https://doi.org/10.14669/AM/189962

STATISTICAL ANALYSIS OF TRENDS IN BATTERY ELECTRIC VEHICLES: SPECIAL REFERENCE TO VEHICLE WEIGHT REDUCTION, ELECTRIC MOTOR, BATTERY, AND INTERIOR SPACE DIMENSIONS

MARKO LUČIĆ[1], JOVANKA LUKIĆ[2], IVAN GRUJIĆ[3]

Abstract

Electric vehicles (EVs) are increasingly being used, as they are more environmentally friendly than conventional vehicles with internal combustion engines (ICE). Battery electric vehicles (BEVs) can be said to have zero exhaust emissions only if the electricity used to drive these vehicles is obtained in an environmentally friendly way. It is common knowledge that BEVs have a significantly higher overall mass than conventional vehicles. The significantly higher total vehicle weight of BEVs can have various adverse effects on energy consumption during movement and the vehicle's dynamics. In contrast to the negative aspects of BEVs, there are also positive aspects that are primarily related to the comfort of drivers and passengers, considering the main fact that they do not require the presence of a floor tunnel. In this paper, trends related to BEVs in the previous five years were statistically analysed. Changes in average sizes related to BEVs are shown, primarily internal dimensions that can be of crucial importance when deciding between BEVs and conventional vehicles. In the paper itself, other important trends are presented, both for the electric motor itself and for the batteries used in BEVs.

Keywords: electric vehicles; batteries; electric motors; vehicle packaging; passenger cars; trend

[1] Faculty of Mechanical Engineering, University of Montenegro, Montenegro,
e-mail: markol@ucg.ac.me, ORCID: 0009-0004-9978-5967

[2] Faculty of Engineering, University of Kragujevac, Serbia,
e-mail: lukicj@kg.ac.rs, ORCID: 0000-0002-5893-3976

[3] Faculty of Engineering, University of Kragujevac, Serbia,
e-mail: ivan.grujic@kg.ac.rs, ORCID: 0000-0003-0572-1205

https://doi.org/10.14669/AM/189962

1. Introduction

The development of road traffic and transport has its positive sides, which are manifested through the creation of new jobs, the connection of different areas, and the improvement of the transport of different loads and logistics. However, road traffic and transport also have their negative impact. This negative impact is related to increased consumption of natural resources and increased emissions, especially greenhouse gas emissions. Greenhouse gas emissions can seriously affect the environment [1]. Road transport vehicles, while in operation, cause harmful consequences for human health. These harmful consequences are caused by the emission of exhaust emissions, as well as noise emissions that increase with the increased use of conventional vehicles [2]. Environmental pollution and climate change are some of the most attractive problems facing the planet at the moment. According to the European Green Deal [3], by 2050, Europe should become the first climate-neutral continent. The goals according to the European Green Deal are very ambitious, especially if we consider the increase in energy consumption from year to year in the transport sector. As road motor traffic is still largely based on transportation using road vehicles that burn fossil fuels in ICE, this sector is characterized as one of the main culprits for the increase in CO_2 emissions. According to data from the International Energy Agency, CO_2 emissions in the world for 2021 amounted to 33,572,105 Mt, and the transport sector had a share of 22.7% in total CO_2 emissions [4]. In the recent past, Europe has passed new laws and regulations on the development and sale of cars, to reduce CO_2 emissions. The use of electric vehicles is being researched and developed to reduce fuel consumption and thus the emission of exhaust gases. In the electric vehicle industry, engineers are studying how to increase battery capacity to increase the autonomy of these vehicles. However, electric vehicles have a big problem with a significantly higher mass compared to conventional vehicles, due to the very heavy battery [5]. Due to the increased weight of BEVs, non-exhaust-related particulate emissions can exceed all particulate emissions, including exhaust from vehicles with ICE [6]. The transition to electric vehicles and renewable energy sources is currently in full swing, but may not be fast enough to achieve ambitious climate change mitigation goals. A full transition to electric vehicles in the US would increase demand for electricity by about 30% if the fleet had the same average size, weight, and power as current electric vehicles. Every 1% increase in weight leads to an increase in electricity consumption by about 1% [7]. In the article [8], it is shown that the wider deployment of BEV relies on several key technologies, each of which has a detailed roadmap with good potential for realization. These roadmaps include lightening the vehicle body through the use of lightweight materials, as well as improvements in BEV drivetrain, battery development, and engine technology. In addition, it was confirmed that the technical potential for reducing the demand for electricity through the improvement of the powertrain and the use of a lightweight body is slightly more than one-quarter of the projected total demand. Certainly, the greater application of BEVs depends on several key factors, such as government policy, cost reduction, and range increase. In the paper [9], the weight reduction potential of BEVs was evaluated. Strategies for reducing vehicle weight, using materials, or reducing components reduce the amount of

https://doi.org/10.14669/AM/189962

energy needed. Careful selection of lightweight materials can result in costs being balanced by a commensurate reduction in battery costs, which would lead to greater vehicle efficiency, but without affecting its production and development costs. Research [10], provides a comprehensive overview of the potential of materials to mitigate vehicle exhaust emissions under a wide range of conditions. In addition, the authors believe that reducing the mass of electric vehicles by using more efficient materials should not be seen as the only solution, because its profitability depends on a large number of factors. Due to fuel efficiency standards for newer vehicle models, vehicle manufacturers are looking for next-generation electric and hybrid electric vehicles (HEV). When considering these next-generation vehicle technologies, weight reduction cannot be overlooked. Following the new vehicle design, the low mass of the vehicle enables better energy efficiency and produces less exhaust emissions. Aluminium stands out as one of the materials that is key in reducing vehicle weight. In the paper [11], it was confirmed that the use of aluminium bodies compared to steel significantly reduces the mass of the vehicle, which has a positive effect on BEV and HEV. As lighter vehicles require smaller capacity batteries, in this way significant savings can be achieved both in the weight of the car and in reducing the price of the vehicle. The author in his research [11], also concluded that greater use of aluminium would accelerate the transition to BEVs and plug-in hybrid electric vehicles (PHEVs). In the paper [12], the impact of reducing vehicle mass on energy consumption as well as the costs related to various advanced electric drive concepts were analysed. Different architectures of BEV and PHEV were compared with conventional vehicles. The results showed that the potential for energy savings through low mass decreases with the increase in the degree of electrification. A better perception of the use of light materials in the automotive industry is given. Some of the main aspects to consider when using lightweight materials in the development of new cars such as availability of raw materials, production possibilities, research, and development efforts to achieve mass savings, safety, and CO_2 regulation are defined. The fact that this problem is also considered in the industry of electric scooters, which have a relatively small mass, shows how important the reduction of vehicle mass is in electric mobility [13]. The study confirmed that energy consumption, battery capacity (as well as its price), autonomy, and maximum engine power depend primarily on the vehicle's mass. Various mass-proportional coefficients were also determined to optimize the vehicle and have low energy consumption. The methodology for minimizing the mass of the electric motor intended for electric vehicles is defined in the paper [14]. Minimizing the mass of individual components, especially the electric motor, is essential because energy consumption and total costs are reduced. For the optimization process, two lines of genetic algorithms were used: a real-coded genetic algorithm and a binary-coded genetic algorithm, and different crossover and mutation operators were compared. An electric motor designed with optimal parameters represents an attractive solution in electric vehicle technology. The authors in the paper [15], present an analytical solution for finding the optimal mass of electric vehicles. It was concluded that the added cost to reduce mass is compensated by the cost savings due to the smaller battery and electric motor needed for constant performance and autonomy. The assessment made in the aforementioned study shows that for a medium-sized electric vehicle, the optimal weight

https://doi.org/10.14669/AM/189962

reduction of 450 kg leads to an estimated reduction in production costs of 4.9%. Reductions in powertrain costs are expected to reduce the importance of mass reduction in cost minimization of electric vehicles of the future, and increases in electricity costs are expected to increase the difference between optimal solutions based on production minimization versus total cost. The authors also concluded that decreasing or increasing the optimal level of mass reduction depends on the relative development of batteries versus the cost of mass reduction. The results presented in the paper [16], show a great potential for mass savings both for vehicles with an ICE and for electric vehicles. The low mass has the potential to reduce vehicle costs however; the results are very sensitive to parameters affecting lifetime fuel costs for conventional and battery electric vehicles. The difference between optimal solutions that minimize production to total costs is greater for conventional vehicles than for electric vehicles. For electric vehicles, the optimal mass and its profitability are sensitive to parameters that affect the price of the battery, while for conventional vehicles the optimal mass is very sensitive to parameters that affect the price of fuel. It was concluded that achieving as little mass as possible is very important for both drives. In the paper [17], the authors proposed an analytical calculation procedure for estimating energy consumption depending on the mass of electric vehicles. A detailed assessment of the life cycle effects involved in reducing vehicle mass requires a rigorous assessment of mass-dependent energy consumption. In addition to assessing energy consumption, this research also assesses the environmental aspects of mass reduction. The methodology for determining the range and dynamic parameters of electric vehicles depending on the change in the basic mass of the vehicle is presented in the paper [18]. Any increase in vehicle mass can lead to an increase in energy consumption per kilometre travelled. The main conclusions reached by the authors in this research are that the mass of the batteries of some models of electric vehicles can reach 25% of the basic mass of the car. Adding batteries to an electric vehicle will increase its range but will impair dynamic characteristics. The authors also concluded that the increase in battery capacity does not lead to a proportional increase in the range of the electric vehicle. The authors also experimentally confirmed that an increase in vehicle mass by 270 kg leads to an increase in the period of acceleration up to 90 km/h and up to 50 km/h by an equal average of 29.8%. In addition, without a load, the vehicle reached a maximum speed of 100.09 km/h, while the maximum speed with an additional load of 270 kg was 95.74 km/h. The range in the city is reduced for the case of a load of 270 kg by 8.2% compared to the case without the mentioned load. In the work [19], an analysis of a certain number of commercially available BEV models on the world market, except for the Chinese market, was performed. There is also an overview of charging costs, as well as costs for 100 km driven, based on the price of average electricity, which can be of great importance to future BEV buyers. In research [20], the authors developed an algorithm for calculating comparative parameters for electric vehicles. The algorithm was tested for 30 different electric vehicles. Using this algorithm, the authors obtained a list of the most economical vehicles out of 30 that were analysed. The total mass of the vehicle has been identified as one of the main parameters affecting the dynamic performance of an electric vehicle. Energy consumption per kilometre travelled is an essential indicator that directly affects the operating costs of an

https://doi.org/10.14669/AM/189962

electric vehicle. This indicator for electric vehicles with high capacity and mass batteries was 80–95% higher ego for low mass electric vehicles. The authors of the paper [21], characterized the reduction of vehicle mass as one of the most difficult tasks in the automotive sector and reviewed the application of composite materials in this sector. A 10% reduction in curb weight is predicted to result in a 6–8% reduction in energy consumption. Topological optimization of the frontal structure of the electric vehicle was proposed in the paper [22]. The serial passenger vehicle P5 was used as a prototype. Based on the given driving mode and battery arrangement of the mentioned electric vehicle, taking into account the static stiffness and crash resistance simultaneously, the equivalent static load method was used to optimize the multiple load topology on the body of the electric vehicle. In the paper [23], a new method of shaping optimization is presented. This method solves the problem of packaging optimization through dynamic simulation of the centre of gravity position. Positions and orientations of components are determined by dynamic vector fields. The packaging of electric vehicles is still an area of research. Research [24], defined a configuration optimization method based on a genetic algorithm. The algorithm was applied to optimize the configuration of a medium-sized truck, where two objectives were considered: clearance and dynamic behaviour. A vehicle packaging model was developed using commercial CAD software, ACIS, to analyse the interfaces between vehicle components. In the paper [25], trends and challenges related to electric motors applied in BEVs and PHEVs are presented. Choosing the right electric motor significantly facilitates the process of designing and packaging powertrain components, given the reduced size and absence of significant thermal limitations. Mounting the electric motor directly on the wheels reduces the vehicle's weight and frees up interior space, enabling innovative bodywork solutions.

