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Impact of Ambient Temperature, Passenger Load, and Delay on the Consumption of Battery Electric Buses

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Abstract

The operation of state-of-the-art battery electric buses (BEB_s) has started recently, and their consumption model is unknown. Therefore, the service providers are lenient regarding the energy used. Our aim was to reveal the effects of ambient temperature and bus service characteristics, such as passenger load and delay, on the energy consumption. Real-time consumption data of BEB_s were analyzed in Nyíregyháza, Hungary, and the functional relationships among the aforementioned variables were revealed. We found that while ambient temperature is negatively correlated with consumption in the cold winter periods, the consumption surplus is positively correlated with passenger load and generally positively correlated with the delay on the trip because of road traffic. In the case of delay, the consumption increase is caused by more frequent acceleration and the greater consumption of auxiliary systems due to longer running times. Accordingly, the energy consumption can be estimated if the characteristics data are available. The results can be used by bus service operators to plan the daily schedule and predict the energy consumption of a BEB.

Keywords

energy consumption, battery electric buses, ambient temperature, passenger load, delay, functional relationships

1 Introduction

The electrification of urban bus services is an ongoing process to reduce local air pollution (Borén, 2020; Laib et al., 2019). There are several electric bus types and related charging infrastructures. The most popular options are:

- Trolleybuses with catenary network and en route dynamic charging,
- Electric buses with small battery capacity and static charging at terminal or stop,
- Electric buses with large battery capacity and in-depot static charging at night.

In this study, we focus on the last option; namely, Battery Electric Buses (BEB) with large battery capacity and in-depot static charging. This option is popular among bus service operators as it requires minor changes in the operation characteristics (trip schedule, dwelling time, etc.) (Gao et al., 2017). However, the range limitation of a currently used BEB is one of the main drawbacks of this technology. In general, one BEB cannot replace a diesel-powered bus. Moreover, the different environmental and bus service characteristics can further reduce the effective range (Rabhi and Zsombók, 2022). As a novelty, this research aimed to reveal the connections between energy consumption and factors varying per day and trip. These factors are the ambient temperature (Corbet et al., 2023), passenger load (Zhou et al., 2016), and delay caused by traffic congestion (Hjelkrem et al., 2021). The hypotheses are as follows: high passenger load and extreme ambient temperature significantly impact energy consumption. Moreover, the delay mostly caused by high road traffic increases energy consumption due to the more frequent acceleration and longer running time.

We analyzed real BEB energy consumption data from Nyíregyháza, Hungary. An Ebusco Viricity model was tested; the data were measured and stored by the vehicle's on-board computer and read out via an online interface. Our results can be used to estimate the energy consumption of a BEB in an unknown environment if the ambient temperature and bus service characteristics are known.

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Moreover, the research results can be used by BEB operators during shift planning.

The paper is structured as follows: the relevant literature is reviewed in Section 2. The materials and methods, namely the case study environment and the data analysis techniques, are described in Section 3. The results and discussion are summarized in Section 4. Finally, Section 5 contains concluding remarks and future research directions.

2 Literature review

More and more researchers are conducting research in the field of operating electric vehicles and analyzing the consumption of driving cycles. The energy consumption is usually analyzed by the acceleration profile. The ambient temperature, driving behavior, and route characteristics were found to be the most important uncertainty factors of the operations (Vepsäläinen et al., 2018). Beckers et al. (2019) compared the measured data with the simulated data. The simulated results were a good approximation of the measured data; however, simulating the uphill and downhill movement had high uncertainty.

