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Comprehensive energy assessment of battery electric buses and diesel buses

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Abstract:

The drive to ban diesel vehicles is well underway in several major European cities with the aim of improving air quality and reducing greenhouse gas emissions, and similar plans have been announced by authorities around the world. This poses a major challenge for the public transport sector given its high reliance on diesel bus technology. Zero-emission battery electric buses (BEB) currently stands as one of the most promising solutions for reducing the overall carbon footprint of public transport, especially with the continuous improvements in electric powertrain and battery technologies and costs. This paper presents a detailed comparative energy assessment between BEB and diesel buses (DB) operating at various driving and weather conditions. The different energy loads encountered in bus operation, including those needed for traction, air conditioning and operation of other electric, hydraulic and pneumatic auxiliaries are all considered in this study. Simulation results show that BEB consumes 2-4 times less energy compared to DB depending on the operating conditions where almost 80% of the energy saving is obtained from the reduction in the traction load.

Keywords:

Battery electric bus, Diesel bus, Traction load energy consumption, Heating ventilating and air conditioning, Non-mechanical auxiliary's system.

1. Introduction

Fossil fuels remain the main source to fulfill the global demand for energy resulting in high CO2 emissions [1]. The transport sector contribution is around 25 % of the global Green House Gases (GHG) emissions and the public transport sector contribution is almost 6% [2]. Emissions resulting from heavy-duty vehicles (trucks and buses) are witnessing the fastest growth among all energy sectors due to the continuous increasing need to transport goods, people and services as part of the economic cycle [3].

BEBs may help cutting CO2 emissions off by more than the half depending on the energy sources used to generate electricity [4,5]. This technology faces many technical and logistic challenges that limit its implementation in the market on a massive scale. Starting with the high capital costs of this technology, mainly reflected in its batteries, [6] and moving to the required infrastructure to deploy this technology widely, the main challenge facing this technology is the bus driving range, or in other words, the number of kilometers the bus can move on a single charge, this problem is referred to as 'range anxiety' [7,8]. For this sake, it is essential to study and quantify all the energy loads in the bus that affect the driving range.

Across the different studies presented in the literature, many works evaluate the traction load energy consumption in electric buses. [9,10] presents mathematical models to assess the traction energy consumption in heavy-duty vehicles. Others developed comprehensive models for batteries [11,12] and other powertrain components and assessed their energy consumption while other works focus on introducing a multi-physical approach to better evaluate the energy consumption and emissions related to the traction load [13]. Moreover, not many studies evaluate the air conditioning load in the bus and its impact on the bus driving range. Most of the studies stress on the HVAC system implementation in the bus without a thorough assessment of the needed thermal load [14–17]. This load had always been set as a fixed demand for energy depending on the external weather conditions, which is not a realistic representation of the air conditioning load inside the bus. Furthermore, very few studies tackle the numerous non-mechanical auxiliaries in the bus. These auxiliaries are high energy consumers and have a Significant impact on the bus driving range. Similar to the air conditioning load, many studies consider the auxiliaries load as a fixed demand for energy [18,19] whereas other studies stress on the importance of introducing more detailed models concerning these auxiliaries [20,21].

None of the studies mentioned above combine all the different energy loads together and quantify their impact on the bus driving range. Hence, this paper models the main energy loads in electric buses and compares their energy consumption to diesel buses segmenting thoroughly the traction load as it remains the largest energy consumer.

The paper starts with presenting the bus configuration highlighting the technological differences between the diesel and the electric bus in section 2. Section 3 introduces the bus model considering the powertrain, cabin, and air condition system and the pneumatic, hydraulic and electric auxiliaries. The results are discussed in section 4 and finally, section 5 concludes on the main findings in this paper.

2. Electric and diesel buses configuration

There are many technological differences between the electric and the diesel bus. It is essential to identify these differences highlighting their impact on the bus energy consumption. These technological differences will be identified at the powertrain level, air conditioning level and non-mechanical auxiliaries level.

