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Analysis of Technical Capabilities, Methodology and Test Results of a Light-Commercial Vehicle Conversion to Battery Electric Powertrain

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Abstract: This paper describes a holistic development and testing approach for a battery electric vehicle (BEV) prototype based on a self-supporting body platform originating from a vehicle powered by an internal combustion engine. The topic was investigated in relation to the question of whether conversion of existing vehicle platforms is a viable approach in comparison to designing a new vehicle ab initio. The scope of work consisted of the development stage, followed by laboratory and on-road testing to verify the vehicle's performance and driveability. The vehicle functionality targeted commercial daily use on urban routes. Based on the assumed technical requirements, the vehicle architecture was designed and components specified that included various sub-systems: electric motor powertrain, electronic control unit (ECU), high-voltage battery pack with battery management system (BMS), charging system, high and low voltage wiring harness and electrically driven auxiliary systems. Electric sub-systems were integrated into the existing vehicle on-board controller area network (CAN) bus by means of enhanced algorithms. The test methodology of the prototype electric vehicle included the vehicle range and energy consumption measurement using the EU legislative test cycle. Laboratory testing was performed at different ambient temperatures and for various characteristics of the kinetic energy recovery system. Functional and driveability testing was performed on the road, also including an assessment of overall vehicle durability. Based on the results of testing, it was determined that the final design adopted fulfilled the pre-defined criteria; benchmarking against competing solutions revealed favorable ratings in certain aspects.

Keywords: electric vehicle; battery electric; induction charging; regenerative braking

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1. Introduction

According to many studies, powertrain electrification is the main leverage to reduce global carbon dioxide (CO_2) emissions from transport sources and only a high level of electrified vehicles in the fleet mix stands a chance of meeting the decarbonization challenge in the European Union (EU) planned in a Green Deal scenario [1–6]. Electric vehicles (EVs) are expected to gradually replace conventional (internal combustion engine-powered) vehicles (ICEVs) because of their higher energy efficiency and zero in-use greenhouse gas (GHG) emissions. The EV market share has continually spread from class A small passenger cars in to the direction of light duty and heavy duty vehicle applications, including buses and trucks [5,6]. The case of electric trucks is particularly interesting, as trucks accounts for about 60% of the overall freight transportation and at the same time this sector is to be based on fuel cell (FC) drivetrains with an on-board hydrogen storage tank [7,8].

Using an electric motor in road vehicle propulsion is not a new idea. Electric vehicles had already appeared in the late 1860s—earlier than vehicles powered by internal combustion engines (ICE, which appeared in 1876); the first applications appeared in 1828. Popularity was boosted by low maintenance, as they did not require a complicated start procedure or preheating, and they produced no emissions. In 1900 EVs were the top selling

road vehicles in the US, with a 28% market share. At the end of the 19th century and at the beginning of the 20th century, electric cars constituted a significant part of the fleet. However, electric vehicles were much more expensive than ICEV. In 1923 the Ford Model T cost $300 and many EVs cost 10 times as much. Despite many advantages, electric motors lost the battle with the internal combustion engine. The biggest disadvantages were low range and limited battery capacity, and the substantial weight of the battery itself. Furthermore, in 1912 the electric starter for ICE vehicles was invented that resolved the inconvenience of start-up by hand crank in gasoline- and ethanol-fuelled engines. By 1935 EVs had become all-but-extinct due to the predominance of ICEs in passenger cars and low gasoline prices [9,10]. The second phase of EV development was during the years 1951–2001, when environmental issues and high oil prices restored the graces of electric propulsion. The third phase of EV development began in 2001, when the public and private sectors again started to develop an electrified vehicle program [10]. Currently, demand for electrified vehicles is rising globally, especially in China, but also in Europe, where the market has been driven by stringent emissions regulation along with increasing awareness of anthropogenic CO_2 emissions' dominant influence on climate change. The development and introduction of innovative electronic solutions have made electric motors better, quieter and much more powerful, electric propulsion is now once again the centre of attention, especially as a way to achieve the "zero" GHG emissions target, making up a crucial development point for the entire automotive industry [11,12]. In 2018, the European Commission finalized its approach concerning the proposed regulation on CO_2 emissions reduction, amending Regulation (EC) No 715/2007. The targets agreed by the European Council for EU fleet average CO_2 emissions in 2025 and 2030 are currently 15% and 37.5%, respectively, for passenger cars and 15% and 31% for light-commercial vehicles using the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) test procedure, compared to the 2020/2021 target (95 g/km using the NEDC test procedure) [10].

The market share of hybrid-electric vehicles rose slowly in the last several years, reaching 1.8% of all new cars sold in the European Union in 2016. Plug-in-hybrid and electric vehicles together were at a level of about 1% among all vehicles sold in 2016 and 1.9% in 2019 [11]. Current European sales of electrified vehicles are about 2.5–3.5% of all new vehicle registrations and may rise to about 4–5% in 2021 and to higher percentages in the years to 2025, when a significant uptake of the electric vehicle market is to be expected. Despite the Covid-19 pandemic causing a major shock to the global economy and decreasing new vehicle sales by about 23-25%, electric car sales have remained strong [13]. The Chinese market has taken the lead, with 138 different EV models available in China, compared to 60 in Europe and only 17 in the USA, while the EV market share in China was 3.1% in 2019 and 2.6% in 2020 [13].

Currently, four types of electrified drivetrains that use electric motors are considered for use in modern road vehicles: HEVs (hybrid electric vehicles with a gasoline or diesel engine), PHEVs (plug-in hybrid electric vehicles, with an engine), BEVs (battery electric vehicles) and HFCEVs (hydrogen fuel-cell electric vehicles and hybrid fuel-cell electric vehicle) [1,9]. An electric (battery) powertrain consists of an onboard high-energy battery or supercapacitor, or both, electric energy converters (inverter), an electric motor and a drivetrain system [14–17]. Energy and power supplied must be sufficient to overcome the following:

- Air drag, which is proportional to the vehicle frontal area, the air drag coefficient and the square of the speed;
- Rolling resistance, which is proportional to vehicle mass and the coefficient of rolling resistance;
- Vehicle inertia, which is caused by the mass of the vehicle and the effect of rotating components, which must be accelerated both rotationally and linearly;
- Gravity (during ascents);
- Power losses (internal and external) e.g., due to friction.