In this paper, a statistical analysis of trends related to BEV vehicles was made, with special reference to the reduction of the vehicle's total weight and the internal dimensions of the passenger and driver's space. Trends related to the use of electric motors and battery packs that are used in BEVs are also given

2. Vehicle mass reduction

Numerous studies have been conducted throughout the automotive industry to achieve the goals of vehicle performance while minimizing their mass. The reason is more than clear: reducing the weight of the vehicle directly reduces energy consumption. In addition to energy savings, a low-mass lift can also have better acceleration and stability characteristics. When it comes to vehicle optimization to minimize the total weight of the vehicle, one should take into account numerous limitations. These restrictions are mainly related to the comfort and safety of the driver and passengers. Special attention should be paid to the design of the front part of the vehicle because this part is often exposed to collisions in traffic accidents. Optimizing the distribution of materials in the front part of the vehicle leads to a significant reduction in mass, but due to safety restrictions, engineers must be very careful when

https://doi.org/10.14669/AM/189962

designing this part of the vehicle [26]. Figure 1 (left) shows the part of the vehicle for which material distribution is optimized, while Figure 1 (right) shows the same part only in disassembled form, and Table 1 shows the optimal choice of materials for certain parts of the front part of the vehicle.

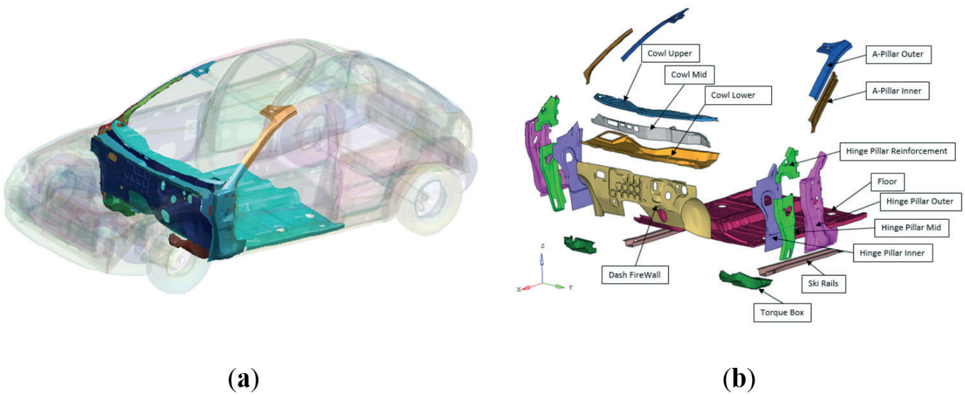


Fig. 1. a) The assembled part of the vehicle for which material distribution is optimized, b) the same part in disassembled form [26]

Tab. 1. Optimal selection of materials for the front part of the vehicle [26]

Design variable	Baseline material	Optimal material from multi-objective optimization
Dash firewall	steel	aluminium
Floor	steel	aluminium
Hinge pillar inner	steel	steel
Hinge pillar reinforcement	steel	steel
Hinge pillar mid	steel	aluminium
Hinge pillar outer	steel	steel
A-Pillar mid	steel	steel
A-Pillar inner	steel	aluminium
Torque box	steel	magnesium
Cowl lower	steel	magnesium
Cowl mid	steel	aluminium
Cowl upper	steel	magnesium
Ski rails	steel	steel

Only by the optimal choice of materials in the part of the vehicle from Figure 1, a weight saving of 15.5% was obtained compared to the previous design. The optimal solution combines parts made of aluminium, magnesium, and steel, while the conventional solution is made

https://doi.org/10.14669/AM/189962

exclusively of steel. The optimal solution also has better absorption during a frontal impact, which is of great importance for the safety of drivers and passengers [26]. The optimal choice of materials can reduce the weight of the vehicle, which leads to a reduction in energy consumption, but also improve the safety of the vehicle itself, which is of great importance for the driver and passengers. Light metal alloys and plastics are widely used in motor vehicles, aircraft, and electronics. Materials such as ultra-light steels, aluminium, magnesium, titanium alloys, ceramics, and polymers are widely accepted in automotive manufacturing. In recent years, the materials for automotive components have changed from steel to aluminium and magnesium alloys, to reduce the overall mass. Certainly, weight reduction can go to a certain point, due to safety and vehicle design. Achieving a balance between safety, reducing exhaust emissions, and reducing mass has forced vehicle manufacturers to find new methods, such as lower friction, thermal optimization, and applying various optimization techniques. A weight reduction of 100 kg leads to 6 g/kg lower CO_2 emissions. Every kilogram of vehicle weight reduction leads to a reduction of CO_2 emissions by close to 20 kg during the working life cycle of the vehicle. If the vehicle speed is constant, the only way to reduce energy consumption is to reduce the vehicle mass as much as possible [27]. Although the reduction of vehicle mass is one of the main priorities in the automotive industry, increasingly strict customer requirements regarding comfort and safety make this priority difficult. A big challenge for engineers is to optimize the design of the vehicle to meet the requirements for reducing the weight of the vehicle while improving the comfort and safety of the driver and passengers. Optimizing the design of any product, including a vehicle, uses numerical algorithms and techniques to help engineers improve the performance, mass, reliability, and cost of the product. Optimization methods are applied during the vehicle development phase or to existing vehicles to identify any potential improvements. Optimizing a vehicle's front bumper or frontal impact absorber is a very challenging task. This is one of the crucial components of the vehicle that affects the safety of the driver and passengers. In shock resistance optimization problems, constraints and objective functions are often non-linear which requires high computer performance. The goal of the bumper optimization problem is to minimize mass and increase energy absorption during a side impact [28]. A comparison of the reference and optimized Toyota Yaris bumper is shown in Table 2. It can be seen that the mass of the bumper is reduced by 11% and the energy absorption is improved.

Tab. 2. Comparison of the results of the reference and optimized bumper model [28]

Response	Referenced model	Optimized model
Energy absorption of Crash box	9 kJ	12.3 kJ
Rigid wall Force	145.8 kN	149.7 kN
Average Crush	93.5 mm	97.2 mm
Torsional Frequency	44.6 Hz	45.8 Hz
Bending Frequency	52.3 Hz	49.4 Hz
Mass	31.4 kg	27.8 kg

https://doi.org/10.14669/AM/189962

Optimizing welded joints can also be of great importance in reducing vehicle mass. In optimizing welded joints, the goal is to reduce their number while maintaining current performance. It has been confirmed that by optimizing the welds of the vehicle's front bumper, the number of spot welds can be reduced by about 8% without compromising the safety performance of this component. By changing the pitch between spot welds, the mass of the welded structure is reduced. When optimizing components that affect safety to reduce mass, it is necessary to be very careful. For example, when it comes to the front bumper, it is not enough to test this component only for frontal impact but also for various other loads to be able to confidently claim that the optimal design will meet all criteria while achieving weight reduction [28]. Reducing the vehicle's mass directly affects the vehicle's energy consumption. It has been proven that the force of the weight of the vehicle has the most dominant influence on the energy consumption of the vehicle. Aerodynamic forces are not directly related to mass but can be correlated in some cases. A large number of studies have investigated the relationship between vehicle mass and energy consumption using empirical studies. It has been confirmed that a 10% reduction in vehicle mass results in a 5.6% reduction in vehicle fuel consumption and a 6.3% reduction in fuel consumption for light trucks. This reduction in fuel consumption for vehicles with an ICE caused by the reduction in mass also leads to a reduction in CO_2 emissions emitted by these vehicles in operation. Reducing the weight of vehicles can also have a positive impact on vehicles with alternative drives, such as BEV and PHEV, by making them more competitive. Reducing the mass of an electric vehicle by 10% can improve the autonomy of this vehicle by 13.7%. While the same reduction in vehicle mass in PHEV brings savings in fuel consumption by 5.1%. By reducing the mass of electric vehicles, it is possible to significantly reduce the selling price of these vehicles due to the use of batteries with a lower capacity. Reducing the mass of an electric vehicle also leads to an increase in production time due to the longer time spent in development due to the optimization process. Reducing the weight of the vehicle is of great importance for trucks because saving mass in this case means a big saving in energy consumption. It is clear that by replacing traditional materials with materials with better characteristics, the weight of the vehicle can be reduced. Those vehicle components cannot be made of only one material, but there are logical requirements for different materials. The requirements for the use of different materials, which have been expressed in recent years, greatly complicate the optimization process. As optimization in the automotive industry is based on computer simulations, it is necessary to perform very good modelling of certain components and to know the characteristics of the materials used. The use of composite materials plays a very important role in reducing vehicle mass [29]. Examples of replacing component materials that provide significant weight reduction while maintaining the packaging requirements and performance of the original steel and aluminium components are shown in Figure 2.

https://doi.org/10.14669/AM/189962

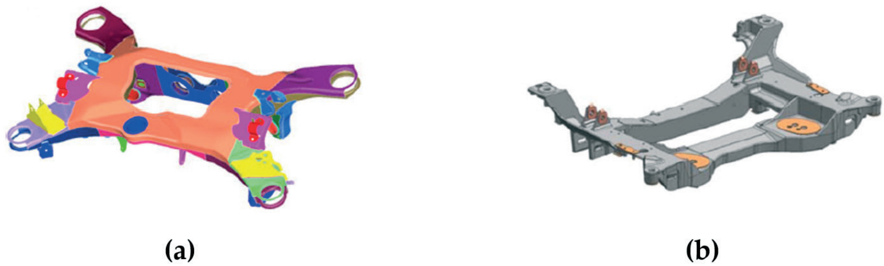


Fig. 2. a) Structure of the rear part of the chassis with 28% less mass compared to the original steel one, b) magnesium motor bed with 35% less mass compared to the original aluminium one [29]

Replacement of materials can also be in complex systems, which is shown in Figure 3. In both examples, the packaging and functional requirements are maintained. In the case of the magnesium-intensive front end of the vehicle (Figure 3, left), several aluminium components were introduced to ensure adequate performance. The European Union Superlight Vehicle (SuperLIGHT-CAR) is 50% aluminium but also includes significant use of magnesium, steel, and composites. The requirement for multi-material solutions introduces an additional layer of technological challenges associated with multi-material joining, corrosion prevention, design tools, and performance prediction [29].

