

Modelling the costs and benefits of hybrid buses from a ‘whole-life’ perspective

Michael R. Emes¹, Alan Smith², Nick A. Tyler³, Richard W. G. Bucknall⁴, Philip A. Westcott⁵ and Stephen Broatch⁶

¹ University College London, UK, mre@mssl.ucl.ac.uk

² University College London, UK, as@mssl.ucl.ac.uk

³ University College London, UK, n.tyler@ucl.ac.uk

⁴ University College London, UK, r_bucknall@ucl.ac.uk

⁵ BAE Systems, UK, phil.westcott@baesystems.com

⁶ BAE Systems, UK, stephen.broatch@baesystems.com

Abstract

Hybrid electric-diesel engine technologies offer the potential to reduce fuel consumption in buses by around 40%. These savings can largely be attributed to regenerative braking – the ability to store in a battery energy that would otherwise have been lost under braking. Lower fuel consumption makes sense economically for bus operators through reduced running costs; hybrid engines have other wider benefits, though, such as reducing emissions and noise, and providing smoother acceleration and braking. The costs associated with hybrid technologies are significant, however, with hybrid vehicles currently costing around 50% more to buy than conventional buses.

With Alexander Dennis and BAE Systems, UCL is conducting a three-year systems engineering research and development project to adapt and optimise hybrid buses for the UK and European market. This paper investigates one aspect of this project – the costs and benefits of introducing hybrid bus technologies from a whole-life perspective. We find that fuel and emissions savings alone do not provide a compelling case for hybrid buses based on current prices. However, as the cost of fuel rises, and when the social and environmental impacts of motor vehicle use are better accounted for, hybrid technology outperforms conventional diesel technology.

Keywords – Whole-life costs, through-life capability management, hybrid bus, cost-benefit analysis

1 Introduction

Through-life capability management (TLCM) has become a fashionable term in the UK defence and systems engineering community, specifying requirements not for specific systems or equipment, but for the capabilities or effects they can deliver ‘through life’ [1]. The term ‘through life’ is perhaps a little misleading. It properly refers to the lifetime of the capability in question, but with capabilities often assumed to ‘endure’, the focus of debate can be drawn to the lifetime of the equipment that is purchased to provide that capability, blurring the distinction between capability and equipment-based requirements. In any case, the question of who ultimately pays for (and benefits from) new systems and the extent to which they offer value for money to the relevant stakeholders are not widely debated in these discussions of ‘through-life’ capabilities.

Outside the defence sector, the notion of capability-based requirements is less common. In the public transport sector, manufacturers’ technology solutions are significantly constrained by standards and regulations, and operating companies are restricted to bidding for the rights to run specific types of vehicles on specific routes. In this context, the adoption of a new propulsion technology for buses should not be undertaken lightly. This paper explores the business case for hybrid diesel-electric buses.

1.1 The project

With BAE Systems and Alexander Dennis, UCL is conducting a three-year systems engineering research project to develop a hybrid transit bus for London and the European market. A prototype bus is shown in Figure 1.



Figure 1 - Alexander Dennis – BAE Systems hybrid

This paper discusses one of the project’s preliminary work packages – an investigation into the costs and benefits of introducing hybrid bus technologies in general, from a

whole-life perspective. We consider different approaches for weighing future costs and benefits relative to current costs and benefits, including Net Present Value and Real Options approaches. The perspectives of different stakeholders are represented, including the bus manufacturer and supply chain, the bus operator, the bus network regulator (Transport for London - TfL), and the general public.

1.2 The technology

Hybrid electric vehicles typically combine an energy storage device, a power plant and a propulsion system. Energy storage devices are usually batteries, but other possibilities include ultra-capacitors and flywheels. Power plants can be internal combustion engines, diesel engines, gas turbines, or fuel cells.

The efficiency of a hybrid system for a given route depends on a number of factors, such as the particular combination of subsystems, how the systems are integrated, and the control strategy employed. Most of the fuel economy benefit of hybrid vehicles is derived from their ability to use regenerative braking – storing energy in a battery that would otherwise have been lost under braking. This energy can later be used to propel the vehicle. Maximising the benefits from a hybrid bus requires optimising the hybrid system for the bus' route, considering the terrain the bus travels, the average speed of the route and the frequency of stopping.

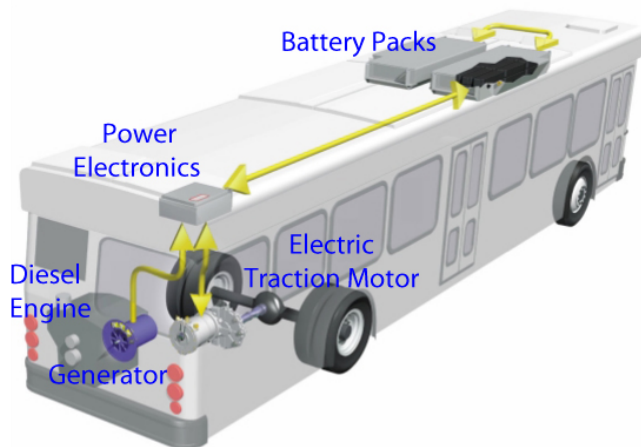


Figure 2 - Schematic of series hybrid bus

There are two basic strategies for hybrid propulsion:

- ‘Series hybrid’, in which the power plant provides electrical power to the motor, which drives the wheels. There is no mechanical connection between the power plant and the wheels. An advantage of this configuration is being able to set the power plant to operate at its maximum efficiency. The ADL BAE hybrid is a series hybrid as shown schematically in Figure 2.