Additionally, to meet the following criteria:

Provide power to other on-board equipment and subsystems, e.g., lights, cabin heating, ventilation and air conditioning (HVAC) systems, radio, power drives, electronic control units, etc. [4,5,18].

In many countries, there is also a growing interest in the use of hybrid [19] or pure electric propulsion in light-commercial vehicles instead of diesel engines, which are the solution mainly used in current urban and extra-urban transport of goods [20–26].

Notwithstanding growing interest and increasing market share, challenges remain in the widespread adoption of EVs and PHEVs. These challenges include meeting consumer demands (particularly those relating to range and charging) and the practicalities of achieving simultaneous electrical charging of large numbers of vehicles [27,28]. The latter aspect has broad implications for drivers and vehicle owners, and parking areas and even for the electricity grid and broader power generation sector. The implementation of intelligent systems for determining rational charging strategies and power management schemes is considered necessary for EV adoption at wide scale, since uncoordinated, ad-hoc charging approaches (first-come-first-served) are likely to prove problematic [27,28].

The aim of this project was to build a prototype, light-commercial battery electric vehicle (LC BEV) on the basis of an ICEV platform. The vehicle was designed to be used in short-distance urban transportation over a limited area and covering relatively small daily distances of around 100-180 km. Therefore, an important aspect of the design was to ensure the market-required functionality of the vehicle, including ease of daily operation, load capacity and cargo capacity. The vehicle featured an energy management system (EMS) with standard alternating current (AC) charging and fast, direct current (DC) charging. The EMS incorporated the capabilities of variable characteristics of kinetic energy recovery as a function of vehicle speed. The vehicle systems' functionality was validated during on-road and laboratory test activities in a climatic test chamber at temperatures ranging from −10 to 30 °C according to the procedures described in [29,30].

2. Materials and Methods

2.1. Scope of Vehicles Conversion Work and Components Definition

The design of the prototype battery electric vehicle was based on the customized vehicle's platform deriving from an ICEV counterpart and manufactured by one of Europe's leading vehicles manufacturers. The platform included complete vehicle bodywork integrated into chassis, and held a European type approval certificate. The platform was equipped with the regular vehicle subassemblies such as: suspension system, braking and various safety systems, cooling system and driveshafts with universal joints.

The implementation of the pure electric battery powertrain incorporated the mechanical design, assembly and electrical/electronical (E/E) integration of the following systems on board the vehicle:

- Electric motor powertrain and electronic control unit;
- Traction battery and the battery management system;
- Battery charging system;
- Vehicle controller area network (CAN) bus architecture;
- Auxiliary vehicle systems.

Mechanical components defined for the systems listed above were designed in a way to reutilize—to the greatest possible extent—the production components from the ICEV version of the vehicle. This allowed costs to be reduced and ensured that the elements used had already been tested by the platform's manufacturer and were of appropriate durability. Before the project was commenced the base assumptions of vehicle parameters and expected values were developed in line with mechanical and electrical components specification. The definition of parameters' expected values was carried out under several stages. At first the groups of potential niche customers were identified for a light commercial electric vehicle, focusing on logistics companies, utility or municipal vehicles. Secondly, the IECV fleet operations were analyzed in terms of replacement possibility with electric vehicles counterpart. The requirements of logistics and delivery specification related to the

vehicle features such as cargo space, comfort and energy demand were analyzed in detail. Key parameter to be evaluated was the optimum range definition for electric commercial vehicles [31]. The list of expected and obtained technical characteristics of the prototype vehicle (i.e., the specification) is shown in Table 1.

Table 1. Prototype vehicle specification.

Parameters	Expected Value	Obtained Value
Vehicle curb weight	Max. 2000 kg	1807 kg
Vehicle range	Min. 100 km	133 km
Battery capacity	Min. 25 kWh	33.2 kWh
Electric motor nominal power	Min. 45 kW	45 kW
Electric motor max power	-	85 kW
Payload	Min. 500 kg	613 kg
Maximum speed	90 km/h	98 km/h
Charging time	Max. AC: 3.5 h/DC: 1.5 h	AC: 2.50 h/DC: 1.0 h
Range increase with EMS and kinetic energy recovery active	10%	3.9%

2.1.1. Electric Motor Powertrain and Electronic Control Unit

The chosen vehicle platform featured front wheel drive (FWD) architecture and that design remained unchanged. Due to the demands of high efficiency, agility and torque density, KOMEL Institute provided a dedicated permanent-magnet synchronous motor (PMSM) solution, as specified in Table 2. The electric motor was located transversely inside the former combustion engine compartment and drove the front wheels through a single-speed gearbox with helical gear and a differential mechanism. For safe parking during vehicle standstill, a parking lock blocking system was designed, which acted on the gearbox input shaft. The components for the parking lock were adopted from an ICEV and the system was activated by linear electric actuators.

Table 2. Electric motor specification.

Parameters	Technical Data
Technology	PMSM, liquid cooled
Continuous power	45 kW
Peak power	85 kW
Peak torque	250 Nm
Voltage	AC 153 V
Maximum current	380 A
Rotation speed max.	7800 rpm
Efficiency	95.0%
Weight	55 kg

Power transfer from the gearbox output to the wheels was realized by ICEV driveshafts and constant velocity joints on the wheel side. The right hand side driveshaft length was extended, and this necessitated displacement of the existing supporting point in order to improve the noise, vibration and harshness (NHV) characteristics. That was achieved by the authors' concept of a metal sleeve design with a roller bearing to ensure a coaxial layout with the gearbox input shaft.

The powertrain unit was suspended on an intermediate frame, designed to utilize the existing elastic elements from the combustion engine and the underbody fixing points. The intermediate frame allowed installation of the Sevcon inverter for electric motor and the Valeo AC chargers for the traction battery.

