain options under the different conditions.

ESTIMATION OF THE IN-SERVICE ENERGY USAGE AND EMISSIONS

The objective of this section is to develop a reasonable estimate of the fuel and electricity usage and in-service emissions for different vehicle configurations. This is accomplished in two steps. In the first step, a commercially available conventional vehicle is chosen as the base vehicle and its simulation model is developed. Then in the second step, the conventional vehicle simulation model is successively altered to obtain models of its electric variants with comparable performance. These simulation models are then used to estimate the energy usage and emissions.

Upon satisfactory validation of the modelling procedure, the components of 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 (HEV) as well as a full battery electric vehicle (BEV).

MODELLING OF BASE VEHICLE

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). In addition, minor modifications are also required with the variables including electrical accessories load, exhaust after-treatment power and the exhaust equivalence ratios. All other components in the existing model were of negligible difference to the Falcon vehicle for which transient dynamometer test results were available to the authors. In Australia, the legislative fuel consumption and emissions requirements are obtained over the New European Drive Cycle (NEDC). The CV model was simulated over the NEDC and the transient simulation responses are compared against the experimental data obtained from Ford of Australia to validate their accuracy. The simulated fuel consumption is recorded as 9.4 l/100km, which is close to the reported consumption of 9.9 l/100km, and gives a degree of confidence in the simulation model accurately predicting the fuel consumption for other driving cycles.

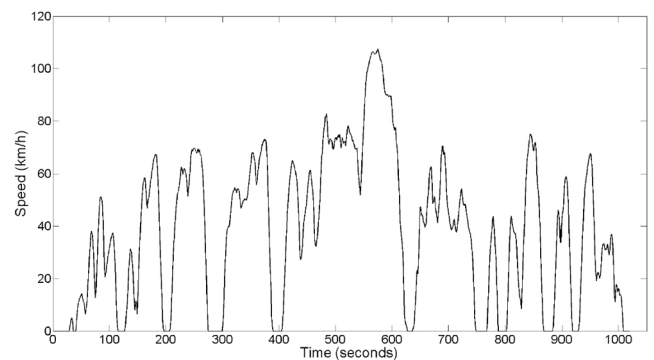


Figure 1. Australian Urban Drive Cycle

While the legislative drive cycles have been used to predict operational costs in other studies, these typically under-represent real world fuel consumption in urban settings and have led to the development of other drive cycles which typically have higher fuel consumption. Examples of real world cycles include the US Federal Test Procedure (FTP-75), the Australian Urban Drive Cycle (AUDC) [17] and the Common ARTEMIS Drive Cycle (CADC) [6]. Since this paper is focussed on Australian driving conditions, the AUDC (Figure 1) will be used to estimate the fuel and

electricity consumption and in-service emissions, of all vehicles considered in this paper.

MODELLING HYBRID AND ELECTRIC VEHICLES

Partial and full electric variants equivalent to the CV modelled in the previous section do not yet exist in the marketplace, so it is necessary to develop realistic models that do not unduly penalise or advantage a specific technology. The approach used in this study is to set operational assumptions and constraints on the vehicle configuration as listed in Table 1, iteratively select the hardware (e.g. motor and engine sizing) and then minimise an economic cost metric to find the battery sizing.

In estimating the economic cost over the vehicle lifetime, there are several general operating assumptions that need to be made. Firstly, the vehicle ownership duration is set to be 10 years based on the average age of passenger vehicles in Australia (page 5, [1]). Secondly, while the vehicle driving behaviour is described by the AUDC, the annual distance travelled is 15,000km over each year of ownership [2]. The baseline fuel (gasoline and diesel) and off-peak electricity prices were assumed to be the average over the 10-year horizon. There is also large uncertainty in the mass production vehicle battery pricing with projections ranging from \$260 per kWh to \$1800 per kWh (see e.g. the summary in Table 13 of [14]), consequently a baseline value was taken to be \$800 per kWh in keeping with the approach used in [9].

