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Electric buses: lessons to be learnt from the Milton Keynes demonstration project

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Abstract

Electric buses deliver zero tailpipe emissions and have the potential to offer solutions to the air quality challenges of urban mobility in the 21st century. However, bus duty cycles are very demanding and unusually large batteries are required if electric buses are to have the range and ruggedness of their diesel counterparts. This research investigates an alternative strategy focusing on the performance of electric buses using wireless charging technology to provide opportunity charging during the working day without interrupting the timetable. In particular, the Milton Keynes demonstration project is analysed in an attempt to detect the factors that affect electric vehicles' functionality, and learn lessons retrospectively in terms of design considerations. Two different approaches are used to evaluate the performance of the eight buses which have taken over the Number 7 route at Milton Keynes since January. Firstly, an overall analysis of the buses has been conducted according to the ambient conditions, driver influence on the performance, vehicles' capabilities, vertical profile of the route as well as the driving and battery conditions. Additionally, the ground system's efficiency is analysed in order to correlate the energy drawn by the buses with the energy drawn from the network during the charging periods at the charging points. Considering the energy consumption and the system's efficiency, the actual performance of the buses and charging system is proven to be reasonably comparable to and consistent with the theoretical one while it is comfortably within the design base. This study raises important points for the crucial factors that affect electric vehicle's performance in a real life context and in a fully operational environment and could be the starting point towards proving that wireless charging is a significant game changer in terms of bus transport in the United Kingdom.

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Keywords: electric vehicles; wireless charging;opportunity charging; electric buses; Milton Keynes; energy consumption

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1. Introduction

In recent years, there has been increasing concern about pollution in cities, and in particular the contribution made by road transportation modes to this issue [1]. Whilst climate change mitigation might have been of high priority in the global political agenda the last decades, the growing interest for the environment and the drive for more sustainable transportation systems that are not related to fossil fuels have resulted in the development of a small but upcoming electric vehicle market [2].

Electric buses are part of this market; they have been involved in many local transport policy debates and have been included in several governmental strategies. They are smooth, clean and quiet, representing very attractive public service vehicles. However, for a large road vehicle like a bus, the range limitations and the recharging times of the battery packs raise the need for massive, heavy as well as expensive batteries in order to extend the operational distance before a lengthy recharge is required. The battery issues rule out the use of electric buses on an economic basis when they are compared with a diesel counterpart.

Achieving an effective operational range for electric buses has been in the spotlight for several studies; Tzeng et al. concluded that a pure electric bus with a reasonable range would be the most appropriate technology while examining for an application in Taiwan [3]. Wireless opportunity charging has been considered as a valuable alternative that could offer a wider acceptable range to electric buses. It has emerged in the last 15 years and in 2009 the contactless charging of electric vehicles was standardised [4].

2. Case study description

The MBK Arup Sustainable Projects (MASP) research that has informed the Milton Keynes electric bus demonstration project has documented the challenges of designing a battery-electric bus system that can not only technically match a diesel bus, but also match it economically. In January 2014, Milton Keynes Council introduced a fleet of eight electric buses on a busy route. Particularly, the buses run on the Number 7 route, which covers 15miles between three major railway stations in the Borough of Milton Keynes; Wolverton, Central Station and Bletchley, having 51 bus stops. The electric buses, instead of recharging their batteries using cable connection, use an innovative system of wireless charging, based on induction power transfer. The buses receive plug-in charge during the night at the cable connected Chargemaster units at the depot. After a night charging, the buses receive wireless boosting charges during periods of timetable when the bus and the drivers are resting. There are two charging points in the whole route, at the start and at end of the route. In this way, electric buses can be in service for more than 17 hours per day, just like a diesel bus.

3. Method of approach

The main question that this research attempted to answer is how electric buses perform in a real life context and in a fully operational environment, focusing on the analysis of the Milton Keynes' pilot project. The approach was divided into two phases; the first stage of this research strategy included the analysis of the electric buses' energy consumption to gain an in-depth understanding of the factors that affect buses' performance. A series of different criteria were used such as drivers' influence, vehicles capabilities, ambient conditions, vertical profile of route, driving and battery conditions. Furthermore, the ground system's efficiency is considered to be another valuable parameter of the project's assessment.

