EMPOWER

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Project Title:
Eco-operated, Modular, highly efficient, and flexible multi-POWERtrain for long-haul heavy-duty vehicles

Acronym: EMPOWER

Grant Agreement No.: 101096028

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Publishable Executive Summary

The based specifications of both vehicle demonstrators are the starting point of the EMPOWER project. These data, parameters and resulting initial performances will be the first benchmark for conceiving and implementing the novel solutions, which will lead to the proposed and targeted efficiency improvements of the demonstrators (FCEV and BEV) and therefore to an enlarged usable real-world driving range.

The initial system layouts and specifications, as well as the foreseen principals behind the final evaluation are depicted and summarised in this deliverable (D1.1) document.

By researching and analysing internal IVECO specifications, a comprehensive overview on the demonstrator vehicles (FCEV and BEV) was created and used as starting point for the next specification steps. This is accompanied by outlines of feasible, but also relevant test cases for evaluating single solutions and also the overall vehicle in their SotA conditions, as well as in their improved version at the end of the EMPOWER project.

At the end, the specifications of the initial demonstrator vehicles are presented. These incorporate information on characteristics and performances.

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Abbreviations and Nomenclature

Table 1: Abbreviations and Nomenclatures

Symbol or Shortname	Description
BEV	Battery Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
ZEV	Zero Emission Vehicle
ZE-HDV	Zero-Emission Heavy-Duty Vehicles
LCA	Life Cycle Assessment
TCO	Total Cost of Operation
VECTO	Vehicle Energy Consumption Calculation Tool
LCV	Light Commercial Vehicle
GVW	Gross Vehicle Weight
GCW	Gross Combination Weight
FCS	Fuel cell system
TRL	Technology Readiness Level
UC	Use-Case
WP	Work Package
HVAC	Heating, Ventilation and Air Conditioning
HDV	Heavy-Duty Vehicles
HVI	Human Vehicle Interaction
V2G	Vehicle-to-Grid
LV	Low Voltage
HV	High Voltage
IVG	Iveco Group
TMS	Thermal management system
Cab	Cabin
VP	Iveco vehicle identification code
P	Pneumatic
FP	Full Pneumatic
SOC	State of charge
DC	Direct Current
PTO	Power take off

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IPMSM	Interior Permanent Magnet Synchronous Machine
IGBT	Insulated-gate bipolar transistor
SiC	Silicon Carbide
e-VECOP	Electrified Vehicle Control Platform
HW	Hardware
SW	Software
VCU	Vehicle Control Unit
EV	Electrical Vehicle
MD	Medium-Duty
CAD	Computer Aided Design
HSS	Hydrogen Storage System
MBD	Model Based Development
BMS	Battery Management System

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1 Introduction

In 2020 the CO_2 emissions of the transport sector in the EU-27 accounted for approximately 27 % [1]. Thereof about 5.6 % are produced by Heavy Duty Vehicles (HDVs) and buses [2]. However, the year 2020 is, due to COVID-19 related restrictions and lockdowns and therefore altered mobility patterns, not very representative. Analyses of the last months in 2020 show that road transport activity was expected to recover to pre-COVID-19 levels in 2021, with CO_2 emissions rising to just 5 % below the 2019 level [3]. Therefore, this sector calls for a massive shift to zero tailpipe emissions to achieve full carbon neutrality by 2050. A study conducted by the European Automobile Manufacturers' Association (ACEA) found out, that in 2020 about 6.2 million medium and heavy-duty commercial vehicles were on the EU's roads [4]. Approximately 96.3 % of these trucks ran on diesel fuel, 0.7 % on petrol and only 0.24 % were zero-emission, providing potential for the transformation of the transport sector to ZE HDVs to reach carbon neutrality by 2050.

The objective of EMPOWER is to deliver two modular and flexible ZE HDVs of VECTO group 9 with a GVW of at least 40 tons, both at TRL 8 level:

- a Fuel Cell Electric Vehicle (FCEV), suitable for long-haul operation conditions with a maximum unrefuelled range of 750 km;
- a Battery Electric Vehicle (BEV) vehicle, designed for regional distribution mission profiles with a maximum un-recharged driving range of 400 km.

The **ambition of EMPOWER** involves the development, implementation, and demonstration of these vehicles at TRL 8, guaranteeing a maximum load capacity of not less than 90 %. They will be compared to conventional trucks of the same vehicle class, making them ready to enter the market in 2029 with equal Total Cost of Operation (TCO) as 2020 engine-based solutions, assuming a production volume of more than 10,000 vehicles/year.

A particular attention will be focused on:

- **Modularity,** between different vehicles with specific electrification technology;
- **Scalability** of content under development with possible integration into other applications (even outside project perimeter);
- **Competitiveness** of product and technology in terms of performance, cost, automotive manufacturing, customer acceptance.

The products that will be presented in the current deliverable (D1.1) contribute positively to the achievement of EU CO_2-targets, depending on customer acceptance and sales volumes. The product specifications will be detailed, and the choice of selected concepts explained, to show how these fit into the project context.

1.1 Scope and objectives

The aim of this document is to present the identified specifications and use cases gathered in WP1 (see Figure 1) and to describe the basic version of the developed simulation models for the interim performance assessment.

The main objectives of this work package are divided in 4 tasks which can be summarized as follows:

- Identification of a platform and preparation of related technical specifications (Task 1.1);
- Definition of UCs based on given mission profiles and vehicle components specifications (Task 1.2);
- Continuous development of a digital twin model of both vehicle concepts (Task1.3);
- Definition of a 2020 (diesel) truck baseline LCA model and estimation of the current and expected LCA/TCO, achieved with the EMPOWER vehicle demonstrators (Task 1.4).

All these objectives are focused on modular and scalable FCEV and BEV vehicles, which components, modules, and systems can be transferred and integrated into other similar vehicle applications (VECTO groups 4, 5, 10, 11 or 12), thereby reducing the TCO.

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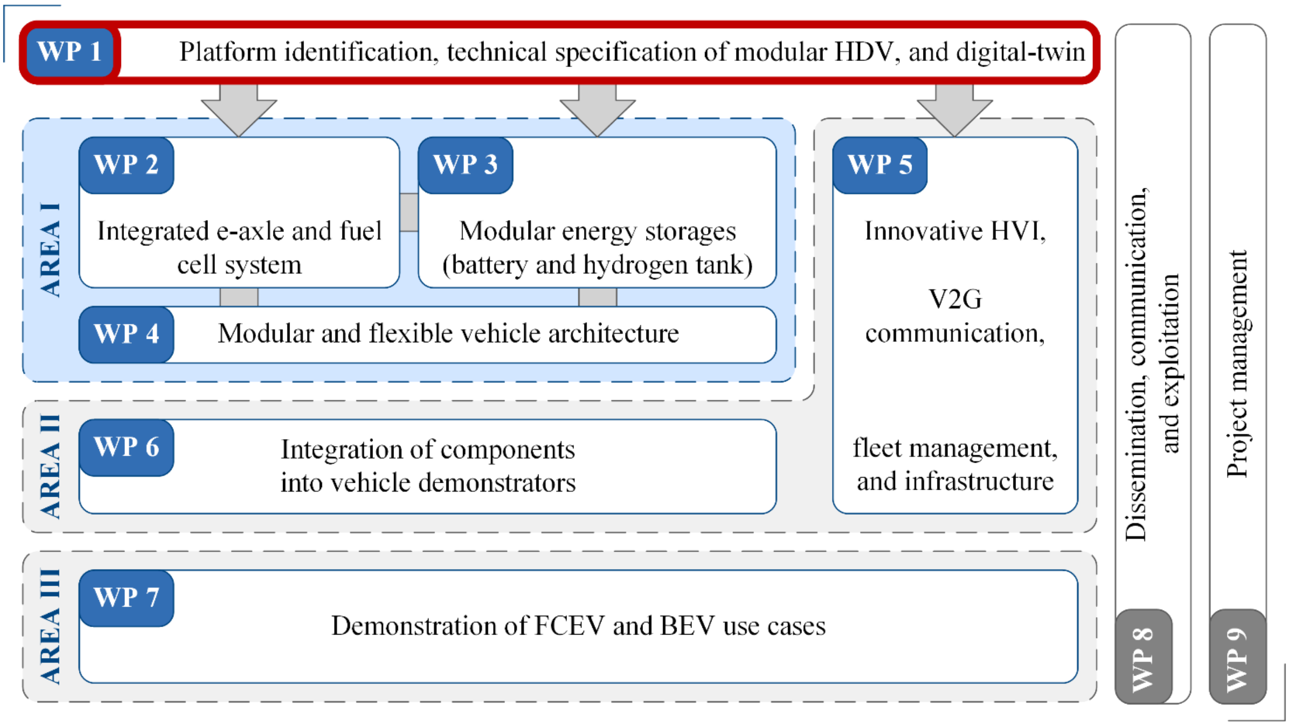

Figure 1: EMPOWER Work packages diagram.

The presented solutions are based on the fulfillment of the nine main objectives of EMPOWER (see Figure 2), moreover, the defined vehicle platform allows the installation of modular (Battery Electric or FC-Electric) powertrain solutions, exploiting the scalability and modularity of the installed power units. This aspect allows cost efficient solutions for any kind of dedicated mission.