- ‘Parallel hybrid’, in which there are two power paths, allowing the wheels to be driven by the power plant, the electric motor, or both. This configuration has the advantage of higher power because the electric motor and power plant can provide power simultaneously, but the disadvantage of lower theoretical efficiency than a series system (since the mechanical linkage between the engine and the wheels couples engine speed to road speed, preventing the engine from operating constantly at its optimum speed).

2 Methodology

The methodology for investigating the whole-life costs and benefits of hybrids is split into three sections. First, we outline the general approach for modelling costs and benefits; then we investigate the direct benefits of hybrids; finally, we identify the stakeholders of hybrid technology.

2.1 Modelling the costs and benefits

The standard method for evaluating the attractiveness of a project that costs some amount C_0 now, but is expected to deliver a stream of benefits B_i for a number of years is to estimate the monetary value of those future benefits, and to determine how much money received in the future is worth to us relative to the same amount received today (i.e. the time value of money). The overall value figure calculated is then called the *net present value* or NPV of the project.

For long-life systems, Browning and Honour suggest calculating whole-life value by simply summing the value generated in each year of the system's life [2]. The more accepted approach for valuing long-term investments, however, is to discount benefits received in the future (by a proportional rate r) relative to benefits received now [3]. This is because money received now could be invested (such as in a bank) and would be expected to increase in real value (i.e. over and above the rate of inflation) over time. Graham and Harvey note that 75% of firms always or almost always use this approach to evaluate investments [4]. The value of a project with a time horizon of N years is then given by the N -year NPV:

$$NPV = \sum_{i=1}^{i=N} \frac{B_i}{(1+r)^i} - C_0$$

The challenge for a project of social benefit like this is to identify:

- What are the benefits and the costs?
- Who will benefit (who are the stakeholders)?
- Can we convert their benefits into monetary terms?
- How much should we discount their future benefits relative to their current benefits?
- What is a reasonable time horizon to value the project over?

2.2 Identifying the direct benefits of hybrids

The direct benefits of hybrid buses are broadly:

- Reduced fuel consumption
- Reduced emissions
- Smoother acceleration and deceleration (hence fewer accidents and increased comfort for passengers)
- Reduced noise
- Reduced wear on brakes (and arguably on engine and transmission as well)

However, these benefits must be traded-off against the increased manufacturing cost of hybrids and the limited lifetime of the battery. Initial experience (1998-2002) in the US from the Orion-BAE Systems hybrid found that the mean distance between in-service failures was approximately half that of a conventional diesel bus, due to poor battery reliability [5]. New lithium-ion battery technology has significantly improved reliability of the Orion-BAE hybrid, however, with mean distance between in-service failures for the hybrid system now comparable to that of a diesel bus. Note that it is unclear at present whether there will be a cost associated with disposal of the batteries when they are no longer useful for buses, since they contain hazardous substances that cannot be disposed of in the general waste. Facilities already exist for disassembling batteries and recovering valuable materials like cobalt and copper, and there may even be opportunities for reconditioning the batteries and selling them on for less demanding applications. Whether there is a cost or a benefit associated with disposal of batteries, the impact of this will occur far enough in the future to be heavily discounted relative to today's benefits.

It is suggested that once teething problems are overcome, hybrids may actually have lower through-life maintenance costs than diesel buses. According to New Flyer Industries, with experience of manufacturing hybrid buses in the US since 1997, hybrids have demonstrated [6]:

- 1.7 times longer engine life, extending the time between minor and major engine overhauls and rebuilds
- Lower transmission related repair and rebuild costs
- Double the brake life of conventional buses thanks to the regenerative braking advantages of hybrids

The fact that hybrid buses operate using the same infrastructure as conventional diesel engine buses means that they can easily be integrated into the existing network.

Compared with conventional diesel buses, hybrids deliver considerable environmental benefits, including [7]:

- 89 per cent reduction in oxides of nitrogen
- 83 per cent reduction in carbon monoxide
- 40 per cent reduction in fuel use
- 38 per cent reduction in carbon dioxide

- 30 per cent reduction in perceived sound levels (noise reduced from 78 to 74 decibels)

2.2.1 Quantifying the benefits

The conflicting data on the maintenance costs of hybrids relative to conventional buses makes it difficult to justify different maintenance costs (including cost of disposal of batteries) in any whole-life cost-benefit analysis. Although noise benefits have been quantified, these benefits have not yet been translated into a willingness to pay figure or other metric that could be compared to a financial benefit. Furthermore, the fact that hybrid buses can be easily integrated into the existing network is not a benefit, but merely the absence of an additional cost. We therefore modelled the benefits with the following initial assumptions:

- A typical hybrid bus will run for 200 miles per day, 6 days per week, 52 weeks per year, covering 62400 miles (covering 750000 miles in 12 years)
- A hybrid uses 40% less fuel than a Euro4 diesel engine (assume 6 mpg Euro4, 10 mpg hybrid)
- The hybrid bus including battery has the same maintenance costs as a conventional diesel engine bus (but a higher initial purchase cost)
- Burning 1 litre of diesel creates 3.2kg CO₂ [8] (in terms of global warming potential, Defra [9] puts a value on CO₂ at £27/tonne for 2010 rising at 2% per annum over inflation)

With these assumptions, the hybrid consumes 15755 litre/yr less diesel than a conventional bus, and saves 50 tonnes/yr of CO₂.

