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Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: An Australian case study

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Abstract

The transit authority in Perth, Western Australia, has put several alternative fuel buses, including diesel-electric hybrid and hydrogen fuel cell buses, into revenue service over the years alongside conventional diesel and natural gas buses. Primary data from this fleet is used to construct a Life Cycle Cost (LCC) model, providing an empirical LCC result. The model is then used to forecast possible scenarios using cost estimates for next generation technologies. The methodology follows the Australian/New Zealand Standard for Life Cycle Costing, AS/NZS 4536:1999. The model outputs a dollar value in real terms that represents the LCC of each bus transportation technology. The study finds that Diesel buses deliver the lowest Total Cost of Ownership (TCO). The diesel-electric hybrid bus was found to have a TCO that is about 10% higher than conventional diesel. The premium to implement and operate a hydrogen bus, even if industry targets are attained, is still substantially greater than the TCO of a conventional diesel bus, unless a very large increase in the diesel fuel price occurs. However, the hybrid and hydrogen technologies are still very young in comparison to diesel and economies of scale are yet to be realised.

Keyword: Hydrogen; Hybrid bus; Transport energy; Life cycle cost; Natural gas; Transit economics

1. Introduction

Global interest in alternative fuels has gained great momentum over recent years, with many viable options being developed and demonstrated, and without the emergence of any clear *silver bullet* solution. A report by Blackburn (2014), published by the National Roads and Motorists' Association (NRMA), clearly indicated the great apprehension in Australia regarding liquid fuel security and the important risks that result from the current lack of fuel diversity, particularly for transport energy.

There are many options which Australia could explore to address this concern, and life cycle assessment is an ideal tool to evaluate these competing technologies. Many researchers have published studies that compare the competing transport technologies. The conclusions vary due to differences in methodology, primary data sources, geographical region, temporal factors, technological advances, and other differences. There is a wide range of results, with no shortage of arguable conclusions, and the debate continues to determine which vehicle and fuel technologies will have a role in the transportation system of the future.

Several aspects of the Australian context are unique. The country has vast resources of both renewable and non-renewable energy, but has experienced a decline in oil production and has become a net importer of transport fuel. As this oil trade deficit widens, so does the energy security risk increase, as does the drive to develop indigenous transportation energy resources. In terms of vehicle choice, the population is sparsely settled which compels people to use vehicles that are capable of long distance driving, reducing the market for battery-only vehicles while expanding the market for hybrid vehicles. These characteristics make the Australian market particularly attractive for the development and deployment of innovative renewable fuels and sustainable transportation technologies (Ally et al., 2015).

The transit authority in Western Australia, Transperth, has put several alternative fuel buses into revenue service including Hydrogen Fuel Cell Bus (HFCB) and diesel-electric hybrid bus technologies, alongside conventional diesel and Compressed Natural Gas (CNG) buses. Life Cycle

Assessment (LCA) modelling from operational data on diesel, CNG and Hydrogen Fuel Cell Bus (HFCB) data in Perth provided an early environmental and energetic comparison of the technologies (Ally and Pryor, 2007).

In parallel with the LCA, the economic context can be explored using Life Cycle Costing (LCC) methodologies. The models can be based on operational data from Transperth's vehicle fleet providing an empirical LCC result, and can be extrapolated into the future using cost estimates for next generation technologies. The inclusion of economic factors provides the commercial data for long-term fleet planning to be explored, as all capital and operating costs are brought within the scope of the study. As the market for diesel vehicles is far more mature than hybrid or fuel cell vehicles, and far larger than the natural gas vehicle market, there is an opportunity to explore how alternative fuel technologies might benefit from economies of scale.

A common definition for the different vehicle technologies is presented in Table 1.

The modelling exercise reported in this paper is applied to a discrete case study – the Perth Central Area Transit (CAT) bus fleet. The CAT buses operate out of a dedicated, centrally-located depot in Perth. The fleet currently consists of a mix of diesel and CNG buses. A single diesel-electric hybrid bus was introduced to the fleet in 2012, and the evaluation of the hybrid concluded in late 2014.

Life Cycle Costing (LCC) provides a dollar value that represents the life cycle cost of each bus transportation technology that is being considered. This is determined using the sum of the expenses for acquisition, operation, maintenance and disposal of each bus technology system. The LCC results can provide an understanding of the economics of the bus transportation technologies, which will provide decision-makers with a comprehensive set of information upon which technology development and fleet planning decisions can be made.

The application of LCC methods is particularly relevant for buses because revenues are not considered in the LCC methodology. Costs are the most relevant aspect upon which to compare bus technologies for fleet selection and fleet planning purposes. Like the LCA, the LCC results can be compared by normalising the data to a common functional unit. The buses included in the LCC for a future Perth CAT fleet are assumed to maintain the current capacity of 65 passengers. Since the passenger carrying capacity is the same for all buses, the LCC result can be compared in terms of the Total Cost of Ownership (TCO). If, in the future, buses are included in the model which have a different carrying capacity, then the LCC result would need to be expressed in a normalised functional unit such as dollars per passenger-kilometre.

Economic comparisons of alternative bus technologies were recently reviewed by Ally et al. (2015) in an article which canvasses several relevant studies of hybrid, hydrogen and battery-only buses including publications by the Fuel Cells and Hydrogen Joint Undertaking, 2012; Zaeta and Madden, 2011; Cooney, 2011; McKenzie and Durango-Cohen, 2012 ; Lajunen, 2014. The fuel cell bus evaluation programs managed by the National Renewable Energy Laboratory (NREL) in the United States are summarised in an annual status report, which includes tabulated cost data, covering all the bus projects that are monitored by NREL (Eudy and Gikakis, 2013). The results are derived from many studies and publications which have been conducted by NREL over the course of multiple fuel cell bus demonstration programs including the very thorough series of reports produced by Eudy and Chandler on each project in the United States, and by Eudy and Post (2014) on the Canadian project in Whistler. Methodologies for hydrogen infrastructure costs which used buses in London as a case study were published by Shayegan et al. (2006). The cost of hydrogen infrastructure for 12 different on-site hydrogen refuelling pathways, and 18 different off-site refuelling pathways, were evaluated based on primary data and methodologies that were developed to model the unit cost of hydrogen based on uptake to fuel the London bus fleet. This work was built upon with a further publication by Shayegan et al. (2009) which examined the effects of hydrogen demand combined with rates of technology development and fuel prices simultaneously, out to 2025.