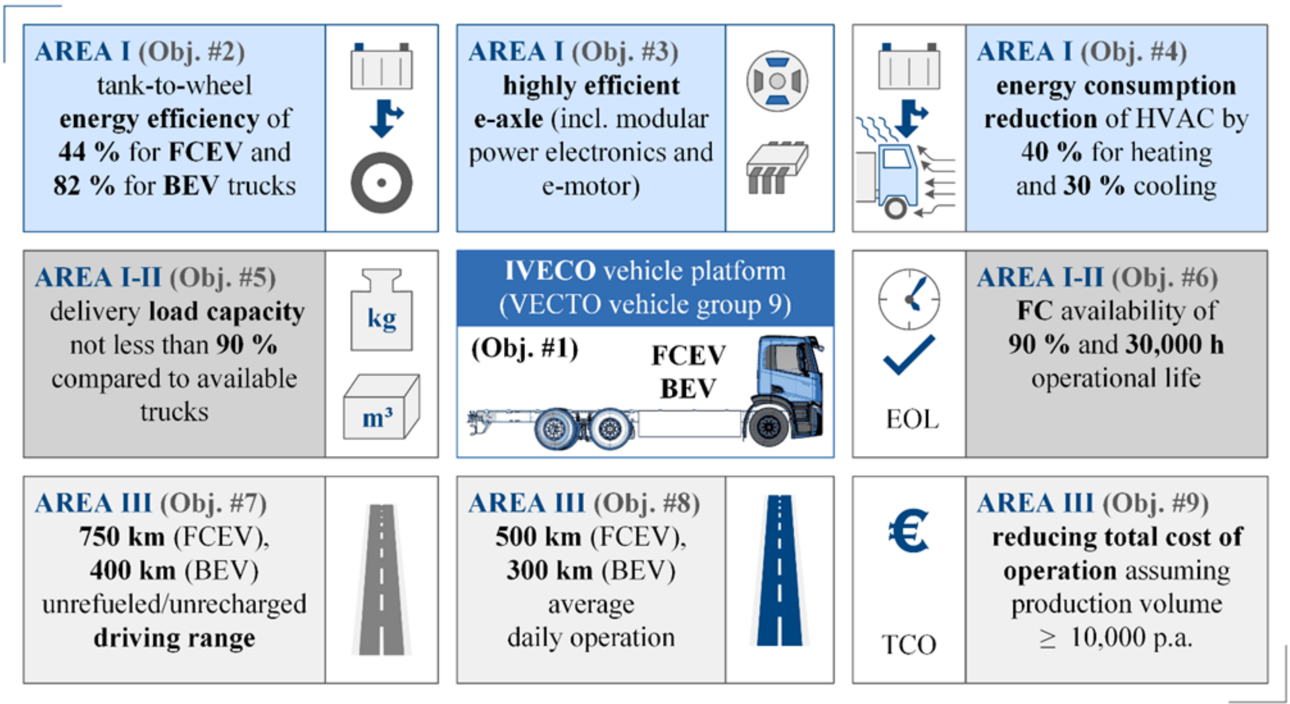

Figure 2: Nine EMPOWER objectives.

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1.2 Timeline

The following timeline (Table 2) focuses on WP1 and its tasks, showing how they are located with respect to the entire program. Task 1.1 and task 1.2 have been closed and they are described in the following chapters.

Task 1.3 consists in the set-up of the digital-twin models, and it goes on along the entire program, integrating continuously the technical contents that directly and indirectly affect the energy consumption. The developed digital-twin models of both vehicle concepts (FCEV and BEV) are validated at the end of the project against the final measurements during the demonstration phase. In Task 1.4 (which is not part of this deliverable) a baseline of a comparable model will be assessed and the interpretation of results will be summarised in Deliverable 1.3 which will be closed at the end 2023.

Table 2: Project timing status

Leader	EMPOWER Gantt chart		Year	2023				2024				2025				2026			
			Quarter	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
IVECO	**WP1**	**Platform identification, technical specs of modular HDV, and digital twin**																	
IVECO	Task 1.1	Platform identification and technical specification ✓																	
IVECO	Task 1.2	Use cases and component specifications ✓																	
AIT	Task 1.3	Interim performance assessment and continuous dev. of digital-twin models																	
POLITO	Task 1.4	LCA and TCO: Goal and scope definition; assessment of baseline vehicle																	
FPT	WP2	Integrated e-axle and fuel cell system																	
FMF	WP3	Modular energy storage (battery and hydrogen tank)																	
AIT	WP4	Modular and flexible vehicle architecture																	
IFPEN	WP5	Innovative HVI, V2G communication, fleet management and infrastructure																	
IVECO	WP6	Integration of components into vehicle demonstrators																	
GLO	WP7	Demonstration of FCEV and BEV use cases																	
AIT	WP8	Dissemination, communication and exploitation																	
AIT	WP9	Project management																	

1.3 Platform identification and technical specifications

The baseline for the EMPOWER development relies on IVECO Groups (IVG) portfolio and systems. An IVG conventional platform will be used as baseline. From this base platform some components or modules can be used as pure carry over or, if necessary, adapted for the integration of the fuel cell system.

Below some examples of components that can be used from existing IVG vehicles as well as ongoing development programs:

- Base vehicle system – cabines, non-driven axles and wheels, suspension components, LV-wiring layout and sensors, wheel-brakes (except electric brake on rear-axle);
- LV Architecture;
- HV components, (inverters, e-fans, HV-harnesses and connectors);
- Batteries;
- Hydrogen tanks and energy supply system;
- Auxiliary systems (e-fans, radiators, air-intake, etc.).

The choice of this mix between new and established content has been made on purpose, in order to minimise the risk during the development of the new vehicles with highly innovative technological contents, as well as to benefit from synergies and scale effects in the components to keep the cost for the product as close as possible to the current production technology. Also, the use and adaptation of existing components supports the approach to modularity with solutions that can be applied on multiple products, as they also support the final intention enabling scalable manufacturing within reasonable timing once the product has demonstrated its effectiveness in the operational use.

Major modifications will refer to the engine bay area to integrate the Fuel Cell System (FCS) (for the FCEV concept), the HV auxiliaries and all thermal system modules. The batteries and the tanks for hydrogen will be positioned between the front axle and the rear e-axle. The LV-architecture will require major adaptation of the

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powertrain control system, as well as adaptations to the vehicle control domain, due to the different performances and requirements by the newly installed systems.

Further components and systems that will require adaptations are:

- Frame with specific layout;
- Rear suspension.

Newly developed systems to the EMPOWER products are:

- Climatisation system of the cabin (HVAC);
- E-axle;
- Fuel cell System;
- Electric brakes;
- Thermal management system, part sizing, etc.

The platform that has been identified for the development of the two demonstrator trucks is a 6x2 rigid truck and the reason of this choice refers to the following characteristics of this product:

- **Adaptability:** since it is suitable for multiple missions (e.g. Long-haul and Regional delivery);
- **Relevance:** very high use in ON-Road transportation (VECTO Group 9), with clearly identified CO_2 reduction targets starting from 2025 to 2040. Further, the configuration is known to the abroad customer base as ICE-driven models. With BEV and FCEV trucks serving the same use-cases, as current ICE-trucks, the customer-acceptance level for the new technology is expected to be high and the new products more easily adopted in addition or exchange to conventional (ICE-) configurations;
- **Versatility:** it is employed in a lot of different use-cases (e.g. truck-trailer combinations, single truck applications);
- **Modularity:** the architecture of the vehicle can be adapted to different missions (e.g. municipality, light off-road tippers, etc.);
- **Scalability:** Multiple configurations can be developed from this configuration (e.g. 4x2 and / or 8x2) in order to fulfill different mission needs (urban distribution, heavy distribution).

In the following chapters, the defined platform (both for the FCEV vehicle and BEV vehicle) will be described in detail, including boundary conditions (mass and dimension) and main technical specifications of the components that will be integrated. Following the scope of the EMPOWER project, this identification considers the preservation of load capacity (payload capacity) of not less than 90 %.

1.4 Baseline: diesel reference trucks

To assess the TCO a comparable and significant diesel configuration is needed. With this configuration a baseline model will be set up and will be later, during Task 7.4, updated with the data of the EMPOWER developments. The reference baseline configurations (Table 3), both for regional and for long-haul distribution, has been defined considering following aspects:

- Customer acceptance (use-cases are known and the type of configuration is suitable and appreciated);
- Commonality of systems and components: this means reducing cost of contents making the product competitive thanks to the possibility of high carry over percentage;
- Significant contribution in Mobility-transition to Carbon Neutrality and Zero-Emission Transport, since it is one of the most used configurations and its impact is highly relevant.

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Table 3: Diesel reference configurations

 

Pivot Model	PIVOT 1	PIVOT 2
Volumes Mix (Rigid On Perimeter)	**50%**	**26% (34% AS+AT)**
Version	6x2	6x2
Cab	AD	AS
Wheelbase	4.200	6.050
Wheel base take rate - vs. Pivot	**41% of 6x2 AD**	**20% of 6x2 AS+AT**
G.V.W. **G.C.W.**	29t 44t	
Suspensions	Full Pneumatic (9t High Stroke)	
Vehicle Set-Up	ON	
Drive	LHD	
Energy On Board (Number of Battery Packs)	**420 kWh** (6)	**560 kWh** (7)
VP 6x2 - P	RV2CD6D1000009	SE4CDCD1000003
VP 6x2 - FP	RV2DD6D1000004	SE4DDCD1000003

The previous table depicts in detail the Diesel baseline configurations that will be used to assess the performance of EMPOWER.