The electric motor was controlled by a Sevcon Gen4Size8 inverter and its control functions and algorithms were implemented in the vehicle's electronic control unit (ECU). The electric motor and inverter worked in motoring and generator modes for kinetic energy recovery. Part of the vehicle's EMS was an adaptive regenerative braking system (RBS)

with variable braking torque settings as a function of electric motor speed thus the vehicle speed, considering the single speed gearbox installed in the vehicle. The actual braking torque value was calculated on the basis of the algorithm implemented in the ECU. The change of the braking torque took place in real time on the basis of the curves assigning a given rotational speed of the motor to the corresponding braking torque level expressed in percent as shown in Figure 1. The R0 setting meant inactive RBS and no electric energy was generated by the motor. Activation of a brake pedal by the driver caused energy recovery to increase by 20%, comparing to base curves and in that case the settings were designated with the letter H (R50H, R10-50H, R20H and R35H). All of the aforementioned regenerative braking settings were tested, using the methods described in Section 2.2. In order to increase the reliability and safety of the system, an additional mechanism was introduced to verify the correctness of data in the ECU memory. A checksum of all programmed values was calculated. In the event of data inconsistencies the energy recovery function was deactivated to eliminate the possibility of unintended high braking torque activation.

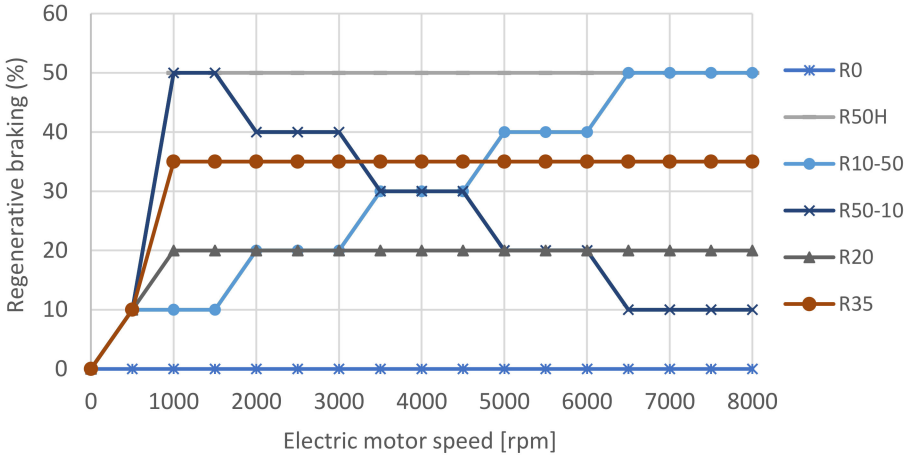
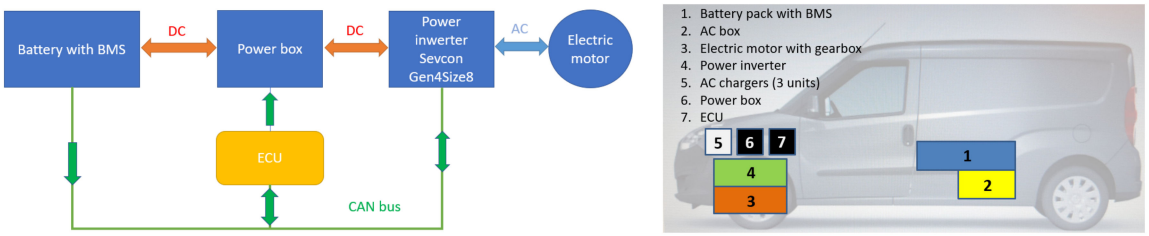


Figure 1. Base regenerative braking curves implemented into the electronic control unit (ECU).

The braking torque value was limited by the maximum current temporarily allowed to battery charging. The ECU controller checked the battery state of charge (SOC) status. For the SOC value above the defined threshold (e.g., 99%) the regenerative braking was not activated as the battery could no longer receive electric energy. The electric current generated during the regenerative mode was constantly monitored by the ECU to not exceed the limit set by the battery management system (BMS). In case of exceedance, the braking torque thus the current generated, was limited by the ECU to protect the battery. The control scheme with possible energy flows and main components location in the vehicle are shown in Figure 2.



(**a**) (**b**)

Figure 2. (**a**) Electric energy flow layout and (**b**) main components location in the vehicle.

2.1.2. Traction Battery and the Battery Management System (BMS)

The lithium-ion battery pack consisted of a total of 96 battery cells designed in 96S01P configuration, (8 modules 12S01P). The technical data is presented in Table 3. The function of the BMS was to monitor and optimize the battery state of operation and protect it against damage. The BMS controller allowed communication via CAN bus. The control algorithms were implemented in the vehicle's ECU. They included battery parameter reading via CAN bus, commanding of charge and discharge permission flags, carrying out the correct sequence of safe battery ON/OFF, controlling the drive system and the charging process in a way that the current limits were not exceeded. Due to its considerable weight and external dimensions, the battery pack was installed inside the vehicle's cargo space. It was encased in flat surfaced metal housing and fixed to the main components of the vehicle body superstructure. The battery pack location was optimized with respect to even load distribution between the vehicle's axles. The battery pack was designed in compliance with the applicable ECE regulations (R100 and R10).

Table 3. Traction battery pack specification.

Parameters	Technical Data
Cells configuration	96S01P (8 modules 12S01P)
Cell chemistry	Lithium-ion NMC
Cell nominal voltage	3.68 V
Nominal energy	33.2 kWh
Nominal capacity	94 Ah at 25 °C
Maximum voltage	398 V
Maximum discharge/charge current (DC) at 25 °C	230 A/100 A
Weight	330 kg

The purpose of the ECU was to integrate the existing electrical installation of the vehicle's platform with the new system and algorithms required for electric vehicle operation. For the correct integration of the new and existing systems, the ECU functionality was extended to emulate the vehicle engine control module (ECM) that originated from the vehicle platform and was isolated from the electric-electronic system. To achieve correct functionality of the vehicle, including safety systems (antilock braking system (ABS) and electronic stability program (ESP)), the relevant signals had to emulated and communicated. The number of signals and the type and value differ between carmakers.

New functions implemented into the ECU controller included:

- Electric motor powertrain control;
- Battery pack and charging process control;
- Gateway function on the low speed CAN bus for control of dashboard signals;
- Communication algorithms with the vehicle's high speed CAN bus;
- Control of subsystems such as HVAC.

Due to the complexity of the control algorithms and the need to support four CAN buses simultaneously, the HY-TTC 540 controller type was selected. The controller software was designed in the CODESYS environment.