We should now consider the beneficiaries of hybrid buses, and how they would value the benefits identified above. We will also consider other benefits that are harder to quantify financially, such as reduced noise and smoother acceleration and deceleration.

2.3 Identifying the stakeholders

The world we live in can be envisaged as an interacting, hierarchical arrangement of systems, each having different stakeholders. Individual systems may combine to form 'supersystems' – the needs of the supersystem thereby place requirements (or perhaps merely expectations) on the capability and outputs of its systems.

A situation where elements of a supersystem have independent design authorities is called a 'system of systems'. Here, the necessary collaboration between systems to create the emergent (and useful) supersystem properties does not follow from a single design source but is often added through communications and operations protocols. Moreover, an individual system may simultaneously be part of a number of supersystems. This leads to important issues of contention, prioritisation and conflicting stakeholder requirements.

The introduction of hybrid buses in a particular region will have implications to its wider environment. These implications can be understood as effects upon the supersystem. Ultimately, hybrid bus introduction is made to meet stakeholder needs. These needs are either rooted in the supersystems of the buses or are spurious. It is the satisfaction of these needs which provides the foundation for the business case for introducing the technology.

However, change often brings with it undesirable and/or unforeseen (or at least underestimated) consequences. The technology involved in hybrid buses is significantly different from that employed by conventional buses, whose fundamental method of propulsion has changed little over the last century. The impacts of introducing the technology will therefore be quite broad and can be seen at various levels of the system hierarchy.

A number of relevant supersystems have been identified; these are classified in Table 1 in two ways:

- We differentiate between ‘unitary’ systems, which have a single design authority, and ‘systems of systems’ (‘SoS’) which have multiple design authorities.
- We specify the relative level within the systems hierarchy. Hybrid bus = 0, first supersystem = 1, super-supersystem = 2, etc.

Table 1 – Supersystems for hybrid buses

Supersystem	Type	Level	Comment
Operating fleet	Unitary	1	Related to a particular bus depot
Bus operator	Unitary	2	e.g. London United Buses
Bus industry	SoS	3	National
Local transport infrastructure	SoS	2	Includes private cars, underground, rail etc.
Society	SoS	3	Includes people, transport infrastructure and destinations
Local Environment	SoS	1	Direct impacts upon humans, other animals and plants
Hybrid bus manufacturer	SoS	1	e.g. ADL and BAE Systems
Transport technology suppliers	SoS	2	Hybrid technology supply chain and its competitors
Governance organisation	Unitary	3	e.g. Transport for London (TfL)

These systems are illustrated in Figure 3. Note that, for clarity, ‘governance organisation’ and ‘society’ are not included in the figure.

The higher the level of the supersystem in the hierarchy, the more diverse the needs of the stakeholders are likely to be. Furthermore, systems of systems will generally have complex and often conflicting requirements.

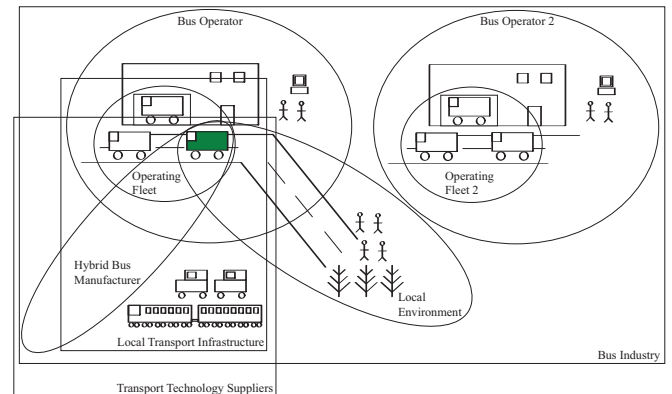


Figure 3 - Systems view of hybrid bus

By analysing Table 1, we can identify four broad groups of important stakeholders:

- (i) General public
- (ii) Government (Transport for London)
- (iii) Bus manufacturers and supply chain
- (iv) Bus operators and employees

Each of the stakeholders identified above will attach different values to each of the benefits, and will have to pay a different amount to access these benefits. These are discussed in turn in the following sections.

2.3.1 General public

We conducted two small surveys and focus groups with members of the public, and found that noise, sudden braking and excessive heat on board (diesel) buses are the biggest sources of dissatisfaction, whilst proximity of routes to destinations and long service hours are the best features of (diesel) buses. The fact that hybrid buses are quieter than diesel buses and offer smoother braking will therefore be welcomed by the public.

Although bus users are sensitive to the cost of bus journeys, research in Luxembourg found that many people would be willing to pay a small amount more for a more environmentally friendly technology. 56% of bus users said they would be willing to pay 0.1 EUR or more to have hydrogen fuel cell buses introduced in Luxembourg. 22% of bus users said they would be willing to pay 0.4 EUR extra or more [10]. Whether the UK public would be willing to pay more through taxation for less polluting buses is not known, although this suggestion proved very unpopular amongst bus users in Luxembourg, who felt that the users of the service should pay for it themselves.

In general, people who already use buses regularly will value hybrids if they are cheaper, quieter, smoother or less

polluting than conventional buses. Non-bus users are more likely to focus on the environmental impacts (emissions and noise) relative to the cost burden upon the taxpayer.

2.3.2 Government

Established in 2000, Transport for London (TfL) is the agency responsible for implementing the Mayor of London's transport strategy for the London transport system. TfL sells franchises granting companies the right to operate buses on specific routes across London, and through these franchises, influences the bus technology used. London is a particularly important city for bus transport – representing approximately 70% of the market for new buses in the UK (about 500 per year). 6500 buses operated on 700 routes in London, carrying 5.4 million passengers per day in 2002 [11]. This had increased to 8300 buses by the end of 2008 [12].