For the **regional distribution**, due to mission type, a rigid truck with 3 axles (2 wheels drive) and day cabin has been chosen. The wheelbase definition is based on a relevant take rate, and it is slightly different from the length foreseen for the EMPOWER demonstrator that will include a high number of batteries between rear and front axles. Nevertheless, this difference has been evaluated as not relevant for maneuverability and for the user experience. The gross vehicle weight has been set at 29 ton with full pneumatic suspension (mechanical suspension are also suitable with a maximum axle weight of 9 ton).

The available amount of energy on board is 420 kWh, a value that can be reached with a pack of 6 batteries used in the EMPOWER demonstrator.

The baseline for the **long haulage vehicle** presents the same configuration as for the reginal one but it includes the sleeper cabin, more suitable for long-haul missions. The wheelbase is longer, and the configuration includes a trailer, raising the gross vehicle weight to a gross combination weight of 44 tons.

The available amount of energy on board is 560 kWh, a value that can be reached with a pack of 7 batteries used in the EMPOWER demonstrator.

Both reference vehicles present a left-hand drive configuration and set-up typical of European road-use.

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2 BEV

2.1 Architecture and layout: regional distribution truck

The architecture that has been chosen for the regional distribution consists of a 6x2 rigid truck (wheelbase 5,100 mm), a flexible vehicle platform that allows the installation of modular powertrain solutions, exploiting the scalability and modularity of the installed power units to allow cost efficient solutions for dedicated missions. For this kind of use a day cab has been foreseen (in regional delivery drivers return to their home base overnight and do not stay with the trucks over a longer time period), but thanks to modularity it can be easily adapted to a sleeper cab solution.

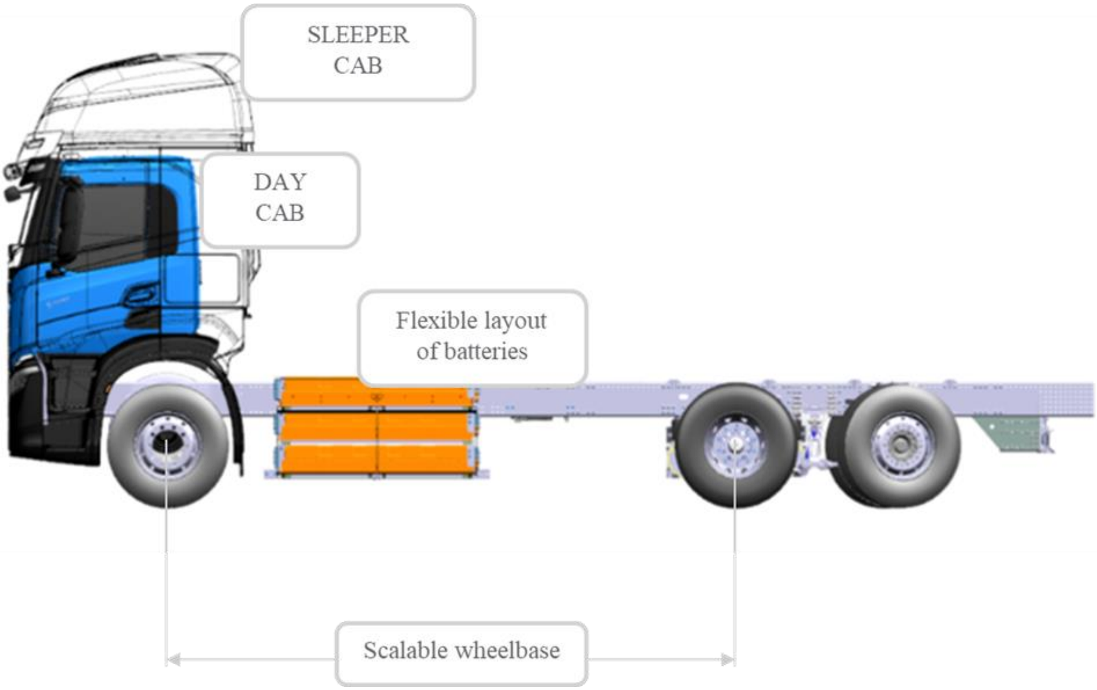

Figure 3: Architecture of BEV.

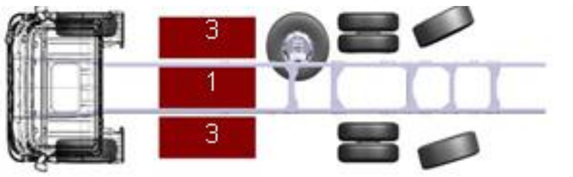

Figure 4: Layout of battery positioning in BEV.

The vehicle has been equipped with 7 batteries (see chapter 2.3 for technical specifications) positioned as represented in Figure 4, nevertheless layout, position and number of elements can be adjusted according to the type of mission (e.g. Figure 5).

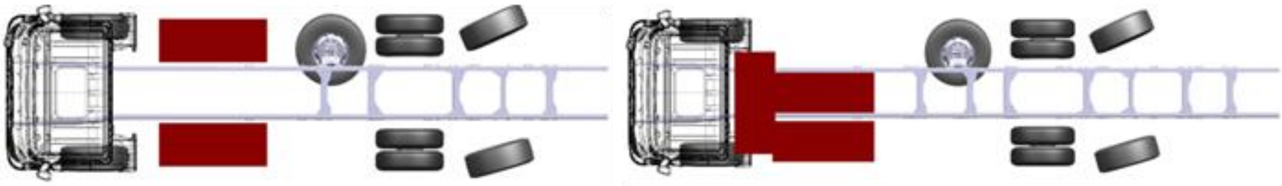

Figure 5: Modularity of the battery layout.

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The possible application range includes single truck configurations or truck-trailer combinations with the possibility of varying the truck wheelbase in a range between around 3500 mm up to 6000 mm. Several components are considered as carry-over from traditional diesel configurations (e.g. front axles, suspensions, tag-axles, trailer connections, the trailer itself) while other systems and applications can be derived from and/or shared with other electrical vehicles (e.g. e-axles, batteries, inverters and power management system).

2.2 Packaging

This paragraph depicts the boundary package of the BEV. The overall dimensions do not exceed the Diesel reference configuration and the weight balance entails an increase within 2 ton, as foreseen in the 96/53/EC [5] for ZEVs. The truck has the same overall dimensions as the ICE-propelled versions, hence this BEV configuration can easily be utilised in addition or replacement of ICE-propelled trucks in the same mission.

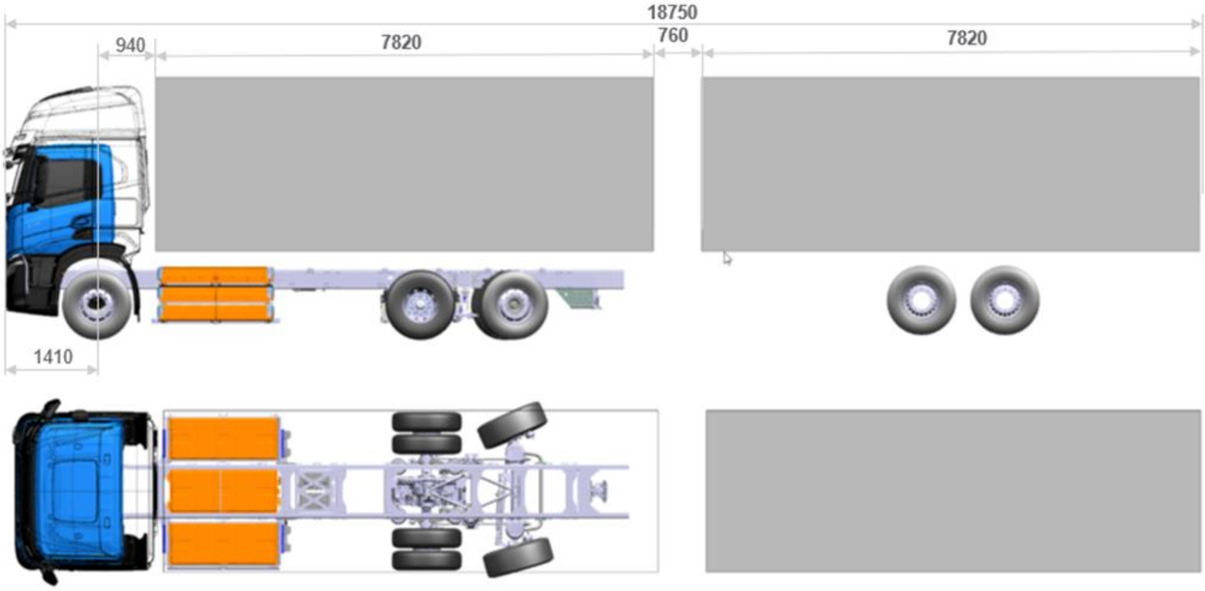

Figure 6: Overall BEV packaging.

The impact to the driver comfort will be limited to the different performance characteristics of an electric-drive vs. ICE-propulsion, but it will not differ in the possible load to carry or the overall manoeuvring on public roads.

2.3 Batteries

Considering the aim of the EMPOWER project, focus is the modularity and the scalability of the solution, and to obtain a competitive and therefore as low as possible TCO for each configuration. The final products can rely on multiple package choices, depending on the customer's mission. The package range moves from two (for the FCEV version) to seven batteries (BEV configuration), and it could potentially go up until ten batteries (under examination). These batteries (see Figure 7) are already used in the Bus product range, that means already available technology with low R&D impacts and high volumes. Using an already available product guarantees an optimal compromise between energy density, dimensions, weight, and lifetime requirements. Furthermore, all necessary safety measures have been already implemented.