Starting with the powertrain, Figure 1 shows the powertrain components of both the BEB and DB. The BEB powertrain consists mainly of the battery pack as the main power/energy source. Mainly a Lithium-ion battery is used in electrified powertrains. A DC-AC converter is used to supply the electric machine (MG) with the needed power to propel the bus. The transmission system consists of a reduction gear (RG) and a differential to transmit the MG torque to the wheels. The energy management strategy (EMS) controls the MG torque and brakes torque in compliance with the driver's commands. As for the DB, the engine is the main power/energy source. The transmission system consists of a clutch, gearbox and a differential to transmit the engine torque to the wheels.

Similarly, the EMS controls the engine torque and brakes torque in compliance with the driver's commands.

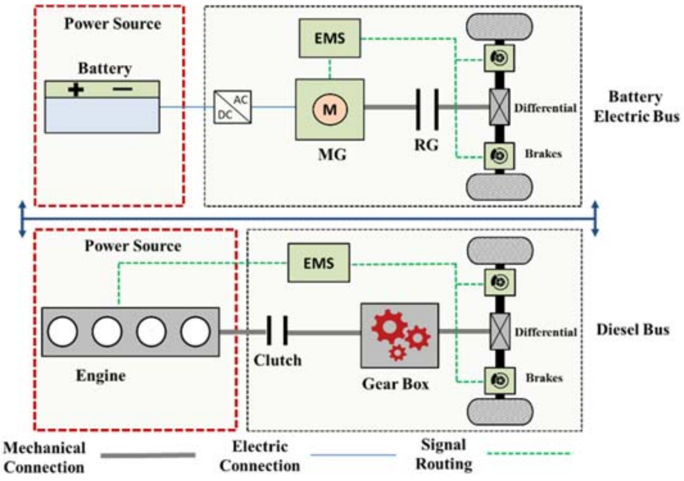

Figure 1: BEB and DB powertrain components

As for the bus cabin and HVAC system, both the BEB and DB share similar technologies. The only difference is that in a DB, the air condoning compressor (AC Comp.) is directly driven by the engine, however, in a BEB, the AC Comp. is driven by a dedicated electric motor demanding its power from the onboard battery.

Concerning the non-mechanical auxiliaries, there are vast differences in the technologies used in a BEB and a DB. First, the non-mechanical auxiliaries in a bus are all other systems that consume energy apart from the powertrain and HVAC. The main non-mechanical auxiliaries in a bus are the doors, suspensions system, parking and service brakes, steering pump, lightings, and wipers. In a BEB, most of the non-mechanical auxiliaries are electric making use of the already built-in electric system. However, in a DB, most of these auxiliaries are pneumatic. In general, the non-mechanical auxiliaries found in the bus are either electric, pneumatic or hydraulic. Table 1 identifies these auxiliaries (AUX) and their corresponding technologies in each bus configuration.

Table 1: Non-mechanical Auxiliaries in BEB and DB

AUX	BEB	DB
Service Brakes	Pneumatic	Pneumatic
Parking Brakes	Electric	Pneumatic
Suspension System	Electric	Pneumatic
Steering Pump	Hydro-Electric	Hydro-Electric
Lights	Electric	Electric
Wipers	Electric	Electric
Doors	Electric	Pneumatic

3. Bus model

The BEB and DB models are developed using the software Dymola [22]. Dymola is a multi-physical tool used to model systems that encounter different physical interactions. In this section, the main powertrain components models are presented for both buses, in addition to the cabin – HVAC model and non-mechanical auxiliaries. The bus studied, in this case, is a 12-m long chassis with three doors with a curb weight of 15500 kg and maximum seated passenger capacity of 50 passengers.

3.1. Powertrain model

This section presents the powertrain models of both BEB and DB. Only the main components are presented in this section such as the battery and electric machine for the BEB and the engine and the gearbox for the DB.