Bartłomiejczyk and Kolacz (2020) and Göhlich et al. (2015) dealt with auxiliary system consumption. Based on their measurements, utility consumption accounts for nearly half of total consumption, and it can be as high as 70% in winter. The use of electric auxiliaries, especially air conditioning, further reduces the range (Basma et al., 2020). The temperature mainly increases the energy consumption of Heating, Ventilation, and Air Conditioning (HVAC) and Battery Thermal Management System (BTMS) up to 8-10 times; thus, the range of vehicles is reduced (Oliva et al., 2013). According to He et al. (2018), the overall electric vehicle range can be reduced by up to 45% with 0 °C resistance heating as a consequence of cooling and heating. In the case of the hottest Italian cities, high differences in consumption were recorded during cooling (Corazza et al., 2021). However, the energy consumption of the auxiliary system can be reduced by alternative techniques. With a CO_2 heat pump, consumption can be reduced by more than 50% (Corazza et al., 2021). Accordingly, it makes sense to use alternative, independent heating solutions in BEBs. Finding the suitable acceleration curve and the appropriate driving style and behavior is necessary to reduce energy consumption and increase battery life (Csonka, 2021; Dirks et al., 2022; Lee et al., 2021; Qiu et al., 2013). Based on the results, optimization methods can be created to minimize consumption per kilometer (Kirchner et al., 2014; Li and Liu, 2019). The consumption can be minimized if the regeneration and energy recovery features of BEBs are utilized. The efficiency and energy of the regeneration are more significant when the vehicle retards with less deceleration (Perrotta et al., 2012).

The regeneration is a narrower area, and refers only to regenerative brakes. Energy recovery can cover all energy recovery methods, such as heat loss recovery system to heating passenger compartment and preconditioning for energy recovery ventilation systems. HVAC systems with this construction design already exist nowadays.

In this sense, the regeneration efficiency is given as a function of speed, and thus, acceleration and deceleration cycles involve higher energy consumption than smooth, uniform movement.

Based on the literature, four factors influencing consumption are identified, see Fig. 1: *topography, stop distance, passenger load, and ambient temperature*. Among these, the passenger load and ambient temperature factors have the most effect on the auxiliary operation, while the rest have the greatest impact on the drivetrain. During this study, we focused on the passenger load and ambient temperature thus the impact of factors influencing the auxiliary operations can be analyzed. Moreover, we revealed that delay-dependent analysis considering mostly the influence of traffic, is lacking in the literature.

3 Materials and methods

3.1 Case study location

The measured data come from the test results of an Ebusco 2.2 bus test run in Nyíregyháza, Hungary, between November and December 2020. The used vehicle is a 3-door, 12-meter bus equipped with a 363 kWh battery.

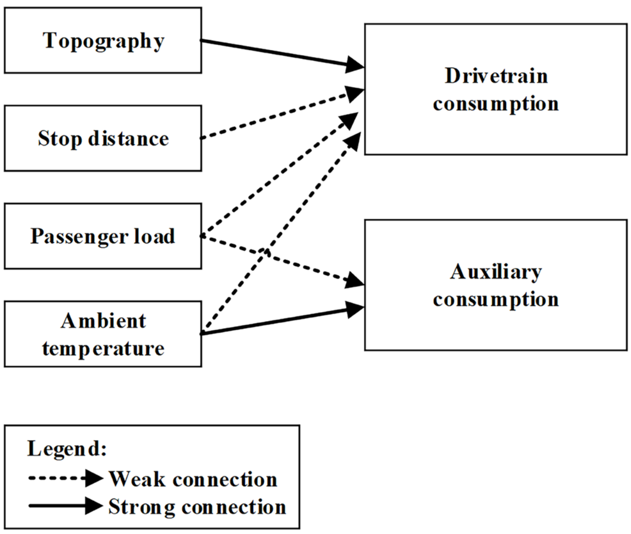

Fig. 1 The effects of influencing factors on consumption areas

The empty weight of the vehicle (without passengers) is 13 tons, and it can accommodate 90 passengers. The maximum weight is 19 tons; based on this, a maximum of 6 tons of portable weight is allowed (passengers).

The main test line was bus line 10 in Nyíregyháza. In addition, test runs were executed on lines 3, 8, 6 (currently 9), 12, 13, 17 K, and 44.

There are suburban radial bus lines, e.g., 3, 6, 8, 10, 13, and 44, whose terminals are at the city center. Furthermore, two city bus lines, 12 and 44, run only in the inner city. The distance covered by a line is between 7–17 km, and the riding time is 20–50 minutes. The difference in altitude is not significant; the city lays on flat land. Ebusco Viricity's on-board computer allows continuous online monitoring of bus activity. The following data of a bus line trip – between terminals – were recorded by the on-board computer: distance covered, running time, speed, used energy, and ambient temperature. The passenger load was given by the bus driver's estimation. The consumption of the vehicle was measured in an hourly breakdown. The exact geolocation via the GPS module was continuously recorded. One trip is considered from a terminal to another terminal (A-B or B-A). According to the directions, there may be small differences in both the distance and the travel time, so these ultimately mean different consumption values. Temperature does not mean a significant difference in the case of a maximum 1-hour trip, so a constant temperature is assumed on the full trip. Table 1 summarizes the basic data of a line and the average values of the measured data. In addition, the consumption rate is given, calculated by the division of the average used energy and the length of a trip. Altogether, 223 evaluable trips were measured during 25 days on the 8 lines.

