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REVOLUTIONIZING VET:AR TRAINING FOR ELECTRIC CARS

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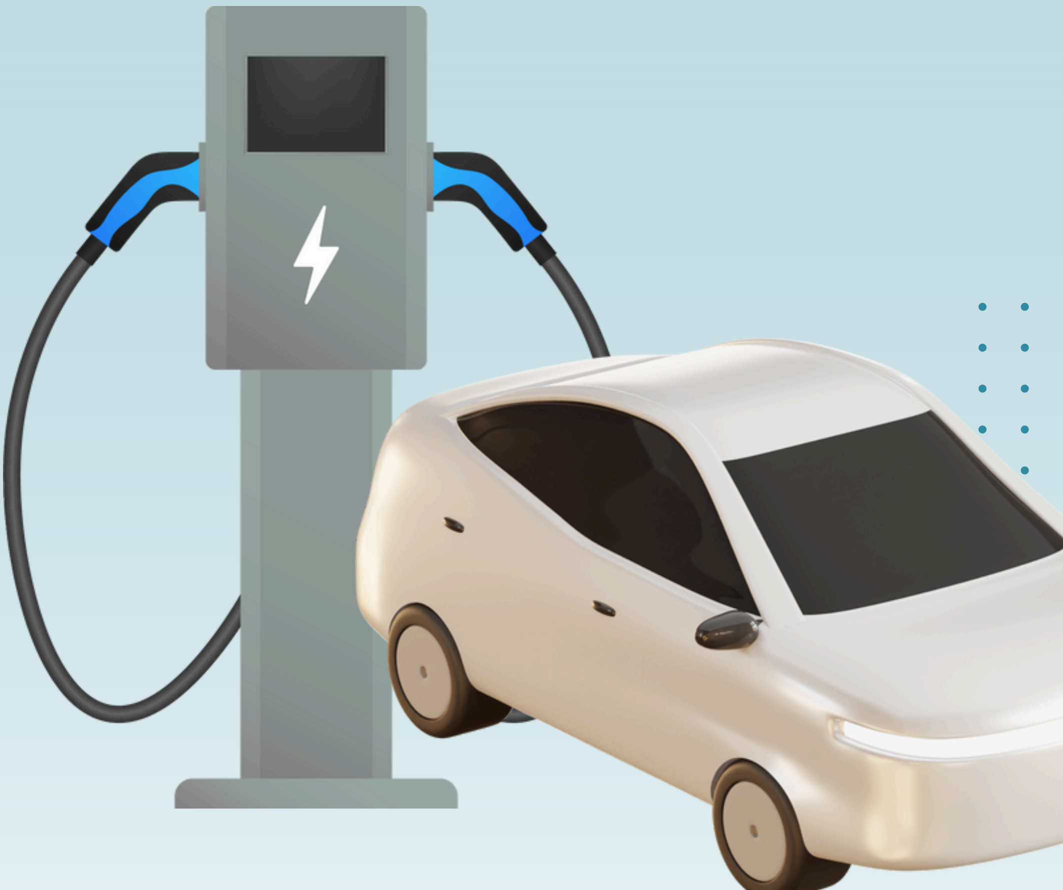
Project Overview

The Merging VET with AR project aims to equip vocational education students with the modern skills, knowledge, and practical experience required to succeed in the rapidly evolving electric vehicle (EV) industry. This curriculum integrates cutting-edge augmented reality (AR) technologies with comprehensive EV-related content—covering battery systems, propulsion technologies, converters, charging infrastructure, and safety protocols. By combining theory, case studies, interactive simulations, and engaging visual materials, the program enhances student engagement, deepens understanding, and improves knowledge retention. Ultimately, it seeks to prepare learners for future-proof careers in the automotive sector by bridging the gap between current vocational training and the demands of the next generation of motor vehicle technologies.

CHAPTER-1

BATTERY ELECTRIC VEHICLES



1-BATTERY ELECTRIC VEHICLES

The general battery electric vehicle (BEV) is conceptually illustrated in Figure 1. As shown Figure 1 drive train consists of three different subsystems as **electric propulsion subsystem, energy source subsystem and auxiliary subsystem.**
Electric propulsion subsystem has an electric traction motor, power converter, electronic control unit, thermal management system and mechanical transmission.

Ø **Electric motor** take power from the traction battery pack, this motor drives the vehicle's wheels. Recently, battery electric vehicles use motor generators that perform both the drive and regeneration functions.

Ø **Power electronics** controller manages the flow of electrical current delivered by the traction battery, controlling the speed of the electric traction motor and the torque it produces.

Ø **Thermal manangement system (cooling):** This system maintains a proper operating temperature range of the engine, electric motor, power electronics, and other components.

Ø **Mechanical transmission (electric):** The transmission transfers mechanical power from the electric traction motor to drive the wheels.

The energy source subsystem includes the battery and energy management unit and the energy
refueling unit.

Ø **Traction battery pack** stores electricity for use by the electric traction motor.

Ø **Battery (for auxiliary)** provides electricity to power vehicle accessories.

Ø **DC/DC converter** converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery.

Ø **Charge port** allows the vehicle to connect to an external power supply in order to charge the traction battery pack.
Onboard charger takes the incoming AC electricity supplied via the charge port and converts it to DC power for charging the traction battery. It also communicates with the charging equipment and monitors battery characteristics such as voltage, current, temperature, and state of charge while charging the pack

The auxiliary subsystem consists of the power steering unit, the hotel climate control unit, and the auxiliary supply unit.

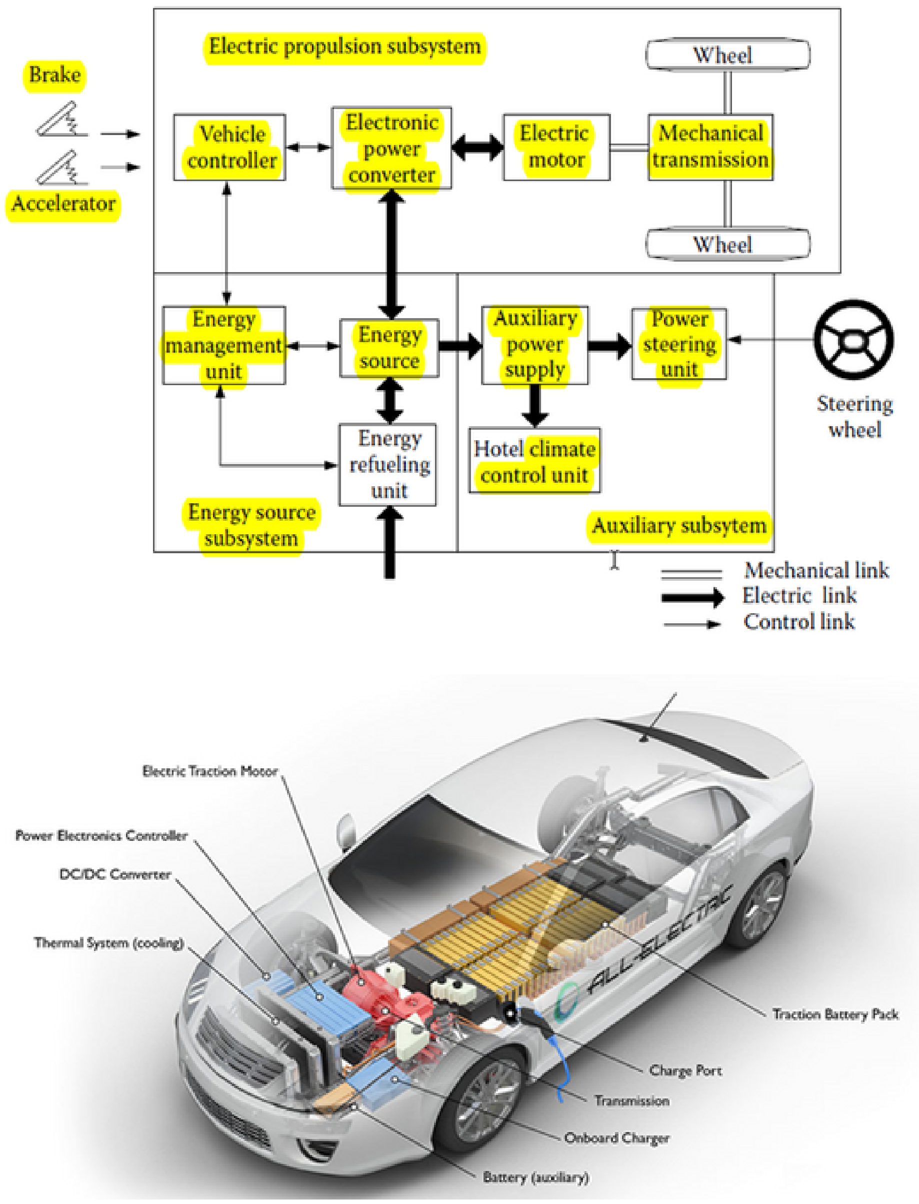


Figure 1. Conceptual illustration of a general BEV configuration

Figure 2 also shows different types of battery electric drive system components. Battery electric drive system includes high voltage DC/DC converter (1), vehicle control unit (2), eAxle system (motor and transmission, power electronics) inverter (4), separate motor-genarator (5), 400 V battery (6), Charger (7), Gearbox (8), 12 V Battery (9).

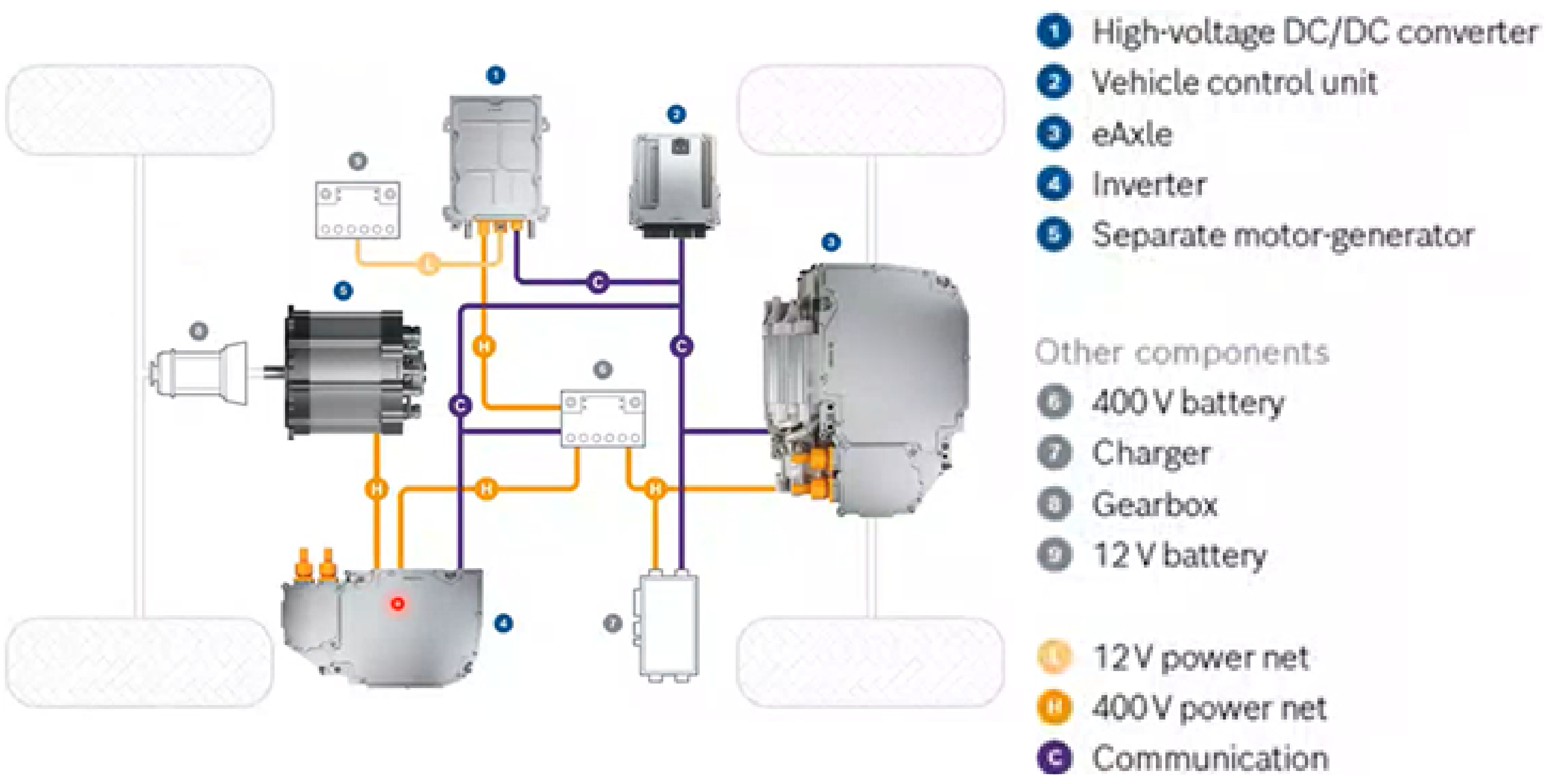


Figure 2. BEV drive systems

1.1 - ELECTRIC PROPULSION SUBSYSTEM

Electric propulsion systems are at the heart of BEVs. They consist of electric motors, power converters and electronic controllers as shown Figure 3. The electric motor has two main works. Firstly, they convert the electric energy into mechanical energy to propel the vehicle, secondly they use to enable regenerative braking and/or to generate electricity. The power converter is the brain of the electric vehicles and carries proper bidirectional voltage and current between electric motor and on-board energy storage. The vehicle control unit take a signal from the driver by usage of accelerator pedal and brake pedal and then send the control signals to the power converter which controls the operation of the electric motor to produce proper torque and speed.

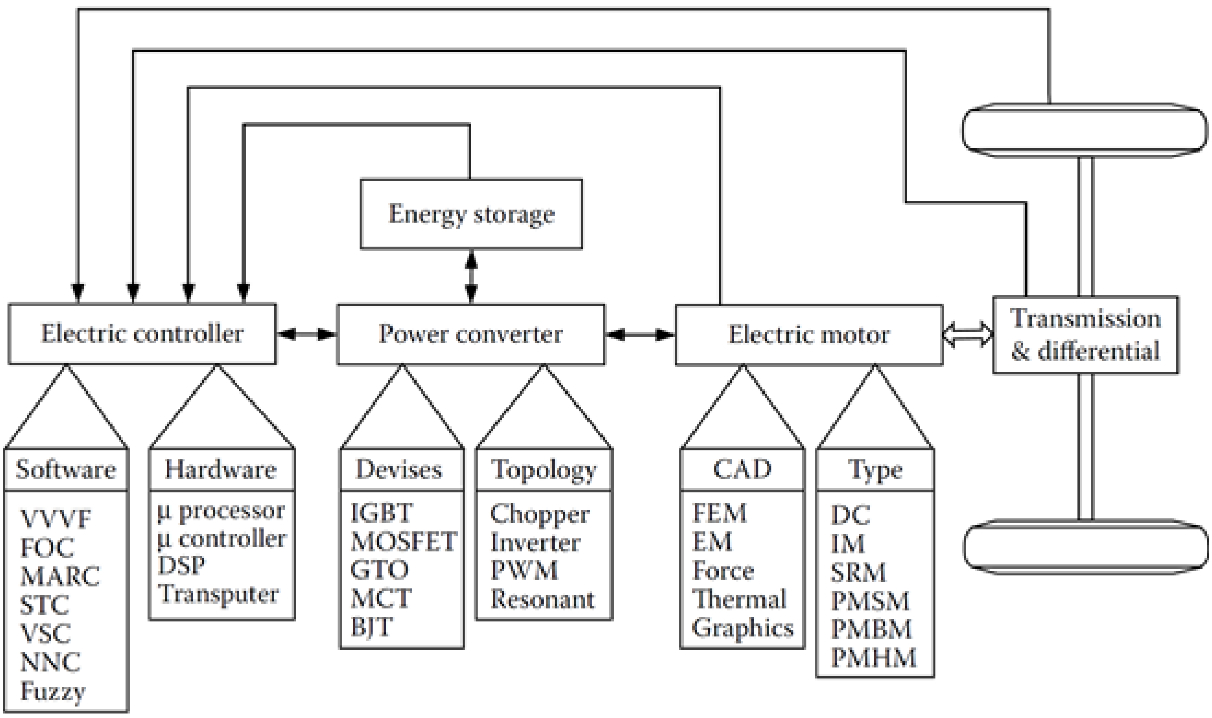


Figure 3. Functional block diagram of a typical electric propulsion system.

1.1.1 - INTRODUCTION OF ELECTRIC MOTORS

The motors used in EVs and HEVs usually require frequent starts and stops; high rates of acceleration/deceleration; high torque and low-speed hill climbing; low torque and high-speed cruising, and a very wide speed range of operation. The motor drives for EVs can be classified into two main groups, namely the commutator motors and commutatorless motors, as illustrated in Figure 4.

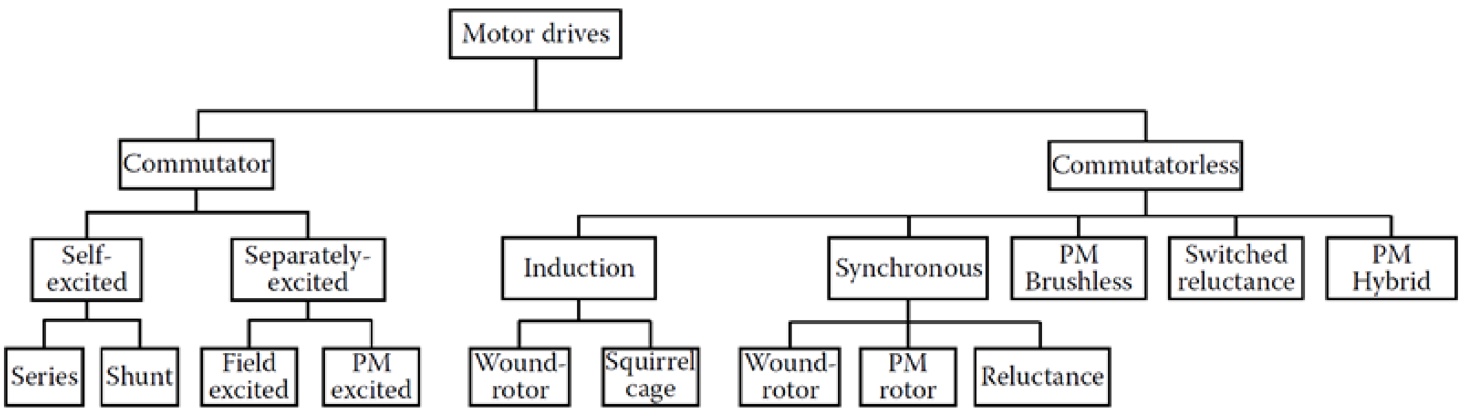


Figure 4. Electric motor drivers for electric vehicles applications

1.1.1.1 - DC MOTORS

DC motors are known commutator motors. There are different types of DC motor used in the electric propulsion systems as series excited, shunt excited, compound excited, separately excited, and permanent magnets (PMs) excited motors as shown Figure 5.

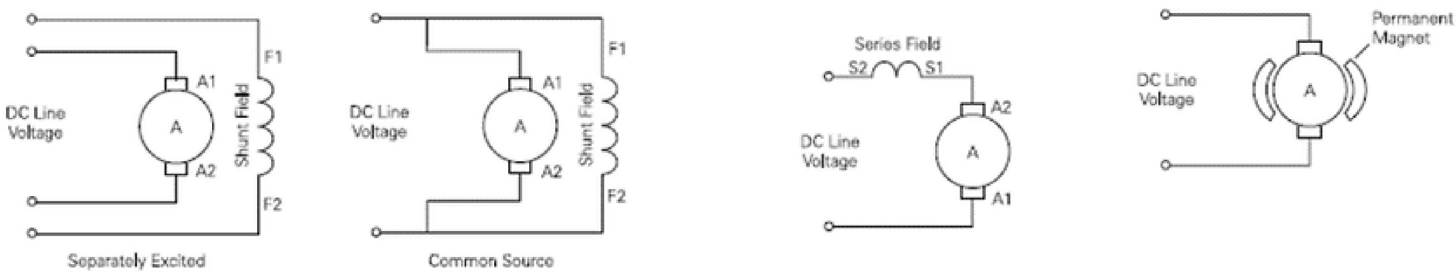


Figure 5. Types of DC Motor

DC motors need commutators and brushes to feed current into the armature as shown Figure 6, thus making them less reliable and unsuitable for maintenance-free operation and high speed. In addition, winding-excited DC motors have low specific power density and drop in efficiency due to generating heat in the brushes. It can be clearly said that because of these disadvantages of the DC motor they cannot use in the electric vehicles.

The other type of DC motor is brushless permanent magnet BLDC motor as given Figure 7. Compared to the brushes DC motor, BLDC motor is more reliable and more suitable for maintenance-free operation. In addition, it has high starting torque, high efficiency and also high power density for low power (60 kW) electric vehicles. On the other hand, this type of DC motor has short constant power range, its torque decreased with increase in speed and high cost due to permanent magnet.

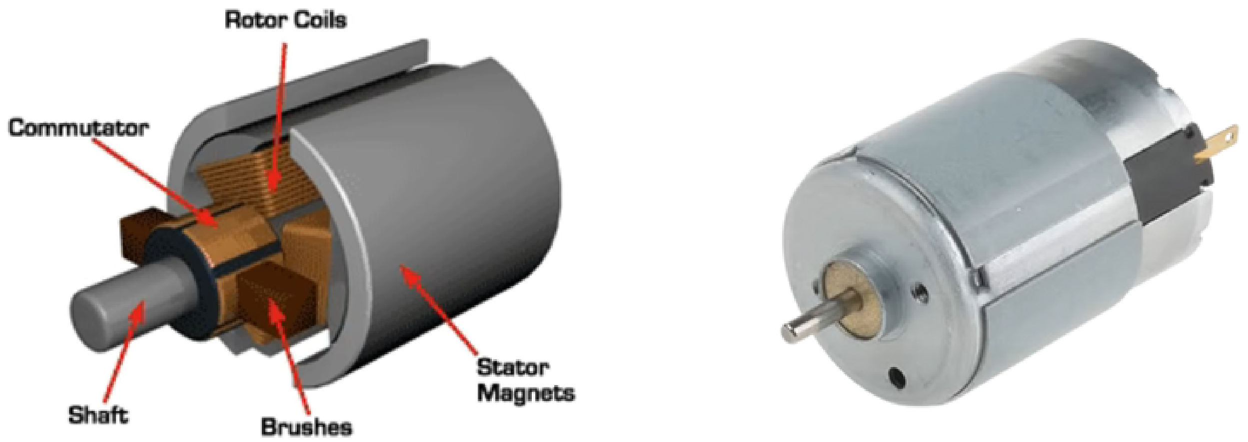


Figure 6. Brushed DC Motor

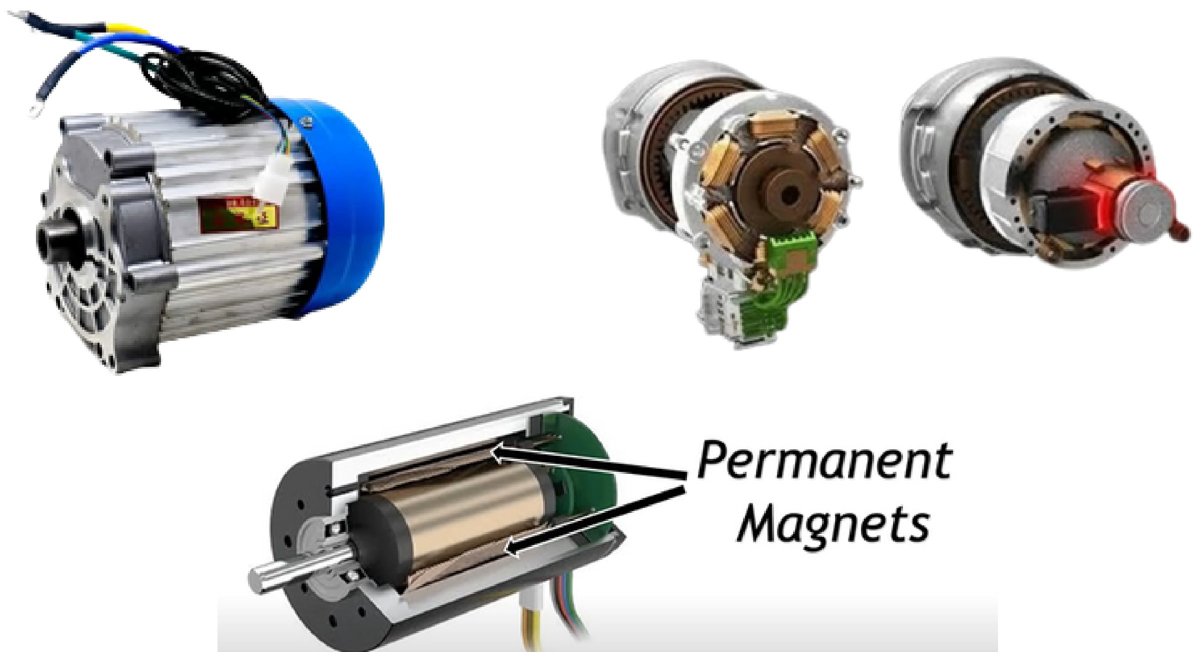


Figure 7. Brushless DC Motor (BLDC)

1.1.2 -INDUCTION MOTORS

Induction motors are known as a commutatorless motor type for EV propulsion as shown Figure 8. This is because of their low cost, high reliability, and maintenance-free operation. However, conventional control of induction motors such as variable-voltage variable-frequency cannot provide the desired performance. It has complex inverter circuit and control of induction motor is difficult. Therefore, this type motor can use to obtain high power density by usage vector and field oriented control topologies.

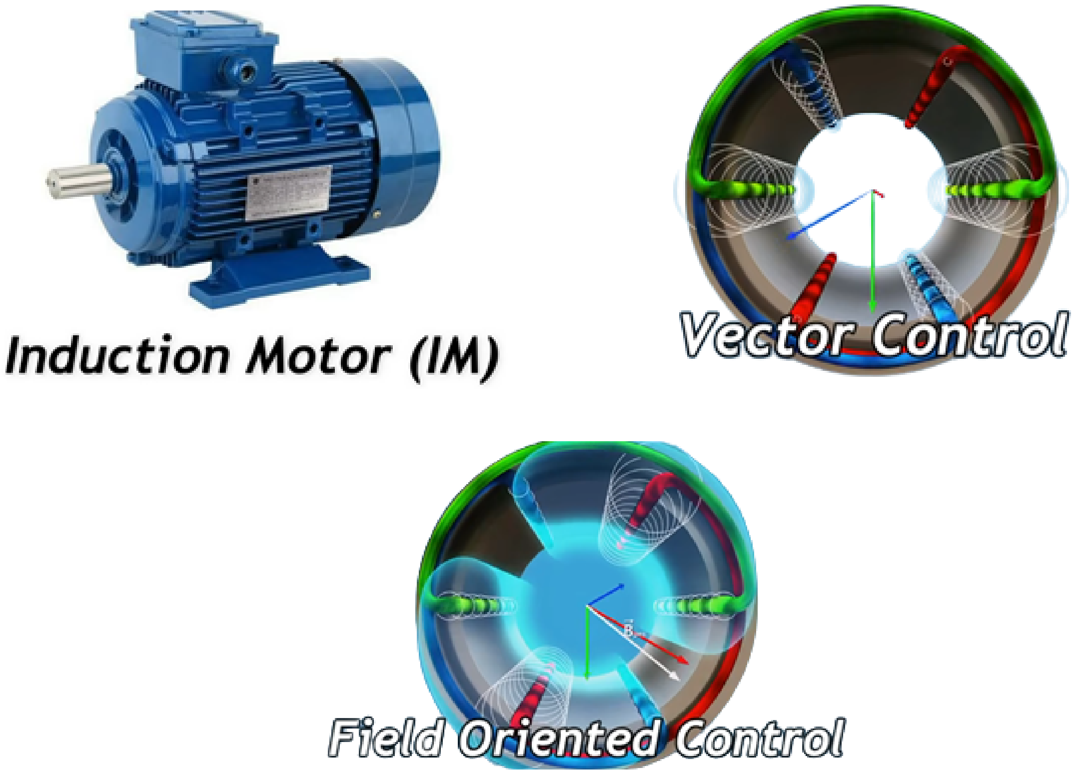
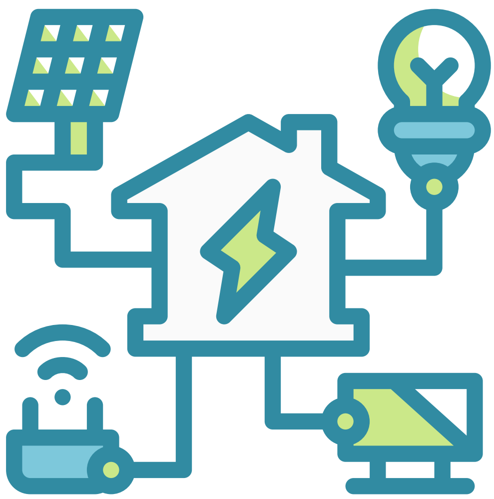


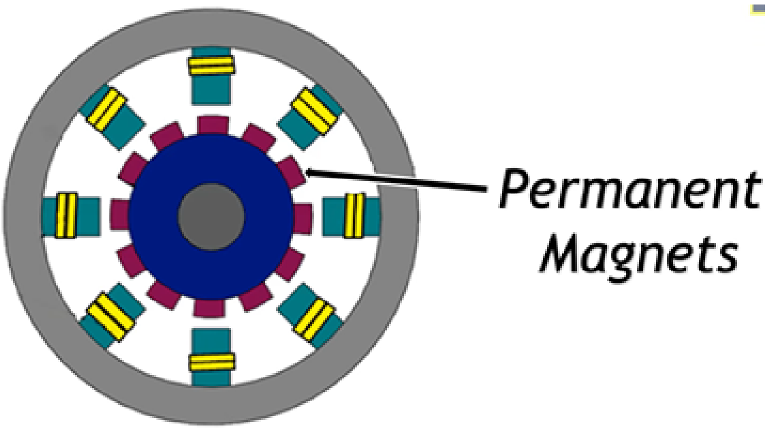
Figure 8. Induction motor and control topologies

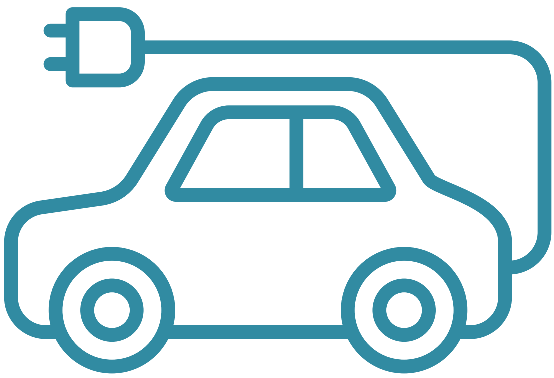


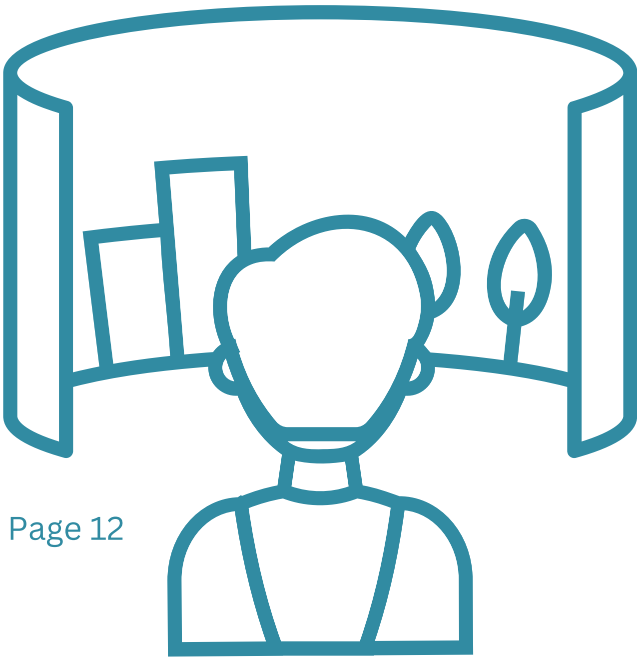
1.1.3 -SYNCHRONOUS MOTORS

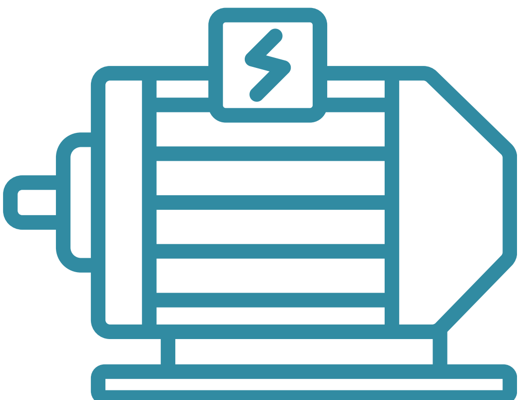
ermanent magnet PM synchronous motors can eliminate conventional brushes, slip rings, and field copper losses and they also called PM brushless AC motor. They can control by usage pulsed waveform modulation (PWM supply) without electronic commutation. They give high torque at low speeds and can operate in different speed ranges without gear set. They have been widely used electric vehicles because of their high power density and high efficiency. It can be only said that their disadvantages are expensive as compared other type motors and huge iron loss.