4. Research Findings – Discussion

4.1. Overall analysis of the buses' performance

The data mining and processing of the daily charging records collected by the electric vehicles offered the opportunity to examine carefully the availability of the buses from day one of their demonstration for the first five months of operation. Since the buses run a heavily-used urban route and the great challenge is the established diesel bus route to be completely electrified, it is vitally important for the fleet to be able to run a continuous service for a whole 17 hours, meeting the needs of the customers. Considering that the project is a demonstration program and the buses are prototypes, as it was expected not all buses were available when the electric buses were launched for the first time in late January. Three buses were delivered at the outset, building progressively to eight buses over the next four months; after some initial teething troubles, a good level of reliability was achieved across the working fleet and the data extracted from the buses was analysed as discussed in the following sections.

Furthermore, taking into account the energy consumption of the buses the average energy consumption per mile was estimated for each week during the first five months of operation. It should be noticed that the operating company provided charging records for a limited number of days per month. Thus using the available records [5], the average consumption (kWh/mile) for all buses per week was calculated and the results are depicted in Figure 1.

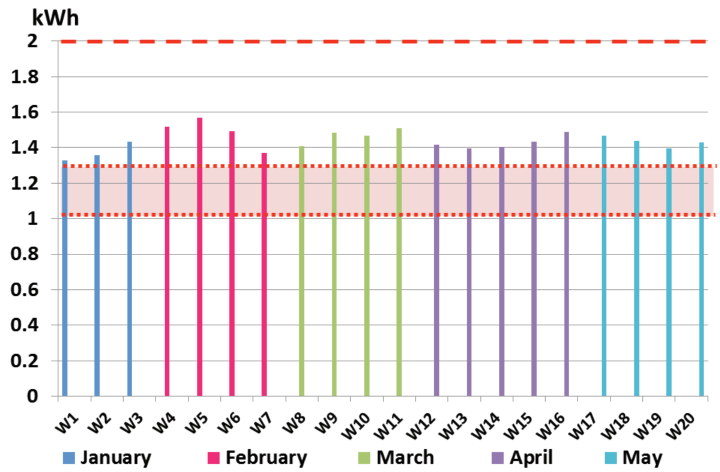

Fig. 1. Total average weekly energy consumption (kWh/mile) of the fleet from January to May 2014.

In Figure 1, the actual performance of the buses is presented in the colour lines, the theoretical performance is illustrated between the red dotted lines and the design base is depicted in the red dash line. The theoretical performance was estimated, based on the performance of a diesel counterpart, to be within a range of 1.06 kWh/mile and 1.33kWh/mile while the vehicle‘s design specification defined a design basis of 2 kWh/mile. The design base was based on a conservative estimation [5]. It accords with common sense that it might take about the theoretical power to drive the bus but it is crucially important to leave some reserve because of some extra power requirements. These requirements might appear on a hot day, when due to the weather conditions for instance the bus has to turn the lights on for the whole day. With respect to the buses' actual performance, in January, February and March many variations could be detected among the different weeks. The several variations during the first three months could be a result of extra power requirements such as severe weather conditions or lack of experience of all the involved stakeholders who were not yet with the buses' operation. Nonetheless, during April and May the average consumption tends to be more stable and close to the expected theoretical consumption.

4.2. Analysis of driver's performance

In order to evaluate the variations among the different drivers, the average energy consumption per mile was analysed for each driver separately, using the data from daily charging records [5]. In Figure 2a the energy consumption per mile is illustrated for each driver.