UK government subsidises bus travel relative to car travel by giving bus operators a rebate of around 80% on the duty paid on their fuel. This means that bus companies typically pay around half as much for fuel as private car drivers. So far, this rebate has increased automatically in line with increases in fuel duty, but the Secretary of State for Transport announced on 16 December 2008 that from April 2010, the grant would only increase for operators who showed increases in fuel economy.

TfL is strongly encouraging manufacturers to develop hybrid buses. TfL mandates that all manufacturers who supply buses for London give the option of a hybrid engine technology and it plans for all new buses from 2012 to be hybrids. At present, to encourage bus operators and manufacturers to employ hybrid technologies, TfL is running hybrid trials with each of the bus manufacturers, and is paying operators the difference in price between a hybrid engine and a conventional diesel engine bus.

2.3.3 Bus manufacturers and supply chain

TfL has required all bus manufacturers who want to continue to sell buses in London to develop a hybrid system. The difference in cost of the system is borne by TfL, with operators benefitting from the reduced fuel consumption at no extra cost (for the time being).

The costs for manufacturers in developing hybrid technologies is subsidised by their ability to charge a premium for these systems (which is covered by TfL). In the future, the costs of hybrid systems will need to be more competitive with respect to the range of benefits offered. Economies of scale and experience curve effects should enable costs to come down over time. Manufacturers and associated transport technology suppliers will see hybrid technologies as an attractive market (in particular because of the way hybrids are being supported by TfL), and a low-risk platform for promoting their own green credentials.

2.3.4 Bus operators

If there were no subsidy available (which we might expect to be the case in the long term), then bus operators would purchase a hybrid instead of a conventional diesel bus only if the cost savings in fuel outweighed the purchase price differential (discounting future earnings relative to current earnings/expenditure). This assumes as outlined above that other difficult to quantify benefits of hybrids are ignored.

If we assume that the real (ignoring inflation) price of fuel is fixed at £1 per litre for diesel and that bus operators pay 50% of this, and that future earnings are discounted by 5% in real terms relative to current earnings, the 12-year *present value* (PV) of saving 15755 litres/yr of fuel is:

$$PV = \sum_{i=1}^{i=12} \frac{15755 \times 0.5}{(1 + 0.05)^i} = \pounds 73000$$

This means that the 12-year NPV, which equals the present value minus the initial cost, will be positive if the price differential between a hybrid and a conventional diesel bus is less than £73000. Current price differentials are in excess of £100000. Hybrid technologies therefore cannot be justified purely in terms of an economic argument of fuel savings over purchase price (furthermore, the assumption that hybrid buses including batteries will be equivalent to conventional buses in terms of maintenance costs seems optimistic).

Note that there will be other costs and other benefits not included in this analysis, such as the potential for increasing ridership by offering a service that is preferred by passengers, and reducing the number of accidents through the smoother acceleration and braking possible with hybrids (there are 77000 buses and coaches registered in the UK, with 8559 accidents per year [13] – a major expense for bus operators). Furthermore, if TfL mandates a transition to hybrid technology as it suggests it will, or if TfL gives significant incentives for emissions reductions, the case for hybrid technology will be significantly improved from the point of view of operators.

3 Discussion

Note that the choice of discount rate is important in establishing the PV figure. Increasing the discount rate to 10% (which in normal economic conditions is probably a reasonable figure), reduces the present value of the fuel savings from £73000 to £59000.

An alternative way of valuing hybrid bus technology is to follow EU Directive COM (2007) 817 on the promotion of clean and energy efficient road transport vehicles. Adopted in October 2008, this directive has the explicit intent to stimulate the market for cleaner, more energy efficient vehicles specifically including buses by compelling the relevant authorities and their operators to factor a “lifetime cost” of fuel consumption and emissions into procurement decisions. The explanatory memorandum to the directive states:

“There is considerable potential for reducing energy consumption and the emissions of CO₂ and pollutants from vehicles. However, broad market introduction of technologies with better performance is often hampered by high initial cost and therefore insufficient customer demand ... Action at Community level is therefore needed in order to encourage the investments required for the manufacture of vehicles that are more energy-efficient and less polluting.” [14]

The EU directive goes beyond suggesting that lifetime costs be taken into account, to requiring a specific approach for quantifying the value of fuel and emissions savings over the life of the bus. This is described in full in the Appendix. It is interesting to note that, although the EU approach seeks to quantify the benefits of clean road transport in financial terms, it does not advocate the discounting of future benefits relative to current benefits. This perhaps reflects the fact that they are interested in social benefits rather than economic ones per se.

Nevertheless, most government bodies do recognise the importance of discounting future benefits for investment appraisal. The UK Treasury, for example, specifies that a real discount rate of 3.5% should generally be used for publicly funded projects [15]. This represents the extent to which society as a whole should discount future earnings relative to current earnings, and is based on:

- Pure time preference for consumption
- The fear that catastrophe may devalue any returns expected in the future
- The expectation that the economy will grow and therefore there will be more wealth available in the future

Applying the government’s rate of 3.5% to the fuel savings calculation above gives a PV of £79000 (cf. £59000 with a typical commercial real discount rate of 10%, £73000 with a real discount rate of 5%).

