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Determining the Distribution of Battery Electric and Fuel Cell Electric Buses in a Metropolitan Public Transport Network

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Abstract

The need to decrease greenhouse gases emissions in the transport sector has resulted in the requirement for zero emission technologies in city centre bus fleets. Currently, battery electric buses are the most common choice, with both single deck and double deck vehicles in regular use. However, long-term operational capabilities are still largely unknown and unreported. Hydrogen fuel cell electric buses are an emerging zero emission technology that have the potential to complement a battery electric bus fleet where the duty cycle is challenging for current battery electric configurations. This paper compares the difference in energy consumption, for a given chassis configuration, passenger load, and heating requirement, of generic battery electric and hydrogen fuel cell electric buses operating in a typical UK city environment. A methodology was employed that will provide bus operators with a robust mechanism to inform buying decisions, based on their route characteristics, when transitioning to a zero-emission fleet. Simulations performed using battery electric and hydrogen fuel cell electric models showed that the hydrogen fuel cell electric bus has a much higher predicted range (465 km) and operating time (23.1 hours) than the battery electric equivalent (273 km and 13.5 hours) when considering a duty cycle of mixed city operation. While the hydrogen fuel cell vehicle showed limited variation in the range across all drive cycles considered, the battery electric bus showed a high percentage decrease (16.4%) in range when subjected to drive cycles with higher average road gradient. Meanwhile, when considering operation on a drive cycle with 0% average road gradient, the battery electric bus was predicted to have a percentage increase in range of 12.5%. This study shows that when considering a zero-emission vehicle technology mix, the characteristics of the service routes should be considered before deciding which powertrain configuration to utilise on each route.

Introduction

Countries across the globe are tackling the issue of climate change. The introduction of "net zero" targets and low and zero emission zones in cities, has increased interest and investment in renewable energy and zero emission projects worldwide.

In the UK, the transport sector is responsible for approximately 30% of recorded equivalent CO_2 emissions [1]. From 1990 to 2019, 50 - 60% of these emissions were produced by passenger cars. However, while the number of passenger cars sold steadily increased from 2005 to 2018 [2] the emissions produced by them decreased. This is because technological advances and the introduction of supportive policies have increased the number of electric cars registered per year in the UK from 249 in 2010 [3] to 72,584 in 2019 [4]. This development in the road car industry has encouraged research and use of zero emission technology in other transport sectors including public transport [5].

Public Transport

Public transport will play a large part in meeting net zero targets in the transport sector. However, there are several challenges which need to be overcome to establish fully zero emission public transport fleets, both within the UK and globally.

The UK bus sector is currently responsible for an estimated 3.1 million tonnes of CO_2 annually [1]. Although, over the past twenty years, there have been significant shifts in the powertrain technologies commonly used in buses. Today, there are numerous low and ultra low emission powertrain technologies in operation on the roads globally, but for zero emission, the focus is primarily on two; battery electric and fuel cell (FC) electric powertrains.

Given the advantages of electric powertrains—high efficiency, good start-stop ability, and quick power response [6]—the percentage of Battery Electric Buses (BEBs) in the European bus market is expected to rise from 19% in 2020 to 52% by 2030 [7]. However, widescale adoption of BEBs has

There is also a notable difference in the average energy consumption rate of the BEB and the FCEB over the low and high-gradient duty cycles (Tables 7-10). For the low-gradient duty cycle the BEB is predicted to average 0.86 kWh/km compared to the FCEB with 2.71 kWh/km. A similar situation arises with the high-gradient route, with 1.16 kWh/km for the BEB and 3.23 kWh/km for the FCEB. While the FCEB would be expected to be less efficient due to the inherent inefficiencies of the fuel cell and associated plant, the relative simplicity of the FCEB model is also contributing negatively to the results. In particular, the simple EMS, the lack of a suitable HVAC model for the FCEB, and the lack of comprehensive efficiency maps for the fuel cell and plant. If these were implemented it is expected that the performance of the FCEB would improve further over its current predictions.