3.2 Calculation method

3.2.1 Energy consumption in the function of ambient temperature and passenger load

As the consumption data was recorded in hourly basis, it was possible to extract accurate consumption data from the longer 40–55 minutes trips. The route-specific energy consumption data was compared with the hourly ambient temperature measured, the passenger load measured on board, and the planned schedule. The temperature correlation and the delay correlation were derived from these data. This was determined for each trip, and then the regression coefficients were determined for each bus line using linear regression.

3.2.2 Energy consumption in the function of delay

The delay (t_{dly}) on a trip is calculated by Eq. (1):

$$t_{dly} = t_{trip} - t_{sched} \, [\text{min}] , \tag{1}$$

where t_{trip} is the driving time in service in a trip, t_{sched} is the planned schedule time of a trip. Time stamp belonged to the start and end of the trip. This delay is mostly traffic-related.

The normalised delay (d) can be determined by Eq. (2). It is the delay normalised with the planned running schedule time. Accordingly, the magnitude of a delay can be expressed with the ratio of the delay and the schedule time. A 10-minute delay during a 15-minute trip has greater significance than during a 70-minute trip:

$$d = \frac{t_{dly}}{t_{sched}} , \tag{2}$$

where t_{dly} is the delay [min] in service in a trip.

The energy difference (positive or negative) is expressed by Eq. (3). It expresses the surplus or deficit between the energy consumed on a given trip (E) and the average energy consumed on a trip ($\bar{E}$).

$$\Delta E = E - \bar{E} \tag{3}$$

The normalised energy consumption, namely the consumption multiplier (e), is given by Eq. (4). It is calculated by the energy consumption normalised with the average energy consumed.

$$e = \frac{\Delta E}{\bar{E}} \tag{4}$$

The consumption multiplier is analyzed considering the normalised delay. Trend analysis was done considering linear, polynomial, and exponential regression.

4 Results and discussion

4.1 Energy consumption in the function of ambient temperature and passenger load

The 223 measurement data points are summarized and depicted as a surface in Fig. 2. The temperature range is between –4 and 12 Celsius, the passenger load factor range is between 10% and 45% according to the available data. A surface shows the measured consumption as a function of temperature and passenger load. The two plane sections of this spatial paraboloid give the consumption relationship between ambient temperature and passenger load. This implies that energy consumption is quadratic with ambient

