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Electric Mobility Teaching Manual

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Electric Mobility Teaching Manual

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Preface

Electro mobility has changed the world. The appearance of new technologies in the automotive industry will enable more efficient use of energy, which can reduce emissions and oil dependency. It will require important technological developments in battery technology, charging systems and powertrains, as well as the installation and operation of new infrastructure. Energy production, battery manufacturing and recycling for sustainability are significant challenges.

This book was created under the framework of PELMOB - Partnership for Promotion and Popularization of Electrical Mobility through Transformation and Modernization of WB HEIs Study Programs (ERASMUS-EDU-2022-CBHE-STRAND-2) with cooperation of 14 universities. The goal of the project is modernizing the Western Balkan higher education institutions' study programs through introduction of new electric vehicles-related courses at the bachelor and master levels of education in WB HEIs.

This book presents ten different electro mobility related topic, like electric motors, battery technology, powertrain systems, electric vehicle safety, control systems, IoT technology, sustainable urban mobility planning, environmental impact of electro mobility and EU regulations.

Editors

Abbreviations

ABS - Antilock Brake System
AC - Alternating Current
ACC - Adaptive Cruise Control
ADAS - Advanced Driver Assistance Systems
BCM - Body Control Module
BETR - Battery Enclosure Thermal Runaway
BEV – Battery Electric Vehicle
BLDC - brushless DC motor
BMS - Battery Management System
CA - Collision Avoidance
CAN - Controller Area Network
CAS - Crash Avoidance Systems
CRM - Critical Raw Materials
DC – Direct Current
ECM - Electronically Commutated Motor
ECU - Engine Control Units
EREV – Extended Range Electric Vehicle
ESD - Energy Storage Devices
ESP - Electronic Stability Program
ESS – Energy Storage System
EV – Electric Vehicle
EVCS - Electric Vehicle Charging Station
FCEV – Fuel Cell Electric Vehicle
GHG - Greenhouse Gas
GPS - Global Positioning System
HEV - Hybrid Electric Vehicle
HMI - Human Machine Interface
HV - High-Voltage
IBS - Intelligent Braking Systems
ICEV – Internal Combustion Engine Vehicle
IGBT - Insulated Gate Bipolar Transistor
IM - Induction Machines
IM - Three Phase AC Induction Motors
INS - Inertial Navigation System
IoT – Internet of things
IPM - Interior Permanent Magnet Machines
ITS - Intelligent Transport Systems
LA - Lane Assist
LA - Lead-Acid Battery
LCA - Life Cycle Assessment
LiB - Lithium-ion Battery
LIDAR - Laser Illuminated Detection and Ranging
LV - Low-Voltage
MHEV – Mild Hybrid Electric Vehicle
MOSFET - Metal Oxide Semiconductor Field Effect Transistor
NaNiCl - Sodium-Nickel Chloride Battery
NaS - Sodium Sulphur Battery
Ni-Cd - Nickel-Cadmium Battery
Ni-MH - Nickel-Metal Hydride Battery
OCPP – Open Charge Point Protocol
OEMs - Original Equipment Manufacturers
PHEV – Plug-In Hybrid Electric Vehicle
PLC - Power Line Communication
PMSM - Permanent Magnet Synchronous Motor
PMSM - Permanent Magnet Synchronous Motors
PPAP - Production Component Approval Procedure
REE - Rear Earth Elements
RES - Renewable Energy Source
SC - Supercapacitors
SoC - State of Charge
SoE - State of Energy
SoH - State of Health
SoP - State of Power
SoS - State of Safety
SoT - State of Temperature
SPM - Surface Permanent Magnet Motors
SRM - Switched Reluctance Machines
SRM - Switched Reluctance Motors
SynRM - Synchronous Reluctance Motor
TCS - Traction Control System
V2G – Vehicle To Grid
V2V – Vehicle To Vehicle
VCU - Vehicle Control Unit
WLAN - Wireless Local Area Network
WRSM - Wound-rotor Synchronous Motor
Zn/Air - Zinc-Air Battery

1 Energy Storage Systems and Battery Technology for Electric Vehicles

1.1 Energy Storage System for Electric Vehicles

Energy storage systems (ESS) are becoming increasingly used in applications related to renewable energy, microgrids, and electric vehicles (EVs). Over the past several decades, electric vehicles (EVs) have gained popularity and are seen to be a good replacement for internal combustion engines (ICE). One third of fossil fuels are used by ICE cars, trains, freight vehicles and aircraft. 94% of vehicles in the transportation industry operated on oil, 2% ran on biofuel, 3% ran on natural gas, and 1% ran on electricity. It has been demonstrated that factories and ICE are major contributors of nitrogen oxides (NO), sulphur dioxide (SO_2), carbon monoxide (CO), and carbon dioxide (CO_2). These gases cause the greenhouse effect and pollute the ecosystem. The ESS in the EV system receives the electric power needed to run the motor and other components [1][2].

Over 5 million electric vehicles have been registered globally (energy revolution). In 2019, more than 50% of new EV sales occurred in Norway. EV sales reached 2% in the USA, 3% in Portugal, 5% in China, 7% in Ireland, and 8% in the Netherlands. There were 450,000 passenger electric vehicles (EVs) in 2015. However, as demand for EVs grew, the number of EVs expanded quickly, reaching 2.1 million in 2019 [3][4].

China and Europe are experiencing daily increases in demand for electric vehicles. Additionally, by using more EVs to replace internal combustion engine vehicles, people all around the world are rising to the challenge of reducing greenhouse gas emissions and global warming. Many nations and states enact laws encouraging their citizens to embrace electric vehicles. These strategies are becoming more widely used and anticipated, which helps to advance the adoption and expansion of EVs. These days, EVs are thought to be a potential distributed energy storage system (ESS) on the grid or micro-grid system through coordinated charging efforts that will help balance the fluctuations in intermittent solar and wind power. EVs provide a potential power supply during the pick load phase for demand-side control. This creates an excellent pathway for the installation of grid-connected renewable power systems and vehicle-to-grid and grid-to-vehicle systems [5].

Several forms of energy storage devices (ESD), such as batteries, supercapacitors (SC), or fuel cells, are employed in ESS for electric vehicle applications. The battery produces electric energy by storing electrochemical energy. The batteries we use today are much smaller than they were in the past.

They are available in different sizes and electrical capacities. Whereas the fuel cell uses mostly hydrogen (H2), SC stores energy as a static electric charge. ESD cells are coupled in series and parallel within the ESD pack to achieve the necessary voltage for EV demand, with each cell having a voltage between 1.5 and 5.5 V. During the charging and discharging periods, a chemical reaction takes place in the electrochemical tank known as the ESD. Additionally, the chemical reaction affects performance, and throughout a cycle, chemical degradation reduces ESD capacity.

Nevertheless, the cell in the ESD pack is not compatible with the other due to manufacturing flaws, overcharge and over-discharge, self-discharging rate, internal resistance, and temperature change. Variations in cell voltage inside the ESD pack can lead to a reduction in capacity and lifespan. Additionally, explosions may occur during the charging and discharging process [6].

The engine, lighting system, other driving systems, and accessories of an electric vehicles system are all powered by stored energy [7]. In the electric vehicles, rechargeable electrochemical ESD is utilized, such as lead-acid, lithium-ion, Ni-Cd, Ni-MH, ZEBRA, Zn/Air, NaS, and supercapacitors. The batteries we use today are much smaller than they were in the past. They are available in different sizes and electrical capacities

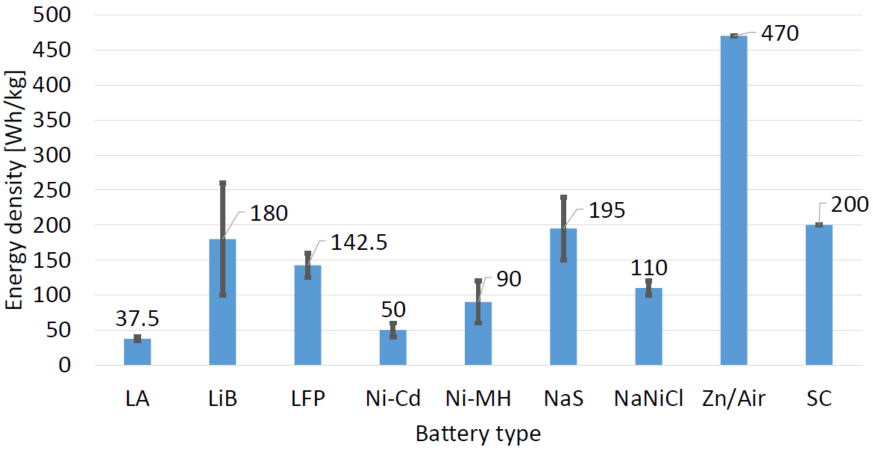


Figure 1.1. *Energy density of batteries.*

The first type of rechargeable battery is the *lead-acid (LA)*. The lead-acid batteries were the first rechargeable batteries to be used commercially. They were created in 1859 by the French physician Gaston Planté. Even after 150 years, there are still no reasonably priced replacements for the automobiles, the golf carts, the scooters, the wheelchairs, and UPS systems. In secondary cells, chemical processes can be reversed. By sending a current through the battery, the reactants that produce an electric current in these batteries (via chemical processes) may be supplied (recharging). The lead acid batteries are made in three different varieties nowadays, and each variety may be made for deep cycle or beginning uses. These include advanced absorbent glass materials (AGM), gelled acid, and flooded acid. The lead dioxide serves as the cathode while metallic lead serves as the anode of a lead-acid battery. An electrolyte of sulphuric acid separates the two electrodes. Lead sulphate is created when sulphuric acid and lead in the anode and cathode combine during battery charging. The energy density of LA is 35-40 Wh/kg.

One of the more recent inventions that provides a large capacity, safe, reusable, and small battery is the *lithium-ion battery (LiB)*. The lithium ions in the lithium-ion batteries go from the negative electrode (anode) to the positive electrode (cathode) during discharge and vice versa during charging. For consumer electronics applications, its high energy density (100-260 Wh/kg), extended cycle and shelf life, and lack of memory effect make it the most preferred option.

The LiB is already becoming quite popular in electric drive vehicles, therefore advancements in these systems may help address concerns about climate change and environmental purity. Millions of people rely on lithium-ion batteries to power their lives every day. Due to its low weight, high energy density, and recharging capability, this technology is becoming more and more commonplace in everything from computers and mobile phones to hybrids and electric cars. Longer cycle life, greater energy density, quicker charging, cheaper single-use costs, and improved performance are all features of Lithium-ion batteries.

The *lithium iron phosphate ($LiFePO_4$)* or *lithium ferrophosphate (LFP)* battery is a lithium-ion battery that uses lithium iron phosphate as the cathode material and a metal-backed graphite carbon electrode as the anode. LFP batteries are cobalt-free. Due to their low cost, high safety, low toxicity and long life, LFP batteries have a wide range of applications in vehicles, utility-scale stationary applications and backup power.

The energy density of LFP batteries is lower than other lithium-ion batteries. LFP batteries also have a lower operating voltage than other lithium-ion battery types. The energy density of CATL's LFP battery is currently 125 Wh/kg, and with improved packaging technology it can be up to 160 Wh/kg. BYD's LFP battery has an energy density of 150 Wh/kg. The energy density of the best NMC (Li-NiMgCo) batteries exceeds 300 Wh/kg. The Panasonic 2170 NCA (Li-NiCoAl) batteries used in Tesla's Model 3 2020 have an energy density of around 260 Wh/kg.

Lead-acid batteries and the *nickel-cadmium (Ni-Cd)* batteries directly compete with one another due to their comparable technical features. However the Ni-Cd battery has better energy density (40-60 Wh/kg) and cycle capabilities. The cathode of a Ni-Cd battery is constructed of nickel oxide hydroxide, whereas metallic cadmium is utilized to create the anode. Because the Ni-Cd batteries contain the very dangerous element cadmium, they are not permitted for use by consumers and pose a serious risk to the environment. For this reason, it is crucial that these batteries be reused appropriately. Furthermore, compared to lithium-ion batteries they are more vulnerable.

Although the *nickel-metal hydride batteries (Ni-MH)* have a larger capacity than Ni-Cd batteries, they can store energy for extended periods. They also do not have the same memory effect as NiCad batteries, so they continue to get a full charge with every usage, making them more ecologically friendly. Nowadays, rechargeable batteries of the nickel-metal hydride are also available. However, both use nickel oxide hydroxide (NiOx), and the chemical reaction at the positive electrode is comparable to that of the nickel-cadmium cell (Ni-Cd). Instead of cadmium, a hydrogen-absorbing alloy is used in the negative electrodes. Generally, because of its low weight, high voltage capacity, and energy density, lithium-ion batteries are preferred by automakers compared to Ni-MH batteries. The average energy density of a Ni-MH battery is 60-120 Wh/kg.

The *sodium sulphur battery (NaS)* that results from using liquid sulphur in the cathode and beta-alumina as the electrolyte has high energy density (150-240 Wh/kg), low reactant costs, high open-circuit voltage, and relatively cheap cathode and anode, which makes the NaS battery a great option for grid-level energy storage applications. The NaS batteries can operate at room temperature, however, NaS batteries have poor cycling characteristics and limited capacity retention. High-temperature sodium-sulphur batteries are the major focus for grid-level storage uses. These batteries offer the ideal advantageous features for grid-level storage applications and normally function between 300 and 400 degrees Celsius. Thermal runaway is a problem with these batteries, particularly when they are operating at high energy densities. The primary disadvantage of NaS batteries is the need for a heat source, which consumes the battery's stored energy and thus lowers battery performance.

Similar to the NaS battery, the *sodium-nickel chloride (NaNiCl)* battery, sometimes referred to as the ZEBRA battery, is a high-temperature battery that has been on the market since about 1995. In terms of safety and cell voltage, the NaNiCl batteries perform better than the NaS batteries. They can also tolerate a limited amount of overload and discharge. These batteries are a good substitute for fleet applications and have been used successfully in many different types of electric vehicle designs. Improved ZEBRA battery types with higher power density values (100-120 Wh/kg) for hybrid electric cars are now under development. High-energy versions are intended to store renewable energy for load-levelling and industrial uses.

The zinc is oxidized with airborne oxygen to power the *zinc-air batteries (Zn/Air)*, which are non-rechargeable, and the zinc-air fuel cells, which are mechanically rechargeable. These batteries are reasonably priced for production and have excellent energy densities (470 Wh/kg). Electricity is produced when the zinc metal combines with oxygen gas. Their low power output is a significant disadvantage, mostly because of the poor performance of the air electrodes. The performance and operation period's reliance on external factors like temperature and humidity is the other significant disadvantage. Because of their comparatively poor efficiency, the zinc batteries lose more energy when charging and discharging than lithium-ion batteries do.

The capacity and energy density of the *supercapacitor (SC)* is significantly higher than those of the regular capacitor, and it also has a higher power density (200 Wh/kg). For devices that need a high-power and long-lasting power unit, these features make it a useful power source. The supercapacitors sometimes referred to as the electrochemical capacitors or the ultracapacitors, are becoming more and more common in a wide range of high-power and high-reliability applications. They are used in regenerative braking energy capture in passenger cars, energy storage for the public transportation sector (such as electric buses), and more.

The Li-ion, the lead acid, the Ni-Cd, and the NiMH rechargeable batteries are the most widely used types. Rechargeable batteries, like any other product, may last longer with proper upkeep and care. Most rechargeable batteries should last you two to seven years with proper use and maintenance.

Since ESD technology has advanced, there has been a sharp rise in the need for ESDs in portable electric components, particularly for EV applications. Lithium-ion batteries have shown promise in the EV industry, despite lead-acid batteries now having a large global market in the field of renewable energy storage systems. Using an ESD, certain parameters are taken into account for the EV application, effectively using full EV systems [8][9].

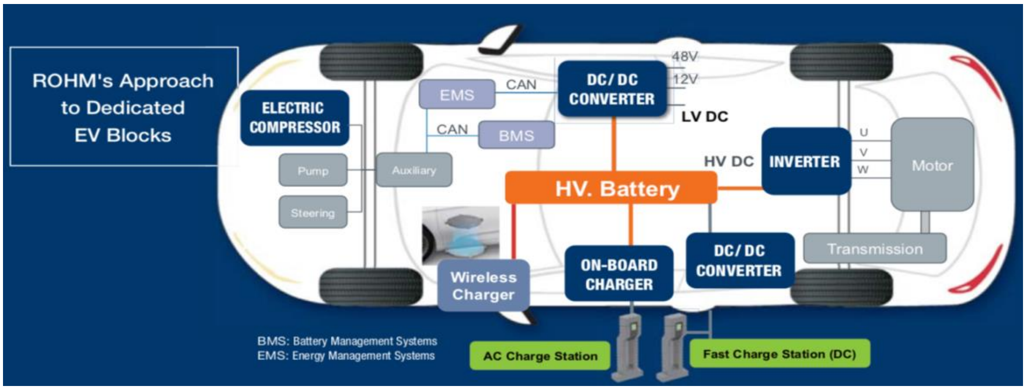


Figure 1.2*. Inside a battery-electric car. Source: Rohm.*

Companies and researchers should take into account overloading, overheating, and short circuit current, which need to be reduced and managed while applying EV power storage systems. The ESD cell voltage or charge imbalance happens as a result of under-, over-, and temperature profiles [10]. The voltage lifetime of the ESD cell will be extended in order to lessen the impacts of imbalance and overheating.

One component that every EV needs is the battery management system (BMS). BMS guarantees that ESD will be shielded from inspected damage, dependable supports, extended lifespan, and continuous power supply while EV driving [11].

1.2 The Role of Battery Management System

EVs, or electric vehicles, have become a popular substitute for cars with fuel. There are different types of batteries according to the performance characteristics of several battery types, including supercapacitors (SC), nickel-metal hydride (NMH), lithium-ion (LiB), and lithium iron phosphate (LFP).

Electric vehicle (EV) battery management systems (BMS), are essential for maintaining safe and effective battery functioning throughout the EV's lifetime. The BMS, which is the brains behind the EV's energy storage system, is essential for keeping an eye on, managing, and safeguarding the battery. The BMS maximizes battery performance by avoiding overcharging, over-discharging, and thermal problems that may otherwise shorten battery life and efficiency [12].

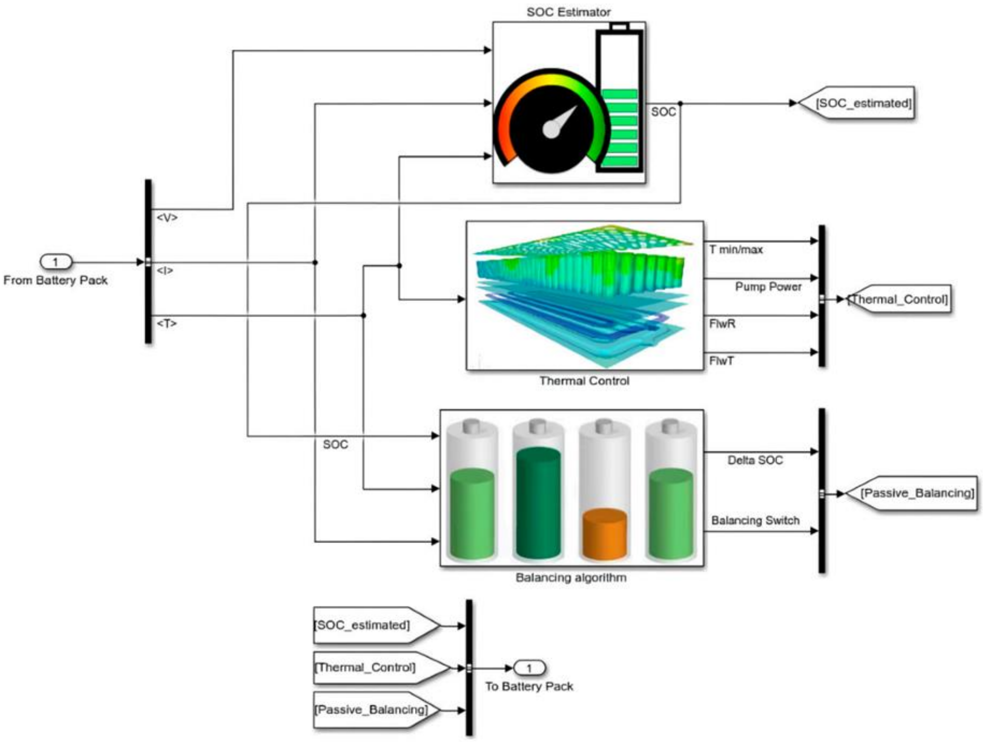


Figure 1.3*. Schematic scheme of the battery management system [20].*

In EVs, safety is of utmost importance. The BMS reduces possible hazards by implementing safety measures to guard against short circuits, over-currents, and over-temperature. Ensuring that the battery works within its safe working limits, reduces the possibility of thermal runaway or fire events, protecting both the environment and the occupants of the vehicle [13]. One of the BMS's most important features is extending the battery's total lifespan. The BMS greatly extends battery life by carefully controlling charge and discharge cycles and maintaining within safe bounds [14].

The balance of individual cells is another important function of the BMS. Differences in the properties of the cells themselves might cause imbalances and impair the overall performance of the battery. To maximize the capacity and efficiency of the battery pack and to promote consistent cell performance, the BMS actively balances the voltages of the cells during charging and discharging [15]. The BMS gathers and stores information about battery health, usage trends, and performance, making it an invaluable troubleshooting tool. Utilizing this data to perform preventative maintenance and diagnostics enables the use of predictive maintenance techniques and lowers the frequency of unplanned battery failures. Coordination and overall vehicle efficiency are guaranteed by the BMS's connection with other vehicle systems, including the motor controller and power electronics. Power flow, torque distribution, and regenerative braking are all optimized by this integration, which improves energy economy and gives EV drivers a better sensation of driving [16].

The battery management systems (BMS) are essential parts of electric cars. In order to guarantee the safe and effective functioning of EVs, their function in monitoring, safeguarding, and improving battery performance is essential. The BMS improves driving range and overall vehicle economy in addition to extending the life of batteries. The reliability, security, and sustainability of electric transportation will only increase in the future thanks to continuous breakthroughs in battery technology and BMS capabilities [17]. The BMS primary function is to control, manage, and safeguard the battery to guarantee its safe and effective performance [18]. To maximize battery performance and raise overall vehicle economy, the BMS communicates with the battery, charger, voltage regulator, current sensor, and temperature sensor, among other parts of the electric vehicle [19].

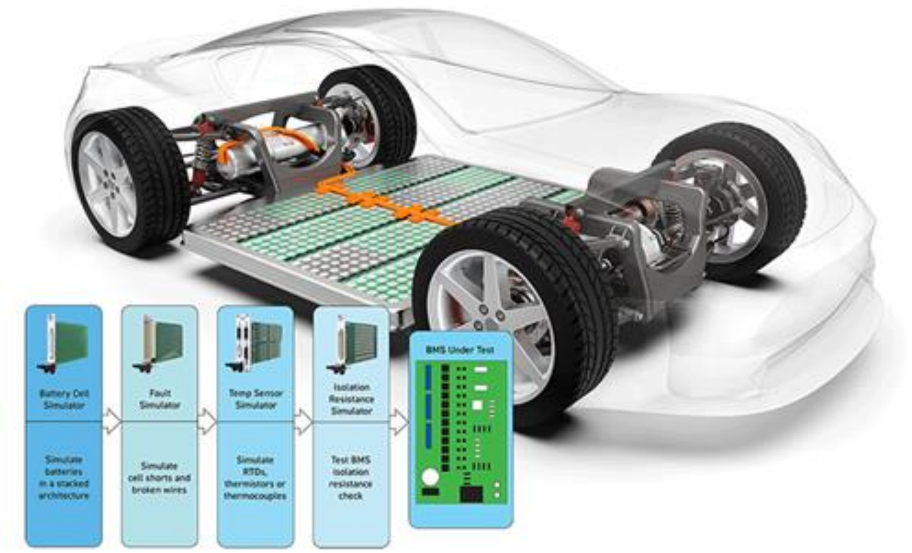


Figure 1.4. *Battery management system [21][22].*

1.3 Modelling the Battery Pack

There is growing pressure on the transportation industry to decarbonize its operations to lower greenhouse gas emissions. Electric cars are one well-known remedy that has surfaced (EVs). The lithium-ion batteries (LiB) are the go-to option for energy storage in electric cars due to their rapid expansion in the industry. It is crucial to remember that temperature and high voltage might have an impact on lithium-ion battery technology [20].

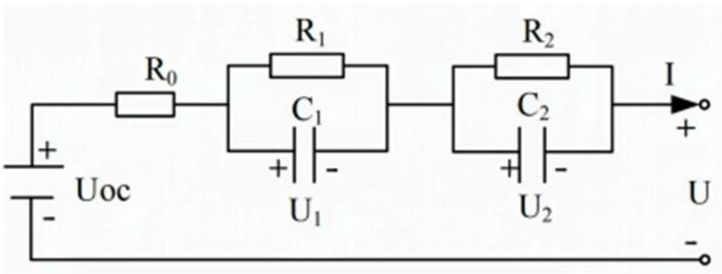
It is essential to design an accurate battery model and a trustworthy State of Charge (SoC) estimator to prevent the battery from being overcharged. The modelling and SoC estimate of lithium-ion battery cells has been the subject of several investigations. Typically, a battery pack is made up of many cells linked in series or parallel to provide the necessary voltage and capacity for electric cars [20]. The ampere-hour integration approach, model-based method, and data-driven method are the three primary categories of SoC estimate techniques that have been developed in the last ten years. The integration of ampere-hour (Ah) approach integrates currents across the whole operating duration to provide estimates in an easy-to-understand manner [23].

To guarantee the battery's safe and dependable functioning, a sophisticated Battery Management System (BMS) must be put in place, though, because lithium-ion batteries are sensitive to high voltage and temperature [20]. Critical metrics including the state of charge (SoC), state of health (SoH), state of energy (SoE), state of power (SoP), state of temperature (SoT), and state of safety (SoS) are all estimated and monitored in real-time by the BMS [24].

Energy storage is the fundamental component of modern EVs, and lithium-ion batteries have become the industry leader because of their exceptional qualities, which include low self-discharge and high energy density [25].

The lithium-ion battery models are divided into three primary categories: electrical equivalent circuit model (EECM), data-driven model, and electrochemical model. The EECM describes the dynamic properties of the battery by utilizing certain electrical components, such as resistors, capacitors, and voltage sources. It has strengths in terms of application and comparatively easy visualization. It is hence preferred in a genuine BMS. In the below figure, a number of EECMs with various structures have been shown.

According to another study, the dynamic properties of a battery, such as its internal resistance, open-circuit voltage (OCV), and one or more pairs of resistance-capacitance (RC) networks, are simulated by an EECM using electrical components. The accuracy will rise in conjunction with the number of RC networks, but correspondingly with the order and complexity. Consequently, the second-order Thevenin model is selected for this work taking these aspects into account [20]. The model is shown in Figure 1.5.

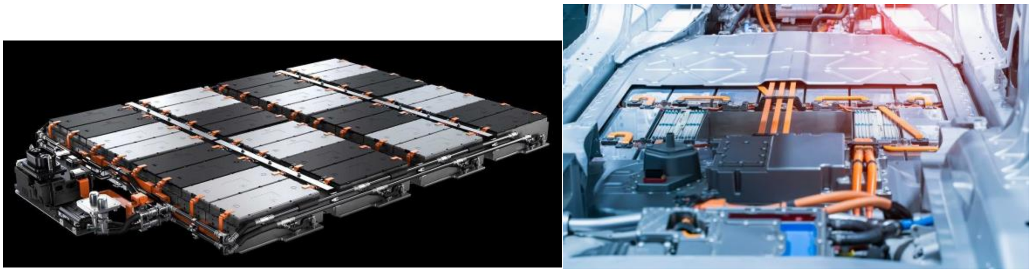


$$U_{bat} = U_{oc} - U_1 - U_2 - R_o \cdot I$$

Figure 1.5. *Second order Thevenin EECM [20].*

U indicates the voltage that was measured, and U_1 and U_2 indicate the voltages across the R_1-C_1 and R_2-C_2 pairs, respectively. The battery OCV is U_{OC}. The internal resistance, or R_0, essentially measures the voltage drop that occurs instantly when a load is attached to the battery system. The battery's nonlinear polarization response is represented by the parallel RC networks. The polarization capacitances are C_1 and C_2, and the polarization resistances are R_1 and R_2. The battery charge capacity, expressed in Ampere-seconds, is parameter Q [20].

The smallest component of the battery system that powers the electric vehicle is the battery cell. The total performance of an electric vehicle may be greatly impacted by the properties of a battery cell. Therefore, the first stage in constructing the battery pack is selecting an appropriate type of battery. Apart from the diverse range of cell chemistry, there exist an equally vast array of cell morphologies. Lithium-ion battery cells often have the following shapes: pouch, cylindrical, and prismatic. Battery modules are accumulations of cells connected in parallel or series. A larger total battery voltage is obtained when cells are connected in series, while a higher entire battery capacity is obtained when cells are connected in parallel. The overall battery system design goals are then met by connecting many battery modules in series and parallel. Incorporating sensors, controllers, and the Battery Management System, the modules are kept in a frame that shields the cells from heat and shocks from the outside world. The ultimate configuration of the battery system within the electric vehicle is called the battery pack [20].



a) *b)*

***Figure 1.6**. The battery packs [26] [27]*

Each battery's positive terminal is linked to the subsequent battery's negative terminal in a series connection. The battery voltages added by this setup will raise the system voltage. However, the battery's capacity doesn't change. All of the battery's negative and positive terminals must be connected in order to create a parallel structure. The cells' capacities will increase if they are wired in parallel, extending the EVs' usable runtime. But the voltage remains the same [20].

An essential component of the EV battery system is the battery cell. Its features affect how well an EV performs. The first step is to select the appropriate type of battery. A single battery cell's voltage and capacity are comparatively low, making it impossible to power an electric car. A battery system must be constructed using numerous cells to satisfy the EV's overall capacity and voltage requirements. The battery cell, module, and pack are the first parts of the EV battery system. As seen in Figure 1.7, the battery pack suggested consists of eight series-connected modules. Through the use of bus bars that are modelled as lumped resistors (R12, R23, R34, R45, R56, R67 and R78), the various modules in the battery pack are linked. There are 144 battery cells utilized, which reduces the complexity. Eighteen cells, three parallel cells per series of six strings, make up each module. The cells are arranged in a 3p6s configuration. The overall pack voltage and capacity are around 172.8 V and 9 Ah, with each ring rated at 3.6 V and 3 Ah/cell [20].

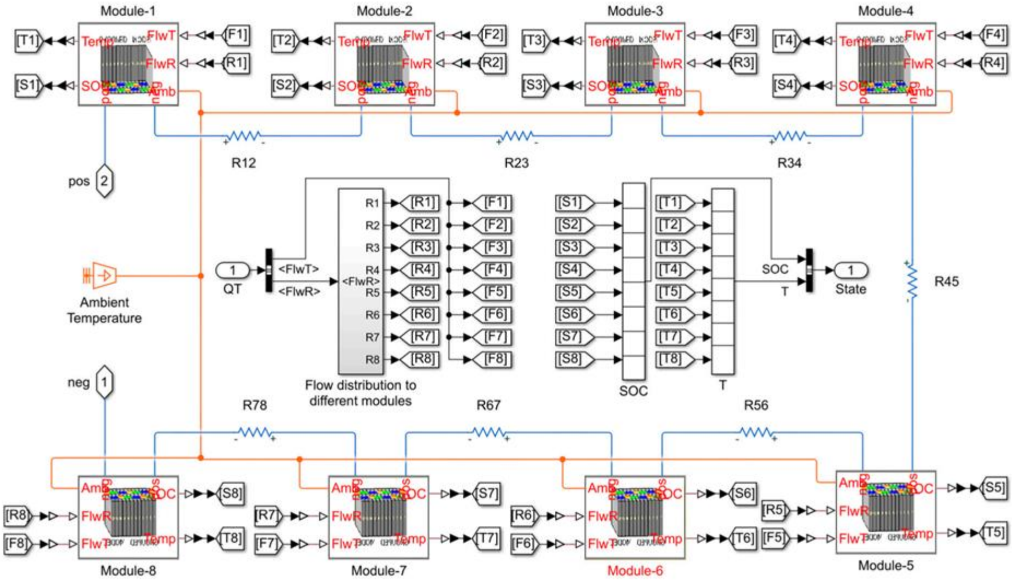


***Figure 1.7**. The schema of a high-voltage battery pack [20].*

1.4 New Battery Technology and Battery Enclosure Materials

In today's market, lithium-ion battery systems, which power everything from electric vehicles (EVs) to portable electronics are becoming more and more necessary for safety and efficiency. Usually, an electric vehicle's whole foundation is powered by its batteries. The car's enclosure cover is crucial since it has to keep the battery safe from the weather and collisions while also containing any threats to the occupants and the car itself.