2.1.3. Battery Charging System

Battery Charging Modes

The EV fleet, especially the portion for commercial purposes, must feature the possibility of different charging modes according to the available local infrastructure. Therefore, in the described design, three different charging modes were enabled, which included standard AC charging (Type 3), household AC charging (Type 1) and fast DC charging (Type 4).

AC Charging (Type 1 and Type 3)

The AC charging system was designed according to the IEC61851 standard. It was defined as slow or semifast charging by means of a dedicated connection to the charging point. Figure 3 presents the overall scheme of the Type 1 and Type 3 charging system implemented into the vehicle.

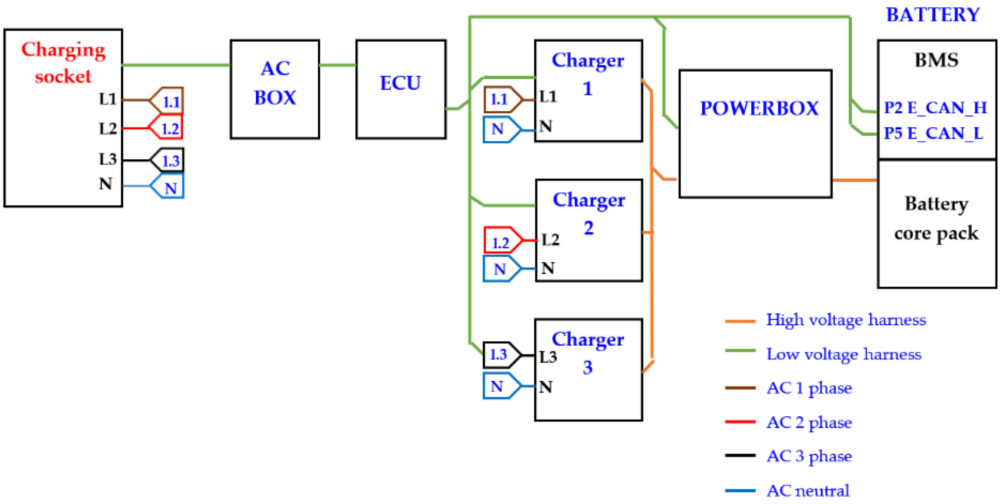


Figure 3. Overall scheme of the Type 3 and Type 1 charging system.

The charging socket was common for all types of charging. The socket selected was the PHOENIX CONTACT, IEC2 type (Combo 2) compliant to IEC 61851-1 and IEC 62196-3. It enabled AC charging at up to 32 A at 400 V AC and DC charging at up to 200 A at 400 V DC. The AC box included a VECTOR VC36PLC-24 controller capable of providing the CAN communication with the vehicle's electronic systems and securing the charging parameters such as the charging current, voltage and battery temperature. Three units of VALEO OBC GEN2.5 chargers (each of power 3.3 kW) were connected in parallel. The power distribution box provided electric energy transition from the chargers to the battery pack. It contained fuses and high voltage contactors controlled by the ECU. The ECU was based on the HY-TTC 500 controller responsible for the management of the battery pack, the charging system and the power distribution box. The estimated battery charging time from 0% the state of charge (SOC) to 100% SOC was 3 h at 9.9 kW power and 400 V AC.

The AC charging system also supported the Type 1 AC 230V/400V one-phase current up to a maximum of 16 A.

DC Charging (Type 4)

The charging system enabled the DC fast charging (Type 4) according to the EC61851 standard. The communication protocol for the charging process was realized according to DIN SPEC 70,121 and ISO 15,118 standards, using the Power Line Communication (PLC). The following components were common for both DC and AC charging: PHOENIX CONTACT IEC2 (Combo 2) charging socket, VECTOR VC36PLC-24, CAN communication controller, power distribution box and the ECU controller. The battery charging time for Type 4 and from 0% SOC to 100% SOC was approximately 1.5 h at the maximum power of 33 kW and 100 A at DC 400 V. The overall scheme of the Type 4 charging implemented in the vehicle is shown in Figure 4.

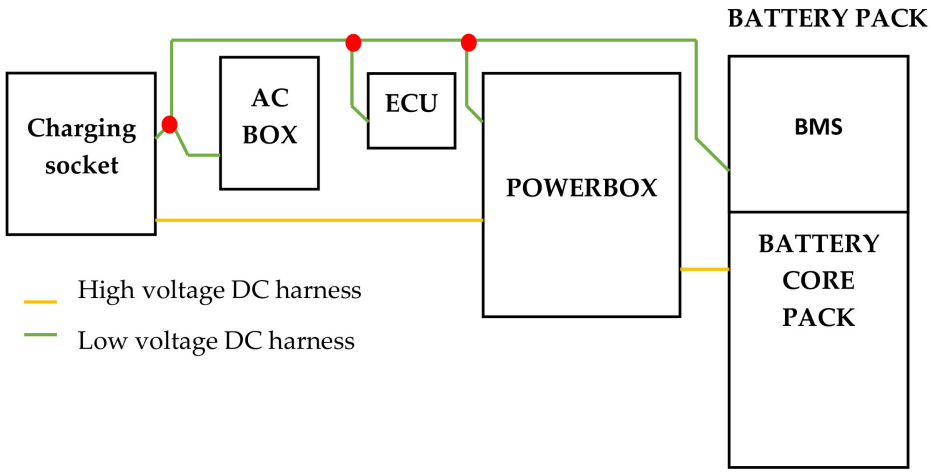


Figure 4. Overall scheme of the Type 4 charging system.

2.1.4. Vehicle CAN Bus Architecture

The vehicle's electric and electronic components' communications was based on four CAN buses connected to the ECU. The ECU function was to read out and generate the necessary input and output data signals of electronic modules to manage their correct functionality. Figure 5 presents the structure of designed CAN buses architecture on the prototyped vehicle. The CAN 1 was the main CAN bus on board the vehicle that connected all electronic modules, besides the electric powertrain components. The CAN 2 was the CAN bus dedicated for communication between electric powertrain components. CAN 2 integrated also electric components active during battery charging process. CAN 3 was responsible for the communication with vehicle dashboard module and control of the information displayed for the driver. The remaining vehicle's platform CAN bus corresponded to CAN 4. In the event of ECU inactivity, the CAN bridge closed the CAN 3 and CAN 4 buses, enabling transfer of control over the vehicle dashboard module to the body control module (BCM).