3.1.1. BEB powertrain model

The main components in a BEB powertrain are the battery and the electric machine. The battery is a Lithium-ion battery pack with 100 kWh energy capacity and 280 Ah charge capacity. It consists of 110 series sets and 113 parallel modules. The modeling approach used is a Thevenin equivalent – circuit quasi-static approach which consists of a voltage source alongside an internal resistance [23]. This modeling approach is widely used in electrified powertrain models [24,25]. Equation 1-3 describe the battery model function of the battery terminal voltage (U_T), open circuit voltage (U_{OCV}), battery power (P_{Batt}), electric current (I_{Batt}), equivalent internal resistance (R_{eq}), state of charge (SOC), initial charge capacity (C_0) and maximum charge capacity (C_{Max}). The battery cells open circuit voltage and internal resistance vary depending on the battery SOC as shown in Figure 2.

$$U_T = \frac{1}{2}(U_{OCV} + \sqrt{\left(U_{OCV}^2 - 4.P_{Batt}.R_{eq}\right)} \tag{1}$$

$$I_{Batt} = \frac{P_{Batt}}{U_T} \tag{2}$$

$$SOC\ (t) = \frac{C_0 - \int_0^t I_{Batt}(t)\,.dt}{C_{Max}} \tag{3}$$

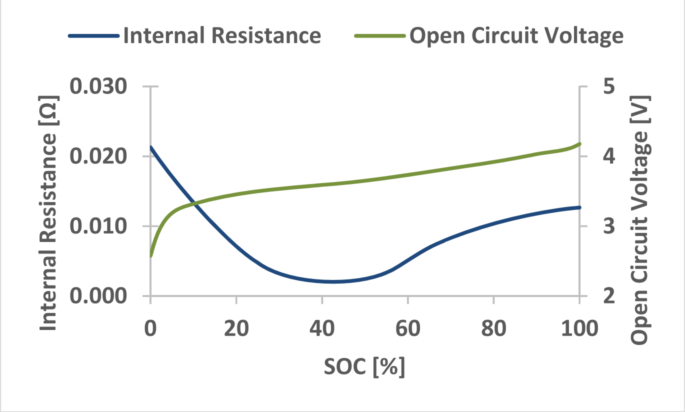

Figure 2: Battery internal resistance and open circuit voltage per cell function of the battery SOC

The electric machine (EM) used in this study is a 284 – kW providing a 1000 N.m maximum torque. The EM is modeled using look-up tables, static maps and defined inertial components in Dymola libraries to consider its dynamic behavior. Equations 4-6 describe the relationship between the EM mechanical power ($P_{EM,mech}$), electric power ($P_{EM,elec}$), rotational speed (ω_{EM}), torque (T_{EM}), electric current (I_{EM}) and efficiency (η_{EM}). The EM efficiency is considered only function of the EM torque and speed. Figure 3 shows the EM efficiency map.

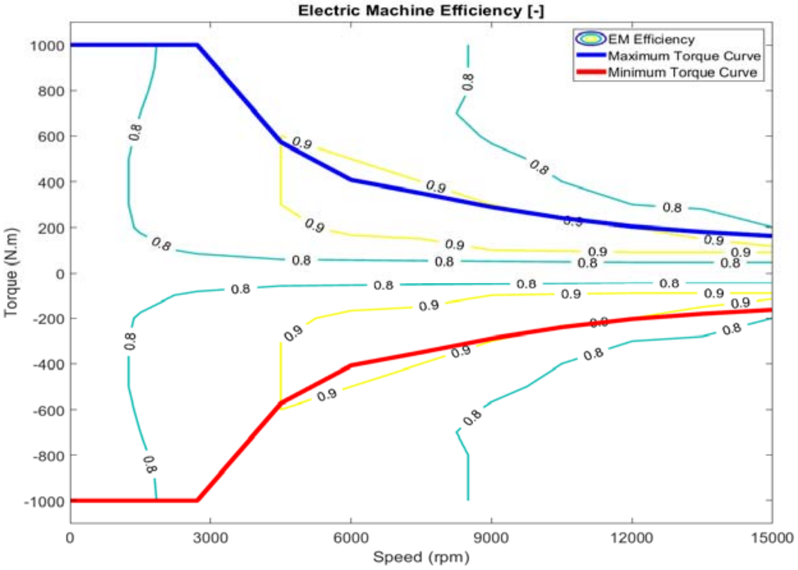

Figure 3: Electric Machine Efficiency Map

$$P_{EM,mech} = \omega_{EM}.T_{EM} \tag{4}$$

$$P_{EM,elec} = P_{EM,mech}.\eta_{EM} \tag{5}$$

$$I_{EM} = \frac{P_{EM,elec}}{U_T} \tag{6}$$

Moreover, brake energy recovery (BER) feature is considered in the EM model. BER allows the vehicle to recuperate part of its kinetic energy during deceleration through the EM. The EM output shaft is not disconnected from the wheels during deceleration, however, it will be driven by the wheels, acting as a generator converting the vehicle kinetic energy into electric energy charging the battery.