The costs of CNG buses can be difficult to find because they are not as common as diesel buses. The fuel efficiency of natural gas buses is often lower than conventional diesel buses across a range of duty cycles (Wayne et al., 2004). However, natural gas buses currently comprise approximately 50% of the Transperth bus fleet, and are therefore an important inclusion for a bus fleet analysis centred on Perth. A comparison of CNG, diesel and diesel-hybrid bus technologies in the United States

(Richardson, 2013) presents comparisons of fuel economy, vehicle cost, and other ancillary costs required to run CNG buses such as natural gas compression and maintenance facility modifications. The diesel-hybrid does not require different facilities or refuelling infrastructures, but does encounter additional costs in the forms of battery replacement and maintenance personnel training, which are also accounted for.

Within Australia the numbers of hybrid buses are relatively low, and very little on-road performance information is available. Transport for New South Wales released a study on a hybrid bus trial that was conducted in Sydney (Williamson, 2012), which used a discounted cash flow analysis and found that the hybrid bus would deliver a negative economic outcome despite a 15% improvement in fuel consumption over the reference diesel buses. The authors calculated that an 88% reduction in the capital cost of the hybrid would be required to break-even with a traditional diesel bus. However, the authors acknowledge that this trial was a relatively early deployment of hybrid bus technology and that there is much room for improvement.

Nylund and Koponen (2012) produced a very detailed study which reported on an international collaboration that collected and analysed measured data from 21 different bus technologies, as well as the upstream fuel production processes, to produce an environmental and economic comparison. Comparing hybrid bus technology to standard diesel technology, the authors find that hybrids are not cost competitive and would reach breakeven if diesel prices increased by 50% over their baseline assumptions and if the capital cost premium for a hybrid reduced by around 35%. Hydrogen buses are not included in the test data set, and are discussed in an appendix of the report.

Grütter (2015) published a comprehensive summary of real world financial performance of large operational hybrid bus fleets, including hybrid bus fleets in New York, London, Bogota, Zhengzhou, several German cities, and other trials. The author assesses all cost factors that are used to determine a Life Cycle Cost, and the results are reported in terms of the *profitability* of an investment in hybrid buses which is expressed as a payback period. The large-fleet data that is collated and compared in this document is a valuable reference for international hybrid bus fleet comparison. The author reports that there are significant variations in capital costs for hybrids between different manufacturers, and while this is a major factor in determining profitability, the overall finding is that the premium can be paid back in 5–6 years if diesel prices are above USD $1.10/L and annual distance travelled exceeds 60,000 km.

Hybrid, hydrogen and other alternative technologies are developing at a rapid pace and one can observe a general a transition towards economic competitiveness occurring over time amongst the references cited above. Upon detailed analysis one also finds that there are many factors that can affect Life Cycle Costs, which can be significantly different between the studies. Factors such as fuel price, price premium for alternative technologies, duty cycle characteristics in each city including average speed and annual distance travelled, and the conventional technologies with which alternative bus technologies are being compared, can all dramatically affect the outcome of an LCC analysis.

There is an ongoing need for advances in LCC results, using methodologies with full academic rigour, to track technology development and provide LCC findings for use by transport energy decision-makers, fleet planners, and researchers.

2. Methodology

The methodology selected for the LCC follows the Australian/New Zealand Standard for Life Cycle Costing, AS/NZS 4536:1999 (Standards Australia and Standards New Zealand, 1999). This is the relevant standard for the practice of LCC in Australia and this standard references the ISO 14040 standards which have been adopted for the LCA as a complementary methodology. Similar to the ISO 14040 LCA standards, the AS/NZS 4536:1999 standard requires the LCC to be reported in accordance with a defined documentation process. The LCC description and analysis which follows complies with the required documentation structure.

The purpose of this analysis is to determine the LCC of the bus transportation systems under consideration. Four technologies are included in the scope – diesel, diesel-electric hybrid, CNG and hydrogen fuel cell. The LCC is applicable to the operation of the buses in the Perth Metro area, specifically on the Perth CAT routes, and this context is used in the selection of the inputs and attributes that are required to complete the LCC analysis. The time frame for the LCC is 15 years, which is the expected lifetime of a bus in Perth. The intended users of the analysis are decision-makers responsible for fleet planning, transport energy policy, and transportation Research & Development (R & D).

3. Data: LCC model description

In keeping with the concept of using actual operational data as input to the life cycle models, cost and economic data that is sourced from Transperth or other Western Australian entities is used wherever possible. For example, capital and operating costs for natural gas and diesel buses are well established. However, the costs of technologies such as hydrogen fuelling stations with on-site electrolysis, which have not yet been implemented in Western Australia but which are highly desirable for inclusion in the models, must be derived from other sources.

The Perth CAT bus routes consist of four inner-city bus routes which are serviced exclusively by the Perth CAT bus fleet. The important statistical characteristics that are useful for describing the duty cycle that is experienced by buses operating on the Perth CAT service are presented in Table 2. These characteristics are derived from actual in-service operating records taken during the Perth Hybrid Bus trial.

The primary energy source for each transport fuel is a key economic input. Indicative prices for diesel and natural gas fuel are obtained from Transperth. Future fossil fuel price movements are an important consideration in the life cycle cost modelling, but rather than speculate on future prices a sensitivity analysis can be used instead. Primary energy costs for hydrogen produced from renewable electricity sources is more difficult to estimate because a price for renewable energy on this scale is not readily available.

The model uses real costs, as opposed to nominal costs. The time frame of a bus lifetime is relatively long at 15 years and the use of real costs eliminates the uncertainty associated with general price inflation. Nominal costs would have been more appropriate if the model was required to determine the actual dollar amounts that will be paid at specific times throughout the life of the bus. However, for this evaluation the key interest is the determination of the Total Cost of Ownership (TCO) expressed in real terms for each bus technology.

The costs for diesel, diesel-electric hybrid and CNG buses are derived from actual Transperth data. For the hydrogen fuel cell bus two cost models are used. The first, denoted as *HFCB*, is representative of present costs for hydrogen bus purchase and operation.