The results of this study show the importance of considering the road elevation of drive cycles when planning for vehicle operation in particular regions, or zones within a city. For the duty cycles considered in this study, the modelled BEB shows a greater variation in range across the different operating conditions. When conducting drive cycles with low average road gradients and flat elevation profiles, the BEB was shown to be capable of a full day of service on a single battery charge, for the battery capacity considered. However, when operating on drive cycles with larger changes in elevation, the energy consumption of the BEB increased significantly, which could result in interrupted service for battery recharge, or the need for a larger battery. It is clear from the simulations that the FCEB is capable of uninterrupted operation across even the most intensive drive cycles considered here and has a much greater range than the BEB. However, in situations where the bus is required to complete repeated start-stop cycles, the FCEB may not perform at its most efficient and a BEB should be considered, range permitting. Additionally, with the capital costs of BEBs being currently much less than that of FCEBs this study shows that bus operators may be required to consider a mixed approach to their fleets, with BEBs being utilised in terrain with a more consistent elevation profile, and FCEBs on more variable elevated terrains. Overall, operators will need to consider the trade-offs between range and operating time as governed by overall fuel consumption, as well as factors such as vehicle cost, infrastructure requirements and component degradation.

The methodology employed in this study should allow fleet operators to make an efficient initial evaluation of the likely fleet makeup for operation in their city. Selecting drive cycles through clustering analysis allows for the entire bus network of a city to be simplified into a small number of clusters, with an individual drive cycle representing all the cycles within the cluster from which it was taken. Therefore, by simulating different vehicle types over a single drive cycle, the operator can decide as to which vehicle is most suitable for operation over an entire cluster of drive cycles. For a more detailed evaluation, there is also the scope to increase the fidelity of the clustering analysis to consider an increased number of routes and clusters, giving a more accurate representation of bus operation across a city bus network. This study shows the capabilities of conducting an energy consumption analysis and vehicle comparison in a relatively quick and inexpensive manner, using synthetic drive cycle production and vehicle powertrain simulation.

Conclusions

This study provides a methodology that could be used by bus operators to make informed decisions on the mix of powertrain technologies when transitioning to a zero-emission bus fleet, including:

- Synthetic drive cycle creation using GPS coordinates and an archive of existing on-road micro-trip data.
- MATLAB/Simulink battery electric bus (BEB) and fuel cell electric bus (FCEB) powertrain modelling.
- Drive cycle characteristic parameter extraction.
- Route clustering analysis.
- Drive cycle simulation and vehicle comparison.

The clustering analysis and drive cycle simulations conducted in this study showed that:

- A city bus network can be simplified into a small number of clusters, with single drive cycles representing vehicle operation for the entire cluster.
- The average road gradient of a route is the characteristic parameter with the greatest correlation to bus energy consumption.
- Based on the two specific vehicle architectures considered, direct comparison shows that the FCEB has a much higher range and capable operating time than the BEB on a single charge/refuel.
- The energy consumption of a BEB is predicted to more sensitive to changes in average road gradient. This vehicle type has been shown to be much more efficient on drive cycles with zero and negative average road gradient, with a full day of operation available on a single charge for the battery size considered. Operation on drive cycles with high positive average road gradients would require the vehicle to be removed from service to be opportunity charged or for a larger battery to be utilised.
- The energy consumption of the FCEB modelled in this study is predicted to be more consistent across all road gradients, capable of a full day of operation on a single refuel for all the drive cycles considered. However, frequent start-stop cycles, and drive cycles in which the battery does not have sufficient opportunity to recharge have an adverse effect on energy consumption.
- For the vehicles considered in this study, the FCEB should be considered over the BEB for drive cycles with high positive average road gradient, or on duty cycles where BEB range or operating time is insufficient. The BEB should be considered for drive cycles that mainly operate on roads with a low average gradient, or on duty cycles where range and operating time are less intensive.