3.1.2. DB powertrain model

The engine and the gearbox are modeled in this section representing the main components in the DB powertrain. The engine used in the DB is a 205 – kW engine providing a 1200 N.m maximum torque at 2000 RPM. Similar to the EM, the engine is modeled using inertial components and static maps quantifying the engine fuel flow only function of the engine torque and speed as shown in Figure 4. The engine fuel consumption is mainly calculated in $L/100\ km$ of diesel fuel, however, in order to compare the DB energy consumption to the BEB energy consumption, the DB fuel consumption is converted to its equivalent electric energy consumption (E_{DB}) measured in $kWh/\ km$ as shown in equation 7 where $\dot{m}(t)$ is the engine fuel flow at each instant, Q_{LHV} is the diesel fuel calorific value and D_{Total} is the total distance driven during the trip .

$$E_{DB} = \int_{0}^{t} \dot{m}(t).dt\,.\frac{Q_{LHV}}{D_{Total}}.\frac{1}{3.6e^{6}} \tag{7}$$

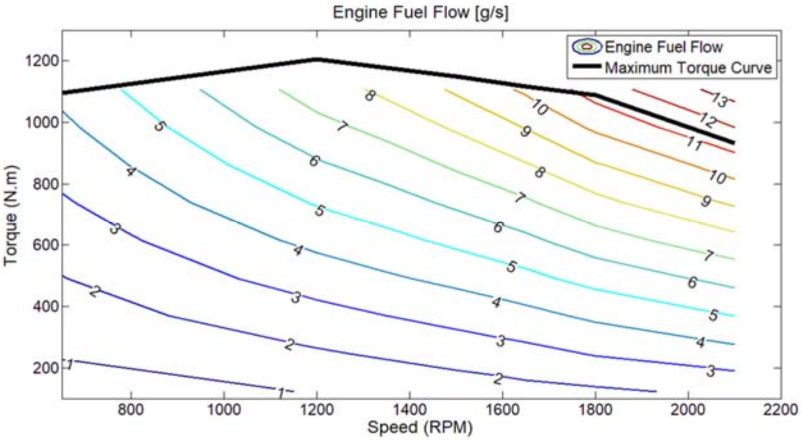

Figure 4: Diesel Engine Fuel Flow Map

As for the gearbox, it is a 4-speed gearbox with a maximum transmission efficiency of 95%. The largest gear ratio is 3.42 and the smallest ratio is 1. The gearbox is coupled to a differential with a final drive ratio equals to 4. The gearbox is modeled using Dymola rotational mechanics library by connecting a set of gears, synchronizers, and controllers all together as shown in Figure 5. Each gear has its own synchronizer which is controlled by the gearbox controller. The gearbox controller receives gear shifts demands from the driver and then it actuates the relevant synchronizers to engage the required gears.