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Figure 7: Battery module.

A battery system consists of:

- The battery packs themselves, between two and seven (theoretically up to ten);
- A central battery management system that controls the battery modules.

Technical specifications of the battery modules:

- Weight: ~ 400 kg each pack;
- Dimensions: ~1,790 mm (length) x ~700 mm (width) x ~ 270 mm (height);
- Cooled by water-glycol;
- IP6K9K / IP67 protected;
- Homologated by ECE R100.2 and ECE R10.6 norms;
- Energy = 67 kWh (= usable SOC range) → ~ 55 kWh "day-by-day";
- Power: continuous discharge power > 80 kW, continuous charge power > 70 kW
- Voltage range: 525 V – 735 V
- NMC Li-ion cell technology;
- Life cycles > 6,000 @ 80 % DoD;
- Smart wiring = possible to connect two modules in a row to save HV DC wiring;
- External accessible fuse + HV-interlock to ease production and service.

A battery management system is dedicated to manage that the cells and modules can work in the best way according to the needed power, battery status and environmental conditions. The BMS control unit communicates with the single modules over a separate high-speed-CAN and is connected to the High-Voltage control unit (e-VECOP) via vehicle drivetrain high-speed-CAN. The BMS takes for example the e-VECOP-command "HV-ON" and forwards it to each module, considering the actual battery system state. It calculates and provides the available current limits that are the basis for the maximum possible drivetrain power or charging power. It calculates and measures the system temperature, requests cooling or heating etc. from e-VECOP, and activates safety measures if necessary.

The BMS also controls

- the (passive) balancing between the modules;
- the (resistor-active) balancing between the cells within a module;
- the pre-charging of the HV DC link;
- the insulation measurement within each battery module before HV-ON;
- the crash and internal failure measures within the battery modules.

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2.4 Power distribution system

The BEV vehicle will contain two power distribution units:

- One in the back, where the HV-DC-connections to the batteries and to the inverters join. This unit contains the main DC fuses and the connection to the front power distribution unit. This box including fuses is dimensioned to carry the peak and continuous HV-DC current from the batteries to the inverters plus the power distribution unit in the front.
- One in the front, which supplies all auxiliary HV components and other purposes: HV-LV-DC/DC, inverter for the mechanical power-takeoff (PTO), electric fans, brake air compressor, compressors for cab and battery conditioning DC switches for the charging inlet.

2.5 Batteries thermal management system

The BEV vehicle will contain four separate cooling cycles for different purposes in the drivetrain and for the attached components:

- Cooling all semiconductor-operated power electronics components like inverters, DC/DC-converters, PTO-inverters plus the main e-machines. This makes sense as these components all need “more or less” the same inlet temperature of the cooling fluid.
- Generating heat for the driver cabin, power sink for endurance brake, generating heat for battery preconditioning.
- Battery conditioning = cooling and heating. With this circuit, including the heat exchangers to the heat-generator and a refrigerating circuit, the battery modules can either be thermally equalized, passively cooled, actively cooled, or actively heated.
- Refrigerating circuit with refrigerant and heat exchangers to cabin conditioning and battery circuit.

Mentioned and described modular approach is flexible and can be adapted to different configurations. Additional components for example in the FCEV, like the main fuel cell DC/DC-converter, can be added to the power-electronics circuit. As the FCEV will need battery conditioning and an endure brake too, the architecture will be similar. More details about the thermal management can be found in Deliverable D4.1 Thermal- and vehicle energy management.

2.6 E-axle system specification

Integrated e-axle

Concerning the identification of requirements for the e-axle development, the analysis of the different platforms confirmed the requirements identified in the pre-study of the EMPOWER project about available space and performance requirements. No significant changes have been identified related to drivability and maximum torque requirements. WP2 (Task 2.1) will focus on the definition of the best technical solution to satisfy the requirements while maximizing platforms commonality.

For the targeted performance focusing on the modularity and scalability, the single e-drive e-axle and dual e-drives e-axle layouts are identified to achieve competitive TCO. Depending on customer mission, the dual e-drives e-axle (from Figure 8) is recommended to reach the power requirement. For the available product based on the dual e-drive layout, the technical specification:

- 2 x 410 Nm / 240 kW for the continuous performance;
- Up to 45,000 Nm axle torque;
- Up to 840 kW peak power;
- Single speed – IPMSM e-Motor;
- IGBT then SiC inverter;
- ~1.4 ton.

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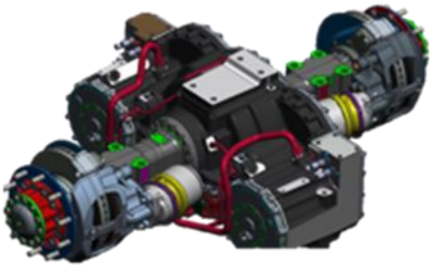

Figure 8: Example of the EMPOWER dual e-drives e-axle.

An improved inverter solution based on SiC is developed to improve the inverter efficiency from 96 % to 98 %. Furthermore, to gain advanced performance for the e-axle, FPT will work with IFPEN to get a new solution for inverter from the latest HW/SW technologies. Under the scope of e-axle requirements, the new feature of the inverter will include high power density, high efficiency, high-level condition monitoring, and advance control/modulation techniques.

2.7 High voltage power control system

The central power control will base on IVECOs electrified VEhicle COntrol Platform (e-VECOP). This is a highly modular platform for all major control functions needed for todays electrified vehicles.

The platform includes:

- The SW itself (C-code, models) which are compiled to an executable program for the control unit;
- Every tool which is needed for the development, versioning, validation and further tasks;
- A structured process for SW-build/-update, parallel programming etc.

The platform is modular and applicable for drive train architectures like FCEV and BEV for:

- Commercial vehicles in the light, medium and heavy range;
- Buses;
- Special applications (e.g. off road).

The included functions control all features which are necessary to operate a FCEV/BEV:

- Battery "HV-on-off" control and further necessary algorithms;
- Energy flow control to all components connected to the main HV DC-link: e-machine-inverters, DC/DC-converters, air brake compressor, fan, charging inlet, also FC in a FCEV application;
- Cooling management: Supervises the temperature of all power electronics components, batteries, and e-machines. Activates and controls the cooling circuits (see chapter 2.5 Thermal system);
- Torque control: Calculates the torque path from the driver's accelerator pedal to the inverters, including complex interfaces to e.g. active cruise control and other driver assistance systems;
- Charging control: Hosts the communication interface to external charging stations, controls the power flow from the charging station to the batteries, calculates values to be shown for driver like SOC, is an interface for remote applications like SOC-gauge on drivers cellphone etc.;
- Manages the PTOs and the necessary interfaces to these PTOs and customer-built body applications;
- Manages LV-energy supply by controlling the DC/DC converters;
- Manages FC control and relevant interfaces to the drivetrain.

e-VECOP is able to run on different HW platforms with different supply voltages (e.g. 12 V or 24 V).

In addition, it offers various further in- and outputs for optimal adaption to the actual application.

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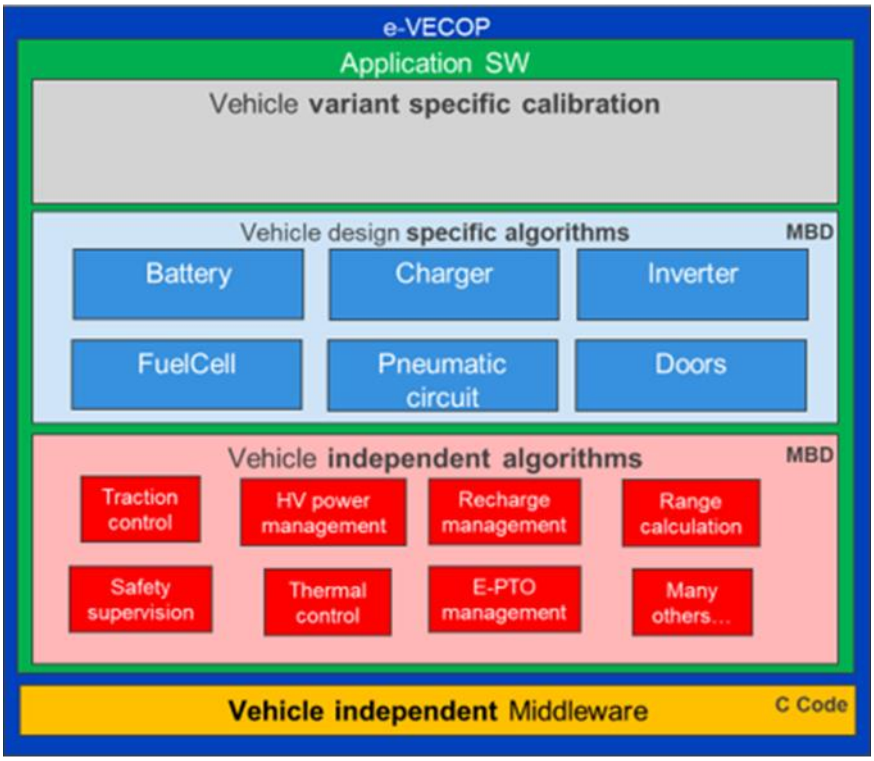

Figure 9: Structure of the electrified VEhicle COntrol Platform (e-VECOP).

