Available online at www.sciencedirect.com
ScienceDirect
Journal of Power Sources 168 (2007) 95–98
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Short communication

Hybrid buses—What their batteries really need to do

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Received 19 November 2006; received in revised form 22 February 2007; accepted 22 February 2007
Available online 2 March 2007

Abstract

Hybrid buses are widely seen as an important element in reducing carbon dioxide and noxious emissions. These buses are now starting to be seen in significant numbers in some city bus fleets. However, whilst some designs have been successful, others have been plagued by battery problems and failure to achieve predicted fuel savings in service. This has sometimes been caused by lack of understanding by both the vehicle designer and battery supplier, who generally have little experience in each other's areas. This paper looks at some key design issues that need to be addressed in developing a successful hybrid bus battery pack design.

Keywords: Hybrid bus; Regeneration; Battery lifetime

1. Introduction

Hybrid buses are seen by various studies, e.g. Ref. [1] as being an important element in a strategy for reducing CO_2 and noxious emissions, particularly in city centres. Whilst such buses can take many forms it is widely considered that a diesel–electric hybrid with on-board battery energy storage is the most practical and cost-effective approach available today. Relatively small, but significant, numbers of these vehicles are now in operation in many parts of the world, e.g. Ref. [2].

Initial experiences with these fleets have been mixed, with battery problems and failure to meet predicted fuel savings seen with some vehicles, but not others. The author has been heavily involved with the design of one particular hybrid bus (Fig. 1) and spoken to those involved with several others. A common theme that has emerged is that those hybrid bus developments where the needs and limitations of the battery have been fully considered have generally been successful and those where less care has been taken have not.

This paper seeks to highlight the key issues that must be considered at the system design stage when specifying, selecting and operating the battery system for a hybrid bus. The battery industry needs to be aware of these issues as some of the battery failures have been due to poor advice from battery suppliers compounding lack of battery awareness at the vehicle designers.

2. Hybrid bus objectives

The objectives for developing what will probably always be a more expensive type of vehicle than a conventional bus are a reduction in fuel consumption, (and hence CO_2 emissions), reduced noxious emissions and reduced vehicle noise. There is also considerable interest in operating the bus in Zero Emission (ZEV) mode relying totally on stored energy to supply the vehicle on part of the route. As will be covered later there are significant penalties in providing ZEV range in terms of battery life and system cost and this mode must inevitably generate greater overall emissions due to the round-trip efficiency of the battery. However, ZEV operation is very attractive to some stakeholders.

3. Other design requirements

Most hybrid buses that have been developed do meet the above objectives, at least to some degree. However, a commercially viable design must also meet the requirements of any bus. It must drive in a similar way to a conventional bus in terms of reaction to the controls, smoothness etc. It must last for 1,000,000 km with the same maintenance schedules, realistically without requiring additional specialist staff. It must meet availability targets without extra in-service failures that require

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doi:10.1016/j.jpowsour.2007.02.063

Fig. 1. Alexander-Dennis Enviro 200H Prototype. Source: Alexander-Dennis.

tow-backs. In addition, the vehicle must be cost competitive over the lifetime of the vehicle and still offer a 5-year or longer warranty. Meeting these requirements is not trivial, especially when each 68 kg additional weight results in one less passenger that can be carried. In spite of the large physical size of the vehicles there is little spare space to fit the additional components, particularly on modern low-floor designs. To avoid the need for specialist maintenance staff it is also necessary to have the battery system configured as a single complete unit, or small number of modules (Fig. 2).

4. Key issues in specifying the battery system

Development of the vehicle system design is normally assisted by the use of a simulation tool [3,4]. Use of these tools quickly shows that there are several important trade-offs to make. For the battery system the key issues to consider are the required battery lifetime and failure statistics, how much energy needs to be recovered during regeneration, whether ZEV operation is required and if so, for what range and performance delivery. The influence on each of these issues on the sizing, selection and design of the battery system is discussed below.

5. Required battery lifetime

The most common problems with poorly specified batteries in hybrid buses to date is that the battery supplier predicts a lifetime of 2–3 years, but they only last 2–3 months. This appears mainly to be due to a lack of understanding on both sides. The bus designer does not realise that a typical battery does not respond well to running over a wide range of SOC with high powers and frequent cycles, but wants to minimise the size and weight of the pack. The battery supplier does not understand the type of duty to which the battery is to be subjected and tends to quote a lifetime that would be typical of a fork-lift battery. The type and statistics of failure are also important. A large 600 V pack with 300 cells may be sized to have an average cell life that is acceptable. However, this would not be a practical solution if there is significant diversity in cell lifetimes, especially if each time one fails the bus needs to be pulled out of service because the battery cannot be used with a failed cell.

