The State-of-the-Art of Battery Electric City Buses

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The State-of-the-Art of Battery Electric City Buses

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Executive Summary

Over the last decade, many manufacturers brought battery electric city buses to the market. By organizing and categorizing the reported specifications of more than 100 of these vehicles, this paper aims to create an overview of the state-of-the-art. The used information is obtained from manufacturer websites and news sources. The results indicate that Lithium-ion Iron Phosphate is the most often used battery cell chemistry. Based on the reported range and battery capacity, the energy consumption is 1.3 kWh/km on average. Therefore, at an occupancy rate of 38% (seated), battery electric buses offer the same energy consumption per person as an average electric passenger car. The current lack of standardization in the reported range makes direct a comparison of individual vehicles difficult.

Keywords: BEV (battery electric vehicle), bus, energy consumption, heavy-duty, public transport

1 Introduction

Over the past decade, Battery Electric Buses (BEBs) are gaining market share in the city transport sector [1]. Compared to conventional Internal Combustion Engine (ICE) vehicles, BEBs offer no local pollutants, reduced noise, and the potential of a reduced Total Cost of Ownership (TCO). Since the introduction of the first BEB prototype vehicles, both established and new Original Equipment Manufacturers (OEMs) have entered the BEB market. Some examples of these vehicles are shown Figure 1.

This paper aims to organize the specifications of BEBs available on the market today and compare the characteristics of these vehicles. To this end, the specifications as provided by manufacturers are gathered and displayed graphically, similar to the methodology presented in [2] for electric trucks.

Figure 1: f.l.t.r.: BYD K9 [3], Ebusco 3.0 [4], VDL Citea SLFA electric 181 [5], BYD ADL Enviro400EV [6], Proterra ZX5 [7], Volvo 7900 Electric Articulated [8], Mercedes-Benz eCitaro [9], Solaris Urbino 15 LE Electric [10], Ankai 12M Electric City Bus [11], and Yutong E12 [12].
2 Battery Electric Bus Overview

The specifications of over 100 individual BEBs have been collected. Only vehicles of a Gross Vehicle Weight (GVW) of more than 8 tonnes that are specifically marketed as 'city bus' are included in the overview. A selection of the data is displayed in Table 1. Manufacturers included are those that are leading the market in 2020 in China [13], Europe [14], North America [15] and India [16], together with several smaller OEMs. While the list includes several prototype vehicles, figures presented in this paper only include data from series-production vehicles, unless stated otherwise.

The information is gathered from OEM webpages and brochures, online news sources, and the ZeEUS eBus Report [1]. The data as provided by the manufacturers or news sources is used directly, without making any statements on the accuracy of these numbers. Additionally, not all EOMs disclose the same specifications. Therefore, figures only display vehicles for which the specifications listed on both axis are known. The information is gathered by January 2021, and typically includes vehicles that are in production or announced to go into production later this year.