The second, denoted as *HFCB**, is representative of a future HFCB bus that incorporates planned and expected technology improvements. For both cases the bus costs and specifications are sourced from international references, and the hydrogen fuel costs are sourced from primary data on Australian hydrogen production and delivery. All costs are converted to 2015 dollars.

A real discount rate is applied to all costs as a means of including the time value of money in the analysis, which is appropriate for an evaluation that extends to 15 years. In accordance with the guidance provided in AS/NZS 4536:1999, the model uses a discount rate of 9% which is the upper-end of the range of real discount rates that are usually set by Australian governments.

The result of the LCC model is therefore a single dollar value for each bus technology that is determined from the sum of all life cycle costs, in real terms, discounted over the 15-year life of the bus. The LCC for each bus technology can then be directly compared and sensitivity analysis can be used to understand the effect of key variables on the LCC results.

The variables that are used in the LCC model are detailed in Table 3 ; Table 4. A detailed description of the components of the LCC model is presented in the subsections that follow.

3.1. Global variables

The variables which apply to all buses operating on the Perth CAT route regardless of technology type include the lifetime of the bus in years and the annual distance travelled on the Perth CAT service. Economic global variables for the LCC are the foreign exchange rate and the discount rate.

3.2. Capital costs

Actual capital costs recorded during the Perth Hybrid Trial provide valuable and precise inputs to the LCC model. Diesel and Hybrid buses were purchased from Volvo under an existing bus procurement contract. As the price for the Hybrid bus was for a single bus to conduct the Hybrid Bus trial, additional information on pricing was sought from Volvo for higher volume orders, up to a maximum of 32 buses to be delivered over three years for replacement of the entire Perth CAT fleet. Transperth is not currently purchasing new CNG buses and the present-day capital cost for a new CNG bus was extrapolated from the most recent actual purchase price available, using Transperth's own estimates for the expected capital cost. The HFCB and HFCB* capital costs are sourced from the US DOE 2016 prices and ultimate target prices, respectively. The 2016 price is consistent with current industry pricing estimates.

3.3. Maintenance costs

Similar to the capital costs, the data for the diesel, CNG and Hybrid buses are derived from Transperth's actual experience. In the case of the Hybrid bus, only one bus was in operation in Perth for a period of 18 months, and during that time several upgrades were undertaken. The bus experienced periods of extended unavailability due to issues that were mainly associated with the operation of the first and only Hybrid bus in Perth and could not be considered representative of fleet operation.

A single bus is an insufficient sample size from which to extrapolate fleet-wide maintenance cost data, and data sourced from Volvo was used instead. The same maintenance data was sourced from Volvo for the diesel bus, and estimated for the CNG bus, for a valid basis of comparison. For the HFCB and HFCB* models the data was sourced from the previously cited US DOE reference.

3.4. Fuel costs

Actual diesel and natural gas prices for the fuel delivered to Transperth were gathered for the fuel cost calculations. These figures are inclusive of excise and other taxes that are applicable to fuel used for on-road vehicles in Western Australia. The operating costs also include AdBlue1 consumption for the Diesel and Hybrid buses, and the actual AdBlue price.

The hydrogen costs are calculated using an LCC model that was developed by PE for CREST (Moore et al., 2012), which uses a detailed model of hydrogen infrastructure cost data derived from actual observations of hydrogen refuelling stations, and adjusted for local Western Australian inputs such as local electricity, natural gas and water prices. Two hydrogen production scenarios are modelled: (1) Hydrogen production from a natural gas steam reformer, and (2) hydrogen production from an electrolyser. Both models assume on-site hydrogen production from a plant sized at View the MathML source.

The PE model calculates capital costs by summing the investment required for site preparation, the hydrogen production unit (steam reformer or electrolyser), the compressor, the dispenser and the energy storage system. A cost of capital of 12% is applied to the capital budget. Operating costs are calculated separately, and comprise the cost of natural gas, electricity, water, losses, compressor efficiency, nitrogen costs, spare parts, maintenance and labour for servicing.

The capital costs and operating costs are then summed, and divided by the total hydrogen production over an assumed 20-year life of the plant, to arrive at a levelised cost of hydrogen.

There are a large number of variables in the hydrogen LCC model, many of which are tuned based on current assumptions of equipment costs for projects overseas. The price for hydrogen determined by PE during the CREST project is 22.40 $/kg and 20.90 $/kg for hydrogen delivered to the bus depot and compressed to 700 bar for hydrogen sourced from grid electrolysis and steam methane reforming, respectively. These costs for delivered hydrogen are considered to be very approximate. To account for this uncertainty, the LCC model is designed to use a range of hydrogen costs which are derived from the upper and lower bounds of the PE model, rather than an absolute hydrogen cost.

3.5. End of life

After a 15-year service life Transperth sells buses that are still roadworthy which recovers a relatively small salvage value into the LCC model at the end of life. This value has been derived from data provided by Transperth for the diesel and CNG buses. The hybrid bus is assumed to have the same End of Life (EOL) value as the diesel bus, and the HFCB bus is assumed to have zero EOL value because it is assumed that the technology for HFCB buses will change substantially over the 15-year life. The EOL values are included for completeness but due to the discount rate the EOL value is immaterial to the LCC results.

3.6. Uncertainty analysis data

Calculating and reporting the uncertainty of an LCC analysis can significantly strengthen the usefulness of the findings, both for decisions-makers and for future researchers that might reference the study. A Monte Carlo Analysis (MCA) is a particularly suitable methodology to quantify the uncertainty of an LCC because the key inputs of the model can be randomly and independently varied about their nominal value in accordance with a Probability Distribution Function (PDF) to generate a new set of LCC results. The MCA iterates this process many times, generating new random inputs for each iteration, and producing a distribution of LCC outputs which provides a quantified understanding of the uncertainty associated with the LCC model.

The parameters selected for inclusion in the LCC are presented in Table 5, along with a description of the PDF that has been defined for each.

The prices of diesel and natural gas are important parameters with significant uncertainty. There is a large amount of literature addressing the problem of forecasting fossil fuel prices, however the results are often conflicting and are furthermore complicated by a tendency to be specific to a discrete sample period (Elliott and Timmermann, 2013). For the present study a log-normal distribution is assumed for diesel and natural gas prices, which is consistent with many studies of absolute prices analysed by Elliott and Timmermann (2013).