References

1. Department for Business Energy and Industrial Strategy, "Final Greenhouse Gas Emissions Tables 2019," 2020.

2. IEA, *Global Car Sales by Key Markets 2005-2020* (Paris, 2020)
3. SMMT, "December 2011—EV and AFV Registrations," 2012, accessed December 14, 2021, https://www.smmt.co.uk/2012/01/december-2011-ev-and-afv-registrations/.
4. SMMT, "December—EV Registrations," 2020, accessed December 14, 2021, https://www.smmt.co.uk/2020/01/december-ev-registrations-3/.
5. IEA, *Global EV Outlook 2020* (Paris, 2020)
6. Hayes, J.G. and Goodarzi, G.A., *Electric Powertrain: Energy Systems, Power Electronics and Drives for Hybrid, Electric and Fuel Cell Vehicles*, 1st ed. (John Wiley & Sons, Ltd., 2018)
7. Guida, U. and Abdulah, A., *ZeEUS eBus Report #2* (Brussels, 2017)
8. Mahmoud, M., Garnett, R., Ferguson, M., and Kanaroglou, P., "Electric Buses: A Review of Alternative Powertrains," *Renew. Sustain. Energy Rev.* 62 (2016): 673-684, doi:10.1016/j.rser.2016.05.019.
9. Doyle, D., Harris, A., Chege, S., Douglas, L. et al., "Hydrogen Fuel Cell Buses: Modelling and Analysing Suitability from an Operational and Environmental Perspective," SAE Technical Paper 2020-01-1172 (2020), doi:10.4271/2020-01-1172.
10. Estrada, M., Mension, J., and Salicrú, M., "Opportunity Charging of Buses. Effects on Bus Operator and User Performance," in *European Transport Conference 2017*, 2017.
11. Ehsani, M., Gao, Y., Longo, S., and Ebrahimi, K.M., *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*, 3rd ed. (Taylor and Francis Group, LLC, 2018)
12. O'Hayre, R., Cha, S.-W., Colella, W., and Prinz, F.B., *Fuel Cell Fundamentals*, 3rd ed. (2016)
13. Tran, D.D., Vafaeipour, M., El Baghdadi, M., Barrero, R. et al., "Thorough State-of-the-Art Analysis of Electric and Hybrid Vehicle Powertrains: Topologies and Integrated Energy Management Strategies," *Renew. Sustain. Energy Rev.* 119 (2020): 109596, doi:10.1016/j.rser.2019.109596.
14. Xu, L., Li, J., Hua, J., Li, X. et al., "Optimal Vehicle Control Strategy of a Fuel Cell/Battery Hybrid City Bus," *Int. J. Hydrogen Energy* 34, no. 17 (2009): 7323-7333, doi:10.1016/j.ijhydene.2009.06.021.
15. Daud, W.R.W., Rosli, R.E., Majlan, E.H., Hamid, S.A.A. et al., "PEM Fuel Cell System Control: A Review," *Renew. Energy* 113 (2017): 620-638, doi:10.1016/j.renene.2017.06.027.
16. Thomas, C.E., "Fuel Cell and Battery Electric Vehicles Compared," *Int. J. Hydrogen Energy* 34, no. 15 (2009): 6005-6020, doi:10.1016/j.ijhydene.2009.06.003.
17. Campanari, S., Manzolini, G., and Garcia de la Iglesia, F., "Energy Analysis of Electric Vehicles Using Batteries or Fuel Cells through Well-to-Wheel Driving Cycle Simulations," *J. Power Sources* 186, no. 2 (2009): 464-477, doi:10.1016/j.jpowsour.2008.09.115.
18. Forrest, K., Mac Kinnon, M., Tarroja, B., and Samuelsen, S., "Estimating the Technical Feasibility of Fuel Cell and Battery Electric Vehicles for the Medium and Heavy Duty Sectors in California," *Appl. Energy* 276 (2020): 115439, doi:10.1016/j.apenergy.2020.115439.
19. Murtagh, M., Early, J., Stevens, G., Cunningham, G. et al., "Modelling and Control of a Hybrid Urban Bus," SAE Technical Paper 2019-01-0354 (2019), doi:10.4271/2019-01-0354.
20. Harris, A., Soban, D., Smyth, B.M., and Best, R., "Assessing Life Cycle Impacts and the Risk and Uncertainty of Alternative Bus Technologies," *Renew. Sustain. Energy Rev.* 97 (2018): 569-579, doi:10.1016/j.rser.2018.08.045.
21. Li, L., Lo, H.K., and Cen, X., "Optimal Bus Fleet Management Strategy for Emissions Reduction," *Transp. Res. Part D Transp. Environ.* 41 (2015): 330-347, doi:10.1016/j.trd.2015.10.007.
22. Brdulak, A., Chaberek, G., and Jagodzinski, J., "Development Forecasts for the Zero-Emission Bus Fleet in Servicing Public Transport in Chosen EU Member Countries," *Energies* 13, no. 6 (2020), doi:10.3390/en13164239.
23. Jin, L., Delgado, O., Gadepalli, R., and Minjares, R., "Strategies for Deploying Zero-Emission Bus Fleets: Development of Real-World Drive Cycles to Simulate Zero-Emission Technologies along Existing Bus Routes," 2020.
24. Dallmann, A.T., Delgado, O., Jin, L., Minjares, R. et al., "Strategies for Deploying Zero-Emission Bus Fleets: Route-Level Energy Consumption and Driving Range Analysis," 2021.
25. Zhu, D., Pritchard, E.G.D., and Silverberg, L.M., "A New System Development Framework Driven by a Model-Based Testing Approach Bridged by Information Flow," *IEEE Systems Journal* 12, no. 3 (2016): 2917-2924, doi:10.1109/JSYST.2016.2631142.
26. Stevens, G., Murtagh, M., Kee, R., Early, J. et al., "Development of a Vehicle Model Architecture to Improve Modeling Flexibility," *SAE Int. J. Engines* 10, no. 3 (2017): 1358-1366, doi:10.4271/2017-01-1138.
27. Stevens, G., Early, J., Cunningham, G., Murtagh, M. et al., "Multi-Fidelity Validation Algorithm for Next Generation Hybrid-Electric Vehicle System Design," *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* 233, no. 13 (2019): 3438-3448, doi:10.1177/0954407018825015.
28. Zhang, Y., Murtagh, M., Early, J., Cunningham, G. et al., "Optimal Control Strategy for the Next Generation Range Extended Electric Bus," SAE Technical Paper 2020-01-0844 (2020), doi:10.4271/2020-01-0844.
29. Preger, Y. et al., "Degradation of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions," *J. Electrochem. Soc.* 167, no. 12 (2020): 120532, doi:10.1149/1945-7111/abae37.
30. Wikner, E. and Thiringer, T., "Extending Battery Lifetime by Avoiding High SOC," *Appl. Sci.* 8, no. 10 (2018), doi:10.3390/app8101825.
31. Zemo Partnership, "Low Emission Bus Certificates," Buses & Coaches, 2018, accessed October 7, 2021, https://www.zemo.org.uk/work-with-us/buses-coaches/low-emission-buses/low-emission-bus-certs.htm.
32. Balazs, A., Morra, E., and Pischinger, S., "Optimization of Electrified Powertrains for City Cars," *SAE Int. J. Alt. Power.* 1, no. 2 (2012): 381-394, doi:10.4271/2011-01-2451.
33. Ou, K., Yuan, W.W., Choi, M., Yang, S. et al., "Optimized Power Management Based on Adaptive-PMP Algorithm for a Stationary PEM Fuel Cell/Battery Hybrid System," *Int. J. Hydrogen Energy* 43, no. 32 (2018): 15433-15444, doi:10.1016/j.ijhydene.2018.06.072.