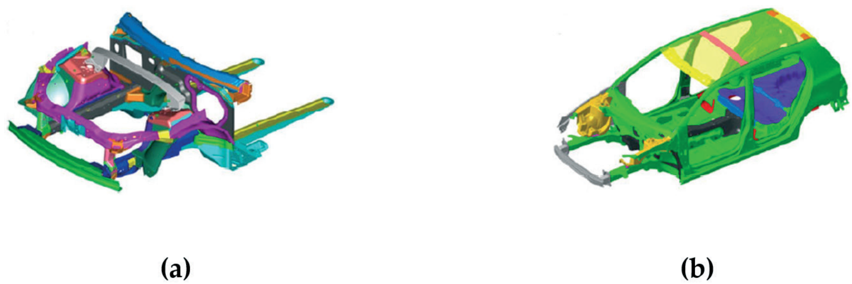


Fig. 3. a) The front end of the vehicle (mostly magnesium) with 45% weight reduction compared to the original version, b) European Union Super Light Vehicle with 35% weight reduction compared to the original version [29]

Despite the significant potential for reducing vehicle mass and the widespread use of high-performance materials, mass reduction is limited by several technical challenges that require continuous research and development. Optimum lightweight solutions require the use of multi-material structures, which presents additional technological drawbacks related to joining, corrosion protection, and design [29]. Reducing vehicle mass can be achieved by redesigning the vehicle or replacing materials. Lightweight vehicles are vehicles in which the

https://doi.org/10.14669/AM/189962

reduction in weight or mass is obtained by using advanced materials with greater strength and stiffness than traditional materials. The use of advanced materials will lead to an increase in production costs [15]. Figure 4 shows the estimated additional costs of the manufacturer per kilogram of reduced vehicle body weight. Table 3 shows the basic characteristics of electric vehicles, mass, and cost structure for 2012, 2020, and 2030, keeping autonomy and performance constant. It can be seen that the effect of changing the size of the powertrain in terms of a smaller battery and electric motor significantly affects the price of electric vehicles, which will make them more competitive [15].

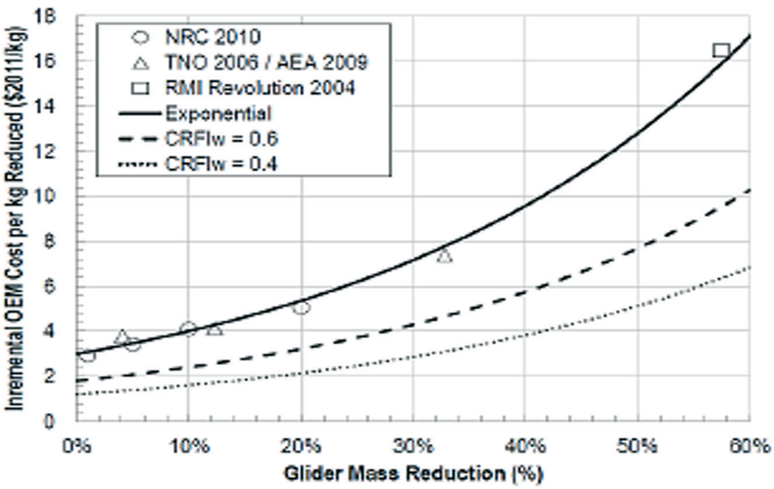


Fig. 4. Estimates of lightweight mass costs [15]

Tab. 3. Basic characteristics of electric vehicles, mass, and cost structure for 2012, 2020, and 2030, while maintaining constant performance and autonomy [15]

	2012		2020		2030	
$EC_{btwNEDC}$ (kWh/100 km)	15.4		15.0		14.6	
Battery capacity (kWh)	25		24.3		23.6	
Range (km)	162		162		162	
Power (kW)	87		82		87.5	
Power/mass (W/kg)	58		58		58	
	Mass (kg)	**Cost ($)**	**Mass (kg)**	**Cost ($)**	**Mass (kg)**	**Cost ($)**
Glider (+stable parts)	1183	11500	1183	11500	1183	11500
Variable parts						
Battery	238	19375	168	10023	98.4	5610
Motor, Inverter	87	1958	82	1479	77.5	1114
Total manufacturing	1500	32832	1417	23002	1336	18222

https://doi.org/10.14669/AM/189962

It is a clear fact that reducing the weight of the vehicle leads to a reduction in energy consumption, whether it is a traditional or electric vehicle. However, reducing vehicle mass can be very expensive [30]. Table 4 and Table 5 show estimates of the absolute costs of the percentage reduction in mass for passenger and light commercial vehicles, respectively.

Tab. 4. Estimates of the costs of reducing the mass of the entire vehicle for passenger vehicles [30]

	Absolute costs [€]			Unit costs [€/kg]
	Small cars	Medium cars	Large cars	
10% reduction in total vehicle mass	31	39	48	0.3
20% reduction in total vehicle mass	200	250	300	0.9
30% reduction in total vehicle mass	738	923	1106	2.2

Tab. 5. Estimates of the costs of reducing the mass of the whole vehicle for light trucks [30]

	Absolute costs [€]			Unit costs [€/kg]
	Small cars	Medium cars	Large cars	
3% reduction in total vehicle mass	83	115	166	2.2
12% reduction in total vehicle mass	719	1010	1439	5.4
25% reduction in total vehicle mass	10809	15053	22123	37.4

Optimal solutions aimed at reducing mass in the automotive industry will be made of several different materials with very good characteristics [30]. Figure 5 shows three conceptual vehicle body solutions with their weight and cost savings.

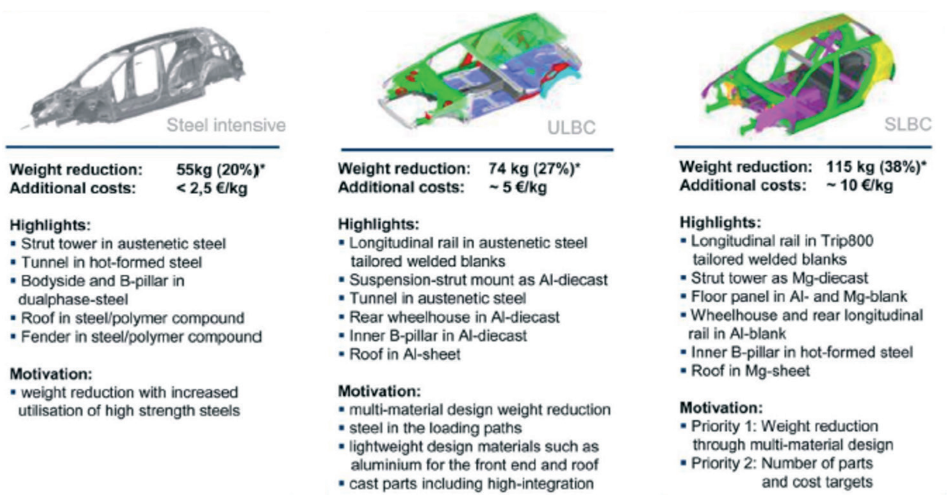


Fig. 5. Three preliminary passenger car body concepts with an emphasis on mass reduction [30]

https://doi.org/10.14669/AM/189962

The steel design is estimated to achieve a weight reduction of 55 kg, the universal lightweight body design a 75 kg reduction, and the super lightweight body concept a 115 kg reduction. Three concepts were used for the final SuperLIGHT-Car, which achieved a reduced mass of 101 kg [30]. Figure 6 shows the final SuperLIGHT-Car design with the materials used.

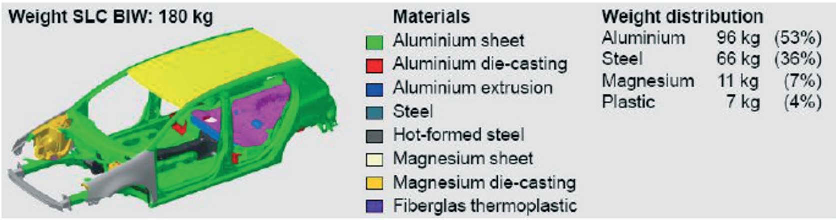


Fig. 6. Materials used for SuperLIGHT-Car design [30]

3. EVs packaging

Packaging is a term used in the automotive industry to describe the activities involved in locating various systems (powertrain systems, cabin climate systems, fuel distribution systems, etc.) and components in the vehicle compartment. It is necessary to allocate space for various vehicle systems (hardware), to accommodate drivers and passengers and to provide storage space for various things (suitcases, curious and other luggage) that people keep in their vehicles. The term "packaging" is used in the industry because the engineering task associated with this term is essentially the fitting of systems and components, produced by other different suppliers, into the vehicle space to function properly, and satisfy customers and users. The budget planned for the development of the vehicle also dictates the weight of the vehicle itself. Fuel consumption and emissions will be reduced if the weight of the vehicle is reduced. HEVs tend to have a slightly higher mass than vehicles with ICE of similar size. However, good design can give HEV vehicles a competitive mass compared to conventional vehicles. A smaller ICE that is installed in HEV can enable a lower weight of the vehicle as a whole. Large savings in HEV can be achieved by reducing the size of the fuel system and removing the 12 V battery [31]. Downsizing the 3.6-liter V6 petrol engine to a 1.9-liter diesel engine did not provide a significant weight advantage, as diesel engines are usually larger and heavier than petrol engines for comparable sizes. The mass of the exhaust system has been increased due to the addition of diesel components. The size of the fuel tank was reduced by 50%, which made it possible to save mass in the HEV. The masses of the electric motor, controller, battery, and thermal energy management system depend on the selected components. The removal of the alternator and the reduction of the 12 V accessory battery allowed for a small mass saving [32].

https://doi.org/10.14669/AM/189962

Tab. 6. Analysis of the mass of a conventional vehicle with a ICE and a hybrid electric vehicle [32]

Component	ICE Vehicle Mass [kg]	Hybrid Vehicle Mass [kg]
Engine and transmission	147	125
Exhaust system	40	50
Fuel system (tank and lines)	13	9
Fuel mass	38	15
Electric drive motor		108
Starter/generator	6	22
Starter/generator controller		26
Electric thermal management		15
Traction battery		75
Battery hardware, cooling		28
12 V battery	14	6
Alternator	5	
Total powertrain	263	479
Climate control and accessory	26	30
Glider with chassis subsystems	1445	1449
Total curb mass	1734	1954