Table 1: Overview of some of the indexed vehicles and some of their specifications.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type</th>
<th>Capacity [passengers]</th>
<th>Unladen Vehicle Weight [kg]</th>
<th>Overall Length [m]</th>
<th>Wheelbase [m]</th>
<th>Reported Range [km]</th>
<th>Charging Power [kW]</th>
<th>Battery Chemistry</th>
<th>Battery Capacity [kWh]</th>
<th>Date Introduced</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADL Enviro400EV 10.3m [after 2020]</td>
<td>Double-decker</td>
<td>EU/China</td>
<td>2020</td>
<td>12.3</td>
<td>15100</td>
<td>19200</td>
<td>67</td>
<td>Li-ion (LFP)</td>
<td>314</td>
<td>2020</td>
<td>Li-ion (LFP)</td>
</tr>
<tr>
<td>Ankai 12m electric city bus [latest]</td>
<td>Single-decker</td>
<td>China</td>
<td>2020</td>
<td>12.6</td>
<td>16000</td>
<td>38</td>
<td>290</td>
<td>Li-ion (unspecified)</td>
<td>314</td>
<td>2020</td>
<td>Li-ion (unspecified)</td>
</tr>
<tr>
<td>BYD K9 [June 2017]</td>
<td>Single-decker</td>
<td>China</td>
<td>2017</td>
<td>12.1</td>
<td>11100</td>
<td>18000</td>
<td>35</td>
<td>250</td>
<td>Li-ion (LFP)</td>
<td>324</td>
<td>2020</td>
</tr>
<tr>
<td>Caetano E.City Gold 10.7m</td>
<td>Single-decker</td>
<td>Portugal</td>
<td>2018</td>
<td>10.7</td>
<td>64</td>
<td>300</td>
<td>Li-ion (NMC)</td>
<td>385</td>
<td>2018</td>
<td>Li-ion (NMC)</td>
<td></td>
</tr>
<tr>
<td>EBUSCO 3.0</td>
<td>Single-decker</td>
<td>NL</td>
<td>2021</td>
<td>12.6</td>
<td>85</td>
<td>18000</td>
<td>95</td>
<td>500</td>
<td>Li-ion (LFP)</td>
<td>250</td>
<td>2021</td>
</tr>
<tr>
<td>Mercedes-Benz Citaro</td>
<td>Single-decker</td>
<td>Germany</td>
<td>2020</td>
<td>12.1</td>
<td>5.9</td>
<td>20000</td>
<td>Li-ion (NMC)</td>
<td>298</td>
<td>2020</td>
<td>Li-ion (NMC)</td>
<td></td>
</tr>
<tr>
<td>Proterra ZX5+ 350kWh</td>
<td>Single-decker</td>
<td>USA</td>
<td>2021</td>
<td>11.3</td>
<td>6.2</td>
<td>13543</td>
<td>19051</td>
<td>29</td>
<td>450</td>
<td>2012</td>
<td>Li-ion (NMC)</td>
</tr>
<tr>
<td>Volvo City SFA-181 Electric</td>
<td>Articulated</td>
<td>NL/BE</td>
<td>2016</td>
<td>18.2</td>
<td>12</td>
<td>19150</td>
<td>29000</td>
<td>133</td>
<td>216</td>
<td>2016</td>
<td>Li-ion (LFP)</td>
</tr>
<tr>
<td>Irisbus 7900 Electric Articulated</td>
<td>Articulated</td>
<td>Sweden</td>
<td>2019</td>
<td>18.7</td>
<td></td>
<td>150</td>
<td>Li-ion (unspecified)</td>
<td>396</td>
<td>2019</td>
<td>Li-ion (unspecified)</td>
<td></td>
</tr>
<tr>
<td>YUTONG E12LF [new]</td>
<td>Single-decker</td>
<td>China</td>
<td>2021</td>
<td>12.6</td>
<td>19100</td>
<td>77</td>
<td>300</td>
<td>Li-ion (LFP)</td>
<td>324</td>
<td>2020</td>
<td>Li-ion (LFP)</td>
</tr>
</tbody>
</table>

3 Battery Technology

First of all, the specified battery technology of the various vehicles is assessed. Several battery chemistries are used. If available, the reported battery chemistry is listed for every vehicle and ordered according to the number of OEMs using this technology, in Table 2. Additionally, in Figure 2, the distribution of observed battery capacities per vehicle is reported in a boxplot per cell technology.

Table 2: Overview of the battery chemistries categorized according to number of OEMs using the technology. OEMs who use multiple technologies are counted multiple times.

<table>
<thead>
<tr>
<th>Cell Chemistry</th>
<th># OEMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-ion (LFP)</td>
<td>8</td>
</tr>
<tr>
<td>Li-ion (NMC)</td>
<td>7</td>
</tr>
<tr>
<td>Li-ion (unspecified)</td>
<td>6</td>
</tr>
<tr>
<td>Li-ion (LTO)</td>
<td>3</td>
</tr>
<tr>
<td>Li-ion (LFP, Solid-State)</td>
<td>2</td>
</tr>
<tr>
<td>Li-ion (LiPo)</td>
<td>1</td>
</tr>
<tr>
<td>Super Capacitor</td>
<td>1</td>
</tr>
<tr>
<td>Unknown</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>37</td>
</tr>
</tbody>
</table>

Figure 2: Boxplots of the reported battery capacity categorized per vehicle according to battery technology.