The mean value of the PDF for diesel and natural gas is set at the nominal values specified in Table 4. The standard deviation for natural gas is calculated from a 2015 study that provides the 80% confidence interval for Western Australian natural gas prices (Nidras et al., 2015), and the standard deviation for diesel prices is calculated from actual retail price data from 2007 to 2015 (Australian Institute of Petroleum, 2016). For the hydrogen price, as hydrogen is an energy vector the price is necessarily dependent on other energy price uncertainties, which makes for a very complex calculation. The LCC model is designed to handle this uncertainty by providing a price range of optimistic and pessimistic price scenarios. For the purposes of the uncertainty analysis, a uniform distribution between the hydrogen price upper and lower bounds in Table 4 is assumed.

The capital costs to acquire a new Diesel, CNG or Hybrid bus in Australia are based on primary data from contracted prices. While these prices are contracted for several years, an element of uncertainty can be introduced by examining data from recent bus purchases in larger jurisdictions. Neff and Dickens (2015) published average bus purchase price data for the United States, and the average price from 2002 to 2014 can be extracted from this report. After adjusting for inflation to convert nominal prices to real prices, the data shows that prices can vary by up to 9.5% in any given year over and above the rate of inflation, with an average of 2.5%. The capital costs for the Diesel, CNG and Hybrid buses are therefore assumed to have a uniform distribution with a minimum set at the actual values in Table 4 and a maximum at 9.5% above these values. The hydrogen bus capital cost is assumed to also have a uniform distribution with upper and lower bounds set at the capital costs for HFCB and HFCB*.

Maintenance costs for the Diesel, CNG and Hybrid buses are derived from fleet-wide data, as described in Section 3.3, and are held constant in the MCA. The hydrogen bus capital cost is assumed to have a uniform distribution with upper and lower bounds set at the maintenance costs for HFCB and HFCB* in Table 4.

The fuel consumption of the Diesel, CNG and Hybrid buses operating on the Perth CAT route, which is a relatively stable and consistent duty cycle, is assumed to fit a normal distribution with the mean set at the values in Table 4 and a coefficient of variance of 4%. The HFCB fuel consumption of a modern fuel cell bus is reported by several studies to be in the range of 9–10 kg/100 km (Eudy et al., 2014; Spendelow and Papageorgopoulos, 2012 ; Fuel Cells and Hydrogen Joint Undertaking, 2012). A normal distribution with a coefficient of variance of 10% is assumed.

4. Results: LCC model analysis

The TCO comparison for all technologies under consideration, including both an HFCB in 2016 and an HFCB that meets the US DOE ultimate targets, is presented in Fig. 1. The conventional Diesel bus provides the lowest TCO, while the Hybrid bus incurs a higher TCO. The fuel savings of the Hybrid bus are insufficient to compensate for both the higher capital cost and the higher maintenance cost of the Hybrid. CNG buses are uncompetitive due to the very high fuel cost. HFCB costs are significantly greater than all other technologies. If the US DOE Ultimate Target performance is attained, the HFCB* is $125,871 more expensive than the CNG buses, and $422,340 above the Diesel TCO. The Hybrid bus falls between the two incumbent technologies at a TCO premium of $87,824 above the Diesel, and a savings of $208,645 below the CNG buses.

The question of how the diesel fuel price affects the LCC results is illustrated in the sensitivity analysis presented in Fig. 2. The TCO result as a function of diesel price is calculated for each technology except CNG. The HFCB results are decoupled from diesel and do not vary with the diesel price. The Hybrid bus reaches TCO parity with the Diesel Bus at a fuel price of 3.20 $/L, well above the current price. However, the maintenance cost of the Hybrid bus is much higher than the Diesel, partly due to the maintenance of the traction battery, but also due to other higher cost components of the hybrid drivetrain which are not yet available in the production volumes of Diesel drivetrain components. To explore the effect of a reduction in Hybrid maintenance cost, a second Hybrid Bus function, denoted *Hybrid**, is illustrated in Fig. 2, in which all parameters are the same except for the maintenance cost which is set equivalent to the Diesel for the purposes of the sensitivity analysis. For the Hybrid* a break-even point with Diesel is found at a Diesel price of 1.95 $/L.

The fuel consumption improvement of the Hybrid bus over the Diesel bus is the primary parameter of interest in the comparison between Diesel and Hybrid technologies, and the sensitivity of this parameter is explored in Fig. 3. The break-even fuel consumption for the Hybrid bus is found at 28 L/100 km. This level of performance would constitute a 43% improvement in fuel consumption over the data recorded during the Hybrid trial for the Hybrid bus operating on the Perth CAT routes.

During the Perth Hybrid Bus trial a one-month data collection period was conducted on suburban routes with a much higher average speed than the Perth CAT routes (Bowers et al., 2015). When operating on the higher speed suburban route the Hybrid bus achieved a fuel consumption of 22.8 L/100 km, which is better than the break-even performance. However, the Diesel bus also performed better on the suburban route achieving a fuel consumption of 36.8 L/100 km, which shifts the break-even point for the Hybrid in comparison with Diesel to below 19.0 L/100 km.

The difference between the HFCB and HFCB* is broken down in the waterfall chart presented in Fig. 4. The largest cost improvement is the reduction in capital costs that occurs if the US DOE target is attained by manufacturers. The reduction in maintenance costs has a relatively minor impact on the TCO. A fuel cost reduction of $239,862 is entirely due to an expected reduction in hydrogen fuel cost for hydrogen sourced from water electrolysis that would occur if the electricity price were reduced.

The CREST LCC model used an electricity price of 0.26 $/kWh which is consistent with the residential electricity tariff but is a relatively high price for an industrial plant. It is assumed that the electrolyser could be programmed to run during the off-peak periods[2] to take advantage of off-peak pricing. Gazetted electricity tariffs from Synergy, the State-owned electricity retailer, for a medium-sized business, price the off-peak electricity tariff at 0.0905 $/kWh (Department of Finance, 2015) with no demand charge. The Synergy R1 off-peak tariff is used to calculate the hydrogen cost presented Fig. 4.

A more detailed study of electricity tariffs for an industrial electrolyser equipped with a demand management system to manage peak demand, access to the wholesale market, and bilateral contracts with renewable energy providers, could be undertaken to determine a more accurate electricity price.