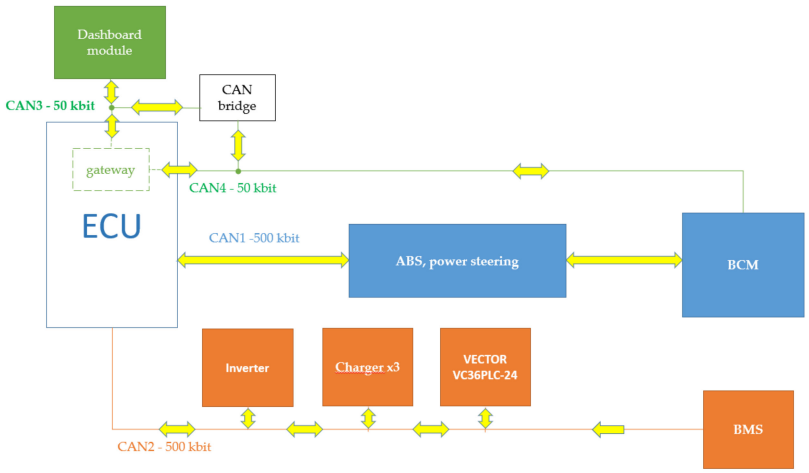


Figure 5. ECU controller and the controller area network (CAN) bus architecture of the vehicle.

For the vehicle development process, a special diagnostic socket was installed, which enabled data reading from all CAN buses.

2.1.5. Auxiliary Vehicle Systems

- Power steering system:

The main components of the power steering system, including the torque sensor, were carried over from the ICEV. However, the poly-V belt-driven power steering pump was replaced with an electrically driven hydraulic pump (12 V DC), produced by TRW Automotive. To ensure proper system functionality, the electric power steering pump operated with a similar characteristic to the conventional pump. Under no-load conditions, the overflow valve was activated to decrease the hydraulic fluid and keep energy consumption to a minimum. When the steering wheels were to be turned, the hydraulic pressure was built up and the fluid was directed to the appropriate side of the power cylinder piston to support the steering rack movement.

- Vehicle cabin comfort:

The vehicle cabin HVAC systems were operated by electric power. For cabin heating, the ICEV vehicle air-coolant heat exchanger was replaced by a PTC heating unit of 3 kW power, produced by 4ABC. The PTC unit was selected to reach the heat exchanger temperature as in the case of the conventional vehicle. The air temperature adjustment was realized by mixing the warm and cold air by means of the standard vehicle's control panel.

The A/C system components such as the condenser, evaporator and control panel were adapted from the conventional vehicle; thus, the modification work aimed at the replacement of the poly-V belt driven A/C compressor with an electric solution. An electric A/C compressor of rotary screw type, produced by Autoclima, was selected.

- Cooling system of electric motor and charging system:

The cooling system consisted of two circuits with the common air-coolant heat exchanger and expansion tank but two separate pumps for each circuit. The first circuit was designated to cool down the electric motor only while the second circuit was for inverter and chargers cooling. In the real life operation of the second circuit, there was no necessity to cool down the inverter and chargers at the same time as the components never worked simultaneously. The cooling system was controlled by the ECU that made use of the signals based on parameters from the BMS and inverter.

2.2. Test Method and Facilities

2.2.1. Laboratory Testing

Energy consumption measurement at different ambient temperatures of the vehicle platform converted to BEV counterpart was conducted at the BOSMAL Emissions Testing Laboratory, as presented in Figure 6. The facility is equipped with a chassis dynamometer located in a temperature-controlled climatic chamber, emissions measurement systems for ICE vehicles and a current measurement system necessary for hybrid and electric vehicle testing, running preconditioning cycles on the chassis dynamometer, as well rechargeable electric energy storage systems (REESS) charge balance measurement [30]. The Horiba VETS management system integrated into the laboratory permitted the execution of the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) driving cycle, according to existing international and global regulations, i.e., Regulation (EU) 2017/1151 and UN ECE GTR No. 15. The WLTC test is part of the broader worldwide and harmonized WLTP procedure, and it was used for electric energy consumption and electric vehicles range measurements. The WLTC test was run at three ambient temperatures, respectively: at −10 °C, 23 °C and 30 °C. The current measurement on the electric vehicle was carried out by using Hioki Power PW3390 Analyzer and suitable current measurement probes integrated into the Horiba VETS emission system. The current measurement is integrated over time at a minimum frequency of 20 Hz, yielding the measured value of current, expressed in ampere-hours (Ah). The Hioki Power Analyzer PW 3390 has four current channels and four voltage channels, and the analyzer provides the possibility to measure and archive all four current and voltage signals simultaneously [28].



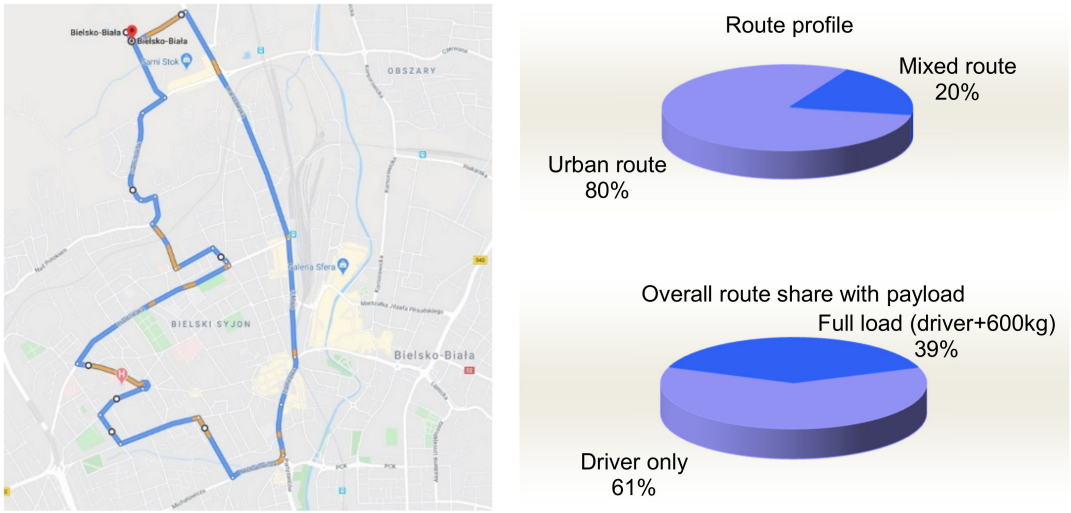
Figure 6. Test vehicle set up in the laboratory on the chassis dynamometer within the climatic chamber.