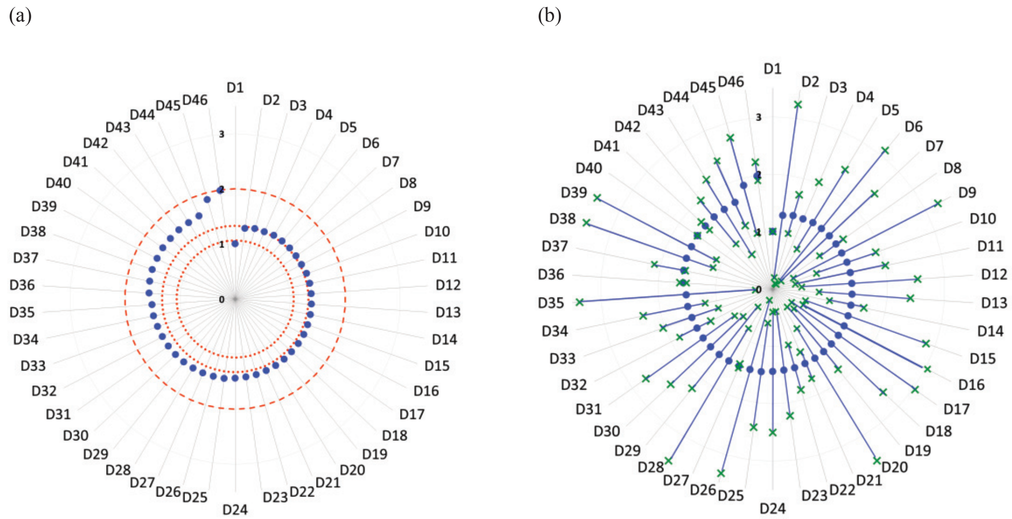

Fig. 2. (a) Average energy consumption (kWh/mile) of all drivers of the fleet from January to May 2014; (b) Average energy consumption (kWh/mile) of all drivers of the fleet from January to May 2014 with min and max values.

In particular the blue dots point out the average energy consumption per mile for all drivers that were on duty from January to May, the theoretical performance is illustrated between the red dotted lines and the design base is depicted in the red dash line. The drivers, where each one is presented by a different number, have been sorted in ascending order considering their average consumption. The minimum consumption per mile corresponds to Driver_1 (1kWh/mile) while Driver_46 is estimated to have consumed approximately 2kWh/mile on average. Thus, it can be seen that there is a variation of 1kWh/mile between the drivers. In the same figure, the average energy consumption is compared again with the theoretical consumption and the design base. It can be seen that the average consumption tends to be identical with the upper limit of the theoretical consumption and is comfortably within the design base.

In Figure 2b the average energy consumption is depicted in the same way as in Figure 2a while the range of each driver's performance is represented with the blue bars that end up to the green crosses. A great deviation between the minimum and maximum values is revealed through this graph. In some cases, for instance in the case of Drivers_6, 9, 26 and 35, the minimum values are very close to zero. There are obviously some errors in these data and clearly there are some data oddities. However, taken as a whole the results could be characterised as reasonably consistent and the average figures are almost within what is theoretically possible.

4.3. Analysis of the route

Findings reveal that, on average, the vertical profile of the route could be responsible for 1%-3% of fuel use, with light-duty vehicles falling on the upper limit of the range and electric vehicles being almost around 1% [6]. In Figure 3a the road grade is analysed for route 7.

It can be concluded that the first part of the route involves significant ripples. Looking more carefully at this part, the first 1.2 miles of the route are small Victorian streets, the next 3.1 miles are mixed roads, and the next 3.1 miles to Central Rail Station are uphill roads presenting the greatest elevation than any other part of the route. Then, the bus runs through new housing estates to Bletchley bus station.