Permanent Magnet Synchronous Motor (PMSM)









1.2 - PHYSICAL CONTROL, MAINTENANCE AND REPAIR TRAINING OF ELECTRIC MOTOR AND CONNECTIONS

Permanent magnet PM synchronous motors can eliminate conventional brushes, slip rings, and field copper losses and they also called PM brushless AC motor. They can control by usage pulsed waveform modulation (PWM supply) without electronic commutation. They give high torque at low speeds and can operate in different speed ranges without gear set. They have been widely used electric vehicles because of their high power density and high efficiency. It can be only said that their disadvantages are expensive as compared other type motors and huge iron loss.

1.2.1 - PHYSICAL CONTROL

Thermal damage control: A blackening in the body when the sockets are removed, arc formation control, melting in the socket high voltage cables (HVC) melting.

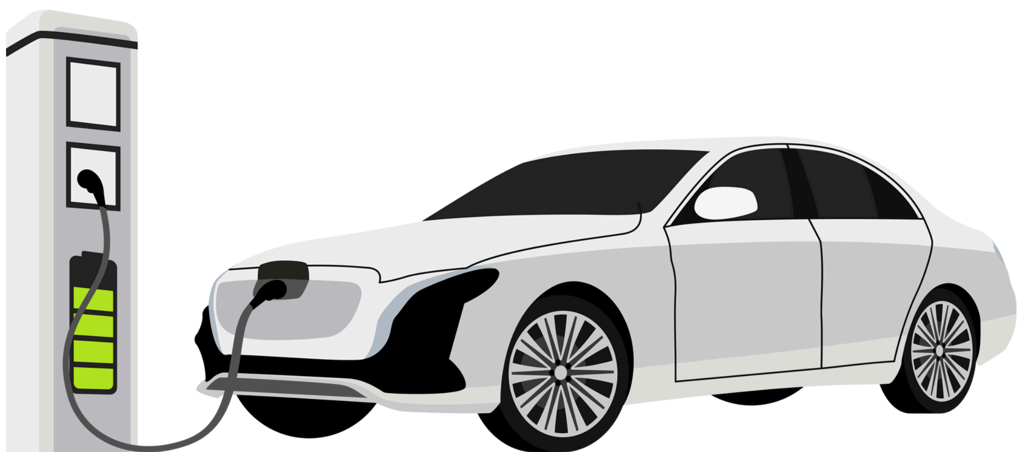
1.2.2 - VISUAL CONTROL

Cooling fluid and oil leakage in the electric motor varies according to the type of motor. Only cooling coolant leakage can be observed in PMSM. Breakage or breakage control is performed in case of breakage of the motor.

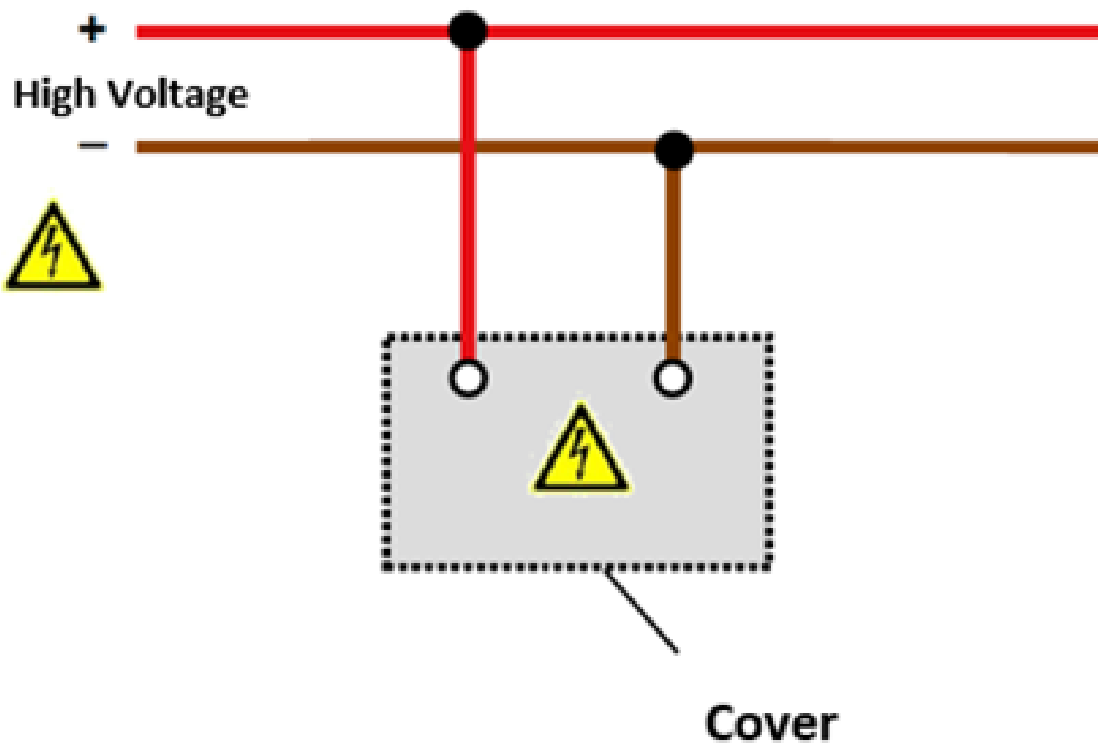
1.2.3 - ELECTRICAL CONTROL

Insulation Measurement;
For the insulation of the HV + cable to the body, the resistance between HV + and the body is measured.
For the insulation of the HV - cable to the body, the resistance between HV - and the body is measured.

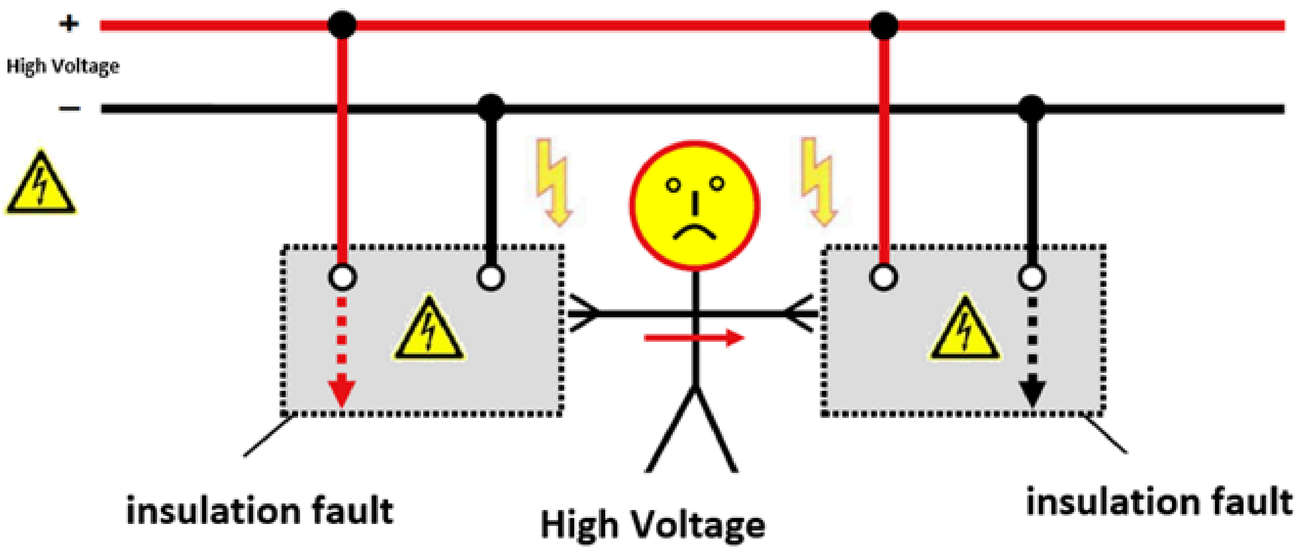
ECE R 100 is used for changes whether the measurements meet the standards. According to this standard, 500 ohm/V should not be kept below this value.



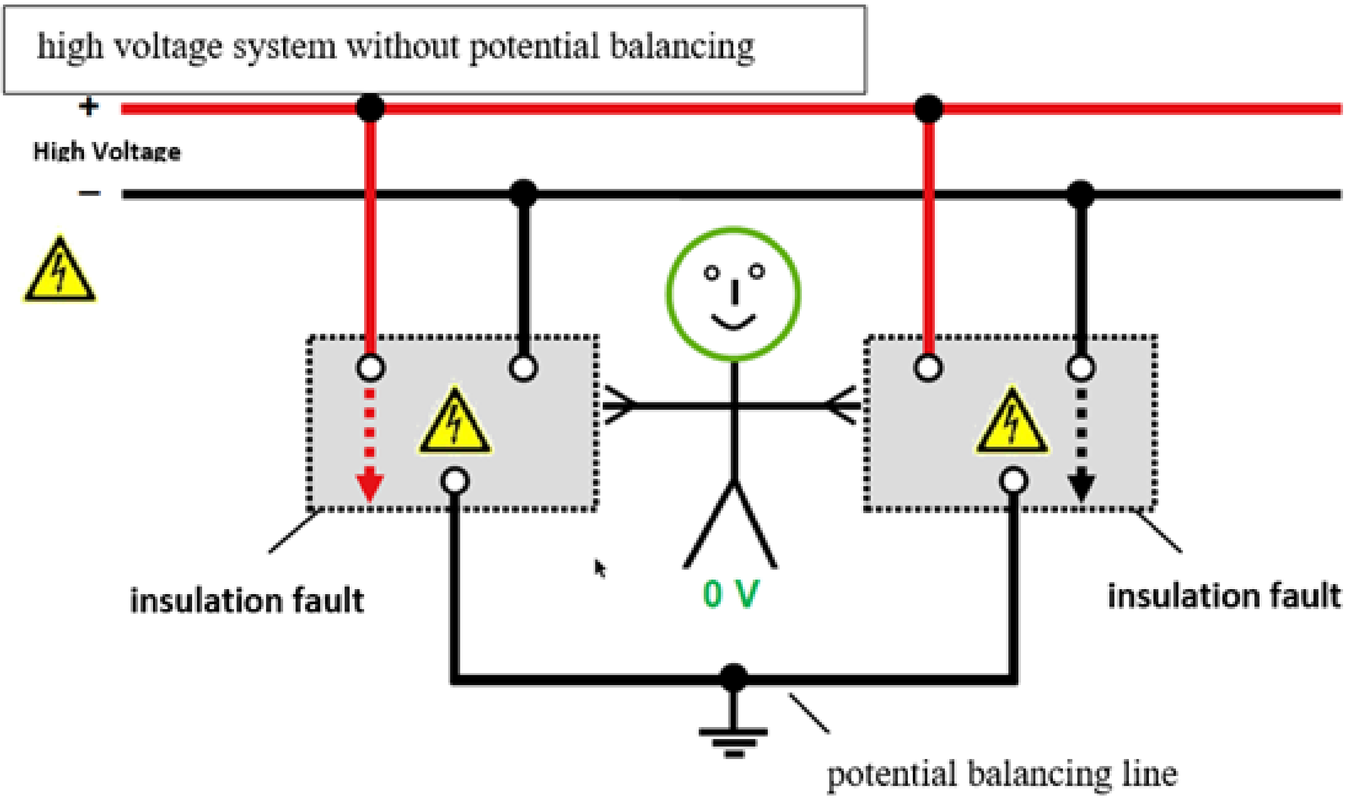
IT NETWORK in HV SYSTEM



high voltage system without potential balancing



Potential Balancing Measurement;
All components operating with high voltage have a ground connection. The resistance between this connection point and the body must not be above the 200 milliohm according to the standard for ECE R 100.

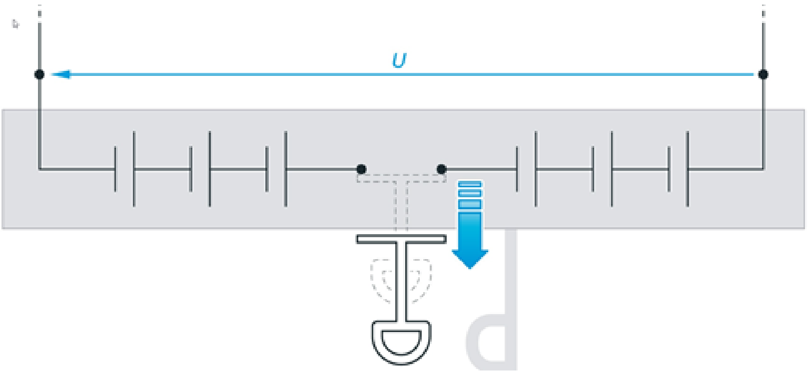


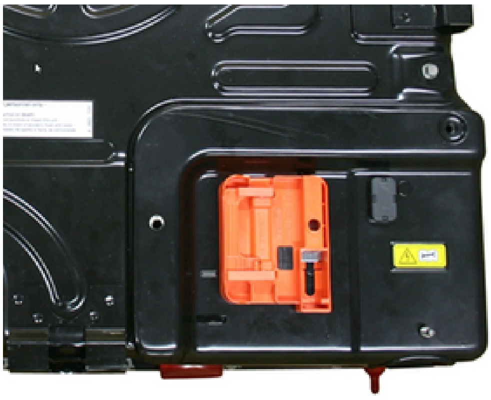
1.2.4 - TRAINING TO IDENTIFY AND RESOLVE ERROR CODES IN ELECTRIC MOTOR / GENERATOR CONTROL SYSTEMS

Electrical Errors; Insulation Error, Rotor sensor errors, temperature sensor errors, IGBT errors, Inverter/Converter Errors.
Physical Failures; Electric Arc, High Temperature Control Switch Damage, Physical Damage to the Body

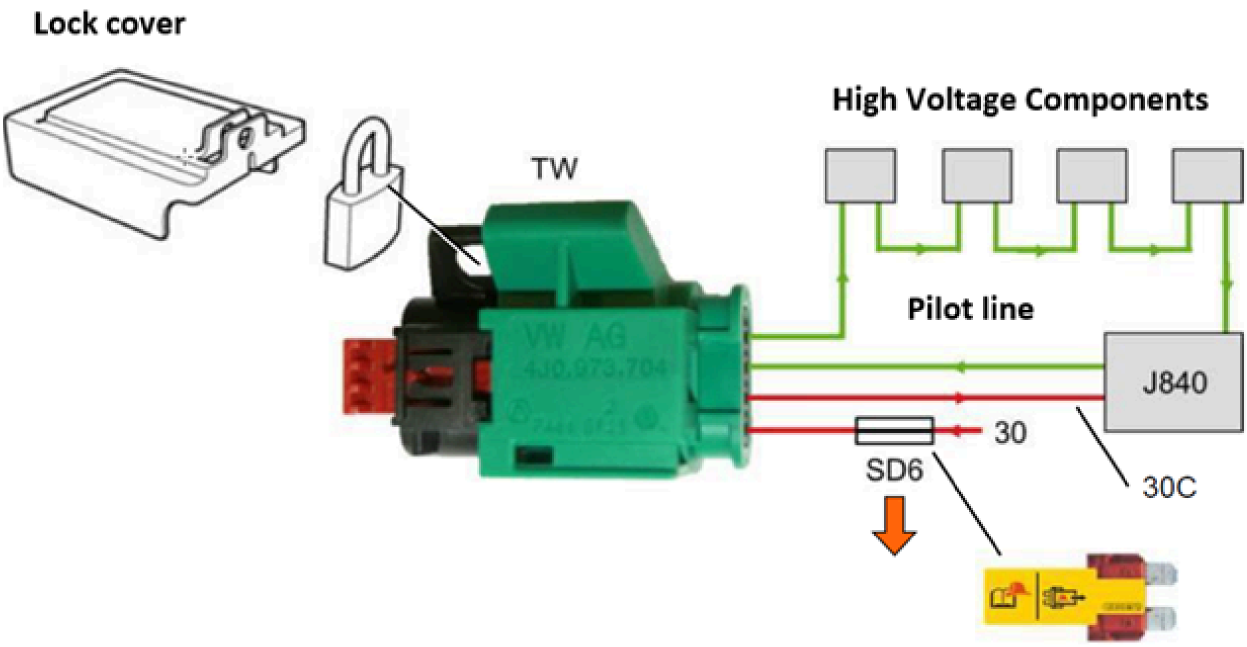
1.2.5 - SAFE DEACTIVATION AND ACTIVATION TRAINING ON THE HIGH VOLTAGE

Physical Shutdown; The serial connection point between the battery modules is controlled by a mechanical switch. If this mechanical switch is physically removed, the high voltage line will be cut off. After the switch is removed from the system, the battery output voltage is measured 5 minutes later to check whether the capacitors are discharged.





Logical Closure; By separating a signal line (interlock loop) or the contactor supply line, the contactors are opened and thus the high voltage is again shut down. In emergency cases, this line can be cut directly to ensure safety.



1.2.6 - CURRENT AND VOLTAGE VALUES UNDER LIVE VOLTAGE ARE MONITORED AND CONTROLLED BY PROFESSIONALS.

1.2.7 - CONTROL OF BATTERY MANAGEMENT SYSTEM AND COMPONENTS

Physical Control Training of the Battery Pack (battery and all sub-units on the battery)
Visual inspection before removing the battery; Melting, tarnishing and physical deformation on the body are checked.
Visual check after removing the battery; Liquid check, lithium leak check (leaves a white stain inside the module, this can be understood from here), check on connection sockets (high and low voltage cables are checked), smoke and odor check, color check on ventilation valves.

Battery Unit, Battery Management System and Communication Control Training
The voltage values of all cells in the battery are read and monitored diagnostically. A possible cellular disorder will disrupt the voltage balance between the cells. This will cause a decrease in performance and range. After the damaged cell is detected by the diagnostic device, the relevant module is replaced.

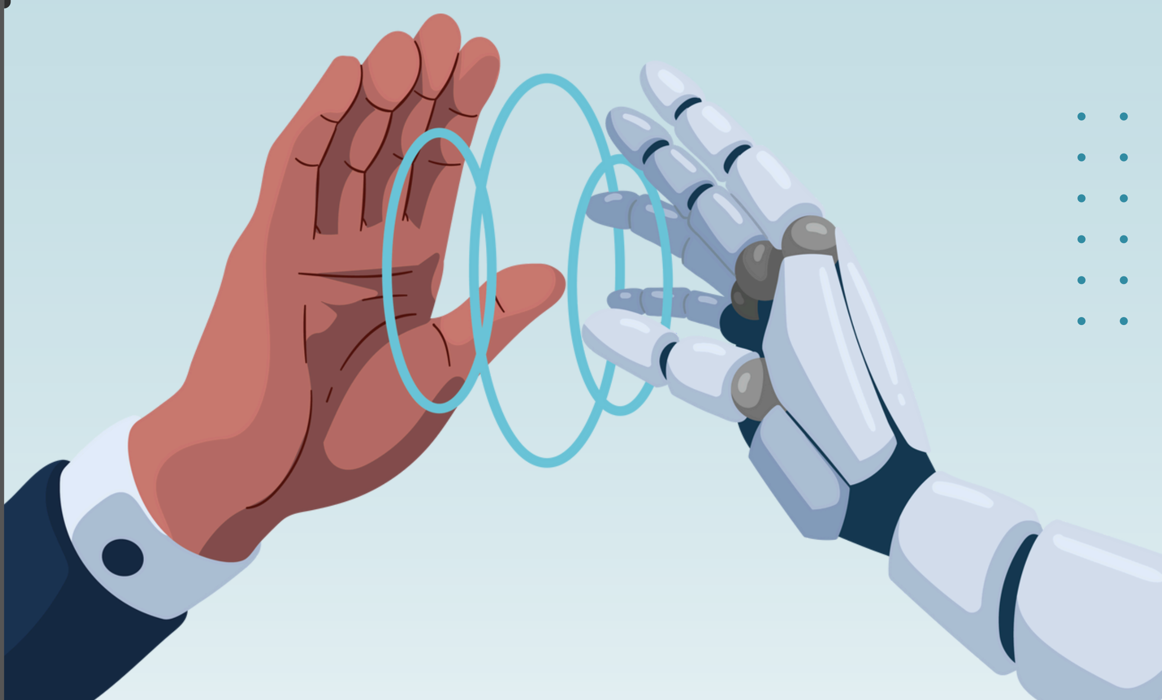
High Voltage Battery Training: Condition Assessment, Safe Storage, and Handling of Faulty/Damaged Units
Check for smoke, burns, heat generation, cracks in the casing, physical deformation, corrosion, loose connection, serial number and security label.

1.2.8 - ELECTRIC DRIVE COOLING AND HEATING SYSTEM MAINTENANCE AND REPAIR

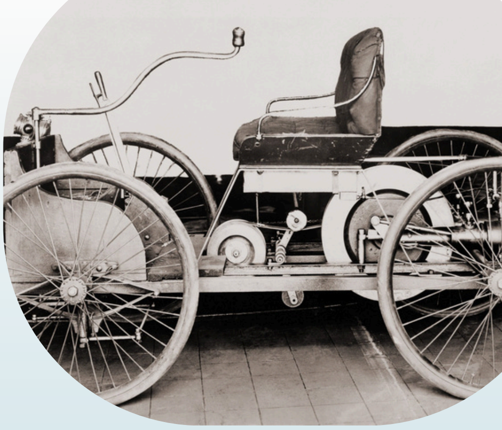
The control consists of 3 parts. It is carried out in the form of pressure control. The pressure control test is carried out at pressure values in accordance with the manufacturer's instructions.
Ø Battery Circuit
Ø Electric Motor Circuit
Ø General Cooling Circuit
The check should always start from the battery circuit. Otherwise, if there is a liquid leak in the battery when pressure is applied to other circuits, all the cooling liquid will fill into the battery.
Then, the pressure control is done in the electric motor circuit. If there is a liquid leak in the electric motor when the pressure is applied, all the cooling liquid will fill into the electric motor.
A general pressure test is applied to the general cooling circuit. This tests the cooling system equipment and leaks at the connection points.

CHAPTER-2

CHARGING SYSTEMS AND INFRASTRUCTURE



History of Electric vehicles



Electric vehicles have a long and storied history. The interest for them largely varied over the years due to environmental issues and available energy resources.

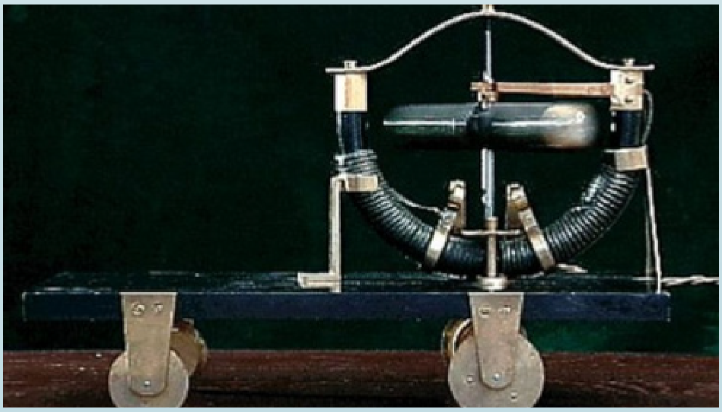


Fig. 1. The electric car model built by Á. Jedlik in 1828 [2]

The history of electrical cars is strongly connected to that of electrical machines. In 1827 the Hungarian Benedictine monk Ányos Jedlik built the firstrudimentary but working d.c. electrical machine. Only within one year, he used it to drive a simple small-scaled car model.

Another small-scale electric cell supplied electrical vehicle was built in 1835 by Sibrandus Stratingh, a professor of chemistry and technology at the University of Groningen (Netherlands). It weighed about 3 kg and could move for 20 minutes with a 1.5 kg load with its fully charged cells.

Fig. 2. Small scale electric car model developed byS. Stratingh in 1835

Scotsman Robert Anderson is **the inventor of the first full-scale electricity driven carriage**. His prototype was built sometime from 1832 to 1839 in Aberdeen It used **primary cells (non-rechargeable batteries)** to generate electrical power and had a maximum speed of 12 km/h..

Fig. 3. The first electric car built by R. Anderson

The first successful commercially available electric cars were named in an inspired way Electrobats. Its first variant was built in **1894** by the combined efforts of a mechanical engineer and a chemist, **Henry G. Morris and Pedro G. Salom** in Chicago upon their own patented technologies. The first variant was a slow and very heavy car having steel tires. The rechargeable batteries alone weighed more than 725 kg of the 2 tons gross mass of the vehicle.

Thanks to the continuous research and development efforts, later Electrobats became lighter, faster, and less unwieldy. They had pneumatic tires and were steered by their two rear wheels. These vehicles were powered by two 1.1 kW claw pole motors. Due to their state-of-theart batteries at the time, they could travel 40 km at an average speed of 32 km/h on a single charge. Due to high interest in these cars, the two partners expanded their business by building several hansom variants based on the model.

Fig. 4. An elegant model of the Electrobat car

Here also the main achievements in this field of the Austrian-born Ferdinand Porsche must be mentioned. In 1899, while working at Jakob Lohner & Company, th 22-year-old brilliant designer created his first electric car. This could achieve a speed of 25 km/h. His electric cars included cutting-edge technology at the time, such as the electrical hub motor that drove the vehicle's wheels directly.

Fig. 5. A Lohner-Porsche Phaéton in the Vienna TechnicalMuseum

He exhibited the world's first functioning revolutionary hybrid car with all four wheels electrically driven three years later. It was given the name **Semper Vivus**, which means "*always living*". Porsche increased the car's range by installing ICEs that drove the electrical generators to charge the battery, rather than relying simply on the battery. The original 74-cell accumulator was replaced with a smaller, having 44 cells to save weight and space. Two water-cooled 2.6 kW ICEs were mounted in the vehicle's center, driving the two independent 1.84 kW generators, each delivering 20 A current at 90 V voltage. Later, its production-ready version was released and named Lohner-Porsche Mixte. Its top speed was 80 km/h.

a) an oldtimer variant

b) its technical details

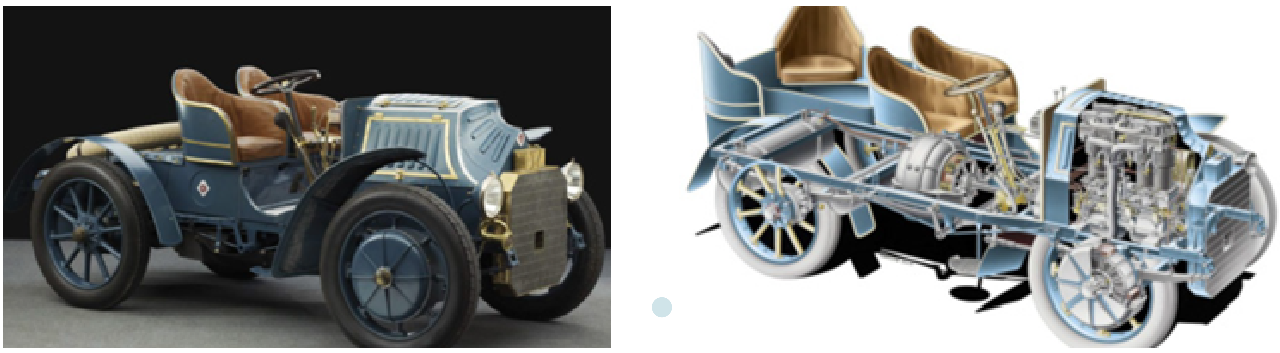


Fig. 6. The Lohner-Porsche Mixte, the first commercially available hybrid car

Later, **Ferdinand Porsche** was the designer also of the iconic *Volkswagen Beetle*, which is set to make a comeback soon as an electric vehicle. An important milestone in the development of electrical machines was the so-called **100-Mile Electric Automobile.**

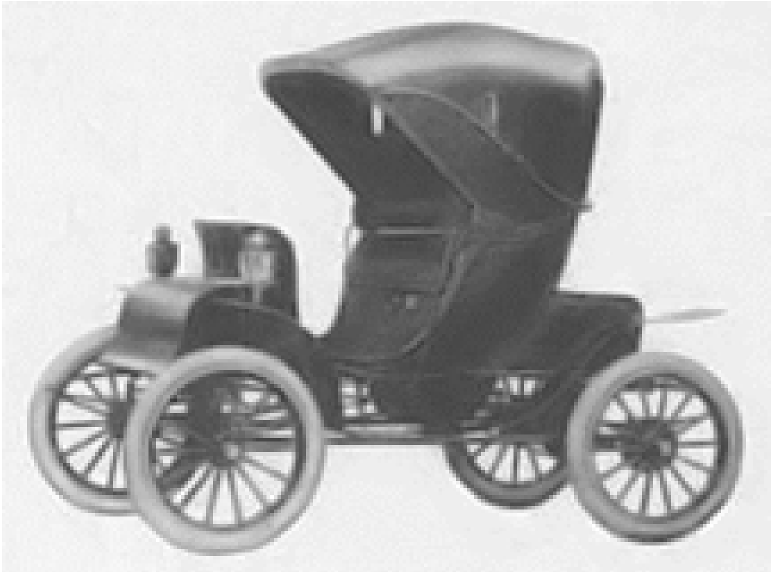


Fig. 7. Fritchle's Victoria, the so-called 100-Mile Electric Automobile

This two-seat electric car weighed 1000 kg, more than 350 kg of which were in batteries. It was built in Denver in 1 908 by **Oliver Parker Fritchle**, an early key pioneer in the field of electric vehicles. He made substantial contributions to both battery and automobile manufacturing. His name is linked to the creation of regenerative braking, too. He concentrated his developments on the endurance of newly designed electric cars. He proposed an audacious challenge in September 1908: to perform the 2,900 km trip between Lincoln and New York in an electric car with no mechanical problems. He accomplished the trip in 20 days, covering on average nearly 100 miles (160 km) a day.

ANALYSIS OF ELECTRICAL CONNECTIONS AND VOLTAGE LEVELS

An electric car, also known as an electric vehicle (EV) or battery electric vehicle (BEV), has an electric motor instead of an internal combustion engine. Unlike traditional vehicles that use an internal combustion engine, electric cars use an electric motor powered by electricity from batteries.

There are a couple of different types of electric cars, which include:

- All-electric: All-electric cars are powered solely by a battery and don’t use gasoline.
- Hybrid electric: Hybrid cars are powered by both electricity and gasoline.

Electric cars work by drawing electricity from a power source and storing it in a battery. This is done by plugging an electric car into a charging point, where the battery can fully charge. The battery then powers the motor, which controls the wheels. While driving, the battery provides energy to the electric motor which replaces the need for a gas engine. Because it runs on electricity, the vehicle emits no exhaust and does not contain the typical fuel components such as a fuel pump, fuel line, or fuel tank.

Most electric cars use this single-gear technology to move the wheels, so there's no need for a transmission. That said, some newer EVs are being built with additional gears, which allow the cars to achieve better performance and a longer range but require a transmission.

Battery electric vehicles (BEVs) use electricity stored in a battery pack to power the motor.

The most common type of battery used is the lithium-ion battery. Lithium-ion batteries have a high power-to-weight ratio, which means the batteries hold a lot of energy for their weight. This is essential for electric cars as less weight means the car can travel further on a single charge. Additionally, lithium-ion batteries can maintain the ability to hold a full charge over time. This ensures the longevity of the battery. It's key to note that electric cars all feature different charge ranges and charge speeds.

When depleted, electric car batteries are recharged using grid electricity. This can be from a home wall socket or a public charging station. Most lithium-ion battery parts are recyclable after their life, making them a good choice for combating environmental damage.

An electric car motor works by mounting one set of magnets to a shaft and another set to a housing that surrounds the shaft. By periodically reversing the polarity, the EV motor leverages these attracting and repelling forces to rotate the shaft. This converts the electricity into torque and, ultimately, turns the wheels.

DIAGRAM OF AN ELECTRIC VEHICLE

When it comes to how an electric car works, it can be helpful to view a simple diagram of the main internal components. The diagram shown below shows the components that make an electric car run, including the battery, battery pack, motor, and charge port.

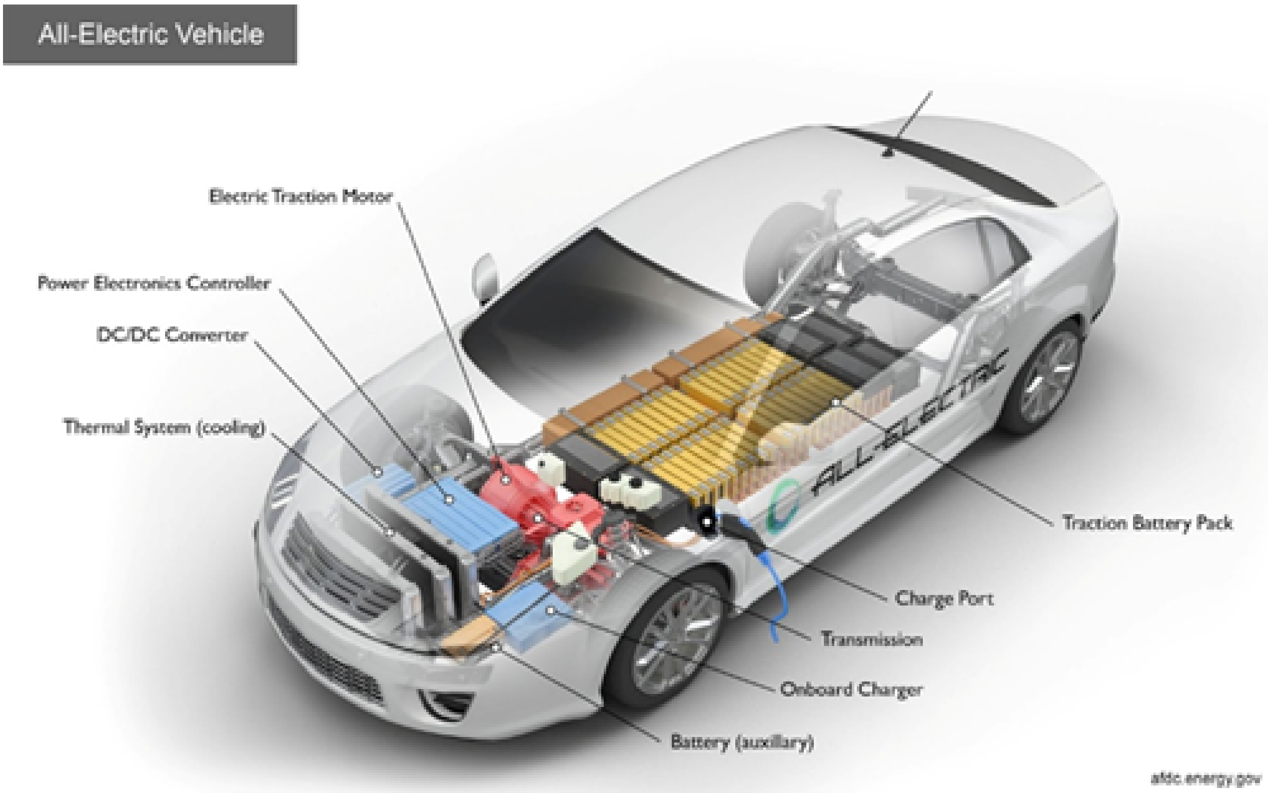


Figure 1

The key components of an EV include:

- **Battery:** In an electric car, the battery stores electricity in a battery pack to power the motor and other vehicle accessories.
- **Charge port:** The charge port allows the vehicle to connect to an external power supply to charge the battery pack.
- **DC/DC converter:** This device converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery.
- **Electric motor:** Using power from the battery pack, the motor converts electricity into torque and turns the wheels.
- **Onboard charger:** The On-board Charger (OBC) is used to convert Alternating Current (AC) from slow chargers or portable chargers used on home outlets into Direct Current (DC).