Table 1. Assumptions used in developing vehicle models

General	(1) Vehicle lifetime km travelled: $D = 150,000$ on AUDC (2) Base battery price: $P_B = \$800/\text{kWh}$ (3) Fuel price: $P_{fuel} = \$1.4/\text{Litre}$ (4) Electricity price: $P_{elec} = \$0.175/\text{kWh}$ (5) CV vehicle mass = 1800 kg (6) CV range = 600 km
BEV	(1) Battery technology: Li-ion (2) Minimal SOC: 20% (3) Range: 160 km (4) Vehicle meets CV drivability
Plug-in	(1) Battery technology: Li-ion (2) All Electric Range: 60 km (3) Controller strategy: Engine on-off (4) Min SOC: 25%, Max SOC in hybrid mode: 30% (5) Vehicle meets CV drivability
Series	(1) Battery technology: Li-ion (2) Controller strategy: Engine on-off (3) Min SOC: 60%, Max SOC: 70% (4) Vehicle meets CV drivability
Parallel	(1) Battery technology: Li-ion (2) SOC target: 65% (3) Engine and motor power equivalent (4) Vehicle meets CV drivability
Mild	(1) Battery technology: NiMH (2) SOC target: 65% (3) Maximum motor power: 20kW

The details of the model development for each vehicle type are now given in the following paragraphs, starting from the fully electric vehicle configurations.

• **BEV:** The main requirements in developing the BEV model is to choose the battery size and motor to meet range and drivability requirements respectively. The choice of the electric motor is governed by the torque and power rating to resemble the driving performance specifications of the base CV, and consequently a 145kW /400Nm motor is required to match drivability with the base CV.

In choosing the battery size, it is necessary to set a range requirement. More than 90 % of the vehicles in Australian cities cover less than 160 km during their daily commuting [21], which is equivalent to the 100 mile range often quoted as necessary for the US market. Consequently, the battery is to be sized to achieve a range of 160 km with an 80 % depth of discharge by iteratively running the PSAT BEV model repeatedly over the AUDC until the range and discharge criteria are met. The resulting battery capacity is 34 kWh.

• **Plug-in and series HEVs:** The plug-in and series hybrid models are both assumed to have a similar powertrain configuration, whereby the electric motor is used to propel the vehicle and the engine is only used as an onboard generator. Since the electric motor is solely responsible for propulsion, the drivability conditions ensure that the electric motor for both plug-in and series vehicles must be the same size as in the BEV, i.e. 145 kW.

The plug-in hybrid operates in a charge depletion mode until the battery state of charge meets some minimum limit. Once the minimum limit is reached the vehicle enters and remains in a charge sustaining mode, where the engine switches on and remains at maximum efficiency until an upper state of charge level is reached at which point the engine switches off. The battery then discharges until the minimum level is reached again. For the series hybrid, there is no initial charge depletion strategy available, and the vehicle starts in a charge sustaining mode.

The choice of the plug-in battery pack is primarily governed by the all electric range (AER) which is covered in the charge depleting mode. In this study, the AER is specified to be 60 km based on the daily distances travelled in Sydney by 80% of commuters [21]. The battery capacity, N_B , which meets the AER requirement might require some adjustment to ensure that the fuel consumption during the charge sustaining mode is such that the overall operating cost is minimized. To ascertain N_B , the utility factor, u , which represents the fraction of time spent in charge depletion mode according to SAE J1711 standard is estimated at 0.79 [21]. The estimate of the electricity consumption, C_e in kWh/km while running in charge depletion mode, the vehicle is run through a drive cycle with an initial state of charge at 100%, while to estimate the fuel consumption, C_f in litres/km during charge sustaining or hybrid mode the simulation is repeated with an initial state of charge equal to the minimum limit. Both of these figures are functions of the battery capacity, N_B .

For a given lifetime distance travelled, D , and battery, P_B , electricity, P_{elec} , and fuel, P_{fuel} , prices respectively, a cost