The weight of the cabin air conditioning system is slightly higher in the hybrid vehicle, due to the switch to an electric motor-driven compressor pump. As can be seen from Table 6, the mass of the hybrid vehicle has increased by 82%. Component packaging must also be carefully evaluated during hybrid vehicle design. A component-packaging diagram must be created to ensure that all system components fit into the vehicle without compromising safety and customer convenience. A simplified component layout diagram based on the Akron hybrid vehicle is shown in Figure 7. Fuel lines and exhaust pipes are not shown to simplify this figure. Packing fuel and exhaust system components can become very cumbersome, especially when converting an ICE vehicle into a hybrid vehicle. Adequate space must be available under the vehicle for the installation of fuel lines and exhaust pipes. Along with the drawing of the fuel lines and the exhaust system, it is necessary to make a drawing of the high-voltage electrical circuits. During package analysis and assembly of hybrid components, the front-to-rear mass ratio must be maintained at 60:40 or less for acceptable ride, driving performance, and braking dynamics. The mass savings in reducing the engine and fuel system in a hybrid vehicle will be offset by additional components. Packaging is much more complicated for the reconstruction of a conventional ICE vehicle than the packaging of components when designing a hybrid vehicle from scratch [32].

https://doi.org/10.14669/AM/189962

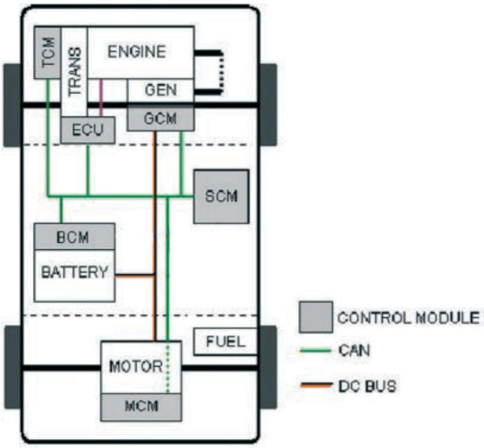


Fig. 7. Packaging of components in a HEV [32]

Complete vehicle design is complex and involves numerous variables, constraints, considerations, and an understanding of system interactions. The interactions are typically interdisciplinary and require multiphysics analysis and simulations. A very important segment is the basic calculations of the dimensioning of the powertrain components. These calculations provide design data to begin computer modelling and simulations for detailed analysis of complex EVs and HEVs. The zero-emission range is the most important specification for sizing battery pack capacity [32]. Powertrain electrification is considered one of the key technologies that will lead to a reduction in CO_2 emissions from traffic. This phase of transition forces original equipment manufacturers (OEMs) to consider a one-time conversion of existing traditional conventional vehicle platforms to electric vehicles [33].

3.1. Development of a new vehicle concept

The starting point for the development of a new vehicle model is often the previous model or a competitor. When new technologies are introduced, it is difficult to use the previous model because the manufacturer developed it with different boundary conditions. On the other hand, this offers new degrees of freedom and enables new, unconventional solutions. Design concept optimization is a common method of assisting engineers in the early stages of design, which includes modelling, dimensioning, and component selection and their impact on overall vehicle performance. Starting with a vehicle equipped with an ICE, engineers barely find room for batteries, as the replaced fuel tank is much smaller. On the other hand, the engine compartment is too large because the electric motor is smaller than the ICE. An electric vehicle developed in this way is called a conversion design. The Volkswagen eGolf is a typical example of this type and is based on the ICE version. If engineers develop

https://doi.org/10.14669/AM/189962

a vehicle from scratch based on a new technology, they can take important boundary conditions into account and take advantage of it from the start. This type of development is called purposeful design. Compared to the eGolf, the Volkswagen ID3 is a good example of a purpose-built design. Compared to the eGolf, the ID3 has a longer wheelbase at a similar length, resulting in more interior space. By increasing the height of the vehicle by only 5%, the ID3 achieves a 38% higher battery capacity. Electrification is a new technology that significantly changes the vehicle for the first time in decades. Apart from electrification, automation as another new technology will change the vehicles as we know them today [34]. Table 7 shows a comparison of conversion and dedicated design using the example of electrification.

Tab. 7. Comparison of conversion and dedicated design on the example of electrification [34]

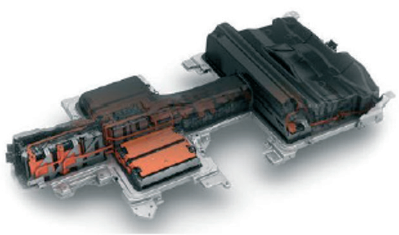
Name	Volkswagen ID3	Volkswagen eGolf
Powertrain and Battery		
Design type	Purpose design	Conversion design
Length (mm)	4261	4270
Width (mm)	1809	1799
Height (mm)	1568	1482
Wheelbase (mm)	2771	2629
Trunk volume (liters)	385	380
Battery capacity (kWh)	58	36

3.2. Energy storage system – batteries

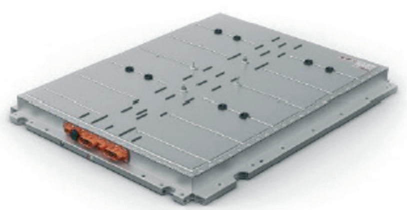
One of the main problems in the electric vehicle industry is related to their battery pack. In recent decades, lithium-ion batteries have become the preferred choice for electric vehicles due to their relatively high energy density and good durability. The energy density of the battery is not comparable to conventional fuels. The main disadvantages of batteries are relatively large mass, serious limitations in driving range, and rather long charging time. It is important to note that the average conventional vehicle with an ICE has a range of more than 600 km, while only high-performance electric vehicles can reach around 500 km on a single charge. The usual range of electric vehicles is around 300 km on average. With the increase in the mass of the battery comes a significant increase in the mass of electric vehicles, which amounts to an average of about 24% compared to conventional vehicles. This increase in mass greatly affects the dynamic behaviour of the vehicle. Currently, the state-of-the-art technology for automotive batteries proposes lithium-ion batteries that can reach energy densities close to 270 Wh/kg. The cells should be integrated into a suitable battery and

https://doi.org/10.14669/AM/189962

housed in a suitable housing. The battery pack and case are required to guarantee support, protection, safety, and thermal management. Considering the external structures, the actual energy density of the battery is reduced to values close to 150 Wh/kg and 200 Wh/l for volumetric energy density, with best-in-class results reaching densities of 180 Wh/kg and 250 Wh/l. Batteries are a key and recognizable component of electric vehicles. The energy storage system is a rather complex assembly because it consists of an energy storage medium, i.e. battery cells, structural housings, temperature control (cooling) systems, electronic devices – Battery Thermal Management System (BTMS), and thermal and electrical safety devices. Electric drive accounts for at least 50% of vehicle costs, with batteries accounting for up to 35% of the vehicle's total cost, while in conventional vehicles, the powertrain accounts for approximately 16% of vehicle costs. When it comes to the weight of the vehicle, it is very important to note that the mass of the battery usually makes up, more than 25% of the total weight of the vehicle, reaching close to 700 kg for the complete battery. The aforementioned facts indicate that it is crucial to focus on battery technology, as well as on the structure of the battery pack to reduce its complexity and cost while simultaneously improving performance. An excellent example of battery pack design evolution is shown in Figure 8, where the battery used by Volkswagen for its MQB platform in 2014 is compared to the newer MEB platform battery pack recently adopted by the same manufacturer. On the MQB platform, the battery is located in such a way that it uses the space available to the traditional floor architecture where there is a longitudinal tunnel, while on the MEB platform, the battery is flat, located under the floor of the passenger compartment. Interestingly, the new battery allowed Volkswagen to improve vehicle performance and autonomy while reducing costs by 50% [35].



a)



b)

Fig. 8. a) MQB platform battery pack, b) MEB platform battery pack [35]

https://doi.org/10.14669/AM/189962

The main functions and critical aspects of batteries are [35]:

- **Stability of the structure**. The battery must be designed to support the cells without affecting their operability and be properly connected to the chassis to support the relevant mass of the battery cells during static and dynamic loading while allowing adequate performance in terms of vibration noise and roughness.
- **Setting up**. The battery should be placed as close to the ground as possible, otherwise the vehicle's centre of gravity would be lowered and thus not affect the dynamic driving performance. Battery placement is also key to determining vehicle styling and occupant ergonomics.
- **Improvement of chassis rigidity**. In the design of new hybrid electric vehicle bodies, the battery is expected to contribute to the structural rigidity of the lower part of the body by joining it and creating a kind of sandwich structure.
- **Crash protection**. The battery must be placed and protected by adequate structures for shock absorption, any deformation of the battery case is not acceptable to avoid cell damage and possible fire or explosion due to cell breakage.
- **Heat management**. Battery cells should be maintained in the optimal operating temperature range between 25°C and 35°C, either by heating or cooling. This is of great importance for reducing the effect of aging and achieving the longest operating life.
- **Protection from the external environment**. The battery must provide adequate protection from road debris to avoid cell damage. Adequate ground clearance and package protection are essential.

Recently, the electric vehicle industry has been working on the problems of space organization and optimization of vehicle design. In conventional vehicles, the ICE is firmly mounted with the chassis with the necessary damping, but the size of the ICE is significantly larger than the electric motor, so electric vehicles have a great advantage in vehicle design. If we compare the energy storage systems of these vehicles, i.e. the fuel tank of conventional vehicles and the batteries of electric vehicles, we conclude that battery packs are significantly heavier and bulkier than fuel tanks. It can also be said that a conventional vehicle with an ICE is equipped with significantly more complex and complicated systems and subsystems compared to electric vehicles. The main problem in the design of electric vehicles is the problem of the location of the battery pack and electric motor. As already known, the battery pack requires solid mechanical support with a functional cooling system. A key issue is the choice of location and type of battery pack in an electric vehicle. Battery packs are generally firmly mounted on the chassis of the vehicle, but there are some models where the battery can be quickly removed or directly removed from the vehicle. In addition, the complete powertrain with the electric motor should be tightly packed in the vehicle in the appropriate location, to achieve the desired body shape. Each component of an electric vehicle has several different versions. Each of these designs has its advantages and disadvantages. Choosing the optimal component can help greatly reduce the size of the vehicle [36].

https://doi.org/10.14669/AM/189962

3.3. Electric motor for BEVs

A BEV vehicle uses only electricity when towing. Several different BEV architectures are available depending on the variation in electric drive layout. In Figure 9, different BEV architectures are presented, and the labels in the mentioned figure represent the components of the electric drive, namely: engine (M), differential (D), gearbox (GB), with clutch (C) or fixed gear (FG). Figure 9a presents the BEV architecture, which includes an electric motor, a clutch, a gearbox, and a differential. This kind of architecture was used in the conversion of an ICE vehicle into an electric vehicle using existing components. In Figure 9b, the clutch has been removed and replaced with a fixed gear and thus the weight of the powertrain is reduced. A BEV architecture that includes one electric motor with a fixed gear and a differential integrated into a single assembly is shown in Figure 9c. Figure 9d presents an architecture with two independent electric motors with fixed gears. A BEV architecture known as In-wheel drive is shown in Figure 9e, and this architecture includes a fixed epicyclic gear system to reduce the engine output speed to a suitable speed. The powertrain defined in this way eliminates the use of a reducer and a mechanical differential because the direct drive motor is placed exactly where the torque is needed. The arrangement of the direct drive motor as shown in Figure 9f simplifies the mechanical appearance, reduces the number of driveline components, reduces energy losses in transmission, improves maintenance, reduces weight, and improves the overall reliability of the system [37].