2.2.2. On-Road Testing

The scope of the on-road testing focused on the assessment of the vehicle's driving performance and its functionality. Particular attention was paid to the vehicle's structural elements that were modified for the electric drivetrain application. Test activities included the following:

- Determination of total battery capacity and the vehicle range on an urban route;
- Mileage accumulation of 1000 km and subjective assessment of the vehicle performance on different route profiles and at various payload levels onboard the vehicle.

The on-road testing was carried out under various atmospheric conditions, with temperature ranging from 12 to 32 °C. The vehicle preparation included verifications of the general technical condition and adjusting the tire pressure to the recommended values according to technical specification. The vehicle range measurements were performed on a defined urban route in the city of Bielsko-Biala. The selected driving route was a loop of length 10 km, consisting of roads with medium and heavy traffic congestion, as shown in Figure 7.



(**a**) (**b**)

Figure 7. (**a**) Scheme of the driving loop for the vehicle range measurement and (**b**) mileage accumulation: type of route profile (top chart) and route share with payload (bottom chart).

The vehicle was charged at BOSMAL's internal charging station equipped with the terminal for both DC fast charging (Type 4) and AC standard charging (Type 2).

3. Results and Discussion

3.1. Laboratory Test Results

As part of the verification process of the combustion engine vehicle platform conversion to the BEV counterpart, the laboratory and on-road test campaign was performed. The laboratory activities consisted of the energy consumption tests at various ambient temperatures, and for different regenerative braking settings. The second research aspect was the vehicle range measurement under the optimal regenerative braking settings.

The electric energy consumption was expressed in Wh/km and the vehicle range test in km. The measurements were carried out and according to UNECE Regulation No. 101 and Commission Regulation (EC) No. 692/2008, modified to use a more modern, representative driving cycle (i.e., the WLTC test). The WLTC test was performed on a chassis dynameters within a climatic chamber at three ambient temperatures: −10 °C, 23 °C and 30 °C. Each test at a given temperature was preceded by 24 h of vehicle conditioning (temperature soaking).

Due to the maximum vehicle speed (98 km/h) and the powertrain configuration, the selected WLTC Class 3b cycle was modified in accordance with point 9 of Sub-Annex 1 of Annex XXI to EU Regulation 2017/1151. The modification was to maintain the correct WLTC 3b test distance (i.e., 23.27 km) with a limited maximum vehicle speed. The modified WLTC 3b cycle is shown in Figure 8.

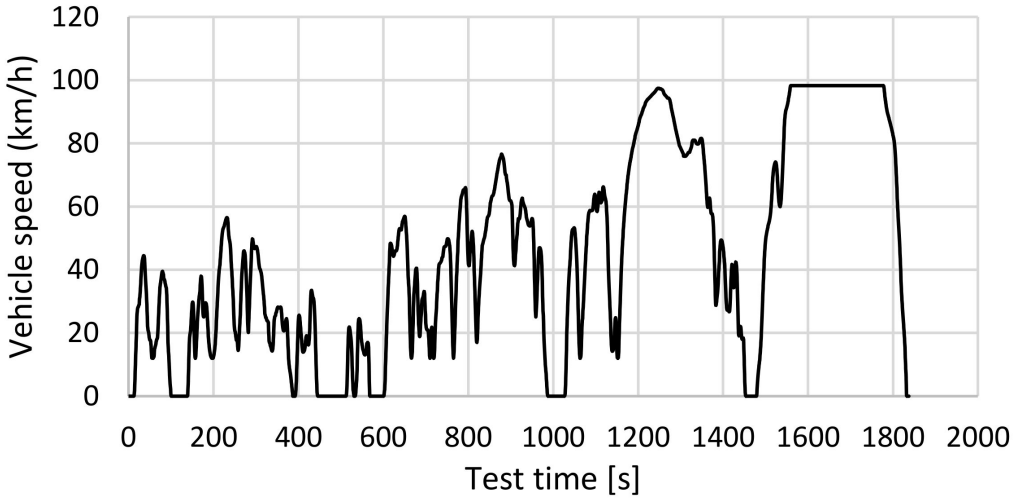


Figure 8. Worldwide Harmonized Light Vehicles Test Cycle (WLTC) legislative test cycle profile with limited maximum vehicle speed.

The chassis dynamometer settings were chosen in accordance with Regulation (EU) 2017/1151. The roller bench loading coefficients (F0, F1 and F2) were determined from the coast down test run in the laboratory. Realistic road load values (used as input for the laboratory road load setting) were obtained at BOSMAL in the course of an on-road coast down test. Energy consumption test results and subjective driving comfort assessment are presented in Table 4 and graphically in Figure 9.

The energy consumption tests were performed on a chassis dynamometer embedded in a climatic chamber with temperature control in the range set for test purposes from −10 to 23 °C [30]. The energy consumption values decreased as the ambient temperature increased and this was the case for all tested regenerative braking settings. The most advantageous setpoints for energy recuperation caused significant reductions in the vehicle driving comfort to be suffered. This was confirmed by three independent test drivers and their subjective assessment giving the possibility to determine which characteristics are not

suitable for everyday use. The braking torque acting with the R50H and R50-10H settings was so high that it led to rough powertrain operation, jerking during accelerator pedal tip in and tip out and also in difficulties maintaining constant speed. The driveability and comfort factors were taken into account at the stage of selecting the optimal regenerative braking settings. A compromise was to be found between the recovered kinetic energy (thus extending the vehicle range) and the drivability and subjective driving comfort. Based on the data presented in Table 4, it can be concluded that the most satisfactory energy recovery setting was the R20 and R20H configurations.