Table 1 Basic data and the average of the measured data per line

Line group	Line	Length [km]		Planned schedule time [min]		Number of mea sured trips [pcs]		Average time in service [mm:ss]		Average driving time [mm:ss]		Average drive speed [km/h]		Average used energy [kWh]		Consump tion rate [kWh/km]		Average ambient tempe rature [°C]		Average passenger load [%]	
Direction		A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
3	3	15.9	16.8	50:00	50:00	4	8	51:00	49:15	37:00	36:38	25.8	28.0	19.27	18.78	1.21	1.12	3.7	3.7	24%	24%
6	6	13.4	–	45:00	–	8	–	51:22	–	34:15	–	23.5	–	23.55	–	1.26	–	3.2	–	21%	–
	6Y	–	15	–	51:30	–	7	–	47:38	–	30:37	–	29.5	–	29.46	–	1.09	–	3.2	–	21%
8	8	7.7	7.7	21:00	21:00	15	15	22:20	21:04	16:28	15:00	28.3	30.9	8.66	8.14	1.12	1.06	3.2	3.3	19%	19%
	8A	–	4.4	–	16:00	–	4	-	17:00	–	10:45	–	24.6	–	5.70	–	1.29	–	3.7	–	24%
10	10	17.2	17.2	55:45	49:45	10	16	47:13	47:52	37:15	47:52	27.9	29.5	19.32	17.87	1.04	1.04	2.9	1.8	21%	19%
	10A	12.4	12.4	28:00	28:00	8	3	29:44	28:40	23:16	22:40	32.1	32.9	12.37	11.22	1.00	0.90	4.1	3.9	20%	12%
	10J	–	15.7	–	34:00	–	4	–	30:00	–	25:40	–	37.0	–	13.17	–	0.84	–	3.6	–	25%
	10J2	–	20.8	–	27:00	–	3	–	51:00	–	38:40	–	32.3	–	19.92	–	0.96	–	4.3	–	25%
12	12	9.1	9.1	33:15	31:30	16	16	31:41	31:41	22:15	23:23	24.7	23.3	11.04	11.36	1.21	1.27	3.3	3.3	21%	21%
13	13	8.5	10.4	31:49	37:49	11	11	30:16	32:22	20:38	23:49	25.1	26.3	11.48	11.85	1.35	1.14	3.5	3.5	22%	22%
17K	17K	8.8	9.1	33:00	34:00	8	8	33:26	31:43	21:51	31:43	24.4	23.6	11.58	11.98	1.32	1.32	2.7	2.7	21%	21%
44	44	14.1	13.8	46:35	43:10	24	24	46:23	43:26	32:50	32:23	26.0	25.7	16.45	14.80	1.17	1.07	3.6	3.6	21%	21%

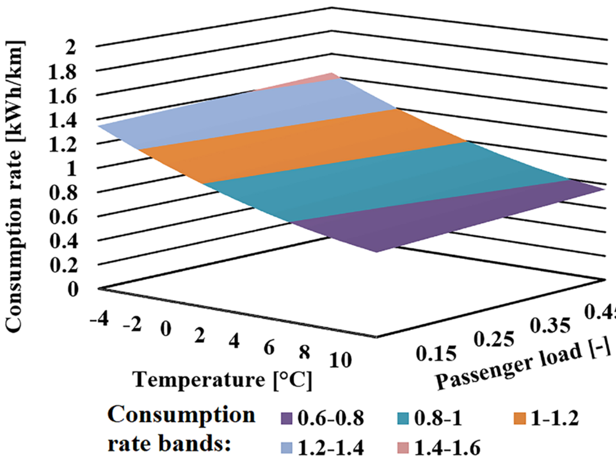

Fig. 2 Average energy consumption in the function of ambient temperature and passenger load

temperature and linear with passenger load. The passenger load increases the mass of the vehicle and thus has a positive effect on both kinetic and potential energy, accordingly, it affects the total energy consumption. Regarding ambient temperature, since the vehicle was mainly in service during the winter period, there is essentially a negative correlation with increasing temperature, i.e., the vehicle consumes significantly more energy in cooler weather due to the high heating demand.

4.2 Energy consumption according to delay

Fig. 3 depicts the consumption multiplier as a function of the normalised delay in four bus lines. The points represent the measured values. The lines represent the result of the linear regression. The linear function is given by bus lines where e is the consumption multiplier, and d is the normalised delay. Values of e less than 1 and negative d mean values less than the mean of the dataset. If $e < 1$, then the consumption is less than the average normalised value, and if d is negative, the vehicle delay was negative, i.e., the vehicle was in a haste. The difference in the lines may result from the characteristics of the line. There are lines running through the city, where there is a higher chance of energy consumption surplus because of the strong traffic congestion. Fig. 3 (a) shows a relevant correlation between energy consumption and delay in the case of bus line 6. This relatively short line runs from the western to the eastern parts of the city through heavily congested sections. In the case of bus line 10 (Fig. 3 (b)) and line 44 (Fig. 3 (c)), the trend lines show a very low correlation; the measured points are scattered. These lines run mostly in the suburban area. It is assumed that energy consumption is mostly