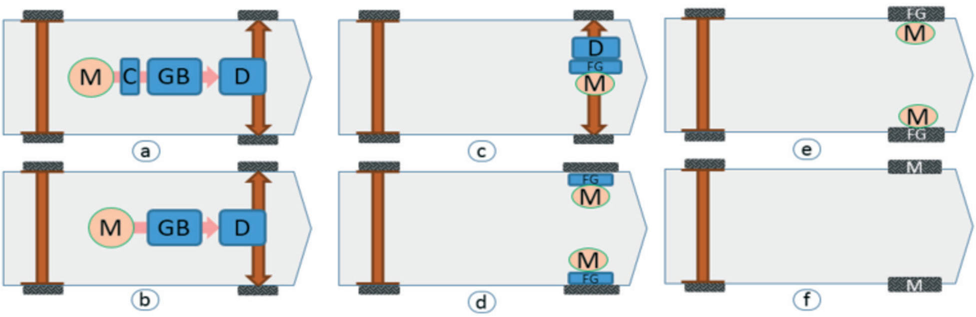


Fig. 9. BEV drive architecture: a) primary architecture, b) reduced architecture, c) modern architecture, d) dual motor architecture, e) in-wheel architecture, f) direct drive architecture [37]

3.3.1. In-wheel drive

Along with the battery pack, the electric motor is the most important component of an electric vehicle. In the paper [38], an analysis of electric motors placed in wheels was performed. One such electric motor placed in a wheel is shown in Figure 10.

https://doi.org/10.14669/AM/189962

Fig. 10. In-wheel electric motor assembly, Protean/Brabus E-class, front-left corner [38]

A powertrain equipped with an electric motor in the wheels opens up a large number of possibilities for shaping the vehicle and positioning other components. Preferably, the in-wheel motor can be installed in a vehicle without the need for special wheel designs or various suspension modifications. Such engines are exposed to a large number of negative external influences, such as relatively frequent contact with liquids, they can be submerged, and exposed to various dirt during exploitation. It is also expected that such electric motors will be exposed to stone impacts, and the cables must be able to withstand various types of repetitive bending at various temperatures, which can be extreme. Protean opted for four engines, each with ¼ of the full total performance required for safe vehicle operation. This means that many, potential failures can be mitigated locally within the electric motor in the wheel. Such a solution can have exceptional safety performance because if one motor in the wheel fails for some reason, the other three work to compensate for its torque. Some failures, such as high-voltage cable failure, cannot be mitigated by such a design solution. What splitting one larger electric motor into four smaller electric motors does is drastically reduce the amount of individual and random failures that result in a change in wheel torque or require mitigation at the vehicle level. Adopting the motor in the wheels leads to an increase in the space for placing part of the battery pack, which can largely be reflected in the performance in terms of the range of the vehicle, but also the dynamics of the vehicle due to a better distribution of mass and height of the centre of gravity [38].

4. Trends in BEVs

To carry out the statistical analysis in this research, a large number of internet sites were reviewed in detail, which provide an overview of the technical characteristics of BEV, however, none of them met the needs for all the data necessary to carry out the statistical analysis. The use of technical data for each BEV model individually was abandoned for the simple reason that the list of references would not be too bulky. In this research, the authors decided to use the necessary technical data and the website (www.evspecifications.com),

https://doi.org/10.14669/AM/189962

which offers quite a solid amount of data for BEV vehicles. According to the body type, on the aforementioned website, vehicles are classified into seven groups: SUV, Hatchback, Sedan, Crossover, Coupe, Pick-up, and Minivan. Since the number of Coupe, Pick-up, and Minivan vehicles is relatively small, and there is also a great scarcity of data, these vehicles were not considered in the analysis. Finally, the full analysis is based on data available only for four categories of newly produced BEVs with model years from 2019 to 2023: SUV, Hatchback, Sedan, and Crossover. The selection of the period from 2019 to 2023 is based on the fact that the availability of newly produced BEVs until 2019 is relatively very small compared to the selected period. In this way, a significantly larger number of vehicles were taken into consideration, which in terms of sample size significantly affects the reliability of the statistical analysis. The number of BEVs by model year that were considered in this paper is shown in Table 8 [39]. The number of hatchback vehicles considered for each model year is relatively small, so trends in these vehicles should be taken with a grain of salt.

Tab. 8. The structure of BEV body type included in the statistical analysis

	2019				2020				2021				2022				2023			
	SUV	Hatchback	Sedan	Crossover	SUV	Hatchback	Sedan	Crossover	SUV	Hatchback	Sedan	Crossover	SUV	Hatchback	Sedan	Crossover	SUV	Hatchback	Sedan	Crossover
Figure 1	12	19	11	3	12	15	11	6	21	7	6	5	48	7	12	10	93	3	17	20
Figure 2a ^{M}	12	–	–	–	14	–	–	–	20	–	–	–	47	–	–	–	54	–	–	–
Figure 2b ^{M}	–	20	–	–	–	19	–	–	–	7	–	–	–	7	–	–	–	3	–	–
Figure 2c ^{M}	–	–	11	–	–	–	11	–	–	–	6	–	–	–	12	–	–	–	15	–
Figure 2d ^{M}	–	–	–	3	–	–	–	6	–	–	–	5	–	–	–	10	–	–	–	20
Figure 2a ^{W}	14	–	–	–	16	–	–	–	22	–	–	–	48	–	–	–	55	–	–	–
Figure 2b ^{W}	–	20	–	–	–	20	–	–	–	7	–	–	–	7	–	–	–	3	–	–
Figure 2c ^{W}	–	–	11	–	–	–	11	–	–	–	6	–	–	–	12	–	–	–	17	–
Figure 2d ^{W}	–	–	–	3	–	–	–	6	–	–	–	5	–	–	–	10	–	–	–	20
Figure 3a	14	–	–	–	16	–	–	–	21	–	–	–	48	–	–	–	55	–	–	–
Figure 3b	–	18	–	–	–	20	–	–	–	7	–	–	–	7	–	–	–	1	–	–
Figure 3c	–	–	11	–	–	–	11	–	–	–	6	–	–	–	12	–	–	–	17	–
Figure 3d	–	–	–	3	–	–	–	6	–	–	–	5	–	–	–	10	–	–	–	20
Figure 3e	14	20	11	3	15	22	11	6	17	7	3	5	41	7	9	10	47	3	16	20
Figure 3f	14	17	11	3	13	22	10	6	16	7	3	5	40	7	7	10	46	3	13	20
Figure 4a	14	19	11	3	16	22	11	6	22	7	6	5	48	7	12	10	53	3	17	20
Figure 4b	14	18	11	3	15	20	11	6	21	7	6	5	47	7	12	10	51	3	17	20
Figure 4c	14	20	10	3	16	22	11	6	22	7	6	5	48	7	12	10	54	3	17	20
Figure 4d	2	10	4	3	6	11	6	5	5	2	0	5	27	4	0	9	15	3	3	19
Figure 4e	8	13	8	3	8	9	10	4	11	4	3	3	22	7	4	7	15	3	11	14

https://doi.org/10.14669/AM/189962

Tab. 8. The structure of BEV body type included in the statistical analysis, cont.

	2019				2020				2021				2022				2023			
	SUV	Hatchback	Sedan	Crossover	SUV	Hatchback	Sedan	Crossover	SUV	Hatchback	Sedan	Crossover	SUV	Hatchback	Sedan	Crossover	SUV	Hatchback	Sedan	Crossover
Figure 4f	8	14	9	3	11	11	11	4	12	4	3	3	29	6	4	7	29	3	5	14
Figure 5a	9	16	11	3	16	11	7	6	17	7	6	5	35	7	12	9	42	3	12	20
Figure 5b	9	16	11	3	15	11	7	6	17	3	6	5	35	3	12	9	42	3	11	20
Figure 5c	9	15	11	3	16	8	7	6	16	3	6	5	34	3	12	9	28	3	12	20
Figure 5d	9	15	11	3	16	8	7	6	16	3	6	5	34	3	12	9	28	3	11	20
Figure 5e	9	13	11	3	14	9	7	6	17	3	6	5	24	3	8	9	39	3	10	20
Figure 5f	9	13	11	3	14	9	7	6	17	3	6	5	24	3	11	9	39	3	9	20
Figure 5g	8	14	11	3	12	8	7	6	15	1	6	5	31	3	9	10	39	3	9	20
Figure 5h	8	14	11	3	12	8	7	6	15	1	6	5	31	3	9	10	39	3	9	20

^{M} average mass, ^{W} average wheelbase

4.1. Electric motor for BEV

Reducing vehicle weight is one of the main goals of the automotive industry. This goal is particularly important for BEVs, because these vehicles have a significantly higher mass compared to conventional vehicles of similar dimensions, mostly due to the relatively large mass of the battery. When it comes to conventional vehicles in previous decades, great attention was paid to reducing the weight of the vehicle. The vehicle body is one of the main components that has been optimized in terms of reducing its weight, and thus the total weight of the vehicle. The light materials in the production of the body are very widely used, but under very rigorous criteria related to the safety of the vehicle user that must be respected, but also the dynamics of the vehicle itself. In BEVs, apart from the battery, a very important component that can be optimized in terms of mass reduction is the vehicle body. In Figure 11, the materials from which the body of the BEV is made are shown.