This suggests that UK government will value the savings generated by the technology investment by 33% more than business would, and this is without attaching a value to the emissions reductions. Note that there is some controversy in economic literature over the extent to which private and public financing of projects should lead to different valuations [16]. In particular, should the private sector’s cost of capital and hence discount rates be greater than the government’s? If this higher discount rate reflects a different assessment of a project’s underlying risk, then perhaps the government is underestimating the risk of a project, or not identifying correctly who is carrying the risk. In this case, taxpayers are bearing the risk in the case of centrally funded subsidies, and bus users are bearing the risk if fares must increase to fund TfL’s subsidies.

The EU approach would attach a value of £63123 to the energy (fuel savings) over the life of the bus (assumed to be

500000 miles, or 12 years at 41667 miles/year), which is lower than the 12-year PV calculated from discounted cash flows (other than for the 10% discount rate case). However, the EU approach attaches an additional figure of approximately £10000 of the lifetime savings in emissions, making the present value of fuel and emissions savings for the hybrid approximately £73000, comparable to the PV calculation. This suggests that a price subsidy of approximately £70000 would be appropriate when purchasing hybrid buses. Yet the cost difference between hybrids and conventional buses is almost twice this level.

The benefits of hybrids relative to conventional diesel buses will increase if:

1. The fuel rebate received by bus operators is reduced. UK Operators currently pay approximately 50% of the normal pump price, but operators elsewhere in the EU do not receive such a subsidy. If this rebate were taken away (or converted into a subsidy per mile travelled instead of a fuel subsidy), the value of the fuel savings would approximately double
2. The price of fuel increases significantly. Over the lifetime of a hybrid bus, the real price of fuel could conceivably double or even quadruple. It seems unlikely that the price of fuel will fall significantly, on the other hand. A doubling in fuel price would approximately double the modelled lifetime benefits
3. The EU values associated with saving energy or reducing emissions are increased. This is possible depending on how environmental concerns develop
4. The efficiency of the hybrid engine increases relative to a conventional engine. The hybrid is estimated to use 60-75% as much fuel as a conventional engine. Significantly higher efficiencies seem quite unlikely
5. The cost of manufacturing hybrid buses falls relative to conventional buses. This will happen over time due to economies of scale as hybrids become established

Note that the EU figure of £10000 for the value of emissions savings may seem low. This is a reflection, however, of the fact that, even in London, buses are responsible for only a small proportion of the total CO₂ emissions. By 2012, the introduction of hybrid buses will account for just a 0.1% reduction in London’s total CO₂ emissions. By the time all buses are hybrid (around 2025), this figure will rise to 0.6%. With this in mind, it is important not to overstate the role hybrid buses will play in improving the environment, especially without considering their cost – 500 buses per year at £100k per bus equates to £50m per year in subsidy in London.

3.1 Sensitivity analysis

The factors outlined above have been explored to find the sensitivity of PV calculations under various discount rates to:

- Efficiency of the hybrid engine
- Through-life distance travelled (in 12 years)
- Fuel price (after any rebate) and value of emissions

3.1.1 Efficiency of the hybrid engine

The default assumption presented so far is that the hybrid engine reduces fuel consumption by 40%, equivalent to an increase from 6 to 10 mpg. This is a relatively optimistic assumption and depends on specific operating conditions and the technology employed.

A more pessimistic approximation would be to say that fuel consumption will reduce by only 25%, corresponding to an increase from 6 to 8 mpg. The result of this is to decrease the fuel savings (and therefore their value) by 37%. This reduces the (5% discount rate) PV of fuel savings from £73000 to £46000.

3.1.2 Through-life distance travelled

The EU directive assumes a distance of 800000 km or 500000 miles for the distance travelled by a bus in its lifetime. Our PV calculation assumed 50% greater distance travelled – 750000 miles. The effect of this is to increase the PV by 50% relative to the EU distance. The PV assuming a 500000 miles lifetime distance travelled therefore falls by a third from £73000 to £49000 (5% discount rate).

3.1.3 Fuel price and value of emissions

The EU approach explicitly separates out the energy value of fuel and the associated emissions. However, since fuel is taxed by government, it seems reasonable to expect the tax to reflect the externalities associated with running a motor vehicle – including both the cost of congestion and the impact of emissions. Rather than exempting bus operators from part or all of the tax on their fuel as is the current situation in the UK, a more sensible approach would be to grant a subsidy to bus operators based on the distance they travel, incentivising them to use fuel-efficient vehicles.

So far, we have assumed somewhat arbitrarily a diesel price of £0.5/litre. This represents approximately what the operators might expect to pay in real terms over the next 12 years, assuming no significant fuel price inflation (relative to general inflation) and no significant change in the approach to offering rebates to UK bus operators.

Calculating all of the external costs associated with motor vehicle use is both difficult and controversial. The International Center for Technology Assessment estimated in 1998 that the external environmental, health and social costs of motor vehicle use summed to between \$0.5 and \$2 per litre of fuel [17]. It is conceivable that the growing

impact of climate change and the increasing cost of congestion in the world’s largest cities would amplify these estimates today.

For this analysis, we have considered a range of scenarios for real fuel prices, in each case assumed to include associated social and environmental costs:

- Price fixed at £0.5/litre throughout (default)
- Price fixed at £1/litre throughout
- Price fixed at £2/litre throughout
- Price ramps up from £0.5 to £1/litre over 12 years
- Price ramps up from £0.5 to £2/litre over 12 years
- Price ramps up from £0.5 to £5/litre over 12 years
- Price ramps up from £1 to £2/litre over 12 years
- Price ramps up from £1 to £5/litre over 12 years

The impacts of these changes are shown in Figure 4 (for discount rate of 5% only), and Figure 5 (for discount rates from 0 to 10%).