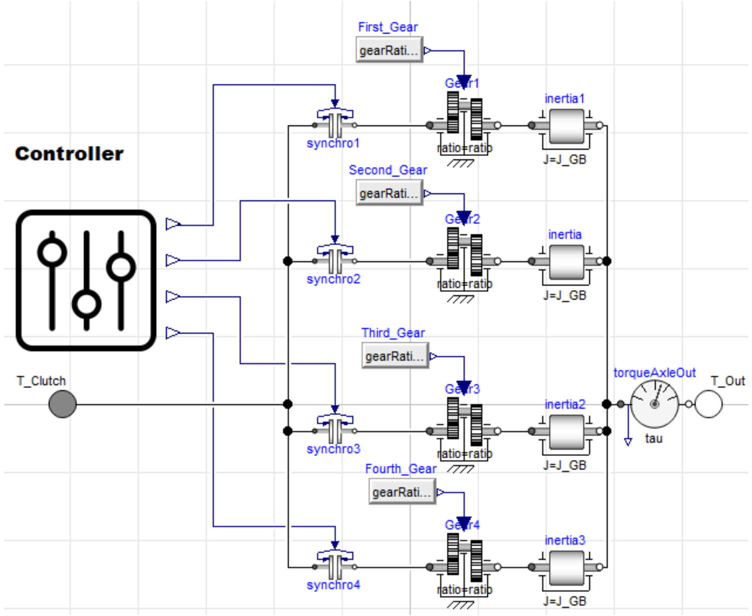

Figure 5: Gearbox Model of the DB in Dymola

3.2. Cabin - HVAC model

The cabin model used in this study is previously developed by the current co-author in [26]. It is a single thermal node from the inside representing a mono-zonal modeling approach. The model considers heat transfer with the bus surrounding through the cabin walls by means of convection, radiation in addition to the transmitted and absorbed heat flow through glazing. The heat exchange internal cabin materials (seating, dashboards) is taken into account. Passengers sensible and latent heat rejections are considered as well. The cabin model quantifies the bus thermal needs in order to attain thermal comfort conditions. Both BEB and DB share the same cabin model.

As for the HVAC model, a Heat Pump (HP) is considered in this study in order to heat up/cool down the bus cabin depending on the weather conditions. The HVAC unit supplies a heat flux that is controlled by the HVAC control unit varying the air flow rate, blown air temperature, blown air humidity, and cabin air recirculation rate in order to meet the thermal comfort conditions. This HVAC model demands energy from the battery (in the BEB case) and from the engine (in the DB case). Equations 8-10 describe the relations between the HVAC unit compressor work ($W_{HVAC,Comp}$), evaporator heat flow (Q_{Evap}), condenser heat flow (Q_{Cond}) and coeeficient of performance (COP) where (T_L) is the cold medium temperature, (T_H) us the hot medium temperature, ($COP_{HP,Carnot}$) is the Carnot COP and (η_{ex}) is the exergetic efficiency. **Error! Reference source not found.** shows the cabin-HVAC unit interaction for both buses.

$$COP_{HP,Carnot} = \begin{cases} \dfrac{1}{\dfrac{T_H}{T_L} - 1} (Cooling) \\ \dfrac{1}{1 - \dfrac{T_L}{T_H}} (Heating) \end{cases} \tag{8}$$

$$COP = COP_{HP,Carnot} \cdot \eta_{ex} \tag{9}$$

$$W_{HVAC,Comp} = \begin{cases} \dfrac{Q_{Evap}}{COP} (Cooling) \\ \dfrac{Q_{Cond}}{COP} (Heating) \end{cases} \tag{10}$$