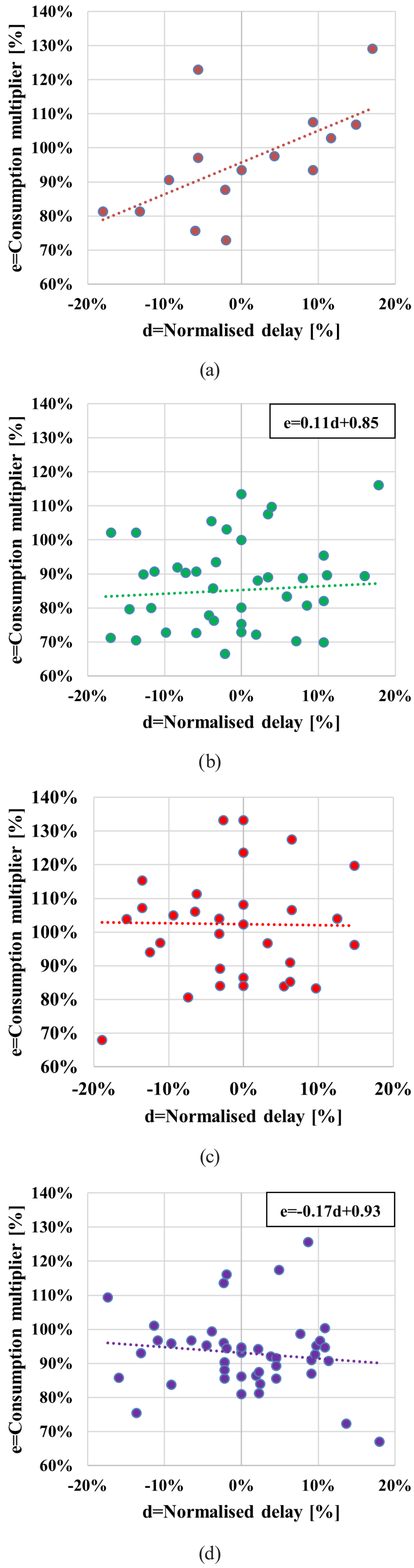

Fig. 3 Consumption multiplier in the function of normalised delay according to lines; (a) line 6 (current line 9); (b) line 10; (c) line 44; (d) line 12

influenced by the driving style, especially in the suburban area. Moreover, as the congested downtown section is shorter, the possible influencing effect of delay caused by congestion is not relevant. Fig. 3 (d) shows a slight negative correlation between energy consumption and delay in the case of bus line 12. This line connects the northern part of the city to the city center. The possible explanation of the negative correlation is the curvy characteristics of the line, accordingly, the average speed is lower, and the recuperation effect can be utilized more effectively. The slope of the trend line varies between –0.17 and 0.93. The higher the slope is, the higher the influence of delay on energy consumption. A positive slope means a positive linear relationship between energy consumption and delay. Namely, if the delay increases, the energy consumption also increases. As the delays are mostly caused by high traffic, even traffic jams, the cause of the increase in consumption is the more frequent acceleration cycles and the resulting high start-up current consumption and the higher auxiliary consumption due to the longer driving time.

Considering all bus lines combined, a weak positive correlation exists between consumption multiplication and normalised delay. Beyond the slope of linear equations, the standard deviation is around 0.2–0.3, which implies a generally weak relationship between delay and energy consumption. However, it makes sense to have a bus with a larger battery capacity on lines where the correlation with consumption is strongly positive, as additional energy consumption in case of delays is expected. In the case of other lines where the correlation is negative, BEB_s with extra battery capacity are not necessary. Accordingly, delay can mean a consumption surplus, while haste (earlier arrival) can mean consumption savings. This means that driving on a road without traffic can even reduce consumption. According to our results, compared to Vepsäläinen et al. (2018), passenger load is also an important aspect. In comparison with Beckers et al. (2019), we have provided that further parameters, namely delay, may affect consumption. This is clearly necessary to be investigated due to the ever-increasing urban traffic and the chance of delay.

5 Conclusion

The main contribution of this paper is the analysis of consumption data for several bus lines. As a key finding, the results show that the consumption of BEB_s is clearly dependent on ambient temperature and passenger load, and that there is a line-specific correlation between delay and energy consumption. Energy consumption is highly correlated with ambient temperature (up to +50–70% in consumption), influenced by passenger load (+10–15%), and slightly influenced by delay. Haste can even cause negative consumption. For example, on low-traffic roads, even a reduction in consumption can be achieved. A future research direction in this area is to take this analysis further and provide exact function relations. As a future extension of this research, this method could be used for consumption prediction and accounting of BEB operations.

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