Furthermore, manufacturers are increasingly using plastics and composites in place of heavier materials for battery enclosures as the car industry seeks to reduce the weight of several components. In order to do this, the enclosure needs to be remarkably robust, resistant to heat and pressure, and lightweight. Therefore, selecting the right enclosure material in advance of constructing a costly prototype is essential to reducing safety risks and other expensive problems.

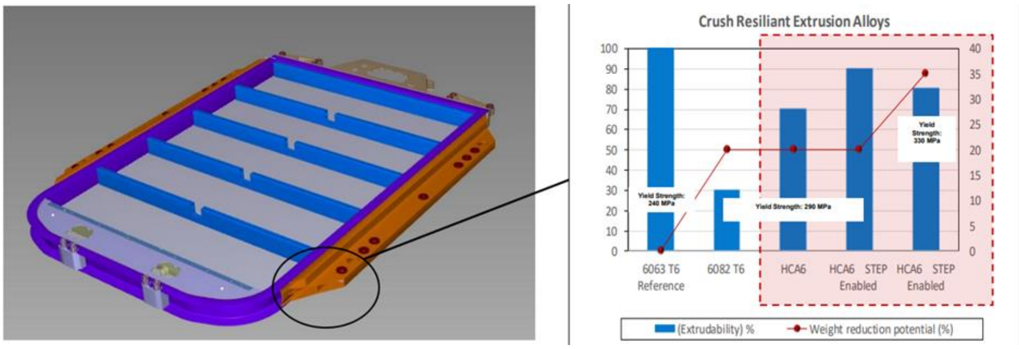
The best automakers and their suppliers select the best EV battery enclosure materials by using the Battery Enclosure Material Screening (BEMS) test. They provide the Torch and Grit (TaG) test and the Battery Enclosure Thermal Runaway (BETR) assessment, which are both covered under the Test Method for Thermal and Mechanical Performance of Battery Enclosure Materials [28]. One of the companies enrolled in this vision is UL Solutions. In order to maximize your time to market, the company offers services that assist you at many points in the product development and automotive supply chain, from planning and design to material selection and the final production component approval procedure (PPAP) [28].

Lithium-ion battery technology is the preferred energy accumulator for handheld electronics as well as cordless devices and equipment. Furthermore, they are the engine that powers the electric automobile (EV) sector. Strong lithium-ion batteries are used in the majority of EVs, however, there are safety issues with these batteries, thus the enclosure of the battery within the car is crucial. The enclosure needs to contain the threats that the battery may bring to the car and its occupants in addition to shielding it from the environment and accidents. Selecting the best EV battery enclosure material is essential for car original equipment manufacturers (OEMs) and their suppliers to reduce possible dangers, thermal runaway being the main one [29]. One of the main risks associated with lithium-ion batteries is thermal runaway, which happens when a cell experiences an uncontrolled, self-heating condition. A thermal runaway occurs when risks include intense heat, flames, smoke, and explosive cell venting, which releases gas, shrapnel, or other particles [29].

The battery enclosure of an electric car needs to be able to protect the car and its occupants from these possible risks. For this to work, the enclosure needs to be incredibly powerful, resilient to pressure and heat, and comparatively light in weight [28]. Another company named Costellium developed some battery enclosure design criteria about Safety, Crash, impact and fire resistance, thermal management, sealing, shielding and durability, and vehicle integration, space and weight optimization [29].

The main aluminium parts are:

- Top protection cover which seals the enclosure and protects the passenger compartment from heat/fire and a stamped aluminium sheet with high formability.
- Structural frame and cross members protect the cells from intrusion in the crash. It is most commonly in extruded profiles and requires very high-strength alloys combined with high ductility.
- Cooling plate / thermal management system which ensures stable operating temperature for the cells. Can be either a brazed sheet or extruded profiles and may also be integrated into the bottom cover.
- Bottom plate / lower protection cover which protects the cells from undercarriage impact, road debris, etc. Welded extrusion and sheet solutions are both used. The sheet can be flat or stamped to also act as a tray and requires high strength / high ductility alloys [30].



a) *b)*

Figure 1.8. *a) Example of battery enclosure; b) Advanced Extrusion Alloy & Design To Provide Cost-Effective Light Weight Solutions [30].*

Generally, aluminium battery enclosures and other platform components provide a 40% weight reduction as compared to a comparable steel design. Improved overall performance, including range, acceleration, payload, energy consumption, and/or reduction of costs at iso-performance by battery, motor, and structural shrinking. Aluminium may be recycled indefinitely without losing any of its qualities. 96% of an automobile's aluminium content is recycled at the end of its life. In North America, aluminium used in automobiles is made up of both primary and recycled metal that is mostly produced using hydroelectric power, a sustainable resource. Recycling aluminium only uses 5% of the energy required for initial manufacturing [30].

Questions

1. What are the energy storage devices (ESD) and electric storage systems (ESS) and their usage?
2. What is the chemical composition of ESD?
3. What are the battery management systems (BMS) and their role in the EV?
4. What are the types of batteries according to their performance?
5. How does battery management systems (BMS) function?
6. What are the battery packs and their composition?
7. How are lithium-ion batteries divided into groups?
8. What are the battery/s enclosure materials, their role, and their composition?

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2 Electric Vehicles Safety

A significant limitation of the widespread adoption of electric vehicles is the limited energy storage capacity of current-generation batteries and capacitors. Furthermore, there is a strong trend towards designing significantly lighter vehicles that consume much less energy, as well as introducing new vehicle architectures to meet the requirements of electric vehicles (centralized motors, relatively large space required for batteries, etc.). Without new safety technologies, there is a significant risk that new vehicle designs become less safe in terms of electrical and fire safety (high-voltage and potentially explosive energy storage systems) and safety in the event of accidents. On the other hand, new components in electric vehicles could open up opportunities for better and safer solutions than today if safety is considered from the initial (conceptual) stage of the vehicle design process.

Active safety [1] (accident prevention) will play a much larger role in the future, but further progress in passive safety (injury prevention) will be necessary to achieve the goal of significantly safer traffic. Conventional boundaries between passive and active safety are quickly disappearing, leading to a new and more comprehensive approach to safety.

It is also important to consider how the existing functionality of dynamic vehicle systems (e.g., ABS, TCS, ESC) can migrate safely and improve for electric vehicles. Regarding passive safety, many new and improved protection possibilities will become available thanks to enhanced pre-collision sensors. The impact of the added battery mass (due to transferring higher kinetic energy) on the passenger load in the vehicle during frontal and side impacts needs to be considered. Compatibility between vehicles for different crash conditions (frontal, side, rear) and for collisions between vehicles of different sizes (truck, SUV, small car) is crucial and must be improved.

2.1 Basic Safety Elements in Electric Vehicles

As with conventional vehicles, special attention must be paid to safety aspects in electric vehicles. There are many issues in this area for all modes of transportation and for all types of propulsion, but when analysing the safety of electric vehicles, the following safety elements need to be addressed:

Battery safety: Batteries are the heart of electric vehicles, and battery safety is of utmost importance [3]. Protocols for protection against overvoltage, overheating, and other issues affecting battery safety exist.

Fire prevention: Although rare, a fire in electric vehicle batteries can be serious. Various preventive measures, such as automatic fire suppression systems and specific design elements, are applied to reduce the likelihood of fires and ensure safety.

Electrical systems: Electrical systems, including electric motor management systems and drive control, must be safe and reliable. This includes protection against overload, short circuits, and other electrical issues.

Standards for electric vehicles: There are international standards and regulations governing the safety of electric vehicles. These standards include testing of vehicles, batteries, and other key components to ensure compliance with safety norms.

Electric infrastructure: The safety of charging stations and other parts of the electric infrastructure is also crucial. Charging equipment must be safe to use, and charging stations are equipped with various protections to prevent issues such as overload and short circuits.

User training: Users of electric vehicles need to be educated about proper vehicle handling, battery charging, and emergency procedures to minimize risks.

Pedestrian protection: Electric vehicles, especially those equipped with quiet electric motors, need to have appropriate warning systems to protect pedestrians from accidents.

2.2 International Standards and Regulations for Electric Vehicles

Safety standards for electric vehicles encompass a range of specifications and guidelines to ensure that electric vehicles are safe for use, both for drivers and passengers and for other road users. Standards play a crucial role in ensuring the safety and performance of electric vehicles. It is extremely important to monitor updates to standards and norms and adapt national regulations accordingly. The entire global electric vehicle industry is based on standards and other regulations that define this field. This fact emphasizes the necessity of understanding the entire regulatory framework to achieve successful implementation of electric vehicles in widespread use. Table 2.1 presents key documents in the field of electric vehicle safety.

Table 2.1*. The most significant documents in the field of electric vehicle safety*

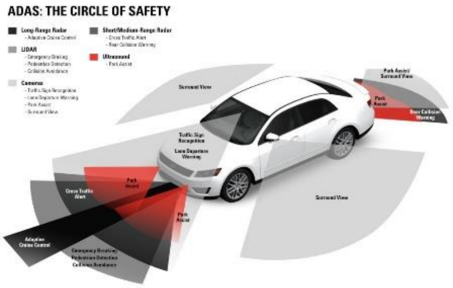
Standard Name	Short Description
ISO 26262 - Functional safety for vehicles	This international standard defines requirements and guidelines for functional safety in electrical and electronic systems in vehicles. Its goal is the identification, analysis, and control of risks related to electrical systems
ISO 6469 - Electric vehicle safety	This standard establishes requirements for the safety of electric vehicles throughout all stages of their life cycle, including manufacturing, use, and recycling
ISO 21498 - Hazard analysis and risk assessment for vehicles	This standard focuses on the identification of potential hazards and risk assessment related to vehicles, including electric vehicles

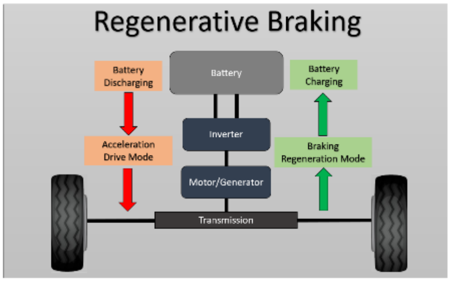
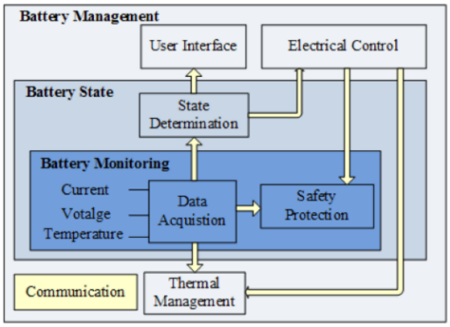
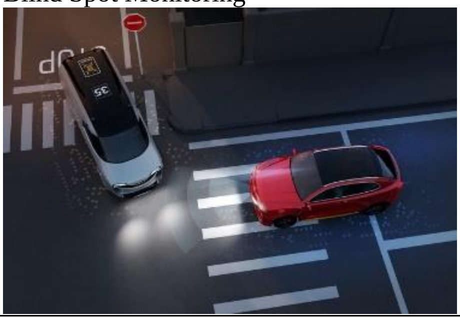
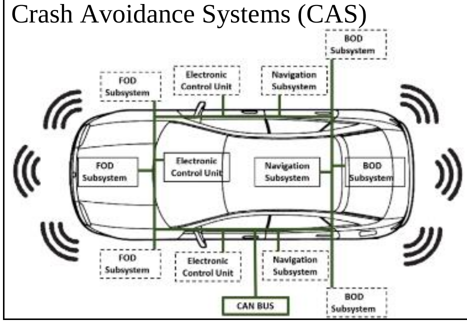
Standard Name	Short Description
ISO 15118 - Communication between vehicles and charging infrastructure	This standard defines communication protocols between electric vehicles and charging infrastructure to ensure safe and efficient communication
UN-ECE R100 - Electric energy for vehicles	This series of regulations governs aspects of electric energy for vehicles, including safety and performance requirements
IEC 62196 - Electric vehicle charging	This standard defines plugs, sockets, connectors, and cables for charging electric vehicles. It relates to the safety and performance of charging systems
SAE J1772 - Electric vehicle connector	This standard defines characteristics of electric connectors and charging for electric vehicles, including safety
UL 2580 - Standard for electric vehicle safety	This standard, developed by the American Association of Laboratories (UL), defines safety requirements for electric vehicles, including batteries, electrical systems, and other components

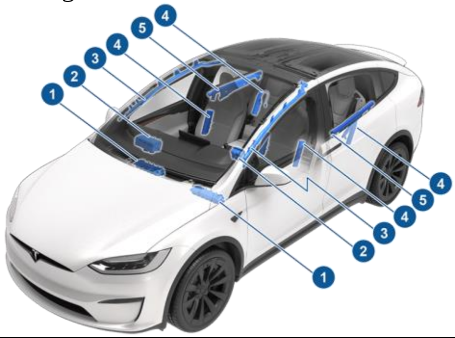
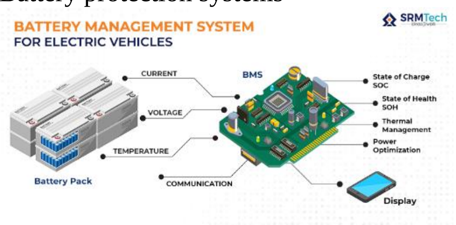
2.3 Safety Systems in Electric Vehicles

Electric vehicles undergo the same crash tests as gasoline-powered cars. The National Highway Traffic Safety Administration (NHTSA) has determined that electric vehicles perform better in overall crash tests than gasoline-powered cars. In fact, NHTSA rated the Tesla Model S as the vehicle with the lowest probability of injury in a crash compared to all other vehicles tested in the same category. This fact is a result of the implementation of a large number of advanced safety systems in electric vehicles. Table 2.2 presents the most common safety systems applied in electric vehicles. It is essential to note that there are many other safety systems, but specific ones with a significant impact on traffic safety are highlighted here.

Table 2.2. *Most common safety systems in electric vehicles*

System Name	System Description
Advanced Driver Assistance Systems (ADAS) 	Advanced Driver Assistance Systems (ADAS) are becoming increasingly common in electric vehicles, providing drivers with additional safety features and an enhanced driving experience. ADAS technology includes features such as adaptive cruise control, lane departure warnings, and automatic emergency braking, helping prevent accidents and reduce the risk of injuries.

System Name	System Description
Regenerative braking  	Regenerative braking is a unique solution in electric vehicles that uses an electric motor to slow down the vehicle and redirect voltage back to the car's battery. This reduces the need for mechanical braking and improves safety by reducing brake wear, providing better control and stability during sudden stops or emergency braking. Regenerative braking contributes to improved energy efficiency and extended vehicle range.
Battery Management System (BMS)  	Battery management systems (BMS) for electric vehicles are designed to monitor and manage battery performance, ensuring safe and efficient operation. BMS technology includes sensors that monitor state of charge, temperature, and battery voltage, making adjustments for performance optimization. It also helps prevent overcharging, overheating, and other issues that could affect battery performance and pose safety risks [9].
Blind Spot Monitoring 	With improved visibility, blind spot monitoring systems alert drivers when a vehicle is in its "blind spot," preventing collisions when changing lanes on highways and supporting safe driving in various environments.
Crash Avoidance Systems (CAS)  	Similar to blind spot detection, Crash Avoidance Systems (CAS) monitor the speed of surrounding vehicles and the vehicle's own speed to provide alerts or warnings to the driver before intervening to reduce speed or severity of an incident.

System Name	System Description
Rear-View camera 	The rear-view camera is introduced in modern vehicles as a replacement for rear-view mirrors to enhance visibility of pedestrians and vehicles behind. In electric cars, OEMs have improved functionality by including a 360-degree panoramic view, also used for autonomous driving capabilities.
Airbags 	Although airbags may seem like a straightforward safety solution, different designs in electric vehicles allow manufacturers to place them in the most suitable locations. Some electric cars are equipped with floor-mounted airbags, such as the Volvo XC40 Recharge, crucial for protecting drivers and passengers in the event of a side collision.
Battery protection systems  	The battery system is a crucial part of electric vehicles, and various protective measures are applied. This includes systems for even charging and discharging of battery cells, temperature management to prevent overheating, as well as protection systems against overloading or short circuits [6][7].

The issue of collisions with pedestrians in electric vehicles is more pronounced compared to conventional vehicles due to the silent operation of electric motors. For this reason, warning systems in electric vehicles are designed to enhance the safety of pedestrians and other traffic participants. To enhance safety in electric vehicles, considering the fundamental performance of electric vehicles, it is desirable for vehicles to be equipped with the following additional features:

Vehicle Approach Warning: Sensors and cameras on electric vehicles can detect the presence of pedestrians near the vehicle. When the system recognizes a pedestrian, it can generate audible or visual warnings to alert the driver.

Low-Speed Warning Sounds: Electric vehicles, especially those with quiet electric motors, are often equipped with audible signals activated at low speeds to make pedestrians aware of the approaching vehicle.

Pedestrian Recognition System: Advanced pedestrian recognition systems are used to identify pedestrians near the vehicle. If there is a risk of a collision, the system can automatically generate warnings or initiate braking to avoid a collision.

Reverse Movement Warning: Reverse movement warning systems can notify the driver when the vehicle is moving backward and pedestrians are nearby.

Crosswalk Warning: When an electric vehicle approaches a pedestrian crossing or an area where pedestrian traffic is expected, warning systems can activate signals to increase the driver's awareness.

Blind Spot Warning: Systems assist drivers in detecting pedestrians outside their field of vision, especially during turning, merging, or parking.

2.4 Characteristics of Electric Vehicles Important for Safety

Electric vehicles operate without fossil fuels - as their electric motors run on electric energy stored in a battery pack. This is different from traditional vehicles that rely on internal combustion engines running on gasoline or diesel fuel. This difference provides several safety advantages: Zero Emissions: Electric vehicles do not produce exhaust gases, meaning they do not emit harmful pollutants into the air. No Fuel System: Electric vehicles lack a fuel system, eliminating the risk of fires associated with traditional cars. Quieter Operation: Electric vehicles are quieter than traditional cars, potentially improving safety by reducing noise pollution and helping drivers hear other sounds on the road, such as emergency sirens or pedestrians.

Lower vehicle center of gravity - the lower center of gravity in electric vehicles results from the placement of the battery, usually located at the bottom of the car. This gives the vehicle greater stability and reduces the risk of rollovers, improving overall vehicle handling [2].

High torque at low speeds - one of the key advantages of electric vehicles is their ability to provide maximum torque from a standstill over a wider range of speeds. This means electric vehicles can accelerate much faster than traditional cars, which can be particularly useful in hazardous driving situations.

Regenerative braking - regenerative braking allows electric vehicles to capture and store energy normally lost during braking. When the driver applies the brakes, the electric motor operates in reverse, converting the car's kinetic energy into electrical energy stored in the battery. Regenerative braking can prevent accidents caused by brake failure or malfunction, reduce wear on the braking system, extend brake life, and prevent overheating or failure.

Flammability of electric vehicles - electric vehicles use lithium-ion batteries that are flammable. There is a potential for combustion if exposed to adverse conditions for an extended period or if energy cells are damaged, leading to a short circuit. However, the likelihood of such events is minimal. To enhance fire prevention, batteries are encased in protective cooling layers.

2.5 Incidents of Fires in Electric Vehicles

One critical safety aspect of electric vehicles is the possibility of fires due to the presence of energy storage batteries. Regarding this issue, it is essential to understand the following characteristics of electric vehicles [8]:

Low probability of fires: the likelihood of fires in electric vehicles during normal use is very low. Modern electric cars undergo rigorous testing and safety standards to ensure their safety.

Automatic fire response S+systems: E+electric vehicles are often equipped with systems that automatically respond to fires. This may include fire suppression systems and other safety measures to prevent the spread of fires.

Lithium-ion batteries: batteries used in electric vehicles are often lithium-ion batteries. While these batteries are relatively safe, there is a risk of fire in case of a malfunction, overheating, or battery damage. Lithium-ion batteries are known to burn if the cell structure is damaged, or if there is overheating or overload. When they burn, they can generate high temperatures and release gases.

Manufacturer safety measures: electric vehicle manufacturers implement various safety measures to prevent battery issues. This includes battery condition monitoring systems, temperature management, and leak detection systems.

While incidents of fires in electric vehicles are rare, a few well-known cases from the past have been investigated due to media attention and their impact on the perception of electric vehicle safety. It is crucial to note that these incidents are exceptions, and the safety of electric vehicles is highly prioritized. Here are several examples of fires involving electric vehicles:

- Nissan Leaf in Arizona: In 2012, a Nissan Leaf was involved in an incident in Arizona where the vehicle caught fire while parked. The investigation revealed that the fire was caused by electric components, but details were not fully clear.
- Tesla model S in China: In April 2019, videos showed a Tesla Model S on fire in a parking lot in Shanghai, China. The investigation showed that the fire was related to damage to battery modules after a collision, leading to fluid leakage and the ignition of the vehicle.
- Chevrolet Bolt EV: In 2020, Chevrolet recalled a certain number of Bolt EV vehicles due to the risk of fires associated with batteries. The manufacturer found that there was a potential for electrolyte leakage and vehicle ignition.
- Electric buses in China: In 2021, footage from China showed the moment an electric bus caught fire, causing a fire that spread to four other buses parked nearby (Figure 2.1).
- Electric buses in London: In 2022, a fire broke out in an electric bus in London. Subsequently, the fire quickly spread to all buses parked nearby (Figure 2.1).

Figure 2.1. Electric buses in China and London exposed to fire

2.6 Crash Protection Zones for High-Voltage Components

Extremely important for the safety performance of battery electric and hybrid vehicles in any accidents is the well-protected arrangement of all safety-critical components. This is especially true for the high-voltage battery, which must not be damaged even in very severe accidents resulting in any critical cell damage or loss of contact protection. In order to define protective zones for better energy storage integration, a special study was conducted by analysing damage from approximately 9000 vehicles involved in serious accidents, using the database of the German In-Depth Accident Study (GIDAS) [4][5].

For each vehicle, deformations in the lower vehicle level (floor) were plotted on a standardized 2-D grid. By consolidating the obtained deformation matrix with the frequency and severity of accidents, the probability of deformation for each vehicle cell in any type of collision can be estimated accordingly. Figure 2.2 compares the obtained deformation matrix of vehicle deformations in standard crash tests [10].

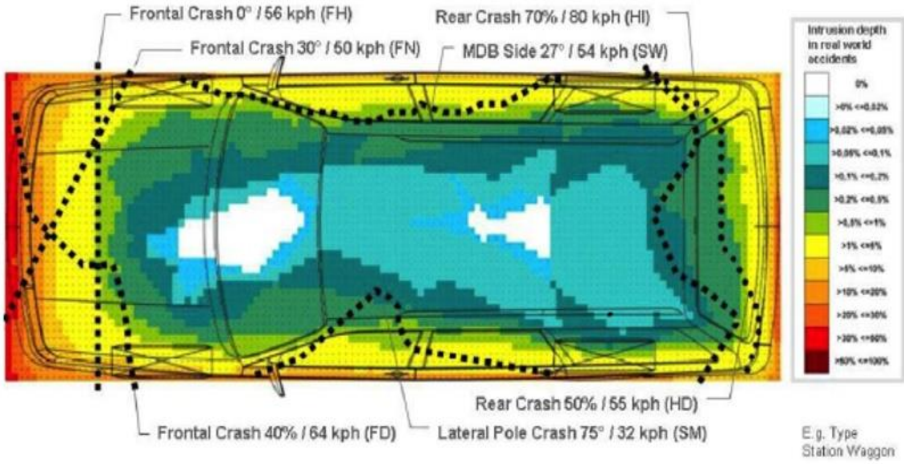


Figure 2.2. *Deformations of conventional vehicles in real accidents*

Based on this probability deformation matrix, three deformation zones for the secure location of high-voltage components have been defined (Figure 2.3):

1. *Protective Zone 1:* The outer area of deformation that has already been damaged in minor collisions without activating the safety system is a prohibition zone for all HV components. If (for any reason) the location of the high-voltage component in this area is unavoidable, it must be well protected from any damage in minor or severe accidents, and the high-voltage wiring must be additionally coated.
2. *Protective Zone 2:* Areas of deformation in moderately severe frontal collisions characterized by the activation of seatbelt tensioners or the first stage of the airbag require enhanced contact protection according to the IPXXB class with a test finger diameter of 12 mm.
3. *Protective Zone 3:* Preferred zones for the placement of high-voltage systems are not damaged in standard crash tests, and only with a probability of less than 2% in real accidents. Areas deformed in standard crash tests should be avoided.

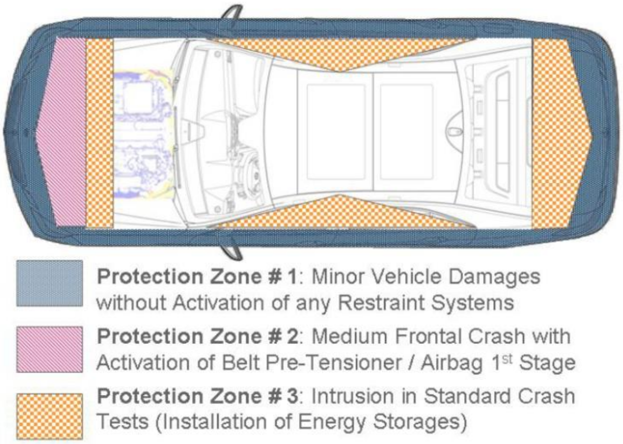


Figure 2.3. *High-voltage safety protection zone*

Questions

1. Which are basic safety elements in electric vehicles?
2. What are the risks associated with electric cars in traffic accidents?
3. What are the safety characteristics in electric vehicles?
4. Are electric cars more likely to catch fire? Why?
5. Are electric cars safe in a car accident? Why?
6. Explain the consideration of responsibility in car malfunction and damage car accidents?

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3 Powertrain and Mechatronic Systems in the Electric Vehicle

Electric vehicles are experiencing a significant increase in popularity, driven in part by their more environmentally friendly nature compared to traditional combustion engine vehicles. However, a key catalyst for this popularity is the constant improvement of electric vehicle technologies, making them more efficient, reliable and cost-effective.

A key factor contributing to this progress is the powertrain and propulsion system of electric vehicles, components that often remain unexplored by many.

The powertrain and mechatronic systems in electric vehicles have seen significant progress in recent years.

Drive systems integrate gears, clutches and other mechanical components with drive motors and motor controllers and affect EV performance.

Innovations in engine design and materials, advanced control strategies and algorithms, and integration with renewable energy sources are helping EV progress. However, there are still many challenges, such as reducing the production costs of electric vehicles, increasing the driving range and optimizing the charging infrastructure. As these areas develop, electric vehicles will play an increasingly important role in the transportation system.

3.1 Powertrain Systems

The powertrain of an EV encompasses all components involved in converting power into movement, including the battery, electric motor, and the drivetrain for generating power required to move the vehicle and deliver it to the wheels. This includes the transmission, axles, and drive shafts [1].

The powertrain main components include [2]:

- Battery pack
- DC-AC converter
- Electric motor
- On-board charger

In addition to these basic components, there are other hardware and software parts in a powertrain, like:

- *Battery Management System (BMS)* constantly monitors the condition of the battery and takes the necessary measures in case of failure.
- *DC-DC Converter* plays a key role in managing the flow of electricity, as the battery supplies a fixed voltage and the demands of different car components vary. The converter helps distribute power to different

systems by converting the output power and delivered via wiring harness [3].

- *Thermal Management* in electric vehicles is a critical aspect that ensures optimal performance, safety, and efficiency. Batteries work best within a certain temperature range. Proper cooling prevents overheating during charging or discharging, and also extends battery life and improves performance. In addition, effective cooling prevents damage to engine components and ensures reliable operation [4].
- *Body Control Module (BCM),* also known as the „body computer“, serves as the brain behind automotive electronics. It is the electronic control unit (ECU) responsible for monitoring and controlling the various electronic components inside the vehicle [5].

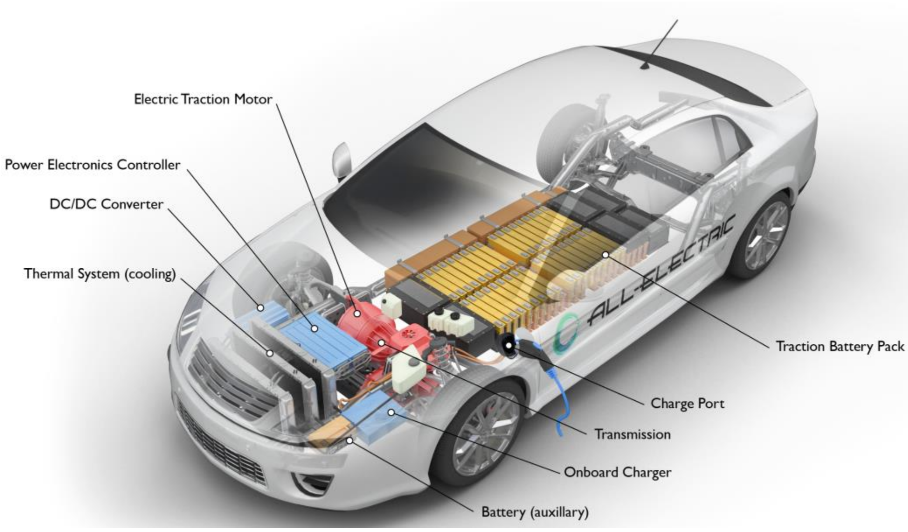

Figure 3.1. *Powertrain components [2].*

3.1.1 Battery Pack

An electric battery is a device that stores chemical energy that is converted into electricity, which enabled us to power most of the modern world with advanced devices such as laptops, smartphones, satellites, and even electric cars.

The batteries that power today's electric vehicles are built to last longer than the vehicle itself [6]. Electric vehicles use lithium-ion batteries because of their high energy density, and many well-known electric car companies have their own lithium-ion battery production.

Table 3.1 shows some characteristics of batteries used in EVs as of 2013, comparing of Li-ion batteries with other types of batteries.

Electric car batteries will slowly begin to lose the amount of energy they can store over time. Battery degradation causes reduced energy capacity, range, power and overall efficiency. Environmental factors, such as constant exposure to extreme temperatures, will affect battery performance and can lead to degradation. Batteries do not perform well when it is very cold and when the energy from the batteries is used to heat the car. The range can temporarily drop by as much as 40%.

Table 3.1. *Characteristics of batteries used in EV [6].*

Battery type	Energy density (Wh/kg)	Power density (W/kg)	Cycle life (charge/discharge)
Lead Acid	30 – 40	120 - 200	200 - 300
NiMH	50 – 80	250 – 1000	300 – 500
Lithium-Ion	100-150	1000 – 1500	500 - 1000

3.1.2 DC-AC Converter

Supplied by the battery pack is converted into alternating current (AC) and then delivered to the electric motor. A sophisticated motor control system (also known as the Powertrain Electronic Control Unit) manages this power transfer. It controls the frequency and magnitude of the voltage supplied to the electric motor, ensuring smooth speed and acceleration based on the driver's instructions via the accelerator and brakes [7].

DC motors have excellent features, you can overload the motor in a short time (up to 10:1 ratio). This is ideal for short-term acceleration. The only limitation is that the engine is overheated. With too much overload, the overloaded motor heats up so much that it destroys itself. AC motors and controls usually have a regenerative function to power the battery.