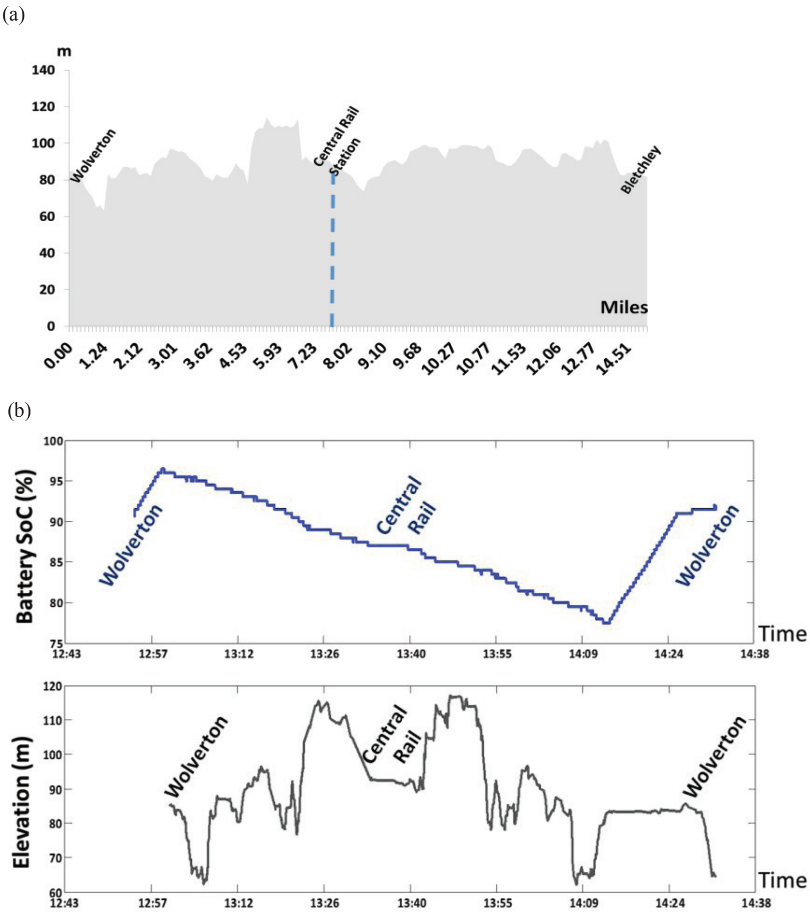

Fig. 3. (a) Elevation chart of the route 7 (Wolverton to Bletchley); (b) Battery SoC and elevation curve for the trip "Wolverton-Central Rail Station-Wolverton" on 16th June 2014.

In order to understand in depth the correlation between the battery State of Charge (SoC) and the vertical profile of the route a specific part of the route was analysed in depth. Since the first part of the route is more interesting in terms of road grade, a trip from Wolverton to Central Rail Station and back to Wolverton was chosen to be analysed for one bus (Vehicle_5) on 16th of June. Specifically, as it can be seen in Figure 3b, the part of the road which has the biggest grade corresponds to the 4.6th mile to 5.5th mile of the route; buses are going through that part of the route when they are going from Wolverton to Central Rail Station and when they are going all the way back to Wolverton as well. In the first case, the road is uphill and the bus consumes 4.5kWh while in the second case is downhill and no energy is required by the bus (Figure 3b).

Additionally, based on the analysis that is presented in Figure 3b, it was estimated that Vehicle_5 while going from Wolverton to Central Rail Station consumed 1.82kWh/mile and on the way back 1.92kWh/mile. Thus, it is clear that there are important differences between the different routes and the elevation of the route should be considered as a factor of major importance for the pilot project.

4.4. Analysis of the battery conditions

The bus consists of three strings of batteries; they are lithium ion batteries (LiNiMnCoO2) and their energy density is almost 327 Wh/L. One of the battery strings is cited on the roof of the bus (string_1) and the other two strings are fitted in the back side of the bus (string_2 and string_3). The position of each battery string could be seen as well in Figure 4. The batteries could be characterised of good quality, in terms of self-discharge, life spam and safety whilst their cost is rather moderate than high.

The battery State of Health (SoH) and the battery SoC seems to be also important factors to consider; both of them proved to be of vital importance for the assessment of the batteries' performance. Battery SoC ranges from 30% to 100%. Less than 30% is outside the recommended operating region. Since driver needs to be aware when the control SoC is reaching the lower limit, the lowest value is displayed on the dash. Driver's warnings begin at 30% while power limits are applied at 25%. In operational environment, the battery SoC of the buses is within the above mentioned limits. Technically, lower levels could be achieved as well, but it is not recommended due to battery long-life issue (limp mode issues).