For the purposes of the present study, the sensitivity of the HFCB TCO to the electricity price, and the sensitivity of the hydrogen price per kilogram delivered at the bus refuelling station, is presented in Fig. 5.

At a very low electricity price of $0.05/kWh, which is arguably well below the realistic range of electricity prices even for an off-peak load procuring electricity from the wholesale market, the hydrogen price is $9.37/kg. For a high electricity price of $0.30/kg, which is pessimistic if the duty cycle uses a blend of peak and off-peak electricity, the hydrogen price reaches $24.80/kg. For reference, the actual hydrogen price paid during the Perth STEP project was $21/kg (Cockroft and Owen, 2007).

The sensitivity analysis illustrated in the previous figures explores the LCC model by varying a single parameter in isolation. A two-variable sensitivity analysis is presented in Fig. 6 which illustrates the break-even points for the HFCB versus a conventional Diesel bus in terms of TCO. The vertical axis indicates the difference, or *delta* , between the two technologies which is determined by calculating *TCOHFCB−TCODiesel*. The sensitivity is explored by varying the Diesel price on one axis of the horizontal plane, and the hydrogen price on the other axis of the horizontal plane. In the surface graph that results, the negative values on the vertical axis illustrate the parameters where the TCO of the HFCB is lower than the Diesel bus. A line is observed which represents the break-even delta of zero, which extends from a diesel price of 2.25 $/L to 19 $/kg hydrogen. The LCC therefore finds that the HFCB has a higher TCO than the Diesel bus as long as the diesel price is below 2.25 $/L regardless of the price of hydrogen. Similarly, it is observed that as the diesel price increases above 2.25 $/L the break-even point on the hydrogen price scale increases with linear proportionality, reaching 19 $/kg at the very high Diesel price of 4.50 $/L.

The Monte Carlo simulation results for 10,000 iterations are presented in Fig. 7. The histograms and cumulative probability curves illustrate the distribution of the MCA results. The 95% confidence interval for each distribution is enumerated and overlaid on each graph. The range of results for the HFCB is significantly wider than that of the other technologies, as would be expected. However, the

MCA results show that the uncertainties in the data do not alter the relative ranking of the TCO results.

5. Discussion

The LCC model and sensitivity analysis clearly shows that the economics of Diesel bus technology deliver the lowest TCO. The hybrid bus trialled in Perth is around 10% more costly than diesel, and future hybrid buses may close this gap if the capital cost can be reduced and fuel consumption continues to improve. The HFCB buses require significant cost performance improvements before they will be competitive on a purely economic basis. The main benefits of lower emissions in the case of the Hybrid, and zero tailpipe emissions in the case of the HFCB, could be included in the analysis by accounting for externalities associated with health and environmental costs from harmful emissions. However, when the costs of these emissions are divided by the full range of emission sources and allocated on a proportional basis, the cost of externalities that are allocated to bus emissions are immaterial, and certainly negligible in their contribution to the TCO outcome (Bowers et al., 2015).

The US DOE performance targets for HFCB technology are ambitious, but the fuel consumption target has already been attained. If no further improvements in fuel consumption are expected then the HFCB can only be made more competitive through advances in capital costs, maintenance costs and hydrogen fuel costs. The analysis shows that improvement in only one of these parameters is insufficient. All variables must be improved to approach the economic break-even points.

The results show that on a TCO basis the cost premium to implement and operate an HFCB is substantially greater than a conventional diesel bus, unless a major increase in diesel fuel price occurs. In comparison, the input-output LCC model that was developed by McKenzie and Durango-Cohen (2012) for the North American market found that the cost premium of HFCBs could be recovered within 5 years if a modest price were placed on carbon emissions. However, the present study finds that to approach the TCO break-even point which requires a much greater emissions price than the range that is currently contemplated in Australian politics.

The results for the hybrid bus can be compared with the literature sources cited in Section 1 on other hybrid bus trials and fleets, both domestically and internationally. The Williamson (2012) data for a 2011 trial in Sydney found that the hybrid resulted in a net present value loss of $113,950 in comparison with diesel, which is similar in magnitude to the TCO loss calculated in the present study. The Sydney trial found a 15% measured fuel efficiency improvement, which is lower than the difference achieved in Perth. Fuel consumption is the key advantage of Hybrid technologies, and its effect on TCO scales with the annual distance travelled. The Sydney bus trial used a much longer annual distance (70,000 km) than the Perth CAT buses (30,000 km), and an improvement in fuel consumption can translate to a significant change in total economic outcome which could bring the Sydney and Perth results even closer.

The analysis conducted by Lajunen (2014), which was based on simulated data rather than on-road measurements, concluded that hybrid buses carried a lifecycle cost that was only slightly higher than conventional diesel buses. This was based on simulated bus operation using a theoretical model of hybrid bus performance, and the estimated fuel consumption and maintenance costs were more optimistic than those measured in Perth.

Nylund and Koponen (2012) found that hybrid buses were cost competitive if diesel prices increased by 50% and if the capital cost premium for a hybrid reduced by 35%. This is similar to the Hybrid* breakeven fuel price increase illustrated in the Fig. 2 sensitivity analysis, although the Hybrid* scenario does not include a capital cost reduction. While this is a rather generic comparison, further comparison becomes complex due to differences in the assumptions of absolute fuel price, distance travelled, capital costs and maintenance cost premiums. However, the overall conclusion on the relative competitiveness of hybrid technology over conventional diesels is comparable to the present study.

The most optimistic of the references previously cited is Grütter (2015), which included data from many large bus fleets, and which focused on data from Zhengzhou, finds a 5–6 years payback period for hybrids if the diesel price is at least USD $1.10/L. The difference between this finding and the results of the Perth trial are revealed through a review of the underlying assumptions. To achieve the 5–6 year payback period the capital cost premium for hybrid buses is set much lower at USD $45,000, and the distance travelled each year is much greater at 55,000 km/year. The diesel fuel price of at least USD $1.10/L and an identical maintenance cost per kilometre are the other key assumptions required to achieve this outcome.

The Hybrid bus deployed during the Perth Hybrid Bus trial uses a parallel-hybrid drivetrain and a relatively small 4.8 kWh battery system. Other Hybrid buses may achieve better cost performance. The LCC model can be adopted to any bus under consideration by adjusting the parameters defined in Table 4. The LCC model can also be modified to compare technologies for different bus routes or contextual circumstances by adjusting the global parameters such as distance travelled, bus life time and discount rate. A longer lifetime or greater distance travelled per year will generally improve the TCO of more efficient buses against the Diesel baseline because annual operating costs increase in importance with increasing utilisation.