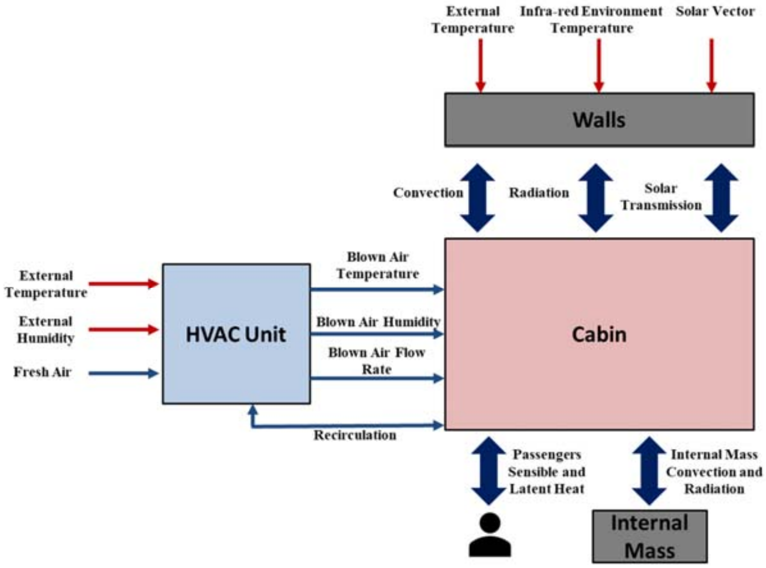

Figure 6: Cabin-HVAC unit configuration in BEB and DB

3.3. Non-Mechanical auxiliaries

The non-mechanical auxiliaries utilize different technologies in each bus configuration. The BEB AUX system is mainly electric and more efficient compared to the pneumatic system found in a DB. However, the pneumatic AUX system is more robust and requires less maintenance. The AUX energy consumption is used to be considered as a constant power demand which is not representative of a real situation. On the contrary, in this paper, each AUX system is modeled as dynamic power demand from the onboard power source whenever its features are actuated introducing a more realistic approach to quantify the energy and power demand of the non-mechanical auxiliaries in buses. Based on the AUX classifications for each bus configuration presented in Table 1, equations 11-13 describe the BEB non-mechanical AUX system.

$$P_{AUX-Electric} = P_{Doors} + P_{Suspension.} + P_{Parking\ Brakes} + P_{Lights} + P_{Wipers} \tag{11}$$

$$P_{AUX-Pneumatic} = P_{Service\ Brakes} \tag{12}$$

$$P_{AUX-Hydraulic} = P_{Steering\ Pump} \tag{13}$$

Equations 14-16 describe the DB non-mechanical AUX system.

$$P_{AUX-Electric} = P_{Lights} + P_{Wipers} \tag{14}$$

$$P_{AUX-Pneumatic} = P_{Doors} + P_{Suspension.} + P_{Parking\ Brakes} + P_{Service\ Brakes} \tag{15}$$

$$P_{AUX-Hydraulic} = P_{Steering\ Pump} \tag{16}$$

4. Results and discussion

Using the introduced models, different simulations are conducted in order to evaluate the energy performance of both the BEB and the DB at different driving and weather conditions. Three levels of traffic are considered representing heavy traffic, normal traffic, and low traffic. Moreover, three different weather conditions are considered representing extreme cold weather conditions (-10 °C), cold weather conditions (10 °C) and hot weather conditions (40 °C). In this section, the different energy loads (traction load, thermal load, and non-mechanical auxiliaries load) encountered in a bus are be quantified at the pre-mentioned simulation conditions.

4.1. Impact of driving conditions

Figure 7 shows the traction load energy consumption at different traffic conditions for both buses. Across all traffic conditions, the DB consumed more energy compared to the BEB. This is due to the powertrain efficiency in both buses. The engine efficiency in the DB ranges between 35%-40% whereas the electric motor efficiency in the BEB is around 80%.

As for the BEB, its traction energy consumption is not sensitive to the traffic conditions and the consumption is always centered around 2 kWh/km. The main reason behind this stability is that the electric motor efficiency is not sensitive to the operating speed. However, the DB shows high sensitivity to the traffic conditions and its consumption doubles at heavy traffic conditions compared to lower traffic conditions. The first reason behind this increase in energy consumption is the diesel engine drop in efficiency at lower speeds (heavy traffic conditions). The diesel engine efficiency can drop down to 10% at very low speeds causing this increase in the traction energy consumption. In addition, engine consumption during idling is another reason that leads to this increase in consumption. Heavier traffic conditions cause more bus stops resulting in huge idling consumption. Section 4.3 thoroughly discusses and segments the traction load for both buses.

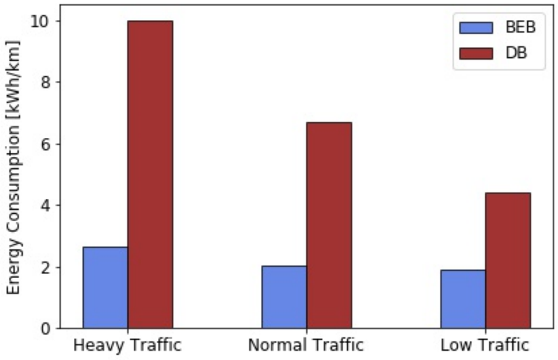

Figure 7: Traction load energy consumption for BEB and DB at different traffic conditions

Traffic conditions don't only impact the traction load energy consumption, but it also affects the non-mechanical auxiliary's energy consumption. Figure 8 shows the non-mechanical auxiliaries load energy consumption at different traffic conditions for both buses. The DB is still recording higher energy consumption compared to the BEB mainly due to its reliance on a pneumatic auxiliary system with higher energy consumption and lower efficiency compared to the mostly all-electric auxiliary system in the BEB.