2.8 Low Voltage Vehicle control system

The Low Voltage (LV) vehicle control system is based on a CAN-Bus architecture that links all electrical and electronical sensors on the vehicle with a network of relevant Electronic Control Units (ECU). These ECUs register the relevant sensors signals and, with support of sophisticated SW and HW, allow for safe, secure, and efficient vehicle handling in all different driving conditions. The electronic vehicle control system is a highly complex and safety-critical area of Heavy Commercial Vehicles (HCV), with OEM-specific liability, know-how and a dedicated organisation to assure safe and secure development, manufacture and service of trucks during their lifetime in different conditions and applications. For ease of understanding, the architecture of relevant ECUs can be grouped according to specific vehicle-operation domains which are illustrated in the simplified Figure 10.

This detailed description of key elements to the LV-electronic architecture of heavy trucks is relevant to the understanding of the setting for the EMPOWER-project and products.The overall electronic architecture can be grouped into two main domains of distinct functionalities, e.g powertrain control and entire vehicle control.

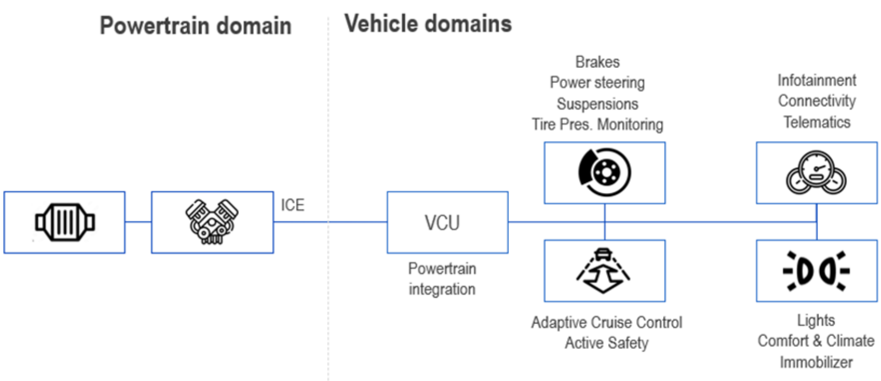

Figure 10: Low voltage management diagram in ICE vehicle.

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The powertrain control domain is responsible for the management of the vehicle propulsion system, providing the necessary power to the vehicle depending on the vehicle status (e.g. current speed, vehicle inertia due to weight and load characteristics, available energy/fuel, …), environmental conditions (e.g. uphill/downhill, set speed-limit, etc.,) and driver command (accelerate/brake, smoothly/harshly,…). It is further responsible for the correct operation of the powertrain and its auxiliaries (e.g. cooling, fueling, exhaust gas management, etc.) for safe and efficient power provision, according (legal) performance criteria. In the above figure these two functionalities are shown with the icon of the engine ( ) and the catalyst ( ) as representation of key-auxiliary for diesel or gas-fueled Internal Combustion Engines (ICE).

Efficient powertrain performance is heavily reliant on accurate information on vehicle conditions, hence the situation of the surrounding environment, the vehicle status, and the driver input. Such information is provided by the vehicle domain systems.

Several ECUs and sub-domains are necessary for the accurate sensing of the vehicle status, the surrounding conditions and for the management of safe and efficient vehicle handling. In the illustration only the key domains are illustrated.

- The chassis control domain ( );
- The vehicle dynamics control domain ( );
- The cabin control domain ( );
- The HMI interface and connectivity control domain ( );
- The vehicle control unit ( ).

Each of these domains is responsible for control and monitoring of specific vehicle performances, but only working and linked together they assist safe and efficient driving.

For example, the chassis domain is responsible for effective and safe vehicle braking. Due to the dimension and weight of commercial vehicles, this is achieved by the combined activation of several systems altogether. On ICE-powered vehicles, the engine is also involved, as are the individual wheel brakes or the gearbox-retarder.

The vehicle dynamics domain is responsible for sensing of the surrounding environment and providing support to essential driver assisting functions, such as Adaptive Cruise Control (ACC), Advanced Emergency Braking (AEB), Electronic Stability Control (ESC), etc.

The cabin control domain controls the cab-settings, including (internal and external) lighting, climate control and (entry) key functions.

The HMI interface and connectivity domain manages the information exchange of vehicle status (speed, power consumption, warnings, etc.) with the driver and it manages the exchange of information with external (cloud) sources. For example, the connections to navigation maps, fleet management systems, service apps or other data exchange. It is further relevant to the assurance of controls meeting cyber security requirements.

All the relevant information about the status of the various vehicle domains is then collected by the central Vehicle Control Unit (VCU) to calculate adequate algorithms for the necessary data-input into the powertrain domain. Vice versa it elaborates the output from the powertrain domain providing all relevant info into the vehicle domains, for instance on engine braking performance to the chassis domain.

As shared above, the setting of the LV-architecture, the management and control of essential vehicle functions and performances is extremely complex. Nonetheless, the LV-architecture is critical to safe vehicle handling on public roads and requires responsible management, including safety functions and legal performance levels. Hence, specific expertise, knowledge and organizations are involved when any of the described domains will be affected by product changes, i.e. a new propulsion system is introduced into the vehicle or when the climate system is going to be modified for power efficiency and lower energy consumption.

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Hence, for the EMPOWER-project the existing LV-architecture for (ICE) heavy duty trucks were chosen to be adapted, where necessary. Thanks to the modular setting of the architecture, in particular between the main domains (powertrain and vehicle) existing modules on the vehicle side can be re-utilized, though adapted to the EMPOWER requirements (e.g. cabin climatisation, regenerative braking with e-axles, etc.) or completely substituted (ICE-powertrain module vs. FCEV or BEV powertrain modules).

The image below shows the architectural setting for the EMPOWER Products (FCEV and BEV), together in the same chart. Although each of the EMPOWER products will have their specific powertrain domain (controlled by the power management system e-VECOP) that links to the existing vehicle domain, shared with diesel- or gas-trucks.

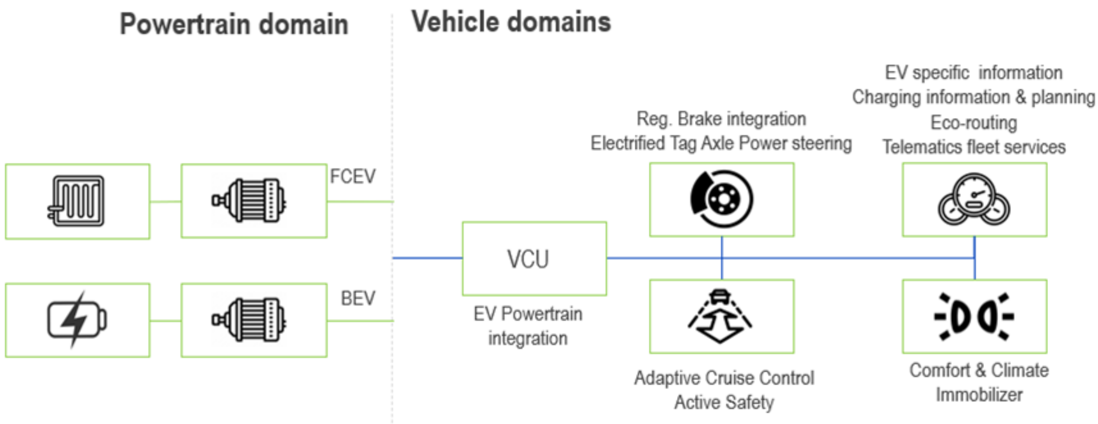

Figure 11: Low voltage management diagram in FCEV and BEV.

Powertrain domain: Both, the battery electric truck demonstrator and the fuel cell electric truck demonstrator share the same e-axle as main propulsion unit, but the auxiliary systems that support and control the efficient and safe propulsion are different and specific to the technology. For simplified illustration the Battery system is shown as Key auxiliary system for the BEV, whereas the cooling circuit is shown for the FCEV. An additional “icon” for the control of H_2-supply system, necessary for FCEV, was left out for simplified illustration.

Vehicle domain: Innovations with the EMPOWER products also affect all vehicle domains as well. This is highlighted by the green framing of each of the single domains. Such changes will require specific algorithms with performance levels for affected systems. These are, among others:

- Chassis domain for regenerative braking on e-axles;
- Cab domain for power saving cab climatization and electrified auxiliaries management;
- Calibration of vehicle dynamic domain, following specific performances by FCEV and BEV (driving, acceleration, added weight for batteries, H_2 storage and relevant auxiliaries, etc.).

HMI and connectivity domain, following new eco-routing, eco-charging and eco-driving developed within EMPOWER-project.

The detailed definition of impact by the content to the EMPOWER products to the LV-architecture, as well as the development of specific algorithms and control mechanisms for safe and efficient driving will be part of the ongoing development within the EMPOWER-project. This will require a structured approach in design, including functional safety assessments and thorough validation through SW- and HW-testing on systems and components, as well as the integrated vehicle set-up.

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3 FCEV

3.1 Architecture and layout of long haulage truck

The architecture that has been chosen for the long-haul distribution consists of a 6x2 rigid truck (wheelbase 5,100 mm). This is the same solution as adopted for the BEV concept. For this kind of use a sleeper cab has been foreseen (driver staying with the truck over longer periods, including overnight stay, hence vehicle space is bigger and allowing for additional comfort, with dedicated features (storage boxes, bed, etc.), but thanks to modularity it can be easily adapted to a day cab solution.