The AC-DC converter is built into the car. It is also called a "car charger", even though it is actually a converter. It converts alternating current into direct current and then powers the car battery. Today, the charging method of electric vehicles and most chargers use AC power.

The main power supply is always alternating current (AC), so the difference between an AC load and a DC load is the switching position of the AC power source. Inside or outside the vehicle. Unlike the AC charger, the DC charger has a converter in the charger, and car battery can be directly powered and can be converted without the need for a built-in charger. DC charging is using on public charging stations as fast charging method. Lately, DC charging is entering the home charging method.

3.1.3 Electric Motor

Electric motor converts electrical energy into mechanical energy. This mechanical energy is then transmitted to the wheels through a single-ratio transmission. Rapid development in the field of power electronics and control technology has helped the development of different types of electric motors used in electric vehicles. Electric vehicles use different types of electric motors, and the most commonly used are [8]:

- DC Series Motor
- Brushless DC Motor
- Permanent Magnet Synchronous Motor (PMSM)
- Three Phase AC Induction Motors (IM)
- Switched Reluctance Motors (SRM)

3.1.4 On-board Charger

On-board Charger converts the alternating current (AC) from the charging source into direct current (DC). It also regulates the amount of current flowing into the battery pack for efficient charging. There are two kinds of usages for batteries in the EV [9]. One is the high-voltage (HV) battery for traction motor drives and the other is the low-voltage (LV) battery for auxiliary power supplies feeding the loads such as lighting and signalling circuits, entertainments, automatic seats, and other electronic devices. The LV battery is charged from the HV battery by the auxiliary charger since alternators are not used, differently from the conventional vehicles equipped with an internal combustion engine.

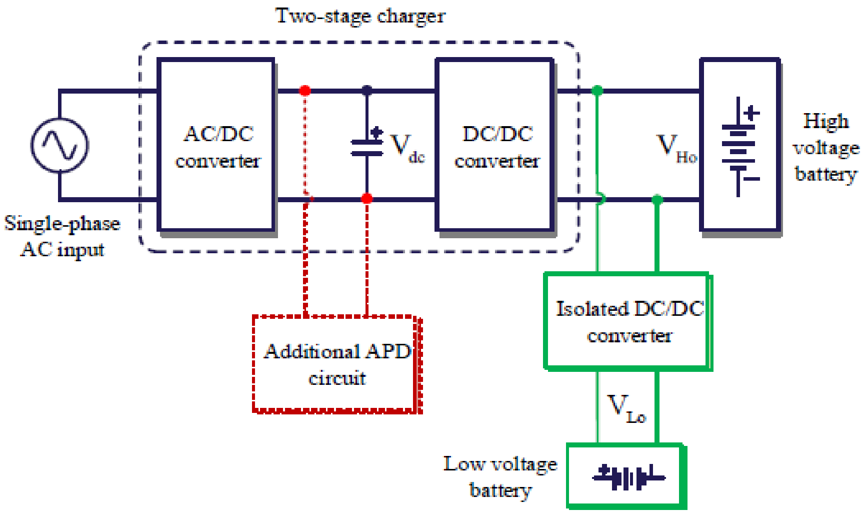

Figure 3.2. *The two-stage onboard charger with additional active power decoupling circuit [10].*

3.2 Mechatronic Systems

Mechatronic systems in electric vehicles are a combination of mechanical components, electronic components, and an information-processing unit. These systems include sensors that capture or measure a physical reality. Then units convert data into electrical signals for processing in electronic control units (ECU) and compared with specified values [11]. Mechatronic solutions have enhanced the automobile in its different subsystems with smart chassis and powertrain devices. This trend has gained substantial momentum due to the electrification of the powertrain, which has enabled the inclusion of more electric components [12].

With the development of mechatronics technology, its applications in the automotive field are becoming more extensive, such as the Car attitude control, Antilock brake system (ABS), Electronic Stability Program (ESP), optimization of a car equipped with a semi-active suspension, steering systems, injection systems, automated gearbox, start-stop systems, engine control units (ECU), etc.

The number of cars is increasing year by year, and the structure of automobiles is becoming more and more complicated. The traditional production mode is low in efficiency and quality, and unable to effectively control many production components, and even the cooperation ability between various systems is insufficient [13]. Mechatronic technology can provide thorough vehicle driving data collection, timely vehicle regulation and effective system control [14].

Here are some key areas where mechatronics is applied in EVs:

- Vehicle Safety Systems
    - Anti-lock brakes (ABS)
    - Electronic stability programs (ESP)
    - Traction Control System (TCS)
    - Collision avoidance (CA)
    - Lane keeping
- Suspension
- Steering Control Systems
- Battery Management System

3.2.1 Vehicle Safety Systems

Automotive vehicle safety systems may be broadly classified into passive and active safety systems [15].

Passive safety systems include seat belts, air bags, and additional structural members. The objective of passive safety is to reduce damage to the driver and passengers of a vehicle during and after an accident.

Active safety systems work before an accident and aim at preventing an accident from happening in the first place. As such, it makes sense to also call them preventive systems.

Antilock brake system (ABS) is a system that automatically controls the braking force of the brake when the car brakes, so that the wheel is not locked in the state of roller sliding, so as to ensure the adhesion of the wheel and the ground in the maximum value. ABS braking system has been widely used in the cars, like an essential part of most vehicles.

The intelligent braking systems (IBS) is introduced to optimize performance, which is obviously better than traditional ABS, and can work with a variety of brakes, sensors and actuators, as well as various types of control algorithms [16].

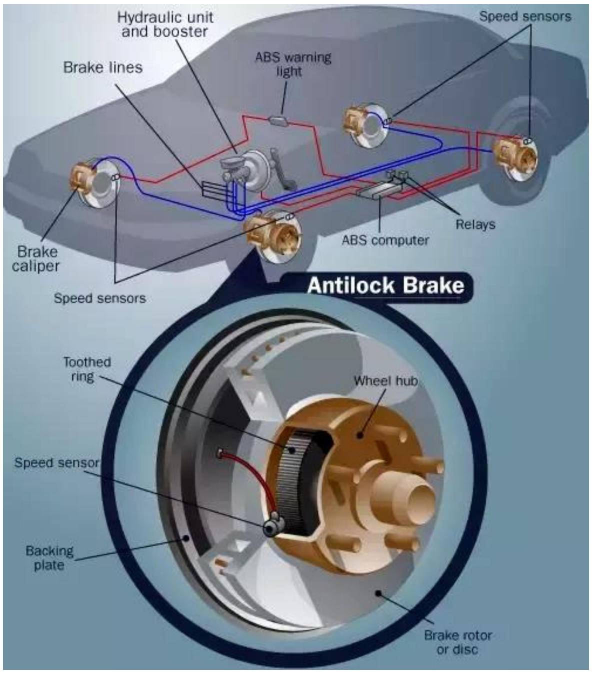

Figure 3.3. *Antilock brake system (ABS).*

Electronic Stability Program (ESP) improves a vehicle's stability by detecting and reducing loss of traction. The common cause of vehicle accidents is skidding. For those situations, ESP compares the driver's expected direction in steering and braking inputs to the vehicle's response through lateral acceleration, rotation (yaw), and individual wheel speeds [17].

The two primary methods of activating ESP systems that generate corrective steering torque are to compensate using steering commands or to use individual wheel braking as this is more easily achieved through pre-existing ABS hardware.

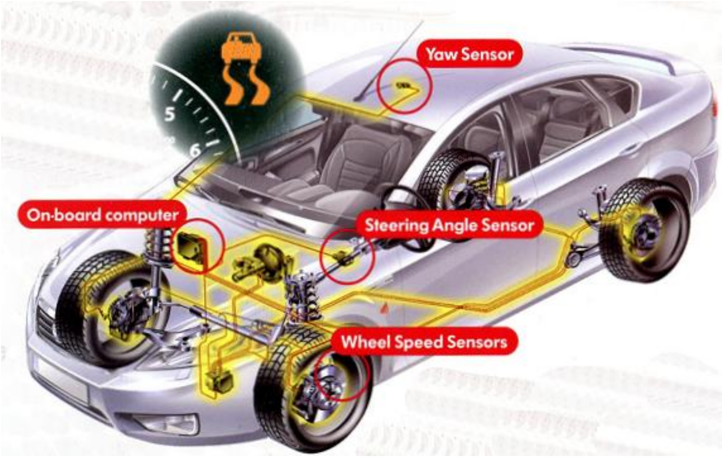

Figure 3.4. *Electronic Stability Program system (ESP).*

Traction Control System (TCS) is longitudinal slip controllers like ABS but they operate after encountering large amounts of longitudinal slip that occur when wheels spin without traction on the road surface. In such cases, a TCS intervenes by applying the brake to the wheel that is spinning until traction is achieved. The result is close to optimum traction on all four wheels. TCS is also becoming standard components on innovative vehicles [18].

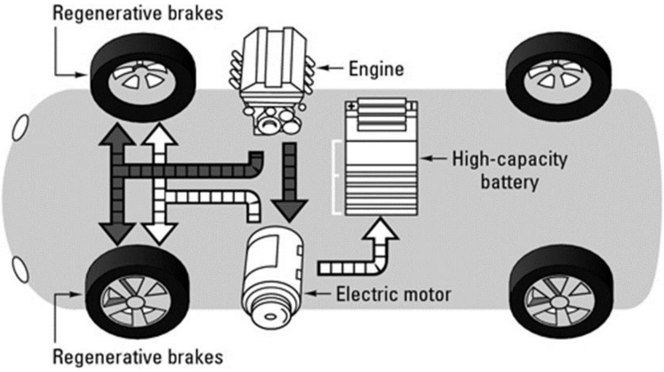

Figure 3.5. *Traction motor in EV.*

Collision Avoidance (CA). Autonomous driving requires the capability of determining and avoiding obstacles in the path of the vehicle. Work on incorporating collision avoidance technology into active vehicle safety control is relatively innovative and benefits from the well-established theoretical and practical results on obstacle-avoidance methods for mobile robots. Automotive vehicles are much faster than mobile robots that can stop and wait to take the necessary evasive action, if necessary. In both cases, it is more difficult to avoid moving obstacles [19].

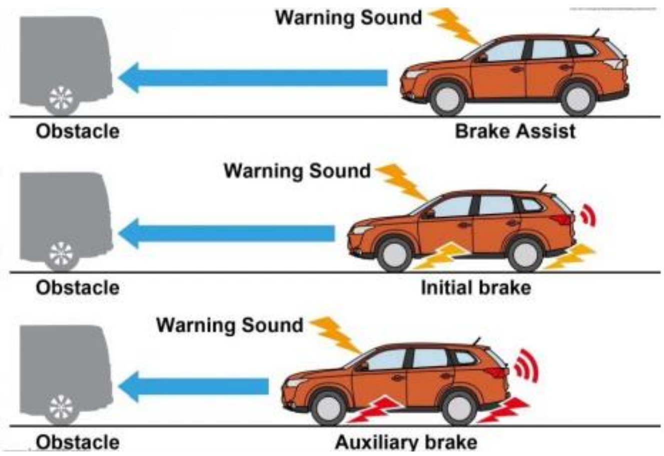

Figure 3.6. *Collision avoidance in EV.*

Collision avoidance can be divided into *two categories*. The first is the determination of a collision-free path between obstacles whose locations have been determined. Another case is the sudden and unexpected detection of an obstacle with an inevitable collision. The collision avoidance algorithm should immediately perform evasive manoeuvres in this case. This scenario is much more difficult to solve, because the evasive manoeuvre should avoid other possible collisions and the loss of lateral or vehicle stability.

Lane Assist (LA) monitors the markers in the lane you are driving as well as the surrounding area for the presence of vehicles or other objects. Lane Assist may provides steering interventions if vehicle drifts into an adjacent lane in which an object, such as a vehicle, is detected. In these situations, lane assist automatically steers to a safer position in the driving lane. When a steering intervention is applied, the screen briefly displays a warning message [20].

Figure 3.7. *Lane Assist in EV.*

3.2.2 Suspension System

Electric vehicles have *suspension* just like internal combustion engines. Typical suspension variants are fixed and independent suspension. In fixed suspensions, the right and left wheels are connected to each other by an axle. In independent suspensions, all wheels in the vehicle move independently of each other. Free suspension system has all wheels independent of each other.

Car attitude control in electric vehicles (EVs) involves managing the vehicle’s orientation and stability during motion, for example a Mechatronic suspension. This is a key component in modern electric vehicles. It involves the use of electronics and microprocessor technology to control the vehicle’s suspension system [14].

Active/electric suspension is keeping the driving comfort at the highest level, which affects many aspects from braking action to steering, controlling the speed of the vehicle to other driving systems, helps to convert kinetic energy into electrical energy. It prevents the outer wheel from leaning towards the inner wheel during turns. The biggest difference of Electric vehicle suspension compared to other types is the advantages it brings in the braking system. Active suspension also allows braking in a much shorter time than other types [21].

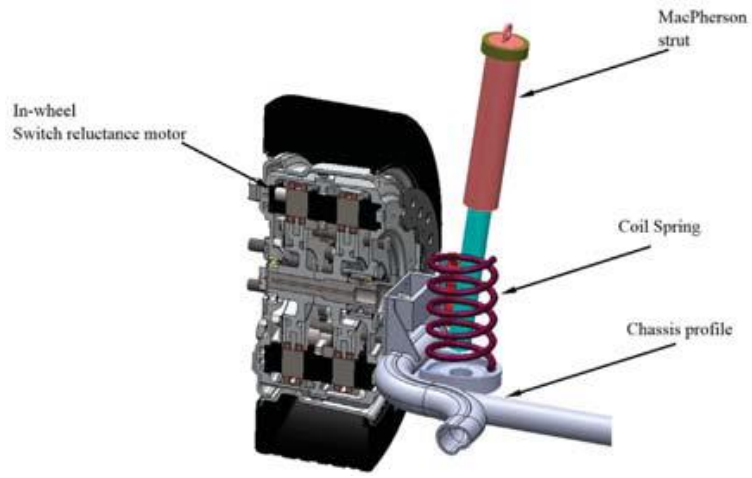

Figure 3.8. *Suspension design of the electric vehicle (EV) with an in-wheel SRM motor.*

3.2.3 Steering Control Systems.

Electric cars are designed to have electric power steering. The technology has already evolved to steer a car just steer-by-wire system. There is no need for rack and pinion at all, with no need for any direct mechanical connection to the wheels.

Four-wheel steering car with the new technology no need any more a complicated mechanical and electrical mix hybrid system but only electrical , also without big faults like some cars had in the past [22].

a) *b)*

Figure 3.9. *Four-wheel Steering Control Systems*
a) opposite direction steering, at low speeds
b) same direction steering, at medium and high speeds

3.2.4 Battery Management System (BMS)

The *Battery Management System* (BMS) manages the electronics of a rechargeable battery and becomes a crucial factor in ensuring electric vehicle safety. BMS monitors the State of Health (SoH) of the battery, collects data, controls environmental factors that affect the cell, and balances them to ensure the same voltage across cells. A battery with a BMS connected to an external data communication system or data bus is about providing information about the battery's power status and other important information. This information can help the device to save energy intelligently [23].

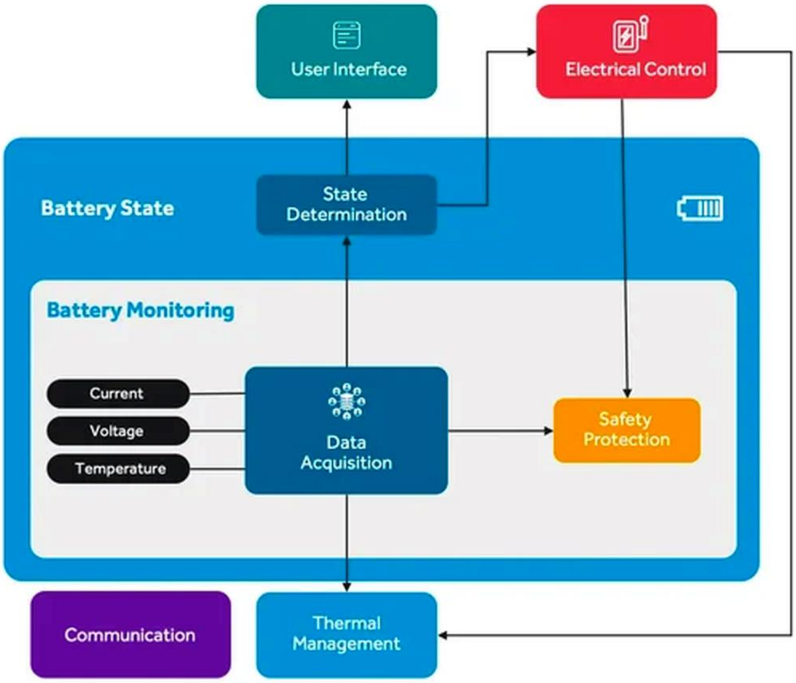

Figure 3.10. *Typical Battery Management System*

Questions

1. What are the main components of the powertrain in an electric vehicle and what are their functions?
2. How does the Battery Management System contribute to the safety and efficiency of an electric vehicle?
3. Can you explain the role of the Body Control Module in managing the electronic components inside the vehicle?
4. What are the differences between AC charging and DC charging in electric vehicles, and how do they affect the charging speed and efficiency?
5. What are some key areas where mechatronics is applied in Electric Vehicles (EVs)?

6. How do the Intelligent Braking Systems (IBS) and Electronic Stability Program (ESP) enhance the safety and performance of a vehicle?
7. What are the two categories of collision avoidance in autonomous driving?
8. What are the benefits of the new steer-by-wire system over the traditional mechanical and electrical mix hybrid system?

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4 Automatic Control Systems in Electric Vehicles

The global transition to a sustainable future is affecting various sectors, including transportation. With the increasing awareness of climate change and the depletion of fossil fuels, there is a growing demand for environmentally friendly transportation options. Electric vehicles (EVs) play a crucial role in this shift, as they operate on electricity rather than traditional fuels, emitting zero emissions and providing a cleaner alternative to conventional vehicles.

There are four types of electric vehicles:

- Battery Electric Vehicle (BEV): Operates solely on electricity, providing higher efficiency compared to hybrid and plug-in hybrid models.
- Hybrid Electric Vehicle (HEV): Combines an internal combustion engine (usually petrol) with a battery-powered motor. The petrol engine is used for driving and charging when the battery is empty. HEVs are less efficient than fully electric or plug-in hybrid vehicles.
- Plug-in Hybrid Electric Vehicle (PHEV): Integrates an internal combustion engine with a battery charged externally via a plug. This allows the battery to be charged with electricity, making PHEVs more efficient than HEVs but less efficient than BEVs.
- Fuel Cell Electric Vehicle (FCEV): Uses cleanly produced electricity from non-fossil fuels, such as hydrogen, employing fuel-cell technology.

Control systems are essential for elevating the efficiency and performance of EVs. Modern EV research and development is grounded in contemporary control technologies, encompassing automotive, motor driver, power electronics, and energy storage technologies. The design process for EVs addresses three key challenges: vehicle technology, electric drive technology, and energy management systems. In other words, automatic control systems in EVs encompass a diverse set of functions, ranging from optimizing traction and overseeing regenerative braking to managing battery performance, regulating power electronics, and controlling thermal conditions. Collectively, these systems synergize to enhance the overall efficiency, safety, and performance of EVs.

The effective selection of control techniques is contingent upon accurately measuring and assessing operational conditions.

4.1 Fundamentals of Control Systems

Control systems engineering is based on the analysis of linear and non-linear feedback control systems and integrates the concepts of network theory and communication theory. Here, the dynamic behaviour of characteristic phenomena, processes, and systems is considered, based on which structures that regulate or control them are designed. Control refers to a set of actions that ensure a certain behaviour of a process or system in the presence of disturbances, while regulation represents the maintenance of a certain physical variable at the desired value.

A system is a collection of components that function together to perform a specific task. The control system is a set of interconnected components that should provide the desired system response to a given excitation. The basic analysis of the system is based on the theory of linear systems, which implies the existence of a cause-effect relationship between the components of the system. In a control system, this relationship is obtained in the form of input-output variables, where the input variables are the cause, and the output variables are the effect of processing the inputs in a way that allows the desired outputs to be obtained. This type of connection can be achieved by open-loop and closed-loop systems, Figure 4.1. An open-loop control system uses a controller or control actuator to obtain the desired response. To compare the actual output with the desired output response, a closed-loop control system uses an additional measure of the actual output called feedback signal. That is why these systems are known as closed-loop feedback control systems.

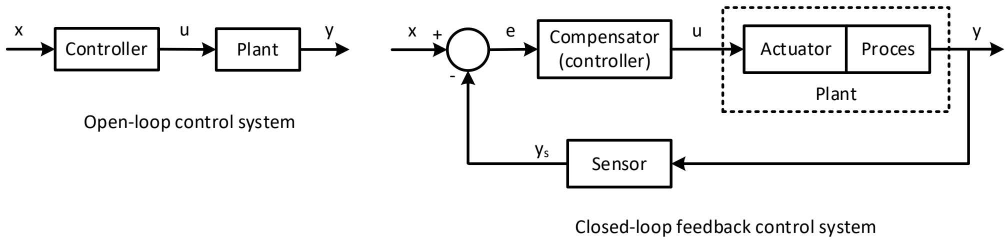

***Figure 4.1**. Open-loop and closed-loop feedback control systems*

The main components of a closed-loop feedback control system are plants, sensors, actuators, and controllers. The control system regulates the output (y) of a system or subsystem called the plant. The goal of the control system is to obtain the system output to be equal to the system input (x) which is often called reference input. The controller is designed to achieve the desired control of the plant, based on a comparison of input and output measured by the sensor (y_S). Whenever a difference between the input and the output, called error (e), is nonzero, the compensator or controller generates a control variable (u) that causes the plant input to change to reduce the error to zero. Plant control is performed by regulating control variable (u) through an actuator. A closed-loop control system must be stable in the sense that a bounded input produces a bounded output.

There are three main conventional types of controllers: proportional (P), proportional-integral (PI), and proportional-integral-differential (PID). Generally, the controller performs a transformation on the error signal to satisfy certain criteria, including transient response characteristics, steady-state error, disturbance rejection, and sensitivity to plant parameter changes over time or with environmental parameter changes. Advanced controllers are designed using fuzzy logic, neural networks, machine learning, and artificial intelligence (AI) techniques. A closed-loop control system must be stable in the sense that a bounded input produces a bounded output. In modern automotive control systems, a controller is implemented by a microprocessor or microcontroller, and its operation is determined by the software.

If the main components of a control system are interconnected over the wired or wireless communication network, then the control system is called a networked control system. These systems are widely used in the automotive industry where different electronic control units and modules communicate with vehicle controller to obtain desired vehicle behaviour and maintain desired vehicle condition.

4.2 Types of Control Systems in EVs

There are numerous examples of feedback control systems in EVs. They are designed to control different functions and operations of EV and some of them will be briefly explained below.

4.2.1 Steering Control

Steering is one of the critical functions of EVs. The steering system gives stability to the vehicle and provides safe driving. It is a set of components that are responsible for giving directional change to the movement of the vehicle and maintaining the driving direction according to the driver's decision. The steering control system enables a vehicle to follow a desired course. A simple block diagram of the steering control system is shown in Figure 4.2.

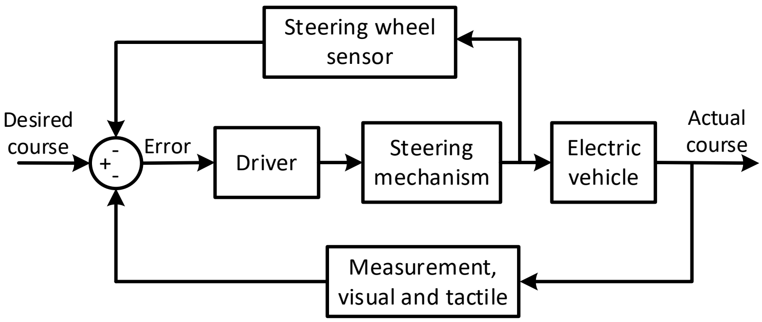

Figure 4.2. *EV steering control system*

4.2.2 Cruise Control

Cruise control is a driving assistance system that allows the driver to set the desired vehicle's speed. When this control is activated, the speed of the vehicle is maintained automatically without touching the accelerator pedal. In this way, the driver can cruise at a speed limit or economic speed. A block diagram of the cruise control system is shown in Figure 4.3.

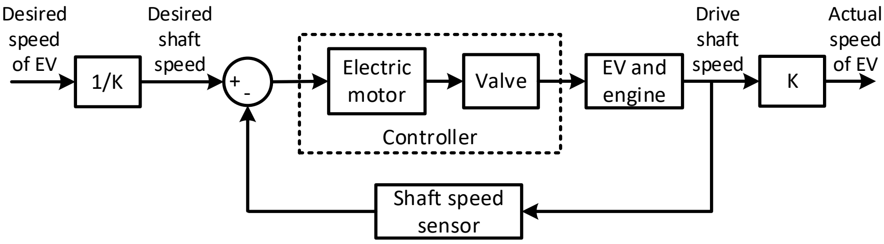

Figure 4.3. *EV cruise control system*

4.2.3 Adaptive Cruise Control

Adaptive Cruise Control (ACC) is a common system that adapts the vehicle's speed relative to other vehicles in front to maintain a safe distance. The control system uses sensor information, commonly from radar and cameras, to detect vehicles and other objects. An ACC usually has two control modes: a speed control mode and a distance control mode. The speed control mode is used when there is no detected vehicle ahead, otherwise the distance control mode is used. A block diagram of a distance control mode ACC system is given in Figure 4.4.

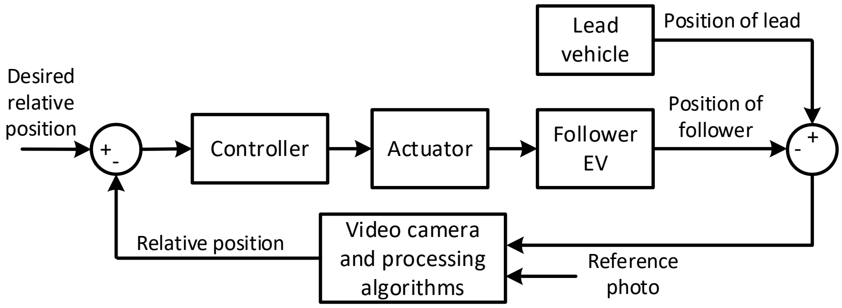

Figure 4.4. *EV adaptive cruise control system*

4.2.4 Traction Control

Vehicle traction control enhances vehicle performance and handling. The objective of this control is to maximize tire traction by preventing locked brakes and tire spinning during acceleration. A traction control system is given in Figure 4.5. It includes antiskid braking and anti-spin acceleration. The difference between the vehicle speed and the wheel speed (wheel slip) is chosen as the controlled variable because of its strong influence on the tractive force between the tire and the road.

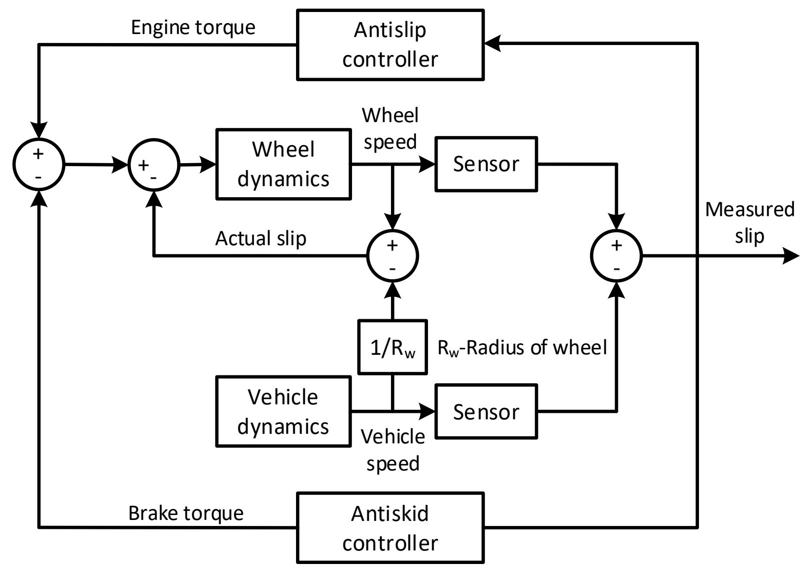

Figure 4.5. *EV traction control system*

4.2.5 Temperature Control

Modern vehicles have thermostatically controlled air-conditioning systems for the comfort of the passengers. Figure 4.6 depicts a block diagram of an air-conditioning system where the driver sets the desired temperature of the vehicle cabin.

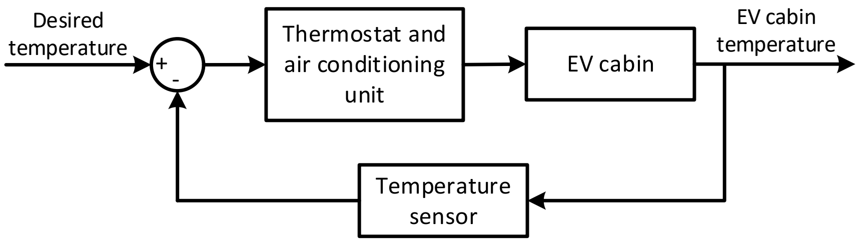

Figure 4.6. *EV temperature control system*

4.3 Integration of EV operation

The EV dynamic control system integrates electrical, electronic, mechanical, chemical, and other nonlinear dynamic systems, such as those presented in Chapter 4.2. It includes motors, converters, batteries, transmission, and other electric control equipment. Because of this, the structure of the EV control system is extremely complicated, and designing it is a very difficult procedure. The overall EV dynamic control system has a distributed hierarchical structure and can be divided into three parts: vehicle control system, motor drive system, and power supply system, Figure 4.7. On the top layer, there is the whole vehicle controller or Vehicle Control Unit (VCU) which is the core component of the control system. On the second layer, there are secondary controllers for vehicle control, motor control, and battery management.

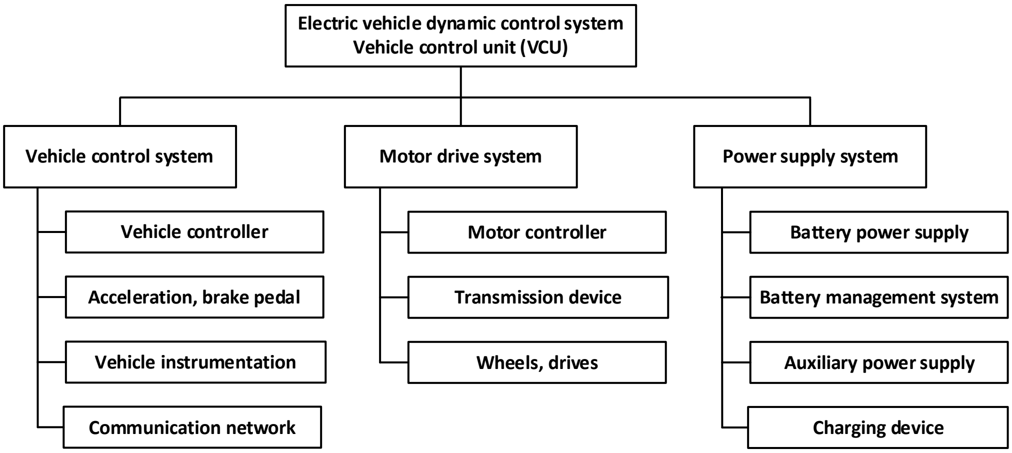

Figure 4.7. *Hierarchical structure of EV dynamic control system*

Figure 4.8 depicts the EV control system consisting of a vehicle controller, motor and motor controller, battery, battery management system (BMS), fault diagnosis management unit, gearbox, auxiliary system, and other components.