https://doi.org/10.14669/AM/189962

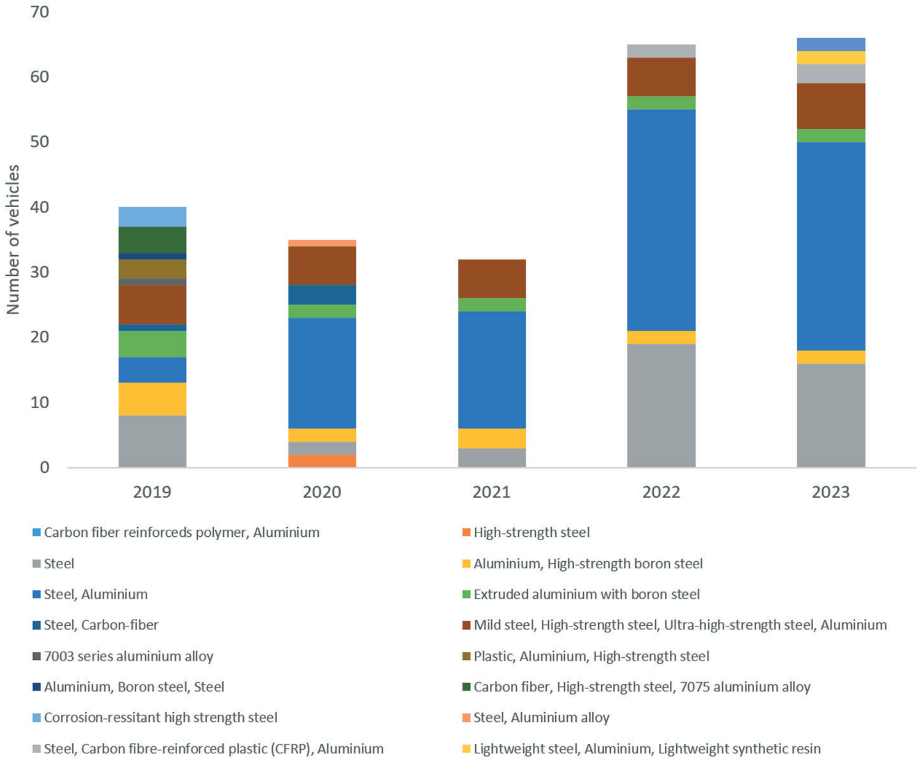


Fig. 11. Materials of the vehicle body

Various types of steel and aluminium mostly dominate and are among the most commonly used materials for the bodywork of BEV vehicles. There is an increase in the use of other materials, such as carbon fibres and plastics. It is important to note that recently the bodies of both conventional vehicles and BEVs have been produced from several different materials to enable weight reduction, without violating safety requirements. Figure 12 shows the average weight of BEV vehicles as well as the average wheelbase for SUV, Hatchback, Sedan, and Crossover vehicles for model years from 2019 to 2023. Observing the average annual mass of SUV vehicles, a relatively large drop in 2020 compared to 2019 of about 20% is observed, while a slight upward trend in the average mass was recorded for the following years. The average mass of Hatchback vehicles also records a decrease in 2020 compared to 2019 of about 5.8%, followed by an increase in 2021 and 2022, so that in 2023 there will be a decrease compared to 2022 of about 15.9%. The average mass of Sedan vehicles in 2020 recorded an increase compared to 2019 of about 11.1%, while in 2021 a decrease was recorded compared to 2020 of about 5.8%. Also in 2023, a slight decrease in the average mass of Sedan vehicles was recorded compared to the average mass of models from 2022 by about 4.3%. A slight increase in the average mass of Crossover vehicles was recorded in 2020 compared to 2019

https://doi.org/10.14669/AM/189962

by about 4.4%, and in 2021, a slight decrease was recorded compared to 2020 by about 1.3%. The average mass of Crossover vehicles in 2022 and 2023 recorded an increase compared to previous years. Almost the same trends were recorded when it comes to the wheelbase of the mentioned vehicles. The decrease or increase in the average wheelbase of BEVs was recorded identically to the average mass of these vehicles. Wheelbase plays a very important role when it comes to vehicle dynamics and it is common knowledge that BEVs that are being developed from the start have a significantly more desirable wheelbase from the aspect of vehicle dynamic characteristics.

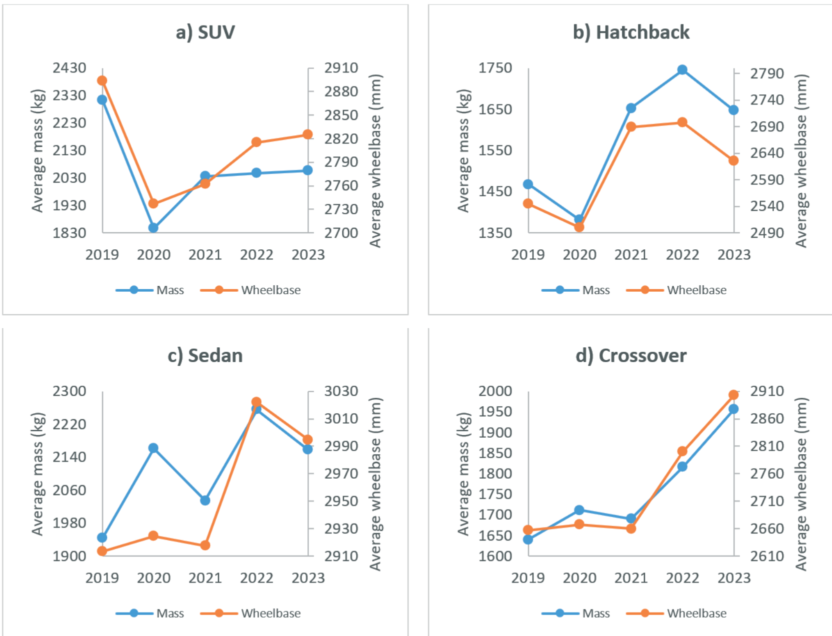


Fig. 12. The average curb weight and wheelbase of the vehicle

4.2. Electric motor for BEV

The trends related to electric motors used in BEVs for the model years from 2019 to 2023 are shown in Figure 13. Three potential locations for installing electric motors in vehicles were singled out the front, the rear when it comes to one electric motor, and the front and at the back, usually in cases where we are talking about vehicles in which more than one electric motor is installed.

https://doi.org/10.14669/AM/189962

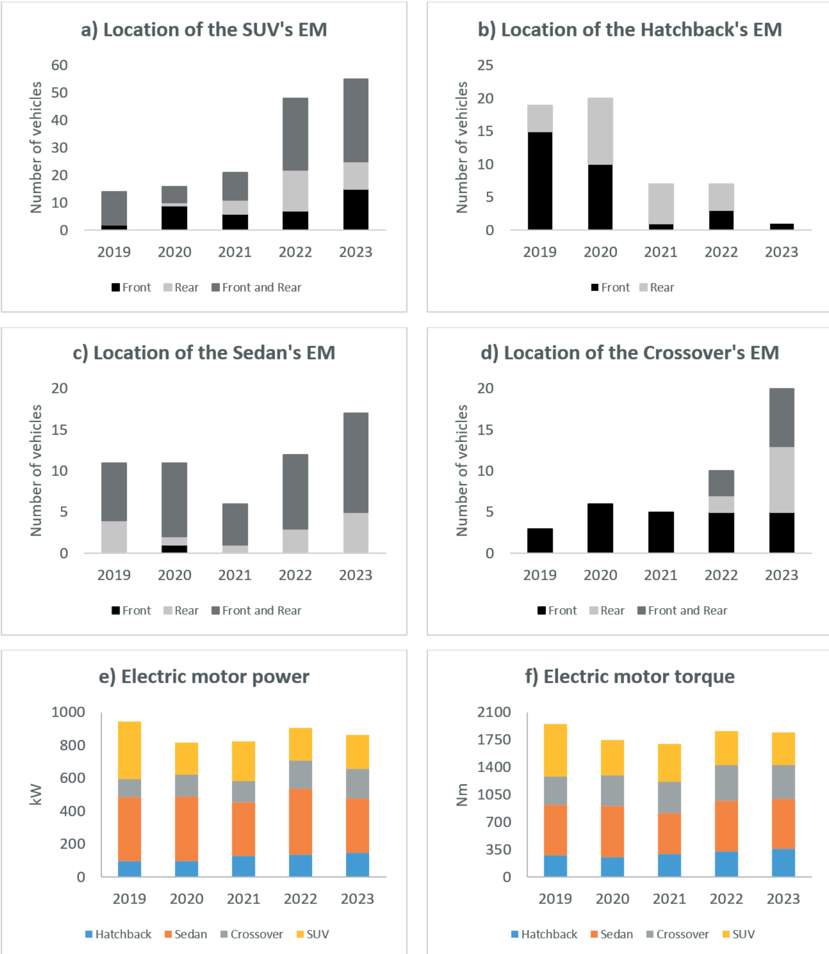


Fig. 13. BEVs electric motor trends

Since SUVs are dominated by models with two electric motors, it is expected that the "Front and Back" locations of the electric motors will dominate. From Figure 13a, it can be noticed that in the case of SUVs, the electric motors are largely placed in the front and back, which is especially pronounced in the 2022 and 2023 model years. There are also BEV models in SUVs where the electric motor is placed in the front or rear. The electric motor of the Hatchback vehicle is placed at the front or the back, while the versions of these vehicles with electric motors at the front and the back are not present, as can be seen in Figure 13b. In the 2019 model year, hatchback vehicles have a dominant front-mounted electric motor, while for example, in the 2020 model year, there is an equal number of vehicles with a front-mounted electric motor and a rear-mounted electric motor. In the 2021 and 2022 model years, a larger

https://doi.org/10.14669/AM/189962

number of Hatchback BEVs are present with a rear-mounted electric motor. Here it is necessary to emphasize once again that when it comes to hatchback vehicles, a very small sample with available data on the location of electric motors has been available for the last three years, and so commenting on any trends from the aspect of the location of electric motors in these vehicles is ungrateful. The dominant positioning of electric motors in the front and back is present in Sedan vehicles, which can be seen from Figure 13c. This stems from the fact that in this research, sedan vehicles with two electric motors, of which usually one is placed in the front and the other in the back, are dominantly taken into account. In Sedan vehicles, the positioning of the electric motor at the rear is present to a solid extent, while only one vehicle of the 2019 model year has the electric motor positioned at the front. The dominant placement of the electric motor at the front is present in Crossover BEV vehicles, especially for the years 2019, 2020, and 2021, when all the vehicles used in this research have an electric motor placed at the front. In the 2022 model year, there are Crossover vehicles that have an electric motor installed in all three locations previously mentioned (Front, Rear, Front and Rear). In the 2023 model year for Crossover vehicles, there is a significant increase in these vehicles with an electric motor installed in the front and in the case where two electric motors are present, front and rear, compared to the 2022 model year. Very interesting trends were also recorded when it comes to the average power of electric motors in the analysed model years. Figure 13e shows the average vehicle power for Hatchback, Sedan, SUV, and Crossover BEV vehicles. It can be noticed that the average electric motor power of Hatchback vehicles has a constant growth trend for all observed model years from 2019 to 2023 model year. In addition, the trend of increasing the average power of electric motors is present in Crossover vehicles. For SUVs in the 2020 model year, a relatively large drop in average engine power was recorded compared to the 2019 model year by about 44%. In the case of SUVs, it can be noted that in 2021, an increase in the average power of the electric motor compared to the 2020 model year was recorded by about 23%, while, for example, in the 2022 model year, a decrease in the average power of the electric motor was recorded with the 2021 model year by about 17.5%. In the 2023 model year, an increase in the average power of electric motors of SUV vehicles was recorded compared to the 2022 model year of about 3.8%. The average power of electric motors installed in Crossover vehicles shows a growing trend for the observed model years. Average torque as a very important characteristic of BEV vehicles is shown in Figure 13f. In Hatchback vehicles, it is observed that the average torque has an increasing trend, and also in Crossover vehicles, a slight increasing trend in average torque is observed. The average torque of Sedan vehicles was kept at an approximately constant level for the observed model years. A decreasing trend in average torque was recorded for SUVs, and in the 2023 model year, this average torque is lower by about 60% compared to the 2019 model year, which is a relatively large reduction even in absolute terms.

https://doi.org/10.14669/AM/189962

4.3. Batteries

The trends related to the batteries used in BEV vehicles are shown in Figure 14. When it comes to the type of battery, all the vehicles included in this research have one of two batteries, a Lithium-ion or a Li-ion Polymer battery. The lithium-ion battery is completely dominant, which can be seen from Figure 14a. The Li-ion Polymer battery found significantly less use when it comes to BEV vehicles that are included in this research.