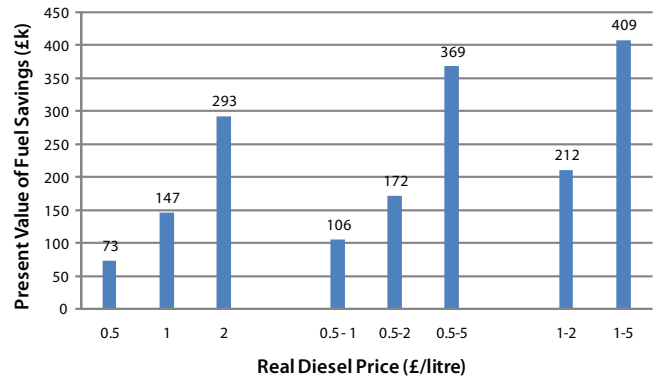


Figure 4 - The impact on present value of fuel price (discount rate 5%)

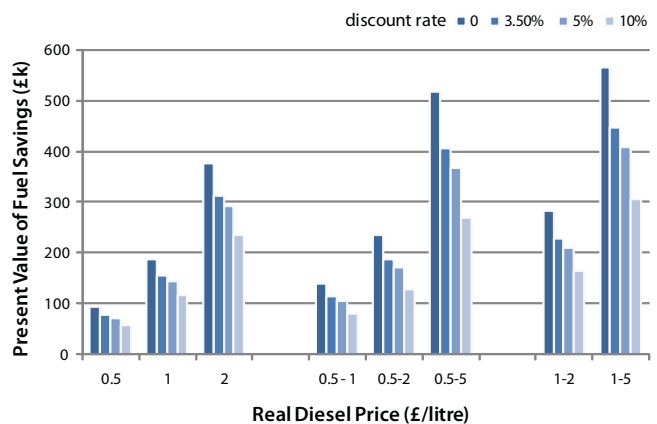


Figure 5 - The impact on present value of fuel price (various discount rates)

3.2 Indirect benefits of hybrid buses

Notwithstanding the fact that the cost-effectiveness of hybrid buses is likely to improve significantly over time due to the factors outlined above, the business case for hybrids may not need to be made purely on direct fuel and emissions savings over the bus' life. In addition to the direct benefits, there are indirect benefits that may follow from developing hybrid technology:

- Increased ridership of buses, as they are seen to be more environmentally friendly
- Technology developed for hybrid buses may be exploited for other value-creating technologies such as other hybrid or fully electric vehicle technologies

3.2.1 Increased ridership of buses

Many in the bus industry feel that passengers would not wait for a hybrid bus if there were a conventional diesel bus waiting at the bus stop. Whilst this may be true, existing bus users will automatically be exposed to hybrid buses as they are introduced on more and more routes. If their experiences with hybrid buses are as positive as early indications suggest, particularly in terms of hybrids' lower noise and smoother braking, it is reasonable to expect customers to develop a preference for hybrid buses over conventional buses. Over time, this may extend to a preference for hybrid buses to alternative means of transport, and conceivably might lead to a greater adoption of hybrid and electric cars over those with conventional petrol and diesel engines.

Furthermore, the novelty of hybrid buses, particularly if they are promoted as a cheap and environmentally-friendly alternative to cars, may encourage non-bus users to try using the bus. Even a very small uptake here would make a significant difference to the environmental argument for hybrids, although it is too early to be able to quantify the value of this effect.

3.2.2 Follow-on technologies

An additional indirect benefit of hybrids over conventional buses is that they encourage the development of novel technologies that may prove to be more valuable for later systems. In particular, fuel cell and fully electric buses and cars will benefit from some of the battery and control system technologies developed for hybrid buses. Much of the value of these future developments will not be captured by an NPV valuation of the hybrid technology alone, but requires a 'real options' approach, based on a decision tree. To illustrate this, consider the following hypothetical example [18]:

A manufacturer is considering getting involved in the development of technology for hybrid buses (at a cost of £6m), and knows that there will be an opportunity to extend the hybrid programme to fuel cell research and development (costing a further £15m). Assume for simplicity a situation where the hybrid development

programme delivers no value in the marketplace on its own. In other words, if the manufacturer conducted the hybrid R&D but decided not to continue to fuel cell R&D, it would not recover any of the initial £6m cost of the hybrid R&D.

The decision of whether to conduct the fuel cell R&D is informed by the outcome of the hybrid R&D programme, whose outcome could be 'Excellent', 'Good', or 'Poor'. This outcome is strongly correlated with the expectations of the final value in the marketplace of the fuel cell R&D, which is predicted to vary between +£60m (80% chance if the outcome of the hybrid R&D is excellent), and -£60m (90% chance if the outcome of the hybrid R&D is poor). The other possibilities are shown as a decision tree in Figure 6 ('decision nodes' are square, 'chance nodes' are circular).