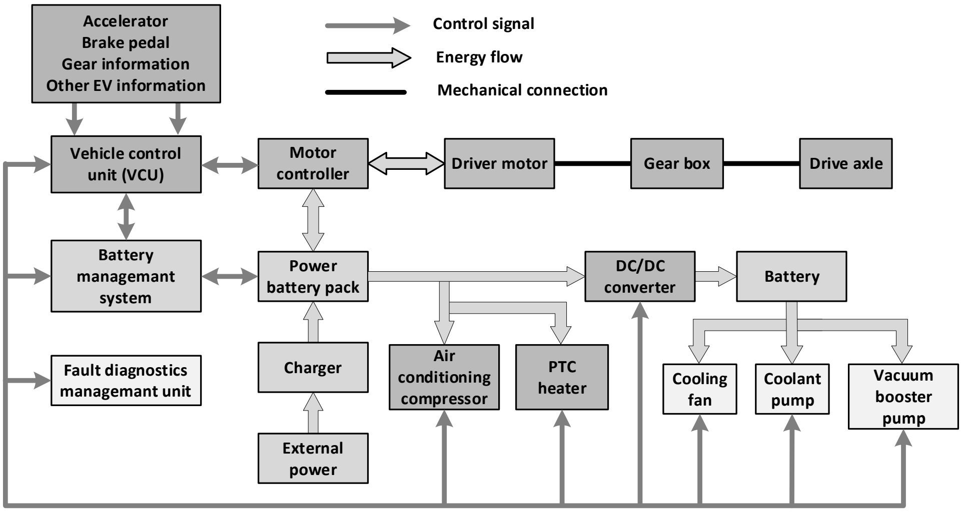

Figure 4.8. *EV control system*

The auxiliary system includes the steering motor and its controller, air conditioning motor and its controller, braking system, DC-DC converters, etc. The battery is the power source of the whole vehicle and provides power for all the equipment. To coordinate the operation and status of each module, the vehicle controller relates to other control units by the CAN (Controller Area Network) protocol. The driver achieves overall control of the vehicle through the EV control system. The driver sends the operation information (accelerator pedal, brake pedal, gear information, etc.) to VCU based on which the driver's actions are predicted and the corresponding operation is determined. According to the control strategy, VCU sends control commands to the motor controller and battery management system. In addition, the required motor output torque and other parameters are calculated to coordinate the movement of various power components and provide normal driving of the EV.

The main VCU functions are:

- Drive torque control: Based on the different degrees of the accelerator pedal, the vehicle controller calculates the whole speed or required torque.
- The braking energy optimization control: The electric motor in EVs acts as a motor or generator depending on the rotation direction. When the brake pedal is used to slow down the vehicle, the motor acts as a generator. According to the accelerator and brake pedal signals, the current vehicle speed, and the battery state of charge, the vehicle controller determines whether regenerative braking is possible at a certain moment. If it is, the vehicle controller issues appropriate instructions to the motor controller to convert the kinetic energy into electric energy and store it in the battery pack. This is the regenerative braking process used to extend the EV driving range.
- Vehicle energy management: To extend the driving range of EV, the vehicle controller optimizes energy usage. When the battery power is low, the vehicle controller sends instructions to auxiliary electrical equipment to improve energy utilization. VCU communicates with the battery management system which makes decisions depending on the information it gathers, and these choices have an impact on the battery's performance and longevity. The battery management system tracks and calculates three important battery metrics: state of charge (SOC), state of health (SOH), and residual capacity.
- Fault diagnosis and processing: The vehicle controller continuously performs real-time monitoring of the vehicle's running status and working conditions. If the malfunction of the electronic control unit is detected, an alarm is activated, and security measures are taken. When the vehicle fault is diagnosed, VCU stores and sends the error code, provides the basis for future vehicle maintenance, classifies faults, and determines which ones are critical for further vehicle moving.
- The vehicle condition monitoring: On-board instrumentation displays the real-time operation state of the vehicle information and sends it to VCU to let drivers know the vehicle state. Vehicle condition monitoring technology is based on CAN bus communication. Intuitive display improves the vehicle interactivity time as the driver accurately grasps the overall vehicle

operation condition to provide convenient conditions. Vehicle condition monitoring technology is based on CAN bus communication.

- CAN maintenance and management of the network: The vehicle controller as the master node of the communication network manages the vehicle network. This network has many master-slave nodes that provide real-time vehicle network state regulation and priority information dynamic allocation. The electronic control unit of the vehicle controller uses primarily CAN bus to send/receive the control instructions. A high-speed CAN bus, with a communication rate of up to 500 kbps, is used for power system components with high real-time requirements (motor controller, BMS, fault diagnostics system, on-board charger). A low-speed CAN bus, with a communication rate of up to 100 kbps, is employed for the acquisition and feedback of control signals with low real-time requirements (air conditioning, combination instrument, cooling system, and vacuum booster pump brake system).

4.4 Challenges, Innovations, and Future Trends

EVs are revolutionizing transportation for a greener future in a time when sustainability is highly valued. They have many advantages, including better air quality and lower greenhouse gas emissions. On the other hand, issues like range anxiety and the requirement for a strong charging infrastructure present difficulty. The major challenges faced by automatic control systems in EVs are:

- Intelligent Integration: It takes sophisticated coordination to achieve the smooth integration of control systems for various EV components, such as power electronics, thermal management, and regenerative braking.
- Energy Management Complexity: Optimal efficiency is challenged by the need to balance energy distribution among multiple components, including the battery, motor, and auxiliary systems.
- Mitigating Range Anxiety: Developing innovative control solutions to address range limitations, considering regenerative braking, acceleration, and energy consumption.
- Standardization and Interoperability: Creating control protocols to improve interoperability among different EV models and components.

Some of the novelties in the domain of automatic control systems in EVs are:

- The process of integrating machine learning algorithms to improve energy efficiency, perform predictive control, and improve overall vehicle performance by utilizing historical data and current conditions.
- The use of advanced optimization techniques to address multiple objectives at the same time, such as energy efficiency, performance, and user comfort, while also optimizing control strategies for different driving scenarios.
- Proactive maintenance can be facilitated and unplanned downtime can be decreased by employing predictive maintenance algorithms that utilize sensor and analytics data to anticipate potential issues.

- Investigating decentralized control architectures, which distribute control responsibilities among the vehicle's subsystems to enhance fault tolerance and overall system dependability.
- The utilization of AI to develop advanced driver assistance systems, such as adaptive cruise control, lane-keeping, and predictive braking, to make driving safer and more intelligent.
- The future of transportation is expected to be influenced significantly by autonomous electric vehicles. Integrating self-driving technology with electric mobility has the potential to create safer, more efficient, and shared transportation systems. These vehicles can optimize routes, minimize traffic congestion, and improve overall energy efficiency.
- Utilizing edge computing technologies to process data locally in real-time can lower latency and increase control systems' responsiveness for crucial tasks like autonomous driving.
- Improved safety and traffic management are made possible by vehicle-to-everything (V2X) connectivity, which integrates V2X communication and allows cars to talk to other cars, infrastructure, pedestrians, and the entire transportation ecosystem.
- Merging cutting-edge Human Machine Interface (HMI) concepts—such as augmented reality displays and natural language processing—to improve driver-EV control system communication.
- Putting strong control measures in place to handle cybersecurity issues with connected EVs is one way to address cybersecurity concerns.
- Innovative control systems for smart charging that optimize charging intervals and grid interactions are known as smart charging solutions. Developments in bidirectional charging control have made it possible for EVs to discharge energy back into the grid in addition to charging from it, enabling vehicle-to-grid (V2G) functionality.
- Implementing control strategies to maximize energy harvesting from sources such as regenerative shock absorbers and solar panels.
- Creating control systems that make wireless charging technologies more convenient and efficient.
- Optimizing temperature control within batteries and other essential components using intelligent algorithms is known as advanced thermal management, which enhances thermal management systems and increases battery efficiency and life.

4.5 Conclusion

In view of the transportation sector's substantial contribution to greenhouse gas emissions worldwide, EVs are becoming more and more popular as a viable alternative. EVs, in contrast to traditional internal combustion engine vehicles, offer a cleaner and more environmentally friendly option by significantly reducing emissions, thanks to their exceptional energy efficiency that further diminishes greenhouse gas emissions. The ongoing development of EVs is heavily dependent on the progress made in automatic control systems. To improve overall efficiency, solve operational issues, and maximize performance, the automotive industry is actively improving EV control systems. Advanced control algorithms are essential for improving driving pleasure, guaranteeing security, and enabling functions like predictive energy management and regenerative braking. Control technology advancements maximize the sustainable potential of EVs by enabling their smooth integration with renewable energy sources. The automotive industry aims to continuously improve the control systems of EVs as it navigates challenges, embraces innovations, and anticipates future trends, paving the way for a more sustainable and efficient transportation future.

Questions

1. What types of electric vehicles exist?
2. Define automatic control systems in the context of electric vehicles.
3. What are the main parts of an EV dynamic control system?
4. How the integration of EV control systems can be achieved?
5. What are the main functions of a vehicle control unit?
6. Identify and elaborate on challenges associated with implementing automatic control systems in electric vehicles.
7. Explain the role of a Battery Management System in an electric vehicle's automatic control.
8. Explore emerging technologies and trends in automatic control systems for electric vehicles.

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5 Internet of Things for Electric Vehicle

5.1 The Term Internet of Things

The term Internet of Things (*IoT*) refers to a network of physical devices that have built-in sensors, software and a network connection that allows them to collect and share data. These devices can also be found under the name "smart objects". Smart objects include simple devices in *smart home* solutions (sockets, thermostats), then portable devices such as smart watches, as well as complex industrial machines and transport systems. In addition to smart buildings, the term "smart cities" is very popular today. Smart cities are based on IoT technologies [1]. IoT devices allow smart objects to communicate with each other in a local network, as well as with other devices when there is Internet access, creating a vast network of interconnected devices. All of them can share data together and perform different tasks independently. This can include managing optimal traffic routes using smart cars, and is particularly applicable to electric vehicles. IoT aims to completely change the auto industry in conjunction with electric vehicles.

There is no precisely defined IoT system architecture, but it can be said that it depends on the purpose of the specific IoT.

The following proposed architecture (Figure 5.1) is adapted to the concept of applying IoT in traffic. Architecture can be displayed through 4 layers:

1. Sensor layer (physical layer),
2. Network device layer (network layer),
3. Data processing layer (AI layer)
4. Application layer (interface layer).

1. Sensors layer

The sensors layer represents the first layer of the IoT architecture. It consists of physical sensors of various purposes that collect data from their surroundings. For this reason, the sensors layer can also be called the physical layer of this architecture. Collected data can be about the charge level of batteries in vehicles, environment humidity and temperature, position of other objects in the surrounding, sound, light, speed of movement and other physical parameters. The devices can be connected to the network through wired or wireless communication network lines.

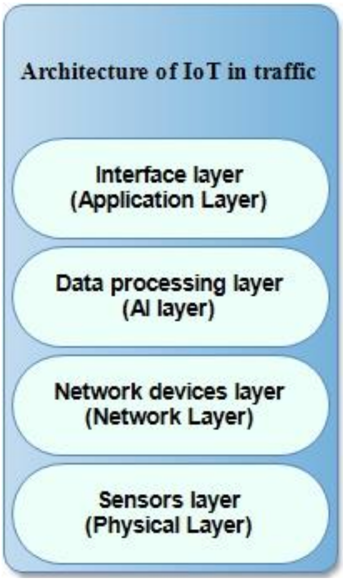

Figure 5.1. *Architecture of IoT in traffic*

2. Network device layer

The layer of network devices or the network layer of the IoT architecture is accountable for ensuring communication between devices in the IoT system on a horizontal level, as well as connecting devices and communicating with a central server for the purpose of further data processing on a vertical level. Some examples of network technologies used in IoT include WiFi, Bluetooth, as well as cellular standards such as 4G and 5G. In addition, the network layer may also include routers that act as intermediaries between IoT systems and the wider Internet. This layer also includes communication protocols. Some of the most important communication protocols used in traffic, which are described in more detail in point 5.3, are:

- Open Charge Point Protocol (OCPP) – intended for communication between the central control system and charging stations.
- ISO 15118 standard – intended for communication between electric vehicles and charging infrastructure.

3. Data processing layer

The IoT architecture's data processing layer (AI layer) encompasses both software and hardware elements, tasked with gathering, examining, and decoding data obtained from IoT devices. This segment handles the reception of raw data, its processing, and ensuring its accessibility for subsequent analysis or actions. Within the data processing layer, various technologies and tools are employed, including data management systems, analytics platforms, and machine learning algorithms. These tools serve to distinguish crucial data from less significant information and facilitate decision-making based on the processed data. with the help of artificial intelligence.

4. Interface layer

The interface layer (Application layer) of the IoT architecture is the highest layer that interacts directly with the end user. It is responsible for providing user interfaces and functionality that allow users to access and control IoT devices. This layer includes various software and applications such as mobile applications, web portals and other user interfaces that are designed to interact with the underlying IoT infrastructure. This may include data visualization tools and other analytical capabilities.

5.2 Integration of IoT and Electric Mobility

In the era of electric mobility, the application of modern technologies has led to the integration of IoT in this area. A key aspect of this integration is the concept of interconnection of all vehicles. As electric vehicles (EVs) become more widespread, communication enabled by the IoT has emerged as a mainstay for the efficiency, reliability and sustainability of the entire electric mobility ecosystem. The integration of IoT into electric vehicles opens up new possibilities for intelligent transportation. Real-time data exchange between electric vehicles and the surrounding infrastructure empowers stakeholders to make informed decisions that optimize traffic performance.

One of the primary benefits of vehicle connectivity is the dynamic interaction between electric vehicles and charging stations. Through IoT-enabled communication, electric vehicles can seamlessly connect to the charging infrastructure, providing real-time updates on battery status, charging progress and estimated completion times (Figure 5.2). This not only offers users greater convenience in managing their charging needs, but also allows charging stations to dynamically adjust their operations based on the grid energy consumption.

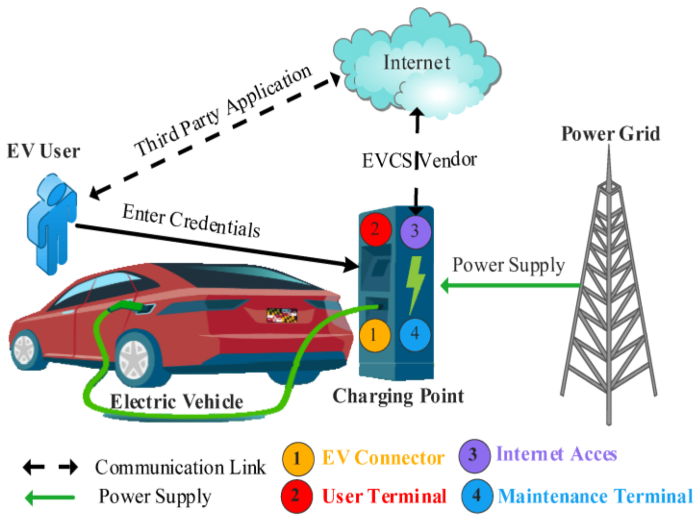

Figure 5.2. *Interconnection of electric vehicle charging and internet services [2]*

IoT sensors embedded in electric vehicles play an important role in collecting data related to battery health and usage patterns. All data collected serves as the basis for predictive maintenance strategies, ensuring that potential problems are identified and proactively addressed. Using the obtained results, electric vehicle manufacturers can extend the life of batteries, reduce maintenance costs and improve the overall reliability of electric vehicles. The concept of vehicle connectivity also extends to the broader ecosystem of smart cities and intelligent transportation systems. With IoT, electric vehicles become integral components of a dynamic network, contributing to the optimization of traffic flow, reduction of congestion and improvement of air quality. This type of connection is not limited to the vehicles themselves, but extends to the infrastructure, creating a relationship that fosters sustainability and efficiency.

Electricity from the grid is transferred to the EV using an Electric Vehicle Charging Station (EVCS). EVCS is a self-contained infrastructure with IoT components running on its own software. The public EVCS is directly connected with the cloud server, which allows users to be shown available chargers in real time, manage billing and monitor consumption statistics. Users of public chargers communicate with the charging management system via the Internet. Users typically schedule charging sessions, set charging speeds, start and end charging, and check the status of their electric vehicles using these services. The energy infrastructure must be functional and ready for the charging process of electric vehicles [2].

As the public EV charger is linked to the power grid and draws power from it, it presents a notable risk to the reliability and safety of the power supply. To ensure the safety and reliability of the ecosystem, it is crucial to secure all data exchanged among the user application, electric vehicle (EV), and Electric Vehicle Charging Station (EVCS). Manufacturers of equipment, state governments, and EVCS operators each have their protocols in place to uphold cybersecurity. Any inconsistencies arising from a lack of protocol standardization can result in significant cybersecurity issues [3].

One of the primary benefits of smart charging infrastructure lies in its ability to be remotely monitored and controlled. This real-time data forms the basis for a sophisticated energy management system, enabling users and service providers to make decisions about how energy is used throughout the life cycle of an electric vehicle. One of the key benefits of energy management through IoT is the implementation of predictive maintenance strategies. By using the insights gained from IoT sensors, problems with the health of the battery or other components can be predicted before they become critical. This proactive approach not only reduces the risk of unexpected breakdowns, but also extends the life of batteries, reducing the overall negative impact of electric vehicles on the environment. Energy management together with IoT encompasses the wider charging infrastructure. Charging stations equipped with IoT sensors can dynamically adjust their operations based on real-time data, optimizing charging schedules to match network conditions and energy availability. This not only improves the overall efficiency of the charging process, but also contributes to grid stability by avoiding over-demand scenarios. Further, IoT facilitates the development of smart algorithms and machine learning models that can analyse massive data sets to identify patterns and trends [4]. These insights can be used to optimize energy consumption, predict when and how an electric vehicle will be used, and adjust the energy management strategy accordingly. This level of intelligence contributes to the creation of a more responsive and adaptive electric mobility ecosystem.

5.3 Integration of IoT Devices

There are different types of integration of IoT devices with traffic infrastructure. All of them are described as communication between vehicles and other entities and are called V2X - Vehicle-to-Everything (V2X). V2X is a communication between a vehicle and any entity that can affect the vehicle. It is a vehicle communication system that includes other more specific types of communication. For the purposes of electric mobility, *Vehicle-to-Grid* (V2G) and *Vehicle-to-Vehicle* (V2V) communication is the most important.

5.3.1 Vehicle-to-Grid (V2G) integration

One of the latest principles in energy management in electric mobility is expressed by vehicle-to-grid (V2G) integration, which is powered by IoT. This innovative concept represents a paradigm shift, transforming electric vehicles from mere energy consumers to active participants in a dynamic and two-way energy exchange system.

V2G integration, enabled by IoT, establishes a communication bridge between electric vehicles and the power grid. This two-way energy flow unlocks additional possibilities, with EVs not only drawing energy from the charging grid, but also having the ability to feed excess energy back into the grid during periods of peak demand on the electrical grid.

At the core of V2G integration is the concept of network flexibility. Electric vehicles, when not in use, can serve as mobile energy storage units. IoT sensors in electric vehicles monitor the state of their batteries and the state of the network grid, allowing intelligent decisions to be made about when to charge, discharge or stay in standby mode. This flexibility allows the power grid to dynamically balance the demand and supply of electricity, improving the overall stability and resilience of the power grid.

V2G integration (Figure 5.3), through IoT, also introduces the concept of demand response. During periods of peak demand, electric vehicles can release stored energy back into the grid, acting as distributed energy resources. This not only relieves pressure on the electricity grid, but also opens up possibilities for grid operators to encourage EV owners to participate in demand response programs, creating a win-win scenario for consumers and energy suppliers.

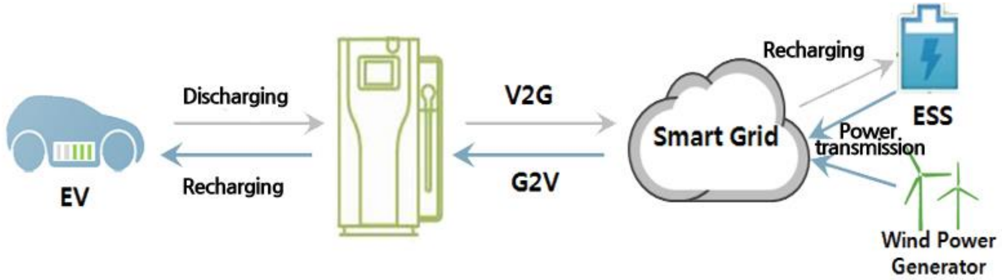

Figure 5.3. *Display of connected systems for the purpose of applying V2G integration [5]*

V2G integration contributes to the efficient use of renewable energy sources. By allowing electric vehicles to store excess energy generated from renewable sources during times of low demand, such as sunny weather or when the wind is blowing, the grid can use this stored energy during periods of peak demand, reducing reliance on non-renewable resources and promoting more sustainable energy efficiency.

V2G IoT systems rely on standardized communication protocols to enable interaction between electric vehicles and the grid. Some of the protocols are the Open Charge Point Protocol (OCPP) for communication with charging stations and the *ISO 15118 standard* for secure communication between electric vehicles and charging infrastructure.

The Open Charge Point Protocol (OCPP) is a widely accepted communication protocol that facilitates the interaction between electric vehicle charging stations and a central management system. OCPP defines a standard set of messages and procedures, ensuring interoperability between different charging station manufacturers and central management software providers.

OCPP uses a client-server architecture, where the charging station (Charge Point) acts as the client and the central management system (CMS) serves as the server. Communication is usually initiated by the charging station.

OCPP messages are exchanged over a web services protocol, typically HTTP or WebSocket. This ensures that communication is platform independent and can be implemented using standard web technologies.

A central management system is responsible for managing multiple charging stations, handling user authentication, monitoring charging sessions, and collecting data for reporting and billing purposes.

ISO 15118 is an international standard that specifies a communication protocol for secure, two-way communication between electric vehicles and charging infrastructure. This standard plays a key role in enabling secure and standardized communication during the charging process.

ISO 15118 covers the entire communication process between EVs and charging infrastructure, including charging initiation, authentication, authorization and transaction management.

The standard operates in the application layer of the OSI model, defining communication protocols for wired (eg. PLC - Power Line Communication) and wireless (eg. WLAN - wireless local area network or mobile network) connections.

ISO 15118 emphasizes security throughout the communication process. It incorporates cryptographic techniques to ensure the confidentiality and integrity of data exchanged between EVs and the charging infrastructure.

One of the key features of ISO 15118 is the *Plug and Charge* concept, which enables automatic and safe communication between an electric vehicle and a charging station. With *Plug and Charge*, EVs can be authenticated and authorized without the need for additional user input.

ISO 15118 relies on the use of digital certificates to establish trust between EVs and charging infrastructure. Digital certificates are exchanged during the communication process to verify the authenticity of both parties.

The standard defines mechanisms for authentication and authorization of EVs to use the charging infrastructure. This includes the exchange of digital signatures and certificates to ensure that both the EV and the charging station can be trusted entities.

5.3.2 Vehicle-to-Vehicle (V2V) integration

Vehicle-to-Vehicle (V2V) communication relies directly on the system of IoT sensor devices embedded in vehicles. The ability to communicate directly between vehicles in traffic is a key feature of this technology. The V2V type of communication is used for the wireless exchange of data on the speed and position of surrounding vehicles.

Direct communication between vehicles (V2V) using Ad Hoc networks is called Vehicular Ad-hoc NETwork (VANET) [6]. VANET networks are conceptually and terminologically directly related to V2V communication. Vehicles can communicate with roadside infrastructure using vehicle-to-infrastructure (V2I) communication. Each vehicle has its own *on-board* unit (OBU) - a vehicle computer with additional functions that enable this type of service. The infrastructure is made up of a network of communication units (RSU) that are placed along the road [7]. Figure 5.4 shows the VANET architecture.

Among the advanced wireless technologies facilitating the connectivity of V2V are:

- *Global Positioning System* (GPS): This technology integrates object location and time data to ensure precise vehicle position tracking. Typically employed for aiding navigation between predefined locations.

- *Inertial Navigation System* (INS): Equipped with embedded IoT sensors, INS tracks and estimates the vehicle's position, direction, and speed.
- *Devices for laser detection* (Laser Illuminated Detection and Ranging - LIDAR) - Devices for laser detection in the vehicle will help the vehicle to recognize its surroundings and the configuration of the terrain. In order to establish an acceptable speed and relative orientation to the environment, accurate distance measurements to objects rely on reliable data. Sensors embedded in traditional road traffic equipment can communicate with embedded laser systems.

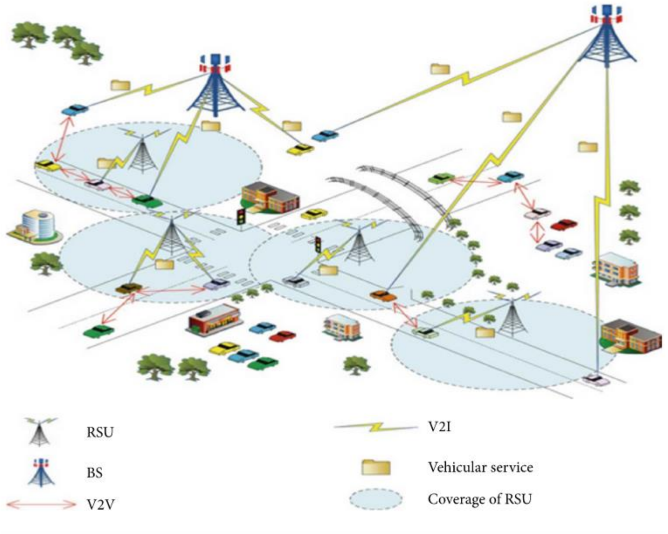

Figure 5.4. *Presentation of the use of the VANET network supported by IoT technology [8]*

New V2V communication technology over vehicle VANET networks will improve road safety by “allowing vehicles to autonomously warn each other of road hazards” [9]. Research has shown that in some cases informing only a part of drivers about the road conditions can have a negative effect and lead to an increase in traffic congestion [10].

Advantages of using V2V technology can be summarized as:

- Improving traffic management,
- Driving assistance,
- Improved fuel efficiency,
- Route optimization,
- Collision prevention.

5.4 Conclusion

IoT devices bring efficiency improvements to the transportation sector, enabling real-time tracking and route optimization. This results in a reduction in fuel consumption and emissions, improves the operational efficiency of transport companies and leads to cost savings.

Transportation safety is enhanced thanks to IoT sensors that collect data on vehicle performance, driver behaviour and road conditions. By analysing this data, potential risks are identified, making it possible to take preventive measures and improve the safety of passengers and goods.

With the increasing connectivity of IoT devices, the transportation sector is becoming vulnerable to cyber threats. Strong cyber security systems are needed to prevent unauthorized access to critical systems.

However, implementing IoT in transportation sector requires significant investment in infrastructure, including sensors, communication networks, and data storage systems. This can be a challenge, especially in developing countries such as the Western Balkan countries.

Questions

1. What is the Internet of Things (IoT)?
2. What layers does the architecture of IoT consist of?
3. Describe the sensor layer.
4. Describe the layer of network devices.
5. Describe the mode of operation of the public charger for electric vehicles - EVCS.
6. Describe Vehicle-to-Grid (V2G) integration.
7. Describe Open Charge Point Protocol (OCPP).
8. Describe the ISO 15118 standard.
9. Describe Vehicle-to-Vehicle (V2V) integration.
10. What are the advantages of using V2V technology?

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6 Motor Drives and Power Converters for Electric Vehicles

6.1 The 'Brushed' DC Electric Motor

6.1.1 Operation of the Basic DC Motor

Electric vehicles use what can seem a bewildering range of different types of electric motors. However, the simplest form of electric motor, at least to understand, is the 'brushed' DC motor. This type of motor is very widely used in applications such as portable tools, toys, electrically operated windows in cars, and small domestic appliances such as hair dryers, even if they are AC mains powered. However, it is also still used as a traction motor, although the other types of motors considered later in this chapter are becoming more common for this application. The brushed DC motor is a good starting point because, as well as being widely used, most of the important issues in electric motor control can be more easily explained with reference to this type of motor.

The classical DC electric motor is shown in Figure 6.1. It is a DC motor, equipped with permanent magnets and brushes.

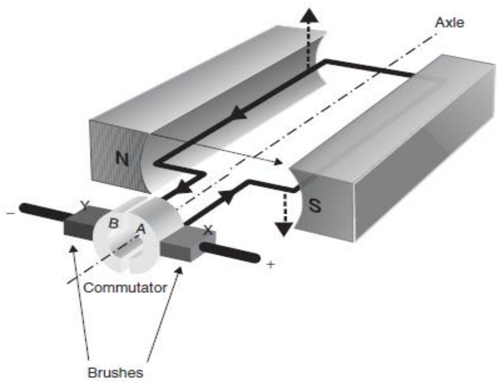

Figure 6.1 *Diagram to explain the operation of the simple permanent magnet DC motor*

This simplified motor has one coil, and the current passing through the wire near the magnet causes a force to be generated in the coil. The current flows through brush X, commutator half ring A, round the coil, and out through the other commutator half ring B and brush Y (XABY). On one side (as shown in the diagram) the force is upwards, and on the other it is downwards, because the current is flowing back towards the brushes and commutator. The two forces cause the coil to turn. The coil turns with the commutator, and once the wires are clear of the magnet the momentum carries it on round until the half rings of the commutator connect with the brushes again. When this happens the current is flowing in the same direction relative to the magnets, and hence the forces are in the same direction, continuing to turn the motor as before. However, the current will now be flowing through brush X, half ring B, round the coil to A and out through Y, so the current will be flowing in the opposite direction through the coil (XBAY).

The commutator action ensures that the current in the coil keeps changing direction, so that the force is in the same direction, even though the coil has moved.

The most important of these are as follows:

- The rotating wire coil, often called the armature, is wound round a piece of iron, so that the magnetic field of the magnets does not have to cross a large air gap, which would weaken the magnetic field.
- More than one coil will be used, so that a current-carrying wire is near the magnets for a higher proportion of the time. This means that the commutator does not consist of two half rings (as in Figure 6.1) but several segments, two segments for each coil.
- Each coil will consist of several wires, so that the torque is increased (more wires, more force).
- More than one pair of magnets may be used, to increase the turning force further.

6.1.2 Torque Speed Characteristics

If a wire in an electric motor has a length *l metres*, carries a current *I amperes* and is in a magnetic field of strength *B webers per square metre*, then the force on the wire is

$$F = B \cdot I \cdot l \quad (6.1)$$

If the radius of the coil is *r* and the armature consists of *n* turns, then the motor torque *T* is given by the equation

$$T = 2 \cdot n \cdot r \cdot B \cdot I \cdot l \quad (6.2)$$

The term $2{\cdot}B{\cdot}l{\cdot}r$ can be replaced by Φ, the total flux passing through the coil. This gives

$$T = n \cdot \Phi \cdot I \quad (6.3)$$

However, this is the peak torque, when the coil is fully in the flux, which is perfectly radial. In practice this will not always be so. Also, it does not take into account the fact that there may be more than one pair of magnetic poles, as in Figure 6.2. So, we use a constant K_m, known as the motor constant, to connect the average torque with the current and the magnetic flux. The value of K_m clearly depends on the number of turns in each coil, but also on the number of pole pairs and other aspects of motor design. Thus we have

$$T = K_m \cdot \Phi \cdot I \tag{6.4}$$

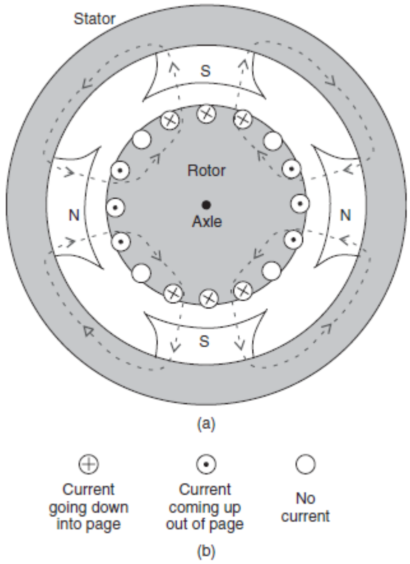

Figure 6.2 *(a) Cross-section through a four-pole DC motor. The dashed lines show the magnetic flux. The motor torque is clockwise. (b) Shows the convention used to indicate the direction of current flow in wires drawn in cross-section.*

We thus see that the motor torque is directly proportional to the rotor (also called armature) current *I*. However, what controls this current? Clearly it depends on the supply voltage to the motor, E_S. It will also depend on the electrical resistance of the armature coil R_a. But that is not all. As the motor turns, the armature will be moving in a magnetic field. This means it will be working as a generator or dynamo. If we consider the basic machine of Figure 6.1, and consider one side of the coil, the voltage generated is expressed by the basic equation

$$Eb = B \cdot l \cdot v \tag{6.5}$$

But as there are *n* turns, we have

$$Eb = 2 \cdot n \cdot r \cdot B \cdot l \cdot \omega \tag{6.6}$$

This equation should be compared with Equation (6.2). By similar reasoning we simplify it to an equation like Equation (6.4). Since it is the same motor, the constant K_m can be used again, and it obviously has the same value. The equation gives the voltage or 'back EMF' generated by the dynamo effect of the motor as it turns:

$$Eb = K_m \cdot \Phi \cdot \omega \tag{6.7}$$

$$T = \frac{K_m \cdot \Phi \cdot E_S}{R_a} - \frac{(K_m \cdot \Phi)^2}{R_a} \cdot \omega \tag{6.8}$$

This important equation shows that the torque from this type of motor has a maximum value at zero speed, when stalled, and it then falls steadily with increasing speed. In this analysis we have ignored the losses in the form of torque needed to overcome friction in bearings, and at the commutator, and windage losses. This torque is generally assumed to be constant, which means the general form of Equation (6.8) still holds true, and gives the characteristic graph of Figure 6.3.