- **Electric power-controlled unit:** The Electric Power Control Unit (EPCU) is an efficient integration of nearly all devices that control the flow of the electric power in the vehicle. It consists of the inverter, the Low voltage DC-DC Converter (LDC), and the Vehicle Control Unit (VCU).
- **Cooling system:** The cooling system maintains a suitable operating temperature for the electric motor, engine, and other components
- **Traction battery pack:** Stores electricity for use by the electric traction motor.
- **Transmission:** The transmission transfers mechanical power from the electric traction motor to drive the wheels, though not all electric cars have a transmission.

TECHNICAL ANALYSIS OF AC/DC CHARGING TECHNOLOGIES AND FAST-CHARGING SYSTEMS

The primary type of EV can run solely on electric propulsion, using only batteries as the energy source. Alternately, they may collaborate with an ICE agent. However, they can utilize alternative energy sources. These are known as hybrid EVs (HEVs). The International Electrotechnical Commission defines a HEV as a vehicle with numerous types of energy sources, storage, or converters, at least one of which is electrical energy. This definition allows many combinations for HEVs. Hence, both experts and the general population have had specific names for each type of combination: vehicles with a battery and a capacitor are called ultra-capacitor (UC) assisted EVs. Those with a battery and a fuel cell are called FCEVs. Based on these distinctions, EVs are categorized into four groups.

BATTERY-ELECTRIC VEHICLE

BEVs deliver power to the drivetrain exclusively via batteries, relying completely on stored energy. Therefore, range is dependent on battery capacity. Normal range per charge is 100-250 kilometers. In fact, various variables including as driving style, road conditions, climate, vehicle layouts, battery type, and vehicle age have historically been implicated. Once the energy is gone, charging the battery can take up to 36 hours , which is significantly longer than refueling a normal ICE car. There are various types that require far less time, however none can compare to refueling a vehicle.

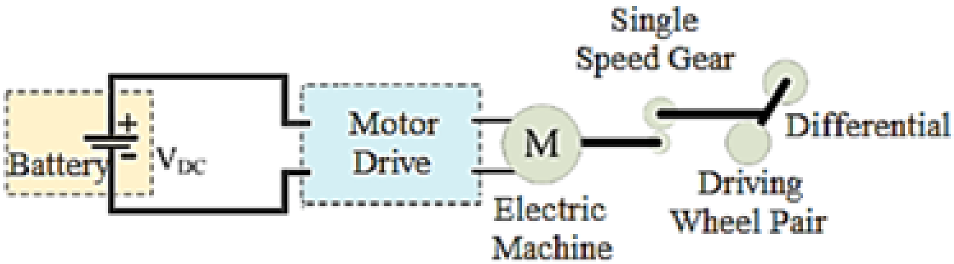


Figure 1. Structure of a BEV, the inverter changes DC electricity to AC power

BEVs offer certain advantages: they have simple construction, easy to operate, and are convenient. They do not produce GHGs and are noiseless, and beneficial for the environment. Electric propulsion can give high torques instantly, even at low speeds. Considering these advantages and the limited range, BEVs are perfect for urban transportation. Currently, Nissan Leaf and Tesla Model S are high-selling BEVs, and some Chinese vehicles such as BYD. *Figure 2* shows the configuration of BEVs: batteries power the EMs via a power converter circuit, and the engines run the wheels.

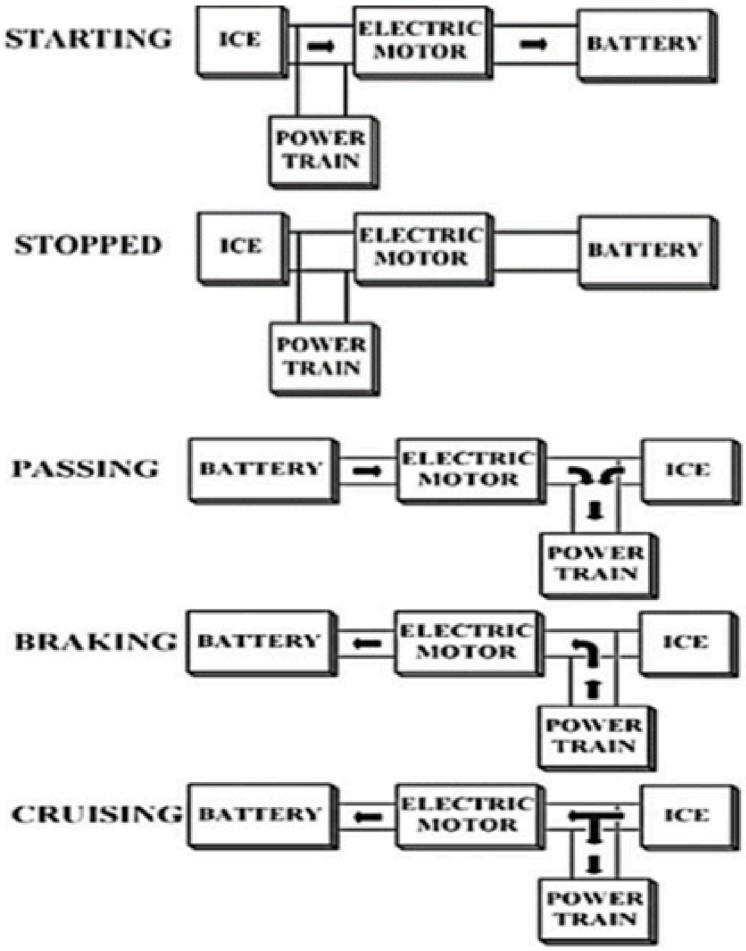


Figure 2. Power flow of HEVs (a) power flow during startup and stop and (b) power transfer during acceleration, braking, and cruising

HEVs are propelled by a combination of an ICE and an electrical power train (PT). This combination can be in different forms, which will be discussed hereafter. HEVs use the electric propulsion system in case of low power demand. This is a great advantage for such conditions as urban transportation, reducing fuel consumption when idling (e.g., during a traffic jam) and reducing GHG emissions. The vehicle turns to the ICE if a higher speed is required. These two trains can also help improve performance. Turbocharged cars like the Acura NSX extensively use hybrid power systems to reduce turbo lag. This set-up bridges the gap between gear changes and enhances acceleration, resulting in improved performance. The batteries can be charged using either the ICE or regenerative break. Consequently, HEVs are ICE-powered automobiles with an electrical propulsion system for improved fuel economy. Automobile manufacturers have broadly authorized HEV layouts for these benefits. *Figure 11* depicts the energy fluxes of a fundamental HEV. *Figures 11(a) and 11(b)*, show that during vehicle beginning, the ICE may employ the motor as a generator to produce and store electricity in the battery. Since both the ICE and the electric motor (EM) operate the PT during passing, it is required to enhance the vehicle's speed. To recharge the battery via regenerative braking, the PT uses the motor as a generator while in motion. To cruise, the ICE acts as a generator, generating electricity to power the motor and charging the batteries. Upon coming to a complete stop, the vehicle's electrical system comes to a complete halt. The energy management mechanisms of HEVs are illustrated in *Figure 12*. Based on driver inputs, vehicle speed, battery state of charge (SOC), and fuel economy, it distributes power between ICE and EM.

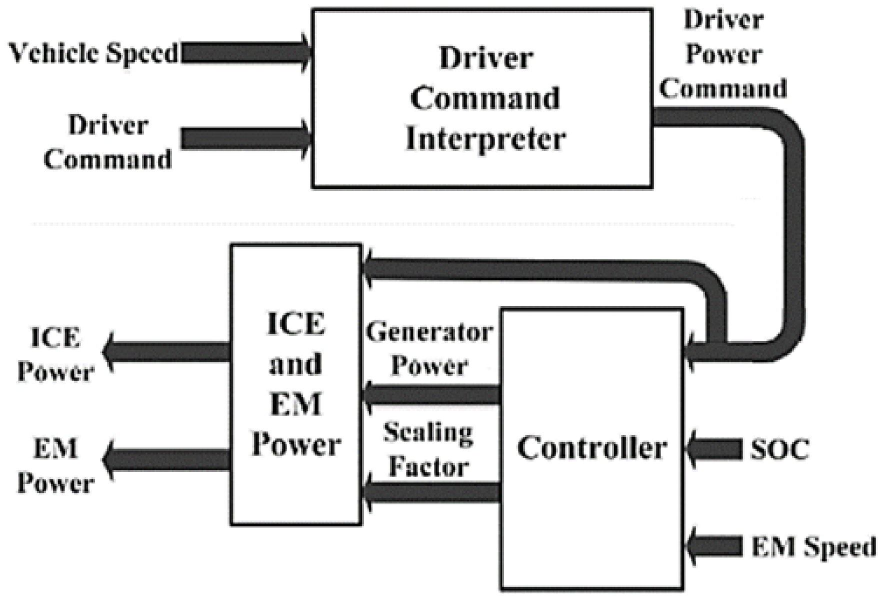


Figure 3. HEV's energy management system

PLUG-IN HYBRID-ELECTRIC VEHICLE

The PHEV concept emerged to extend HEV all-electric range. Again, the ICE and electrical PT are used, but with PHEVs, the electric motor is the main drive, necessitating a larger battery. PHEVs run on electricity and only use ICE when the batteries are low. The ICE boosts or charges up the battery, extending the vehicle's range. Unlike HEVs, PHEVs can charge directly from the grid and benefit from regenerative braking. Since, they can mostly run by electricity, PHEVs have less carbon footprint. They also consume less fuel, which reduces costs. Currently, Chevrolet Volt and Toyota Prius are two examples of hybrid vehicles that are now available on the market.

PLUG-IN HYBRID-ELECTRIC VEHICLE

FCEV can also be called fuel cell vehicle, these EVs are run by fuel cells that produce electricity through chemical reactions . FCEVs are used hydrogen fuel cell vehicles because hydrogen is the most fuel widely used in this industry. The hydrogen is carried in special high-pressure tanks. Oxygen is also required for power generation and is obtained from ambient air. The energy supplied by the fuel cells is transferred to the EM, which drives the wheels. The extra energy is stored in a battery or supercapacitor. Batteries are used in several commercially marketed FCEVs, such as the Toyota Mirai and the Honda Clarity. FCEVs produce water during power generation, and the vehicle ejects this water from the tailpipes. *Figure 5* shows the configuration of an FCEV. These vehicles have the advantage of producing their electricity without emitting carbon compared to any other type of EV. Besides, refilling an FCEV takes no more time than filling a conventional vehicle at a gas pump. So, these vehicles may be recommended much more widely soon. However, the shortage of hydrogen fuel stations is a key obstacle to the widespread use of this technology. However, even a few years ago, charging stations for BEVs or plug-in hybrids were not commonplace. Another concern is safety regarding flammable hydrogen that could potentially leak out of the tanks. If all these obstacles were eliminated, FCEVs would represent the future of vehicle transportation. Because, considering their advantages, FCEVs appear to be better than BEVs in numerous aspects. *Figure 6* illustrates this comparison. As a result, the figure compares two ranges (320 versus 480 km), taking into consideration a variety of criteria such as weight, beginning GHG emissions, and necessary storage volume, in addition to other parameters. The horizontal axis stands for the attribute ratio of BEV to FCEV. All these features are indicated so that higher ratios mean a disadvantage.

Based on the figure, BEVs are only better in fuel cost per kilometer and require wind energy. The former is still a significant drawback for FCEVs, as there has yet to be a way for producing hydrogen in an environment-friendly, cheap, and sustainable way. Also, the refueling infrastructure seems to fall behind. Still, these problems may all be solved soon.

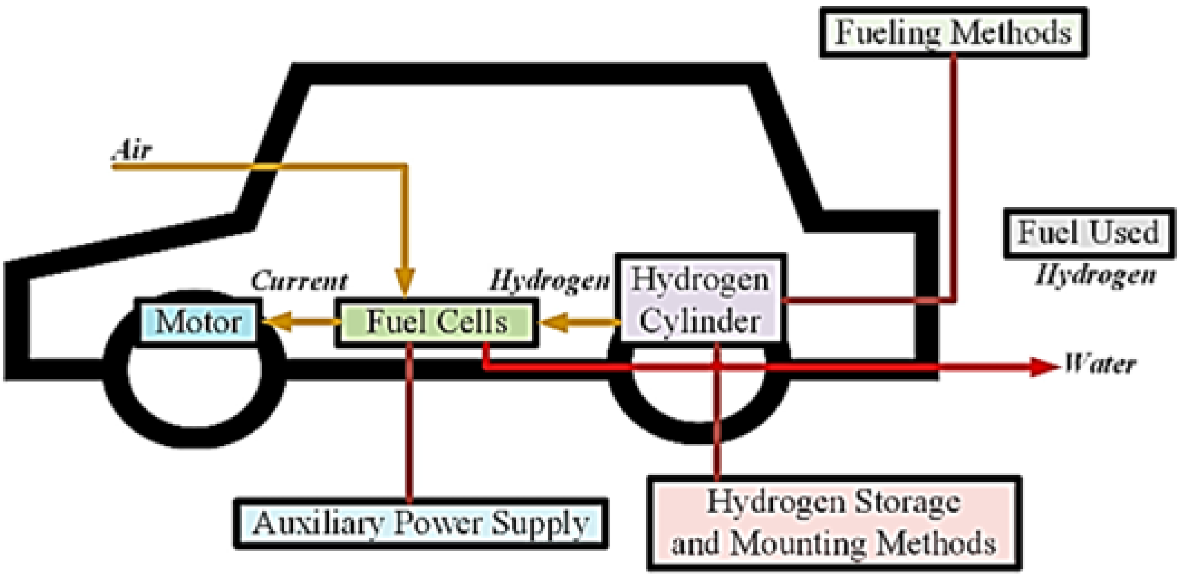


Figure 4. FCEV's configuration

In general, the availability of charging stations, charging power, and connector compatibility are important factors influencing the charging experience for hybrid and electric vehicle owners. The continued expansion of public charging infrastructure and the evolution of charging technologies are contributing to the increasing viability of electric vehicles.

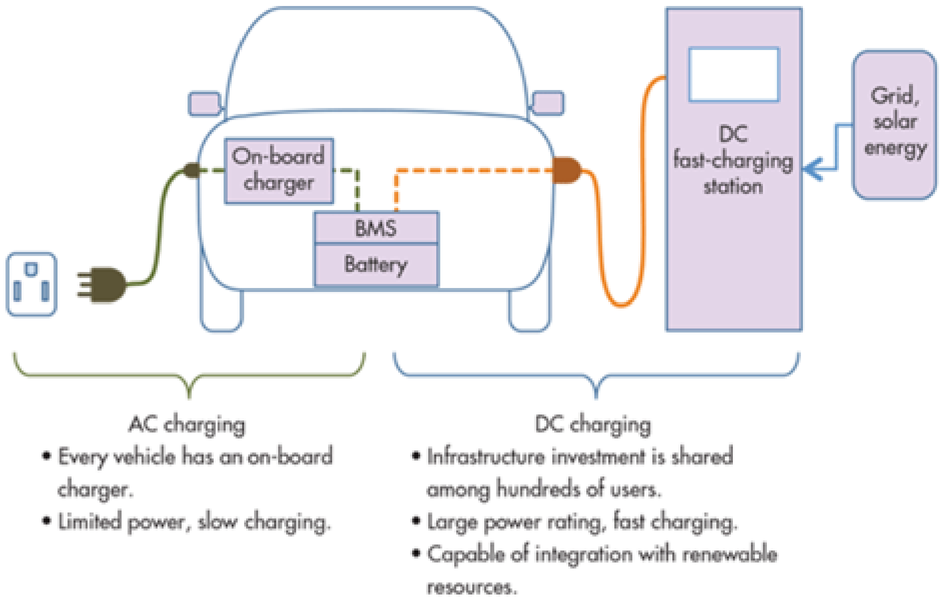


Figure 5. Schematic representation of differences in on-board chargers and off-board chargers (orDC-fast charging station)

In the context of the evolution of sustainable mobility, it is critical to understand the differences and evaluate the advantages and disadvantages of off-board and on-boardcharging systems for hybrid and electric vehicles. Off-board charging stations, such aspublic charging stations, offer the convenience of fast charging speed, which is ideal for longdistancetravel and situations where fast charging is needed. These stations are increasinglyavailable in urban areas and along highways, increasing accessibility to electric vehicles. Inaddition, many of these stations are compatible with a wide range of vehicles, regardlessof model or manufacturer. Some of them also provide high-power charging, allowingsubstantial charging in very little time. However, there are also disadvantages to consider,such as the user fees associated with certain public stations, which can increase totalcharging costs compared to home charging. In addition, crowding and limited availability in some areas can cause inconvenience to drivers. On the other hand, on-board charging athome offers maximum convenience and keeps the vehicle always ready for use, eliminatingthe need to travel to public charging stations. The ability to schedule charging overnight bytaking advantage of cheaper energy rates helps reduce operating costs. In addition, thelack of user fees makes this option cheaper in the long run. However, on-board charging at home has some limitations, including a more limited charging speed than public stations or fast charging solutions. This could be problematic for those who require fast charging. In addition, mobility is limited to locations where a dedicated charging station has bee installed, and initial installation can incur significant costs, especially if changes have to be made to the existing electrical system. In conclusion, the choice between off-board and on-board charging systems is influenced by the individual needs of drivers. Often, the best approach is to use a combination of both systems to maximize convenience and reduce the cost of operating hybrid and electric vehicles.

Off-board systems, including public charging stations, rapid charging stations, and wireless charging systems, offer a wide presence of stations in urban areas and along highways. These systems are known for their ability to provide fast charges and are ideal for long-distance travel. However, they may involve higher costs due to usage fees at some stations and can be affected by congestion in certain areas. On the other hand, on-board systems primarily rely on home charging stations. They offer maximum convenience, allowing drivers to recharge their vehicles directly at home. This approach eliminates usage fees and provides the flexibility to schedule charging during cost-effective energy rate hours. However, charging is slower compared to high-power public stations, which could be a concern for those in need of fast charging.

IAdditionally, it requires the installation of a dedicated home charging station, incurring associated costs. The comparison between these two systems is vital for electric vehicle drivers as it will significantly impact their charging experience and associated costs. The choice between off-board and on-board systems will depend on individual driver needs and the charging conditions available in their region.

ON-BOARD CHARGERS FOR HV/EV CHARGING SYSTEMS

Motivation to Move on OBCs

On-board chargers (OBCs) represent a dominant technology trend over off-board chargers in electric and hybrid vehicles due to a number of key advantages. First, their direct integration into vehicles offers significant convenience to users. It is no longer necessary to carry an external charger or to search for dedicated charging stations. The ability to charge directly from a standard power outlet, such as the one in one's home, greatly simplifies the daily lives of motorists. In addition,OBCs can be designed and optimized specifically tosuit the needs of the vehicle's battery. This results in greater efficiency during the charging process. OBCs can deliver more consistent and controlled charging power than off-board chargers, which must be designed to fit a variety of vehicles. The integration of OBCs into vehicles also enables more direct and sophisticated communication. Many OBCs are equipped with two-way communication systems that enable the vehicle to interact with the power grid and charging infrastructure. This paves the way for advanced features, such as scheduling charging time to take advantage of low energy rates or managing power in response to grid needs. From a size and weight perspective, integrated OBCs take up less space than external chargers and can contribute to overall weight savings in vehicles.

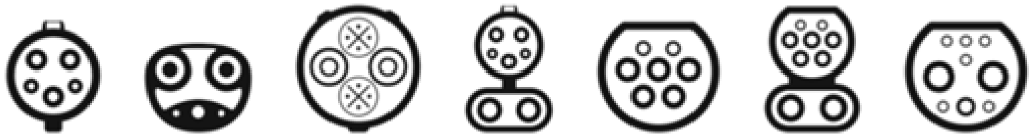
In terms of safety, OBCs can be designed with advanced protection systems to ensure the safety of the vehicle and the charging system. These systems include short-circuit detection, temperature monitoring, and overload protection. Finally, there is a trend toward the standardization of OBCs. Automakers and industry organizations are working to establish common standards, thereby simplifying the production and use of electric and hybrid vehicles. In summary, on-board chargers offer a convenient, efficient and integrated solution for charging electric and hybrid vehicles. Although they can be complemented by external charging stations for longer trips or public needs, their predominant role in meeting daily charging needs is a major step forward in the transition to electric mobility.

Standards and Classification

In electric vehicles, On-Board Charger (OBC) device connectors play a crucial role in battery charging. There are different types of connectors around the world, each with its own specific characteristics and applications. **The J1772 (Type 1)** connector is commonly used in the United States, Canada, and some other regions. However, its charging speed is limited compared to newer standards and is associated with vehicles such as the Nissan Leaf and Chevrolet Volt, both made in the United States. Tesla uses a proprietary connector, known as the Tesla Connector, which offers high charging powers, greatly accelerating the charging of Tesla vehicles, including the Model S, Model 3, Model X, and Model Y.

However, this standard is exclusive to Tesla vehicles and is not compatible with those of other manufacturers. In Japan and some regions of the world, the CHAdeMO connector is common and offers fast DC charging. It is often associated with vehicles such as the Nissan Leaf, Mitsubishi i-MiEV, and Kia Soul EV. The Combo Charging System (CCS) connector has been increasingly adopted in Europe and North America.

It offers the versatility of supporting both DC and AC charging and is associated with vehicles from brands such as BMW, Volkswagen, Ford, Audi, and others. In Europe, the Type 2 connector (IEC 62196) is widely used for AC charging. It is associated with vehicles such as the Renault Zoe and BMW i3, among others. Although it does not support DC charging, it is well established in Europe and offers reliable charging. CCS (Type 2) is an extension of the CCS standard used in Europe, which also includes AC charging. This standard is used by many European automakers, including BMW, Volkswagen and others, for vehicles with DC and AC charging capabilities. In China, the GB/T connector (GBT 20234) is used as a national standard and is compatible with DC and AC charging. It is associated with vehicles produced by companies such as BYD and NIO. The choice of connector depends on geographic region, automaker, and preferred charging strategy, as described in Figure 15. Global standards, such as CCS, are becoming more common to increase compatibility between vehicles and the availability of charging stations. However, it is important to consider connector compatibility with the vehicle and local infrastructure when making the choice of an electric vehicle. On-board chargers (OBCs), used in electric and hybrid vehicles, can be classified according to the power levels they are capable of delivering. These power levels are critical in determining the charging characteristics of a vehicle. Let us now look at a description of the voltage and power levels typically involved.



	J1772	Tesla	CHAdeMO	CCS	Type 2	CCS (2)	GB/T
N. America	AC/DC	AC/DC	DC	DC			
Europe	AC	AC/DC	DC		AC	DC	
Japan	AC		DC				
China							AC/DC

Figure 6. Type of connector and their usage in related areas.

Standard power levels include “Level 1” and “Level 2”. Level 1 is characterized by single-phase voltages of 120 V (in the United States) or 230 V (in Europe) and can deliver a power output of about 1.3–1.9 kW (typically). This level is commonly used for home charging, especially overnight, and is suitable for vehicles with smaller batteries. The charging time for Level 1 chargers can vary depending on the vehicle’s battery capacity,but it typically takes several hours to fully recharge a vehicle from near empty to full. Level 2, on the other hand, operates on single-phase voltages of 240 V (in the United States) or 230 V (in Europe) and can deliver a larger power, generally ranging from 3.7 kW to 22 kW, depending on whether the device is in a single-stage configuration or two/multiplestage configuration, respectively. This level is the most common for home and public charging and is suitable for most electric and hybrid vehicles. Charging times at Level 2 are significantly faster than Level 1, and many vehicles can be fully recharged overnight or within a few hours, depending on battery capacity. As for high power levels, we find “Level 3” or “DC Fast Charging”. This level involves much higher voltages and direct DC conversion. Voltages can vary widely, but can be as high as 600 V or more, with powers exceeding 50 kW or even 350 kW (as in Tesla superchargers). Level 3 chargers provide exceptionally fast charging times. Depending on the specific charger and vehicle, some Level 3 chargers can replenish a significant portion of the battery’s capacity in as little as 30 min to an hour. This level is designed to allow much faster recharging than the lower levels and is used in fast-charging stations along highways and in public areas (Figure 16). The choice between single-phase and three-phase systems depends mainly on the available supply voltage and the specifications of the electric vehicle. Single-phase systems use a single phase of alternating current (AC) and are the most common type for home charging. They are suitable for single-phase voltages of 120 V or 230 V and are a convenient solution for home charging, offering relatively faster charging times than Level 1.

This configuration is ideal for home charging and vehicles with moderate capacity batteries. The two-stage configuration is more complex and uses two AC/DC converters: one for charging at low powers and one for charging at high powers, often from 22 kW up to 350 kW or more. It is ideal for vehicles that require a wide range of charging powers. It offers greater flexibility and supports high-power DC charging, greatly reducing charging time. The multi-stage configuration is the most advanced and uses three or more AC/DC converters. It is designed to handle extremely high charging powers, such as those above 350 kW, making ultra-rapid charging possible. This configuration is critical for commercial vehicles and high-power public charging stations. However, it is also the most complex and expensive to implement. In summary, the choice of OBC configuration depends mainly on the power requirements of electric vehicles. Single-stage configurations are suitable for moderate power and home charging, while two-stage and multi-stage configurations are essential for high-power and ultra-rapid charging, often associated with commercial vehicles or public charging stations. Complexity and cost increase with the number of stages, so the choice is driven by the need to support specific charging powers.

A rectifier is a key component in electrical conversion systems and is often the first conversion stage in any On-Board Charger (OBC) configuration in electric vehicles. Its main function is to convert electrical energy from an initial form, usually in the form of alternating voltage (AC), to a usable form, namely direct voltage (DC).

This conversion is essential to enable the effective charging of electric vehicle batteries.

There are two main types of rectifiers: passive rectifiers and active rectifiers, each of which has a different operating principle. Passive Rectifier: A passive rectifier uses passive components such as diodes to convert AC to DC. The diode is the key component in a passive rectifier. The operation of a passive rectifier occurs in two phases: – Half-Wave Phase (Half-Wave Rectification): In this phase, the diode allows the positivevoltage from the input AC to pass through, while blocking the negative voltage. This means that only half of the AC wave is transmitted to the output DC. This is an inefficient process since half of the energy is discarded.

– Full-Wave Phase (Full-Wave Rectification): In this phase, two diodes are used to capture both the positive and negative parts of the AC wave. This results in more efficient conversion, but it is still imperfect because the AC wave is split into two separate halves and the result is a pulsing DC wave.

Active Rectifier: An active rectifier uses transistors or controlled semiconductor devicesto convert AC to DC more efficiently than a passive rectifier. There are two main types ofactive rectifiers: bridge rectifiers and controlled rectifiers.

– Bridge Rectifier: This type of active rectifier uses four diodes in a bridge circuit to convert AC to DC. The operation is similar to that of the passive full-wave rectifier,but with four diodes instead of two. This allows a more complete conversion of AC to DC and is the most common type of rectifier used in domestic applications.

– Controlled Rectifier (Controlled Rectifier): This type of rectifier uses controlled transistors or GTO to adjust the output voltage as needed. These devices can be turned on or off in a controlled manner, allowing the more precise and flexible conversion of AC to DC. Controlled rectifiers are used in applications where accurate voltage control is needed, such as in switching power supplies.

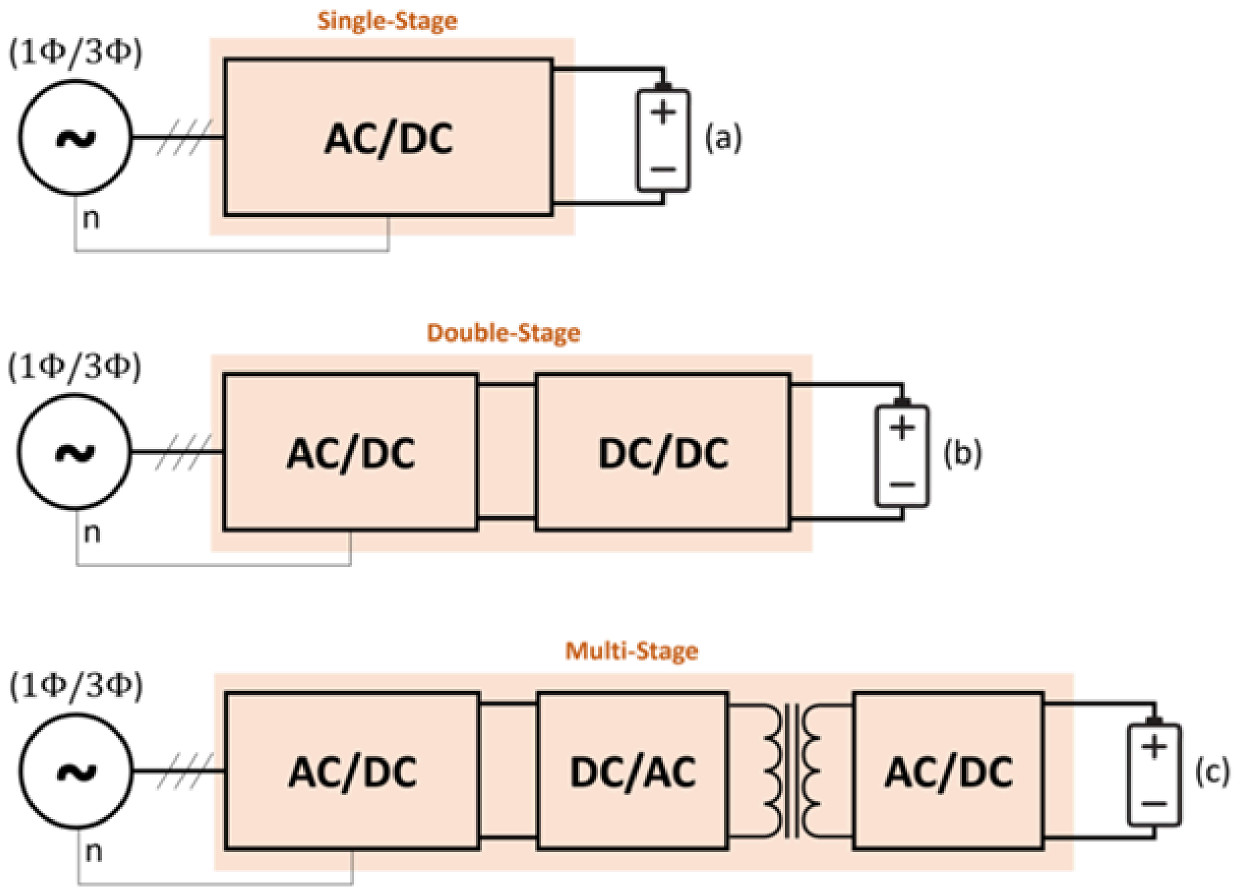


Figure 8. Typical configurations of an OBC device: (a) single stage with only one device that act as

AC/DC; **(b)** double-stage with a rectifier to reach the DC-link voltage level and a "compact" DC/DC
converter connected to the battery; and (c) multi-stage where typical galvanic isolation is integrated.

Main differences between passive and active rectifiers:

i Efficiency: Active rectifiers are generally more efficient than passive rectifiers because they reduce power losses.

ii Control: Active rectifiers allow more control over the output voltage.

iii Applications: Passive rectifiers are suitable for simple applications, while active rectifiers are preferred when more advanced and precise power conversion is required.

In general, the choice between a passive and an active rectifier depends on the specific needs of the application and the requirements for efficiency and accuracy. DC/DC converters play a crucial role in electric vehicle OBC devices, enabling the efficient management of electrical energy. Their main purpose is to regulate the incoming direct current (DC) voltage to the DC voltage required to charge the battery or power other vehicle systems.