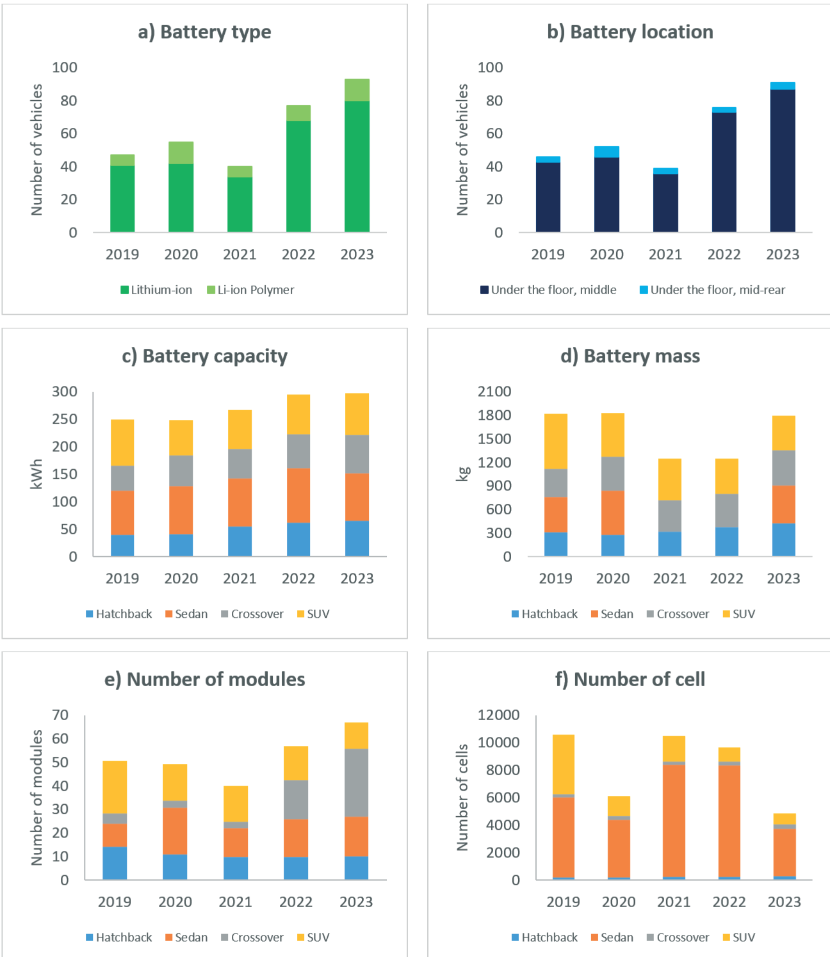


Fig. 14. BEV battery trends

https://doi.org/10.14669/AM/189962

The location and positioning of the battery, as one of the heaviest components of a BEV is very important, primarily for safety reasons, but also due to the correct distribution of the vehicle's mass and the impact on the vehicle's dynamic characteristics. For safety reasons, the BEV battery is usually placed under the floor of the vehicle, because this location is the safest, and it also has a very favourable effect on the position of the vehicle's centre of gravity. Although there is a different positioning of the batteries under the vehicle, in this research two locations were singled out for the available data, both under the floor of the vehicle, one of which is centrally under the floor, and the other under the floor of the vehicle but dominantly placed in the rear part of the vehicle. In Figure 14b, it can be seen that placing the battery under the floor of the vehicle centrally dominates over placing the battery under the floor centrally at the rear. Figure 14c shows the average capacity of batteries installed in BEVs by model year. An increasing trend in the average battery capacity was recorded for hatchback vehicles. In addition, the average battery capacity has a constantly growing trend in Crossover vehicles, but also in Sedan vehicles. The downward trend of the average battery capacity was recorded only in SUVs. As the battery is marked as one of the BEV components with the largest mass, it is very important to see what trends are related to the mass of batteries that are installed in the mentioned vehicles. Figure 14d shows the average mass of batteries installed in BEVs for certain model years. The average mass of batteries installed in hatchback vehicles has an increasing trend for the observed model years. As the analysis itself in this research does not provide data on the mass of batteries installed in Sedan vehicles for the 2021 and 2022 model years, the trends related to these vehicles will not be commented on. A growing trend was also noted when it comes to the average mass of batteries installed in Crossover vehicles. The decreasing trend of the average mass of the battery was recorded only in the case of batteries that are installed in SUVs. Batteries installed in BEVs have a constant increase in capacity, but also a constant increase in battery mass, except for SUVs. This is coupled with a major effort in the BEV industry to increase the range of these vehicles. Currently, the BEV range is increased by installing larger capacity batteries, and higher battery capacity is achieved by installing heavier battery packs. This increase in the average mass of batteries is directly reflected in the growing trend of the total mass of BEVs, which was previously illustrated in Figure 12. How great the range disadvantage of BEVs is, is shown by the fact that the mass of batteries, but also the mass of BEVs themselves, is increasing, despite the great aspirations and efforts of the automotive industry in the field of vehicle optimization from the aspect of reducing the total weight of the vehicle. Figure 14e shows the average number of battery modules installed in BEVs, while Figure 14f shows the average number of battery cells. The average number of battery modules installed in hatchback vehicles has a slight downward trend, which is best illustrated by the decrease in the average number of battery modules in 2023 of about 28.5% compared to 2019. The downward trend of the average number of battery modules is also present in SUVs, where in 2023 a decrease of about 50% was recorded compared to 2019. The growing trend of the average number of battery modules was recorded in Crossover vehicles, where in 2023 a relatively very large increase of about 660% was recorded, compared to 2019, which is also a very large increase

https://doi.org/10.14669/AM/189962

in absolute values. Also, the growing trend of the average number of battery modules was recorded in Sedan vehicles, but this trend is significantly milder compared to the trend in Crossover vehicles, which can be seen from the fact that in 2023 an increase of 70% was recorded. A decreasing trend in the average number of battery cells was recorded in SUVs, so in 2023 a decrease in the average number of battery cells of about 82% was recorded compared to 2019. The growing trend of the average number of battery cells is also present in Crossover vehicles (from about 53% in 2023 compared to 2019), but also in Hatchback vehicles (from about 31.5% in 2023 compared to 2019). The average number of battery cells in Sedan vehicles does not have any visible increasing or decreasing trend. When it comes to Sedan vehicles, say the 2020 model year saw a drop in the average number of battery cells compared to the 2019 model year by a little more than 27%, while the 2021 model year saw an increase compared to 2020 of approx. 93%, but also compared to the 2019 model year of about a little more than 40%. The 2022 model year saw a slight decrease in the average number of battery cells compared to the 2021 model year Sedan vehicle, of about 0.7%, but this average number of battery cells is higher compared to all previously analysed model years. Looking at the total number of battery cells, the lowest average number of battery cells was achieved in 2023 compared to all other model years, which were processed in this analysis, so it can be concluded that the BEV vehicle industry is followed by a constant decrease in the total number of battery cells.

4.4. Internal dimensions of the BEV related to the driver and passengers

The internal dimensions related to the driver and passenger are very important, first of all, because they somehow define the comfort and convenience of the vehicle user, whether it is the driver or the passengers. In some cases, when choosing a vehicle, a significant role can be played by the interior space of the vehicle, i.e. the dimensions related to the placement of the driver and passengers in the vehicle. The dimensions of the interior space can be of particular importance if the vehicle is used for longer journeys. Precisely for the reasons mentioned in Figure 15, the average dimensions of the interior space of BEVs in certain model years are shown, to better understand the trends related to the interior space of these vehicles. In Figure 15a, the average dimensions of the Front head-room BEV are shown. Hatchback, Crossover, and Sedan vehicles have a slightly increasing trend if you look at the average Front headroom dimensions, while SUVs have a slightly decreasing trend. The situation is also similar when it comes to the average Rear head-room dimensions, which can be seen from Figure 15b, i.e. for Hatchback, Crossover, and Sedan vehicles, a slightly increasing trend was recorded when it comes to Rear headroom, while a slightly decreasing trend was recorded for SUV vehicles. The average dimensions for Front shoulder room have a slight increasing trend in Hatchback, Crossover, and Sedan vehicles, while a slight decreasing trend was recorded in SUV vehicles, which can be seen in Figure 15c. When it comes to the average dimension of the Rear shoulder room, a slightly increasing trend was recorded in Hatchback, Crossover, and Sedan vehicles, while again

https://doi.org/10.14669/AM/189962

a slightly decreasing trend of the mentioned average dimension was recorded in SUV vehicles, which can be seen from Figure 15d. The average dimensions of Front legroom are shown in Figure 15e and it can be noted that an increasing trend was recorded for Hatchback, Crossover, and SUV vehicles. Sedan vehicles show a downward trend when it comes to the average dimension of Front Legroom. The average dimension of Rear legroom is shown in Figure 15f. The situation is very similar when it comes to trends for the average dimension of rear legroom. Hatchback, Crossover, and SUV vehicles recorded a slight upward trend, while a slight downward trend was recorded for Sedan vehicles. Figure 15g shows the average dimensions of the Front hip room. It can be seen that an increasing trend has been achieved when it comes to the average size of Front hip room in sedans and SUVs. Contrary to the growing trend realized in SUV and Sedan vehicles, a slightly decreasing trend was recorded in Hatchback and Crossover vehicles when it comes to the average dimensions of Front hip room. Trends related to the average dimensions of Rear hip rom by model years are shown in Figure 15h. A decreasing trend in the average size of the Rear hip room was recorded in Hatchback and SUV vehicles, while an increasing trend in the average size of the Rear hip room was recorded in Sedan and Crossover vehicles. It is interesting to note that the increasing trends of interior dimensions that define the space for the passenger were recorded in most cases when it comes to Hatchback, Crossover, and Sedan vehicles, while on the contrary, a decreasing trend was recorded in SUV vehicles in most cases. The downward trend in the dimensions of the interior space of SUVs can be related to the trade-off between reducing the weight of the vehicle and increasing the dimensions of the interior space. The importance of the demands of vehicle users in the automotive industry is precisely illustrated by the trends related to the dimensions of the vehicle's interior space, given that one of the main demands of vehicle users, be it the driver or passengers, is an increase in comfort and convenience. Potential users of vehicles increasingly influence trends in the automotive industry itself, so considering that one of the main requirements, in addition to safety requirements, is related to increasing the useful space for the driver and passengers, the trends illustrated in Figure 15h are, in a way, expected.