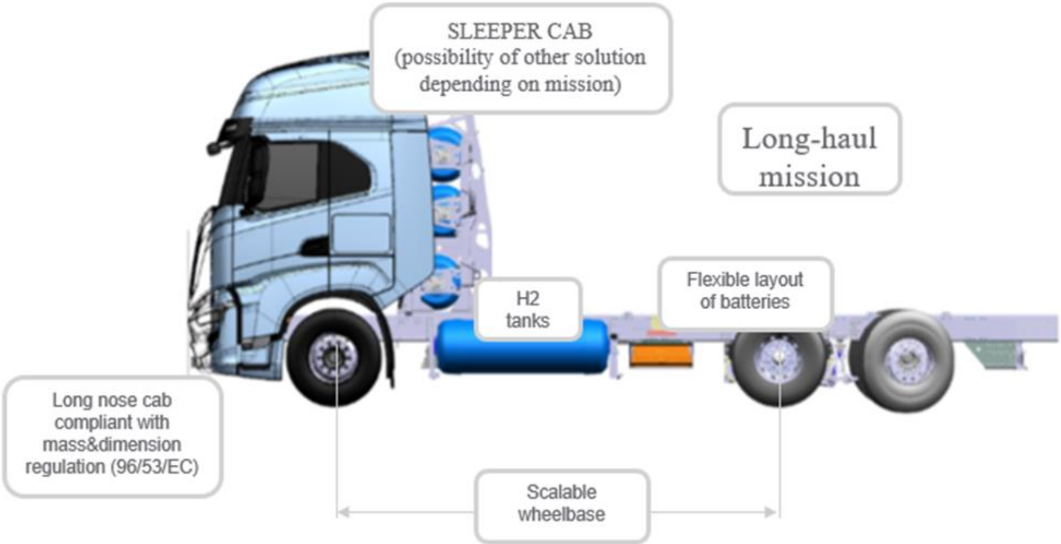

Figure 12: Architecture FCEV.

Several components can be taken as carryover from the diesel configuration (e.g. front axles, suspensions, tag-axles, trailer connections) while other systems and applications can be taken or adapted for fuel cells integration from the BEV concept, for example:

- Batteries;
- E-axles;
- Power control architecture;
- Electronic vehicle control systems.

The vehicle will be equipped with two batteries (carry over from BEV concept, see chapter 2.2 for technical specifications) positioned as represented in Figure 13. Their layout, position and number of elements can be adjusted according to the type of mission.

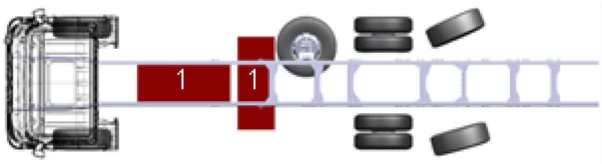

Figure 13: Batteries layout FCEV.

Batteries are required for fast provision of electric power in transient driving conditions when the power increase by the fuel cell unit is not fast enough. They also serve as a buffer of energy balancing the power requirements. In downhill conditions the e-axle can serve as an electric generator, charging the batteries. Hence the overall net consumption of energy will be partially recuperated and stored in the batteries. Simulations on the Trans-alpine corridor have shown that a package of two batteries is recommended to assure comfortable

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driving characteristics and vehicle speeds comparable to other (ICE-propelled) trucks on the road. A dedicated battery charger is not foreseen on the FCEV.

The hydrogen will be stored in five tanks (see chapter 3.2 for more technical specifications) mounted in a dedicated structure behind the cab (three tanks) and directly on the chassis (one tank per each side), as represented in Figure 14.

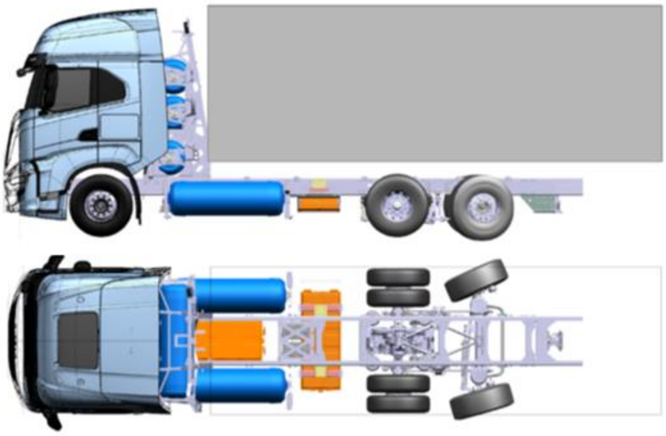

Figure 14: H_2 tanks in FCEV.

3.2 Packaging

This paragraph depicts the boundary package of the FCEV. The overall dimensions exceed the diesel reference configuration but stay within the limit defined in the 96/53/EC regulation. Without updates on mentioned regulation for ZEVs, the technical back-up solution includes an aerodynamic front-end that allows overcoming 18.75 m of total length.

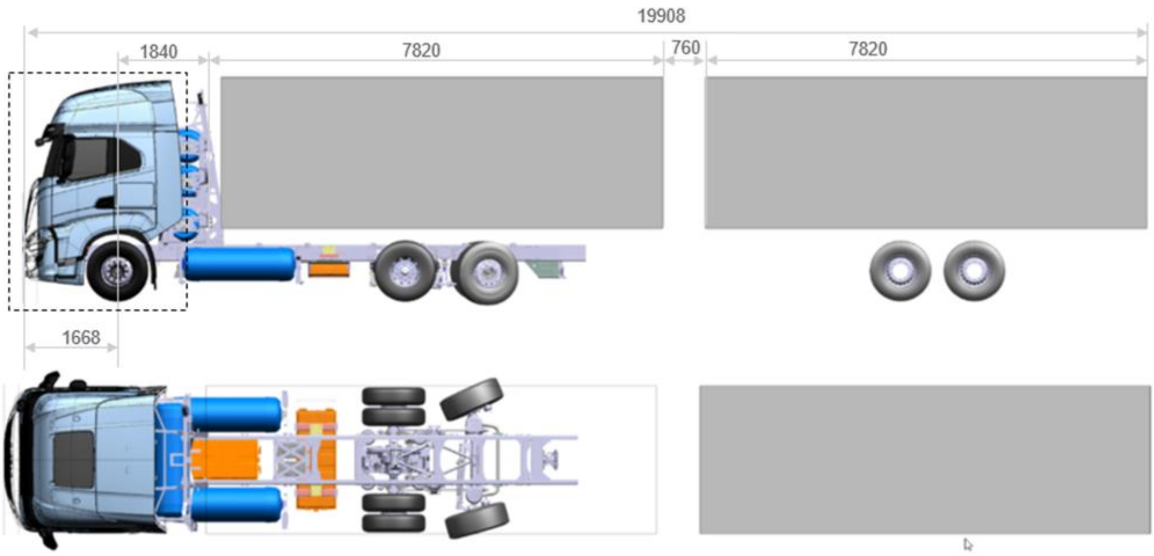

Figure 15: Packaging of the FCEV.

As far as the weight is concerned, the balance entails an increase within 2 t, as foreseen in the 96/53/EC for ZEVs. The connection between rigid truck and trailer will be managed with a towbar, which length will be deeper investigated to guarantee required manoeuvrability and optimal loads distribution.

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Figure 16: New cabin concept with aerodynamic front-end.

3.3 Hydrogen fuel cells

This chapter delves into a critical aspect of this funded project on advancing fuel cell technology, modularity, and performance targets. As one of the major goals of the EMPOWER project, navigating the ever-evolving landscape of sustainable transportation, the ability to adapt and customize fuel cell systems to various vehicle platforms while maintaining stringent performance standards is paramount. In this chapter, the methodologies employed to identify the dimensions suitable for different vehicle platforms are identified and the performance criteria in terms of power and efficiency to meet the project's overarching objectives are defined.

Modularity: Fitting fuel cells to diverse vehicle platforms. The first step to achieve modularity, is to carry on a comprehensive study to identify the critical dimensions for the applications to be considered in addition to the target vehicles of the project; additionally, considerations on the installation of one or two systems were conducted to allow for future power scaling needs. In this first iteration, a target envelop space to serve as boundary for the fuel cell system development was identified. Developing within this boundary, allows to have a system that can be used both in the rigid and artic vehicle platforms and allows for one or two systems to be installed based on the cabin configuration. Furthermore, with minor design changes, this envelope boundaries would allow for fitting in Medium-Duty (MD) vehicles and coach buses.

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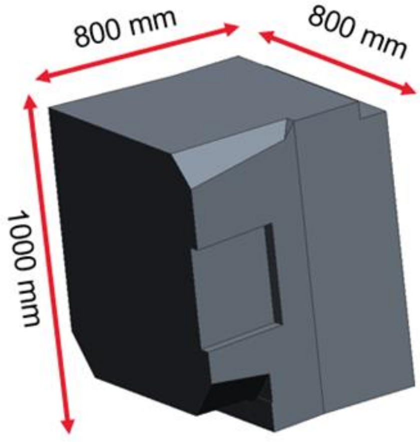

Figure 17: Fuel cell volume.

Leveraging advanced CAD modelling and simulation tools, the key factors are explored influencing system size and shape, in particular the activities started from stack configurations analysing both horizontal and vertical orientations, to determine the most space-efficient layout while ensuring performance targets.