These converters are often designed to operate in different modes depending on the specific needs of the vehicle and context of use. Some of the most common modes include:

i Buck Mode: In this mode, the converter reduces the DC input voltage to a lower level of DC output voltage. This operation is useful when it is necessary to lower the voltage of the traction battery to power lower voltage devices, such as the cooling system or the control circuit.

ii Boost mode: Boost mode is the opposite of Buck mode. In this case, the converter boosts the DC input voltage to a higher level of DC output voltage. This is crucial when you want to charge the battery at a higher voltage than that provided by the mains.

iii Buck–Boost Mode: This mode allows you to adjust both higher and lower voltages than the input voltage. It is useful when maximum flexibility in power management is required.

iv Isolation Mode: Some DC/DC converters are designed to provide electrical isolation between the input and output. This is important to ensure safety and protection of vehicle circuits.

v Regulation Mode: DC/DC converters can also be used to adjust the output voltage according to specific battery charging requirements, ensuring that the battery receives the correct voltage and current during the charging process.

DC/DC converters in OBC devices are often designed to be highly efficient to minimize energy losses during conversion. This is crucial to maximizing the range of electric vehicles and minimizing operating costs. In general, DC/DC converters play a key role in the electric vehicle ecosystem, helping to ensure the reliable and efficient operation of OBC devices as well as optimized power management.
Electromagnetic Interference (EMI) filters are essential components in On-Board Charger (OBC) devices in hybrid and electric vehicles. Their main function is to manage and reduce electromagnetic interference generated during the electric charging process.

During the charging process, current and voltage fluctuations can occur that generate electromagnetic interference. EMI filters are designed to capture this electromagnetic interference and conduct it to ground or absorb it, thus preventing it from spreading into the power grid or interfering with other electronic devices. Regulatory bodies and electromagnetic compatibility (EMC) standards place restrictions on the level of electromagnetic interference a device can emit. Installing EMI filters helps ensure that the OBC device complies with these regulations, avoiding legal penalties and ensuring safe and efficient operation. OBC devices contain sensitive electronic components, such as control circuitsand power devices. Electromagnetic interference can damage or disrupt the proper functioning of these components. EMI filters protect such components from harmful interference. Likewise, EMI filters also prevent external interference, such as radio waves or other sources of interference, from affecting the operation of the OBC device. EMC regulations, such as CISPR (Commission Internationale de l'Éclairage Special Committee on Radio Interference) and FCC (Federal Communications Commission), impose limits on electromagnetic emissions from electrical and electronic devices. OBC devices must be designed in accordance with these regulations to ensure electromagnetic compatibility with other electronic devices and to avoid unwanted interference.

In addition, regulations may vary from region to region. For example, in Europe, CE marking is a requirement that indicates compliance with EMC regulations. EMI filters are critical components in hybrid and electric vehicle OBC devices because they help ensure that the charging process is efficient, safe, and complies with EMC regulations. Their presence is critical to protect electronic components, prevent external interference, and ensure compliance with design regulations.

REVIEW OF ELECTRIC VEHICLE CHARGING TECHNOLOGIES

The continuous global increase in demand for electric vehicles presents engineers with several new challenges. The adoption of electric vehicles brings several advantages, such as reducing the carbon footprint, lowering harmful emissions into the environment, and improving air quality in populated areas. This is crucial because in densely populated urban areas, where internal combustion engine vehicles are predominantly used, high levels of fine particulate matter in the air pose a serious problem.

In addition to improving electric cars themselves, investment in charging stations is necessary. The growing integration of electric car charging stations into the power grid introduces several challenges, such as planning, maintaining stable grid operation without disturbances, ensuring stability and safety.

Electric vehicles and plug-in hybrid electric vehicles can be charged at charging stations. Most users prefer charging at home. The expanding deployment of charging stations at workplaces, public parking lots, gas stations, large supermarket chains, and other locations will contribute to the rapid growth of this sector.

The largest electric vehicle market is China, where sales are continuously growing at a fast pace, followed by Europe. The rapid expansion in Europe is supported by numerous European Commission programs that encourage sales. In Germany, anyone who purchases a brand-new electric vehicle receives a €10,000 subsidy.

The EV comprises one or more electric motors and a high voltage battery pack with a charging system. The electric motor either assists completely via electric power or ICE depending on the EV type. Additionally, the electric motor functions as a generator and provides power to charge the battery using a bidirectional DC-AC converter during the braking and deceleration of the vehicle. Conversely, the converter enables power to flw from the battery to the motor during driving mode.

The hybrid vehicle has a conventional ICE vehicle design and a battery to power the vehicle using fuel and electric energy. The capacity of the battery defies the driving range of the vehicle in electric mode. Hybrid EVs (HEVs) and plug-in hybrid EVs (PHEVs) are two types of hybrid vehicles in the market.

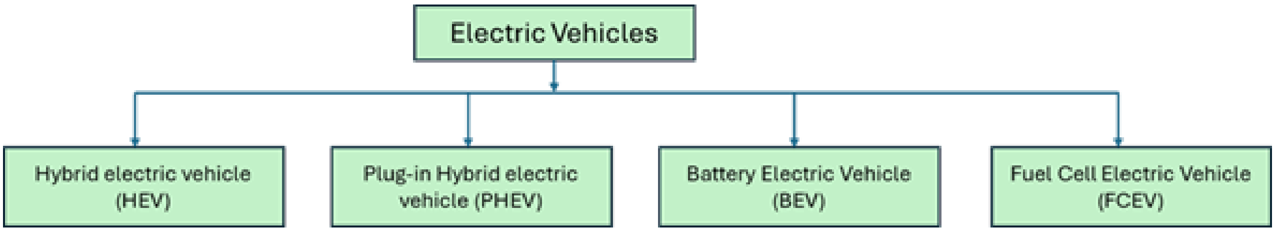


Fig. 1. Types of Electric Vehicles.

Charging levels and equipment

There are various charging technologies for electric vehicles (EVs), adapted to their specific technical and energy requirements. To facilitate their market integration and enhance competitiveness compared to traditional internal combustion engine (ICE) vehicles, standardized levels and models of electric charging have been developed and implemented.

The electric drivetrain of plug-in EVs typically includes a high-voltage battery pack (ensuring stable voltage and current levels), a battery management system (BMS), voltage regulation converters, control units, and drive inverters.

EV charging systems can be classified according to several criteria: onboard or offboard; unidirectional or bidirectional; depending on the direction of energy flow; with or without a transformer. Charging methods include conductive charging, battery swapping, and wireless (inductive) charging, as illustrated in *Fig. 2*.

The most widely used method is conductive charging, where the battery is connected directly to the power grid via a cable. This type of charging is categorized into three levels—Level 1 through Level 3—according to the SAE J1772 standard, and four modes—Mode 1 through Mode 4—based on the IEC 61851-1 standard.

Wireless charging uses time-varying magnetic fields to transmit energy from the grid to the vehicle's battery. Depending on the working principle, this type of charging is divided into three main categories: capacitive, inductive, and resonant inductive.

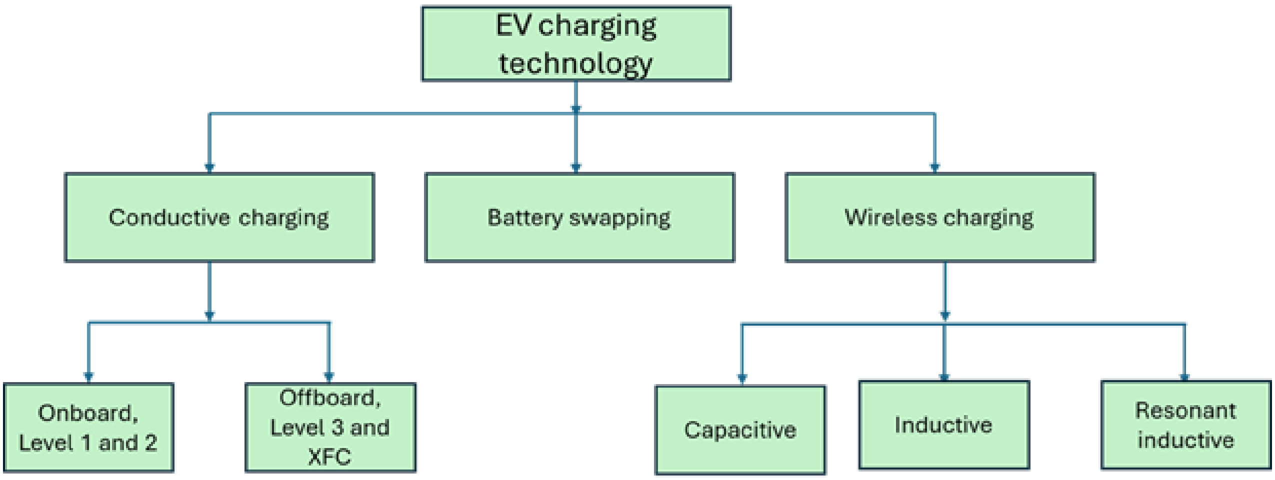


Fig. 2. Electric Vehicles charging technology.

The specifications of types of electric vehicles are presented in Table 1 in terms of the type of vehicle, battery capacity, driving range and connector type. The driving range of an EV depends on the battery capacity, and their consumption profile during the road.

Hence, modern BEVs have higher battery capacity, and a driving range from 200 to 490 km on a single charge. Fast and extremely fast charging stations are growing to meet high power requirements with EVSE. On average, a usual BEV takes about 8 hours to charge a 60kWh battery pack from empty to full, which can cover up to 320 km of distance.

Vehicle model	**Type**	**Driving range (km)**	**Battery capacity kWh**	**Connector type**
Volvo XC40	PHEV	43	10.7	CCS, Type 2
Toyota Prius	PHEV	40	8.8	SAE J1772
Nissan Leaf	BEV	480	64	CHAdeMo, Type2

Vehicle model	Type	Driving range (km)	Battery capacity kWh	Connector type
Tesla Model S	BEV	620	100	Supercharger
Tesla Model 3	BEV	500	100	Supercharger
Nissan Leaf	BEV	580	82	Supercharger
Kia Nero	BEV	460	64	CCS, Type 2
Lexus UX 300	BEV	320	54.3	CHAdeMo, Type2
BMW i3	BEV	310	37.9	CCS, Type 2

Vehicle model	Type	Driving range (km)	Battery capacity kWh	Connector type
Honda e	BEV	220	28.5	CCS, Type 2
Porsche Taycan	BEV	410	93	CCS, Type 2
Volkswagen e-Golf	BEV	35.8	230	CCS, Type 2
Audi 3-tron	BEV	400	95	CCS, Type 2
Mercedes EQA	BEV	420	66.5	CCS, Type 2

Cable charging refers to the connection between the vehicle's charging inlet and a charging station. It is classified into three levels—Level 1, Level 2, and Level 3—depending on the charging power, as shown in Table 2. Level 1 and Level 2 are commonly used with onboard chargers operating on alternating current (AC) and apply the same set of standards. A Level 1 charger operates on single-phase 120 V AC power and provides the slowest charging speed, with a power output of up to 1.92 kW, without requiring additional infrastructure. Due to the low power, this type of charging is suitable for extended or overnight charging, typically taking between 10 and 40 hours to charge an EV battery with a capacity ranging from 15 to 60 kWh.

Level 2 offers significantly faster charging compared to Level 1, making it the preferred option for integration into public buildings and parking facilities. Thanks to its higher power capacity, the charging time with Level 2 is 3 to 5 times shorter. These chargers can deliver up to 19.2 kW using single-phase 240 V power supply. For this, specialized electrical components and proper installation are required. Charging time generally ranges from 2 to 3 hours for batteries with a capacity of 30 to 50 kWh.

Charging connectors for Level 1 and Level 2 comply with the IEC 62196-2 standard in Europe, while in the USA, the SAE J1772 and Tesla Supercharger standards are applied.

Level 2 charging stations are commonly found in public garages, shopping centres, and office buildings. They support smart charging features, including mobile app control and scheduling. To optimize power grid usage, some Level 2 stations offer bidirectional charging capability. This enables the use of the vehicle's battery as a temporary energy storage unit (V2G – Vehicle-to-Grid). The advancement of such technologies plays a crucial role in integrating EVs into the smart energy systems of the future.

Charging levels	Charging power, kW	Charger type	Charge Location	Charging time	Power Supply
Level 1	1.44 - 1.9	Onboard slow charging	Residential	200 km – 20h	230V, Single phase
Level 2	3.1-19.2	Onboard semi-fast charging	Private and commercial	200 km – 5h	230V, Single phase
Level 3	20-350	Offboard fast charging	Commercial	80% of 200 km – 5h	400V Three phase
Extreme fast charging XFC	>350	Offboard ultra-fast charging	Commercial	Approximately 5min with high energy density	1000V DC, 400A

The use of a direct current (DC) grid for Level 3 charging enables both alternating current (AC) and DC to be applied for rapid and efficient charging of electric vehicle (EV) batteries. Level 3 charging systems operate over a wide power range—from 20 kW to 350 kW—supplying DC voltages between 300 Vdc and 800 Vdc via external charging stations. These chargers are connected directly to the vehicle through off-board modules integrated into a three-phase power grid. Chargers rated at 90 kW or higher can achieve charging times between 0.2 and 0.5 hours, significantly faster compared to Level 1 and Level 2 systems. Various standardized interfaces are used for Level 3 charging, including CHAdeMO, Tesla Supercharger, and CCS Combo 1 and 3.

Despite the high efficiency of Level 3 chargers, lower-power systems (Level 1 and 2) exert minimal impact on the electrical grid during peak demand periods. Large-scale deployment of DC fast chargers may lead to overload of the local distribution infrastructure due to the high instantaneous energy draw. For this reason, integration of smart energy systems for load management and consumption optimization is highly recommended.

Extreme Fast Charging (XFC) systems offer charging performance comparable to refuelling an internal combustion engine vehicle. These systems support power levels above 350 kW and use internal DC bus voltages of 800 Vdc, enabling full battery charging in approximately five minutes. XFC stations are designed with advanced power electronic components, including solid-state transformers (SST), isolated DC-DC converters, and front-end AC-DC converter stages with precision controllers.

SST technology offers significant advantages over conventional line-frequency transformers—including higher efficiency, more compact design, and improved protection selectivity. Additionally, SST enables multistage conversion and flexible real-time energy flow management. XFC stations are particularly well suited for transportation corridors and logistics hubs where dwell time is a critical factor. Hybrid configurations combining solar panels and energy buffers are being developed to reduce stress on the grid. XFC infrastructure is expected to play a key role in building the high-efficiency, sustainable EV charging ecosystems of the future.

Charging connectors for electric vehicles

Electric vehicle (EV) chargers consist of several key components—including power outlets, connectors, cables, and plugs—which together form the core of the EV supply equipment (EVSE). These elements ensure safe and reliable charging, discharging, and protection of the electrical system. Their technical characteristics and applicable standards may vary depending on national regulatory frameworks and market requirements. Nevertheless, regulatory authorities and manufacturers are actively collaborating to ensure interoperability through the development of international standards, communication protocols, and universal connectors for both slow and fast charging systems, helping to avoid inconsistencies and technical challenges.

AC chargers are generally used for slow charging, where a full charge may take between 6 and 8 hours. In contrast, DC chargers are primarily intended for fast charging and support power levels of up to 400 kW, significantly reducing the total charging time. EV connectors can be categorized into three main groups according to the IEC 62196-2 standard, which promotes compatibility across various vehicle brands and charging infrastructure.

Type 1 connectors are widely used in Japan and USA for AC single-phase charging and follow SAE J1772 standards. They have low power charging capability (maximum capacity of 19.2 kW) with a voltage of 120 V or 240 V with a maximum current of 80 A.

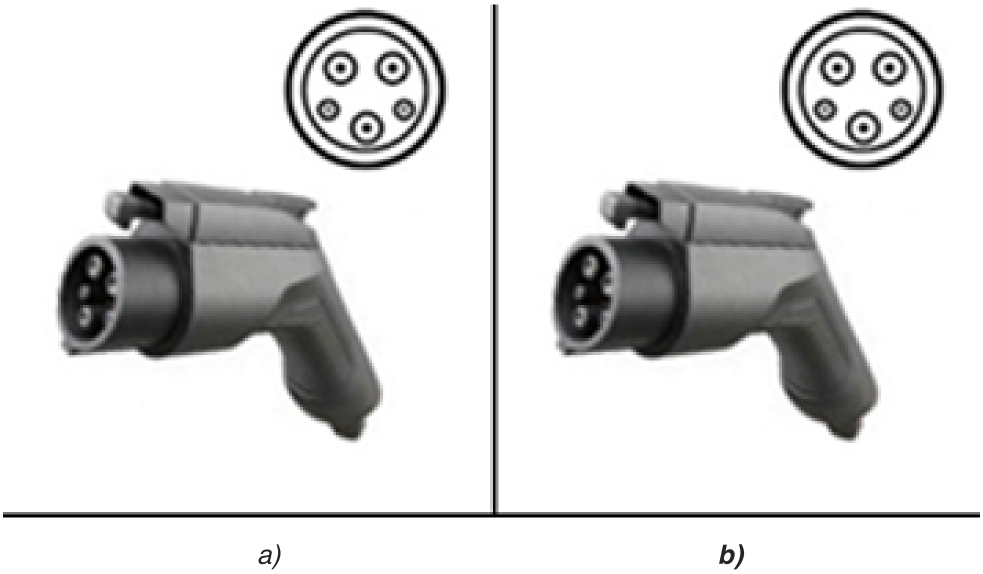


Fig.3. Type 1 AC connector, a) Japan, b) USA.

Type 2 connectors are considered as standard type in all countries which support single-phase and three-phase charging by following IEC 61851-1 standards [61]. Type 2 - Mennekes connectors are utilized in Europe and Type 2 - GB/T are used in China. This connector supports charging with 22 kW power.

Fig.4. Type 2 connector.

The DC chargers or superchargers deliver the fastest charging rate which follows the combined current system (CCS) and IEC 62196 standards. The IEC 62196-3 standard specifies four types of coupler configurations for DC fast chargers. combined current system (CCS) and IEC 62196 standards. The IEC 62196-3 standard specifies four types of coupler configurations for DC fast chargers. They are configuration AA (CHAdeMO), configuration BB (GB/T), configuration EE (CCS-Combo 1), and configuration FF (CCS-Combo 2).

Fig.5. DC connector CHAdeMO.

Fig.6. DC connector CCS Combo 1.

Level 3 Charging / DC Fast Charging (DCFC)

Designed for commercial use, Level 3 Charging works with 480 V and up to 125 A of current and 90 kW of power. In order to charge the EV's battery directly this type of charger bypasses the on- board AC-DC convertor, used for the other types of charging. The average charging time takesween 30 and 60 minutes, providing about 95 to 160 km per 20 minutes of charging. The main disadvantage is the high installation cost, which requires high- power electrical infrastructure. Furthermore, Level 3 charging introduce technical challenges such as battery thermal management [3].

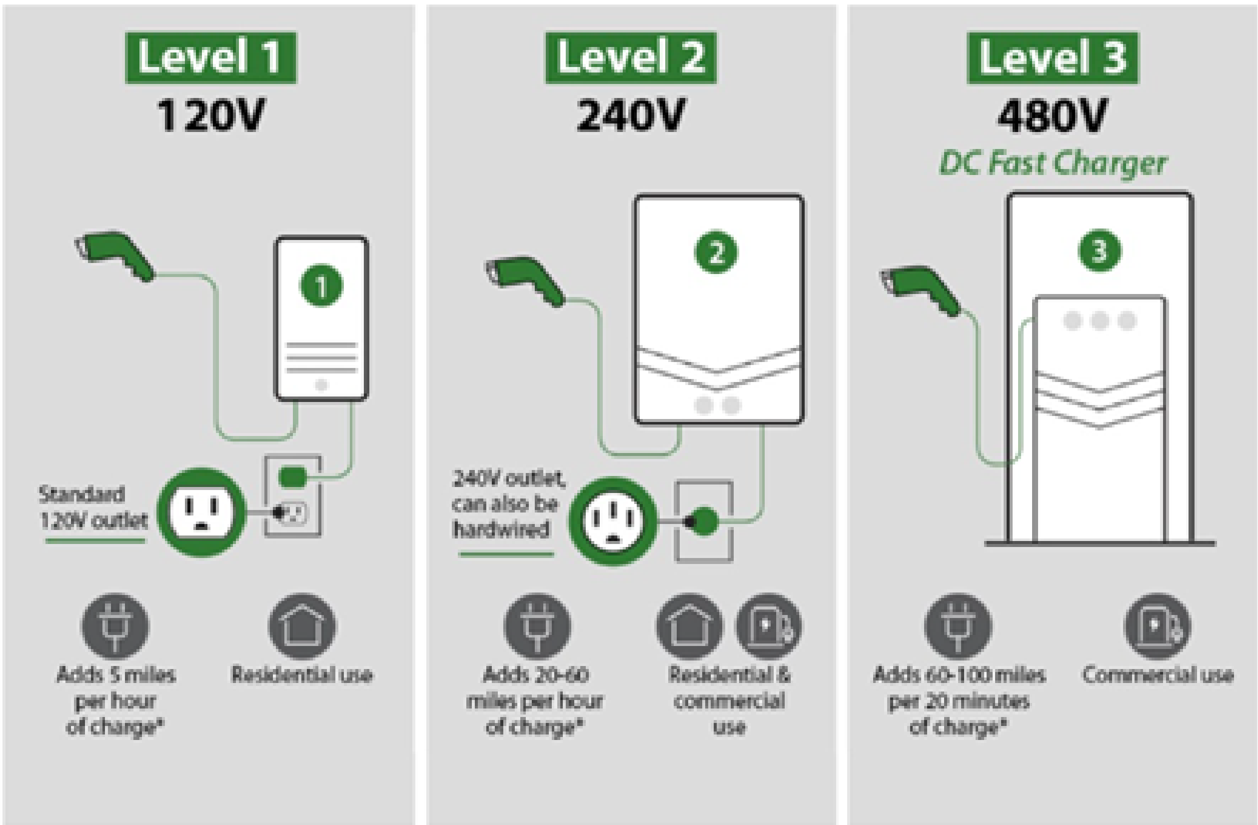


Fig. 1. Types of Charging Stations

Connector Types

J1772 (Type 1)

J1772, also known as J Plug, is the standard connector used in North American and Japan for Level 1 and Level 2 AC charging. It features five pins, two single- phase AC lines (L1, L2/N), a Control pilot (CP) for post- insertion signaling, a Proximity pilot (PP) for pre- insertion signaling and a Protective earth (PE). The disadvantages of this type are that only allows single- phase use and the lack of a locking mechanism, which other connectors utilize.

The supply input is between 120 V and 240 V, with 16 A and 80 A respectively.

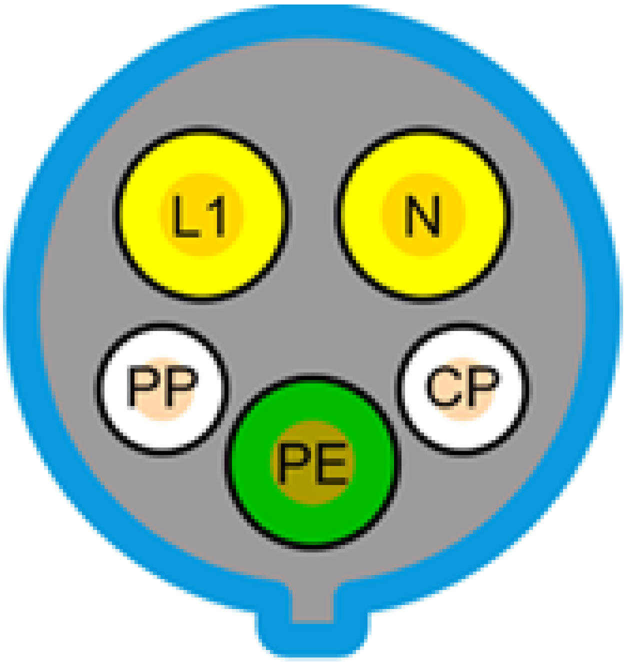


Fig. 2. J1772 (Type 1) Connector

Mennekes Connector (Type 2)

The Type 2 connector is an AC Level 2 charging one that is mainly integrated in the EU and the UK. It supports both single- phase (32 A and 230 V) and three-phase current (32 A and 400 V) thus making it more versatile than Type 1 connector. In addition to that, Mannekes has a locking mechanism, which prevents accidental removal during charging. This type of plug utilizes 7 pins- 3 line pins, all of which could work with three- phase AC, one Neutral pin (N), CP, PP, PE. It provides 7.6 kW at 230 V and 22 kW at 400 V of maximum output power.

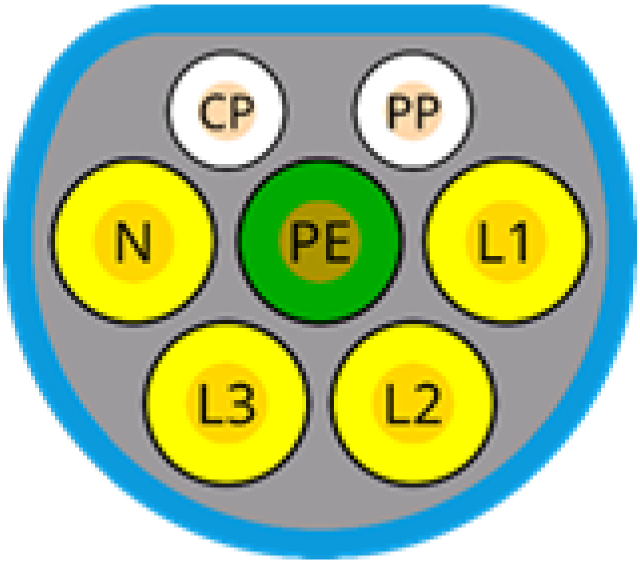


Fig. 3. Type 2 Connector

Combined Charging System (CCS) Connector (Type 1 and Type 2)

The Combined Charging System Connector Type 1 (CCS Combo 1) is an extension of the J1772 for North America and the Type 2 (CCS Combo 2) is for the EU and the UK. With the two added DC pins, they enable high- power fast charging. CCS Combo 1 and CCS Combo 2 are the most used charging connectors for Level 3 / DCFC in North America and Europe respectively.

CCS Combo 1 utilizes 480 V and has a maximum current output of 500 A thus providing 360 kW power. On the other hand, CCS Combo 2 uses a slightly lower voltage at 400 V, but its maximum current output and power are the same as Combo 1.

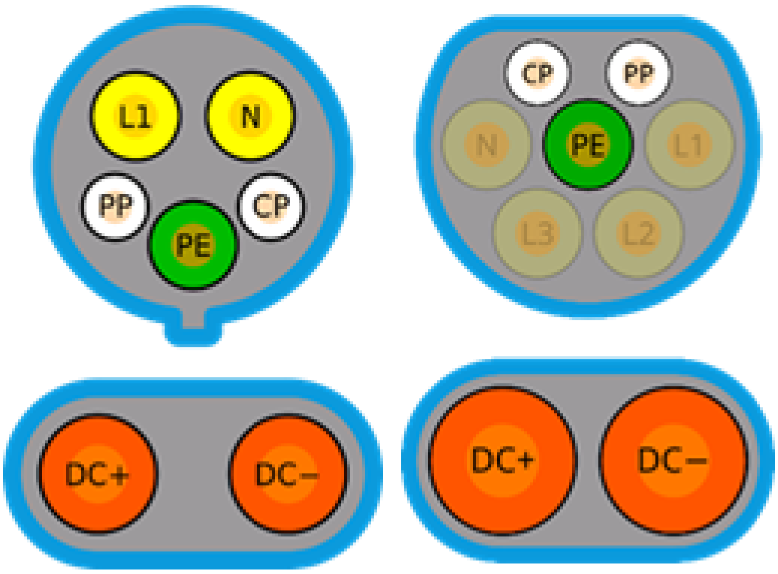


Fig. 4. CCS Combo 1 (left) and CCS Combo 2 (right) Connector

CHAdeMO

The Japan- made connector CHAdeMO is a DC fast- charging standard that has the ability to charge with maximum output current of 400 A at 400 V, resulting in a power of 400 kW. CHAdeMO has 10 pins, two of which are not for carrying power, but are data connections utilizing CAN (Control Area Network) bus communication protocol. The pins are named as follows: Ground (FG), Charge sequence signal (SS1/ SS2), Not connected (N/C), Charging enable (DCP), DC Power (DC+/ DC-), PP, CAN Bus (C-H, C-L). The main disadvantage of this connector type is that users need an additional charging port for AC- charging.

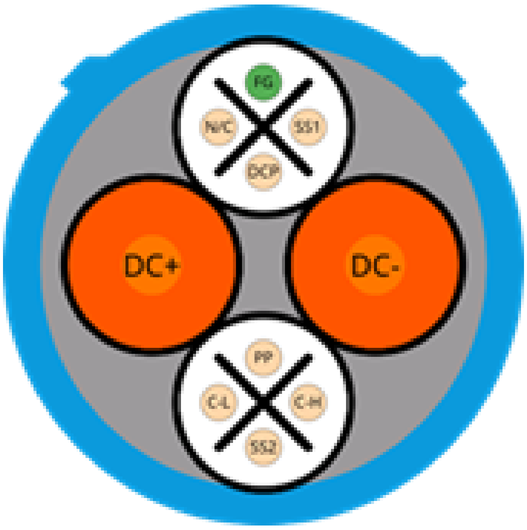


Fig. 6. CHAdeMO Connector

GB/T (AC and DC)

GB/T (Cuobiao national standards) are connector types from China, one is an AC-type charging (Level 2) and the other is DC (Level 3). The former works with 250 V three- phase voltage and 32 A current whereas the latter utilizes 440 V and 250 A. Their maximum output power is 7.4 kW and 237.5 kW respectively. GB/T (AC) has 7 pins- CC, CP, PE, N, L(1,2,3) and GB/T (DC) has 9- S+/S- (CAN Bus protocol), CC1/CC2 Charting confirmation, DC+/DC- main DC power, PE, A+/A- Axillary DC power.

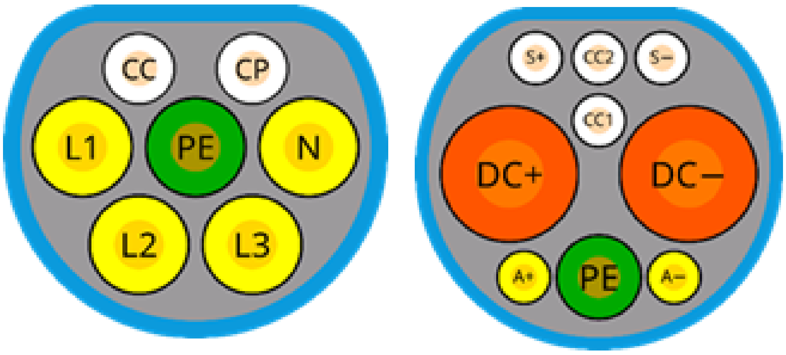


Fig. 5. GB/T (AC) (left) and GB/T (DC) (right) Connectors

TESLA

In North America Tesla utilizes North American Charging Standart (NACS), which supports both AC and DC charging as well as single and three- phase supply input. For AC NACS can deliver 48 A of current and for DC it goes to 400 A. The maximum provided output power is 250 kW. It has DC+/L1, DC-/L2, Ground, CP and PP pins.

In Europe and the rest of the World, Tesla offers adapters for their vehicles that utilize J1172 and CCS stations.