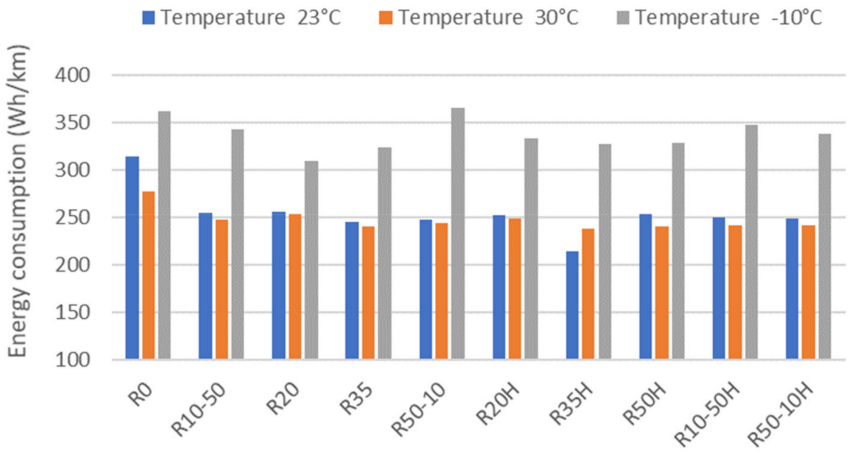


Figure 9. Energy consumption test results under the laboratory legislative cycle.

Table 4. Energy consumption test results under the legislative cycle and subjective driving comfort assessment.

Regenerative Braking Setting	Energy Consumption (Wh/km) and Ambient Temperature			Test Driver/Assessment Result [1]		
	23 °C	30 °C	−10 °C	no.1	no.2	no.3
R0 (inactive energy recovery)	314	277	362	OK	OK	OK
R10-50 (increased energy recovery 10–50%)	255	247	343	NOK	OK	OK
R20 (constant 20% energy recovery)	256	253	309	OK	OK	OK
R35 (constant 35% energy recovery)	245	240	324	OK	OK	NOK
R50-10 (decreased energy recovery 50–10%)	248	244	365	OK	NOK	NOK
R20H[2] (constant 20% energy recovery)	252	249	333	OK	OK	OK
R35H (constant 35% energy recovery)	214	238	327	NOK	NOK	NOK
R50H (constant 50% energy recovery)	253	240	328	NOK	NOK	NOK
R10-50H (increased energy recovery 10–50%)	250	241	347	NOK	OK	NOK
R50-10H (decreased energy recovery 50–10%)	249	241	338	NOK	NOK	NOK

[1] OK—smooth driving, full control over the vehicle; NOK—difficulty maintaining required speed, severe and unpleasant braking feeling while driving; [2] activation of brake pedal (H) caused energy recovery to increase by 20%.

The measured energy consumption decrease for a given regenerative braking setting depended on the ambient temperature. For operation at −10 °C, the limitation of the charging current during energy recuperation was active and it was commanded by the BMS to prevent possible damage to the battery cells.

The laboratory activities included vehicle range measurement carried out under WLTC test runs on the chassis dynamometer at ambient temperature of 23 °C. The covered distance in kilometers was measured from the state of battery fully charged (SOC = 100%) up to the point where its complete discharge resulted in powertrain shut down and the vehicle stopping. Tests were performed for two regenerative braking settings: R0 (recuperation inactive) and R10H. The R10H setting (constant 10% energy recovery increased by 20% during brake pedal activation) was chosen in the course of further subjective comfort evaluations under on-road conditions. The results are presented in Table 5.

Table 5. Vehicle range measurement under legislative cycle.

Regenerative Braking Setting	Vehicle Range (km)
R0	128
R10H	133

The EMS and R10H setting for kinetic energy recuperation allowed the vehicle range during the WLTC test to be extended by 3.9% compared to the inactive energy recovery configuration (R0).

3.2. On-Road Test Results

3.2.1. Determination of the Traction Battery Capacity

Battery pack capacity measurement relied on the full battery discharge (defined as the SOC parameter equal to zero). Subsequently, the charging process was initialized and continued until it was completed resulting in the SOC parameter reaching 100%. The mean amount of energy delivered to the battery pack during two tests was 34.69 kWh, as measured by the DC charger (type: Efacec QC45).

3.2.2. Vehicle On-Road Range Measurement

The urban driving route for the vehicle range measurement assumed a maximum driving speed of 50 km/h, the regenerative braking function activated and all electric energy consumers deactivated (except for the systems required for the safe and legal vehicle operation). The urban route for vehicle range determination was run twice. The first route was run without any payload onboard the vehicle and the second was executed with maximum permissible payload (600 kg). Both test runs were carried out by the same driver, in order to maximize repeatability of the driving style and mean speed. Before starting each test run, the battery was fully charged (SOC = 100%). The battery capacity was read at the end of the test loop by an Automex ATMX 962 instrument. Two main test criteria were selected for determining the vehicle range. The first one was the distance covered to reach battery SOC = 5%. The Second criteria were the distance covered until the battery was fully discharged (SOC = 0%). The vehicle range measurement results are summarized in Table 6.

Table 6. Vehicle on-road range measurement results.

Urban Test Driving Loop						
Run	**Payload (kg)**	**Ambient Temperature (°C)**	**Mean Speed (km/h)**	**Range**		**Energy Consumption (kWh/100 km)**
				Up to 5% SOC (km)	**Up to 0% SOC (km)**	
Day I	0	16–20	27.7	177	185	18.68
Day II	600	18–25	27.8	149	156	22.15

The well correlated mean speeds between the test drives (day 1 and day 2) indicated similar traffic conditions. The measured 149 km range of city driving down to SOC = 5% and with maximum vehicle payload was the lowest value. The 600 kg payload carried on board the vehicle decreased the mileage by 28 km and increased energy consumption by 3.47 kWh/km. Considering the obtained test results of the real driving range in urban traffic, it was concluded that the vehicle satisfied requirements for daily door-to-door urban transportation use.

3.2.3. Mileage Accumulation and Subjective Vehicle Performance Assessment

The proposed methodology of subjective vehicle assessment was based on 1000 km of test driving split into urban and mixed routes. The assessment focused on four principal areas and the overall results are presented in Table 7. The subjective rating scale according

to a relevant SAE standard [32], applied for vehicle ride and handling assessment, is shown in Appendix A. The results (scores) obtained confirmed the compliance of the converted systems with the technical requirements and customers' expectations.