The LCC model can be improved by increasing the granularity of input data for the capital cost of the HFCB technology which would likely require a procurement process to be initiated. Maintenance costs can also vary widely due to many factors including the number of buses of the type under consideration, the ability of the manufacturer to provide expert on-site support, the level of commercialisation, manufacturing volumes and many other factors.

The diesel and CNG fuel costs are based on actual prices. For a 15-year LCC model the long-term fuel price forecast is extremely uncertain. Any transportation system that is fuelled by diesel or CNG is necessarily linked to global price volatility in these fuels. The LCC does not currently take into account the cost of fossil fuel price volatility, or the fuel security benefit that may accrue to HFCB technologies through the use of indigenous renewable electricity sources to fuel the vehicle fleet.

A business case could be developed for a large-scale electrolysis plant to be sized and controlled for participation in the wholesale electricity and demand-side management markets, potentially using inexpensive off-peak electricity for hydrogen production. The Western Australian grid currently has a significant oversupply of capacity. The supply-demand balance for 2014/15 was estimated to be around 1280 MW of excess capacity, with no new capacity required to be built until 2023 (Independent Market Operator, 2014). The growth in renewable wind capacity exacerbates the excess generation capacity overnight when demand is relatively low and wind generation is relatively high, occasionally driving the spot price to a negative value. A hydrogen plant could benefit from very low cost electricity, reducing the cost of hydrogen and improving the utilisation of the generators on the grid.

6. Conclusions and policy recommendations

The common objective of public bus fleet planners and operators is to provide a transportation system that minimises economic costs and environmental impacts while maximising the utility and serviceability of the fleet. Environmental problems associated with vehicle emissions is an increasingly significant problem in major cities, and the upwards trend in greenhouse gas emissions and fossil fuel consumption for transportation shows no signs of abatement. Simultaneously, continuous growth in the bus market in Australia, and worldwide, combined with the very high efficiency and low fuel consumption of buses on a passenger-kilometre basis, establish buses as an increasingly popular mode of transport. These factors merit further research into ways of reducing the energetic and environmental burden of bus systems while keeping costs within a range that society is willing to tolerate.

From an economic perspective, the capital cost to purchase a Hybrid bus will always be greater than that of a Diesel due to the additional drivetrain components such as traction batteries and electric motors. Similarly, the capital cost of an HFCB will always be greater than a Hybrid unless the cost for a fuel cell module decreases to the cost of a diesel engine. The key question is whether an operating cost reduction can offset the higher capital cost to arrive at a lower TCO, without any compromise in service delivery.

The LCC model and sensitivity analysis shows that the economics of Diesel bus technology delivers the lowest TCO. The Hybrid bus trialled in Perth carries a TCO that is around 10% higher than the Diesel. The results show that on a TCO basis the cost premium to implement and operate an HFCB is still substantially greater than the TCO of a conventional diesel bus, unless a very large increase in the diesel fuel price occurs or the HFCB cost reduction exceeds the US DOE targets.

However, the Hybrid and HFCB technologies are still relatively young in comparison to the baseline Diesel technology, and the economies of scale that might be available from a large-scale ramp up could change the economic comparison. Two possible ideas to achieve greater scale for HFCBs is the use of a large-scale electrolysis plant to increase the utilisation of excess electricity generation capacity in Western Australia, and building on the bus chassis export market which could be used to manufacture a common hydrogen bus short-chassis which could then be exported to global markets.

The scope of the present study does not include Electric Buses or Plug-in Hybrid Buses. These technologies could be added relatively easily within the LCC framework if sufficient primary data on vehicle and infrastructure costs is available.

This project has established a base of LCC empirical results and a scenario analysis which can be applied to a wide range of transportation system applications. Integrating LCA and LCC in fleet-planning and policy decision-making processes enhances visibility of long term consequences, allows further opportunities for industry development to be recognised, and provides tools for optimisation of the entire product lifecycle.

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Fig. 1. Comparison of LCC model results expressed in TCO.

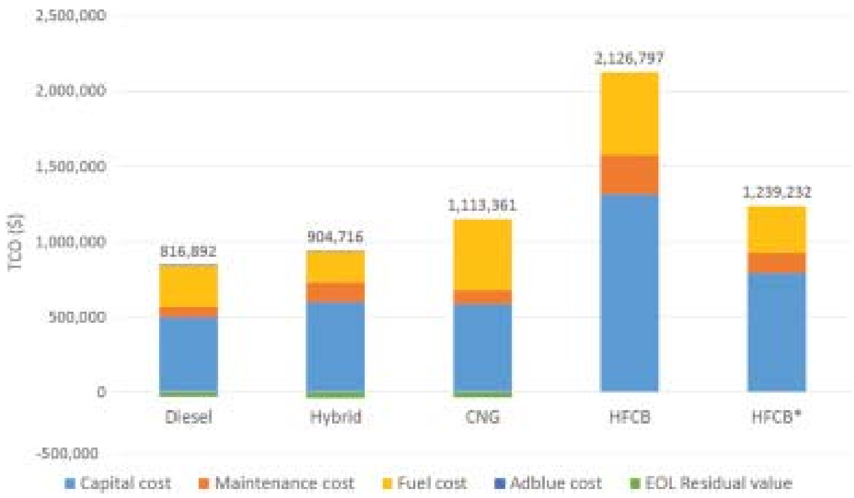

Fig. 2. TCO for Diesel, Hybrid and HFCB buses as a function of the diesel fuel price.

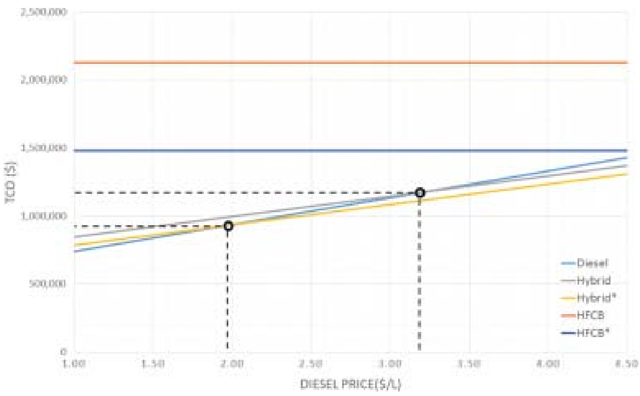

Fig. 3. TCO for Diesel and Hybrid buses as a function of the Hybrid bus fuel consumption.