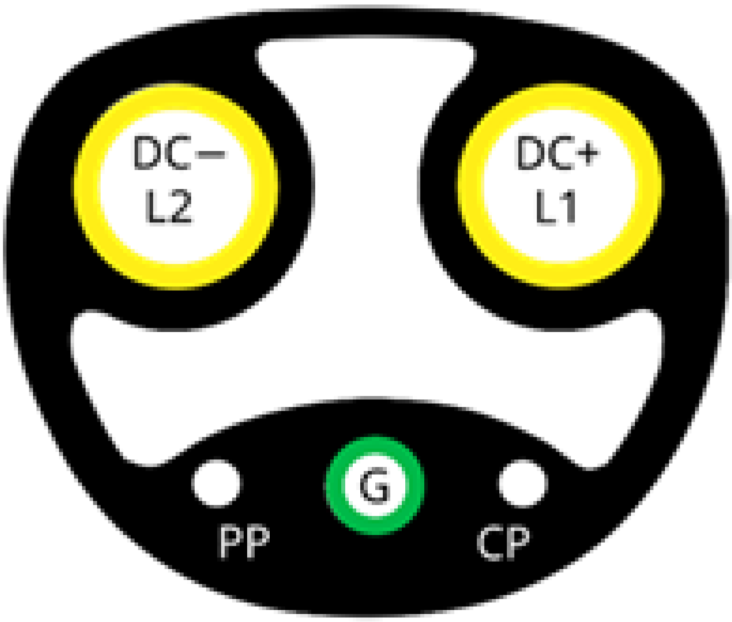


Fig. 5. NACS Connectors

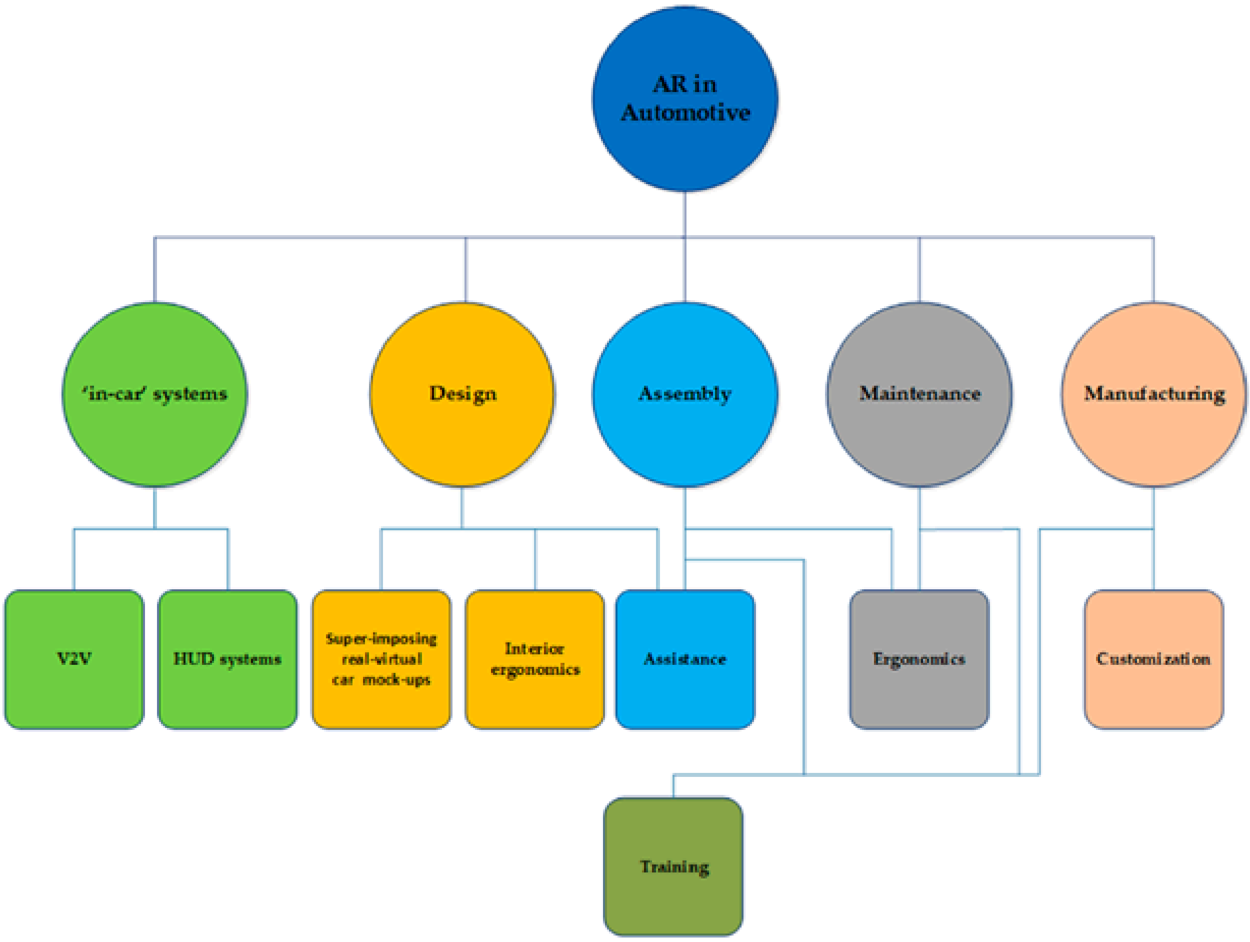
THE INTEGRATION OF AR AND VR TECHNOLOGIES IN ELECTRIC VEHICLES

The rise of electric vehicles (EVs) has triggered a parallel evolution in how vehicles are designed, operated, and experienced. Beyond advancements in battery technology, autonomous systems, and power electronics, immersive technologies—specifically Augmented Reality (AR) and Virtual Reality (VR)—are playing an increasingly vital role across the EV value chain. These technologies enabling smarter user interfaces, more efficient development cycles, and safer maintenance and training environments.

One of the most prominent applications of AR in EVs lies in enhancing human-machine interaction (HMI). AR-based head-up displays (HUDs) project critical driving information—such as speed, navigation cues, battery charge status, and adaptive cruise control data—directly onto the windshield. These overlays are precisely aligned with the driver's field of view, utilizing real-time data from GPS, LiDAR, and onboard cameras to maintain accurate positional awareness. This eliminates the need for drivers to divert attention from the road, thereby increasing safety and reducing cognitive load.

Further integration of AR in navigation systems enhances situational awareness by superimposing route guidance elements—like arrows and lane-change indicators—onto the real-world environment. When embedded in HUDs or mobile AR applications, this functionality supports real-time decision-making and streamline route adjustments. For EV drivers, such systems can also overlay information about charging station availability, estimated queue times, and power output directly onto the surrounding environment, creating a more intelligent and responsive driving experience.

Beyond driver assistance, AR also supports diagnostic and maintenance processes. Technicians equipped with AR-enabled glasses or tablets can visualize system schematics, highlight fault codes, or follow guided repair workflows superimposed on physical components. This capability significantly reduces training time, improves service efficiency, and minimizes the risk of human error, particularly crucial for high-voltage EV systems that require strict safety compliance.



AR applications in automotive

While AR is reshaping the real-time vehicle interface, VR is transforming how EVs are conceptualized, designed, and validated. Automotive engineers now employ VR environments for rapid prototyping and digital validation of vehicle platforms. In virtual design reviews, teams across discipline mechanical, electrical, and software—can collaboratively assess ergonomic layouts, thermal packaging of battery modules, or crashworthiness scenarios without physical mock-ups. This leads to faster iteration cycles and a reduction in prototyping costs.

VR also plays a key role in system-level simulation. Coupled with high-fidelity physics engines, engineers can model drivetrain behavior, regenerative braking systems, and thermal characteristics under varying load and environmental conditions. VR-based vehicle dynamics simulations can be integrated with Hardware-in-the-Loop (HIL) frameworks to test embedded control systems in real time, expediting software validation under realistic driving scenarios before road trials.

In manufacturing and field service domains, VR is used to train personnel in a safe, repeatable environment. Workers can be immersed in simulations of EV assembly processes, battery handling procedures, or emergency disconnection protocols, mitigating the inherent risks of working with high-voltage systems. This is especially valuable in scenarios where live equipment exposure would be impractical or unsafe.

From a commercial standpoint, AR and VR also enhance the EV customer experience. Many OEMs are implementing virtual showrooms and interactive configurators that allow prospective buyers to explore vehicle features, compare models, and customize options through VR interfaces—either online or in dealership environments. Virtual test drives enable customers to experience torque response, user interface dynamics, and even assisted driving functions in a fully immersive simulation, improving customer engagement and accelerating purchase decisions.

Volkswagen ID Series – AR HUD

- The Volkswagen ID.3 and ID.4 electric vehicles feature an AR head-up display that projects navigation arrows, lane guidance, and adaptive cruise control information onto the windshield.
- The system uses GPS and sensor fusion (radar, cameras) to align graphics with the driver's view of the real world.

Hyundai – AR-Based Maintenance App

- Hyundai offers an AR mobile application called "Virtual Guide", which overlays maintenance and repair instructions on physical vehicle components.
- This allows EV owners to perform basic diagnostics or maintenance on models like the Hyundai Ioniq 5 using their smartphones.

Porsche Taycan – AR Charging Guidance

- The Porsche Taycan, an electric performance vehicle, integrates AR to assist drivers with finding and navigating to charging stations, showing direction overlays via the infotainment screen or compatible mobile devices.

VIRTUAL REALITY (VR) IN EV DEVELOPMENT AND TRAINING

Ford – VR in EV Prototyping and Ergonomics

- Ford uses VR to design and validate EV interiors, such as that of the Mustang Mach-E, by simulating human interaction with touchscreens, controls, and seating ergonomics before physical prototyping.
- Their immersive Vehicle Environment (iVE) platform enables global teams to collaborate in VR on vehicle packaging and design.

BMW – Virtual Assembly Training

- BMW has implemented VR training modules at their EV production lines (e.g., for the BMW iX and i4) to train factory workers on high-voltage battery installation and safety protocols.
- Trainees can practice complex procedures in a risk-free environment, reducing onboarding time and errors.

Audi – VR in Customer Experience

- Audi, including its e-tron line of electric vehicles, uses VR showrooms to allow customers to explore different configurations, test drive simulations, and see how features like regenerative braking work.
- These are deployed in dealerships and marketing events globally.

SOFTWARE AND PLATFORM PROVIDERS

Unity and Unreal Engine – EV Simulation

- Automotive manufacturers use game engines like Unity and Unreal Engine to create VR-based EV driving simulations and training environments.
- These platforms support immersive design reviews, vehicle dynamics modeling, and battery performance visualization.

Porsche & Holoride – In-Car VR Experience

- Porsche collaborated with Holoride, a VR entertainment company, to offer passenger VR experiences synced with real-time vehicle motion in electric vehicles.
- The system uses vehicle telemetry (e.g., acceleration, turns) to reduce motion sickness and enhance immersion for backseat passengers.

AR/VR IN EV SAFETY AND EMERGENCY TRAINING

Jaguar Land Rover – High Voltage EV Safety VR Modules

- Jaguar Land Rover has developed VR-based high-voltage safety training for their technicians and emergency response teams working on EV models like the Jaguar I-PACE.
- This training includes hazard identification, PPE usage, and emergency shutdown simulations.

Application Area	Technology	Example
Driver Assistance	AR	VW ID.4 – AR HUD for navigation and safety
Customer Experience	VR	Audi e-tron – VR showrooms and virtual test drives
Maintenance & Training	AR/VR	Hyundai Virtual Guide, BMW factory VR training
Design & Prototyping	VR	Ford Mustang Mach-E – VR design validation
Entertainment/Infotainment	VR	Porsche + Holoride – VR for rear passengers

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CHAPTER-3

POWERTRAIN OF ELECTRIC VEHICLES

Fundamentals of steering, suspension, and braking systems

Cars are complex machines designed to transport people and goods efficiently, comfortably, and safely. At the heart of a car's operation lie various interconnected subsystems, each playing a crucial role in ensuring the vehicle performs its intended function. A well-integrated vehicle design ensures these subsystems work together seamlessly, providing drivers with a smooth and controlled driving experience. These subsystems can be broadly categorized based on the different operational aspects they manage.

Steering System

The steering system enables the driver to control the direction of the vehicle. A well-functioning steering system ensures safety, handling, maneuverability, and comfort while driving. With the advent of electronic systems and autonomous driving technology, steering systems are evolving from purely mechanical linkages to intelligent control modules. A typical steering system consists of several key parts that work together to translate the driver's input into wheel movement:

- **Steering Wheel:** Interface between the driver and the steering mechanism.
- **Steering Column**: A shaft that connects the steering wheel to the steering gear.
- **Steering Gear (Gearbox):** Converts the rotational movement of the steering column into lateral motion to turn the wheels. Common types include rack-and-pinion and recirculating ball systems.
- **Tie Rods:** Connect the steering gear to the steering knuckles, allowing for controlled movement.
- Steering Knuckles – Pivot points that allow the wheels to rotate left or right.
- **Power Steering System:** Provides hydraulic or electric assistance to enhance precision and reduce steering effort.

The steering system lets the driver guide the car along the desired path by turning the front wheels. When you rotate the steering wheel, it turns the steering column, which connects to a steering mechanism (usually a rack-and-pinion or recirculating-ball gearbox). This mechanism converts the steering wheel's rotation into lateral movement, pushing or pulling the tie rods attached to the wheels. The wheels pivot on their knuckles, changing direction smoothly based on steering input. Proper alignment ensures stability and precise control while driving.

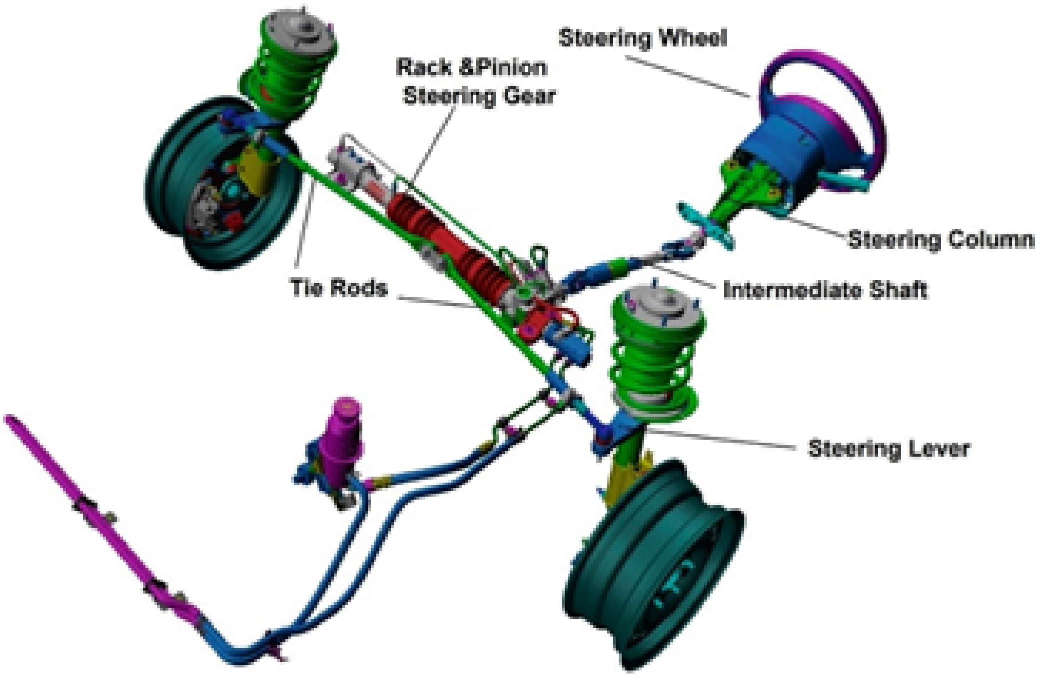


*Figure 1. Parts of the Steering System -**Source***

Power steering (hydraulic or electric) assists the driver in modern cars, significantly reducing the necessary physical effort. Hydraulic Power Steering (HPS) systems use fluid pressure generated by a pump (usually driven by the engine) to assist steering. Electric power steering (EPS) systems rely on an electric motor to provide steering assistance, improve fuel efficiency, and allow for advanced features like lane-keeping assistance and self-parking.

Steering systems require regular inspection to ensure safety and performance. Routine maintenance, such as wheel alignment, fluid level checks, and timely replacement of worn components, can extend the system's life. Common issues include Hard steering, which could indicate low power steering fluid or pump malfunctioning in HPS or a failing EPS motor; steering play or looseness, due to worn tie rods, steering gear, or bushings; and steering wheel vibration, often due to unbalanced wheels or worn suspension parts.

SUSPENSION SYSTEM

The suspension system provides ride comfort, vehicle stability, and improved handling and control by absorbing shocks from road irregularities and maintaining tire contact with the ground (especially during cornering, braking, or acceleration). A well-designed suspension system mediates between the car’s body and the road and is crucial for safety, comfort, and vehicle performance. As automotive technology evolves, suspension systems become more intelligent and adaptive. A typical suspension system consists of several essential parts:

Springs: Support the vehicle's weight and absorb and distribute energy from bumps and potholes.Common types include: coil springs, leaf springs, torsion bars, and air springs (see Figure below)

Shock Absorbers (Dampers): Control the rebound and compression of springs to prevent excessive bouncing.

·**Struts:** A structural component that combines the coil spring and shock absorber in one unit (see Figure below).

- **Control Arms:** Connect the wheels to the chassis, allowing up-and-down movement.
- **Ball Joints and Bushings:** Flexible joints that allow controlled movement of the suspension components. They reduce friction and noise between metal parts.
- **Stabilizer Bars (Anti-roll bars):** Reduce body roll during cornering for better stability.

Modern suspension systems are becoming increasingly sophisticated, able to adjust stiffness and damping in real time for optimal performance. Some recent breakthroughs include adaptive or active suspension, which adjusts the damping force in real time based on driving conditions, and using sensors and actuators to control the vertical movement of the vehicle's wheels and axles relative to the chassis.

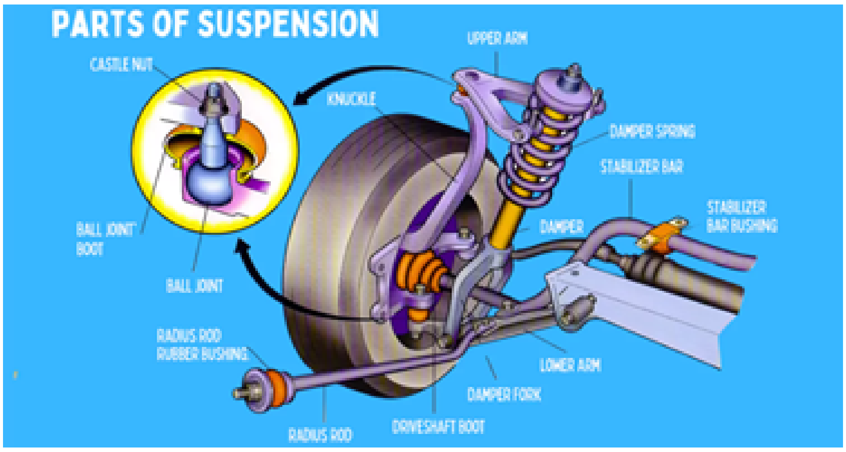


Figure 2. Parts of Suspension System - Source

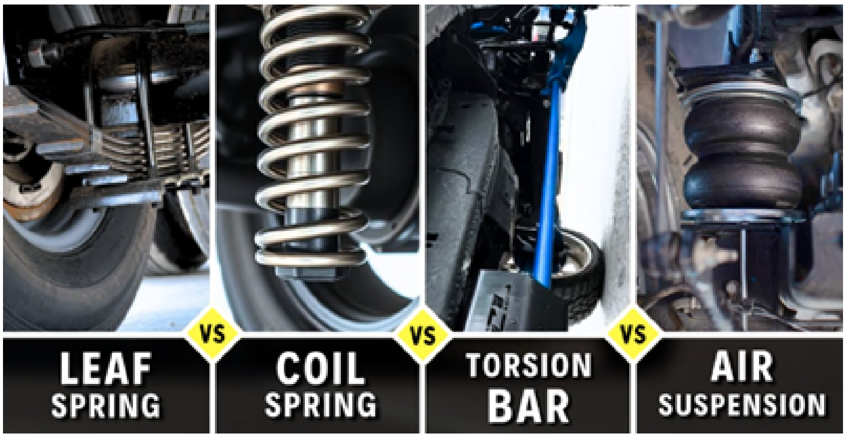


Figure 3. Spring types

Figure 4. Strut - Source

Car suspension systems can be broadly categorized into two types:

1. **Dependent (Solid Axle) Suspension** – A rigid axle connects the wheels. Movement in one wheel affects the other. This type is common in trucks, SUVs, and older vehicles. It provides durability but with less comfort and handling precision.
2. **Independent Suspension** – Each wheel moves independently, providing better handling and comfort. On the other hand, they are more complex and expensive to repair. This type of suspension is common in modern passenger cars. Examples of independent suspension are MacPherson Strut (combines a shock absorber and a coil spring into a single unit; compact and cost-effective) and Double Wishbone (uses two control arms to hold the wheel; offers better control, but is costly, used in sports cars).

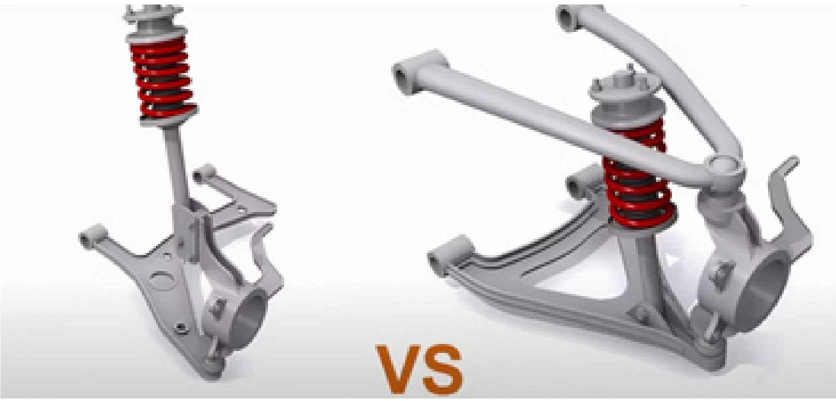


Figure 5. MacPherson Strut VS Double Wishbone

Routine shock absorbers, bushings, and alignment checks ensure the system functions properly and safely. A failing suspension system can lead to:uneven tire wear, excessive bouncing or nose-diving, steering instability, and clunking or squeaking noises.

BRAKING SYSTEM

The braking system is one of a vehicle's most critical safety components. It ensures the car can slow down or stop safely and efficientlyby converting kinetic energy into heat. This is typically achieved through friction, though modern systems may involve hydraulic or electronic components. A properly functioning braking system ensures the safety of the driver, passengers, and pedestrians, provides control during emergencies, and enhances vehicle handling on different road conditions. That's why regular inspections of brakes are a must. The braking system typically includes:

- **Brake Pedal:** Allows the driver to initiate braking.
- **Master Cylinder:** Converts pedal force into hydraulic pressure.
- **Brake Lines and Hoses:** Tubes that carry brake fluid from the master cylinder to the brake calipers or drums of each wheel, transmitting pressure to the brakes.
- **Disc or Drum Brakes:** Create friction to slow the wheels.
- **Brake Pads and Rotors:** Wearable components that engage to create friction.
- **Anti-lock Braking System (ABS):** This system prevents wheel lockup during emergency braking by rapidly pulsing the brakes, allowing the driver to maintain control.

When the driver presses the brake pedal, the master cylinder converts this force into hydraulic pressure. Brake fluid flows through the lines to the calipers, which push the brake pads against the rotors (they spin with the wheels), generating friction. This way, the wheels slow down, and the vehicle comes to a stop. Sensors monitor wheel speed in cars with Anti-lock Braking System (ABS). If a wheel is about to lock up, the ABS uses brakes to maintain grip. In modern vehicles, we can also see new tendencies in braking systems, such as brake-by-wire technology that uses electronic controls instead of hydraulic systems, or regenerative Brakes in hybrid and electric vehicles that convert kinetic energy back into electrical energy.

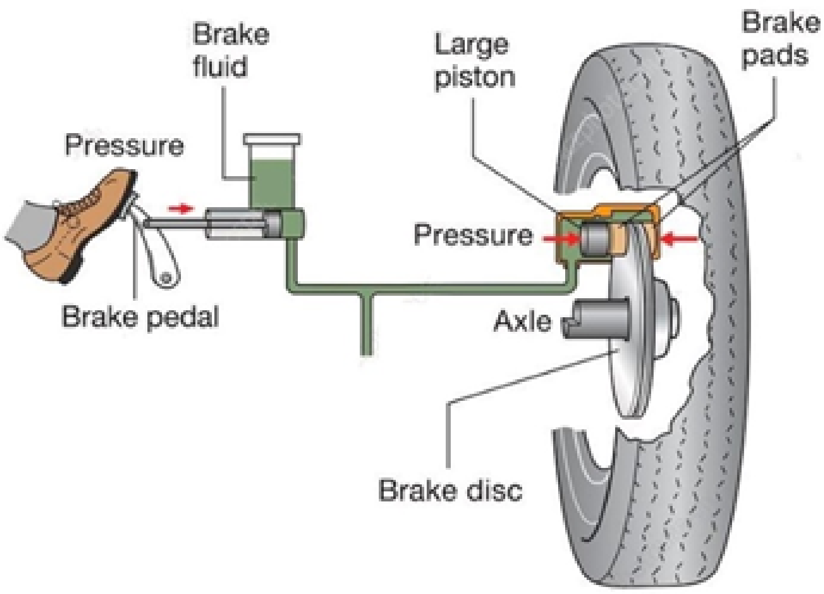


*Figure 6. Parts of Breaking System - **Source***

MECHANICAL-ELECTRICAL INTEGRATION EXAMPLES FOR EVS

Innovative principles in the automotive industry have led to the transition from internal combustion engines (ICEs) to electric vehicles (EVs). While traditional vehicles are dominantly mechanical systems, EVs contain subsystems that rely on synergy between mechanical components, such as chassis, drivetrain, powertrain, thermal systems, and electrical elements, such as batteries, motors, power electronics, etc. This combination integrates these two subsystems to obtain more efficient, safer, and optimized components, reducing space and weight, positively affecting construction and assembly complexity.

One of the key components in mechanical-electrical integration is battery packs, used for storing electrical energy, representing the most significant and heaviest elements of each EV. Integration is reflected in mounting the battery modules as a structural element of the vehicle chassis, providing a compact product contributing to the chassis stiffness. Another EV part is the electric motor that replaces the ICE in traditional vehicles. The integration is mainly related to synthesizing electric motors with gearboxes and cooling systems, ensuring efficient energy consumption. The power electronic systems, which include inverters, converters, and control units (CUs), manage the power flow of the EVs, and they are usually packed with electrical motors in integrated drive units. Shared cooling units are also incorporated into an EV chassis for optimal operating temperatures for battery packs, engines, and other electronics. Braking systems, where regenerative braking is used to recapture kinetic energy, exemplify the synergy between mechanical brakes and the electronic control systems of EVs.

INTEGRATION LEVELS AND ARCHITECTURES

COMPONENT-LEVEL INTEGRATION

Component-level integration is based on redesigning individual components to obtain unified EV elements for optimized physical and functional merging. In conventional ICEs, mechanical power from the engine is transmitted via a clutch and short shaft to the gearbox, which delivers power to differential gears and drives the wheels through two drive shafts (Figure 7a). In EVs, component-level integration combines power electronics and electric motors (Figure 7b), where direct current (DC) from batteries is converted to alternating current (AC) for motors. The produced mechanical energy is transmitted to drive wheels through the drive shaft, with integrated designs reducing complexity while minimizing installation space and providing flexibility. The inverter ensures a reliable on-demand power supply through electronic motor control and monitoring.

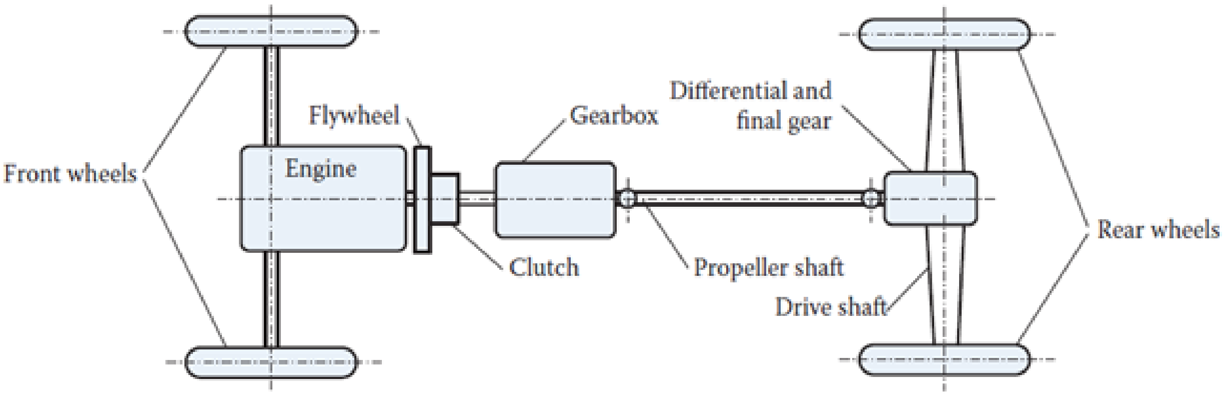


Figure 7a: Conventional ICEs

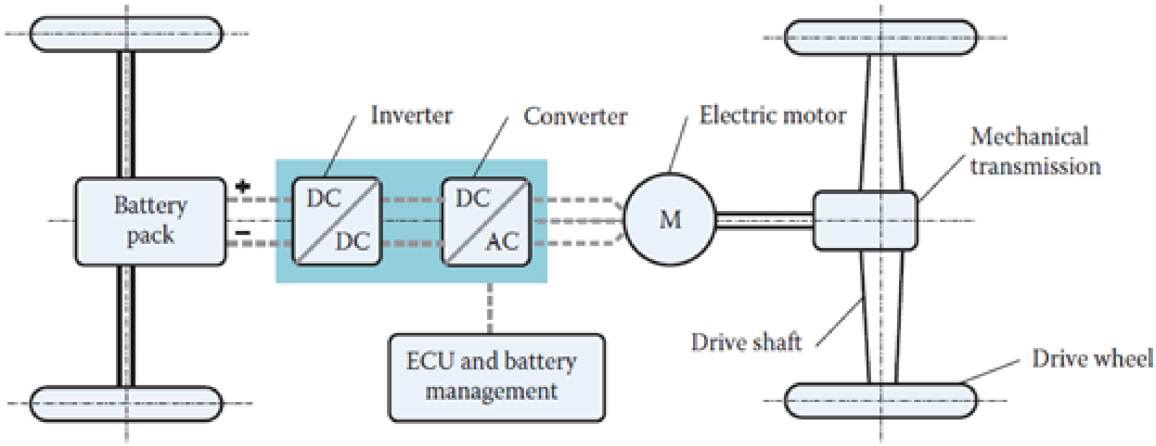


Figure 7b Conventional EVs

An example is the electric drive module in *Figure 8*, which improves energy density and thermal management but may increase repair costs due to modular designs requiring complete disassembly for single-element replacement.

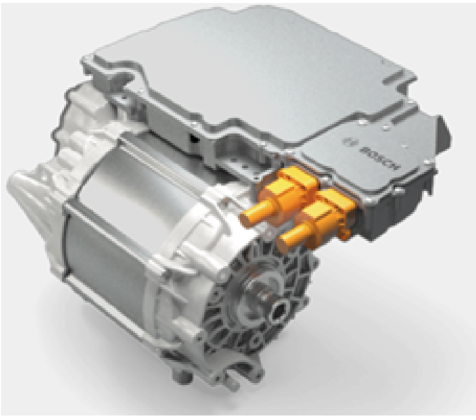


Figure 8 Electric drive module – Bosch **Source**

SUBSYSTEM INTEGRATION EXAMPLE

This integration combines multiple components into single functional units, such as electric drive units housing motors, inverters, and transmissions in one assembly. An example is the in-wheel motor drivetrain, which simplifies EV mechanical design. In-wheel motors can be deployed in front-wheel, rear-wheel, or four-wheel drive arrangements (Figure 9), directly driving vehicles while offering regenerative braking. Advantages include flexible manufacturing and high torque for impressive acceleration.

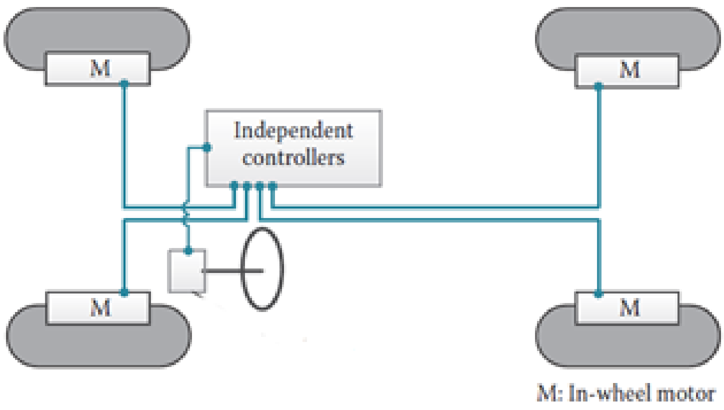


Figure 9: In-wheel motor

Modular designs reduce complexity and allow power, torque, and installation space customization. Bosch's eAxle (Figure 11) is a compact system usable across EV models.

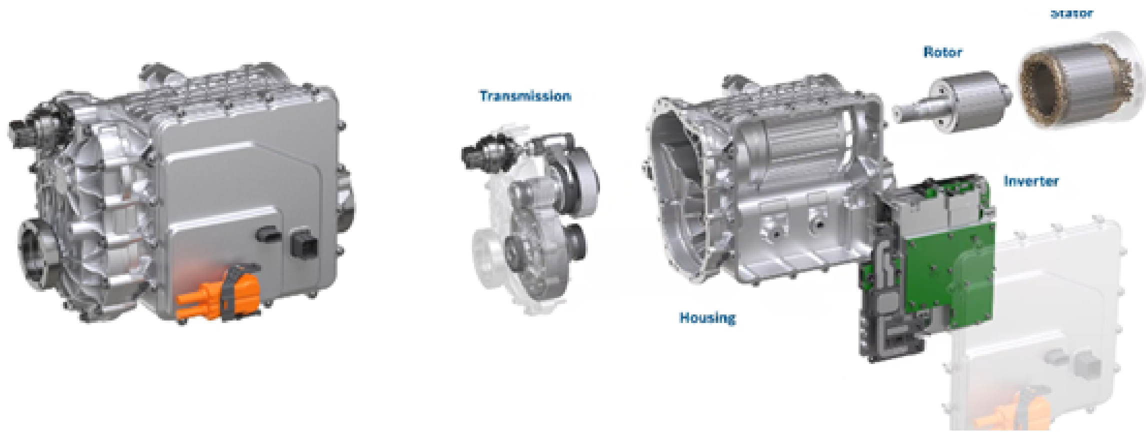


Figure 11 Bosch eAxle system **Source**

STRUCTURAL INTEGRATION

Structural integration improves vehicle stiffness and crash performance by embedding components like battery packs into the chassis. The e-powertrain's simplicity has led to skateboard chassis designs, where energy sources and e-powertrains are enclosed within the chassis (Figure 12). Originally implemented by GM in 2002 (AUTOnomy chassis), this concept enables greater flexibility, passenger space, and modular platforms for varied vehicle types.