An ideal battery system would last at least 5 years. However, it is probably more important to have no unplanned failures, or at least have sufficient warning to allow some kind of remedial action at a normal maintenance interval. Even more important is that the bus can continue to operate with a failed cell, or cells, accepting that the hybrid performance will be compromised until the battery is repaired. An absolute minimum, and then only if the batteries were very inexpensive to replace, would be a 1 year life, but there would have to be a high level of confidence in no unplanned failures before this. Some kind of pack refurbishment would be possible at this time. It is worth mentioning that some bus operators consider even a 5-year life too short.

Fig. 2. Complete battery module. Source: Zebra.

6. Energy recovery during regeneration

A hybrid vehicle has two main areas where it can offer improved efficiency. Firstly, the diesel engine can be operated in a more efficient way, generally by minimising transients, operating in 'better' parts of its operating envelope and/or by stopping the engine at idle. Real-world strategies follow these general principles, but are more sophisticated in the way they are implemented. Secondly, the vehicle recovers a proportion of its kinetic energy when slowing (regeneration) and stores this in an energy store, normally a battery, for later use.

To get a really significant fuel consumption improvement it is essential to gather a good percentage of the available energy during regeneration. It is worth noting here that the minimum theoretical energy required to traverse the route (E_{min}) can be

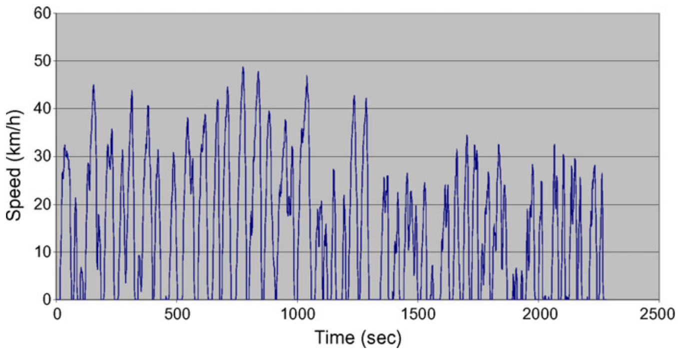

Fig. 3. MLTB cycle. Source: Millbrook Proving Ground.

obtained to a good first approximation from:

$$E_{\min}\,(\mathrm{J}) = M_{\mathrm{v}} g C_{\mathrm{rr1}} D + P_{\mathrm{F}} T \tag{1}$$

where M_{v} is mass of the vehicle in kg; g acceleration due to gravity in m s^{-2}; C_{rr1} first rolling resistance coefficient; D distance in m; P_{F} fixed, mainly electrical power drain on the vehicle in W and T is time to transit the route in seconds.

This assumes that the aerodynamic loads on the vehicle are negligible, which is a reasonable assumption for an advanced city bus at typical city speeds. As the fixed loads can be significant, particularly with an air-conditioned bus, the best way of reducing the total energy is to keep T as small as possible. Unfortunately, accelerating and decelerating the bus inevitably results in a loss of energy, but this is minimised if the bulk of the energy imported to the vehicle during acceleration is recovered by regeneration during deceleration.

A 12 tonne bus travelling at 70 km h^{-1} has a maximum recoverable energy of around 0.5 kWh, so an ideal battery would be able to recover all of this on each stop. This might look straightforward at first, but the power requirement needs to be considered as well. Fig. 3 shows the speed profile of the MLTB cycle which was developed by Millbrook based on actual measurements on route 159 in London (Fig. 4). This cycle is now used as the official test of Low Carbon Buses in the UK on the chassis dynamometer at Millbrook. If this data is processed to identify the acceleration and deceleration levels at various speeds (Fig. 5), one can see that the bus is often operated outside the generally accepted comfort limits of ±0.1 g, and that a reasonable design maximum deceleration for sizing regeneration capability would be 0.15 g.

Fig. 6 shows the percentage of recoverable energy decelerating from designated speeds to rest, as a function of maximum allowable battery regeneration power. It can be seen that a high battery recharge power capability is required to get a high recovery percentage. If the battery is sized so that the 0.5 kWh cycles represent 2% SOC swing this would result in a 25 kWh pack, around 40 Ah for a 600 V string. Accepting 240 kW into such a pack would result in approximately 10 C recharge currents.

Considering battery lifetime, a bus operating on the MLTB cycle has approximately 1 regeneration event per minute of 0.25 kWh. This would give 1080 regeneration events in an 18 h day, typical of operation in London, giving a daily throughput of 270 kWh. For our assumed 25 kWh pack above, assuming a lifetime throughput of 1000 nameplate cycles or 25 MWh for 1% DOD cycles, this would give a lifetime of around 90 days. Therefore, to get even a 1-year life needs a much larger pack capacity, especially when one considers that even early outlier failures effectively dictate a complete pack change.

Fig. 4. Classic Routemaster bus on route 159.