Performance targets: Power and efficiency meeting the performance targets for the FCEV of the EMPOWER project necessitates a thorough understanding of the power demands across different vehicle classes. To this end, a parallel workstream was pursued, focused on identifying the required power output for each application; the numbers anticipated in the preparation of the WP2, were confirmed by the simulation activities, confirming the need to develop a high power and highly efficient system to minimize the H_2 consumption. The H_2 consumption has a double impact: it heavily affects operational costs, and it defines H_2 storage capacity needs for a given mission.

The identified targets for fuel cells, are pointing to have a 150 kW to 200 kW system, with unprecedented efficiencies, above 50 % also in the least efficient points. This will allow high flexibility and configuration potential:

- 1X system configuration, will allow very good efficiency levels and enough power to cover mountain mission demands, while having a moderate impact on vehicle weight and overall system cost;
- 2X system will allow for outstanding efficiency level, unseen power availability at the expense of increased weight and cost.

3.4 Hydrogen storage

The definition of the HSS (Hydrogen Storage System) is based on the best compromise between several aspects. The most important are space availability, needed ground clearance, range objective and the passive safety requirement. The layout includes 5 tanks with a total weight of 73 kg H_2: 3 are placed behind the cabin while the others laterally, on each side of the chassis. The solution will include the fast flow re-fuelling system with the possibility of operation at 350 and 700 bar (Figure 18, Figure 19 and Figure 20).

To reduce design and control development efforts, a study on the packaging has been conducted in order to find the more suitable solution from IVG Portfolio products, including the control unit as well. The most suitable carry over components between available HSS solutions means that the available space has been as much as possible utilized by choosing the most suitable product. A future specific development of tanks could optimize even the available space to further increase the operational range.

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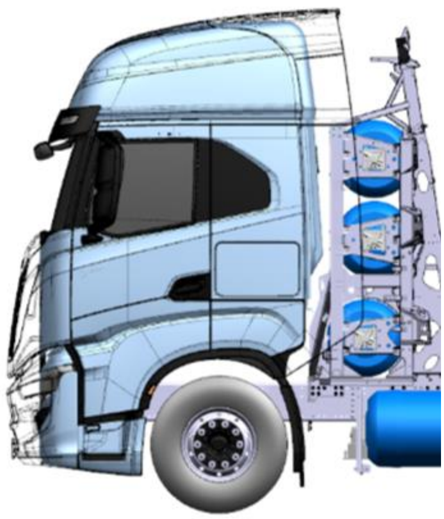

Figure 18: Hydrogen Storage system.

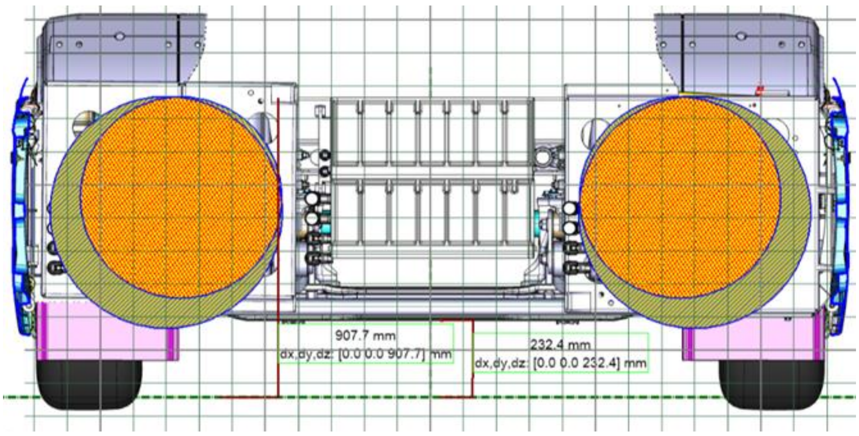

Figure 19: X section of H_2 lateral tanks.

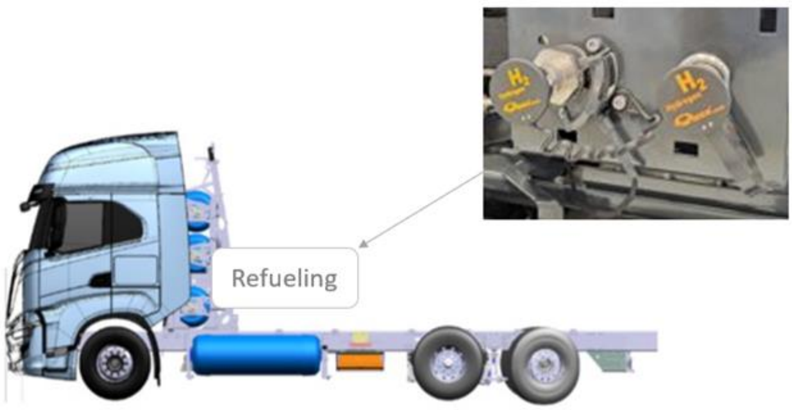

Figure 20: Double re-fueling system at 350 and 700 bar.

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3.5 Batteries

Modularity and scalability described in chapter 2.3, can be applied also to the FCEV. The battery itself, even if integrated in a different propulsion system, can be taken as carry over from the BEV model.

Technical specifications:

- Weight: ~ 400 kg each pack;
- Dimensions: ~1,790 mm (lenghts) x ~700 mm (widths) x ~ 270 mm (heights);
- Cooled by water-glycol;
- IP6K9K / IP67 protected;
- Homologated by ECE R100.2 and ECE R10.6 norms;
- Energy = 67 kWh (= usable SOC range) à ~ 55 kWh “day-by-day”;
- Continuous discharge power > 80 kW,
- Continuous charge power ;> 70 kW;
- Voltage range: 525 V – 735 V;
- NMC Li-ion cell technology;
- Life cycles > 6,000 @ 80 % DoD;
- Smart wiring = possible to connect two modules in a row to save HV DC wiring;
- External accessible fuse + HV-interlock to ease production and service.

The functionality of BMS is described in chapter 2.3 for BEV demonstrator.

The aim of having batteries in the FCEV meets the need of extra power in some route condition (e.g. crossing mountains) and for this reason an architecture with two batteries has been foreseen.

The nominal power in normal use condition will count on fuel cell.

3.6 Power distribution system

The modular approach allows to use the same distribution units. For FCEV further components have to be added to connect the fuel cell system to the HV-DC-link.

3.7 E-axle system specification

The integrated e-axle system described in chapter 2.6, can be applied also to the FCEV.

3.8 High Voltage Power control system

The Platform is applicable for drive train architectures BEV, FCEV and Hybrid. Further details can be found in chapter 2.7.

3.9 Low Voltage Vehicle control system

The modular approach of the software platform allows to apply the same concept described in chapter 2.8.

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4 Use Cases

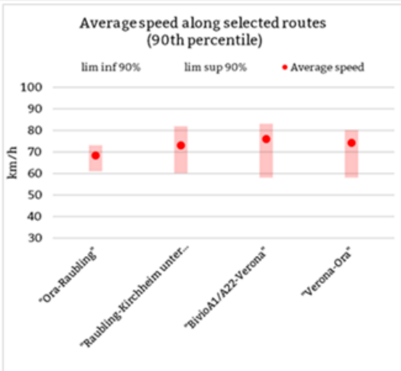
As a part of WP1, the Use Cases (UCs) have been agreed with the assigned partner GLO and reported as part of D1.1. In the Table 4 the vehicle specifications and related modularities are depicted.

Table 4: Vehicle configurations

	 Long Haul	 Regional distribution
Vocation	General Cargo Volume transport Controlled Temperature Container/Swap-Body	General Cargo Controlled Temperature Food and Beverages Tanker
Mission Drivers	TCO Liveability Productivity Safety	TCO Liveability Productivity Product cost
ARTIC/RIGID MIX (%)	80/**20**	35/**65**
AXLE CONFIGURATIONS	4x2, **6x2**	4x2, 6x2, 8x2 (1+3)
GVW (ZEV + 2t)	up to 44 t	16t / 26t / 32t / 44t
CAB TYPE	**Sleeper**	Sleeper / **Day Cab**
YEARLY MILEAGE (km/year)	120.000 – 200.000	50.000 – 100.000
DAILY MILEAGE (km/day)	**400 - 800**	**200 - 500**

The following table shows the routes in which the transport will be simulated and an analysis of the average speeds along these routes, with focus on long-haul UCs:

Table 5: Use cases

Mission	Use-case	Route	Speed	Weight	Temp
Long-Haul	1	Along Scandinavian-Mediterranean corridor **Parma ↔ Ulm** Verona ↔ Ulm Bologna ↔ Ulm 		**42t** (extra weight included) Load factor **80%**	-10° C Brenner area in winter condition
	2	Along TEN-T Mediterranean corridor **Iveco plant Turin ↔ Iveco plant Lyon** 			Not relevant
	3	optional			
Regional	4	Under evaluation			
	5				

Two UCs have been fixed with the possibility of adding a third one (optional). The first UC will simulate the connection between Parma and Ulm, considering, as alternative, the connection Verona – Ulm and Bologna – Ulm. The route goes through the Scandinavian-Mediterranean corridor that runs between north and south of Europe and the speed considered to evaluate the UC with an average commercial speed.

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The second UC between IVECO plants in France (Lyon sur Mer) and Italy (Turin) will consider the same parameters previously described. This average speed has been calculated considering hundreds of trucks running along the route and the 90th percentile of the medium range of speed anyway reached by some trucks during the trip.