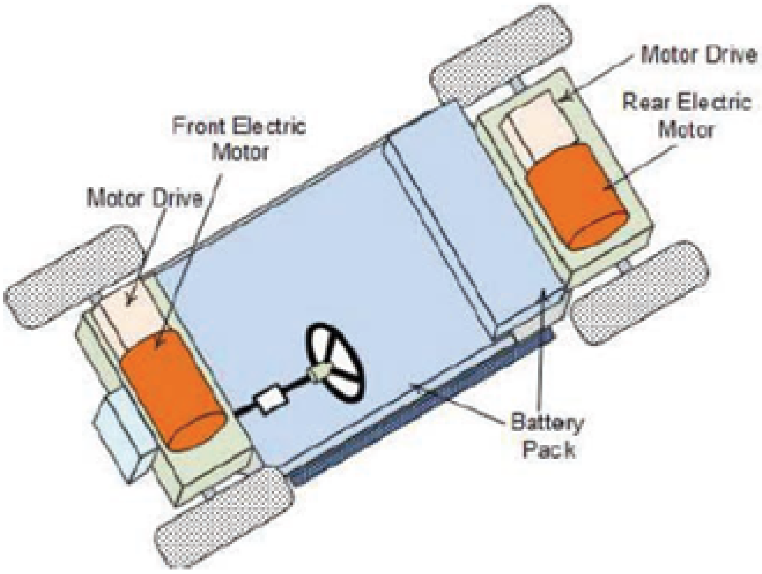


Figure 12 Skateboard chassis Source

BY-WIRE TECHNOLOGY EXAMPLE

Conventional vehicles have pedals and steering wheels that transfer the driver's controls to the vehicle's driving components through mechanical elements. Using electronic components and electromechanical actuators to substitute mechanical and hydraulic components in ICEs is known as by-wire technology. Examples of by-wire technologies are steer-by-wire and brake-by-wire.

STEER-BY-WIRE

This technology uses algorithms, electronics, and actuators to eliminate mechanical steering connections (steering shaft, column, and gear reduction). Without physical steering wheel-tire connections, motor controllers use position sensors and phase current feedback to control output torque (Figure 13).

Figure 13 Steer-by-wire concept **Source**

BRAKE-BY-WIRE

Brake-by-wire engages brakes via electronic controls and electromechanical actuators, supporting all conventional hydraulic brake functionalities while offering faster response, smoother control, improved packaging, and easier assembly (Figure 14). It simplifies safety/stability features and improves fuel economy by reducing drag. Eliminating hydraulic pumps and brake fluid enhances reliability and maintenance. Force sensors estimate brake clamping force, with feedback generating electric motor torque commands for actuators.

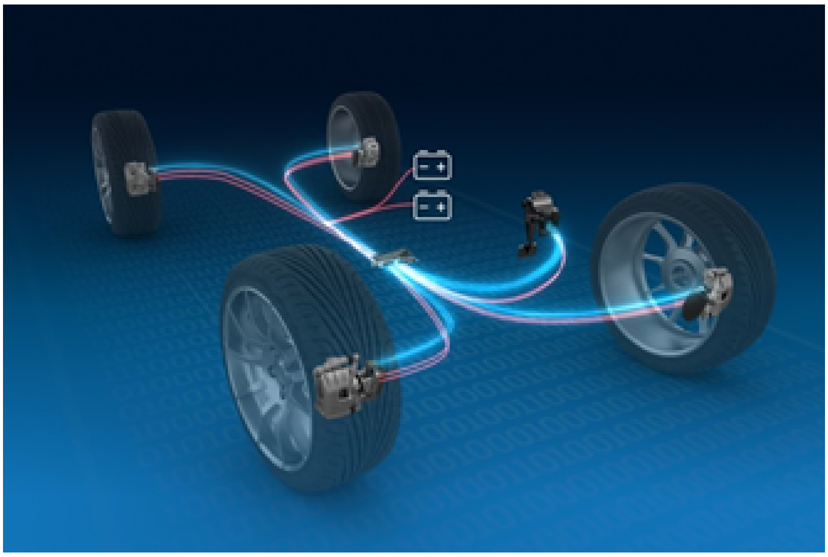


Figure14 Brake-by-Wire **Source**

AR/VR TRAINING SCENARIO: BRAKE-SYSTEM FAILURE SIMULATION & REPAIR WORKFLOW

INTRODUCTION

As electric vehicles become increasingly sophisticated, the ability to train technicians in diagnostics and repair workflows becomes crucial. Traditional hands-on training is limited by cost, safety, and access to real malfunctioning systems. AR and VR offer immersive, interactive training environments where students and professionals can engage with realistic simulations of failure scenarios. This section focuses on the development and pedagogical value of an AR/VR training scenario centered on brake-system failure in electric vehicles.

SCENARIO OVERVIEW

The following scenario puts a learner in a highly detailed virtual workshop that mirrors a professional EV service bay. A full-scale electric vehicle chassis is suspended on a programmable lift, surrounded by various diagnostic instruments, digital multimeters, and live-feed system analytics projected on wall-mounted screens. VR participants navigate the space wearing headsets, while AR users employ tablets or smart glasses to cover interactive overlays on physical brake components.

Figure 15. VR participants navigate the space wearing headsets

At the start, trainees witness the vehicle's control system issuing a series of fault codes via a simulated OBD-II interface (highlighting anomalies in brake-by-wire performance). Warning indicators such as a blinking ABS icon and a color-coded energy-recovery gauge draw attention to the core malfunction: irregular regenerative braking output. Detailed telemetry charts can display, for example, fluctuating hydraulic pressure and inconsistent motor torque commands, while time-stamped logs could point out a steady decline in recovered kilowatt-hours during deceleration tests.

Students will then be tasked with engaging the virtual scan tool, tapping icons to retrieve error descriptions and access live sensor feeds. They can pause the simulation to review historical performance graphs or drill down into raw CAN bus messages for insight into pulse-width-modulation irregularities and encoder miscounts. Once the diagnostic data is collected, trainees physically or virtually interact with the brake actuator assembly, applying gesture-based controls to open the housing and inspect individual parts.

REPAIR WORKFLOW IN THE SIMULATION

The simulation workflow of the reparation process should include the following steps:

1.Initial Diagnostics

Scan the system using a virtual diagnostic tablet:

- Power on the tablet and select the "Brake Subsystem" profile.
- View live data streams for hydraulic pressure, actuator motor current, and sensor voltage.
- Use gesture controls or a touchscreen to freeze specific data frames for closer inspection.

Retrieve error codes related to brake actuation and pressure sensors:

- Open the "Error Codes" menu to list active errors (e.g., C1215: Actuator feedback fault; C1382: Pressure-sensor mismatch).
- Tap each code to read detailed descriptions and possible causes.
- Access suggested troubleshooting steps linked to each fault code.

Figure 16. Retrieving error codes

Review historical performance logs and sensor anomalies:

- Navigate to the “Performance Logs” section to display time-stamped graphs of brake-line pressure versus vehicle speed over the last 100 km.
- Identify highlighted anomaly markers where values exceed built-in tolerance thresholds.
- Review the timeline to correlate pressure drops or spikes with corresponding ABS warnings and torque-command deviations.

1.Component Inspection

Interactively disassemble the brake actuator in the simulation:

- Engage the virtual detachment tool to unlock mounting bolts and remove the actuator cover.
- Use hand-tracking or controller inputs to slide out the actuator assembly, revealing internal gears and electronics.
- Place components on the virtual workbench for isolated inspection.

Inspect and test sensors (e.g., force sensors, motor encoders):

- Select each sensor module to run built-in diagnostic routines (e.g., force sensor calibration test, encoder signal integrity check).
- Observe live readings, such as force values in Newtons and encoder pulse counts, and compare against nominal ranges.
- Flag any sensor exhibiting irregular behavior or out-of-spec outputs for further analysis.

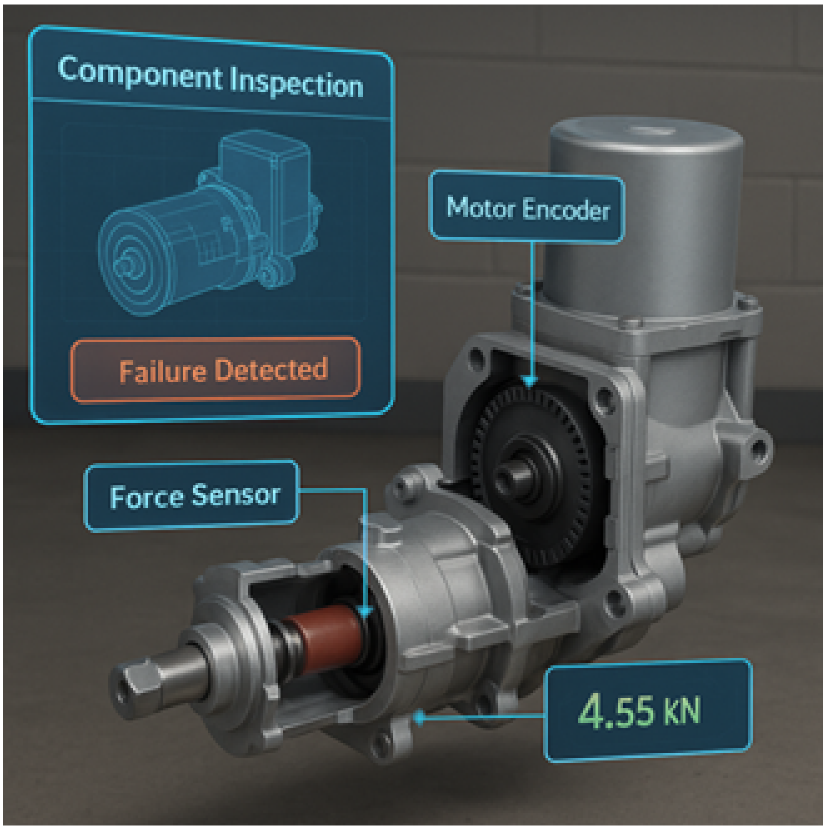


Figure 17. Running built-in diagnostic routines

Use AR overlays to view data points and failure locations:

- Activate AR-mode to overlay heatmaps directly onto the actuator housing, indicating thermal hotspots.
- Display color-coded callouts for sensor nodes, showing last-known voltage/current values and fault histories.
- Toggle between overlay modes (voltage, temperature, vibration amplitude) to pinpoint exact failure sites.

1.Repair and Replacement

Remove and virtually replace the faulty actuator or sensor:

- Detach the malfunctioning actuator/sensor from its mount using a virtual tool.
- Retrieve a replacement part from the digital parts bin and align it with the mounting points.
- Secure the new component, torquing mounting bolts to specified values.

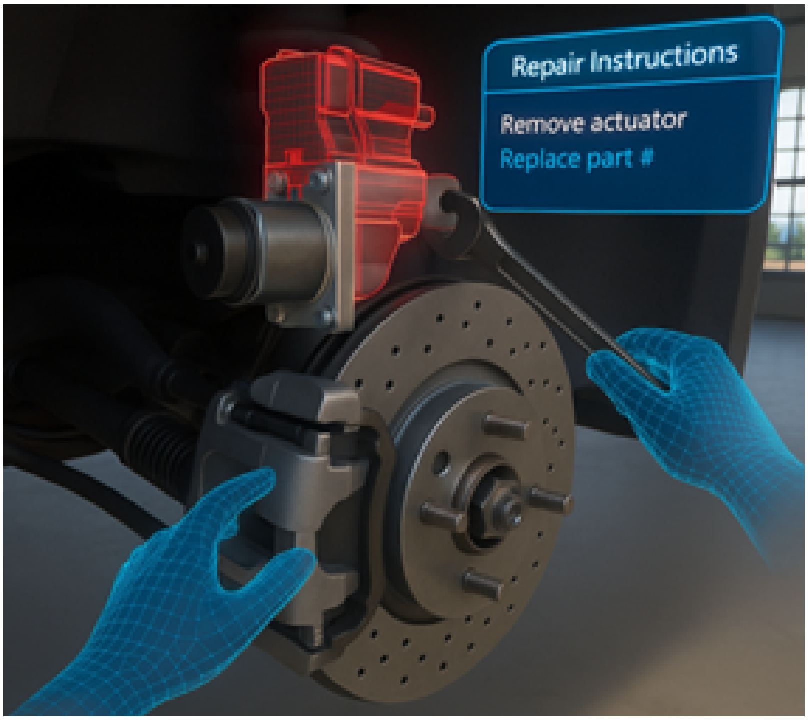


Figure 18. Virtually replacing the faulty actuator

Re-calibrate the control unit using simulated software tools:

- Launch the calibration interface on the virtual diagnostic tablet.
- Run the "Brake Actuator Zero-Point" routine to reset positional offsets.
- Adjust pressure thresholds and feedback gains according to manufacturer specifications.
- Save and verify calibration parameters by executing a test actuation cycle.

Update system firmware if necessary:

- Access the "Firmware Manager" within the simulation's menu.
- Upload the latest firmware image and initiate the update process.
- Monitor progress bars and logs to ensure a successful flash without errors.
- Perform a quick reboot of the control unit and confirm the version number matches the updated release.

1.Validation

Conduct a virtual road test (e.g., urban route with stop-and-go traffic):

- Select the "City Loop" scenario from the simulation menu.
- Navigate through intersections, traffic signals, and pedestrian crossings.
- Execute multiple braking events at various speeds and road conditions (wet, dry, uphill).

Figure 19. Conducting a virtual road test

Monitor real-time telemetry: brake pressure, actuator response time, ABS behavior:

- Display the floating telemetry dashboard showing live brake-line pressure curves and actuator position graphs.
- Observe ABS activation indicators and pulse frequencies during emergency stops.
- Track response latency between pedal input and actuator movement to ensure performance targets.

Pass the safety checklist before ending the simulation:

- Verify that all Diagnostic Trouble Codes remain cleared.
- Confirm that measured brake pressure and actuator response times are within specified tolerances.
- Check that ABS engages only under threshold conditions and does not lock wheels.

Understand the functionality of brake-by-wire and regenerative braking systems:

- Explain the principles of electronic pedal actuation, signal processing, and actuator mechanics.
- Describe how regenerative braking integrates with friction braking to maximize energy recovery and maintain safety.
- Compare different EV braking architectures, including single-motor vs. dual-motor regen strategies.

Diagnose failure using digital tools and system feedback:

- Operate virtual diagnostic tablets to retrieve and interpret errors, sensor logs, and performance graphs.
- Correlate error codes with real-time telemetry such as pressure curves, motor current spikes, and ABS activation events.
- Utilize historical data logs to identify intermittent faults and pattern anomalies in braking performance.

Apply procedural steps to replace and calibrate EV braking components:

- Follow safe disassembly protocols in augmented or virtual reality, including proper tool selection and torque specifications.
- Execute actuator and sensor replacement procedures, ensuring accurate part alignment and electrical connections.
- Perform zero-offset calibration, pressure-bleeding routines, and control-unit configuration via simulated software interfaces.

Evaluate repair effectiveness through data-driven validation:

- Conduct virtual road tests under varied scenarios (urban stop-and-go, high-speed emergency braking) to measure outcome metrics.
- Analyze key performance indicators: brake-line pressure consistency, actuator response latency, and regenerated energy percentages.
- Document results in an electronic logbook, comparing pre- and post-repair data to confirm restoration of system parameters within tolerances.

EV MALFUNCTION CASE 1: BATTERY THERMAL MANAGEMENT SYSTEM FAILURE

1. Fault Description

The electric vehicle shows a warning on the dashboard: "Battery temperature too high. Reduced power mode activated." The driver reports that the warning appears after 20–30 minutes of driving. He experiences a sudden reduction in vehicle acceleration, and the cooling fan runs continuously without turning off.

2. Initial Inspection

The service person inspects the coolant reservoir for the correct fluid level and looks for leaks or cracks in coolant lines around the battery pack. He listens for fan operation and unusual noises. He then uses a diagnostic tool to check for Diagnostic Trouble Codes (DTCs). Common DTCs for this issue should be P0A82: Battery Pack Cooling System Performance, P0A80: Replace Hybrid Battery Pack, or U0293: Lost communication with hybrid/EV battery control module.

3. Detailed Diagnostic Procedure

The service person connects to the vehicle's Electronic Control Unit (ECU) and logs DTCs to monitor real-time data for battery cell temperatures and coolant pump status. He then checks the coolant pump function. If it doesn't activate, he should check the pump connector's voltage supply and resistance. The next step is to inspect coolant temperature sensors and use a thermal camera to look for hotspots in battery modules.

4. Root Cause Identified

Let's assume that the service person determined the malfunction: the coolant pump failed due to an internal electrical short, preventing coolant circulation through the battery pack and leading to overheating.

5. Corrective Action

The broken part should be replaced. The failed coolant pump should be removed by disconnecting it, draining the coolant, and eliminating the lines and connectors. Then, a new coolant pump should be installed by reconnecting hoses and wiring and refilling the coolant system. This ensures that no air pockets remain in the system. Ultimately, the service person should clear DTCs, test run the pump via scan tool, and verify coolant flow and stable battery temperature under load.

6. Post-Repair Testing

Finally, the service person performs a road test with real-time temperature logging to ensure no warning messages or DTCs reappear. After that, he checks for correct fan behavior and coolant level and confirms that vehicle performance is restored to normal mode.

7. Customer Handover and Reporting

The service person explains the cause of the fault and the repair steps to the client and provides preventive advice, such as regular coolant check intervals.

Summary Table – Step Description

- Fault: Battery temperature warning, reduced performance
- Initial: Visual check, DTC scan
- Diagnosis: Coolant pump unresponsive
- Cause: Internal electrical failure in the pump
- Action: Replace the pump, refill the coolant
- Test: Road test, data monitor
- Close: Customer explanation, documentation

EV MALFUNCTION CASE 1: BATTERY THERMAL MANAGEMENT SYSTEM FAILURE

1. Fault Description

The driver notices that the vehicle does not slow down as expected when releasing the accelerator, and the deceleration is reduced, although the brake pedal feels normal. The regenerative braking icon does not illuminate on the dashboard, and the energy flow screen shows that less energy is being returned to the battery.

2. Initial Inspection

The service person performs visual inspections of wheel speed sensors and checks for warning lights (ABS, ESC, brake system). Next, he examines the brake pedal position sensor wiring and reviews the battery charge level because regenerative braking is limited when the battery is nearly complete. Most importantly, in this phase, he uses a diagnostic tool to check for DTCs. Standard codes in this case may include: C1234: Brake pedal position sensor malfunction, P1C73: Regenerative braking disabled, U0401: Invalid data from brake control module, and P0C79: Generator inverter performance.

3. Detailed Diagnostic Procedure
The service person connects the scan tool and reads DTCs from the brake control module and inverter. He monitors brake pedal position sensor data and the regen request signal. He performs a test drive with the scan tool connected to record inverter status, watch regen torque values, and note brake pressure and pedal sensor signals. He also inspects and tests the inverter and motor-generator response to the braking command.

4. Root Cause Identified
Let's assume that the service person determined the malfunction: the brake pedal position sensor is malfunctioning, sending an inconsistent or no regenerative request signal to the inverter. The sensor's analog voltage output is outside the expected range (e.g., stuck at 0.2V when it should vary between 0.5V and 4.5V).

5. Corrective Action
The service person should replace the broken part (brake pedal position sensor). First, he safely disconnects the 12V and HV systems and then removes and replaces the brake pedal position sensor. Then, he checks and cleans the sensor connector and harness and reconnects and calibrates the sensor using a scan tool. Additionally, he should clear DTCs, test regen braking engagement, and inspect other systems (e.g., ABS, ESC) for communication.

6. Post-Repair Testing
After corrective action (replacement of broken part), the service person should perform a road test to confirm proper deceleration when lifting off the accelerator and confirm that the regen indicator activates. He should use a scan tool to monitor regen torque and energy flow to the battery and check the system for any recurring faults or alerts.

7. Customer Handover and Reporting
In the end, the service person explains the function of regenerative braking and the nature of the failure to the client. He provides post-repair recommendations, such as avoiding full battery charging to preserve regen braking availability. He also updates the service log and resets maintenance indicators if required.

Summary Table - Step Description

- Fault: Regen braking inactive, vehicle coasts
- Initial: Visual check, DTC scan, pedal sensor test
- Diagnosis: Pedal sensor sends no regen request
- Cause: Faulty brake pedal position sensor
- Action: Replace sensor, calibrate system
- Test: Monitor regen torque, road test
- Close: Explain repair, update records

PROBLEM-SOLVING EXAMPLES

Challenge 1: Gear Ratio Riddle

Background: In an electric vehicle (EV), the motor often spins at very high speeds, while the wheels rotate at much lower speeds. The motor's speed must be reduced using a gearbox to make the EV operate efficiently and safely. This challenge focuses on calculating the correct gear ratio for a single-speed reduction system and understanding its effects.

Data:

Parameter	Value
Motor Maximum Speed	12,000 RPM
Desired Maximum Wheel Speed	1,200 RPM
Motor Torque Output	250 Nm
Efficiency of Gearbox	95%
Wheel Diameter	0.6 meters
Vehicle Mass	1,500 kg

Student Tasks:

1. Calculate the minimum gear ratio needed
Motor Speed: __________
Wheel Speed: __________
Gear Ratio = __________

2. What is the output torque at the wheels?
Motor Torque: __________
Gear Ratio (from Q1): __________
Gearbox Efficiency: __________
Output Torque at Wheels = __________ Nm

3. Why is speed reduction important in EV drivetrains?
Choose the two best answers and explain:
A. To increase torque at the wheels
B. To improve motor temperature
C. To match motor RPM with wheel requirements
D. To reduce battery voltage

Answer Choices: _____ and _____
Explanation: ____
____

Challenge 2: Gearbox Whine Noise

Background: Gearbox noise is especially noticeable in EVs due to the lack of engine masking noise. After integrating a single-speed reduction gearbox into a prototype EV, the engineering team noticed increased whining noise at high speed and vibration peaking around 4000 RPM.

Data:

Parameter	Value
Gear Type	Straight-cut spur gears
Motor Max RPM	12,000 RPM
Wheel Target RPM	1,200 RPM
Measured Vibration Peak (Hz)	67 Hz
Gearbox Material	Cast aluminum housing
Gearbox Mounting Type	Rigid frame bolted
Cabin Noise Level at 60 km/h	63 dB
Cabin Noise Level Target (EVs)	≤ 58 dB

Student Tasks:

4. Identify two likely mechanical causes of the observed whining and vibration. Use data from the table above to justify your answer.
Answer 1: ___________________________________
Answer 2: ___________________________________

5. Estimate the Gear Mesh Frequency
Assume: 1 gear mesh per revolution of the output shaft. Use motor speed and gearbox ratio to find mesh frequency in Hz.
- Output shaft RPM = ______
- Mesh frequency = ______ Hz

Calculation:
____

6. Suggest one practical design or material change to reduce noise/vibrations.
Answer: ___________________________________

7. Why are noise/vibration issues more noticeable in EVs than in ICE vehicles?
Answer: ___________________________________

Challenge 3: Sudden Drop in Regen Efficiency

Background: EVs use regenerative braking to recover energy during deceleration and feed it back into the battery. However, sometimes drivers report a sudden drop in energy being regenerated. This could be due to temperature, battery state-of-charge (SOC), or motor control limitations. In this challenge, students will explore data and reason through what may cause a drop in regeneration efficiency.

Data:

Parameter	Value
Initial Battery SOC	92%
Battery Temperature	44°C
Ambient Temperature	31°C
Regen Efficiency Yesterday	72%
Regen Efficiency Today	35%
Brake Pedal Pressure Applied	Medium

Student Tasks:

8. What is the percentage change in regenerative braking efficiency?
Old Regen Efficiency: __________
New Regen Efficiency: __________
Percentage Change = __________ %
Use the formula:
Percentage Change = ((Old - New) / Old) × 100

9. Which of the following is the most likely cause of the efficiency drop?
- A. Cold battery
- B. Full battery (high SOC)
- C. Low brake pressure
- D. Motor failure

Answer: __________

10. How could regen efficiency be improved in this scenario?
Provide two specific technical or usage-based suggestions.

1.____
2. ____

Answer Key Pointers:

1. Gear Ratio Calculation:
use the formula: Gear Ratio = Motor Speed / Wheel Speed
Gear Ratio = 12,000 / 1,200 = 10:1

2. Output Torque at Wheels:
use the formula:
Output Torque = Motor Torque × Gear Ratio × Gearbox Efficiency
Output Torque = 250 Nm × 10 × 0.95 = 2,375 Nm

3. Best Answers:
- A. To increase torque at the wheels
- C. To match motor RPM with wheel requirements

4. Likely Mechanical Causes:
- Poor gear meshing (e.g., straight-cut spur gears are noisier than helical)
- Resonance from a rigidly mounted gearbox
- Lack of vibration damping in the cast aluminum housing

5. Gear Mesh Frequency Estimate:
Given:
- Motor RPM = 12,000
- Gear Ratio = 10:1
- Output RPM = 12,000 ÷ 10 = 1,200 RPM
- 1,200 RPM ÷ 60 = 20 RPS → Gear mesh frequency ≈ 20 Hz
- Harmonics may cause peaks at 40 Hz, 60 Hz, etc.
- Vibration peak at 67 Hz might indicate a 3rd harmonic or housing resonance.

6. Design/Material Changes:
- Switch to helical gears for quieter meshing
- Use damped or composite gearbox housing
- Add elastomeric (soft) mounts for isolation

7. EVs vs ICE noise/vibration:
- Electric motors are nearly silent, so mechanical noises like gear whine stand out more in EVs than in ICE vehicles, where engine noise masks them.

8. Percentage Change:
((72 - 35) / 72) × 100 ≈ 51.39% drop

9. Best Answer:
B. Full battery (high SOC)
Explanation: When the battery is nearly full (above 90%), regenerative braking is limited to avoid overcharging.

10. Suggestions May Include:
- Pre-conditioning the battery to optimal temperature
- Avoid starting long descents with high SOC
- Using blended braking techniques that prioritize regen

INTERACTIVE MODULES ON MOTION TRANSMISSION AND VEHICLE DYNAMICS

EVs use a fundamentally different drivetrain architecture than internal combustion engine (ICE) vehicles. With fewer mechanical parts but more integration between hardware and software, understanding how torque is generated, controlled, and transferred to the road becomes technically challenging and educationally valuable. This motion transmission process strongly influences vehicle dynamics (like how a car behaves during acceleration, braking, and cornering).

This section describes potential solutions of interactive simulation modules that help learners visualize and manipulate drivetrain components and dynamic parameters in virtual environments. These modules are defined to replicate real-world EV scenarios, allowing experimentation with variables that would be difficult, dangerous, or expensive to explore physically.

MODULE 1 - POWERTRAIN EXPLORATION

This module introduces students to the foundational concept of how power is transmitted from an electric vehicle's battery to the wheels. While EVs typically lack complex multi-gear transmissions found in ICE vehicles, they require precise tuning of motor characteristics and reduction gear ratios to achieve the desired performance and efficiency. The module enables learners to visualize and manipulate each stage of this process and assess the resulting impact on vehicle behavior under different driving conditions.

Interactive Energy Flow Diagram

A dynamic, color-coded system diagram below presents the full energy path: from battery discharge, through the inverter and motor, passing through the reduction gear and differential, and finally reaching the drive wheels. The visual flow could be additionally animated with pulsing arrows that reflect real-time variables such as voltage, torque, and energy loss at each stage.

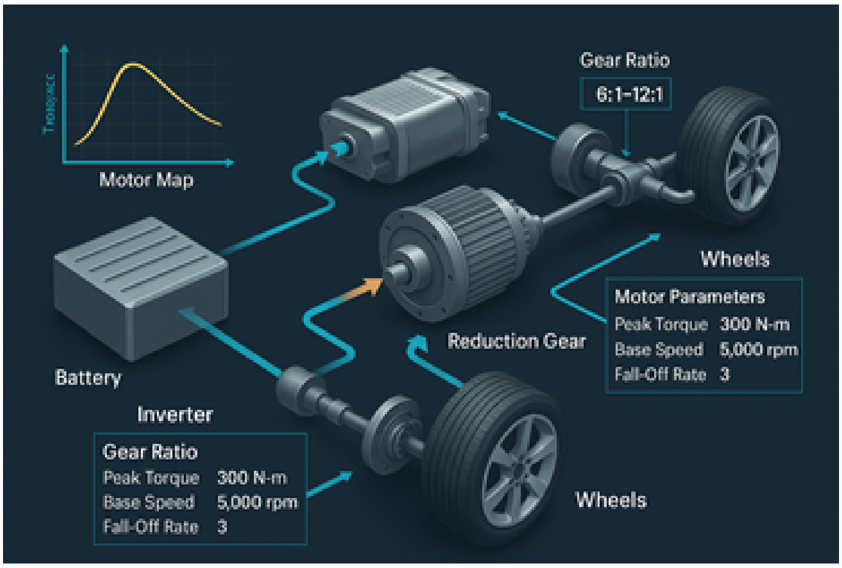


Figure 20. Interactive energy flow diagram

Adjustable Motor Parameters

Students can conceptually modify motor characteristics to see how performance changes. Adjustable fields include:

- **Peak torque** (e.g., 250 Nm to 500 Nm)
- **Base speed** (e.g., 4,000 to 7,000 RPM)
- **Torque fall-off rate** beyond base speed. These settings shape the torque curve and illustrate trade-offs between power output and motor control strategy.

Motor Efficiency Maps

A conceptual 3D efficiency plot below shows how motor performance varies with speed and torque. Users can explore operating zones and identify regions of peak efficiency. As they change load conditions or vehicle speed, the simulation shifts the efficiency footprint, helping students understand how driving habits affect energy use.

Image 21 presents a simulated EV dashboard showing real-time data on torque delivery, gear ratio selection, acceleration time, and energy consumption. It visually represents how different drivetrain settings impact vehicle performance, reinforcing the interactive tasks by connecting configuration choices with measurable driving outcomes.

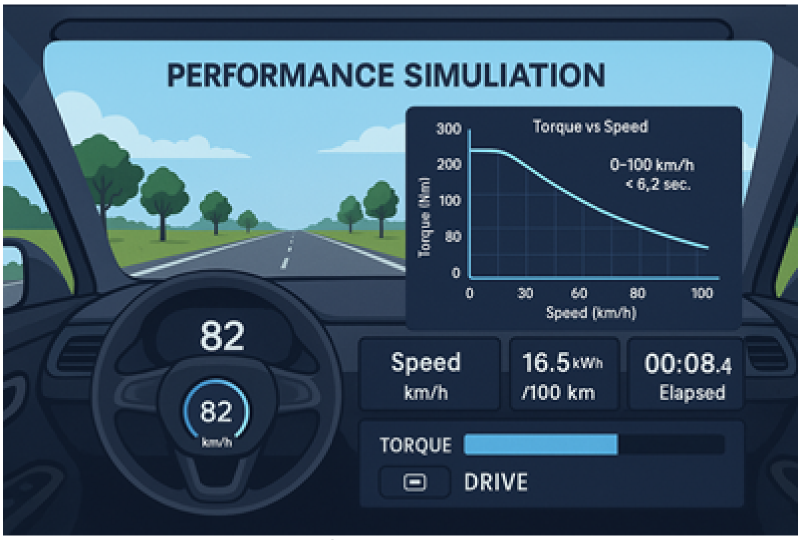


Figure 21. Simulated EV dashboard

Tasks and Activities

As part of the interactive module, students engage in various simulation-based tasks designed to deepen their understanding of electric vehicle powertrain behavior and performance trade-offs.

The first activity involves running acceleration simulations from 0 to 100 km/h. Learners configure different gear ratios and motor torque settings, then analyze results such as acceleration time, wheel slip events, and battery energy consumption. They are challenged to find the optimal configuration that delivers fast acceleration without exceeding thermal thresholds or causing traction loss.

Another core activity involves evaluating highway efficiency over a simulated 10-kilometer drive at a steady speed, such as 90 km/h. Students explore different motor efficiency maps, selecting operating zones optimized for low energy usage. They compare total energy consumption across configurations to quantify the impact of drivetrain tuning on long-distance driving efficiency.

Learners also perform torque delivery comparisons to reinforce the relationship between tuning decisions and real-world drivability. With real-time data overlays enabled, they examine torque output curves under varying conditions, such as urban stop-and-go traffic or uphill climbs. This exercise highlights how powertrain behavior influences throttle response and vehicle handling.

For advanced learners, an optional task could include monitoring thermal load within the motor and inverter. This activity allows students to visualize how aggressive torque profiles increase component heating, reinforcing concepts like thermal derating and the importance of managing temperature for long-term system reliability.

Regenerative braking plays a critical role in EV energy efficiency by converting a portion of the vehicle's kinetic energy back into electrical energy during deceleration. However, achieving an optimal balance between regeneration and conventional friction braking is essential for maintaining energy recovery and vehicle safety. This module allows students to interactively tune regenerative braking parameters under various driving conditions and observe how these changes influence braking performance, vehicle stability, and energy efficiency.

Simulation Tools

The regenerative braking simulation module should have a user-friendly interface that allows learners to explore and manipulate key parameters influencing braking performance and energy recovery. One of the core features is the ability to adjust the strength and blend ratio of regenerative braking, enabling students to control how much deceleration is handled by the electric motor versus the conventional hydraulic braking system. This provides an opportunity to explore how braking effort is distributed under different conditions.

Learners can also configure threshold triggers, determining the pedal position or deceleration rate at which regenerative braking activates or deactivates. This helps students understand how system tuning impacts smoothness and responsiveness during real-world driving scenarios. In parallel, live telemetry displays present instantaneous data on braking force, battery charge input, and deceleration rate, allowing users to assess system behavior in real time.

Figure 22 shows a simulated interface of a regenerative braking tuning module, featuring live telemetry graphs for brake pressure, regen power recovery, and ABS activation. It visually presents how adjusting blending curves affects energy recovery and vehicle stability during braking scenarios.