The result show that Li-ion type batteries are by far the most used in BEBs. Of the various cell technologies observed, cells with Lithium-Iron-Phosphate (LFP) cathodes are the most common, followed
by cells with Nickel-Manganese-Cobalt cathode material. As can be seen from Figure 2, battery packs with these two technologies exist in roughly the same capacity range. Cells with Lithium-Titanate-Oxide anodes (LTO) are encountered less frequently, and are often used in high-power, low-energy applications, as is also evident from Figure 2. Also one vehicle featuring super-capacitor based energy storage is included in the overview, resulting a energy storage capacity. Lastly, the results also show that there are already multiple OEMs that have vehicles with a solid-state electrolyte on the market [17]. Based on the data available, this technology shows the highest average battery capacity.

### 3.1 Charging Power

Most OEMs offer multiple charger options for their range of vehicles. This includes a default charging option, which often consists of one - or two parallel - CCS Type 2 charger plugs, and an optional secondary charging option. The secondary charging option is typically marketed as 'fast charging', and often happens via an overhead pantograph. For each vehicle indexed, the power at which these charging options operate are recorded and visualised in Figure 3. In case a vehicle only supports fast (pantograph) charging, it is listed as the first charging option.

![Figure 3: Charger power, including optional secondary charging option, as function of battery capacity. Data also includes prototype vehicles.](image)

The results show that various charger powers are offered, ranging from 22 kW [18] to 480 kW [1, p. 155]. While it is difficult to recognize any trend in the maximum charger power, there are rarely batteries that charge slower than 1/6 C. This indicates that OEMs consider 6 hours to be the maximum charging time for any charging solution.

### 4 Driveline Topology

Generally, two types of driveline topologies can be identified for BEBs; a central electric machine, which powers the wheels via a differential, or a drive-axle where the wheels are powered by two individual motors located in the wheel hubs. These same two principles are encountered in different configurations, where mostly one but also sometimes two of the vehicle’s axles are driven. In Table 3 the two observed driveline technologies are ordered according to the number of OEMs using this technology. Furthermore, in Figure 4 the distribution of the reported continuous power and peak power per driven axle is visualized per topology.
Table 3: Overview of the driveline type categorized according to number of OEMs using the technology. OEMs who use multiple technologies are counted multiple times.

<table>
<thead>
<tr>
<th>Driveline Topology</th>
<th># OEMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central motor</td>
<td>12</td>
</tr>
<tr>
<td>Wheel hub motors</td>
<td>12</td>
</tr>
<tr>
<td>Unknown</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>42</td>
</tr>
</tbody>
</table>

The results show that, in the group of vehicles indexed in this research, both driveline topologies are encountered equally often. It is not uncommon for one OEM to use different topologies across their range of vehicles. Figure 4 shows that the continuous power of both these systems is comparable, and gives a slight indication that wheel hub motors offer a higher peak power.

The driveline power is generally higher for longer, heavier vehicles. This is confirmed by the data in Figure 5, which shows both the continuous and peak driveline power versus the gross vehicle weight. The results show that the continuous power-to-weight ratio is approximately 7 kW/t (0.009 hp/kg). The peak power shows a similar trend, with an additional 100 kW offset.

Figure 4: Boxplots of the driveline power per driven axle categorized according to driveline technology.

Figure 5: Total driveline power per vehicle. Both continuous power and peak power are indicated.

5 Energy Consumption and Driving Range

Total battery capacity is one of the main vehicle specifications of a BEV. It directly affects the driving range, but also relates to other important parameters, such as vehicle mass and passenger capacity. Regardless of battery capacity, minimizing the vehicles energy consumption is relevant to maximize the driving range, and minimize TCO.

Figure 6a shows the driving range reported by the manufacturers as function of the specified battery capacity. In the same figure the GVW is indicated, which shows that the larger battery capacity is generally reserved for the heavier vehicles. By taking the ratio of battery capacity and range, the average energy consumption averaged over all vehicles is found to be 1.3 kWh/km.