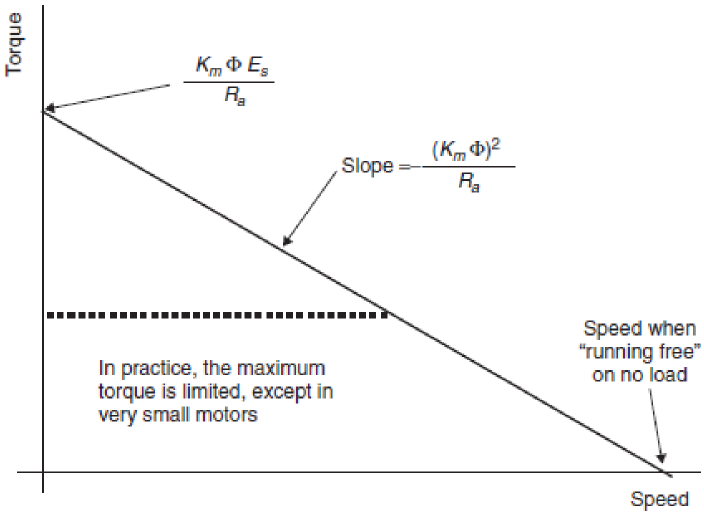

***Figure 6.3** Torque/speed graph for a brushed DC motor*

6.1.3 Controlling the Brushed DC Motor

Figure (6.5) and Equation (6.7) show us that the brushed DC motor can be very easily controlled. If the supply voltage E_S is reduced, then the maximum torque falls in proportion, and the slope of the torque/speed graph is unchanged. In other words, any torque and speed can be achieved below the maximum values. We will see in Section 6.2 that the supply voltage can be controlled simply and efficiently, so this is a good way of controlling this type of motor.

However, reducing the supply voltage is not the only way of controlling this type of motor. In some cases we can also achieve control by changing the magnetic flux Φ. This is possible if coils rather than permanent magnets provide the magnetic field. If the magnetic flux is reduced then the maximum torque falls, but the slope of the torque/speed graph becomes flatter. Figure 6.5 illustrates this.

Thus the motor can be made to work at a wide range of torque and speed. This method is sometimes better than simply using voltage control, especially at high-speed/low-torque operation, which is quite common in electric vehicles cruising near their maximum speed. The reason for this is that the iron losses to be discussed in Section 6.1.5 below, and which are associated with high speeds and strong magnetic fields, can be substantially reduced.

So, the brushed DC motor is very flexible as to control method, especially if the magnetic flux Φ can be varied. This leads us to the next section, where the provision of the magnetic flux is described.

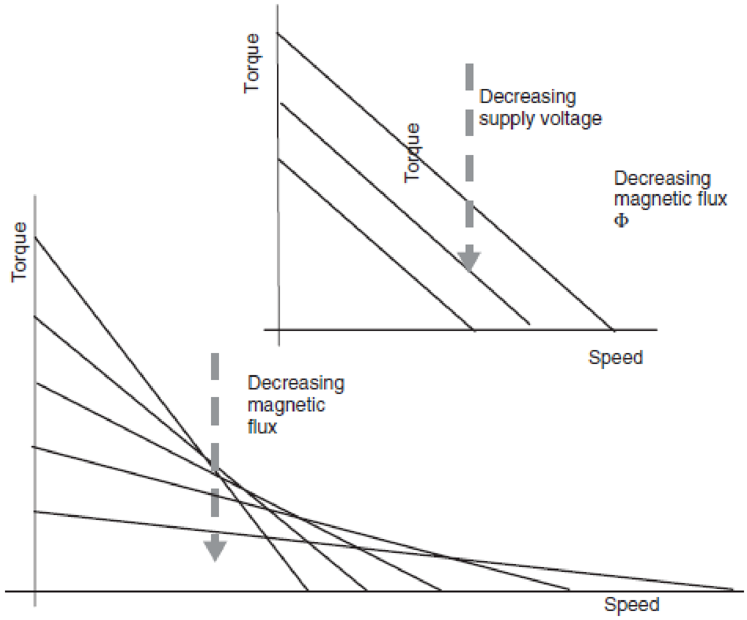

Figure 6.5 *How changing the supply voltage and the magnetic field strength affects the torque/speed characteristic of the DC motor.*

6.1.4 Magnetic Field Generation for DC Motors

In Figures 6.1 and 6.2 the magnetic field needed to make the motor turn is provided by permanent magnets. However, this is not the only way this can be done. It is possible to use coils, through which a current is passed, to produce the magnetic field. These *field windings* are placed in the stator of the electric motor.

An advantage of using electromagnets to provide the magnetic field is that the magnetic field strength Φ can be changed, by changing the current. A further advantage is that it is a cheaper way of producing a strong magnetic field, though this is becoming less and less of a factor as the production of permanent magnets improves. The main disadvantage is that the field windings consume electric current and generate heat, thus it seems that the motor is almost bound to be less efficient. In practice the extra control of magnetic field can often result in more efficient operation of the motor, as the iron losses to be discussed in the next section can be reduced. The result is that brushed DC motors with field windings are still often used in electric vehicles.

There are three classical types of brushed DC motor with field windings, as shown in Figure 6.6. However, only one need concern us here. The behaviour of the 'series' and 'shunt' motors is considered in books on basic electrical engineering. However, they do allow the control of speed and torque that is required in an electric vehicle; the only serious contender is the 'separately excited' motor, as in Figure 6.6c.

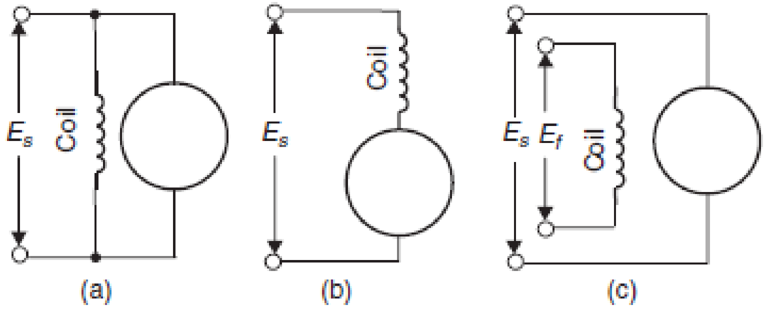

Figure 6.6 *(a– c) Three standard methods of supplying current to a coil providing the magnetic field for brushed DC motors.*

6.1.5 DC Motor Efficiency

The major sources of loss in the brushed DC electric motor are the same as for all types of electric motor, and can be divided into four main types.

Firstly, there are the *copper losses*. These are caused by the electrical resistance of the wires (and brushes) of the motor. This causes heating, and some of the electrical energy supplied is turned into heat energy rather than electrical work. The heating effect of an electric current is proportional to the square of the current:

$$T = I^2 \cdot R \tag{6.9}$$

However, we know from Equations (6.3) and (6.4) that the current is proportional to the torque T provided by the motor, so we can say that

$$P_c = k_c \cdot T^2 \tag{6.10}$$

where P_C is the Copper losses, k_C is a constant depending on the resistance of the brushes and the coil, and also the magnetic flux Φ. These copper losses are probably the most straightforward to understand and, especially in smaller motors, they are the largest cause of inefficiency.

The second major source of losses is the *iron losses*, because they are caused by magnetic effects in the iron of the motor, particularly in the rotor. There are two main causes of these iron losses, but to understand both it must be understood that the magnetic field in the rotor is continually changing.

The third category of loss is that due to *friction and windage*. There will of course be a friction torque in the bearings and brushes of the motor. The rotor will also have a wind resistance, which might be quite large if a fan is fitted to the rotor for cooling. The friction force will normally be more or less constant. However, the wind resistance force will increase with the square of the speed. To get at the power associated with these forces, we must multiply by the speed, as

$$\text{Power} = \text{torque} \times \text{angular speed} \quad (6.11)$$

The power involved in these forces will then be

$$P_f = T_f \cdot \omega \text{ and } P_\omega = k_\omega \cdot \omega^3 \quad (6.12)$$

where P_f – friction power, T_f - friction torque and P_w - windage power, k_W is a constant depending mainly on the size and shape of the rotor, and whether or not a cooling fan is fitted.

$$Total\ losses = k_c \cdot T^3 + k_i \cdot \omega + k_w \cdot \omega^3 + C \quad (6.13)$$

6.1.6 Electric Motors as Brakes

The fact that an electric motor can be used to convert kinetic energy back into electrical energy is an important feature of electric vehicles. How this works is easiest to understand in the case of the classical DC motor with brushes, but the broad principles apply to all motor types.

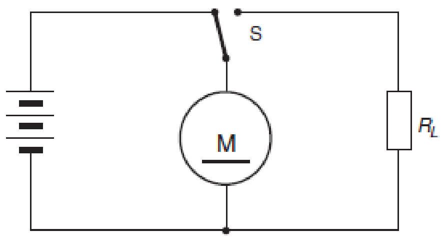

Figure 6.7 *Motor circuit with resistor to be used for dynamic braking*

Consider Figure 6.7. A DC motor is connected to a battery of negligible internal resistance, and voltage E_S. It reaches a steady state, providing a torque T at a speed ω. These variables will be connected by Equation (6.7). Suppose the switch S is now moved over to the right. The motor will continue to move at the same angular speed. This will cause a voltage to be generated, as given by Equation (6.6). This voltage will be applied to the resistor R_L, as in Figure 6.7, with the current further limited by the resistance of the rotor coil (armature).

The result is that the current will be given by the formula

$$I = \frac{K_m \cdot \Phi \cdot \omega}{R_a + R_L} \quad (6.14)$$

This current will be flowing *out* of the motor, and will result in a negative torque. The value of this torque will still be given by the torque equation produced earlier as Equation (6.4). So, the negative torque, which will slow the motor down, will be given by the equation

$$T = \frac{(K_m \cdot \Phi)^2 \cdot \omega}{R_a + R_L} \quad (6.15)$$

We thus have a negative torque, whose value can be controlled by changing the resistance R_L. The value of this torque declines as the speed ω decreases. So, if R_L is constant we might expect the speed to decline in an exponential way to zero.

This way of slowing down an electric motor, using a resistor, is known as 'dynamic braking'. Note that all the kinetic energy of the motor (and the vehicle connected to it) is ultimately converted into heat, just like normal friction brakes. However, we do have control of where the heat is produced, which can be useful. We also have the potential of an elegant method of controlling the braking torque. Nevertheless, the advance over normal friction brakes is not very great, and it would be much better if the electrical energy produced by the motor could be stored in a battery or capacitor.

If the resistor of Figure 6.7 were replaced by a battery, then we would have a system known as 'regenerative braking'. However, the simple connection of a battery to the motor is not practical. Suppose the voltage of the battery is V_b, and the motor is turning at speed ω; then the current that will flow out of the motor will be given by the equation

$$I = \frac{V}{R} = \frac{K_m \cdot \Phi \cdot \omega - V_b}{R_a} \quad (6.16)$$

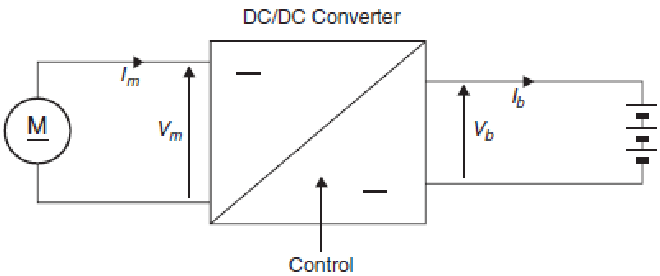

Figure 6.8 *Regenerative braking of a DC motor.*

The slowing down torque will be proportional to this current. Once the value of ω reaches the value where the voltage generated the motor (=$K_m \Phi \omega$) reaches the battery voltage, then there will be no more braking effect. Unless the battery voltage is very low, then this will happen quite soon. If the battery voltage is low, then it will be difficult to use the energy stored in it, and the braking effect might well be far too strong at high speeds, with the current given by Equation (6.16) being impracticably large.

A solution lies in a voltage converter circuit as in Figure 6.8. The converter unit, known as a 'DC/DC converter', draws a current from the motor I_m, which will occur at a voltage V_m. This voltage V_m will change with motor (and hence vehicle) speed. The current I_m will change with the desired braking torque. The

DC/DC converter will take this electrical power (=V_m x I_m) and put it out at an increased voltage (and reduced current) so that it matches the rechargeable battery or capacitor that is storing the energy. The battery might well be the same battery that provided the electricity to make the motor go in the first place. The key point is that the motor voltage might be considerably *lower* than the battery voltage, but it can still be providing charge to the battery.

6.2 DC Regulation and Voltage Conversion

6.2.1 Switching Devices

The voltage from all sources of electrical power varies with time, temperature and many other factors, especially current. Fuel cells, for example, are particularly badly regulated, and it will always be necessary to control the output voltage so that it only varies between set boundaries. Battery voltage is actually quite well regulated, but frequently we will want to change the voltage, to a lower or higher value, usually to control the speed of a motor. We saw in the previous section that if an electric motor is to be used in regenerative braking we need to be able to boost the voltage (and reduce the current) in a continuously variable way.

Most electronic and electrical equipment requires a fairly constant voltage. This can be achieved by dropping the voltage down to a fixed value below the operating range of the fuel cell or battery, or boosting it up to a fixed value. In other cases we want to produce a variable voltage (e.g. for a motor) from the more or less fixed voltage of a battery. Whatever change is required, it is done using ‘switching’ or ‘chopping’ circuits, which are described below. These circuits, as well as the inverters and motor controllers to be described in later sections, use *electronic switches*.

The metal oxide semiconductor field effect transistor (MOSFET) is turned on by applying a voltage, usually between 5 and 10 V, to the gate. When ‘on’ the resistance between the drain (d) and source (s) is very low. The power required to ensure a very low resistance is small, as the current into the gate is low. However, the gate does have a considerable capacitance, so special drive circuits are usually used. The current path behaves like a resistor, whose ON value is R_{DSON}. The value of R_{DSON} for a MOSFET used in voltage regulation circuits can be as low as about 0.01Ω. However, such low values are only possible with devices that can switch low voltages, in the region of 50 V.

The insulated gate bipolar transistor (IGBT) is essentially an integrated circuit combining a conventional bipolar transistor and a MOSFET, and has the advantages of both. The IGBT requires a fairly low voltage, with negligible current at the gate to turn on. The main current flow is from the collector to the emitter, and this path has the characteristics of a p–n junction. This means that the voltage does not rise much above 0.6V at all currents within the rating of the device. This makes it the preferred choice for systems where the current is greater than about 50 A. IGBTs can also be made to withstand higher voltages.

The thyristor has been the electronic switch most commonly used in power electronics. Unlike the MOSFET and IGBT, the thyristor can only be used as an electronic switch – it has no other applications. The transition from the blocking to the conducting state is triggered by a pulse of current into the gate. The device then remains in the conducting state until the current flowing through it falls to zero. This feature makes it particularly useful in circuits for rectifying AC, where it is still widely used. However, various variants of the thyristor, particularly the gate turn-off (GTO) thyristor, can be switched off, even while a current is flowing, by the application of a negative current pulse to the gate.

6.2.2 Step-Down or 'Buck' Regulators

The 'step-down' or 'buck' switching regulator (or chopper) is shown in Figure 6.9. The essential components are an electronic switch with an associated drive circuit, a diode and an inductor. In Figure 6.9a the switch is on, and the current flows through the inductor and the load. The inductor produces a back EMF, making the current gradually rise. The switch is then turned off. The stored energy in the inductor keeps the current flowing through the load, using the diode, as in Figure 6.9b. The voltage across the load can be further smoothed using capacitors if needed.

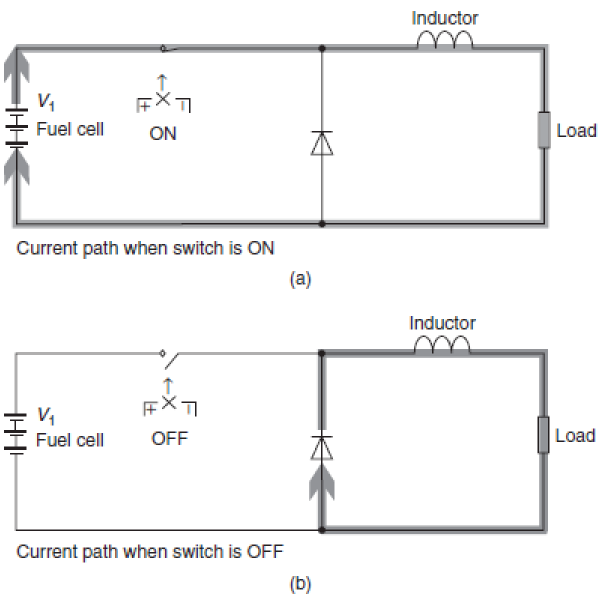

Figure 6.9 *Circuit diagram showing the operation of a switch-mode step-down regulator*

If V_1 is the supply voltage, and the 'on' and 'off' times for the electronic switch are t_{ON} and t_{OFF}, then it can be shown that the output voltage V_2 is given by

$$V_2 = \frac{t_{ON}}{t_{ON}+t_{OFF}} \cdot V_1 \quad (6.17)$$

6.2.3 Step-Up or 'Boost' Switching Regulator

It is often desirable to step-up or boost a DC voltage, regenerative braking being just one example. This can also be done quite simply and efficiently using switching circuits. Voltage boost circuits are also needed for regenerative braking. The circuit of Figure 6.10 is the basis usually used. We start our explanation by assuming some charge is in the capacitor. In Figure 6.15a the switch is on, and an electric current is building up in the inductor. The load is supplied by the capacitor discharging. The diode prevents the charge from the capacitor flowing back through the switch. In Figure 6.10b the switch is off. The inductor voltage rises sharply, because the current is falling. As soon as the voltage rises above that of the capacitor (plus about 0.6V for the diode) the current will flow through the diode, and charge up the capacitor and flow through the load. This will continue as long as there is still energy in the inductor. The switch is then closed again, as in Figure 6.10a, and the inductor re-energised while the capacitor supplies the load. Higher voltages are achieved by having the switch off for a short time. It can be shown that for an ideal convertor with no losses

$$V_2 = \frac{t_{ON}+t_{OFF}}{t_{OFF}} \cdot V_1 \tag{6.18}$$

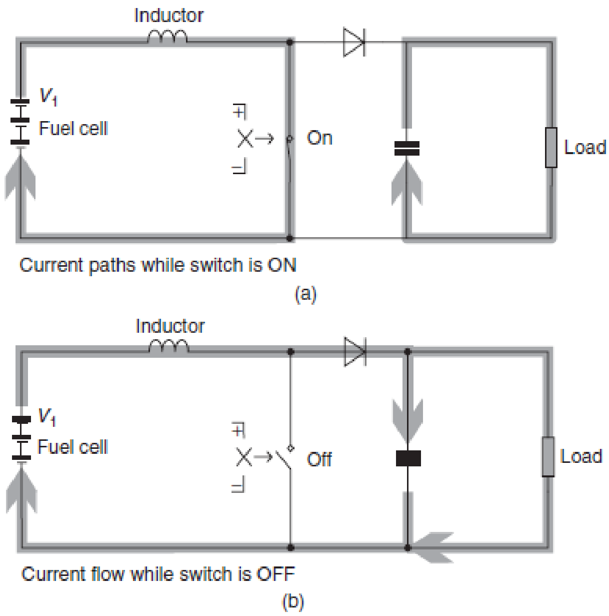

Figure 6.10 *Circuit diagram to show the operation of a switch-mode boost regulator.*

These step-up and step-down switcher or chopper circuits are called DC/DC converters.

6.2.4 Single-Phase Inverters

The circuits of the previous two sections are the basis of controlling the classical DC motor. However, the motors to be considered in the next section require alternating current. The circuit that produces AC from DC sources such as batteries and fuel cells is known as an inverter. We will begin with the single-phase inverter.

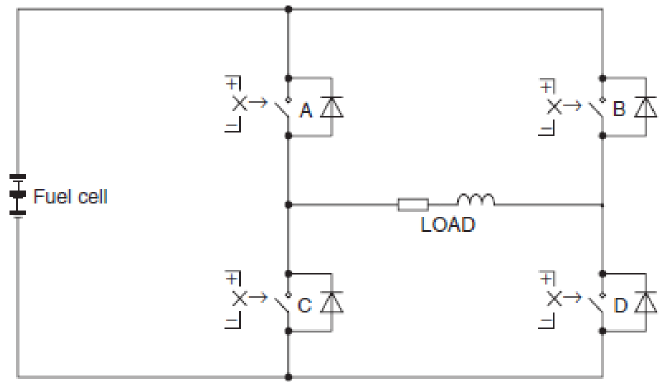

Figure 6.11 *H-bridge inverter circuit for producing single-phase alternating current*

The basic operation of the inverter is quite simple. First switches A and D are turned on, and a current flows to the right through the load. These two switches are then turned off – at this point we see the need for the diodes. The load will probably have some inductance, and so the current will not be able to stop immediately, but will continue to flow in the same direction, through the diodes across switches B and C, back into the supply. The switches B and C are then turned on, and a current flows in the opposite direction, to the left. When these switches turn off, the current 'freewheels' through the diodes in parallel with switches A and D.

The difference between a pure sine wave and any other waveform is expressed using the idea of 'harmonics'. These are sinusoidal oscillations of voltage or current whose frequency, *fv*, is a whole-number multiple of the fundamental oscillation frequency. It can be shown that *any* periodic waveform of *any* shape can be represented by the addition of harmonics to a fundamental sine wave. The process of finding these harmonics is known as Fourier analysis. For example, it can be shown that a square wave of frequency *f* can be expressed by the equation

$$v = sin(\omega t) - \frac{1}{3} sin(3\omega t) + \frac{1}{5} sin(5\omega t) - \frac{1}{7} sin(7\omega t) + \frac{1}{9} sin(9\omega t) \ldots$$

So, the difference between a voltage or current waveform and a pure sine wave may be expressed in terms of higher frequency harmonics imposed on the fundamental frequency.

6.2.5 Three Phase

Most large motors, of the type used in electric vehicles, have three sets of coils rather than just one. For these systems – as well as for regular mains systems – a ‘three-phase’ AC supply is needed.

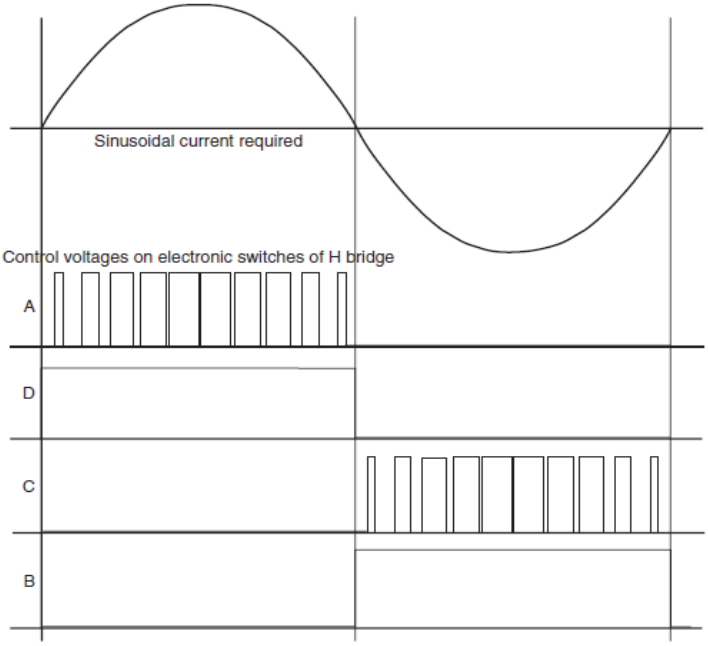

Figure 6.12 *Pulse width modulation switching sequence for producing an approximately sinusoidal alternating current from the circuit of Figure 6.17*

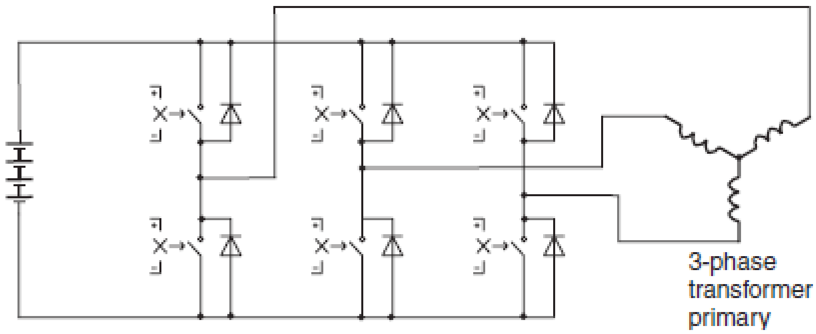

Figure 6.13 *Three-phase inverter circuit*

Such a supply is only a little more complicated than single phase. The basic circuit is shown in Figure 6.13. Six switches, with freewheeling diodes, are connected to the three phase transformer on the right. The way in which these switches are used to generate three similar but out-of-phase voltages is shown in Figure 6.14. Each cycle can be divided into six steps. In practice the very simple switching sequence of Figure 6.14 is modified using pulse width modulation.

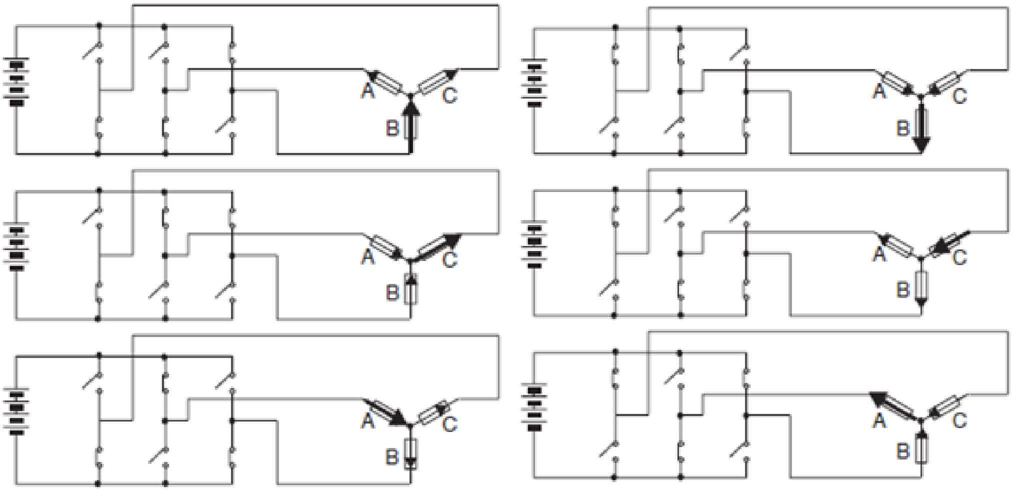

Figure 6.14 *Switching pattern to generate three-phase alternating current*

6.3 Brushless Electric Motors

In Section 6.1 we described the classical DC electric motor. The brushes of this motor are an obvious problem – there will be friction between the brushes and the commutator, and both will gradually wear away. However, a more serious problem with this type of motor was raised in Section 6.1.5. This is that the heat associated with the loses is generated in the middle of the motor, in the rotor. If the motor could be so arranged that the heat was generated in the outer stator that would allow the heat to be removed much more easily, and allow smaller motors. If the brushes could be disposed of as well, then that would be a bonus. In this section we describe three types of motors that are used as traction motors in vehicles that fulfil these requirements.

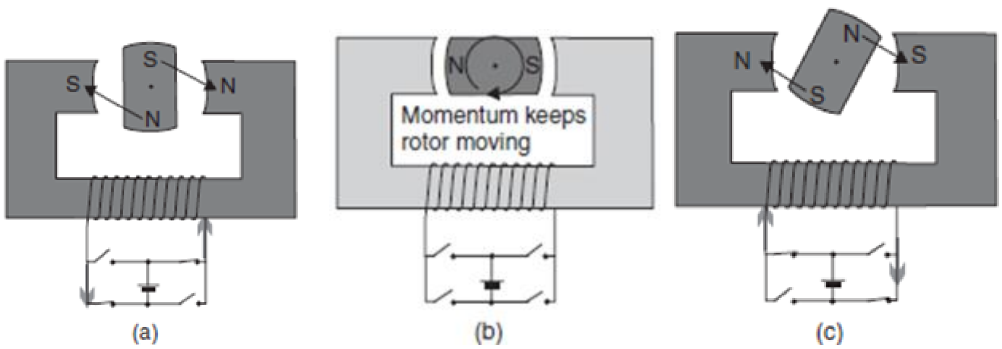

Figure 6.15 *(a–c) Diagram showing the basis of operation of the brushless DC motor*

The brushless DC (BLDC) motor is really an AC motor! The current through it alternates, as we will see. It is called a 'brushless DC motor' because the alternating current *must* be variable frequency and so derived from a DC supply, and because its speed/torque characteristics are very similar to the ordinary 'with brushes' DC motor. As a result of 'BLDC' being not an entirely satisfactory name, it is also known as a 'self-synchronous AC motor', a 'variable frequency synchronous motor', a 'permanent magnet synchronous motor' and an 'electronically commutated motor' (ECM).

The basis of operation of the BLDC motor is shown in Figure 6.15. The rotor consists of a permanent magnet. In Figure 6.15a the current flows in the direction that magnetises the stator so that the rotor is turned clockwise, as shown. In Figure 6.15b the rotor passes between the poles of the stator, and the stator current is switched off. Momentum carries the rotor on, and in Figure 6.15c the stator coil is re-energised, but the current and hence the magnetic field are reversed. So the rotor is pulled on round in a clockwise direction. The process continues, with the current in the stator coil alternating.

Obviously, the switching of the current must be synchronised with the position of the rotor. This is done using sensors. These are often Hall Effect sensors that use the magnetism of the rotor to sense its position, but optical sensors are also used.

A feature of these BLDC motors is that the torque will reduce as the speed increases. The rotating magnet will generate a back EMF in the coil which it is approaching. This back EMF will be proportional to the speed of rotation and will reduce the current flowing in the coil. The reduced current will reduce the magnetic field strength, and hence the torque. Eventually the size of the induced back EMF will equal the supply voltage, and at this point the maximum speed has been reached. This behaviour is exactly the same as with the brushed DC motor of Section 6.1. We should also notice that this type of motor can very simply be used as a generator of electricity, and for regenerative or dynamic braking.