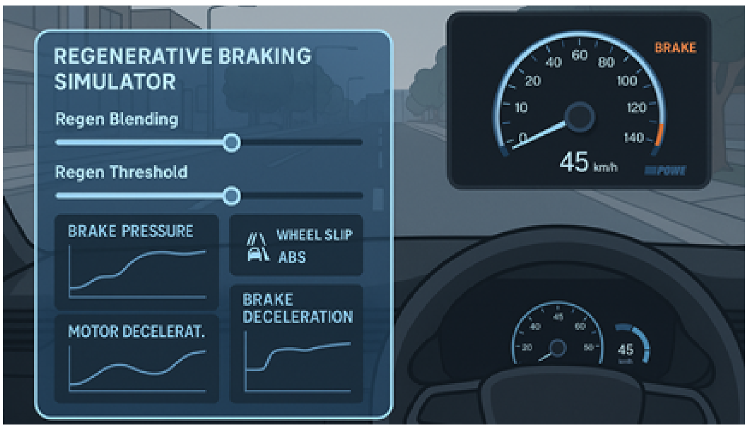


Figure 22. Simulated interface of a regenerative braking tuning module

Scenarios

1.Urban Drive Simulation

The learner simulates a 10-minute city drive cycle with frequent stops, moderate speeds, and varying traffic flow. The goal is to maximize energy recovery while preserving a smooth and predictable braking experience. Students adjust blending parameters and observe the impact on driving feel, regen kWh gain, and braking distance. They must identify settings that offer high energy return without introducing harshness or instability at low speeds.

2.Emergency Braking Scenario

A high-speed emergency stop is triggered, simulating a pedestrian crossing or sudden traffic halt. Learners are tasked with tuning the regen cut-out threshold to ensure friction brakes engage rapidly enough when regenerative deceleration reaches its safe physical limit. They must avoid wheel lock-up and maintain directional stability using live slip ratio graphs and ABS feedback. Success is measured by stopping distance and whether regen and friction systems engage seamlessly and predictably.

Figure 23 below compares two braking scenarios (urban and emergency), showing differences in deceleration behavior, energy recovery levels, and brake system response. It visually emphasizes how regenerative braking must be tuned differently for efficiency versus rapid stopping.

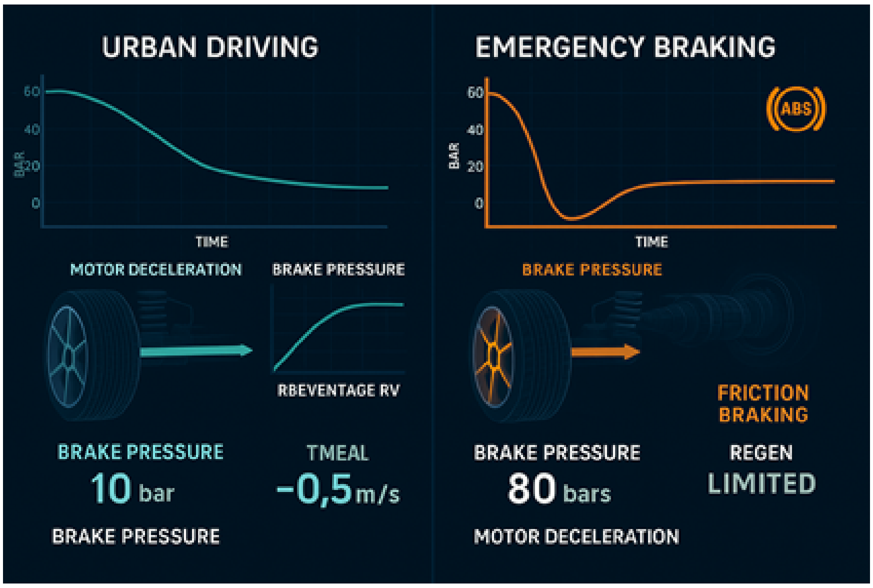


Figure 23. Comparison of urban and emergency braking scenarios

AR and VR technologies offer powerful tools for training in electric vehicle dynamics by immersing students in realistic driving environments. Unlike conventional simulations on screens, AR/VR allows learners to experience vehicle response from a driver's perspective, feeling every turn, brake, and surface change while observing live telemetry and receiving real-time system feedback. This module transforms abstract engineering principles into hands-on experience by placing learners inside high-fidelity EV scenarios that respond dynamically to their tuning decisions.

Environment Highlights

- **Realistic Driving Environments**

Students can explore various simulated conditions, including urban city streets, high-speed highways, mountain roads, and uneven off-road terrains. Weather and surface properties can be modified in real time to simulate rain, ice, gravel, or heat-affected asphalt. These environments help test vehicle setups in ways that would be costly or unsafe in the real world.

- **Live Telemetry Overlays**

Real-time data is projected into the user's field of vision or layered on physical vehicle models (in AR). This includes yaw rate, lateral acceleration, torque distribution, brake pressure, regenerative energy flow, tire slip angles, and wheel speed differentials. The overlay can be toggled or focused on specific subsystems for detailed analysis.

- **Multisensory Integration:**

The experience is enhanced with haptic steering wheels, brake pedals, and motion platforms that simulate suspension feedback, vibrations, and G-forces. Sound cues such as ABS activation or motor pitch add to realism. These cues reinforce student learning by linking physical sensation with system behavior.

Example Scenarios

1.Wet Cornering Test

Students drive through a simulated wet curve at various speeds, comparing vehicle stability with and without active torque vectoring. The system allows them to adjust the torque split between front and rear axles and observe the resulting changes in understeer/oversteer behavior, slip angles, and yaw stability. This scenario teaches the importance of dynamic torque management in low-friction environments.

Image 24 shows a VR driving simulation with a wet cornering scenario. It highlights real-time telemetry overlays such as tire slip angle, torque distribution, and yaw rate. It visually demonstrates how tuning decisions impact vehicle behavior under low-traction conditions.

Figure 24. VR driving simulation with a wet cornering scenario

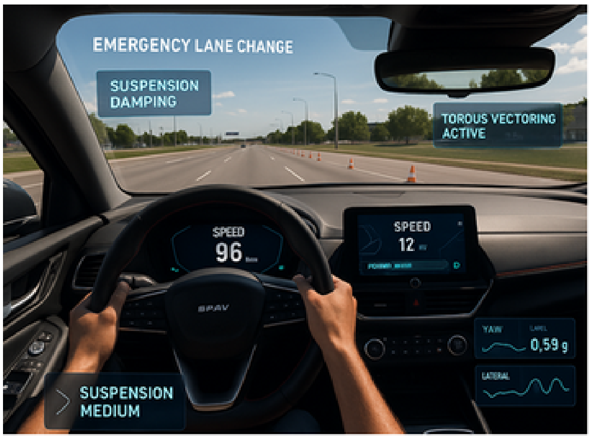


Figure 25. VR driving simulation of a high-speed emergency lane change

2.High-Speed Lane Change

In this exercise, learners perform a sudden double-lane change at 100 km/h. By modifying suspension stiffness and damping settings beforehand, they assess how different setups affect the vehicle's response time, body roll, and directional control. Failures in setup (e.g., too soft damping) result in delayed steering response or instability, helping students learn by consequence.

3.Emergency Obstacle Avoidance

Students approach an unexpected obstacle at 90 km/h and must brake and steer to avoid it. The scenario tests their system tuning (brake response, suspension stiffness, torque vectoring) and personal reflexes. Success depends on the engineering setup and the driving technique, mirroring real-world conditions.

The image below captures a VR driving simulation of a high-speed emergency lane change. It shows rapid steering input, vehicle body roll, and real-time feedback on suspension behavior and lateral acceleration, illustrating how dynamic settings affect control and stability under sudden maneuvers.

CHAPTER-4

OCCUPATIONAL HEALTH AND SAFETY (OHS)

Occupational Health and Safety in Electric Vehicle Service: A Comprehensive Analysis and Implementation Guide

Introduction

Electric vehicles (EVs) have initiated a revolutionary transformation in the automotive sector, driven by environmental sustainability goals. With the potential to reduce reliance on fossil fuels and build a cleaner future, EVs are becoming an indispensable part of daily life. This rapid growth increases the importance of EV service operations while bringing forth new occupational health and safety (OHS) risks that differ from and are more complex than those in traditional vehicle services. Particularly, high-voltage electrical systems, the unique hazards of lithium-ion batteries, and the specialized maintenance procedures required by these technologies create serious safety challenges for service technicians.

This report aims to deeply examine the primary OHS risks encountered in electric vehicle service operations, detail the personal protective equipment (PPE) and work procedures necessary to mitigate these risks, and explain risk analysis methodologies in service areas along with the integration steps for augmented reality (AR) and virtual reality (VR) supported simulation applications. Furthermore, emergency response steps for scenarios such as fire, electric shock, and gas leaks, as well as the development processes for AR/VR-based hazard recognition training modules, will be addressed. Finally, a poster design proposal titled "Safe Work Guide in Electric Vehicle Service" will be presented to raise awareness in the field. This comprehensive analysis seeks to provide the necessary knowledge and strategies to ensure the safety of personnel working in electric vehicle services and to foster a proactive safety culture in the industry.

1. HIGH VOLTAGE SAFETY RISKS AND PERSONAL PROTECTIVE EQUIPMENT

In electric vehicle services, high voltage constitutes one of the most critical safety risks for technicians. This section will thoroughly examine the definition of high voltage, voltage levels in electric vehicles, potential high-voltage-related hazards, and the personal protective equipment and work procedures that must be used to counter these dangers.

1.1. HIGH VOLTAGE DEFINITION AND ITS APPLICATIONS IN ELECTRIC VEHICLES

High voltage is defined in occupational electrical safety regulations as voltages greater than 1000 Volts. For safety precautions, all voltages above 1000 volts are considered high voltage, while any voltage with an effective value above 50 volts is classified as "dangerous voltage".[1] This distinction is a fundamental starting point for understanding the severity of risks encountered when working in electric vehicle services.

Electric vehicles typically have two main voltage systems:

Low Voltage Systems: Similar to traditional internal combustion engine vehicles, EVs also contain 12V lead-acid batteries. These batteries support the vehicle's standard operations such as lighting, infotainment systems, and other auxiliary electrical accessories.[2]

High Voltage Systems (Traction Batteries): Lithium-ion battery packs, which form the propulsion system of electric vehicles, typically operate at voltage levels ranging from 400V to 800V, and can even reach up to 1200V in some models.[2] This high voltage is necessary to provide the vehicle's performance and fast-charging capability. Specifically, DC fast charging stations operate within voltage ranges of 400V to 900V.[4]

This wide voltage range in electric vehicles indicates that a single type of electrical safety training will be insufficient for service technicians. Each voltage level has different risk profiles and intervention requirements. For example, it is recommended to wait up to 3 minutes after disabling the 12V battery due to the possibility of airbags still deploying, and up to 5 minutes after disabling the high voltage battery to allow capacitors to discharge.[5] This situation highlights the need to develop detailed and practical modules for specific voltage levels in technician training, rather than general electrical safety. These modules should cover specific procedures and risks for each voltage level under separate headings such as "Low Voltage System Safety" and "High Voltage System Safety."

1.2. HIGH VOLTAGE-RELATED RISKS

High-voltage electric vehicle systems pose various serious hazards:

Electric Shock: Electric shock is physiological damage caused by electric current passing through the human body. The degree of this damage depends on many factors, including current intensity, voltage, current type (AC/DC), duration of exposure, contact surface area, factors increasing conductivity (such as water contact), and the path the current takes through the body.[6] The heart and nervous system are most affected by electric shock; vital dangers such as cardiac arrest (asystole) or irregular rhythms (ventricular fibrillation) and respiratory arrest can occur.[6] While tingling is felt at low currents, currents of 50-100mA can lead to ventricular fibrillation, and 5-10A can cause asystole.[7] Accidental disconnection of a high-voltage battery or touching damaged components can result in electrical discharge and severe electric shock.[8]

Arc Flash and Arc Blast: Arc flash is a sudden and violent release of energy that occurs in high-voltage electrical circuits. This event can cause extremely high temperatures (thousands of degrees Celsius), bright light, a pressure wave, and molten metal splatter, leading to severe burns, blindness, and traumatic injuries.[10] There is a risk of current jump or sparking, especially when intervening with critical high-voltage circuits like the service plug.[9] The effectiveness of protective clothing against arc flash is determined by its "arc rating," measured in calories.[10]

Thermal Runaway and Fire Risk: Thermal runaway of lithium-ion batteries is one of the most serious fire risks in electric vehicle services. This condition begins with the uncontrolled overheating of battery cells, leading to hazards such as fire, explosion, and toxic gas release.[12] Temperatures during battery fires can reach up to 1000°C.[12] Burning batteries release toxic gases (such as hydrogen fluoride, phosphorus oxyfluoride, carbon monoxide), and inhaling these gases can cause poisoning.[5] Accidents, overcharging, mechanical damage, and extreme temperatures (especially charging outside the 15%-85% charge range or exposing the battery to excessively hot/cold environments) can trigger thermal runaway.[9] Damaged high-voltage batteries can pose a fire risk even after an accident.[9]

High-voltage risks are generally not isolated incidents; rather, the triggering of one risk can trigger another, creating a "cascade effect." For example, an arc flash occurring during an electric shock can cause mechanical damage to the battery, triggering thermal runaway. This can initiate a chain reaction leading to fire, toxic gas release, and even explosion.[13] Therefore, risk management requires dynamic modeling that considers not only individual hazards but also potential chain reactions and their combined effects. Preventive measures and emergency plans should aim to break this cascade effect.

1.3. PERSONAL PROTECTIVE EQUIPMENT (PPE) FOR HIGH VOLTAGE SAFETY

Where hazards cannot be completely eliminated, personal protective equipment is vital to protect workers. Employers are legally obligated to provide appropriate, standard-compliant, and maintained PPE.16 Technicians working in high-voltage environments are required to use specially designed and certified PPE to protect against electric shock, arc flash, and thermal burns.

Insulated Gloves: Must be compliant with EN 60903 standard, CE certified, and insulated according to the voltage level to be worked on (e.g., Class 00 for low voltage systems).[18] Gloves must be free from defects such as seams, cracks, tears, bubbles.[18] The use of insulated rubber gloves is mandatory when intervening with high-voltage circuits.[9]

Face Shields / Visored Helmets: The use of face shields is mandatory against the risk of arc flash and sparks.[9] Helmets protect the head against falling objects, impacts, and energized conductors [19], and should have an integrated, adjustable eye protection apparatus (EN 166 compliant).[18]

Arc-Rated Clothing (Arc Flash Suit): Protective clothing against the thermal hazards of electric arc must comply with standards such as ASTM F1959 and IEC 61482.[10] These garments must have a specific calorie/cm² (cal/cm²) energy resistance rating (ATPV or EBT) and must not melt or drip.[10] Different arc ratings are determined based on risk categories (e.g., 4 cal/cm² for Category 1, 40 cal/cm² for Category 4).[11]

Insulated Footwear: Insulated footwear must be used in electrical work.[20] While EN ISO 20345 compliant, S3 – CI – SRC rated safety shoes provide general protection [18], special insulated-sole shoes should be preferred for electrical work.

Insulating Mats: Insulating mats should be used in the work area, laid on the ground to act as a protective barrier between the technician and electrically conductive surfaces.[20]

Respiratory Protectors: Full-face masks and filtered breathing apparatus must be worn for toxic gas emissions during fire or thermal runaway.[21] Respiratory protectors compliant with standards such as EN 136 (full-face mask), EN 140 (half-face mask), and EN 141/EN 143 (gas and dust filters) should be used.[19]

PPE should be treated not as individual pieces but as a "system." Different pieces of PPE, such as insulated gloves, arc-rated clothing, and face shields, form a complete layer of protection when combined. This requires each piece of PPE to be compatible with others and to provide maximum protection against the hazard as a whole. Furthermore, the correct use and regular maintenance of PPE are as important as its procurement for its effectiveness.

1.4. WORK PROCEDURES FOR HIGH VOLTAGE SAFETY

In addition to using PPE, strict adherence to specific work procedures is necessary to manage high-voltage risks:

Energy Isolation and Lockout/Tagout (LOTO): LOTO is a method of locking and tagging applied to prevent unexpected startup of any machine or device or discharge of hazardous substances from a line.[16] This is the primary and preferred method for controlling hazardous energy and bringing equipment to a "zero energy state".[16] LOTO locks must be distinguishable from other locks in the facility, and tags must be uniform, durable, and carry clear warnings such as "DO NOT OPERATE," "DO NOT OPEN," "DO NOT ENERGIZE".[22] Even during shift changes, LOTO procedures must be fully applied, with the incoming worker checking that the lockout is correctly performed and attaching their personal lock.[22]

One Hand Rule and Prohibition of Working Alone: The "one hand" rule and the "never work alone" rule must be applied when working with electrical equipment.[17] The one-hand rule aims to prevent current from passing through the heart in case of an electric shock, by using only one hand during measurements if possible.[23] The prohibition of working alone ensures immediate assistance in case of an accident and prevents erroneous operations in hazardous work such as electrical tasks.[24] Although there is no specific prohibition on working alone in legislation, applying this rule based on risk assessment is vital.[24] Situations like electric shock or faulty wiring can lead to much more serious consequences when working alone.[26]

Compliance with Manufacturer Instructions: Electric vehicle chargers and all related equipment must be installed, used, and maintained in accordance with the manufacturer's instructions.[28] Maintenance and repair operations must be performed according to vehicle catalogs, and manufacturer instructions and rules must be followed when using hand tools.[29] As electric vehicle technologies rapidly evolve, each model and component may have unique safety requirements. Strict adherence to manufacturer instructions is a fundamental principle for ensuring both equipment safety and worker health.

Procedural safety measures such as LOTO, the one-hand rule, and the prohibition of working alone not only reduce technical risks but also affect legal liabilities. Violation of these procedures can increase the legal responsibility of the employer and employee in workplace accidents.[27] Operationally, these rules create a "culture of discipline" in work processes, reducing error rates and increasing efficiency. Given the high risk inherent in high-voltage work, the critical role of these procedural controls in preventing workplace accidents, in addition to being a legal requirement, indicates that non-compliance with these rules not only increases technical risks but also entails legal responsibilities for employers and employees. This emphasizes that procedural safety is not just a "to-do" but also a "legal and operational necessity."

The table below summarizes high-voltage risks, relevant personal protective equipment, and additional safety measures in electric vehicle services:

Table 1: High Voltage Risks and Related Personal Protective Equipment in Electric Vehicle Services

RISK TYPE	RISK DESCRIPTION	RELEVANT PPE	PPE STANDARD/CLASS	ADDITIONAL SAFETY MEASURES
Electric Shock	Physiological damage caused by electric current passing through the body; cardiac arrest, respiratory arrest, nerve damage.6	Insulated Gloves, Insulated Footwear, Insulating Mats	EN 60903 (Class 00, etc.), EN ISO 20345 (S3, CI, SRC) [18]	LOTO (Lockout/Tagout), One Hand Rule, Prohibition of Working Alone, Compliance with Manufacturer Instructions 16
Arc Flash	Sudden energy discharge in high-voltage circuits; high temperature, bright light, pressure wave, molten metal splatter.10	Face Shield/Visored Helmet, Arc-Rated Clothing, Insulated Gloves	EN 166, ASTM F1959 (ATPV/EBT), IEC 61482 9	LOTO, Safe Working Distance, Voltage Verification 16
Thermal Runaway and Fire	Uncontrolled overheating of lithium-ion batteries, leading to fire, explosion, toxic gas release.12	Respiratory Protectors (Full-face mask, filtered breathing apparatus), Arc-Rated Clothing, Insulated Gloves	EN 136, EN 140, EN 141, EN 143, EN 403, ASTM F1959, IEC 61482 10	Battery Cooling Systems, Charge Level Management, Mechanical Damage Prevention, Emergency Plan 12

2. RISK ANALYSIS IN SERVICE AREAS AND OPERATIONAL STEPS FOR AR/VR SUPPORTED SIMULATION APPLICATIONS

Electric vehicle service areas are complex environments that, in addition to high voltage, contain various chemical, ergonomic, and mechanical risks. Effective management of these risks requires a comprehensive risk analysis methodology and innovative training approaches. Augmented Reality (AR) and Virtual Reality (VR) supported simulation applications offer significant potential in this field.

2.1. RISK ANALYSIS METHODOLOGY IN SERVICE AREAS

Risk assessment is a fundamental step for systematically identifying, analyzing, and controlling potential hazards and risks in electric vehicle services. This process is not only a legal requirement [31] but also forms the basis of proactive safety management and provides a framework compliant with international standards such as ISO 45001.[32]

Importance of Risk Assessment: Fire risks arising from charging electric vehicles in commercial and industrial facilities must be carefully assessed.[28] It is essential to identify elements threatening health and safety in the workplace and take necessary precautions.[29] No work in dangerous or very dangerous classes should commence without a risk assessment and emergency action plan.[31]

Risk Analysis Approaches: Structured methodologies such as Fault Tree Analysis (FTA) are powerful tools for deeply understanding the root causes and possible scenarios of complex events like electric vehicle fires.[33] This approach provides a holistic perspective by identifying five main causes: human factors, vehicle factors, management factors, external factors, and unknown factors.[33] This allows for the development of control measures that target underlying causes, not just symptoms.

Service Area-Specific Risks and Precautions:

Charging Areas: Sufficient and safe parking space must be provided for charging points, and charging equipment and cables must not obstruct emergency exits.[28] Charging points should be protected against mechanical damage from vehicles (e.g., by curbs, bollards, barriers).[28] Charging areas should be physically separated from process and storage areas, and risk control should be ensured for times when buildings are unoccupied.[28] Sprinkler protection is highly recommended for enclosed car parks.[28] End-of-life lithium-ion batteries must be disposed of properly.[28]

General Service Area Layout: The work area should be kept tidy and safe by taking occupational health and safety measures.[29] Special safety measures must be taken when working with flammable, combustible, and explosive materials.[29] Necessary safety precautions must be applied during vehicle lifting and lowering operations.[29]

Chemical Risks: Lithium-ion batteries used in electric vehicles can cause gas or liquid leaks due to manufacturing defects, misuse, overheating, or collisions.[35] These leaks may contain electrolytes that can produce toxic and corrosive hydrofluoric acid (HF).[35] Additionally, refrigerants used in electric vehicle air conditioners (e.g., R-134a, R-1234yf) can pose a hazard in case of leaks.[36] Some refrigerants (R32, R600A) can be flammable and form explosive mixtures when exposed to sparks.[38] Exposure to these gases can lead to health problems such as lung irritation, pulmonary edema, headache, dizziness, and cardiac arrhythmias.[40] Hydrogen gas used in fuel cell vehicles is also highly flammable and explosive, and its odorless and pale flame makes it difficult to detect.[41]

Ergonomic Risks: Electric vehicle components, especially high-voltage batteries, can be heavy and bulky, making manual handling difficult and causing physical strain that can lead to musculoskeletal disorders (MSDs).[35] Lifting aids and devices must be used during the installation, removal, storage, and transport of batteries and other heavy components.[35]

Mechanical Risks: In service areas, safe use of hand tools, lifting and supporting vehicles, and basic mechanical operations such as cutting, filing, grinding, and drilling require the use of appropriate PPE and the presence of machine guards.[29]
- Electromagnetic Field (EMF) Risks: High currents in electric vehicles can induce magnetic fields that can cause eddy currents in the human body. Exposure to EMF is potentially dangerous, especially for individuals with pacemakers.[35]

2.2. OPERATIONAL STEPS FOR AR/VR SUPPORTED SIMULATION APPLICATIONS

AR/VR technologies have the potential to transform risk analysis and safety training in electric vehicle services. These technologies can visualize "invisible hazards" (e.g., gas leaks or overheated battery spots) in real-time, increasing situational awareness.[43] This allows risk analysis to evolve from a static and periodic process to a continuous and dynamic one.

The development and integration of AR/VR supported simulation applications should include the following steps:

1.Needs Analysis and Scope Definition:

Current State Assessment: Existing risks in the service area, accident data, and the effectiveness of current training programs are examined. It is determined which hazards (high voltage, thermal runaway, chemical leaks, etc.) can be better addressed with AR/VR.

Target Audience Identification: The needs, knowledge levels, and learning styles of technicians (new hires, experienced specialists) and OHS managers who will receive training are analyzed.

Identification of Application Areas: Specific application areas such as risk analysis, emergency drills, hazard recognition training, or procedural guidance are clarified.

2.Technical Infrastructure and Hardware Selection:

Software: Simulation software is developed using physics engines like Unity and programming languages such as C# and Javascript.[45] AR/VR platforms like Havelsan's H-ARF (Augmented Reality Platform) and virtual maintenance trainers can serve as examples.[46]

Hardware: VR headsets (e.g., Oculus, HTC Vive) or AR glasses (e.g., Microsoft HoloLens), smartphones/tablets, and other devices suitable for the user experience and application purpose are selected.[47]

Database: User data (performance, error rates, training progress) is recorded via databases like MySQL to enable monitoring and reporting of training effectiveness.[45]

3.Simulation Content and Scenario Design:

3D Modeling and Environment Creation: The electric vehicle service area, vehicle models, high-voltage cables, battery packs, charging stations, and other equipment are created with realistic 3D models.[45]

Interactive Scenario Flows: Branched scenarios are designed to show the consequences of user decisions and actions.[43] For example, potential outcomes of incorrect PPE selection, non-compliance with LOTO procedures, or errors in emergency response can be simulated.

Hazard Visualization: AR overlays digital information (hazard area signs, voltage levels, gas leak warnings, overheated battery spots) onto the real world to provide instant situational awareness.[43] VR allows dangerous situations such as fire, electric shock, or gas explosions to be experienced in a safe virtual environment.[49]

Feedback Mechanisms: Systems that evaluate user performance, identify errors, and suggest corrective actions are integrated. Instant feedback accelerates the learning process and prevents the recurrence of errors.[43]

1.Module Testing, Feedback, and Continuous Improvement:

Pilot Implementation: Developed simulations are tested with a small target audience (pilot group).

Performance Analysis: Users' hazard recognition, decision-making, and intervention skills are measured. Recorded performance data is used to evaluate training effectiveness.

Feedback Collection: Detailed feedback on user experience, technical issues, and content quality is collected from participants and instructors.

Improvement Cycle: The module is continuously improved and updated based on collected data and feedback. Technical infrastructure updates and content renewals are performed regularly.

AR/VR simulations can function not only as training tools but also as real-time risk analysis and "situational awareness" tools.[43] Service technicians can visualize high-voltage components, battery status, or potential gas leaks of a vehicle in real-time through AR glasses, enabling faster and more accurate detection of invisible hazards. While traditional risk analysis is often static and periodic, AR/VR's ability to integrate and visualize real-time data allows for faster detection of dynamic and immediate hazards, increasing situational awareness and enabling proactive intervention. This ensures that risk analysis becomes a continuous and dynamic process.

The table below summarizes the steps and expected benefits of AR/VR supported simulation applications in electric vehicle services:

Table 2: AR/VR Supported Simulation Applications in Electric Vehicle Services: Steps and Gains

STEP	DESCRIPTION	AR/VR ROLE	EXPECTED BENEFITS
1. Needs Analysis	Identification of existing risks, accident data, and training deficiencies. Definition of training objectives and target audience.	Visualization and analysis of risks to identify potential application areas.	Increased risk awareness, clarification of training needs.
2. Technical Infrastructure	Selection and setup of software platform (Unity, C#, Javascript), hardware (VR/AR headsets, tablets), and database (MySQL).	Forms the foundation of the simulation environment. Provides realistic physics engines and visualization capabilities.	Efficiency of the development process, system performance, and scalability.
3. Content Development	3D modeling of service area, vehicles, equipment. Design of interactive scenario flows, hazard visualization, and feedback mechanisms.	Experiencing dangerous situations (fire, electric shock, gas leak) in a safe virtual environment (VR). Overlaying digital information onto the real environment (AR) for instant guidance and hazard recognition.	Increased risk awareness, reduced error rates, improved knowledge retention, reinforcement of safe behaviors.
4. Testing and Improvement	Pilot testing of developed modules with target groups. Analysis of user feedback and performance data. Continuous improvement and updates.	Optimization of user experience, validation of simulation realism and effectiveness.	Continuous improvement of training quality, cost-effectiveness, adaptability.

3. EMERGENCY SCENARIOS: ACTIONS IN CASES OF FIRE, ELECTRIC SHOCK, GAS LEAK, ETC.

Emergency situations that may occur in electric vehicle services are complex events requiring rapid and correct intervention. This section will cover general management principles and detailed intervention steps for fire, electric shock, and gas leak scenarios.

3.1. GENERAL EMERGENCY MANAGEMENT PRINCIPLES

Every electric vehicle service area must have a comprehensive emergency action plan.[21] This plan must be regularly rehearsed, evaluated, and updated.[28]

First Response and Communication: Remaining calm and not panicking is the first step when an emergency occurs.[21] Activating the alarm system to alert all employees and emergency teams, then immediately notifying the fire department, emergency coordinator, and other relevant units with detailed information, is essential.[21]

Personnel Training: All personnel must be trained in emergency procedures, basic first aid knowledge (especially for electric shock), and quick communication numbers.[28]

3.2. FIRE EMERGENCY SCENARIO AND INTERVENTION

Electric vehicle fires have different characteristics from traditional vehicle fires and require special intervention strategies.

Characteristics of EV Fires: Lithium-ion battery fires can generate high temperatures up to 1000°C during combustion.[12] These fires involve reactive chemicals that can react with water to produce hydrogen gas.[12] They are also characterized by the release of flammable and toxic gases (such as hydrogen fluoride, phosphorus oxyfluoride, carbon monoxide).[5] EV fires can re-ignite even after being extinguished and can last for hours.[5]

Intervention Steps:

1.Establishing a Safe Zone: Attempting to move the burning vehicle to a safe area and creating a safety zone of at least 10-15 meters around it is essential.[5] Care must be taken not to inhale toxic gases emitted from burning battery packs.[9]

1.Electrical Isolation: Main electrical cut-off buttons should be used to disconnect power to the charging unit and connected vehicles.[21] It should be remembered that the high-voltage cut-off switch should not be disconnected except in emergencies, and high-voltage cables or batteries should absolutely not be cut, as this can lead to serious injury or death.[5]

2.Fire Extinguishing and Control:

- **Use of Water:** Water is the most effective extinguishing agent for lithium-ion battery fires and must be applied directly to the battery system.[5] It is critical to continue cooling for at least 10 hours with continuous thermal camera monitoring.[21]

- **Special Extinguishers:** Extinguishing agents specifically designed for lithium battery fires, such as AVD (Aqueous Vermiculite Dispersion) [51] and Lith-Ex extinguishers, can be used.[51] Systems incorporating Watermist technology and F500 extinguishing agent can also yield effective results.[12]

- **Other Extinguishers:** For fires starting in the electric charging unit, carbon dioxide (CO2) or dry chemical powder (DCP) type extinguishers can be used.[21] However, it should be noted that CO2 and other chemicals may not cool the battery in battery fires, prevent re-ignition, or even lead to the release of toxic/explosive gases.[13] Foam application is generally not recommended.[5]

3.Fire Blanket: The electric vehicle can be covered with a fire blanket to control the spread of flames.[21]

4.Ventilation: If the fire occurred inside a building, ensuring ventilation and operating exhaust systems is important.[21]

5.Professional Intervention: If the extinguishing team's capacity is exceeded, the fire department should be awaited, and clear and concise hazard information, such as fire locations and electrical isolation facilities, should be provided to them.[28]

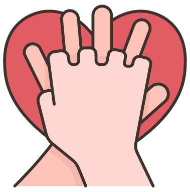
Traditional firefighting approaches (completely suppressing flames) may be insufficient for electric vehicle battery fires. The primary goal in such fires is to cool the battery for a long duration (up to 10 hours) to stop thermal runaway and prevent re-ignition, and to control toxic gas emissions. This requires a paradigm shift for fire and service teams from "extinguishing the fire" to "controlling and cooling the fire." Given the high temperature and re-ignition tendency of lithium battery fires, the fact that merely extinguishing flames is not enough, and that prolonged battery cooling and preventing thermal runaway take precedence, forms the basis of this new philosophy.

3.3. ELECTRIC SHOCK EMERGENCY SCENARIO AND FIRST AID

In electric shock cases, the most important consideration is that the rescuer does not risk their own life.[6]

Rescuer Safety and Isolation: It is necessary to move the victim away from the current source with a non-conductive object (e.g., wood).[6] Do not approach high voltage closer than 20 meters, and absolutely wait for the current to be cut off.[6] It is important to turn off the switch to cut the current, not be damp or wet, wear rubber gloves if possible, and stand on a non-conductive surface (e.g., wood) during rescue.[6]

First Aid Applications (ABCD Protocol):

	**Activation of Emergency Medical System (112)**	Immediately call 112 and request emergency medical assistance.[7]
	**Rapid CPR**	If the victim is unconscious and not breathing, start rapid cardiopulmonary resuscitation (CPR) without delay.[7] Use an automated external defibrillator (AED) if available.[7]
	**Removal of Clothing**	Burnt clothing, shoes, and belts should be removed to prevent continuous heat contact.[7]
	**Trauma Approach**	Every patient exposed to electric shock should be approached as a trauma patient, and spinal protection should be provided.[7]
	**Hospital Transfer**	Every patient exposed to electric current should first be taken to a medical center for admission and discharged with the permission of that center after examinations.[6] Hospitalization is indicated in cases of high voltage exposure, current passing through the chest and head, systemic symptoms, abnormal EKG findings, or suspicion of arrhythmia.[7] It should be noted that in electric shock cases, externally visible damage (skin burns) may not fully reflect internal organ damage (heart, nervous system). This increases the importance of comprehensive medical evaluation and long-term follow-up (24-48 hours EKG monitoring).[7]

3.4. GAS LEAK EMERGENCY SCENARIO AND INTERVENTION

In electric vehicle services, gas leaks can occur, especially from refrigerants leaking from air conditioning systems or hydrogen leaks in fuel cell vehicles.