(a) (b)

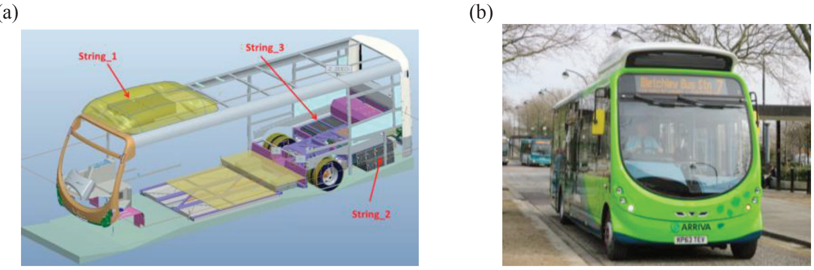

Fig. 4. (a) Inside look of the electric buses
(source: Wrighbus Limited, personal communication on 1/8/14); (b) Route 7 from Wolverton to Bletchley

In order to detect whether the three strings of batteries perform in same way or there are significant variations, the battery SoC and SoH was plotted for Vehicle_8 on 13th of June (Figure 5a) [5].

(a) (b)

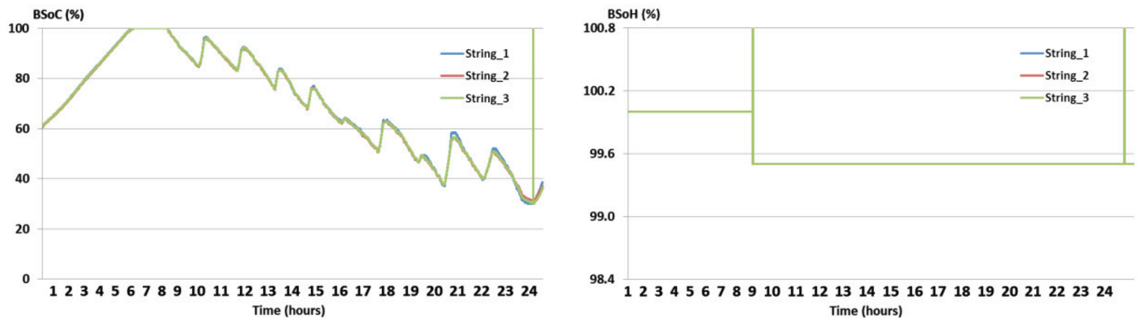

Fig. 5. Battery SoC (a) and SoH (b) of the three battery strings for Vehicle_8 on 13th June 2014

The curves of the three different strings look almost identical following exactly the same pattern. Looking at the sections of the curves which are below 100% in the first figure, it is apparent that the graphs are declining smoothly and gradually, presenting small differences between the three strings. During the periods that the bus receives booster charges, the battery SoC level is increased also gradually. It can also be concluded that the battery SoH for all the strings ranges among three different values: 99%, 99.5% and 100%. Values that exceed the 100% have not been considered for the analysis.

4.5. Ground system's performance assessment

Given the influence of the ground system on the project's performance, a correlation between the power drawn by the bus, as measured with the on-board systems, and the power drawn from the network, as measured by the network meters, took place.

The theoretical efficiency of the charging system was calculated considering all the basic components and their real power requirements. More particularly, the main consumers connected are two cooling units (3.5kW each, when compressor is on) and the two charging systems (60kW each). The nameplate power of 60kW refers to the real power delivered to the battery of the electric vehicle. Based on an efficiency of 90%, each charger will require 66.7kW. Including 700W of auxiliaries, the total power requirement is about 140kW. Thus, since 60kW is the real power delivered from each charging system to the buses' batteries, it is estimated that the efficiency lies at 80%.