Moreover, heavier traffic conditions have a significant impact on the auxiliary's energy consumption. With heavier traffic conditions, the auxiliaries are used more frequently resulting in this increase in their energy consumption. For example, the service brakes are used more during heavier traffic conditions resulting in additional consumption. Furthermore, the steering pump hydraulic power demand is significantly higher at lower vehicle speeds which is the case at heavier traffic conditions resulting in higher energy consumption. In addition, heavier traffic conditions encounter more bus stops resulting in a more frequent actuation of the suspension system which is a significant energy load in heavy-duty vehicles.

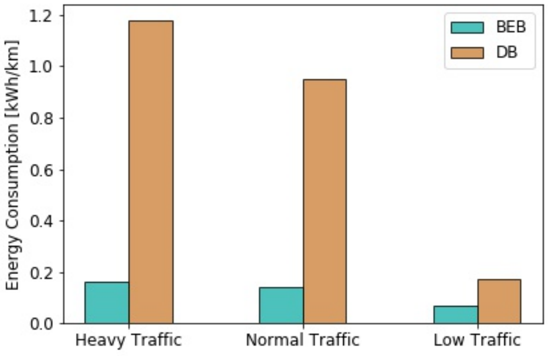

Figure 8: Non-mechanical auxiliaries load energy consumption for BEB and DB at different traffic conditions

4.2. Impact of weather conditions

The weather conditions significantly affect the energy consumption of the bus especially if extreme weather conditions are considered. Figure 9 shows the thermal load energy consumption at different weather conditions for both buses. Both buses record very high energy consumption at extreme weather conditions. This consumption is almost equivalent to the traction energy consumption. In other words, the energy needed to air condition the bus is equal to the energy needed to propel the bus. For a BEB, this means a drastic reduction in its driving range creating schedule disruptions and disturbances in operation as it must be charged more frequently to compensate for this energy consumption due to air conditioning. The DB also witnesses a decrease in its driving range at extreme weather conditions, however, this is not a big concern as its refueling process is very fast compared to the BEB.

On another hand, the DB consumes almost as twice as the BEB to air condition its cabin across all weather conditions. The main reason is that the HVAC system efficiency in the DB is way lower than that in the BEB since the AC Comp. is driven by the engine in the DB which operates at lower efficiencies compared to the electric motor that operates the AC Comp. in the BEB. It is important to note that waste heat recovery from the diesel engine is not considered in this study. Waste heat recovery can help reduce the total energy demand for heating inside the DB.

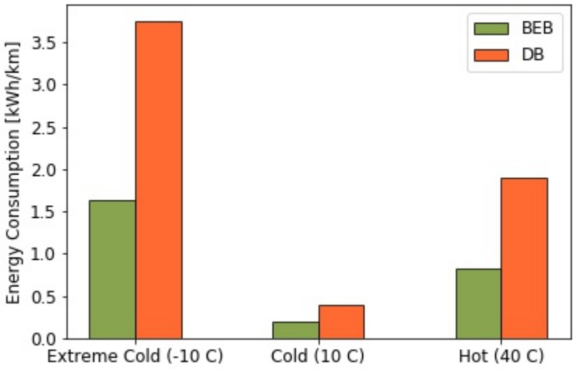

Figure 9: Thermal load energy consumption for BEB and DB at different weather conditions

4.3. Traction load segmentation

A big portion of the difference in the energy consumption between the BEB and the DB comes from differences in the traction load energy consumption. For this sake, it is interesting to segment this load to better understand and evaluate this difference in energy consumption. Figure 10, Figure 11 and Figure 12, show the traction load segmentation for both buses at heavy, normal and low traffic conditions respectively. The traction load is segmented as follows:

1. Energy consumed during the bus acceleration (Acceleration).
2. Energy consumed during the bus idling (Idling).
3. Energy recovered during the bus braking (BER).