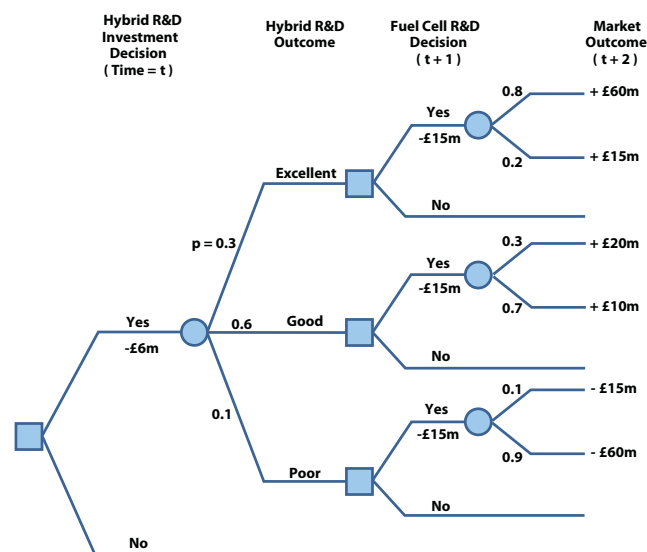


Figure 6 - Real options example for hybrid/fuel cell buses

If we were now to calculate the standard NPV of the hybrid R&D project with a discount rate of 5%, we would obtain:

$$-6 - \frac{15}{1.05} + \frac{0.3(0.8 \cdot 60 + 0.2 \cdot 15) + 0.6(0.3 \cdot 20 + 0.7 \cdot 10) + 0.1(0.1 \cdot -15 + 0.9 \cdot -60)}{1.05^2} = -4.4$$

If, on the other hand, we were to recognise that we have the option not to continue to the fuel cell R&D project if the hybrid R&D outcome is not excellent, we obtain the 'real options' valuation of:

$$-6 - \frac{0.3 \cdot 15}{1.05} + \frac{0.3 \cdot (0.8 \cdot 60 + 0.2 \cdot 15)}{1.05^2} = +3.6$$

The value of +£3.6 tells us that we expect to generate £3.6m of value over and above the £6m cost of performing the hybrid R&D (and including the £15m cost of performing the fuel cell R&D if the hybrid R&D has an excellent outcome). The real options approach gives the hybrid R&D programme an £8m higher value than the

standard NPV calculation, and is a fairer reflection of the true value since it recognises that there is no obligation to perform the fuel cell R&D if the hybrid programme is unsuccessful. Such follow-on benefits may represent a significant contribution to the whole-life value of hybrid bus technology, although predicting them now will be difficult.

Note that neither of these indirect benefits is specific to hybrid technologies rather than, say, fuel cell or fully electric buses. The indirect case for hybrid buses, is therefore a two-part argument: (i) is there value in promoting a more energy efficient and lower emissions alternative to the conventional diesel bus, and (ii) what is the best technology to achieve this? Hybrids have a significant advantage relative to fuel cell or fully electric buses, as they require no change to the existing infrastructure, and their costs are therefore significantly lower. Furthermore, developing hybrid technology now may help to reduce the costs of fuel cell and fully electric buses in the future. It is for this reason that TfL and other governance organisations around the world are promoting hybrid buses.

3.3 Does TLMC make sense for buses?

It may be interesting to reflect at this point on the value of applying TLMC to this situation. As far as the required capability is concerned, we can say that a bus service fulfils government's need to provide a way for members of the public to travel in and across a city without recourse to private vehicles of any kind. The service must be safe, reasonably cheap, and accessible, even to those with disabilities. It must operate for long hours, be (at least) somewhat comfortable, reasonably efficient in terms of journey times, and it must not adversely effect users or the surrounding environment significantly (in terms of noise, pollution, etc.)

There is no foreseeable end to the need to provide these capabilities. Environmental or other concerns may encourage the development of technologies fundamentally different to a bus, but the need for a governance organisation to provide cheap public transportation that is accessible to the masses will remain. Such an organisation can therefore afford to take a long-term view of the technologies it promotes (although this may be clouded somewhat by the timetable for re-election of officials).

In this situation, although it may be possible to specify the capability required in broad terms, the benefit of applying a TLMC approach to requirements specification is likely to be limited for three reasons. Firstly, the potential for innovation by the manufacturer in terms of the type of service offered is limited. This is particularly true given that the customer (TfL) is partitioned according to mode of transport – so that bus operations are overseen by a different group to underground operations. This both reflects and perpetuates the traditional mindset that the vehicles available for public transport are just buses,

underground trains, and surface trains. Given the infrastructural constraints of transport, particularly in densely populated cities like London, such a mindset is understandable. But in this situation, we cannot expect radical innovations from the supply chain alone (as TLMC would encourage). Instead, the spur for innovation must come from the network regulator, TfL. Secondly, the number and diversity of stakeholders concerned with the provision of bus services is much greater than it is for defence equipment. The job of specifying the requirements of a public transport system without reference to the solution envisaged is both difficult, and subject to political re-interpretation. Thirdly, the market for road transport systems is imperfect due to externalities and is unpredictable due to the government's changing attempts to correct these. In particular, there is real uncertainty over the costs that will be levied on contributions to atmospheric pollution (including global warming) and congestion in the future, which significantly change the economics of various modes of transport and facilitating technologies.

4 Conclusions

The International Council on Systems Engineering's mission is to "... produce technologically appropriate solutions that meet societal needs" [19]. To achieve this, systems engineers must reflect from time to time on the extent to which technologies represent value for money for society.

The whole life benefits of hybrid buses relative to conventional buses are unproven. Making an overall decision on the merits of different technologies that are valued in different ways by different stakeholders is difficult. This is especially true if you consider different scenarios for the future [20], considering different regimes for taxing pollution, for example. The maintenance costs in particular are unknown; replacement costs of a hybrid's battery are expected to be significant but battery disposal costs may be positive or negative (there may be a resale market for use in less demanding applications). Maintenance of the engine, transmission and brakes may be less costly for hybrids than for diesel engines, but reliable data on this is not yet available. Further benefits such as noise reductions and smoother deceleration are valued by passengers, but difficult to quantify in financial terms.