https://doi.org/10.14669/AM/189962

Fig. 15. Average dimensions of interior passenger space in vehicles

https://doi.org/10.14669/AM/189962

5. Conclusion

The BEV industry is increasingly committed to reducing the total mass of vehicles, primarily for the reason that with a reduction in mass, energy consumption also decreases, and the range of these vehicles is characterized as one of their main disadvantages. When optimizing a BEV from the aspect of mass reduction, it is necessary to pay special attention to the safety of the driver and passengers, considering that the safety of the vehicle user has recently been a priority requirement. The vehicle body is one of the main components that is optimized from the point of view of mass reduction. Various types of light materials are used more and more, of which aluminium is the most widely used, but steel is still the inevitable material from which vehicle bodies are made. In addition to the vehicle body, great efforts are being made to optimize other components and systems in terms of weight reduction. The positioning of the BEV electric motor and battery plays a very important role in the distribution of the vehicle mass. For the location of the electric motor, the three most common locations were singled out: front, rear, and in the case of having two electric motors, front and rear. In Hatchback vehicles, the electric motor is located either in the front or in the back, since these vehicles usually have only one electric motor. The electric motor in SUVs and Crossover vehicles is often located in both the front and the back since they often have two electric motors, and in the case of one electric motor, it is located either in the back or in the front. In Sedan vehicles, there are very rare cases where the electric motor is located at the front. When it comes to batteries, the market is dominated by Lithium-ion, and you can also find Li-ion Polymer batteries, but they are significantly rarer. The BEV industry has practically agreed on placing the battery in the vehicle itself, that is, the battery is usually placed under the floor of the vehicle, centrally under the floor, or in the rear part of the vehicle under the floor. The reduction of the negative characteristic of BEVs in terms of autonomy is currently solved by the use of battery packs of higher capacity, which have a significantly greater mass, which also leads to an increase in the total mass of these vehicles. When it comes to the dimensions of the interior space, it can be concluded that they are getting bigger every year in Sedan, Hatchback, and Crossover vehicles, except for SUVs. One of the main priorities in the BEV industry is comfort and convenience, so the constant increase in this space in Sedan, Crossover, and Hatchback vehicles is not surprising. The reduction in the dimensions of the interior space in SUVs is probably the result of a compromise between reducing the mass of these vehicles and increasing the range on the one hand at the expense of space for the driver and passengers on the other. It is very important to note that when it comes to interpreting the trends related to the internal dimensions of the BEV related to the driver and passengers, one should be very careful because a large number of BEV vehicles are developed on the platform of conventional vehicles.

https://doi.org/10.14669/AM/189962

6. Nomenclature

BEV battery electric vehicle
CO_2 carbon dioxide
EVelectric vehicle
HEV hybrid electric vehicle
ICE internal combustion engine
NEDC new European driving cycle
PHEV plug-in hybrid electric vehicle
SUV sport utility vehicle

7. References

[1] De Abreu VHS, Santos AS, Monteiro TGM. Climate Change Impacts on the Road Transport Infrastructure: A Systematic Review on Adaptation Measures. Sustainability. 2022;14(14):8864. https://doi.org/10.3390/su14148864

[2] Burchart-Korol D, Folęga P. Impact of road transport means on climate change and human health in Poland. Promet – Traffic & Transportation. 2019;31(2):195–204. https://doi.org/10.7307/ptt.v31i2.3074

[3] The European Green Deal - European Commission 2023. Available from: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (accessed on March 27, 2024)

[4] IEA IEA. Energy Statistics Data Browser – Data Tools - IEA. Available from: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=CO2%20emissions&indicator=CO2BySector (accessed on March 27, 2024)

[5] Wenlong S, Xiaokai C, Lu W. Analysis of energy saving and emission reduction of vehicles using light weight materials. Energy Procedia. 2016;88:889–893. https://doi.org/10.1016/j.egypro.2016.06.106

[6] Beddows DCS, Harrison RM. PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. Atmospheric Environment. 2021;244:117886. https://doi.org/10.1016/j.atmosenv.2020.117886

[7] Galvin R. Are electric vehicles getting too big and heavy? Modelling future vehicle journeying demand on a decarbonized US electricity grid. Energy Policy. 2022;161:112746. https://doi.org/10.1016/J.ENPOL.2021.112746

[8] Zhou W. Cleaver CJ, Dunant CF, Allwood JM, Lin J. Cost, range anxiety and future electricity supply: A review of how today's technology trends may influence the future uptake of BEVs. Renewable and Sustainable Energy Reviews. 2023;173:113074. https://doi.org/10.1016/j.rser.2022.113074

[9] Nicoletti L, Romano A, König A, Köhler P, Heinrich M, Lienkamp M. An estimation of the lightweight potential of battery electric vehicles. Energies. 2021;14(15):4655. https://doi.org/10.3390/en14154655

[10] Wolfram P, Tu Q, Heeren N, Pauliuk S, Hertwich EG. Material efficiency and climate change mitigation of passenger vehicles. Journal of Industrial Ecology. 2021;25(2):494–510. https://doi.org/10.1111/jiec.13067

[11] Bull M. Mass Reduction Performance of PEV and PHEV Vehicles. 22nd International Technical Conference on the Enhanced Safety of Vehicles (ESV). 2011, Washington

[12] Redelbach M, Klötzke M, Friedrich HE. Impact of lightweight design on energy consumption and cost effectiveness of alternative powertrain concepts. European electric Vehicle Conference. 2012, Brussels, Belgium. Available from: https://elib.dlr.de/80771/ (accessed on March 27, 2024)

[13] Sivert A, Betin F, Vacossin B, Lequeu T, Bosson M. Optimization of the mass for a low-power electric vehicle and consumption estimator (e-bike , e-velomobile and e-car). WSEAS Transactions on Advances in Engineering Education. 2015;12:105–114

[14] Naourez B, Tounsi S, Neji R, Sellami F. Modelling and optimization of electric motor mass to improve electric vehicle cost and consumption. International Multi-Conference on Systems, Signals & Devices, 2007, Tunisia

[15] Hofer J, Wilhelm E, Schenler W. Optimal lightweighting in battery electric vehicles. World Electric Vehicle Journal. 2012;5(3):751–762. https://doi.org/10.3390/wevj5030751

[16] Hofer J, Wilhelm E, Schenler W. Comparing the mass, energy, and cost effects of lightweighting in conventional and electric passenger vehicles. Journal of Sustainable Development of Energy, Water and Environment Systems. 2014;2(3):284–295. https://doi.org/10.13044/j.sdewes.2014.02.0023

[17] Del Pero F, Berzi L, Antonacci A, Delogu M. Automotive lightweight design: Simulation modeling of mass-related consumption for electric vehicles. Machines. 2020;8(3):51. https://doi.org/10.3390/machines8030051

[18] Berjoza D, Jurgena I. Influence of batteries weight on electric automobile performance. Engineering for Rural Development. 2017;16:1388–1394. https://doi.org/10.22616/ERDev2017.16.N316

[19] Josijević M, Živković D, Gordić D, Končalović D, Vukašinović V. The Analysis of Commercially Available Electric Cars. Mobility & vehicle mechanics. 2022;48(1):19–36. https://doi.org/10.24874/mvm.2022.48.01.02

[20] Berjoza D, Jurgena I. Effects of change in the weight of electric vehicles on their performance characteristics. Agronomy Research. 2017;15(S1):952–963

[21] Wazeer A, Das A, Abeykoon C, Sinha A, Karmakar A. Composites for electric vehicles and automotive sector: a review. Green Energy and Intelligent Transportation. 2023;2(1):100043. https://doi.org/10.1016/j.geits.2022.100043

[22] Zhang J, Ning L, Hao Y, Sang T. Topology optimization for crashworthiness and structural design of a battery electric vehicle. International Journal of Crashworthiness. 2021;26(6):651–660. https://doi.org/10.1080/13588265.2020.1766644

[23] Carrick C, Kim IY. Packaging optimization using the dynamic vector fields method. International Journal for Numerical Methods in Engineering. 2019;120(7):860–879. https://doi.org/10.1002/nme.6161

[24] Miao Y, Blouin VY, Fadel GM. Multi-Objective Configuration Optimization With Vehicle Dynamics Applied to Midsize Truck Design. ASME 2003 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. 2003;2A:319–317, Illinois, USA. https://doi.org/10.1115/DETC2003/DAC-48735

[25] Venkitaraman AK, Kosuru VSR. Trends and Challenges in Electric Vehicle Motor Drivelines – A Review. International Journal of Electrical and Computer Engineering Systems. 2023;14(4):485–95. https://doi.org/10.32985/ijeces.14.4.12

[26] Mohan R, HariRam V, Subramanian M. New mass optimization technique to achieve low mass BIW designs using optimal material layout methodology on the frontal vehicle crash. Journal of Mechanical Science and Technology. 2016;30(12):5617–5623. https://doi.org/10.1007/s12206-016-1130-5

[27] Kacar I, Durgun I, Ozturk F, Simmons RJ. A review of light duty passenger car weight reduction impact on CO2 emission. International Journal of Global Warming (IJGW). 2018;15(3):333–349. https://doi.org/10.1504/IJGW.2018.093124

[28] Patil SA, Moradi R, Lankarani HM. Vehicle mass optimization for frontal structure using I-sight and study of weld parameterization for mass improvement. ASME 2014 International Mechanical Engineering Congress and Exposition. Canada.2014;12. https://doi.org/10.1115/IMECE2014-37311

[29] Joost WJ. Reducing vehicle weight and improving U.S. energy efficiency using integrated computational materials engineering. JOM. 2012;64(9):1032–1038. https://doi.org/10.1007/s11837-012-0424-z

https://doi.org/10.14669/AM/189962

[30] Ricardo AEA. Report for European Commission – DG Climate Action: The potential for mass reduction of passenger cars and light commercial vehicles in relation to future CO2 regulatory requirements. 2015. Available from: https://climate.ec.europa.eu/system/files/2016-11/ldv_downweighting_co2_report_en.pdf (accessed on March 27, 2024)

[31] Bhise VD. Ergonomics in the automotive design process. CRC Press Taylor & Francis Group, London. 2016. https://doi.org/10.1201/b11237

[32] Iqbal H. Electric and hybrid vehicles: design fundamentals. CRC Press Taylor & Francis Group, London. 2021

[33] Rajasekhar MV, Perumal J, Rawte S, Nepal N. Integration and packaging for vehicle electrification. SAE Technical Papers. 2015. https://doi.org/10.4271/2015-26-0115

[34] König A, Telschow D, Nicoletti L, Lienkamp M. Package planning of autonomous vehicle concepts. Proceedings of the Design Society. 2021;1:2369–2378. https://doi.org/10.1017/pds.2021.498

[35] Belingardi G, Scattina A. Battery Pack and Underbody: Integration in the Structure Design for Battery Electric VehicleS – Challenges and Solutions. Vehicles. 2023;5(2):498–514. https://doi.org/10.3390/vehicles5020028

[36] Patel R, Kumar S. Analysis of Packaging issues in current Electric vehicles. International Journal of Engineering Research and Application. 2017;7(8):50–55. https://doi.org/10.9790/9622-0708015055

[37] El Hadraoui H, Zegrari M, Chebak A, Laayati O, Guennouni N. A Multi-Criteria Analysis and Trends of Electric Motors for Electric Vehicles. World Electric Vehicle Journal. 2022;13(4):65. https://doi.org/10.3390/wevj13040065

[38] Fraser A. In-wheel electric motors The Packaging and Integration Challenges. 10th International CTI Symposium. Berlin. 2011

[39] EVSpecifications – Electric vehicle specifications, electric car news, EV comparisons n.d. https://www.evspecifications.com/ (accessed on March 27, 2024)