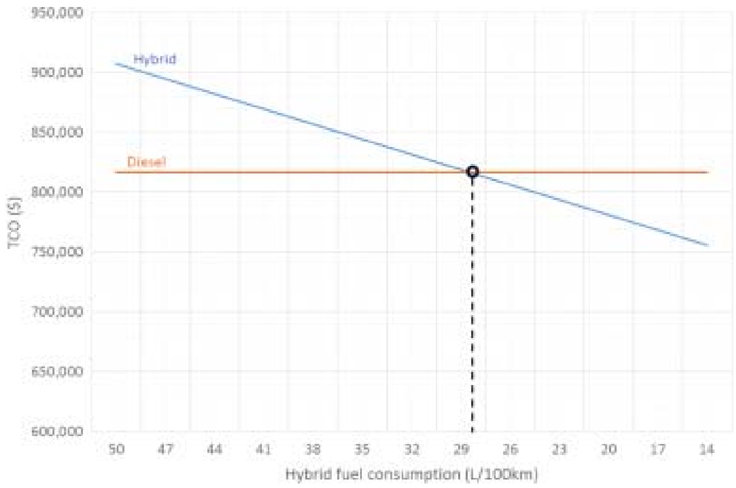

Fig. 4. TCO transition from 2016 result to the DOE Ultimate Target for an HFCB operating on the Perth CAT.

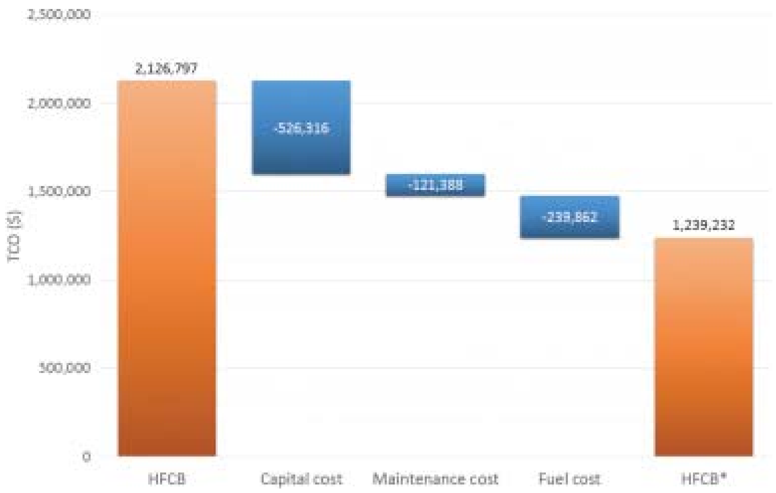

Fig. 5. Hydrogen fuel cell bus TCO and hydrogen fuel price as a function of the electricity price.

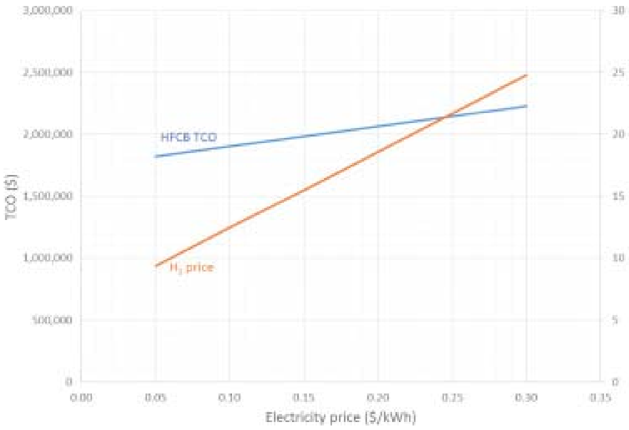

Fig. 6. HFCB TCO minus Diesel TCO as a function of the diesel price and the hydrogen price.

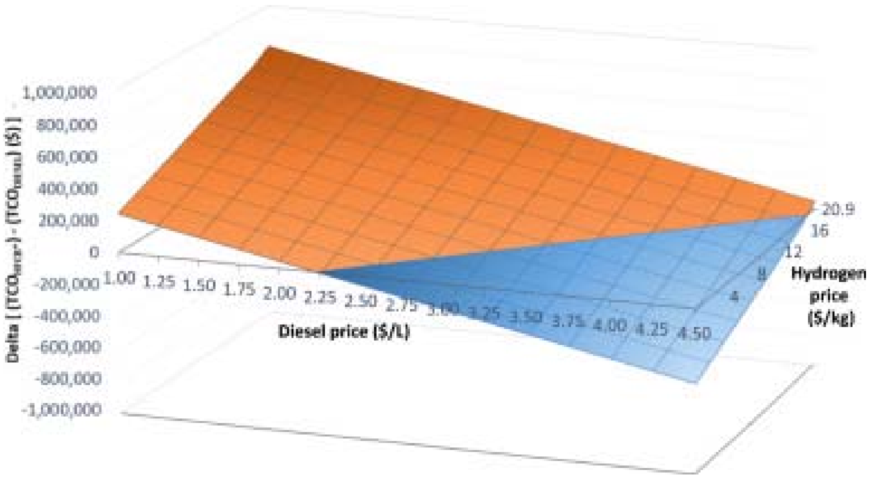

Fig. 7. Monte Carlo simulation results.