Questions

1. Describe the operation of a DC Motor.
2. How can we control the speed of a Brushed DC Motor?
3. Which are the major sources of loss in a brushed DC motor?
4. Describe the operational work of Electric Motors as Brakes.
5. Describe 3 electronic components that are mostly used as switching devices on power converters.
6. Describe the principal work of 'Buck' and 'Boost' Regulators.
7. Describe the principal work of Single-Phase Inverters.

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7 High Power Density Electrical Machines for Electric Vehicles

7.1 Electrical Machines for Electric Vehicles

High power density electrical machines for electric vehicles can be categorized into several types based on their design. Each of these machine types has its own unique characteristics and design considerations, and the selection of a specific type depends on factors such as performance requirements, efficiency targets, packaging constraints, and cost considerations in the context of electric vehicle applications.

The efficiency and performance of electric machines significantly affect the energy consumption, acceleration, high-speed performance, and driving comfort of the electrified powertrains. The electric traction motors have stringent operational requirements concerning torque-speed characteristics. It is crucial to have the ability to operate at specific operating points based on the application.

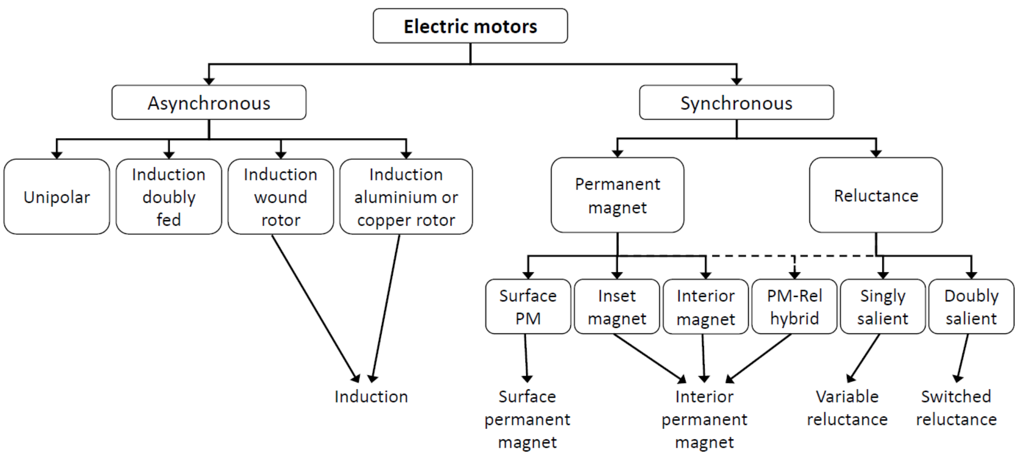

Figure 7.1 *Classification of electric motors [1][2][3]*

The use of the right electric machines is inevitable for the effective operation of electrified transportation. There are several types of electric machines used in powertrains, and it depends on the specifications, performance, and application at hand.

7.2 Permanent Magnet Synchronous Machines (PMSM)

Permanent Magnet Synchronous Motors (PMSM) are a type of electric motor that uses permanent magnets to create the magnetic field within the motor. These motors are widely used in various applications, including electric vehicles, industrial machinery and renewable energy systems. They offer high efficiency, high power density, and precise speed and torque control. PMSMs are commonly used in electric vehicle applications due to their compact size and excellent performance. They offer high torque density and efficiency, making them commonly used in electric vehicles [4][5][6].

The PM motors are relatively easy to control and exhibit excellent performance, in terms of maximum torque per ampere control and optimal extended speed operation. Different types of PM machines are proposed according to the position of PMs in the rotor and can be classified as surface or interior mounted magnets.

PMSMs have efficiency benefits over conventional induction motors due to their high-power density obtained from magnetic flux between the stator and rotor. This means they require less current than comparable induction motors in order to achieve the same output of torque or speed.

The rotor design also has advantages when it comes to torque control, as permanent magnet synchronous motors can easily be adjusted with variable frequency drives.

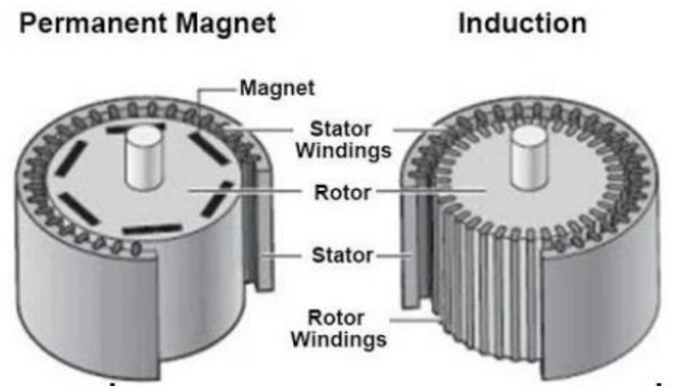

Figure 7.2 *Induction motor and Permanent magnet SM - Same stator and different rotor design [7]*

PMSMs are known for their high efficiency, which means they can convert a high percentage of electrical input power into mechanical output power. This contributes to energy savings and reduced operating costs. PMSMs have a high-power density, meaning they can deliver a relatively high amount of power in a compact and lightweight design. This makes them suitable for applications where space and weight constraints are important, such as electric vehicles. PMSMs offer precise control over speed and torque, making them well-suited for applications requiring accurate and responsive motor performance. The absence of brushes in PMSMs reduces the need for maintenance compared to brushed motors, contributing to lower operating costs and increased reliability. PMSMs can be used in regenerative braking systems, allowing them to recover energy during braking and improve overall system efficiency. Permanent Magnet Synchronous Motors are valued for their high efficiency, compact design, precise control capabilities, and suitability for a wide range of applications across various industries.

Surface permanent magnet motors (SPM) are a type of electric motor that is commonly used in various applications, including electric vehicles, industrial machinery, and appliances. These motors utilize permanent magnets on the surface of the rotor to generate the magnetic field necessary for motion. SPM motors are employed in a wide range of applications, including electric and hybrid vehicles, elevators, household appliances, HVAC systems, and industrial machinery [8].

SPM motors feature a rotor with embedded permanent magnets on the surface, which interact with the stator's electromagnetic field to produce motion. This design eliminates the need for a separate field winding on the rotor, simplifying the motor construction. SPM motors are known for their high efficiency, as the use of permanent magnets allows for a strong magnetic field without the energy losses associated with traditional rotor windings. This leads to improved overall motor efficiency and reduced energy consumption. The use of permanent magnets in SPM motors enables high power density, meaning that these motors can deliver strong mechanical output within a compact and lightweight form factor. This makes them well-suited for applications where space and weight constraints are important.

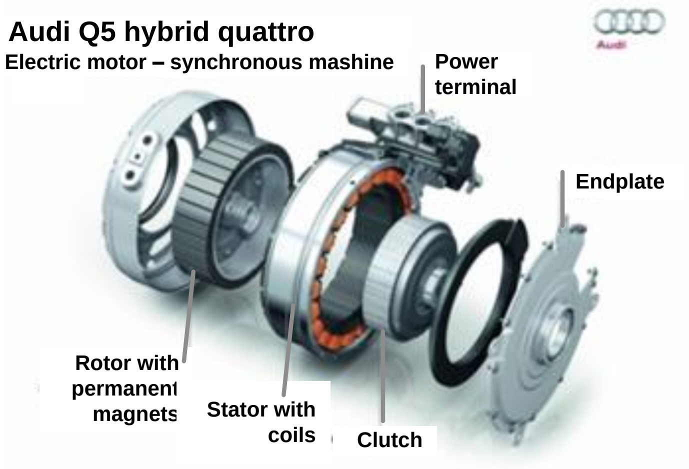

Figure 7.3 The Audi Q5 hybrid quattro's with surface permanent magnet motors (SPM) [9]

SPM motors can be designed for variable speed control, making them ideal for applications requiring precise speed and torque regulation. This flexibility in speed control contributes to their widespread use in electric vehicles and industrial automation systems. SPM motors are often utilized in regenerative braking systems, where the motor operates as a generator during braking, converting kinetic energy into electrical energy for storage or immediate reuse.

Proper thermal management is important for SPM motors, as excessive heat can degrade the performance of the permanent magnets. Effective cooling methods are employed to maintain optimal operating temperatures. The choice of permanent magnet material, such as neodymium or ferrite, influences the motor's performance characteristics, cost, and environmental impact. SPM motors offer several advantages, including high efficiency, compact design, and precise control capabilities, making them a popular choice for numerous electromechanical systems. Their application in electric vehicles, in particular, contributes to improved energy efficiency and performance in the transportation sector.

Interior Permanent Magnet Machines (IPM) are a subtype of PMSMs where the permanent magnets are located inside the rotor core. These magnets create a strong magnetic field, which interacts with the stator windings to produce mechanical motion. Interior Permanent Magnet Machines are valued for their high efficiency, power density, precise control capabilities, and suitability for a diverse range of applications, making them a preferred choice in many industrial and commercial settings. This configuration allows for improved torque density and efficiency, making IPMs well-suited for electric vehicle propulsion systems with space constraints [10].

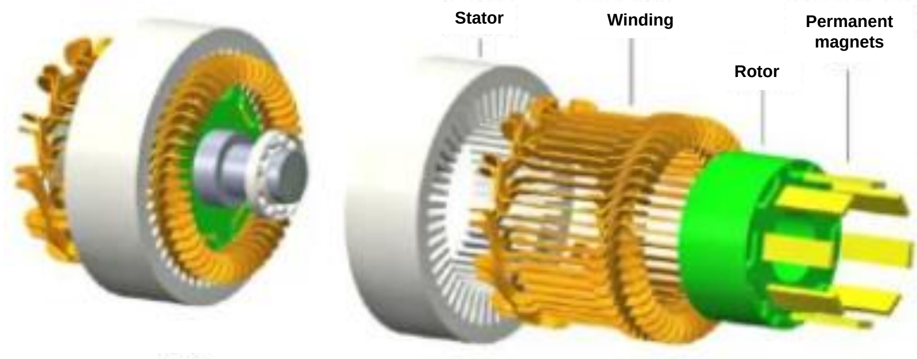

Figure 7.4 *Structure of an interior permanent magnet synchronous motor (IPM)*

IPMs are known for their high energy efficiency, which means they can convert a high percentage of electrical input power into mechanical output power. This efficiency helps reduce energy consumption and operating costs. IPM machines have a high-power density, allowing them to deliver significant power output in a compact and lightweight design. This makes them well-suited for applications where space and weight are important considerations.

IPMs offer precise control over speed and torque, making them suitable for applications that require accurate and responsive motor performance. Similar to other types of electric motors, IPMs can be used in regenerative braking systems, allowing them to recover energy during braking and improve overall system efficiency.

The absence of brushes in IPMs reduces the need for maintenance compared to brushed motors, contributing to lower operating costs and increased reliability.

7.3 Induction Machines

Induction machines (IM), also known as induction motors, are used in a wide range of applications, including electric vehicles (EVs). They are also relatively maintenance-free [3]. IMs are characterized as having a simple and strong structure, low cost, high reliability, small torque ripple, low noise, and maintenance-free. IMs can be easily run at high speed over 15 000 rpm with a wide constant power range [11].

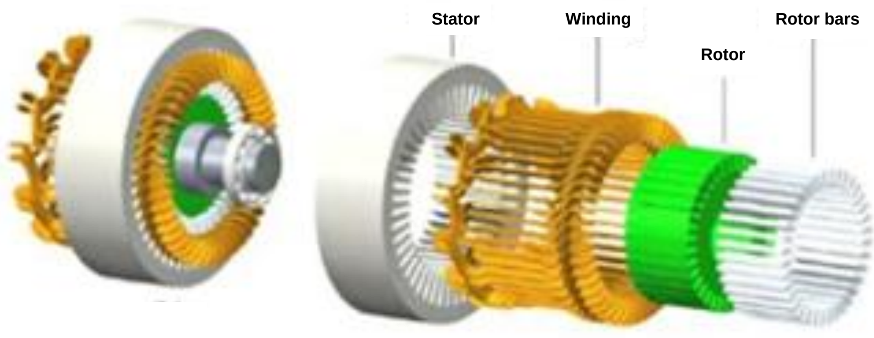

Figure 7.5 Induction motor - typical electric machine type employed for traction applications

Induction machines can be used in *regenerative braking systems*, allowing them to recover energy during braking and improve overall vehicle efficiency. Induction machines feed with power converters can deliver high torque at low speeds, which is beneficial for accelerating heavy vehicles such as EVs from standstill and providing good driving performance. Compared to some other motor types, induction machines can offer a cost-effective solution for EV manufacturers, contributing to the affordability of electric vehicles. With advancements in motor control technology, induction machines can achieve high levels of efficiency and performance, making them a competitive choice for EV propulsion.

In EVs, induction motors have a lot of good points. They are easy to use and durable, and they can work at a wide range of speeds and loads. They also have a high-power density and work well, which makes them good for a wide range of EV uses. However, induction motors in EVs also have some problems. At low speeds and with light loads, they tend to be less efficient, and they can make a lot of electromagnetic noise, which can be a problem in some situations. While induction machines have many advantages, they also have challenges related to control complexity, power factor correction, and speed regulation at high speeds.

The induction motor solution with copper rotor technology is one of the best solutions for driven motor for electrical vehicles. The most successful electrical vehicles currently in the world, has adopted copper rotors for their driven system. Copper rotor motor has higher efficiency, mature control system, higher reliability, lower cost when compared with other solutions [12][13].

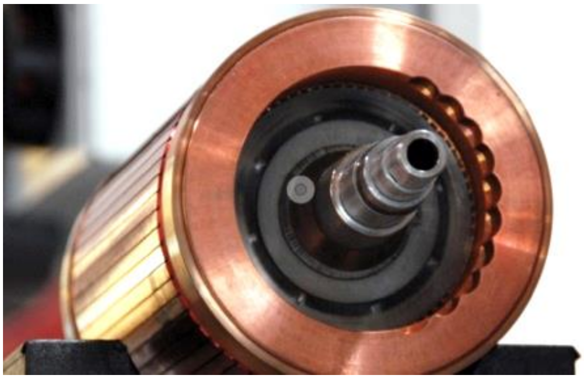

Figure 7.6 *Tesla's electric motor rotor in 2007 [14]*

7.4 Switched Reluctance Machines (SRM)

The *Switched Reluctance Machines (SRMs)* rely on variations in reluctance due to changes in the position of the rotor and stator to generate torque. They are known for their simple construction, fault tolerance, and potential for high efficiency and torque capabilities, making them suitable for high-power electric vehicle propulsion systems [15][16].

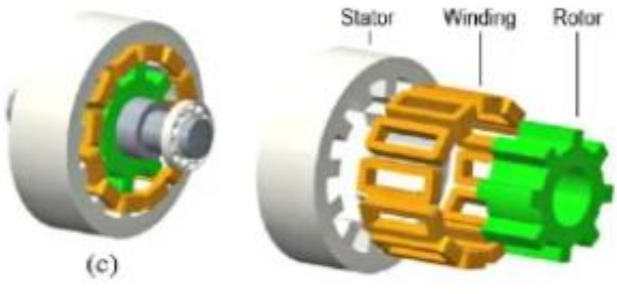

Figure 7.7 *Switched Reluctance Motor (SRM)*

SRM is known to have the simplest, most robust, and lowest cost structure compared to IPMSM and IM. It typically has a salient pole structure made of laminated silicon steel. In this case, the torque production is based on the change of magnetic reluctance. The key disadvantage of conventional SRM is the significant torque ripples and lower power density.

SRMs have a relatively simple construction compared to other types of electric motors, as they do not require permanent magnets or rotor windings. This can make them more cost-effective and easier to manufacture. They operate by capturing the reluctance torque generated in the motor when the rotor aligns with the stator's magnetic field. SRMs can achieve high power density due to their unique construction. SRMs are known for their high torque density, which means they can deliver high torque output relative to their size and weight. This makes them suitable for applications where space and weight are important considerations.

Due to their simple construction and lack of rotor windings or magnets, SRMs are inherently robust and resistant to certain failure modes, making them suitable for applications in harsh environments. SRMs can operate over a wide range of speeds, making them suitable for applications where variable speed control is required.

Despite their advantages, SRMs also have challenges related to control complexity and the need for sophisticated control algorithms to optimize performance, efficiency, and minimize acoustic noise.

Switched Reluctance Machines offer a unique set of advantages such as simplicity, high torque density, robustness, and variable speed operation, making them suitable for various industrial applications including automotive, aerospace, and other industries where their specific characteristics are beneficial.

7.5 Synchronous reluctance motor – (SynRM)

The *Synchronous Reluctance Motor (SynRM)* is a type of electric motor that operates on the principle of reluctance torque. Unlike traditional induction motors, synchronous reluctance motors use a specialized rotor design to generate torque without the need for slip rings or permanent magnets. It features a rotor with salient poles and a stator with windings that produce a rotating magnetic field [17].

The Synchronous Reluctance Motor (SynRM) is becoming of great interest in the recent years and represents a valid alternative for electric and hybrid vehicles due to its simple and rugged construction. The main advantage of the SynRM relies on the absence of the rotor cage losses or PM losses, allowing a continuous torque higher than the torque of an Induction Motor (IM) of the same size. Despite these drawbacks, it is possible to obtain high torque density and high efficiency motors through an optimized rotor design.

Specific power in SynRM is enhanced by increasing the rotor operating speed and the flux-weakening region. Nevertheless, the optimal geometry for motor performances needs to be refined to guarantee the mechanical integrity of the rotor at high speed. The rotor of a synchronous reluctance motor typically features salient poles, which are shaped to optimize the magnetic reluctance. This design aims to create a reluctance torque that drives the rotor to follow the rotating magnetic field produced by the stator.

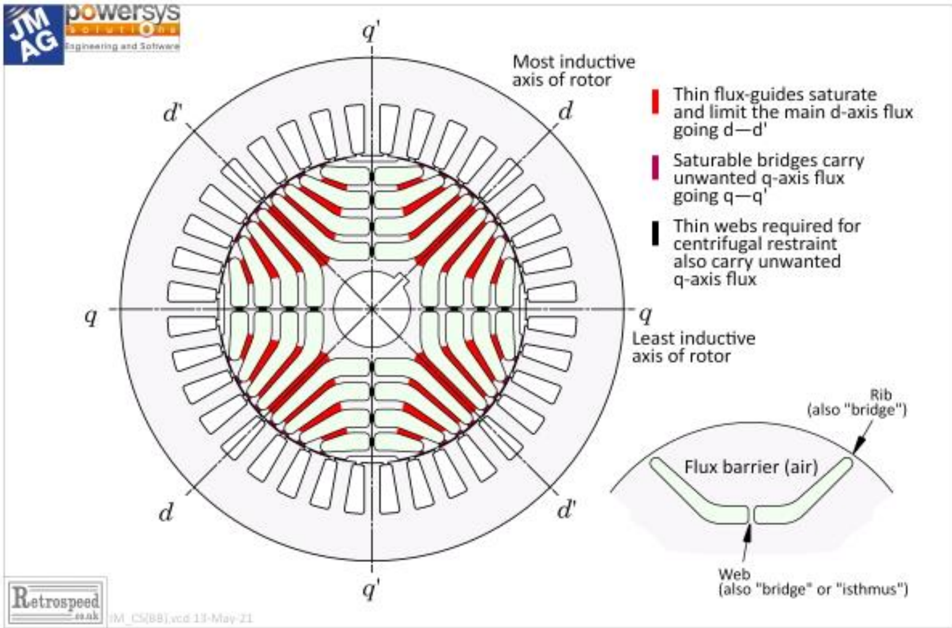

Figure 7.8 *Synchronous Reluctance Motor (SynRM) [18].*

Synchronous reluctance motors are known for their high energy efficiency, especially in variable speed drive applications. The absence of rotor windings and permanent magnets reduces losses and contributes to improved efficiency. Synchronous reluctance motors can be effectively controlled using variable frequency drives (VFDs) to achieve precise control over speed and torque. This makes them suitable for applications where variable speeds or high torque control are required.

Despite their advantages, synchronous reluctance motors may exhibit lower power factor and may require more sophisticated control strategies to optimize performance in certain operating conditions.

Synchronous reluctance motors offer a compelling combination of high efficiency, precise control, and versatile applications due to their unique rotor design and controllability with VFDs. This makes them a promising option for various industries seeking energy-efficient and reliable motor solutions.

In the Model 3, the Tesla company used IPM-SynRM motor (Internal Permanent Magnet - Synchronous Reluctance Motor), known also as PMa-SynRM Permanent Magnet Assisted Synchronous Reluctance Motor (Figure 7.9). In general, it is a type that combines internal permanent magnet motor type with synchronous reluctance motor rotor type to achieve a more desired characteristic in EV application: high efficiency at low and high speeds.

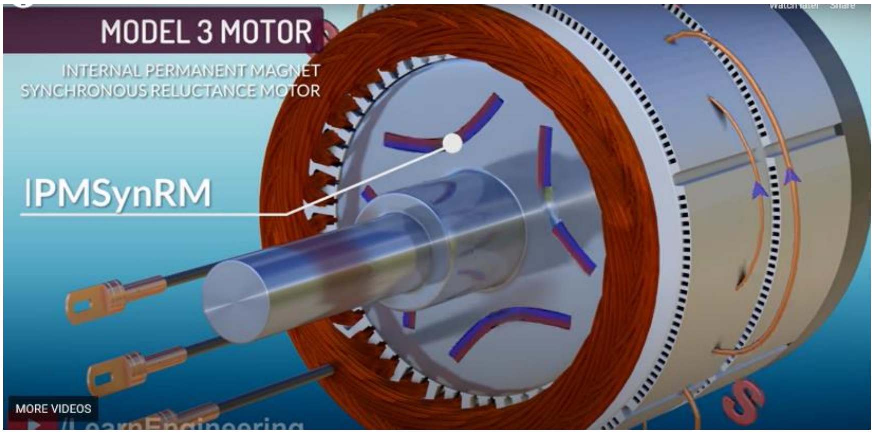

Figure 7.9 Permanent Magnet Assisted Synchronous Reluctance Motor – Tesla 3 EV model [19].

7.6 Wound-Rotor Synchronous Motor

The *Wound-Rotor Synchronous Motor* (WRSM) operates at a fixed synchronous speed due to the alignment of rotor and stator poles, relying on slip rings for DC power supply. The DC supply for the rotor is usually supplied from the main AC supply, rectified into a DC circuit supplied to the rotor, so while two different supply voltages are required, they both make use of the incoming 3-phase AC supply [20][21].

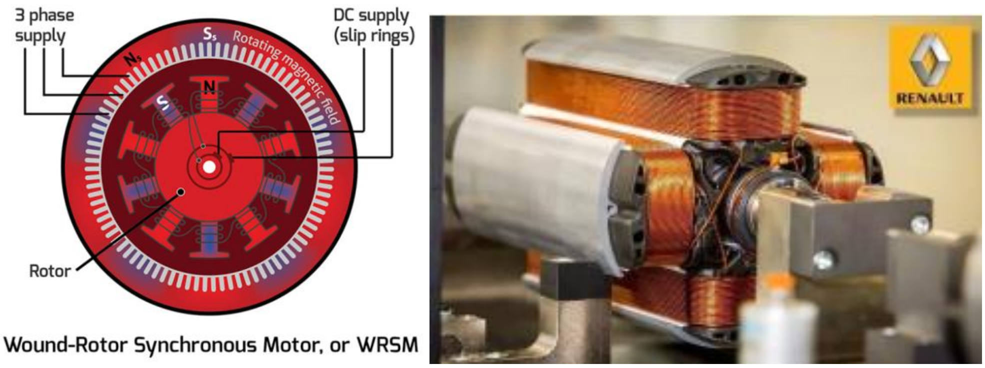

Figure 7.10 A rotor with windings connected to slip rings on wound-rotor synchronous motor [20].

The temperature limitations of rare earth magnets, such as neodymium type found in Permanent Magnet Synchronous Motors (PMSMs), can have significant drawbacks on motor performance. The resistance to demagnetization of such magnets starts decreasing at low temperatures, as low as 80°C for neodymium magnets, which can restrict the continuous power delivery capability of the motor. This limitation can hinder the motor's ability to sustain high torque and speeds, affecting its overall performance and efficiency.

A rather under-appreciated benefit of matching the field excitation to the torque demand is that the WRSM will present as a unity power factor load to the inverter. This eliminates the reactive current that would otherwise slosh back and forth between the inductance of the motor windings and the DC link capacitance, doing no useful work in the process, but still heating up the bridge switches and anti-parallel diodes.

Another potential advantage of the WRSM over the PMSM is that electromagnets can achieve a higher field flux intensity than even the strongest rare earth PMs which could actually reduce the size of the motor for a given power output. Electromagnets in Wound-Rotor Synchronous Motors (WRSMs) offer enhanced control over torque and speed compared to permanent magnet motors. Unlike permanent magnet synchronous motors (PMSMs), WRSMs utilize electromagnet coils in the rotor for the field, eliminating the reliance on rare earth magnets and their associated limitations.

The improved control over torque and speed achieved with electromagnets in WRSMs positively impacts motor efficiency and operation. By utilizing electromagnets instead of rare earth magnets, WRSMs can be operated at higher temperatures and are immune to demagnetization, enhancing their durability and reliability. Additionally, the controllability of torque and speed in WRSMs contributes to enhanced overall motor efficiency by facilitating optimized performance based on operational requirements. The ability to avoid uncontrolled generator scenarios and operate at a unity power factor further enhances the efficiency and stability of WRSMs.

7.7 Axial Flux and In-wheel Motors

In addition to the traditional on-board radial flux motors in EVs, there are two emerging alternatives that are of great interest but are at an early stage of market introduction, namely axial flux and wheel-mounted motors [22]. Axial flux motors and in-wheel motors are indeed emerging as innovative options for electric vehicle propulsion, each offering distinct advantages and unique characteristics that have the potential to contribute to the advancement of electric vehicle technology.

Axial flux motor is characterized by their compact design, high power density, and efficient torque generation. Their axial configuration allows for efficient cooling and thermal management, making them well-suited for electric vehicle applications. The regenerative braking capabilities of axial flux motors can also contribute to increased energy efficiency and driving range, aligning with the goals of sustainable transportation. As research and development efforts continue, axial flux motors are poised to play a significant role in the evolution of electric vehicle propulsion systems.

The axial flux motor, sometimes referred to as a ‘pancake motor’, is a type of electric motor where the magnetic field is aligned along the axis of rotation, hence its name. This structure is in contrast to the traditional radial flux motors, where the magnetic field follows a path along the radius of the motor [23].

An axial flux motor is a type of electric motor that has a distinctive design where the magnetic flux flows parallel to the axis of rotation, rather than radially as in conventional motors. Key components of an axial flux motor include the rotor, stator, and windings. The rotor contains permanent magnets, while the stator, positioned parallel to the rotor, has windings that create a magnetic field when powered. The interaction between these magnetic fields generates torque, leading to rotation.

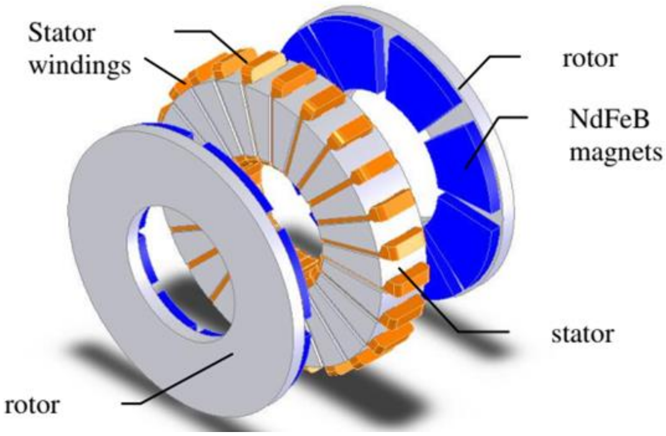

Figure 7.11 *8-pole 24-slot axial flux PM motor [23].*

The magnetic fields created by the rotor and stator align in the same direction (axially), which is a key characteristic of axial flux motors. This configuration allows for a more efficient use of magnetic flux and reduces power losses, improving overall motor efficiency. Axial flux motors use less material and so are intrinsically less expensive if the heat transfer and volume manufacturing challenges can be solved. These can deliver a power density of 10 kW/kg, which is four times the power density of a radial flux motor for an electric vehicle.

Axial flux motors consist of multiple stator and rotor discs stacked together, with the stator coils and permanent magnets arranged alternately. This configuration allows for a more compact and lightweight motor design compared to traditional radial flux motors.

In-wheel motors, also known as hub motors, offer unique advantages such as individual wheel control, simplified vehicle layout, and potential improvements in traction, stability, and handling. The direct integration of motors into the wheels enables innovative vehicle dynamics and opens up possibilities for novel vehicle designs. While challenges related to unsprung weight and packaging considerations exist, ongoing advancements in material science, engineering, and vehicle integration are driving progress in the development of in-wheel motor technology.

In-wheel motors, also known as hub motors, are electric motors integrated directly into the wheels of a vehicle, providing propulsion and driving force [24].

***Figure 7.12** The components of an in-wheel electric motor. The PD18 incorporates the power electronics and a disc brake to replace the OEM brake, making the packaging exercise much simpler [25].*

In-wheel motors are designed to be integrated within the wheels of a vehicle (Figure 7.12), either in the front, rear, or all four wheels. This integration eliminates the need for a traditional drivetrain, including components like axles, differentials, and transmissions, simplifying the vehicle's overall layout. In-wheel motors offer several advantages. They provide direct torque to the wheels, which can result in improved traction control and dynamic handling characteristics. Additionally, they free up space within the vehicle, allowing for more design flexibility and potential weight savings.

With in-wheel motors, each wheel can be controlled independently, enabling advanced vehicle dynamics and stability control systems. This individual wheel control can enhance traction, stability, and manoeuvrability, especially in challenging road conditions.

Questions

1. What are the key design characteristics that make Permanent Magnet Synchronous Machines (PMSM) suitable for electric vehicle applications?
2. How does the absence of brushes in PMSMs contribute to lower operating costs and increased reliability?
3. What challenges do induction machines face in electric vehicles, especially in terms of efficiency and electromagnetic noise generation?

4. What advantages do copper rotor technology bring to induction motors for electric vehicles, and how does this technology affect performance and cost?
5. In what ways do Switched Reluctance Machines differ from IPMs and IMs in terms of torque production, construction, and suitability for high-power applications?
6. In what ways does the design of Synchronous Reluctance Motors (SynRM) allow for higher torque density and energy efficiency, particularly in variable speed drive applications?
7. What advantage does matching field excitation to torque demand offer in Wound-Rotor Synchronous Motors (WRSMs)?
8. How do axial flux motors contribute to increasing energy efficiency in electric vehicles? What are the key advantages of in-wheel motors compared to traditional propulsion systems?

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8 Electric mobility in Sustainable Urban Mobility Planning

8.1 Concept of a Sustainable Urban Mobility Planning

A sustainable urban mobility plan is established upon a comprehensive vision for the advancement of transportation and mobility within the functional urban area. This plan encompasses all types of transportation, including public and private, passenger and freight, motorized and non-motorized, as well as moving and stationary modes. Additionally, it addresses infrastructure and services. The sustainable urban mobility plan outlines short-term strategies for achieving goals and targets through specific measures. It also includes a timetable for implementation, budget considerations, allocation of responsibilities, and identification of necessary resources. Sustainable urban mobility planning aims to address the mobility needs of individuals residing in or visiting the urban area, including institutions and companies. This approach emphasizes transparency and active participation by involving citizens and stakeholders in the development and execution of the plan. By promoting participatory planning, people are more likely to take ownership of the sustainable urban mobility plan and its policies, leading to enhanced public acceptance and support, and minimizing potential political challenges during implementation.

A sustainable urban mobility plan is developed through a detailed evaluation of the present and future functionality of the transportation system within the urban area. It involves a thorough examination of the current scenario to set a benchmark for measuring progress. The planning process establishes achievable goals and targets that align with the overall vision, along with defining performance indicators for each. These indicators are crucial for evaluating both current and future conditions. Additionally, the analysis includes an assessment of existing resources, capacities, and the institutional framework for planning and implementation.