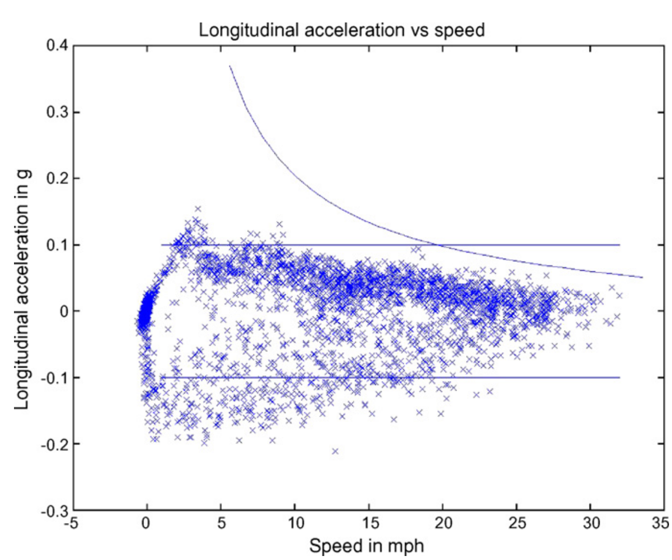

Fig. 5. MLTB cycle presented as acceleration vs. speed.

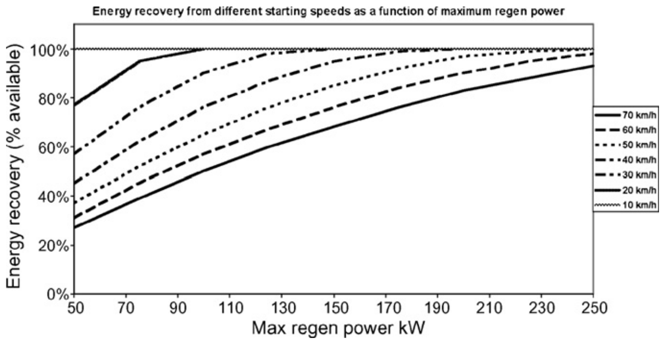

Fig. 6. Energy recovery as a function of starting speed and regeneration power available.

Some hybrid system designs further stress the battery by running the engine at a fixed power level, often switching off at, say, 80% SOC and on at, say, 30% SOC, and using the battery to match the delivered power to the instantaneous requirement.

7. ZEV operation

As mentioned before, many stakeholders find ZEV operation very attractive, but this clearly puts significant energy demands on the battery, consequently having a deleterious effect on lifetime. If the example vehicle is operated for 10 km at 10 km h^{-1} with a fixed power drain of 6 kW it will consume at least 30 MJ or around 9 kWh and allowing for unrecoverable acceleration/deceleration energy probably closer to 15 kWh. Whilst this is approximately the same mean power as for full hybrid operation the cycle depth of discharge is 30 times larger which for most batteries significantly reduces the lifetime nameplate throughput cycles.

8. Practical implementation

Once the tradeoffs have been made and the battery correctly sized it is necessary to consider some other practical issues. The bus operator does not have staff with specialist high voltage or battery skills, so the battery system needs to be replaceable as a single unit, or at most a few units. This is common with some battery chemistries, e.g. NiMH, NaNiCl, LiIon. The pack needs to be thermally managed especially as often the only practical location is on the bus roof with varying solar heating loads. Interface to the vehicle needs careful thought and a battery management system is mandatory both to detect faulty modules and to report SOC for use by the vehicle energy management system.

9. The optimum design

Whilst it is not possible to give details of the author's actual designs for reasons of confidentiality, the process inevitably involves a complex trade-off between potential fuel usage (and CO_2 and noxious emissions) reductions, battery cost, battery life and installation and maintenance issues. It is also very important to design the complete vehicle system as a whole and not as a collection of disparate sub-systems. The detail is important and due consideration of the specification, implementation and operating strategy of the battery a key element in ensuring a successful design is achieved.

The market, heavily influenced by relevant legislation, will eventually determine the optimum design, as this is a strongly commercial sector albeit heavily influenced by political factors. However, it is already clear from detailed discussions with bus operators and other industry experts, based on current economic conditions, that the extremes of high performance/high cost and naïve low cost/short life solutions are unlikely to be viable in the market. Indeed, some kind of regulatory, policy or financial incentives are probably essential before widespread adoption can be assured.

10. Conclusions

Developing a battery system for use on a hybrid bus requires knowledge of the application and a number of difficult tradeoffs to be made, most of which result in a battery which is heavier, larger and more expensive than the customer would like, yet offer lower performance and life than desired. However, the result of ignoring these real issues is that the battery fails after a few months of service. The initial reaction may be that this is a 'bad module,' but as can be expected the time between failures reduces until the whole pack has to be replaced. When the replacement pack starts to fail in the same way the bus operator loses patience and withdraws the bus from service and does not buy any more hybrids for a while. This has actually happened in the UK.

With a correctly designed pack, proper battery management and a vehicle that can tolerate battery failure until the pack is repaired there is a potentially significant market for hybrid buses. However, unrealistic expectations or incorrect battery pack design will prevent this market developing to the point where all buses are hybrid, which should be the goal.

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