34. Song, K. et al., "Multi-Mode Energy Management Strategy for Fuel Cell Electric Vehicles Based on Driving Pattern Identification Using Learning Vector Quantization Neural Network Algorithm," *J. Power Sources* 389 (2018): 230-239, doi:10.1016/j.jpowsour.2018.04.024.

35. Hayes, D., "Ultra-Low Emission Bus Scheme: Test Guidance for Certification," 2018.

36. Afrasiabian, E., Douglas, R., and Best, R., "Dynamic Modelling and Performance Prediction of a Recovery Fresh Air Heat Pump for a Generic Bus," in *15th International Conference on Ecological Vehicles and Renewable Energies, EVER 2020*, 2020, doi:10.1109/EVER48776.2020.9243005.

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Definitions, Acronyms, Abbreviations

BEB - Battery Electric Bus
CP - Characteristic Parameter
EMS - Energy Management System
FC - Fuel Cell
FCEB - Fuel Cell Electric Bus
FCEV - Fuel Cell Electric Vehicle
GVW - Gross Vehicle Weight
KML - Keyhole Markup Language
LUB - LowCVP UK Bus
NMC - Nickel Manganese Cobalt
RHP - Recovery Heat Pump
SOC - State of Charge
UKBC - UK Bus Cycle
ULEB - Ultra-Low Emission Bus