Next, the energy consumption per passenger is detailed in Figure 6b, which is on average 1.6 kWh/100 km/person. A ratio of 2.4 is assumed between maximum passenger capacity, reported in Figure 6b and the seated passenger capacity. This assumption is based on the passenger capacity data of the indexed vehicles.
Figure 6: Reported range versus battery capacity (a) together with the average energy consumption. Energy consumption is shown versus passenger capacity in (b). Marker size indicates vehicle weight. Also prototype vehicles are included.

vehicles. This results in an average energy consumption per seated passenger of

\[ \hat{E}_{\text{BEB}} = 3.8 \text{ [kWh/100 km/pers.]} \],

assuming all the seats are occupied, but no passengers are standing. This value can be compared to the energy consumption of electric series production passenger cars, for which 15 kWh/100 km is considered low [19], and the average number of occupants per vehicle is approximately 1.5 [20], resulting in

\[ \hat{E}_{\text{car}} = 10 \text{ [kWh/100 km/pers.]} \].

Therefore, a BEB offers approximately the same person-specific energy consumption as an electric passenger car if approximately 1/3 of the BEB seats are occupied. Alternatively, if standing passengers are included, a fully occupied BEB transports passengers seven times more efficiently than the average electric passenger car.

The energy consumption as shown in Figure 6a can be categorized according to the driveline topology as discussed in Section 4. The results are presented in Figure 7 and indicate that, based on the data available here, there is no clear distinction between the energy consumption of central motors versus wheel hub motors. This is probably because the efficiency of the electric drivelines is generally high and any created difference is small compared to other influences, such as vehicle weight and Heating, Ventilation and Air Conditioning (HVAC) consumption.

5.1 Discussion on Driving Range Standardization

Back in Figure 6a an uncertainty interval surrounding the average energy consumption by ±25% is indicated with dashed lines. This 25% is considered the approximate difference that could be caused by either including or excluding the HVAC consumption in the reported driving range number [21, Fig. 1].

Still, there are several vehicles that exceed this boundary, indicating that there is a large spread in reported energy consumptions.

Whereas some differences are to be expected due to design differences, part of the spread is likely caused by a lack of standardization surrounding the reported range. Only a handful of OEMs specify which drivecycles or environmental conditions are considered for the reported driving range number or explain whether the number originates from simulations or driving tests. This makes a direct comparison of individual vehicles difficult.

Several standardized drive cycles exist specifically for BEBs [22, 23]. However, the variety of different cycles is still large and the usage of a particular cycle seems to be correlated with the geographic region where the OEM operates. There are even examples of single public transport operators specifying their own standardized cycles [24]. Additionally, based on the data indexed here, these cycles are seldomly used when reporting driving range numbers publicly.
6 Conclusion

The specifications of over 100 BEBs are gathered and categorized. The results show that LPF is the most common cell chemistry, followed by NMC. Both a central motor and wheel hub motors are often encountered across all vehicles and the average power-to-weight ratio is 7 kW/t.

Results based on the reported driving range show that the overall average energy consumption is 1.3 kWh/km, and that an occupancy rate of 38% (seated) is already enough for a BEB to match the specific energy consumption of an electric passenger car. Reported range results vary significantly, likely because standardisation in reporting these values is currently seldomly reported.

Acknowledgments

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References


Author Biography

Camiel Beckers is a PhD student in the Department of Mechanical Engineering at Eindhoven University of Technology (TU/e) since 2017. His current research interests include energy consumption modeling of battery electric vehicles, with a focus on battery electric city buses.

Igo Besselink is an Associate Professor and Chair of Vehicle Dynamics in the Department of Mechanical Engineering at Eindhoven University of Technology (TU/e). His key area of expertise is Vehicle Dynamics: the analysis of road vehicle motions, vibrations and stability as a result of steering, driving, braking and external disturbances. Igo’s main research interests are aerodynamics of commercial vehicles, tire behavior and modeling, battery electric vehicles and vehicle control.

Henk Nijmeijer is a Full Professor at Eindhoven University of Technology (TU/e) and Chair of the Dynamics and Control group. Henk’s research focuses on Control Systems Engineering, Mechanical Engineering and Automotive Engineering. His areas of expertise include (advanced) control theory and systems, robotics, mechatronics, (system) dynamics and control systems engineering.