Energy Policy 94 (2016) 285–294

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

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

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## HIGHLIGHTS

- A Life Cycle Cost model is constructed using data from bus trials in Perth.
- Hybrid and hydrogen technologies are compared with diesel and gas.
- Results are represented as Total Cost of Ownership – a dollar value in real terms.
- The TCO of conventional diesel is lower than the alternative technologies.
- The TCO improvement that would make alternatives competitive is quantified.

## ARTICLE INFO

*Article history:*
Received 11 November 2015
Received in revised form
26 February 2016
Accepted 28 March 2016

*Keywords:*
Hydrogen
Hybrid bus
Transport energy
Life cycle cost
Natural gas
Transit economics

## 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.

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## 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,

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http://dx.doi.org/10.1016/j.enpol.2016.03.039
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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.

**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 |

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) and 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,

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