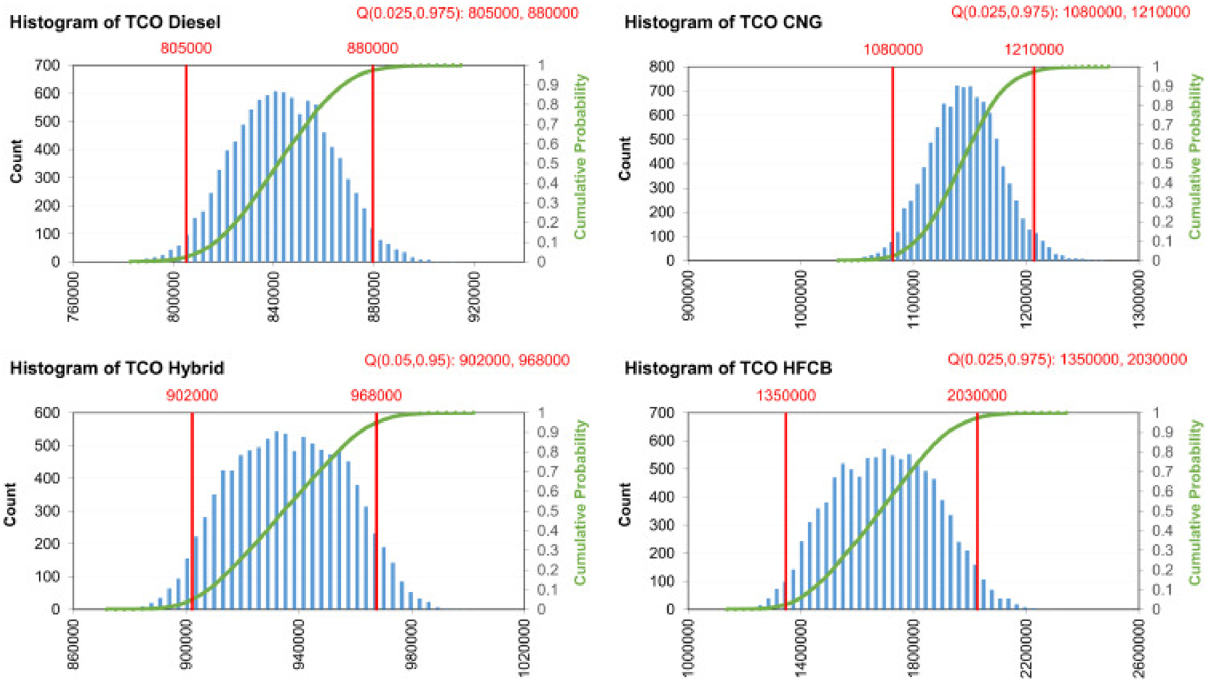

Table 1. Bus drivetrain nomenclature.

Bus type	**Drivetrain description**
Diesel	Conventional diesel bus
CNG	Conventional compressed natural gas bus
Hybrid	Diesel electric hybrid bus
HFCB	Hydrogen fuel cell bus
EB	Battery electric bus

Table 2. Attributes that define the duty cycle for buses operating on the Perth CAT service.

Parameter	**Unit**	**Data**	**Source**
Distance	km/yr	30,500	(Transdev 2012–2014)
Operating time	hrs/km	0.106	Transdev, 2012 to 2014 ; Volvo, 2012 to 2014
Stops per distance	stops/km	4.95	(Volvo 2012–2014)
Percent idle time	%	25	(Volvo 2012–2014)
Average operating time per day	hrs/day	12.85	(Volvo 2012–2014)
Average speed	km/hr	9.5	(Volvo 2012–2014)

Table 3. LCC model global parameters.

Phase	**Parameter**	**Unit**	**Value**	**Ref.**
Global	Annual distance	km/year	30,000	Bowers et al. (2015)
	Vehicle life	years	15	Bowers et al. (2015)
	Discount rate	%	9	Standards Australia and Standards New Zealand (1999)
	Exchange rate	AUD/USD	0.76	Reserve Bank of Australia (2015)

Table 4. Summary of the LCC model key input parameters (all currency values expressed in Australian Dollars).

Phase	Parameter	Unit	Value	Ref.
Bus acquisition	Diesel	$	498,722	Bowers et al. (2015)
	Hybrid	$	599,485	Bowers et al. (2015)
	CNG	$	585,640	Bowers et al. (2015)
	HFCB	$	1,315,789	Spendelow and Papageorgopoulos (2012)
	HFCB*	$	789,474	Spendelow and Papageorgopoulos (2012)
Maintenance	Diesel	$/km	0.27	Bowers et al. (2015)
	Hybrid	$/km	0.50	Bowers et al. (2015)
	CNG	$/km	0.34	Bowers et al. (2015)
	HFCB	$/km	0.99	Spendelow and Papageorgopoulos (2012)
	HFCB*	$/km	0.53	Spendelow and Papageorgopoulos (2012)
Fuel consumption	Diesel	L/100 km	65.0	Bowers et al. (2015)
	Hybrid	L/100 km	49.4	Bowers et al. (2015)
	CNG	L/100 km	103.2	Bowers et al. (2015)
	HFCB	kg/100 km	10.0	Spendelow and Papageorgopoulos (2012)
	HFCB*	kg/100 km	10.0	Spendelow and Papageorgopoulos (2012)
AdBlue consumption	Diesel	L/100 km	2.215	Bowers et al. (2015)
	Hybrid	L/100 km	1.441	Bowers et al. (2015)
	CNG	–	–	Bowers et al. (2015)
	HFCB	–	–	Spendelow and Papageorgopoulos (2012)
	HFCB*	–	–	Spendelow and Papageorgopoulos (2012)
Fuel prices	Diesel	$/L	1.3882	Bowers et al. (2015)
	AdBlue	$/L	0.95	Bowers et al. (2015)
	CNG	$/L	1.5127	Bowers et al. (2015)
	HFCB	$/kg	20.90	Spendelow and Papageorgopoulos (2012)
	HFCB*	$/kg	11.80	Spendelow and Papageorgopoulos (2012)
End of life	Diesel	$	102,682	Bowers et al. (2015)
	Hybrid	$	123,429	Bowers et al. (2015)
	CNG	$	120,541	Bowers et al. (2015)
	HFCB	$	0	Spendelow and Papageorgopoulos (2012)
	HFCB*	$	0	Spendelow and Papageorgopoulos (2012)

Table 5. Summary of the Monte Carlo Analysis parameters.

Bus type	**Parameter**	**Probability distribution function**
Diesel	Bus acquisition	Uniform
	Fuel consumption	Normal
	Diesel price	Log-normal
CNG	Bus acquisition	Uniform
	Fuel consumption	Normal
	Natural gas price	Log-normal
Hybrid	Bus acquisition	Uniform
	Fuel consumption	Normal
	Diesel price	Log-normal
HFCB	Bus acquisition	Uniform
	Fuel consumption	Normal
	Maintenance cost	Uniform
	Hydrogen price	Uniform