A straightforward whole-life appraisal of the costs and benefits of hybrid buses therefore necessarily focuses on the fuel savings of hybrids relative to conventional diesel buses, and the reduction in emissions. The outcome of such an analysis depends heavily on the assumptions we make concerning the distance the bus will travel in its lifetime, the size of the efficiency advantage of the hybrid engine over a diesel engine, the rate at which we discount future benefits relative to current benefits, and our expectations about the price of fuel. The last of these is particularly pivotal. It seems reasonable to assert that the real price of fuel in the UK (including social and environmental impacts) is now at least £1/litre, and over a 12-year period will

increase to more than £2/litre. In this case, and adopting the government's preferred real discount rate of 3.5%, a 10 mpg hybrid bus covering the EU specified figure of 500000 miles will save £154000 in fuel costs in its lifetime. If the hybrid managed only 8 mpg, it would still save £96000 in fuel costs. This alone makes a reasonable case for investing in hybrids, but not a truly compelling one, since hybrids cost somewhere in the region of £100000 more than conventional diesel buses to manufacture.

However, investing in hybrid technology may still make good financial sense, as this cost differential is expected to fall as hybrid volumes increase, and the value of the benefits is likely to increase due to efficiency improvements. Furthermore, even if the case for hybrids can still not be made in terms of these direct benefits, the successful promotion of hybrid buses as an environmentally friendly alternative to the car may encourage a small proportion of car drivers to try the bus. Even a small effect here could make a big difference to the environmental argument (with the added benefit of reducing congestion on the roads). Finally, but of no little significance, the investment in hybrid buses may be a crucial stepping stone to achieving more radical improvements in efficiency from related technologies like fuel cell buses and fully electric vehicles.

5 Acknowledgments

This project is sponsored by the UK Technology Strategy Board (TSB) and the Department for Transport.

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7 Appendix

Directive of the European Parliament and of the Council on the promotion of clean and energy efficient road transport vehicles

Article 3

Energy and environmental costs as award criteria in the procurement of vehicles

1. For the purposes of this Directive, operational lifetime costs for energy consumption, CO₂ emissions, and pollutant emissions linked to the operation of the vehicles under procurement shall be monetised and calculated following the methodology set out in points (a), (b) and (c).

(a) The lifetime cost of the energy consumption for the operation of a vehicle shall be calculated using the following methodology:

– the fuel consumption per kilometre of a vehicle according to paragraph 2 of this Article shall be converted into energy consumption per kilometre, using the conversion factors of Table 2 in the Annex for the energy content of the different fuels;

– a single monetary value per unit of energy shall be used. This single value shall be the lower of the cost per unit of energy of petrol or diesel before tax when used as a transport fuel;

– lifetime cost of the energy consumption for the operation of a vehicle shall be calculated by multiplying the lifetime mileage according to paragraph 3 by the energy consumption per kilometre according to the first indent of this paragraph, and by the cost per unit of energy according to the second indent of this paragraph.

(b) The lifetime cost for the CO₂ emissions of the operation of a vehicle shall be calculated by multiplying the lifetime mileage according to paragraph 3 by the CO₂ emissions in kilograms per kilometre according to paragraph 2, and by the cost per kilogram taken from Table 3 in the Annex.

(c) The lifetime cost for the pollutant emissions of the operation of a vehicle shall be calculated by adding up the lifetime costs for emissions of oxides of nitrogen, non-methane hydrocarbons, and particulate matter. The lifetime cost for each pollutant shall be calculated by multiplying the lifetime mileage according to paragraph 3 by the emissions in grams per kilometre according to paragraph 2, and by the respective cost per gram taken from Table 3 in the Annex.

2. Fuel consumption, CO₂ emissions, and pollutant emissions per kilometre for vehicle operation shall be based on standardised EU test procedures for the vehicles for which such test procedures are defined in EU type approval legislation. For vehicles not covered by standardised EU test procedures, comparability between different offers shall be ensured by using widely recognised test procedures, or the results of tests for the authority, or in the absence of these, information supplied by the manufacturer.

3. Total lifetime mileage of a vehicle shall be based on the technical specifications used in the procurement. In their absence, it shall be taken from Table 4 in the Annex.

Annex

Data for the calculation of external lifetime costs of road transport vehicles for the purpose of this Directive

Table 2 – Energy content of motor fuels

Fuel	Energy Content
Diesel	36 MJ/litre
Petrol	32 MJ/litre
Natural Gas	38 MJ/Nm ³
LPG (liquefied petroleum gas)	24 MJ/litre
Ethanol	21 MJ/litre
Biodiesel	33 MJ/litre
Emulsion fuel	32 MJ/litre
Hydrogen	11 MJ/Nm ³

Table 3 - Cost for emissions in road transport (2007 prices)

CO ₂	NO _x	NMHC	Particulates
2	0.44	0.1	8.7
€/cents/kg	€/cents/g	€/cents/g	€/cents/g

Table 4 - Lifetime mileage of road transport vehicles

Vehicle category (M and N categories as defined in Directive 2007/46/EC)	Lifetime mileage
Passenger cars (M1)	200000 km
Light commercial vehicles (N1)	250000 km
Heavy goods vehicles (N2, N3)	1000000 km
Buses (M2, M3)	800000 km