Unlike traditional planning approaches, sustainable urban mobility planning places a strong emphasis on citizen and stakeholder involvement, policy coordination across various sectors (including transportation, land use, environment, economic development, social policy, health, safety, and energy), and extensive collaboration among different levels of government and private entities. This approach also highlights the importance of integrating all aspects of mobility (both people and goods), modes of transportation, and services in a holistic manner, while considering the entire "functional urban area" rather than just a single municipality within its administrative boundaries. In recent years, there has been a significant shift in the approach to transportation planning in both academic and planning practice. Figure 1 provides a concise overview of the main differences between traditional approaches and sustainable urban mobility planning.

Traditional Transport Planning		Sustainable Urban Mobility Planning
Focus on traffic	→	Focus on people
Primary objectives: Traffic flow capacity and speed	→	Primary objectives: Accessibility and quality of life, including social equity, health and environmental quality, and economic viability
Mode-focussed	→	Integrated development of all transport modes and shifttowards sustainable mobility
Infrastructure as the main topic	→	Combination of infrastructure, market, regulation,information and promotion
Sectoral planning document	→	Planning document consistent with related policy areas
Short and medium-term delivery plan	→	Short and medium-term delivery plan embedded in a long-term vision and strategy
Covering an administrative area	→	Covering a functional urban area based on travel-to-workflows
Domain of traffic engineers	→	Interdisciplinary planning teams
Planning by experts	→	Planning with the involvement of stakeholders and citizens using a transparent and participatory approach
Limited impact assessment	→	Systematic evaluation of impacts to facilitate learning andimprovement

Figure 8.1. *The main differences between traditional approaches and sustainable urban mobility planning*

Urban mobility planning should focus on enhancing accessibility and delivering high-quality, sustainable transportation services across the entire functional urban area. A sustainable transportation system:

- Ensures accessibility and fulfils the basic mobility needs of all users;
- Addresses the varied demands for mobility and transport services from residents, businesses, and industry;
- Promotes a well-rounded development and improved integration of various transport modes;
- Meets sustainability requirements by balancing economic viability, social equity, health, and environmental quality;
- Enhances efficiency and cost effectiveness;
- Utilizes urban space and existing transport infrastructure and services effectively;
- Improves the attractiveness of the urban environment, quality of life, and public health;
- Enhances road safety and security;

- Reduces air and noise pollution, greenhouse gas emissions, and energy consumption;
- Contributes to the overall performance of the trans-European transport network and Europe's transport system as a whole.

The development and implementation of a Sustainable Urban Mobility Plan needs to be based on a high level of cooperation, coordination and consultation across different levels of government and between institutions (and their departments) in the planning area.

Sustainable urban mobility planning should be based on:

- Cooperation to ensure the consistency and complementarity of the Sustainable urban mobility plan with policies and plans in sectors related to transport (e.g. land use and spatial planning, social services, health, energy, education, enforcement and policing).
- Close exchange with relevant authorities at other levels of government (e.g. district, municipality, region and state).
- Coordination with public and private sector providers of transport.

8.2 The Importance of E-Mobility

Sustainable urban mobility planning considers the social and environmental factors of transportation, emphasizing the importance of sustainable modes such as walking, cycling, and public transport over traditional transportation methods. This shift in focus promotes a balanced approach to transportation that enhances accessibility, health, and environmental well-being. Sustainable urban mobility planning plays a crucial role in European transport policy. The European Commission, in its Action Plan on Urban Mobility, has put forward a proposal to expedite the adoption of Sustainable Urban Mobility Plans across Europe.

Sustainable urban mobility planning: e-mobility contributes to pollution reduction. Many European cities suffer from poor air quality. Electric vehicles, on the other hand, do not emit any pollutants from fuel combustion. Consequently, the electrification of transportation will play a pivotal role in enhancing air quality within urban areas. Moreover, when coupled with the utilization of renewable energy sources, we can effectively diminish the carbon dioxide footprint. The industrial sector and households have successfully decreased greenhouse gas (GHG) emissions, whereas the transportation sector lags significantly in contributing to climate protection efforts. Despite widespread acknowledgment of the necessity to lower GHG emissions, the European transportation industry continues to release more emissions compared to levels in 1970. Figure 2 illustrates the evolution of global greenhouse gas emissions from 1970 to 2022[1].

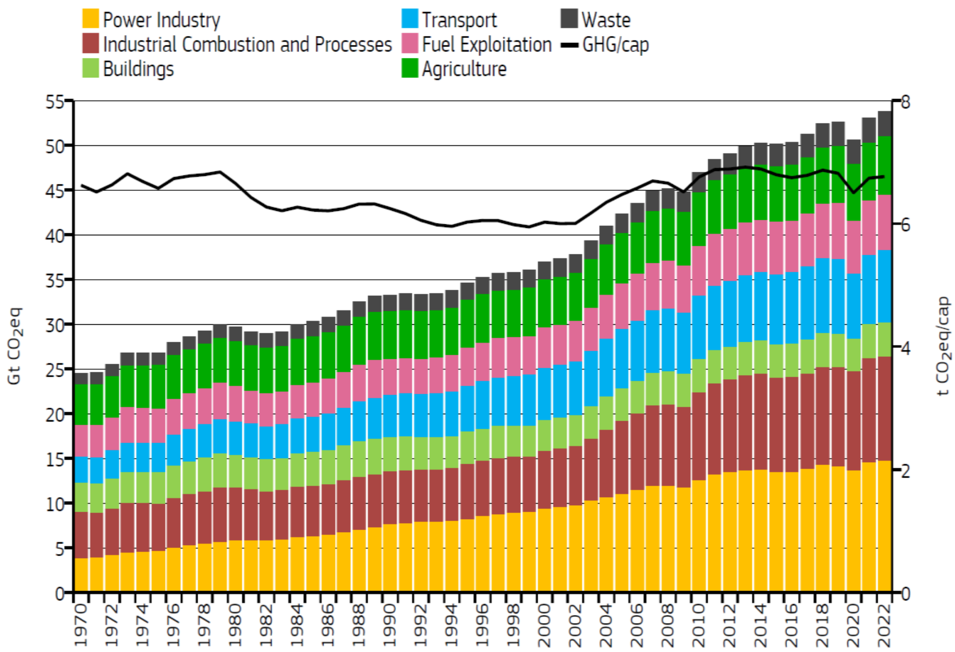

Figure 8.2. *Global GHG emissions by sector and per capita, 1970-2022 [1].*

Figure 8.2 shows the emission trends for key sectors such as the power industry, industrial combustion and processes, transport, buildings, agriculture, waste, and fuel exploitation. The COVID-19 pandemic had a significant impact on global emissions, resulting in a 3.7% decrease in 2020 compared to 2019 levels. This interruption broke a more than ten-year increasing trend.

Following the pandemic, global GHG emissions began to rise again, reaching 53.8 Gt CO2eq in 2022. This level is 2.3% higher than 2019 and 1.4% higher than 2021. In 2020, the transport sector experienced the largest drop in emissions, with a decrease of 14.1% compared to the pre-pandemic year. However, in 2022, this sector witnessed the largest increase, rising by 4.7%. The building sector, on the other hand, only saw a marginal decrease of 0.4% in GHG emissions in 2022 compared to 2021. In the previous year, these emissions had grown by 4.6%. Additionally, global per-capita emissions increased by 0.4% in 2022, reaching 6.76 t CO2eq/cap. However, this value is still 0.8% lower than the 2019 level.

8.3 Factors for E-Mobility and the Urban Transportation Strategies

There are several factors to take into account for electric mobility and the development of sustainable urban transportation strategies.

Energy source

The significant potential of electric mobility in reducing greenhouse gas emissions is heavily reliant on the energy source it utilizes. In order to truly achieve this potential, it is imperative that the majority of charging is done using renewable energy. To have the maximum impact on climate protection, this transition must be accompanied by a broader shift in the energy sector towards renewable sources and improved electricity management. However, it is important to note that the battery is not the sole aspect of a car that consumes resources. It is crucial to consider thoughtful construction, usage, and recycling of all vehicle components. With this holistic approach in mind, electric mobility should encompass more than just propulsion technologies. REpowerEU [2] proposal includes a suggestion to increase the EU's target for renewable sources' share in final energy consumption to 45% by 2030, up from the current goal of 40%. It also advises streamlining the permitting process for large-scale renewable projects. Furthermore, the plan recommends raising the binding energy consumption reduction target for 2030 to 13%, a significant increase from the 9% target set for 2020.

Space

European cities are facing a significant issue with an excessive number of cars. A crucial factor contributing to this problem is the availability of parking spaces. On average, private cars in Europe are utilized for only one hour per day. Consequently, for the remaining 23 hours, when the vehicle is parked, the type of driving becomes insignificant. Surprisingly, an electric car occupies the same amount of space as a conventional car. Therefore, if families opt to include electric cars for their short trips, it could potentially exacerbate the existing parking challenges. The attractiveness of Personal Light Electric Vehicles (PLEV) might become a game changer by shifting to smaller vehicles and offering new sharing options.

Congestion

Electric vehicles not only help to decrease energy consumption through the use of efficient electric motors and reduce greenhouse gas emissions, ultimately combating global warming and climate change. They also enhance energy security, lower public health costs by reducing air pollution, particularly in densely populated urban regions. Furthermore, electric mobility offers quieter operation compared to conventional vehicles. All vehicles occupy a similar amount of space. Transitioning from traditional to electric vehicles can lead to less congested roads. Sustainable Urban Mobility Planning aims to create comprehensive strategies for alleviating congestion. European cities' congestion rankings clearly indicate that cities with a cycling culture experience significantly lower levels of congestion.

Safety

There are European, national and local goals to improve road safety, particularly related to fair treatment of vulnerable road users. These require more than just the electrification of cars.

8.4 Electric Mobility and Sustainable Urban Mobility Planning

In order to promote sustainable transportation, a sustainable urban mobility plan focuses on achieving a balanced and integrated development of all relevant modes of transport. This plan prioritizes the implementation of sustainable mobility solutions and presents a comprehensive set of measures to enhance the overall quality, security, safety, accessibility, and cost-effectiveness of the mobility system. It encompasses various elements such as infrastructure development, technological advancements, regulatory frameworks, promotional activities, and financial strategies. The plan also addresses different aspects of mobility, including collective transportation (both traditional and sharing-based services), active mobility (walking and cycling), intermodality (use several type of vehicles), door-to-door mobility, road safety, vehicles in motion and at rest, freight and service delivery, logistics, mobility management, and Intelligent Transport Systems (ITS).

Electric mobility has the potential to greatly enhance sustainable urban mobility planning, as long as it is integrated into a comprehensive strategy. Taking a holistic approach, it is evident that in numerous instances, low-tech options such as walking and cycling prove to be more efficient for urban mobility than solely relying on technological advancements.

Various strategies are implemented in sustainable urban mobility planning to address the issue of space occupied by transportation in cities, beginning with reducing traffic congestion through spatial planning and organizational modifications (e.g. telecommuting or corporate mobility management). Enhancing workplace mobility management involves incorporating travel planning, behaviour-focused programs, and carpooling, along with providing charging stations and appealing parking spaces for electric vehicles. The transition towards walking, cycling, and public transportation is also crucial for sustainable urban mobility planning, necessitating safe, convenient, and attractive infrastructure for pedestrians, cyclists, and public transport services.

Sustainable urban mobility planning encompasses 4 frames with total 12 steps [3]. The initial milestone is a decision to prepare the sustainable urban mobility plan.

First frame is *Preparation and analysis* and includes following steps:

1. Set up working structures
    - 1.1 Evaluate capacities and resources
    - 1.2 Create inter-departmental core team
    - 1.3 Ensure political and institutional ownership
    - 1.4 Plan stakeholder and citizen involvement
2. Determine planning framework
    - 2.1 Assess planning requirements and define geographic scope (‘functional urban area’)
    - 2.2 Link with other planning processes

    - 2.3 Agree timeline and work plan
    - 2.4 Consider getting external support
3. Analyse mobility situation
    - 3.1 Identify information sources and cooperate with data owners
    - 3.2 Analyse problems and opportunities (all modes)

The milestone of this first frame and set of steps is Analysis of problems and opportunities concluded.

The second frame is *Strategy development* with following steps:

4. Build and jointly assess scenarios
    - 4.1 Develop scenarios of potential futures
    - 4.2 Discuss scenarios with citizens and stakeholders
5. Develop vision and objectives with stakeholders
    - 5.1 Agree common vision of mobility and beyond
    - 5.2 Co-create objectives for all modes with stakeholders
6. Set targets and indicators
    - 6.1 Identity indicators for all objectives
    - 6.2 Agree measurable targets

The milestone of this frame and set of steps is Mobility strategy agreed.

The third frame is *Measure planning*:

7. Select measure packages with stakeholders
    - 7.1 Create and assess long list of measures with stakeholders
    - 7.2 Define integrated measure packages
    - 7.3 Plan measure evaluation and monitoring
8. Agree actions and responsibilities
    - 8.1 Describe all actions
    - 8.2 Estimate costs and identify funding sources
    - 8.3 Agree priorities, responsibilities and timeline
    - 8.4 Ensure wide political and public support
9. Prepare for adoption and financing
    - 9.1 Finalise and assure quality of ‘Sustainable Urban Mobility Plan‘ document
    - 9.2 Develop financial plans and agree cost sharing

The milestone of this frame and set of steps is Sustainable Urban Mobility Plan adopted.

The final frame is *Implementation and monitoring* with following steps:

10. Manage implementation
    - 10.1 Coordinate implementation of actions
    - 10.2 Procure goods and services
11. Monitor, adapt and communicate
    - 11.1 Monitor progress and adapt
    - 11.2 Inform and engage citizens and stakeholders
12. Review and learn lessons

12.1 Analyse successes and failures
12.1 Share results and lessons learned
12.3 Consider new challenges and solutions

The milestone of final frame and set of steps is Measure implementation evaluated.

8.5 Electrification as a Support of Sustainable Modes

Undoubtedly, European cities must transition from relying on single-occupancy cars to embracing walking, cycling, shared modes, and collective transport. The implementation of different electric mobility elements within sustainable urban mobility planning strategies can play a crucial role in facilitating this transition. Some of these elements include:

a) Electric support for bicycles

Cycling is an incredibly efficient mode of transportation when it comes to space utilization. It requires minimal space for parking and traveling. In comparison to car-friendly cities, cycling cities experience significantly lower levels of congestion. Just envisioning all the cyclists in cities sitting alone in cars highlights the immense value of space saved in cycling cities. Additionally, incorporating electric assistance into cycling makes it less physically demanding and extends the range for longer distances.

The introduction of electric support presents a tremendous opportunity for increased cycling in European cities, benefiting both individuals and logistics. Electrically assisted bicycles, like any other bicycles, necessitate well-designed and appealing infrastructure. As the number of electrically assisted bicycles continues to rise in urban areas (alongside an overall increase in bicycle usage), it becomes imperative to modify the existing infrastructure to accommodate greater speed variations, increased overtaking, wider and longer bicycles, and bicycles with trailers. Furthermore, the demand for electrically assisted bicycles is on the rise. Figure 8.3 shows the number of electric bicycles sold in the European Union (EU-28) from 2006 to 2021(in 1,000 units).

Electrically-assisted bicycles are ideal for regular commuting as they do not require recharging infrastructure along the way. The range of e-bikes is more than enough for daily commuting, and the batteries can be conveniently detached from the bike for recharging at home or at the workplace. However, for leisure and tourism purposes that may involve longer trips, having the option of recharging en route can be highly beneficial.

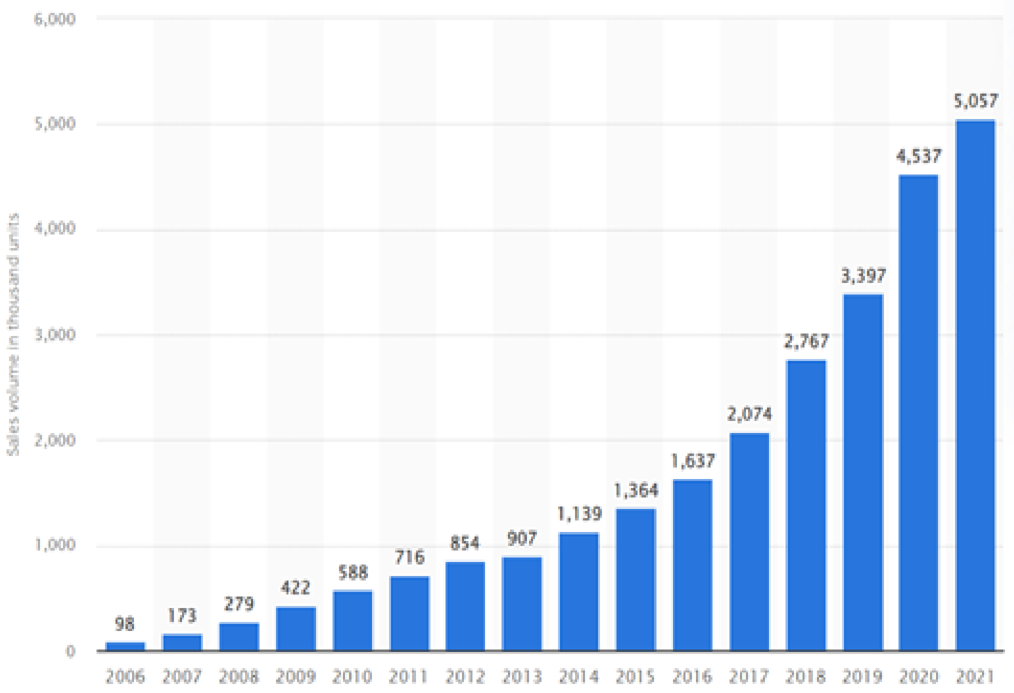

Figure 8.3. *Number of electric bicycles sold in the European Union (EU-28) from 2006 to 2021(in 1,000 units) [4].*

b) Electrification of buses

Public transportation is also a key element of sustainable transportation plans. It enables the movement of large numbers of passengers along set routes that adhere to a schedule. Buses play a significant role in the public transport systems of many cities and towns. In Europe, the majority of buses are powered by diesel engines, accounting for nearly 90% of the fleet. However, electric buses only made up a mere 1.2% of European buses in 2013, according to ZeEUS report [5]. It is worth noting that public transport vehicles, such as buses, operate for much longer periods, typically ranging from 12 to 16 hours, compared to private cars that are used for less than an hour a day. Considering the larger engine size of buses, the impact of electrifying urban buses is approximately 100 times greater than that of private cars. This is particularly relevant for cities that exceed the EU-mandated NO_2 concentration levels, primarily caused by diesel emissions. These cities are keen on transitioning from diesel to electric buses, although further advancements in the reliability and performance of battery-electric buses are still necessary. Trolleybuses have achieved a significant level of development and can now be integrated with batteries to enable prolonged operation without the need for overhead wires. European regulations mandate the acquisition of a specific percentage of environmentally friendly buses beginning in 2025.

c) As part of new mobility services (e.g. on-demand minibus services)

Mobility as a service revolutionizes the way collective transport is delivered. The extensive digitalization of public transportation ensures a seamless and user-friendly experience, ultimately drawing in more passengers. Mobility as a Service caters to individual preferences by offering personalized transport options, real-time travel updates, efficient trip planning, and convenient payment methods.

d) As part of new sharing concepts

Shared mobility solutions have the potential to bring about transformative change by enhancing the quality of life in urban areas. These solutions promote inclusive mobility for all citizens, resulting in substantial benefits for personal and spatial accessibility. While e-mobility solutions can play a role in encouraging shared mode transport, the issue of vehicle charging presents certain challenges. However, the emergence of light e-vehicles within the sharing concept offers an exciting new approach that effectively addresses gaps in mobility demand.

e) As part of new logistics concepts (micro-hubs to shift to smaller e-powered/ e-supported vehicles like cargo bikes)

Cargo bikes can significantly improve urban deliveries by providing a more efficient and eco-friendly alternative to traditional vans. The presence of delivery hubs is essential to facilitate the loading of cargo bikes for the final leg of the delivery process.

8.6 Adapting to the Local Context

A sustainable urban mobility plan plays a crucial role in the growth and progress of an urban area. It is essential to have effective mechanisms in place to ensure that the plan meets the professional standards and complies with the requirements of the sustainable urban mobility plan concept. This endeavour is definitely worth pursuing. It is important to give special attention to data quality assurance and risk management during the implementation phase. These responsibilities can be entrusted to external quality reviewers or other government institutions at the regional or national level. Additionally, the use of tools such as the sustainable urban mobility plan Self-Assessment Tool can greatly facilitate the process.

The challenge of preparing and implementing a sustainable urban mobility planning is to adapt the sustainable urban mobility planning to a given local context without compromising the main principles behind sustainable urban mobility planning:

- The planning process can be customized to suit the specific characteristics of the city being studied, taking into account factors such as its size (whether it is a small urban area or a metropolitan region), its relationship with the surrounding suburbs, and its geographic location (such as being coastal or inland). In the case of secondary cities, they often encounter circumstances that go beyond the capabilities and jurisdiction of local authorities. For instance, the functional area of the city may extend beyond the current administrative divisions, and responsibilities may be divided among different institutions and levels. In such situations, the Sustainable urban mobility plan should establish a strategy to involve all relevant stakeholders, thereby laying the foundation for potential institutional reforms.

- The policy emphasis differs based on the mobility circumstances, prevailing concerns and obstacles, and the specific political or public priorities at the local level. Consequently, the allocation of resources for each subject should be adaptable, and actions should be customized to meet the requirements. While Sustainable urban mobility plan should aim for inclusiveness, it is acceptable to sacrifice exhaustiveness in favour of targeted enhancements or priority areas.
- Local factors such as the geographical features, weather patterns, socioeconomic conditions, and user preferences should be taken into account during the planning of transportation initiatives. While ideas and concepts from other cities may provide valuable insights, they need to be customized to suit the specific local context. This can be achieved through a collaborative and inclusive approach involving the participation of various stakeholders.

Finally, it is important to highlight that in order to promote sustainable urban mobility with electric vehicles, it is crucial to implement policies at various government levels that support their usage. These policies may include incentives like subsidies for electric vehicle purchases, the establishment of electric vehicle sharing programs, the installation of charging stations for both private and public vehicles, and the development of smart grids and Internet of Things technology. Additionally, it is essential that the electricity used to power these vehicles come from renewable sources to reduce the environmental impact of transportation in the area.

Questions

1. What is the goal of sustainable urban mobility planning?
2. What are the advantages of sustainable urban mobility compared to traditional transport planning?
3. What are the main factors to consider for electric mobility and the development of sustainable urban mobility strategies?
4. What are the steps in planning sustainable urban mobility?
5. Which elements of electric mobility plays an important role in the transition to sustainable urban mobility?

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9 Environmental Impacts of Electric Vehicles

9.1 Introduction

Worldwide vehicle production growth over the past decades has caused strong emissions increments, which have affected both population and industrial sectors globally. EU-28’s CO2 emissions correspond to 10.8% of global CO2 emissions [1]. Global warming and urban pollution focused a great interest on hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs) as cleaner alternatives to traditional internal combustion engine vehicles (ICEVs). The environmental impact related to the use of both ICEV and HEV mainly depends on the fossil fuel used by the thermal engines, while, in the case of the BEV, depends on the energy sources employed to produce electricity. Moreover, the production phase of each vehicle may also have a relevant environmental impact, due to the manufacturing processes and the materials employed [2].

Whether combustion or battery-powered, the production, use and disposal of every vehicle has an impact on the environment. While in the case of internal combustion engines, the main environmental impact is caused not only by production but also by use, battery production accounts for a significant proportion of the environmental impact of battery-powered vehicles. [3]

9.2 Life Cycle Assessment

Life cycle assessment (LCA) is a means of assessing the environmental impact associated with all stages of a product's life. The stages relevant to BEVs have been used to structure this report. LCA is recognized as being the best framework for assessing the environmental impacts of products [4]. Increased understanding of upstream and downstream environmental impacts of products helps avoid shifting the burden from one stage to another in a product's life cycle, and it reduces the potential for this burden to move from one country to another [5]. This is why the LCA of the HEV and BEV must include different stages (Figure 9.1).

In terms of coverage of impacts, LCAs typically include up to 16 categories [5][7] including climate change, ozone depletion, ecotoxicity and resource depletion.

Environmental impacts are grouped under the following themes:

- climate change;
- health impacts, particularly focused on:
    - 'human toxicity';

  - air quality impacts on health with a focus on nitrogen oxides (NOx) and
  - particulate matter, e.g. in relation to;
- ecosystem impacts, including: – freshwater ecotoxicity.

These themes reflect the key topics covered in the LCA literature on electric vehicles.

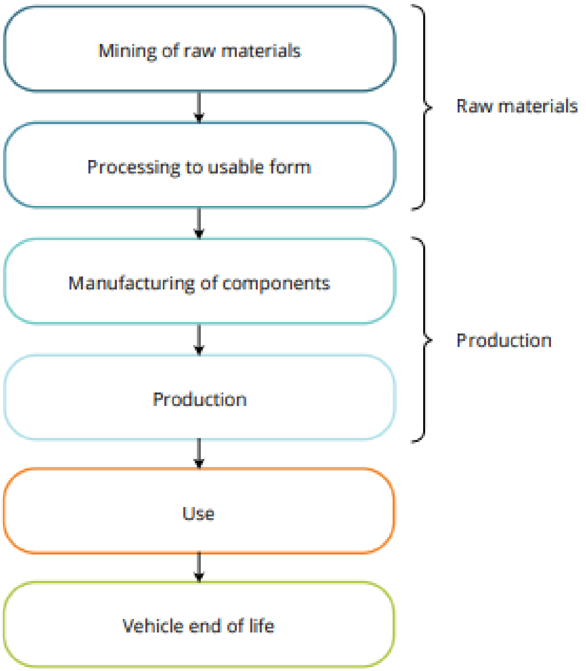

Figure 9.1. *Scope of the analysis for the Life Cycle Assessment of HEVs and BEVs [6].*

9.2.1 Production Phase and Mining Raw Material

Production of BEVs requires a range of raw materials. Compared with an ICEV, the main differences in the materials required arise from the battery, power electronics and electric motor in a BEV.

Currently, for the BEV body and auxiliary systems, in many cases the same materials and similar quantities are used as for ICEVs for BEV models adapted directly from an ICEV model. However, because of the importance of maximizing vehicle range for BEVs, in some cases BEV bodies are specifically designed using more lightweight materials such as aluminium, carbon fibre and plastic composites. Known as 'lightweighting', this process may become increasingly important in the future.

The key metals and other raw materials required for those BEV components that are used in greater quantities than in ICEVs are illustrated in Figure 9.2.

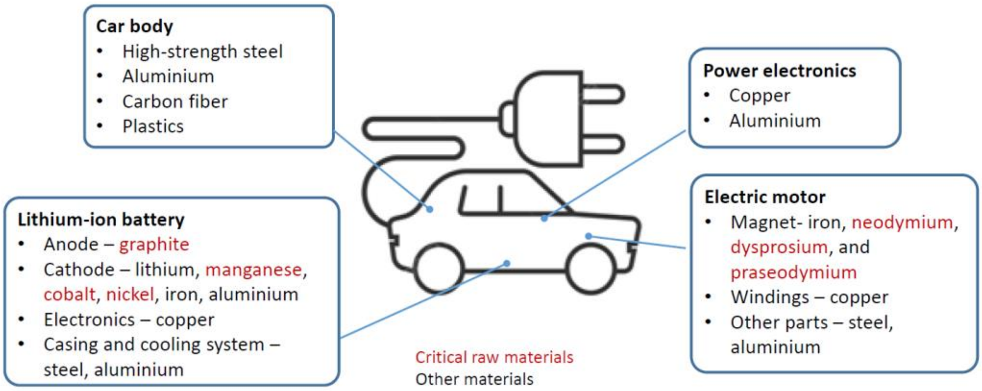

***Figure 9.2** Major raw materials commonly used in BEVs [6][8].*

There are number of environmental impacts that are exacerbated by the use of raw materials in larger quantities or exclusively in BEVs. These include:

- the greenhouse gas (GHG) and the air pollutant emissions from energy-intensive mining and refining processes;
- health and ecosystem impacts of:
  - the air pollution from metallurgical processes;
  - the water and the soil contamination from mining activities;
- ecosystem impacts of land use for mining;
- depletion of critical raw materials (CRM) and rear earth elements (REE).

Although the issue depletion of CRMs and REEs is not considered an environmental impact itself, extraction of those materials can cause a great impact. This is mainly due to the locations of findings of those materials. The tendency of companies to mine and process materials in countries, where safeguards for human health and environmental protection are weak pose a great concern. Although lithium is not officially classed as a CRM, its use in lithium ion (Li-ion) batteries and the rapid increase in demand from rising electric vehicle uptake could place pressures on the supply of this material.

Expected growth in the electric vehicle market will be accompanied by increasing demand for CRMs, including cobalt and REEs contained in Li-ion batteries [9]. For example, under a scenario of limiting average global temperature rise to 2 ºC, global lithium demand will rise to 160 000 tonnes in 2030 and 500 000 tonnes in 2050. Electric cars will account for 82% of the road transport-related demand in 2030 and 83% in 2050. This assumes that in 2030 electric car annual sales (BEVs, PHEVs and FCEVs) will be around 26 million and in 2050 will be around 97 million [10]. Figure 9.3 shows demand for CRMs and REEs in the EU to 2030.

Figure 9.3 *Expected increase of demand for CRM and REE [11].*

9.2.2 Climate Change

The processes involved in raw material sourcing, which include extraction, separation and refining, are resource intensive. Large volumes of water, energy and other substances such as ammonia are consumed. This contributes to making material extraction and processing into a useable form a significant contributor to energy use and correspondingly greenhouse gas (GHG) emissions [9][12][13].

Estimates of the GHG emissions from raw material extraction and processing for Li-ion batteries vary widely, but recent LCAs suggest that it is responsible for around 20% of the total GHG emissions from battery production [14].

The energy used in raw material extraction and processing may be in the form of electricity, heat or fossil fuels used in vehicles and machinery. Compared with BEV manufacture and use, in which electricity is the dominant energy source, a larger proportion of the energy demand for raw material extraction and processing comes from fuel combustion in vehicles and to provide heat. For the portion of energy provided by electricity, the climate change impact depends on the carbon intensity of electricity generation types feeding into the grid at the time and location of use. This varies considerably by country: those with the highest carbon intensity are those where coal-fired power stations dominate.

As well as GHG emissions from energy use, another key source of GHGs is direct emissions of CO2 and perfluorocarbons arising from aluminium production. Depending on the vehicle model, this could be a more important source for BEVs than for ICEVs because of the greater quantity of aluminium used for lightweighting of vehicle components in BEVs.

The resource intensity of raw material supply can be reduced through recycling, as this reduces the need to source virgin raw materials. For example, producing primary aluminium requires around 20 times as much energy as recycling scrap aluminium [15][16]. Moreover, other research suggests that using recycled materials for the entire battery could result in reductions in GHG emissions of up to 50% across the battery production process [13].

9.2.3 Environmental Impact on Ecosystems

Mining processes, the release of toxic emissions and leakages of toxic substances can have harmful impacts on human and ecosystem health. For ecosystems this can include:

- eutrophication;
- acidification of water bodies and wetlands;
- soil contamination with heavy metals and soil erosion;
- biodiversity loss, including of land vegetation and aquatic species, especially fish [8][13][17].

Energy use results in emissions of air pollutants from fuel combustion, including NOx and sulphur oxides (SOx), which contribute to eutrophication and acidification. In addition to emissions from energy use, producing the metals used results in direct emissions of acidifying gases:

- Sulphur dioxide (SO2) is released during primary production of copper and nickel from sulphide ores for batteries, electronics and electric motors.
- Hydrogen chloride and hydrogen fluoride (which also have local health impacts) are released during aluminium production [18].

Information on the ecosystem impacts of rear earth elements (REE - dysprosium, neodymium and praseodymium) is currently limited; however, studies to investigate the environmental impacts of REE mining are becoming more numerous. Traditionally, REEs were thought to be low risk to ecosystems, as they are largely immobile and insoluble. Recent laboratory studies have, however, revealed the potential for bioaccumulation and toxicity of REEs among aquatic species. For example, REEs have been shown to inhibit the growth of plants and of certain species of marine algae as well as causing decreased chlorophyll production [19][20].