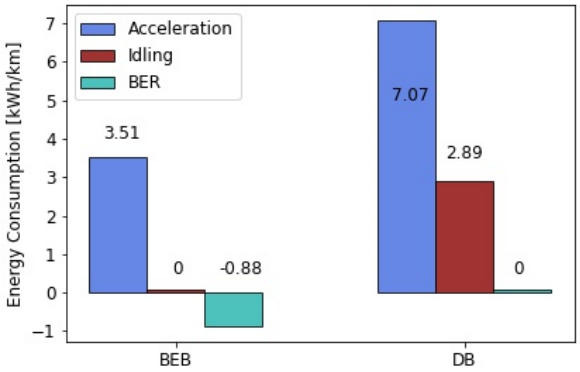

Figure 10: Traction load segmentation at heavy traffic conditions

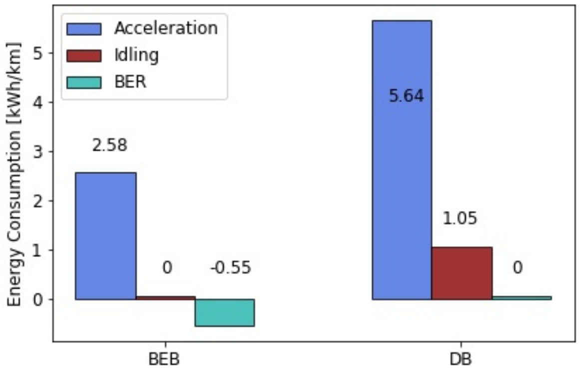

Figure 11: Traction load segmentation at normal traffic conditions

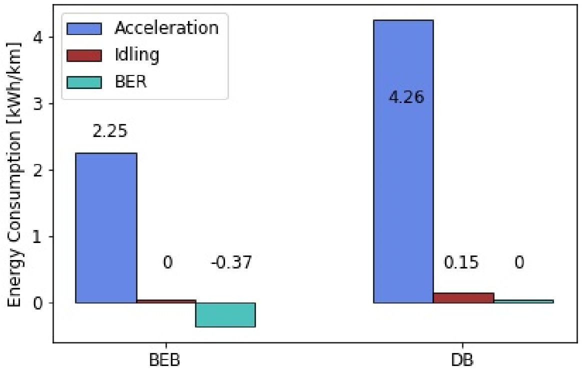

Figure 12: Traction load segmentation at low traffic conditions

The acceleration energy consumption for both buses across all traffic conditions is directly related to the powertrain efficiency as discussed earlier in section 4.1. The BEB has higher traction efficiency and this is the first reason behind its lower traction energy consumption

As for the idling energy consumption, the DB encounters very high idling energy consumption during heavy traffic conditions as shown in Figure 10 due to frequent bus stops. This value decreases as traffic becomes less congested. On the other hand, the BEB encounters no idling energy consumption since its electric motor is turned off during bus layovers or stops due to traffic. The idling consumption represents almost 40% of the DB total traction energy consumption and this is the second reason behind its higher traction energy consumption.

Moreover, the BEB has the BER feature which is not possible in the case of the DB. The BER allows the BEB to recuperate part of its kinetic energy during braking resulting in a reduction in the total traction energy consumption that may reach 20% depending on the recuperation level. This highlights the last reason behind the BEB lower traction energy consumption.

5. Conclusion

This study comprehensively evaluates and compare the energy consumption of BEB and DB considering all the different energy loads encountered in the bus such as the traction load, air conditioning load, pneumatic, hydraulic and electric auxiliaries loads. The paper highlights the technological differences between the DB and BEB as well, as they have a direct impact on the buses energy consumption. Different simulations are conducted representing different driving and weather conditions. The results show that a BEB can consume up to 4 times less energy compared to the DB especially in heavy traffic conditions where most of this reduction comes from the reduction in the traction load energy consumption. In addition, the impact of thermal load is evaluated as well, and the results show a drastic increase in energy consumption at extreme weather conditions. Finally, the traction load is further segmented, and the analysis revealed that powertrain efficiency, diesel engine idling consumption and BER feature all favor the BEB to have a way lower traction energy consumption compared to the DB.

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