Furthermore, using the data provided by the electricity distribution network operator the actual power drawn from the network was estimated [5]. It should be stressed that all the data used for the analysis is sample data recorded on the 16th of June at both charging points. Taken the power factor to be around 0.977 during the sustained charging and the recorded apparent power, the real power and the required energy was calculated for all the charging periods that took place the examined day at Bletchley.

What is more, the daily charging records taken from the bus drivers on May were used as well. Considering the battery SoC of each bus on that day before and after charging, the amount of energy that was delivered to the batteries at each charging period was estimated.

All these considered, in Figure 6 the comparison between data taken from the ground-side of the Inductive Power Transfer (IPT) system and data collected from the on-board systems from the bus-side is presented. The data is records taken on 16th of June at Bletchley charging point.

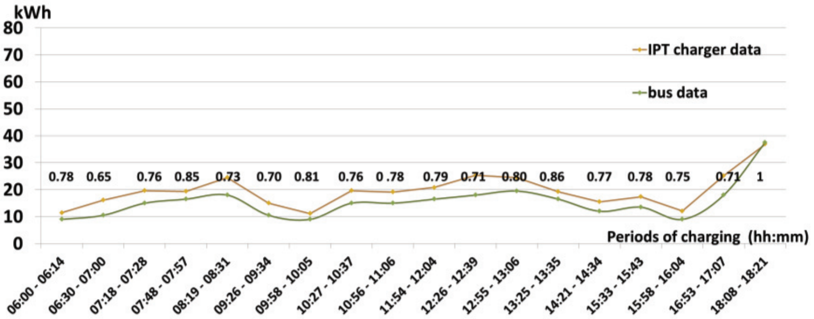

Fig. 6. Energy measured (kWh) on the buses Vs energy delivered by the IPT system on the 16th June 2014 (Bletchley charging point)

In the above Figure the energy delivered by the network and the energy received by the bus are presented for all the charging periods on 16th of June at Bletchley charging point. The data represents all the wireless boosting charges that the fleet's buses received that day. It is evident from the charging periods that almost every minute during the day there is a bus from the fleet parked on the charging point while each bus requires different amount of time on the charger. As a result, there is a range of 10kWh to 40kWh at the received energy by the buses that day during each charging period. In the same figure, the ratio of the received energy by the bus and the energy drawn by the system is illustrated. This ratio lies between 65% and 86% while the average ratio is estimated to be 78%. It is reasonable to expect the efficiency within a range since when the alignment of the bus is not proper, the batteries are not receiving full charge [2].

Overall, the actual efficiency of the IPT system could be characterised as the most important factor when assessing the whole system's performance. Based on the conclusions drawn from the presented comparison, despite the fact that the actual efficiency is within a small range, it is reasonably comparable to and consistent with the theoretical one.

5. Conclusion

The analysis enabled the initial estimation of the wireless charging system's efficiency and the comparison with the theoretical expected efficiency, concluding that the actual efficiency of the system seems to be very close to what theory would predict. In addition to that, the research work proved that the IPT devices that are installed at the two charging points can enable the buses to re-charge during the working day without interrupting normal timetabled operations and the system does not result in additional downtime, requiring for a larger fleet.

All in all, this research constitutes an initial assessment of the Milton Keynes demonstration project and could be utilised as a blueprint towards the technical availability of low-carbon transport. The important findings that came from the analysis of a great amount of data offered viable information regarding the performance of electric buses in a real life context and in a fully operational environment. Since the demand for transportation worldwide is gradually rising while the dependence on fossil fuels is challenged in economic and environmental terms, the need for alternative fuel vehicles is a high priority target. This research work could be the starting point towards proving that wireless charging could be a significant game changer in terms of bus transport in the United Kingdom. The analysis underlined that there are many parameters that should be considered beforehand as well as retrospectively in such a project. But since the actual performance of the buses is comfortably within the design basis and very close to what theory would predict, a landmark has been made for this demonstration test and this pilot project could be considered as the beginning of the road, not the end.

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