9.3 Vehicle and Battery Production

From a life cycle perspective, GHG and air pollutant emissions from BEV production are generally higher than those from ICEV production. This is largely due to the energy-intensive process of battery manufacture [6]. This higher energy use has associated broader health and ecosystem impacts. The impacts vary according to the battery chemistry and size and the energy mix used in the production processes. From a circular economy perspective, the negative environmental impacts of vehicle production can be minimised by:

- increased use of renewable electricity to provide energy for BEV production;
- recycling — increasing the use of recycled rather than virgin materials;
- changes in consumption patterns by encouraging consumers to choose the smallest possible vehicle category — this is can be facilitated through shared mobility services;
- reducing waste generation — by taking advantage of economies of scale and new techniques in battery and vehicle production;
- choosing battery types with the lowest impact per unit of energy provided.

Deploying BEVs is one of the main initiatives to decarbonize and reduce emissions from the transport sector, as they have no tailpipe emissions and can significantly reduce impacts on climate when charged with electricity from renewable energy sources (RESs) [21] [22]. However, the environmental impact of their manufacturing is higher than that of internal combustion engine vehicles due to battery production, shifting the environmental burden from the use stage to production [23]. The demand for larger battery sizes to tolerate longer driving ranges has exacerbated the problem. As a result, extending the life of used BEV lithium-ion batteries for secondary application has been proposed to reduce the environmental impact of battery manufacturing on the BEV life cycle [24].

Additionally, refurbishing EV batteries aligns with the EU's Circular Economy Action Plan to reduce or eliminate waste and pollution and transform products and materials to remain in supply chains for as long as possible.

Most LCAs of BEVs find that battery production is responsible for the largest proportion of energy use (and GHG emissions) in the production phase [25], with estimates ranging between 10 and 75 % of manufacturing energy and 10 and 70% of manufacturing GHG emissions [26]. A recent review found that all stages of battery production account for 33‑44% of total BEV production emissions. Of this total, LCAs report that cell manufacturing and battery assembly accounts for anything between 3 and 80% of total battery production emissions depending on the approach taken, with the rest arising from raw material extraction and processing [14].

9.4 Dependence on the Electricity Grid

Considering an individual vehicle, the total environmental impact arising from the use stage of a BEV depends on both the impact per kilometre and the distance driven over a particular period, i.e.:

$$\text{Total impact} = \text{impact per kilometre} \times \text{kilometres driven}$$

Results can be expressed by grams of CO2 or CO2-equivalent per unit distance (gCO2/km or gCO2e/km).

In the available research literature on the in-use environmental impacts of BEVs and comparisons with ICEVs, most studies focus on impacts per kilometre driven.

This is influenced by a number of factors, including:

- electricity generation sources;
- characteristics of vehicles;
- driving style and location;
- charging patterns.

Key concept used when quantifying use stage impacts are the terms 'well-to-tank' (WTT), 'tank-to-wheel' (TTW) and 'well-to-wheel' (WTW), to distinguish impacts occurring from different stages of the fuel cycle. The WTW (well to wheels) we study is one type of LCA of vehicles, which focuses on the life cycle of the energy carrier used to propel the vehicle, such as liquid fuel or electricity.

WTW life cycle can be subdivided into the well-to-tank (WTT) stage, which focuses on the delivery of energy from its source to the storage equipment in the vehicle, and the tank-to-wheel (TTW) stage, where the energy carrier is used to propel the vehicle during operation. The WTT stage involves all processes from harnessing a primary energy flow or stock to different forms of conversion, distribution, and storage of energy carriers. The environmental burden of the WTT stage differs a lot, depending on how the energy carrier is produced.

For example, there is a large difference between electricity produced from hydropower- and coal-fired plants.

BEVs emit no GHGs locally (TTW stage); however, they are emitted during electricity production (WTT stage).

The majority of LCAs suggest that the WTW GHG emissions per kilometre driven of BEVs in Europe are lower than those of ICEVs and hybrid vehicles. Based on the carbon intensity of the EU electricity mix in 2015, the WTW emissions of a mid-sized BEV were between 60 and 76 gCO2e/km. This is between 47% and 58% lower than the emissions of an average mid-sized passenger ICEV in 2015, at 143 gCO2e/km [25].

Extended-range and plug-in hybrid electric vehicles (EREVs and PHEVs) also have lower in-use WTW GHG emissions than ICEVs, allowing emissions savings of up to 48% and 36%, respectively.

The key factors affecting BEV GHG emissions are the BEV driving energy consumption; and the GHG emissions per unit of electricity required.

BEVs have a superior in-use energy efficiency relative to ICEVs; BEVs can convert 70-90% of the energy stored in the battery into movement, whereas the theoretical peak efficiency of ICEVs is only 40%.

Despite this, replacing the approximately 246 million combustion-powered passenger cars in Europe [27] with electric cars would be completely misguided. For example, newly registered electric cars in Europe currently emit an average of 75 gCO2e/km over their entire life cycle, which is around 69% less greenhouse gases than comparable petrol-driven vehicles. [30]. If green electricity is used during production and operation, CO2 emissions are reduced even further. The resource consumption of the two drives can be classified as high in each case. The battery drive requires a large proportion of abiotic resources (minerals and metals) in its production phase. The combustion engine consumes a great amount of biotic resources, such as gasoline and diesel, during the use phase, which cannot be recycled after a single use.

9.5 End of Life

The end-of-life stage, considered in isolation, has the smallest impact in terms of total life cycle emissions. However, encouraging sustainable practices during this stage could result in benefits across all life cycle stages.

These include:

- a reduced need for virgin materials and hence a reduction in the impacts of mining and production;
- a reduced or delayed need for disposal and hence a reduction in impacts from landfilling;
- a move towards a more circular economy through the reuse and remanufacture of batteries or their components and from recycling or recovery of materials.

Further research and development is required in order to make end-of-life processes more efficient and sustainable.

Therefore, there is a need to:

- consider standardization to encourage large-scale recycling and reuse processes;
- real-life testing of battery second-use applications and other end-of-life options;
- develop systems for REEs contained in magnets.

Although the recycling process does require additional energy inputs at the end of a vehicle's life, the benefit in terms of resources saved by not producing new products usually outweighs this. For example, recycling electric vehicle batteries through pyrometallurgy can reduce primary energy demand by 6-56 % through material recovery [29]. However, the extent to which such resource savings can be achieved through recycling depends, in part, upon the economic attractiveness of different end-of-life options.

Currently, the literature on LCAs of BEVs and comparisons with ICEVs is dominated by climate change impacts [30]. The comparative life cycle GHG emissions of BEVs and ICEVs depend on a number of factors, including the size of vehicle considered, the lifetime mileage, assumptions about the electricity generation mix and whether the ICEV is a petrol or diesel vehicle.

9.6 Footprint of EV

The majority of LCAs show that BEVs have lower life cycle GHG emissions than ICEVs. In general, GHG emissions associated with the raw materials and production stage of BEVs are 1.3-2 times higher than for ICEVs [15] [14]. However, this can be more than offset by lower per kilometre use stage emissions, depending on the electricity generation source reported life cycle GHG emissions from BEVs charged using the average European electricity mix 17-21 % and 26-30 % lower than similar diesel and petrol vehicles, respectively. This is broadly in line with more recent assessments based on the average European electricity mix [15].

LCA show that the battery drive has a significantly lower CO2 footprint over the entire life cycle (production, use and disposal) than the combustion drive. With the current EU electricity mix - i.e. a 44.6 % share of renewable energies - the CO2 emissions of an electric car are 66-69 % lower than those of a comparable car with a combustion engine [30]. Whereas a diesel vehicle under normal driving conditions in Europe emits up to 250 g CO2 e/km taking into account the entire life cycle, an electric vehicle with a battery capacity of 53 kilowatt hours (kWh) emits only 75 g CO2 e/km. Thus, an average medium-sized diesel car of the “Golf class” produces about three times as much CO2 e/km as a comparable electric car [31].

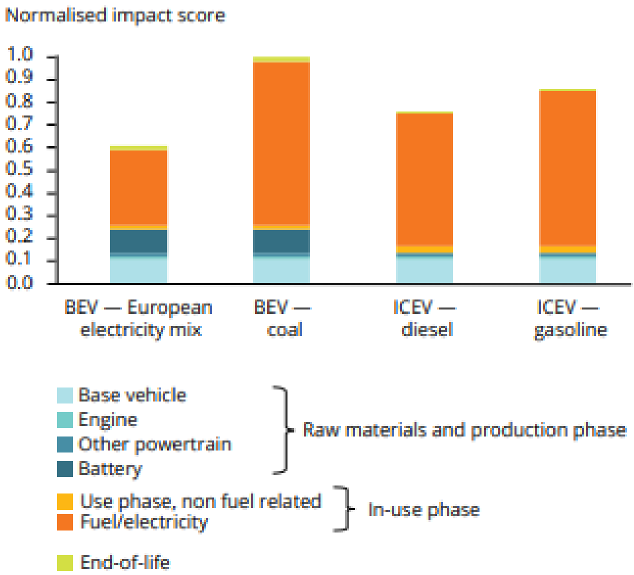

Figure 9.4 *Climate Change Impact – comparison between BEVs and ICEVs Source [8]*

Questions

1. Why is Life Cycle Assessment the best methodology for analysis of environmental impact of Electric Vehicles?
2. What stage of the product life when referring to BEVs is the most critical in terms of potential negative environmental impact?
3. How and why environmental impact of BEVs differ in active usage stage?
4. What are the methods of minimizing the impact of end of life stage for BEVs?
5. What are main concerns of the environmental impact of the BEVs on ecosystems?
6. In general, what would be the main advantage of BEVs comparing to ICVs in terms of environmental impact?

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10 Electric Mobility EU Regulations

Today's level of scientific and technological development is on the path to enabling the development of motor vehicles that would meet the challenge of overcoming all resistances during movement, saving energy, protecting the environment, and meeting the needs of modern society with full autonomy in all usage conditions.

It can be said that today we are witnessing the greatest expansion of the automotive industry since the inception of motor vehicles. Vehicle manufacturers are legally obligated to accept responsibility for all stages of the vehicle's life cycle (from development to end-of-life product disposal) from the perspective of environmental protection and the concept of sustainable development.

Ultimately, in order to avoid energy and environmental problems today and in the future, new motor vehicle production technologies are focused on producing vehicles with electric motors and autonomous driving.

The application of electric vehicles (EVs) is a potential way to decarbonize road networks, while simultaneously offering broader environmental benefits such as reducing air and noise pollution in urban areas. Technological advancements in EVs, increasing focus on renewable energy sources, potentially reducing the impact of transportation on climate change, and other important environmental issues have led to continuous growth in EV sales worldwide today. The largest acceleration in EV sales is happening in Europe, with Norway being the largest market for EV sales in Europe.

The European Union (EU) is intensively working on establishing a legal and regulatory framework for the intensified development and implementation of electric mobility. Transitioning from conventional vehicles with fossil fuels to electric propulsion and using energy from renewable sources can help in the global decarbonisation process. Additionally, the EU expresses its ambition to become a climate-neutral continent.

10.1 Existing Electric Mobility Legislation for the Western Balkans

The rapid technological development of electric vehicles has led to a lag in the legislative regulations governing their use on the road. However, the fundamental prerequisite to make EVs safe and efficient is to establish harmony between their technical solutions and regulations for their use.

Despite the economic development of certain Western Balkan (WB) countries, there is already a need for them to have national legislation in place containing provisions for the use of electric and even Level 5 autonomous vehicles (AVs).

Especially considering that the European Commission (EC), after the first traffic accident involving an autonomous vehicle with a fatal outcome in Arizona (March 2018), sent a letter to relevant EU institutions entitled "On the Road to Autonomous Driving - EU Strategy for Future Mobility."

The key reason for the delay in adopting national legislation for the use of electric vehicles, especially in the micro-mobility sector, in WB countries is conditioned by their availability in the market and to consumers. Additionally, the EC adopted a plan for a single transport market with competitive transport systems and efficient resource utilization in the White Paper (2011). The document stated that new vehicle and traffic management technologies would be crucial for reducing emissions from transport in the EU and the rest of the world. One of the defined goals in the document is to halve the use of conventional vehicles with fossil fuels in urban areas by 2030 and to completely ban their use in urban areas by 2050. The White Paper lists numerous measures, some of which relate to electric mobility, its promotion, and implementation. This indicates that WB countries need to work intensively on adopting legislation that will implement the EC's recommendations outlined in the White Paper or EU directives.

EU legislation on electric mobility should be implemented by WB countries (some of the directives: 2009/28, 2009/33, 2012/27, 2013/1316, 2014/94, 2018/674, 2018/844, 2018/858, 2018/2001, 2018/2089(INI), 2019/631, 2019/944, 2019/1161, 2019/1745, 2019/2144, 2023/1804 (repeals directive 2014/94), etc.) in order to accelerate the decarbonisation of transport, while addressing barriers related to charging infrastructure and raising public awareness about the importance of EV usage.

With the implementation of *Regulation 2019/2144/EU* [5], for the first time since 2019, the definition of an autonomous vehicle in terms of compliance with vehicle homologation regulations appears in WB countries. It is affirmative that the legislative framework of WB countries does not contain barriers to importing EVs. Additionally, it can be noted that WB countries recognize the importance of electric mobility through National Sustainable Development, Transportation, or Energy Strategies, but they are slowly beginning to establish electric mobility systems.

10.2 Regulatory Framework for Electric Mobility in the EU

The transformation of the transport sector is a significant challenge in terms of reducing domestic demand for fossil fuels (and thus imports), increasing energy security, combating local air pollution, and reducing greenhouse gas emissions in line with sustainable development goals.

The transport sector accounts for approximately 28% of global energy demand, 65% of global oil demand, and 24% of global energy-related carbon dioxide (CO_2) emissions, with road (mostly passenger) transport emitting 77%. The road transport sector, with the least diversification of final energy use, is almost entirely dependent on fossil fuels (>95% in 2018).

The European Commission (EC) in its communications sets the political framework for reducing greenhouse gases, with electric mobility being one of the necessary measures to achieve the required level. According to the Paris Agreement, EU countries have committed to making the EU climate-neutral by 2050. The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 states at the United Nations Climate Change Conference (COP21) in Paris on December 12 2015, and entered into force on November 4 2016.

The sustainability of transportation is also echoed in the European Green Deal, which aims to reduce greenhouse gas emissions from transportation by 90% by 2050. The Commission intends to adopt a comprehensive strategy to achieve this goal and ensure that the EU transport sector is compatible with a clean, digital, and modern economy. The milestones of the sustainable and smart mobility strategy are shown in Figure 10.1.

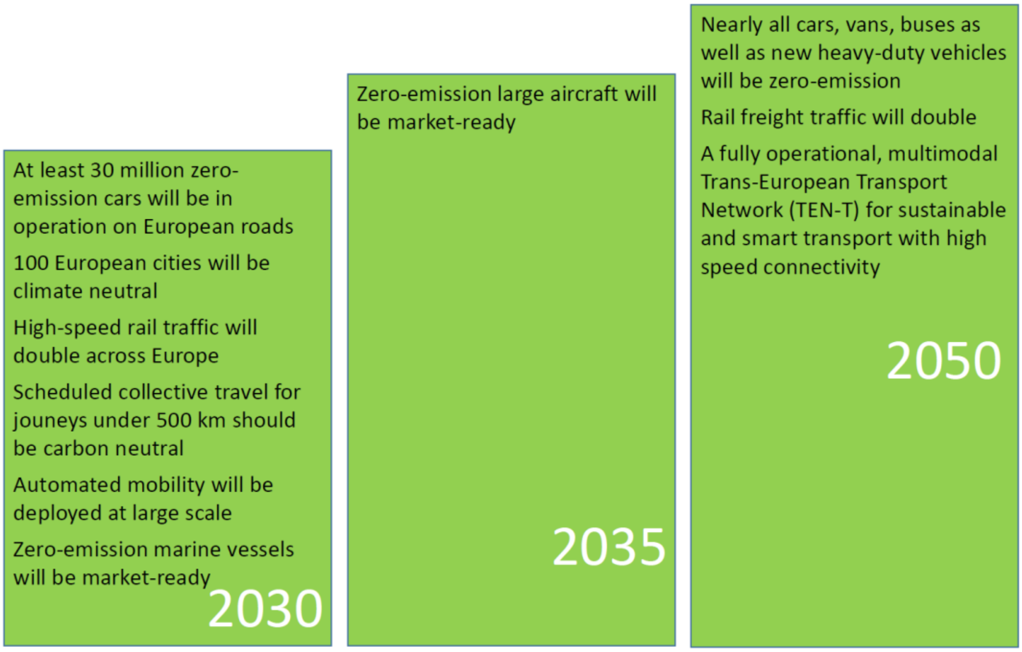

Figure 10.1. *Milestones of the sustainable and smart mobility strategy [3].*

In the EU, the transportation sector accounts for one-quarter of greenhouse gas emissions, as shown in Figure 10.2. The main goal of the EU is to achieve a sustainable, competitive, safe, and decarbonized transportation sector, with a reduction in energy consumption from fossil fuels, so that the growth of electric mobility in Europe can be achieved through coordination of legislative frameworks, institutional, and financial aspects.

To strengthen the EU´s actions towards sustainable transport and mobility, the urban mobility package was adopted in 2013. The action plan provides recommendations for all levels of government as well as other important stakeholders such as public and the private sector to participate in actions toward more sustainable urban mobility. More recent initiatives in this area include the EU Urban Agenda established in 2016 and the Partnership Action Plan on Urban Mobility finalised in 2018. From the environmental perspective, the most significant EU transport policies and strategies include the Eurovignette Directive and its revisions; the directive on alternative fuels infrastructure; the air pollutant and greenhouse gas emission standards for cars, vans, and heavy-duty vehicles; the revised Clean Vehicle Directive; and the Environmental Noise Directive [3].

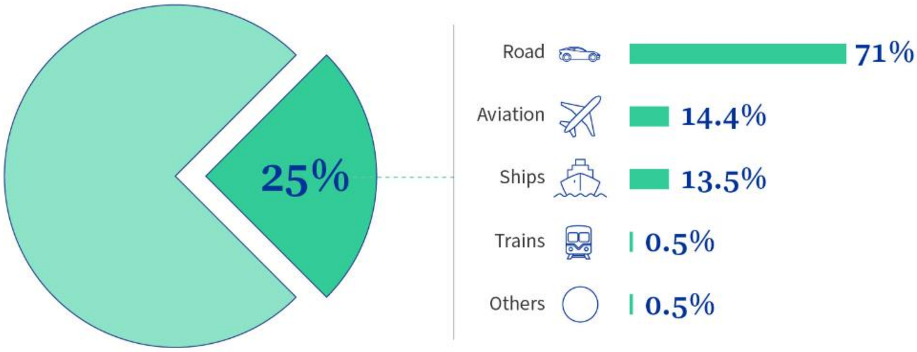

Figure 10.2. *Share of the transportation sector in the EU's greenhouse gas emissions [12]*

The timeline of the most important milestones in the development of EU transportation legislation and strategic documents is shown in Figure 10.3, while Figure 10.4 illustrates the regulatory framework for electric mobility in the EU.

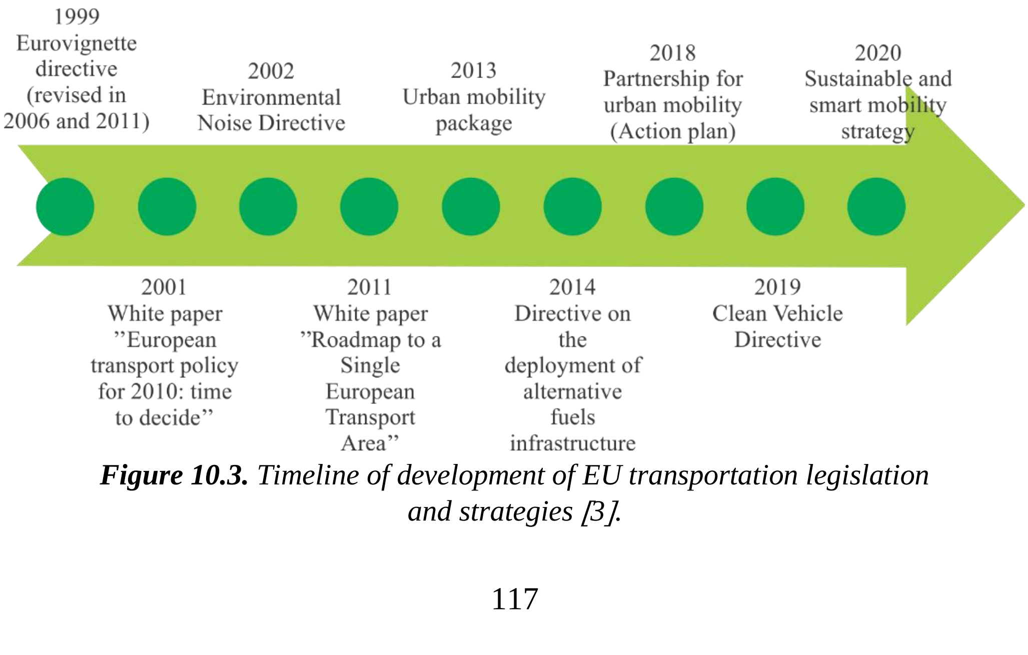

Figure 10.3. *Timeline of development of EU transportation legislation and strategies [3].*

A new National Emissions Ceiling (NEC) *Directive 2016/2284/EU* entered into force on 31 December 2016. Replacing earlier legislation, it sets 2020 and 2030 national emission reduction commitments for EU member states for five main air pollutants that contribute to the negative impact on the environment and human health. Although not directly focused on transport, a very close connection can also be found with the "Clean Energy for all Europeans package" focused to the transition from fossil fuels towards cleaner energy [3].

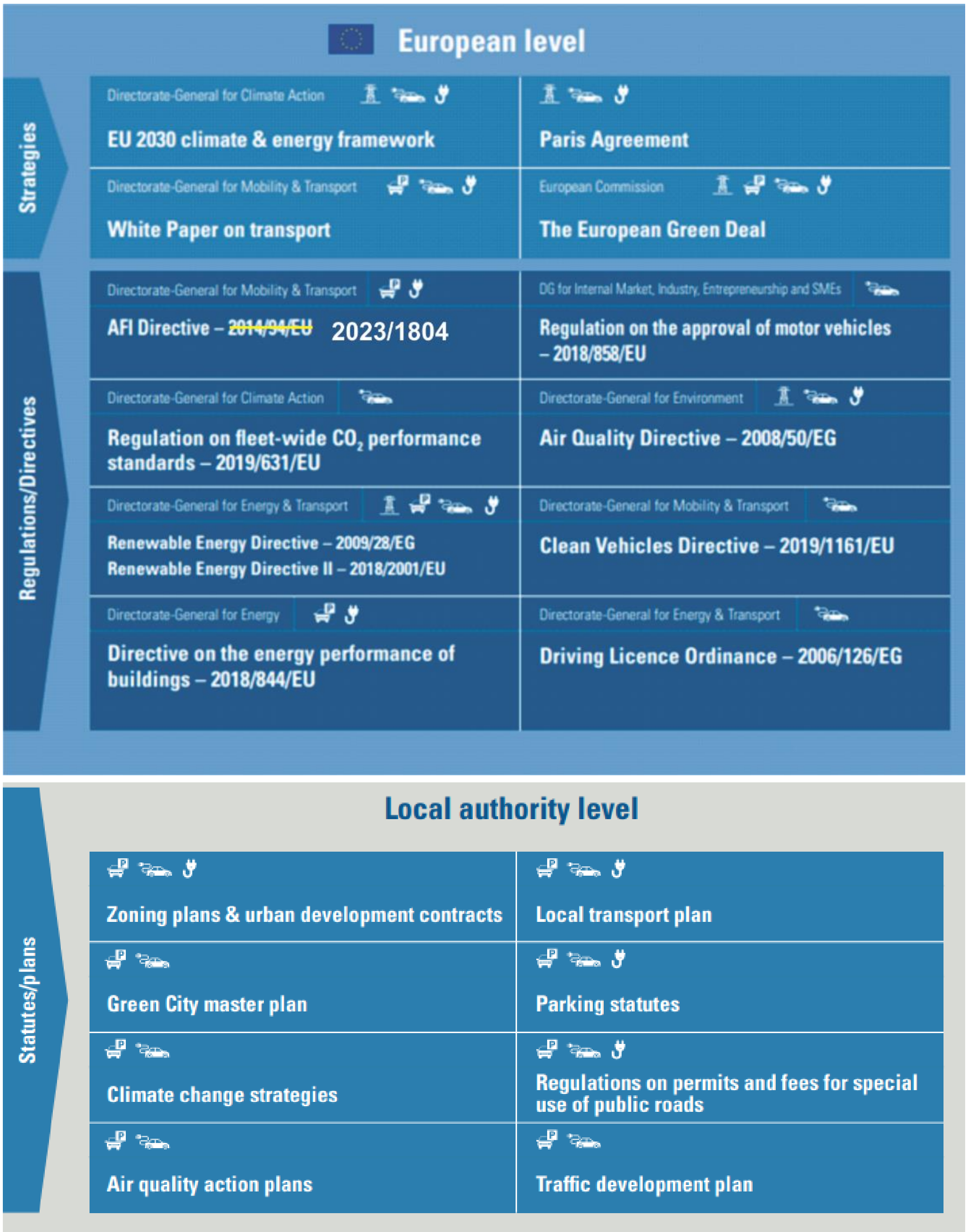

Figure 10.4. *Regulatory framework for electric mobility [6].*

In November 2018, the Commission adopted the communication "A clean planet for all: a European strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy". It provides a vision for a climate-neutral Europe through a positive long-term transformation focused for example on energy efficiency, deployment of renewables, and more circular and resource-efficient economy including bio-economy and natural carbon sinks but also to cleaner, safer, and connected mobility [3].

So, with its European Green Deal, the EU has set itself the objective of making Europe the world's first climate-neutral continent by 2050. In the transport sector, air pollutant emission limits are to be tightened for vehicles with internal combustion engines and alternative fuels are to be supported by paving the way towards zero emission mobility and in particular by significantly expanding the charging post infrastructure to meet the objectives of the European Green Deal.

10.2.1 Legislation for Greener Vehicles

Directive 2009/33/EC [7], adopted by the European Parliament and the Council of the European Union on April 23 2009, concerning the promotion of clean and energy-efficient road vehicles, addresses the need to provide support for EU member states to enable and structure exchanges of knowledge and best practices in promoting the purchase of clean and energy-efficient vehicles, i.e. accelerating the use of electric vehicles. This directive recommends that when purchasing road vehicles, the following factors should be considered, as shown in Figure 10.5:

- Energy consumption,
- Carbon dioxide (CO_2) emissions,
- Nitrogen oxides (NOx) emissions,
- Non-methane hydrocarbon (NMHC) emissions, and
- Particulate matter (PM).

Figure 10.5. *Harmful substances in the exhaust emissions of motor vehicles [10].*

Due to certain shortcomings, especially in accelerating the process of decarbonizing the transportation sector and procuring environmentally cleaner vehicles, *Directive 2009/33/EC* [7] was amended and supplemented on June 20, 2019, by *Directive 2019/1161/EU*.

Directive 2019/1161/EU [15] introduces a second package of proposals aimed at contributing to the EU's pursuit of low-emission mobility. This package of proposals, presented in the EC Communication of November 8 2017, entitled "Delivering on low-emission mobility - A European Union that protects the planet, empowers its consumers, and defends its industry and workers" includes a combination of supply and demand-oriented measures to position the EU on the path to low-emission mobility while simultaneously enhancing the competitiveness of the EU mobility ecosystem. The promotion of clean vehicles should proceed in parallel with further development of public transportation as a means to reduce road congestion, thereby decreasing emissions and improving air quality, as shown in Figure 10.6.

Figure 10.6. *Promotion of clean and energy-efficient vehicles for road transport European Union [12]*

By introducing new technologies, emissions of carbon dioxide (CO_2) from vehicles can be reduced, along with decreasing air and noise pollution, while aiding the decarbonisation of the transportation sector. Increased use of road vehicles with low and zero emissions will lead to a reduction in CO_2 emissions and certain pollutant emissions (such as particulate matter, nitrogen oxides, and non-methane hydrocarbons), thus improving air quality in cities and other polluted areas, while simultaneously contributing to the competitiveness and growth of the EU industry.

10.2.2 Legislation for the Infrastructure

The future of electric vehicles is bright, as production and usage costs for batteries are rapidly declining. In addition, more and more affordable, long-range electric vehicles are being produced that run entirely on electricity and can significantly increase their range.

One of the drawbacks is the lack of an adequate number of charging stations. This problem can be overcome as the number of electric vehicles increases. Especially when it comes to developing countries, special emphasis should be placed on the proportional development of electric vehicle charging stations alongside the number of electric vehicles themselves. Therefore, the construction of electric vehicle charging stations must be a focus of every country.

Directive 2014/94/EU, adopted on October 22, 2014, was enacted to establish infrastructure for alternative fuels.

Prior to the adoption of *Directive 2014/94/EU*, it was observed that the lack of coordinated infrastructure for alternative fuels across the EU and the hindered introduction of alternative fuel vehicles to the market were delaying the benefits these vehicles could have for the environment. In its communication of November 8, 2012, entitled "CARS 2020: Action Plan for a competitive and sustainable automotive industry in Europe," the EC adopted the main recommendations from the report of the CARS 21 High-Level Group of June 6, 2012, and presented an action plan based on them. This Directive contains key recommendations regarding infrastructure for alternative fuels announced by the EC. Based on *Directive 2014/94/EU*, investments in sustainable mobility and the establishment of infrastructure for alternative fuels in the EU have been initiated, and the EC and EU member states will adopt a framework for national policies for the development of alternative fuel markets in the transport sector and the establishment of infrastructure for vehicles using alternative fuels.

Through *Directive 2018/674/EU* [17] of November 17, 2017, *Directive 2014/94/EU* was amended and supplemented regarding locations for charging motor vehicles of category L, shore-side electricity supply for inland waterway vessels, hydrogen supply for road transport, and natural gas supply for road and inland waterway transport.

Through *Directive 2019/1745/EU* [18] of August 13, 2019, *Directive 2014/94/EU* was amended and supplemented, and *Directive 2018/674/EU* was repealed.

So, *Directive 2019/1745/EU* is amendment of *Directive 2014/94/EU* of the European Parliament and the Council as regards charging points for L-category motor vehicles, shore-to-land electricity supply vessels for waterways, hydrogen supply for road transport and natural gas supply for road and water transport and repeal of Commission Delegated Regulation 2018/674/EU.

Provisions for ‘interoperability’ in the context of this Delegated Regulation strictly refer to the capacity of recharging and refuelling stations to supply energy that is compatible with all vehicle technologies in order to allow seamless EU-wide use of alternative fuels vehicles.

Directive 2023/1804/EU [19], adopted by the European Parliament and the Council of the EU on September 13, 2023, regarding the establishment of infrastructure for alternative fuels, repeals *Directive 2014/94/EU* and will be applicable from April 2024. One of the main goals of *Directive 2023/1804/EU* is to establish publicly accessible infrastructure for charging road vehicles with alternative fuels. Additionally, the Directive aims to address the uneven distribution of publicly accessible electric vehicle charging infrastructure across the EU, as the European Parliament and the Council consider that the use of light electric vehicles is jeopardized, thereby limiting connectivity across the EU.

Questions

1. Does the legislative framework of the countries of the Western Balkans (WB) contain barriers to the import of electric vehicles (EVs)?
2. What should contribute to the introduction of new technologies in the production of vehicles, and especially in the part of the introduction of the electric engine?
3. What does Directive 2019/1161/EU refer to?
4. What does Directive 2014/94/EU refer to?
5. Which directive is repealed by Directive 2023/1804/EU?
6. Define one of the main objectives of Directive 2023/1804/EU!

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