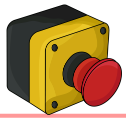
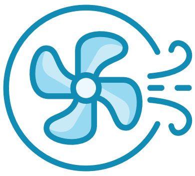
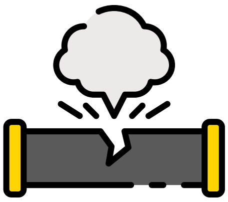
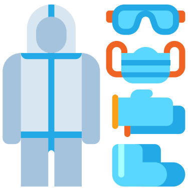
Types of Gas Leaks and Hazards:

Refrigerant Gases: Modern electric vehicle air conditioners typically use R-134a or R-1234yf gases, which are environmentally friendly.[37] However, some refrigerants (e.g., R32, R600A) can be flammable and pose an explosion risk at certain concentrations when exposed to sparks.[36] Inhaling these gases can lead to serious health problems such as lung irritation, pulmonary edema, headache, dizziness, and cardiac arrhythmias.[40]

Hydrogen Gas: Hydrogen gas is used in fuel cell electric vehicles.[41] Hydrogen gas release can also occur in lithium-ion battery fires.[28] Hydrogen is highly flammable and explosive when mixed with air. Its odorless and pale flame can make its presence difficult to detect.[41]

The odorless nature or pale flame of refrigerants or hydrogen makes their detection difficult by traditional methods. This causes technicians to face an *"invisible threat."*

Intervention Steps:

	**Do Not Panic and Notify**	The first step is to remain calm, establish a safety perimeter, and call relevant personnel and supervisors (e.g., Natural Gas Emergency 187 in Turkey) from a safe distance from the gas leak.[52]
	**Cut Off Gas Source**	It is necessary to close the gas valve and press the emergency stop button.[52]
	**Ventilation**	Opening doors and windows to ventilate the area is important.[52] If the gas is heavier than air, it should be swept from low-lying and secluded areas; if lighter, from above.[52]
	**Prevent Ignition Sources**	It is vital not to use lighting and communication devices that could cause sparks (electrical switches, mobile phones, cigarettes), not to touch electrical switches, not to use a phone, and not to use open flame sources like cigarettes, matches/lighters.[52]
	**Ignited Gas Leak**	If the leak can be cut off from its source, the flame is extinguished, and the leak is stopped.[52] Gas fires should not be intervened with water.[52] If there is a leak in the cylinder body, the cylinder should be taken to an open area and allowed to burn in a controlled manner until empty.[52]
	**Use of PPE**	Personal protective equipment (protective mask, covering mouth/nose with a wet wipe) must be worn before intervention.[52]
	**In Case of Poisoning**	The poisoned person should be removed from the environment, their respiratory system checked, artificial respiration performed if stopped, placed in a recovery position, given oxygen, clothing loosened, kept warm, and the nearest healthcare facility notified.[52]

Wrong actions such as intervening with water in gas fires or creating sparks increase the risk of explosion, indicating that emergency training should specifically focus on these "wrong intervention" scenarios. The fact that gas leaks become an "invisible threat" increases the importance of technological solutions like gas detectors and AR/VR-based hazard visualization training.[43]

The table below provides a summary intervention flowchart for emergency scenarios that may be encountered in electric vehicle services:

Emergency Scenario	Initial Steps (Notification, Safety)	Intervention Methods (Extinguishing/Isolation/ First Aid)	Aftermath (Follow-up, Reporting, Normalization)
Fire	Stay calm, activate alarm, call fire department (112) and relevant units, provide detailed info, establish safe zone (10-15m).5	Isolate electricity (main cut-off buttons), do not cut high-voltage cables.5 Cool with water for prolonged periods (10 hours with thermal camera monitoring).5 Use special extinguishers like AVD/Lith-Ex.51 Cover with fire blanket.21 Ensure indoor ventilation.21	Await professional teams (fire department), provide them with information.28 Continuous monitoring for re-ignition risk.21 Prepare incident report, perform root cause analysis.21
Electric Shock	Ensure rescuer safety (non-conductive object, 20m distance, cut power).6 Call 112.7	Remove victim from current source, cut power, stand on insulated ground.6 Perform rapid CPR if unconscious.7 Remove burnt clothing, approach as trauma patient.7	Transfer patient to nearest healthcare facility.6 Hospitalization and 24-48 hour EKG monitoring if high voltage or systemic symptoms.7
Gas Leak	Do not panic, establish safety perimeter, call relevant units (e.g., 187).52	Close gas valve, press emergency stop button.52 Open doors/windows, ventilate area.52 Prevent ignition sources (electrical switches, phone, cigarette).52 If ignited, cut source, do not use water.52 Use PPE.52 Remove poisoned person from environment, provide first aid (respiration, oxygen).52	Ventilate area, check with gas detectors. Prepare incident report. Continuous monitoring and review of safety measures.

4. OPERATIONAL STEPS FOR DEVELOPING AR/VR BASED HAZARD RECOGNITION TRAINING MODULE

Traditional occupational health and safety (OHS) training may have limitations in terms of knowledge retention and behavioral change.[49] Augmented reality (AR) and virtual reality (VR) technologies offer significant potential to overcome these limitations, enhancing workers' risk perception and safe behavior habits.[43] This section will describe the step-by-step processes for developing an AR/VR-based hazard recognition training module.

4.1. TRAINING NEEDS ANALYSIS AND OBJECTIVE SETTING

The first and most critical step in module development is to conduct a comprehensive needs analysis.

Current State Analysis: The effectiveness of traditional OHS training, limitations on knowledge retention, and the lack of knowledge among teachers/trainers about AR/VR technologies are evaluated.[49] Existing accident data and near-miss incidents are examined to identify the most frequently encountered hazards and related knowledge or skill gaps.

Target Audience Identification: The needs, learning styles, and current knowledge levels of different groups, such as electric vehicle service technicians (new hires, experienced personnel) and OHS managers who will receive training, are determined. For example, basic hazard recognition for new hires and complex emergency scenarios for experienced personnel can be targeted.

Training Objectives: Specific, measurable, and achievable objectives are set, such as recognizing high-voltage hazards, selecting and using correct PPE, applying Lockout/Tagout (LOTO) procedures, developing emergency response skills, and increasing overall risk awareness.[43]

4.2. CONTENT DEVELOPMENT AND SCENARIO DESIGN

Training content and scenarios are designed in line with identified needs and objectives.

Hazard Recognition Scenarios: Hazard scenarios from real service environments or those posing potential risks are designed in detail. These scenarios may include damaged high-voltage cables, battery leaks, improperly parked vehicles, faulty charging equipment, gas leaks, etc. Scenarios should reflect real-world problems that technicians may encounter.

Interactive Learning Modules:

- **VR Modules:** Dangerous tasks (e.g., fire scenarios, electric shock simulations, chemical spills) are experienced in a safe virtual environment.[49] These modules offer users the opportunity to make critical decisions and develop intervention skills without real-world risk. For example, intervening in a battery fire or applying first aid during an electric shock can be practiced in a virtual environment.

- **AR Modules:** Digital information (high-voltage warnings, PPE usage instructions, LOTO points, hazardous gas detection, overheated components) is overlaid onto the real service environment to provide instant guidance and hazard visualization.[43] For example, marking high-voltage components of a vehicle through AR glasses can help technicians identify invisible hazards.

Feedback and Evaluation Mechanisms: Systems that evaluate user performance, identify errors, and suggest corrective actions are integrated. Instant feedback accelerates the learning process and prevents the recurrence of errors.[43]

4.3. TECHNICAL INFRASTRUCTURE DEVELOPMENT AND INTEGRATION

The technical requirements of the training module are determined, and the development process begins.

Software Platform Selection: Simulation software is developed using powerful physics engines like Unity and programming languages such as C# and Javascript.[45] Solutions like Havelsan's H-ARF (Augmented Reality Platform) offer a modular infrastructure that allows application development on different operating systems.[46]

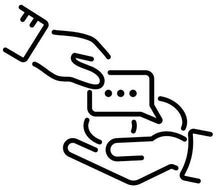
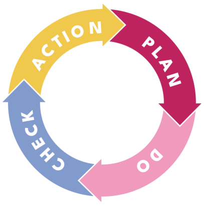
Hardware Selection: Hardware such as VR headsets (e.g., Oculus, HTC Vive), AR glasses (e.g., Microsoft HoloLens), or smartphones/tablets are selected based on the targeted experience and budget.

Database Integration: Training data (participation, performance, error rates, scenario completion times) is recorded in databases like MySQL to enable monitoring and reporting of individual and collective progress.[45] This data is used to measure training effectiveness and identify areas for improvement.

Integration with Existing OHS Management Systems: The developed module aims to be integrable with the company's existing OHS management systems (e.g., ISO 45001).[32] This integration allows training data to be correlated with overall safety performance.

4.4. PILOT IMPLEMENTATION, EVALUATION, AND CONTINUOUS IMPROVEMENT

It is important to test the developed module under real-world conditions and subject it to a continuous improvement cycle.

	**Pilot Training**	The developed module is piloted with a small target audience. At this stage, the module's technical performance, usability, and achievement of training objectives are observed.
	**Performance Analysis**	Participants' hazard recognition, decision-making, and intervention skills are measured through data recorded within the simulation. Error rates, response times, and correct procedure application percentages are analyzed.
	**Feedback Collection**	Detailed feedback on user experience, technical issues, content quality, and the overall effectiveness of the training module is collected from participants and instructors.
	**Improvement Cycle**	The module is continuously improved and updated based on collected data and feedback. This ensures that the content remains current, technical issues are resolved, and the user experience is optimized.

AR/VR-based training can change not only knowledge transfer but also workers' "risk perception" and "safe behavior" habits.[43] While traditional methods only provide "information," AR/VR provides "experience." This experience allows workers to experience dangerous situations "as if real," increasing risk awareness and reinforcing safe behaviors.[43] Consequently, the goal is to develop an understanding of not just "what to do" but "why to do it," leading to behavioral change. This significantly increases knowledge retention and real-life application rates.

The table below summarizes the AR/VR-based hazard recognition training module development process and its key components.

Stage	Sub-Steps	Key Activities	AR/VR Integration	Expected Outcomes
1. Needs Analysis	Current State Analysis, Target Audience Identification, Training Objectives Setting	Review accident/near-miss data, conduct surveys/interviews, gather OHS expert opinions.	Visualize risks and hazards in 3D to identify potential training areas.	Clear training objectives, target audience profile, prioritized hazard scenarios.
2. Content Development	Hazard Recognition Scenarios, Interactive Learning Modules, Feedback Mechanisms	Write realistic scenarios, 3D modeling, animations, interactive task flows, error scenarios.	Experience dangerous situations in a safe environment with VR. Overlay digital warnings and guidance onto the real environment with AR.	Detailed scenario documents, 3D asset library, interactive training modules.
3. Technical Infrastructure	Software Platform Selection, Hardware Selection, Database Integration, Existing System Integration	Develop software with Unity/C#/Javascript. Procure VR/AR headsets. Set up MySQL database. Integrate with ISO 45001.	Form the technical foundation of the simulation. Provide realistic physics and visualization.	Functional software, compatible hardware, data recording system, integration infrastructure.
4. Pilot Implementation	Pilot Training, Performance Analysis, Feedback Collection, Improvement Cycle	Conduct test training with a small group. Measure participant performance. Collect feedback via surveys and interviews.	Evaluate user experience and training effectiveness under realistic conditions.	Module improvement report, updated scenarios, technical corrections.

5. POSTER DESIGN: “SAFE WORK GUIDE IN ELECTRIC VEHICLE SERVICE”

Safety posters are an effective way to convey important safety information visually and concisely. This section will present the purpose of safety posters, key design principles that enhance their effectiveness, and design recommendations for a poster titled "Safe Work Guide in Electric Vehicle Service."

5.1. PURPOSE AND EFFECTIVENESS OF SAFETY POSTERS

Safety posters are used to attract workers' attention [55], reinforce safety messages [55], support training [56], increase awareness, and foster a positive safety culture in the workplace.[55]

Purpose: Posters should highlight specific safety issues, target real problems, and encourage positive actions.[55] They visually reinforce information given in training, helping workers remember and apply safety rules.[55]

Methods to Increase Effectiveness:

- **Placement and Rotation:** Posters should be regularly moved to different locations and placed in various "hot spots" (restrooms, break rooms, entrances, time clocks, elevators) where they are frequently seen.[55] Posters left in the same place for too long become unnoticed over time.[56]
- **Update Frequency:** Most safety professionals believe that frequently changing posters increases their effectiveness.[55] New colors, visuals, and slogans attract attention.
- **Clear and Single Message:** Posters should contain a single, clear, and understandable message.[56] Complex phrases and excessive information should be avoided.[56]
- **Use of Humor:** When appropriate, humor can increase the memorability of the message.[55] However, humor may not be suitable for every safety topic.[56]

5.2. BASIC DESIGN PRINCIPLES

When designing an effective safety poster, visual communication principles must be considered.

Visual Hierarchy and Clear Message: Hierarchy in design ensures that important information (title, main message) is highlighted through visual weight, size, color, or position.[56] The message should be easy to read, understandable, and clear, avoiding unnecessary clutter.[55]

Color, Balance, Contrast, and Originality: Bright colors and high contrast can be eye-catching [56], but should not be overdone. Balanced distribution of visual weight (symmetric or asymmetric balance) creates an aesthetic appearance.[57] Original visuals and themes help workers notice the poster.[55]

Audience Appropriateness and Positive Approach: The message should be appropriate for the target audience's (technicians, new employees) knowledge level, and should not use condescending language towards experienced employees.[55] A positive, encouraging tone should be adopted, and "do" messages should be preferred over "do not" messages.[55]

Visual Literacy and Cultural Appropriateness: The effectiveness of safety posters depends not only on technical design principles but also on the target audience's "visual literacy" level and the "cultural dynamics" of their working environment. For example, the use of humor may not be appropriate in every setting or for every safety topic.[56] Posters should not only convey information but also serve to build a safety "culture" by considering workers' values and perceptions. This means that posters, as a communication tool, should reflect and shape the safety culture, not just convey information.

5.3. "SAFE WORK GUIDE IN ELECTRIC VEHICLE SERVICE" POSTER DESIGN RECOMMENDATIONS

For a poster titled "Safe Work Guide in Electric Vehicle Service," the following design recommendations can be considered:

Content Focus:

- **High Voltage Warnings:** Visuals of orange high-voltage cables [9], dangerous voltage levels (e.g., "400V+", "800V+") [2], and the location and importance of the service plug/disconnect switch.[8]
- **PPE Use:** Clear, understandable visuals of essential PPE such as insulated gloves, face shields, arc-rated clothing, insulated footwear, and brief usage instructions.[9]
- **LOTO Procedure:** Simple visuals of Lockout/Tagout devices (lock, tag) and clear warnings like "DE-ENERGIZE!", "DO NOT OPERATE!".[22]
- **Emergency Numbers:** Important emergency numbers such as Fire (112), Ambulance (112), Gas Emergency (187) should be prominently displayed.[53]
- **Battery Safety:** Battery temperature, ideal charge level (20%-80%) [14], mechanical damage warnings, and thermal runaway symptoms (smoke, odor).[9]
- **One Hand Rule / Prohibition of Working Alone:** Simple icons or textual reminders illustrating these rules.[17]

Visual Elements and Slogans:

- Clear, simple, and eye-catching icons and pictograms should be used.[58]
- Minimalist design and the "less is more" principle should be adopted.[55]
- Short, memorable slogans should be preferred (e.g., "High Voltage, High Alert!", "Safety in Your Hands!", "Safety First, Service Second!").
- Realistic or caricatured visuals [59] appealing to the target audience (technicians) can be chosen.
- The color palette should include warning and hazard colors (yellow, orange, red), but generally present a clean and professional look.

Placement Strategies: Posters should be placed in strategic locations such as service area entrances, break rooms, charging stations, and near high-voltage equipment in hazardous zones.[56] Regular rotation and updating of posters are recommended to maintain message freshness and awareness.[55]

Example Poster Design (with Textual Description):

Poster Title: Safe Work Guide in Electric Vehicle Service

Design Concept: Minimalist and icon-driven, with quickly understandable messages. Main colors: Dark blue (background), bright orange (high voltage/warning), white (text), yellow (caution).

Top Section (Title and Logo Area):

- Title: "SAFE WORK GUIDE IN ELECTRIC VEHICLE SERVICE" (Large, bold, white font)
- Subtitle/Slogan: "High Voltage, High Alert! Safety in Your Hands." (Smaller, white font)
- Company logo or OHS logo in the top right corner.

Middle Section (Main Message Areas - 3 Column Layout):

Column 1: HIGH VOLTAGE SAFETY

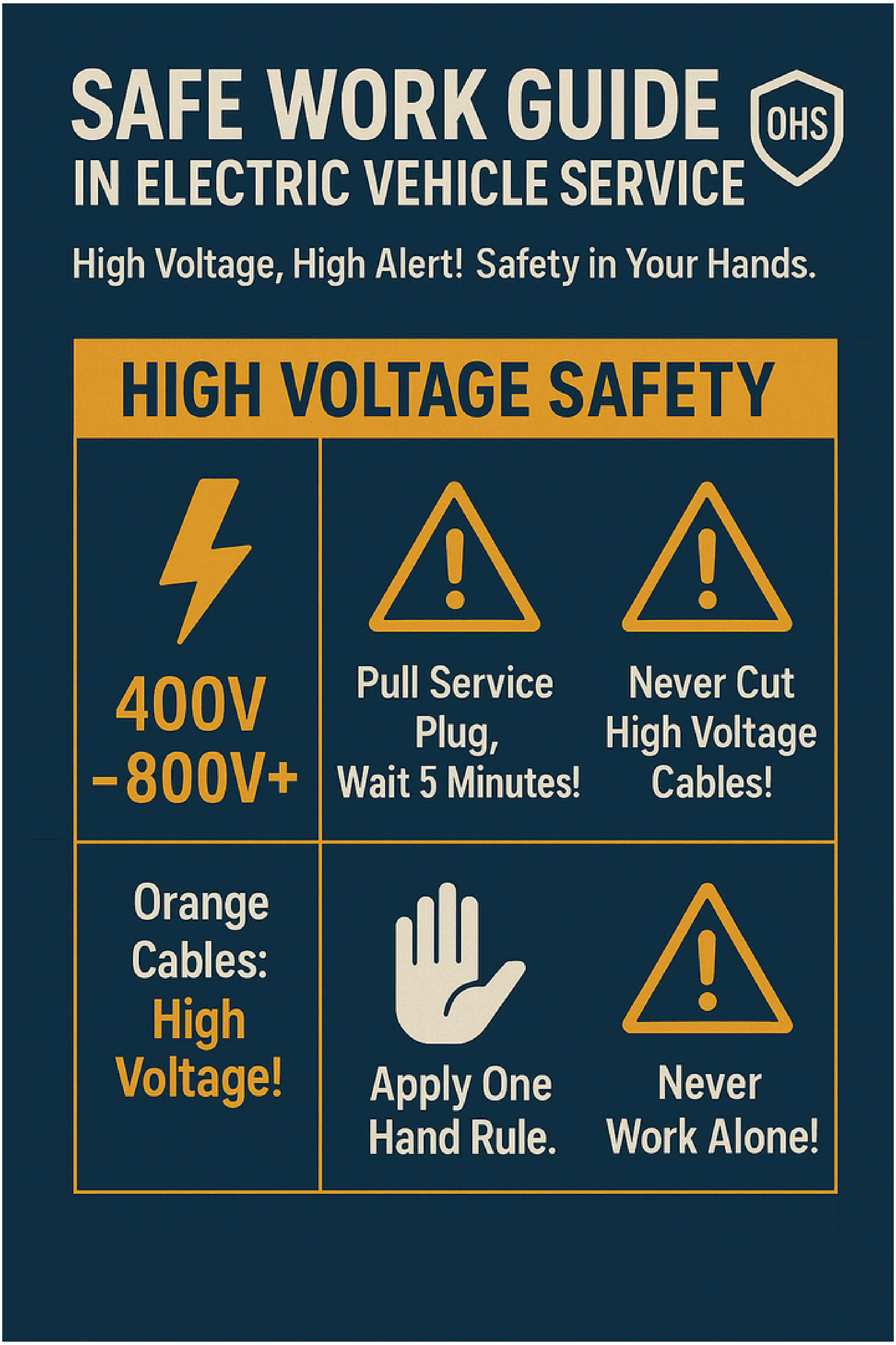
Icon: Bright orange lightning bolt symbol for high voltage.
Text:

- "400V - 800V+" (Large, orange font)
- "Orange Cables: High Voltage!" [9]
- "Pull Service Plug, Wait 5 Minutes!" [5]
- "Never Cut High Voltage Cables!" [5]
- "Apply One Hand Rule." [23]
- "Never Work Alone!" [17]

Column 2: PERSONAL PROTECTIVE EQUIPMENT (PPE)

Icon: Helmet, gloves, goggles symbols.
Text:

- "Correct PPE Saves Lives!"
- Insulated Gloves: EN 60903 (Class-appropriate) [18]
- Face Shield/Visored Helmet: Against Arc Flash [9]
- Arc-Rated Clothing: Check ATPV/EBT Value [10]
- Insulated Footwear: S3 Standard [18]
- Respiratory Mask: Against Toxic Gases [21]
- "Inspect Your PPE Before Each Use."


SAFE WORK GUIDE
IN ELECTRIC VEHICLE SERVICE
OHS
High Voltage, High Alert! Safety in Your Hands.
HIGH VOLTAGE SAFETY
400V -800V+
Pull Service Plug, Wait 5 Minutes!
Never Cut High Voltage Cables!
Orange Cables: High Voltage!
Apply One Hand Rule.
Never Work Alone!

Column 3: EMERGENCY AND INTERVENTION

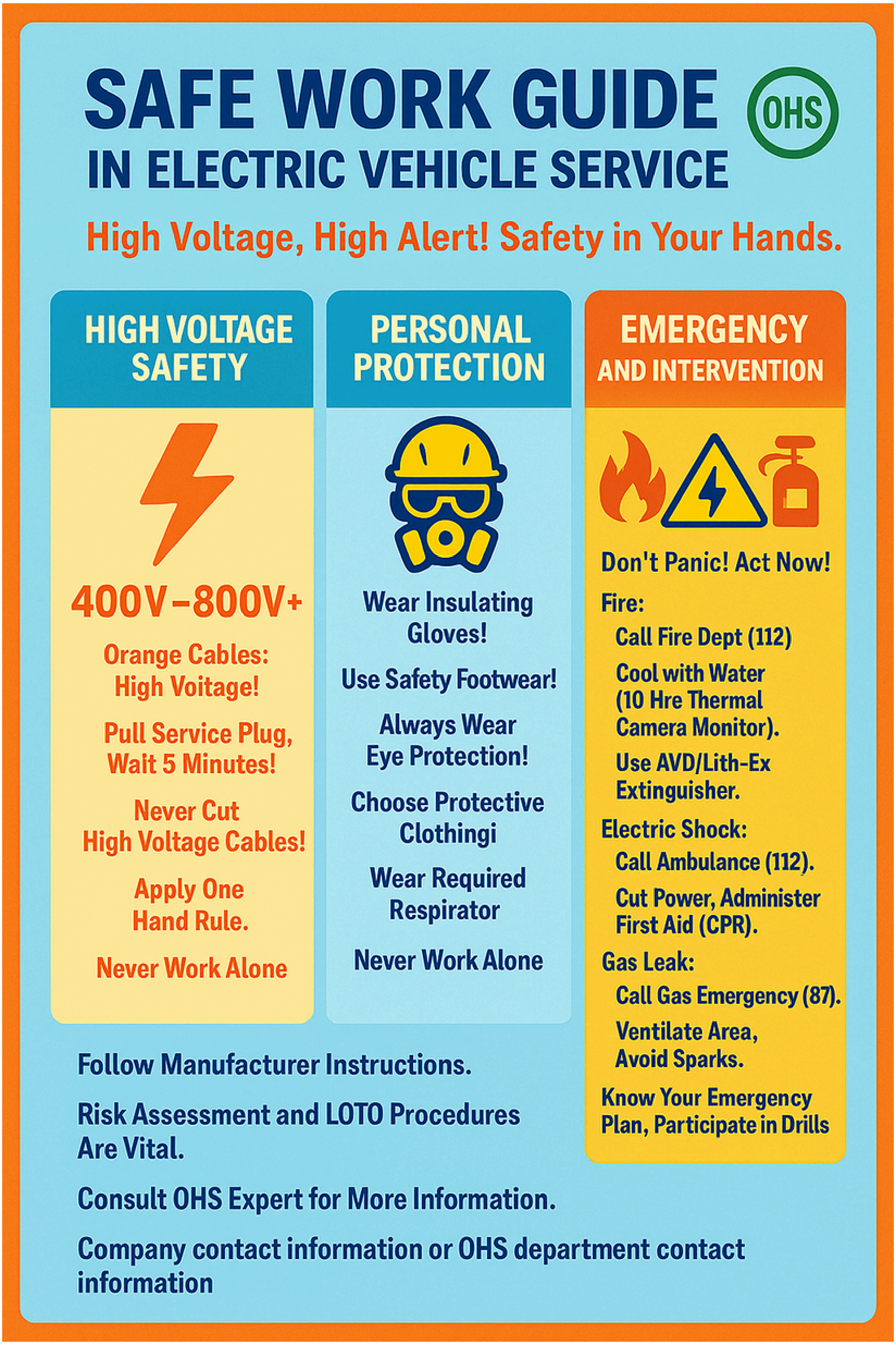
Icon: Flame, electric shock, gas symbols.
Text:

- "Don't Panic! Act Now!"
- Fire: "Call Fire Dept (112)." [53] "Cool with Water (10 Hrs Thermal Camera Monitor)." [21] "Use AVD/Lith-Ex Extinguisher." [51]
- Electric Shock: "Call Ambulance (112)." [7] "Cut Power, Administer First Aid (CPR)." [6]
- Gas Leak: "Call Gas Emergency (187)." [53] "Ventilate Area, Avoid Sparks." [52]
- "Know Your Emergency Plan, Participate in Drills." [28]

Bottom Section (Additional Information and Contact):

- "Follow Manufacturer Instructions." [28]
- "Risk Assessment and LOTO Procedures Are Vital." [16]
- "Consult OHS Expert for More Information."
- Company contact information or OHS department contact information.

This poster design aims to quickly convey the fundamental risks and necessary precautions for workers in electric vehicle services, both visually and textually. With clear icons, eye-catching colors, and short, action-oriented messages, it will increase worker awareness and reinforce safe work habits.


SAFE WORK GUIDE
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Never Cut High Voltage Cables!
Apply One Hand Rule.
Never Work Alone
PERSONAL PROTECTION
Wear Insulating Gloves!
Use Safety Footwear!
Always Wear Eye Protection!
Choose Protective Clothingi
Wear Required Respirator
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EMERGENCY AND INTERVENTION
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Know Your Emergency Plan, Participate in Drills
Follow Manufacturer Instructions.
Risk Assessment and LOTO Procedures Are Vital.
Consult OHS Expert for More Information.
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6. CONCLUSION AND COMPREHENSIVE RECOMMENDATIONS

Electric vehicle service operations represent the future of the automotive sector, yet they bring new and complex occupational health and safety risks that are difficult to manage with traditional approaches. The findings of this report have revealed the multifaceted nature of these risks (high voltage, thermal runaway, arc flash, chemical exposure, ergonomic strains) and their potential cascading effects. Effective management of these risks requires not only legal compliance but also a proactive safety culture and an integrated approach focused on continuous improvement.

6.1. SUMMARY OF KEY FINDINGS AND INTEGRATED APPROACH

The main risks encountered in electric vehicle services and strategies to address them can be summarized as follows:

High Voltage Risks and PPE: High-voltage systems in electric vehicles (400V-800V and above) pose vital hazards such as electric shock, arc flash, and thermal runaway. The use of specialized personal protective equipment, including insulated gloves compliant with EN 60903 standards, arc-rated clothing compliant with ASTM F1959/IEC 61482 standards, face shields, and insulated footwear, is mandatory against these risks. It is critical to treat PPE not as individual items but as a "protection system" and to ensure its regular maintenance.

Safe Work Procedures: Energy isolation and Lockout/Tagout (LOTO) procedures are fundamental administrative control methods to prevent unexpected energy releases. The "one hand rule" and "never work alone" principles are vital, especially in high-risk electrical work, to mitigate the consequences of potential accidents and ensure immediate intervention. All operations must be performed in strict compliance with manufacturer instructions to keep pace with the rapid technological advancements.

Risk Analysis and Environmental Factors: Comprehensive risk assessments (e.g., Fault Tree Analysis) should be conducted in service areas for fire, chemical (especially battery electrolytes and refrigerants), ergonomic (heavy battery handling), and mechanical risks. Precautions such as physical separation of charging areas, protection against mechanical damage, and proper disposal of lithium-ion batteries must be taken.

Emergency Management: Detailed and rehearsed emergency action plans must be in place for emergencies such as fire, electric shock, and gas leaks. Due to the unique characteristics of electric vehicle fires, such as high temperatures, toxic gas release, and re-ignition tendency, a "control and cooling" strategy (especially prolonged cooling with water) should be adopted instead of "extinguishing." In electric shock cases, rescuer safety and rapid CPR with professional medical referral are paramount, while in gas leaks, preventing ignition sources and ensuring ventilation are priorities.

AR/VR Supported Training: Given the limitations of traditional training, AR/VR-based simulations offer revolutionary potential in enhancing hazard recognition, risk awareness, and emergency response skills. These technologies enable workers to learn about risks "experientially," increasing knowledge retention and reinforcing safe behaviors. AR/VR can also be used as a real-time risk analysis and situational awareness tool.

Compliance with Legal Regulations: In Turkiye, Law No. 6331 on Occupational Health and Safety, "Battery Electric and Hybrid Vehicle Maintenance and Repairman" national occupational standards set by the Vocational Qualification Authority (MYK), TSE standards, and international standards (OSHA, NFPA, ISO 45001) form the basic legal framework in this field. Compliance with these regulations is mandatory to ensure a minimum level of safety.

6.2. CONTINUOUS IMPROVEMENT, TRAINING, AND FUTURE PERSPECTIVES

As electric vehicle technologies continuously evolve, OHS strategies must also be dynamic and adaptable.

Continuous Improvement: OHS management systems (ISO 45001) must be in a continuous improvement cycle, risk assessments should be updated periodically, and technological developments (solid-state batteries, advanced battery management systems) should be closely monitored. This ensures that new risks can be anticipated and proactive measures taken.

Training and Competence: It is critical for electric vehicle technicians to receive continuous and specialized training. Qualification certificates issued by institutions like MYK standardize competence in this field. The potential of AR/VR technologies to enhance the effectiveness of these trainings must be fully utilized. Training should aim to develop not only technical knowledge but also practical skills and decision-making abilities.

Proactive Safety Culture: It is essential to establish a proactive safety culture not only by complying with rules but also by increasing workers' risk awareness and involving them in safety processes. This enables workers to view safety as their own responsibility and encourages safe behaviors in the workplace. Visual communication tools like safety posters play an important role in reinforcing this culture.

Future Perspectives: With the development of electric vehicle technologies (e.g., wireless charging, smart charging management), new risks may emerge, and OHS strategies need to adapt accordingly. Research and development activities should focus on safer battery technologies and firefighting methods.

In conclusion, occupational health and safety in electric vehicle service operations is a multi-layered and continuously evolving field. Comprehensive risk analysis, correct use of personal protective equipment, meticulously applied work procedures, effective emergency planning, and the integration of AR/VR-supported innovative training approaches are indispensable for maximizing safety standards in this area. This integrated and proactive approach will both protect the health and safety of workers and contribute to the sustainable growth of the electric vehicle sector.

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Glossary of Terms

AVD (Aqueous Vermiculite Dispersion): A water-based vermiculite dispersion fire extinguishing agent specifically designed to extinguish, control, and cool lithium-ion battery fires.[51]

Arc Flash: A sudden and violent energy discharge in high-voltage electrical circuits, resulting in high temperature, light, and a pressure wave.[10]

ATPV (Arc Thermal Performance Value): The amount of energy a material can withstand before causing a second-degree burn or breaking open when exposed to an electric arc, measured in calories/cm².[10]

EBT (Breakopen Threshold Energy): The amount of energy a material can withstand before breaking open prior to the onset of a second-degree burn.[10]

EMF (Electromagnetic Field): Magnetic fields associated with high currents in electric vehicles that can induce eddy currents in the human body.[35]

FTA (Fault Tree Analysis): A methodology used for root cause analysis, graphically representing the possible causes of an undesirable event (e.g., fire) in a system and their logical relationships.[33]

PPE (Personal Protective Equipment): Equipment designed to protect workers from workplace hazards.[18]

DCP (Dry Chemical Powder): Fine chemical particles used in fire extinguishing, acting as a flame retardant.[42]

LOTO (LockOut/TagOut): A safety procedure applied to prevent unexpected startup of a machine or device or the release of hazardous energy.[16]

MSD (Musculoskeletal Disorders): Disorders resulting from physical strain, such as manual handling of heavy or bulky objects.[35]

AED (Automated External Defibrillator): A portable medical device that helps restore the heart to its normal rhythm by applying an electric shock in cases of cardiac arrhythmias.[7]

Thermal Runaway: A chain reaction starting with the uncontrolled overheating of lithium-ion battery cells, which can lead to fire or explosion.[12]

VR (Virtual Reality): Technology that completely immerses the user in a digital environment, isolating them from the real world.[49]

AR (Augmented Reality): Technology that overlays digital information (text, images, 3D models) onto real-world images, enriching reality.[48]

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AR-VET

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