Tests results revealed that special care and attention should be paid to vehicle loudness, especially in light of the presence of the single-speed gearbox. Additionally, the precise information on the available vehicle range and remaining battery energy level is critical for convenient daily driving. Therefore, a key finding was that it is recommended to verify the gearbox performance and set up an additional LCD display to present the driver with detailed information regarding the current battery level (SOC) and vehicle range data.

Table 7. Subjective vehicle's assessment during the on-road test run.

	ASSESSMENT AREA	MEAN SCORES	
	Payload	**Driver Only**	**Full Load**
1	Electric powertrain and functionality of controls	5.94	5.88
2	Drivability: - steering behavior and braking - suspension system	6.30	6.23
3	Comfort: - loudness - ergonomics - overall servicing	5.78	
4	Performance and functionality	5.50	

3.3. Benchmark Test Results

The vehicle's powertrain conversion permitted construction and validation of a commercial BEV that offered mechanical and electrical functionality on a level competitive to global vehicle manufacturers' counterparts. Obtained key technical parameters of the vehicle built at BOSMAL were benchmarked with market-available competitors. The payload, range and charging time were found to be competitive, except when compared to the range value of the Renault, which was the highest. Comparisons of the vehicles' parameters are presented in Table 8.

Table 8. BEV benchmark results.

Parameter/Vehicle	BOSMAL's Prototype Vehicle	Peugeot Partner Electric L2	Renault Kangoo Z.E. Maxi Combi (2017)
Curb weight	1807 kg	1569–1628 kg	1426–1553 kg
Battery type/capacity	Li-ion/33.2 kWh	Li-ion/22.5 kWh	Li-ion/33 kWh
Range	133 km WLTP	170 km NEDC	270 km NEDC
Payload	613 kg	552–611 kg	up to 650 kg
Charging time 0–100%	3.5 h/onboard charger	7.5 h/onboard charger	6h/onboard charger

The highest value of the curb weight value of the prototype vehicle (in comparison to the other vehicles used for benchmarking) revealed a drawback of vehicle conversion as a non-manufacturer prototyping activity. However, conversion of an ICEV to the battery electric powertrain can provide the functionality required by customers, with limited vehicle cargo volume for battery pack installation. That disadvantage could not be avoided, due to the standardized size of the battery packs and their limited availability on the market. The conversion process can offer customers a bespoke approach, e.g., for charging modes/power, which can be important from the final user's point of view. Converted ICE vehicles can be an alternative for a commercial BEV under the circumstances of economic and environmental viability therefore detailed cost analysis of conversion need to be carried out for at least a small-lot production. The above should compensate the drawback

of non-OEM powertrain system conversion, limitation in payload and cargo space and presumably lower long term durability of the vehicle in reference to commercial BEV.

4. Conclusions

The methodology presented in this paper confirms the possibilities for converting regular ICEV light-commercial vehicles into a pure electric powertrain derivative and the following conclusion were drawn:

- Obtained results of laboratory, on-road and benchmark testing of prototype vehicle, allowed one to state that the vehicle's technical parameters and functionality are acceptable for a real-life operation.
- Configuration of the vehicle was suitable for a city driving and the last-mile delivery of goods.
- The vehicle functionalities can be further adopted for municipal services or special applications such as the mobile energy storage point, e.g., for emergency vehicles charging. Convenient charging infrastructure in the vehicle parking spot needs to be provided.
- Battery pack installation inside vehicle loading space significantly limits the volume and payload capability therefore a raised roof version of the vehicle should be considered.
- The number of electrical and mechanical components was difficult to purchase on the market. Optimization of bill of materials is required and cost analysis of a kit-of-parts for a given vehicle conversion.
- Long term durability of converted vehicles needs to be evaluated under in-service conditions.

Mechanical and electric-electronic modifications according to BOSMAL's concept were based on market-available components and resulted in the correct functionality of the vehicle. The proposed laboratory and on-road testing program allowed the optimal configuration of ECU and EMS settings to be defined, including determining the regenerative braking mode to obtain the maximum range without a driver comfort penalty. The testing activities carried out confirmed that the main and auxiliary systems satisfied basic customer requirements for driveability, payload and vehicle range. Additionally, the charging system implemented would offer customers different charging modes according to their needs and requirements. The scope of conversion work for a vehicle can differ depending on the manufacturer of the original base vehicle. Nevertheless, the idea of powertrain conversion can be an alternative to new BEV purchase for customers interested in the prolongation of service life and giving their combustion engine vehicle fleet a "second life".

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Abbreviations

ABS	Antilock braking system
A/C	Air conditioning
AC	alternating current
BCM	body control module
BEV	battery electric vehicle
BMS	battery management system
CAN	controller area network
CO_2	carbon dioxide
DC	direct current
E/E	electrical/electronical
ECU	electronic control unit
EMS	energy management system
ESP	electronic stability program
EVs	electric vehicles
FC	fuel cell
FWD	front wheel drive
GHG	greenhouse gases
HEVs	hybrid electric vehicles
HFCEVs	hydrogen fuel-cell electric vehicles
HFCEVs	hybrid fuel-cell electric vehicle
HVAC	heating, ventilation, and air conditioning
ICEV(s)	internal combustion engine vehicle(s)
LC BEV	light-commercial battery electric vehicle
NEDC	New European Driving Cycle
NHV	noise, vibration and harshness
NMC	lithium nickel manganese cobalt oxides
PHEVs	plug-in hybrid electric vehicles
PLC	power line communication
PMSM	permanent-magnet synchronous motor
RBS	regenerative braking system
REESS	rechargeable electric energy storage system
SOC	state of charge
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

Appendix A

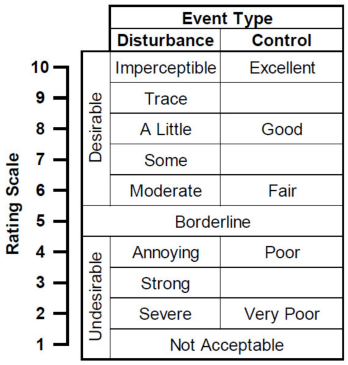


Figure A1. Subjective rating scale [32].

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