The maximum weight possible, therefore, will be considered (according to the regulation) with a load factor of 80 %. The temperature in some segment of the route could reach -10 °C in winter conditions and this will be considered to assess fuel cells functionality. The UCs for regional distributions will be defined afterwards so no simulation is so far needed.

GLO performed, moreover, an analysis to fix and to address potential issues during loading phase of EMPOWER trucks and two attention points have been identified. To perform this analysis, an IVG Vehicle unit of VECTO Vehicle Group Nr. 9 6x2 has been used (Figure 21). This vehicle is used to carry swap bodies and usually combined with an additional trailer. The full truck + trailer combination is 18.75 m.

Figure 21: The vehicle unit.

During the loading phase, the driver approaches in reverse to the swap body and performs a visual manoeuvre to align the swap body with the truck chassis. Mainly for the FCEV version, since the manoeuvre is carried out without external support, a further investigation will be done in order to avoid any potential risk of collision between H_2 tanks behind the cabin and the swap body (cf. Figure 22).

Figure 22: The vehicle space behind the cabin.

Furthermore, supporting legs of the swap body are used to ensure stability when the swap body is parked (cf. Figure 23).

Figure 23: The supporting legs of the swap body.

During the manoeuvre for loading the swap body, the support legs remain in place till the end of the loading phase. When the loading is completed, the driver raises the tractor chassis till the chassis frame touches the swap body. During this operation, the swap body is raised from its initial position and the supporting legs are no longer resting on the ground.

Having the supporting legs raised from the ground, the driver is now able to fold them in the longitudinal position and put the stop pin to block the support. In order to guarantee that the supporting leg is integral with the swap body and is fixed in a safety position closed to the frame of the swap body, there is a clamp used to support the hold up the supporting leg (Figure 24).

In case the clamp is damage and bend, the supporting leg is no longer blocked properly in the longitudinal position. This condition could cause a contact between the supporting leg and any equipment of part of the tractor chassis which is located below the supporting leg (e.g batteries of the BEV vehicle or H_2 tanks in FCEV). Further investigation will follow to avoid this risk of contact.

Figure 24: The supporting legs position of the swap body during driving conditions.

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5 Modelling and Simulation

AIT was dealing with the development of a vehicle simulation for both EMPOWER demonstrators including all vehicle components that are relevant for calculation and analysis of the energy consumption. For parameterising the demonstrators and their components in the simulation model, the parameters and data identified by data sheets and measurements of the vehicle and vehicle components will be used. All developed components and models will be calibrated and validated to achieve an accurate representation of the energy consumption in a real-world driving cycle.

A simulation library named "EMPOWER" was developed in the multi-physical simulation language Modelica using Dymola as simulation software. All models were implemented using algebraic and ordinary differential equations. The "EMPOWER" library has an intuitive structure where all components and models are described as ready-to-use components. The main packages of the developed "EMPOWER" library are "Examples", "Chassis", "ChargingStation_E_Loads", "Strategies", "Axles", "Cabin", "HVAC", etc. as shown in Figure 25.

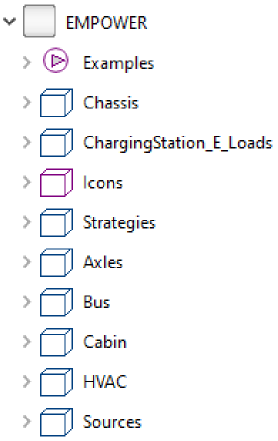

Figure 25: Developed EMPOWER Modelica library.

5.1 Simulation tools used for demonstrator modelling

For modelling and simulating the EMPOWER BEV and FCEV demonstrators the software platform Dymola is used. Dymola is a simulation environment using the objects described in Modelica syntax. It allows the software engineer to create models of any kind of objects that can be described by algebraic and ordinary differential equations [6]. With Dymola simulations of the behaviour and interaction between systems of different engineering fields, such as mechanical, electric, thermodynamic, hydraulic, pneumatic and control systems are possible. The modelling language Modelica itself is open which means that users are free to create their own model libraries or modify standard libraries. To better match the users individual modelling and simulation needs AIT developed the "SmartPowerTrains" [7], the "SmartCooling" [8] and "ElectricEnergyStorages" [9] [10] simulation libraries which have been used for simulating the powertrain, the electric machine, the Heating, Ventilation and Air Conditioning (HVAC) system, the traction battery and fuel cell system of the EMPOWER demonstrators (see Figure 26).

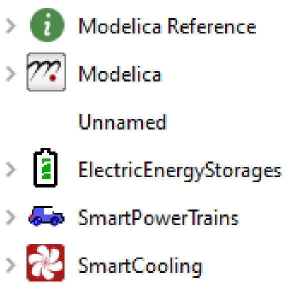

Figure 26: Used Modelica library.

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5.2 Development of the BEV and FCEV simulation models

In Figure 27 a screenshot of the developed Modelica vehicle models is depicted, which are realised in the simulation environment Dymola. The implementation represents the entire vehicle model of a FCEV and BEV demonstrator.

As shown in the picture, the simulation model consists of several, object oriented sub-models which are interconnected via connectors and interfaces in the bus system. Since the different truck concepts are available as study subject at IVECO, a large amount of measurement data is available in order to ensure validity of the vehicle models but also to provide real-life (real-world) data (like driving cycles etc.) during the simulation run. This data is available in the "simPars" block whereas different data sets can be loaded before simulation starts. Different driving cycles (e.g. long haul, regional delivery, measured real-world driving cycles) can be used in simulations to predict performance respectively energy consumption and losses of transmissions, electric motors, batteries, fuel cell, auxiliaries (like heating, ventilation and air conditioning systems, etc.).

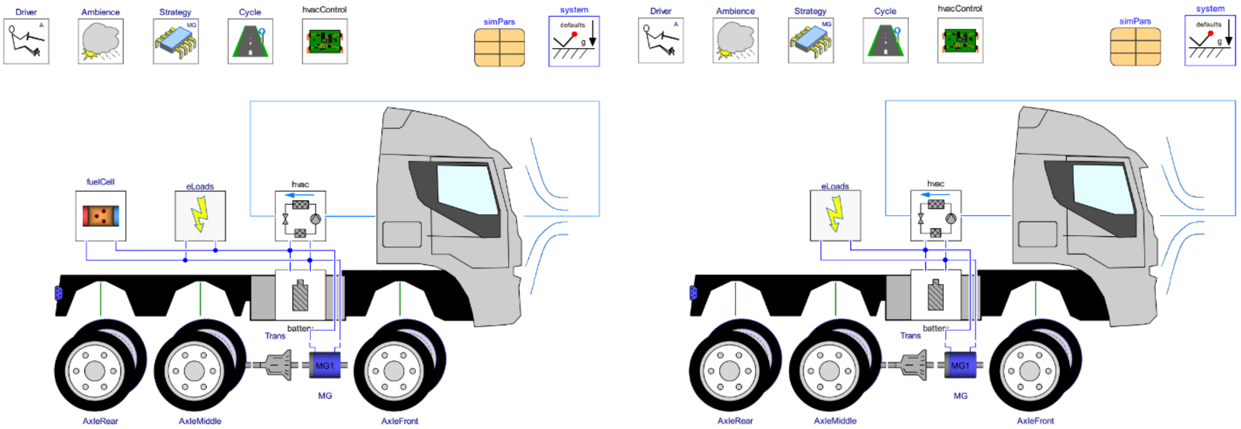

Figure 27: Entire vehicle model of FCEV (left) and BEV (right) demonstrator.

5.3 System architecture

The "Driver" block (cp. Figure 27) represents a virtual driver model which controls the position of the accelerator and the brake pedal. It contains the parameters for the drive controller defining the start values for the accelerator or the brake pedal. The 'Strategy' block allows the user to choose between different recuperation strategies (e.g. 'no recuperation' or 'braking with recuperation' or 'recuperation then braking'). The "Ambience" block provides different ambience sub-models enabling the parameterisation of different types of ambiences (e.g. constant air data or imported air data from measurements). The chassis model represents the chassis of the BEV and FCEV providing mechanical connectors and bus connectors. The input variables and parameters of the chassis model can be taken from the "simPars" block or added directly. The air density is taken from the "Ambience" block. The output variables of the chassis model are the vehicle position, the vehicle velocity, and the vehicle acceleration. The "Axle" models consist of a front, middle and a rear axles model whereas each axle model contains two or more tires, brakes, slip models, the adapters for the bus and mechanical connectors to the chassis block. The transmission ("Trans") block represents a transmission with a gear. The parameters inertia, gear ratio and gear efficiency are considered in the model. The "MG" block depicts the equation-based model of an electric traction machine. Considered parameters e.g. are the inertia of the rotational shaft, the nominal load speed and maximum overload. The "Battery" model is build up by a state of charge- (SOC) and temperature- dependent capacitor and a SOC- and temperature dependent internal resistor. The internal calculated SOC is available for further computations on the bus system. For parameterisation of the battery following values are required like the nominal admissible electric charge per cell, the minimum and maximum open-source voltage per cell, the minimum and maximum state of charge (SOC), the initial SOC, the serial cell resistance of the equivalent circuit, the overall charging/discharging energy efficiency, the number of serial and parallel connected cells. The "HVAC" block represents the main auxiliary consumer in an electric driven truck.

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The controller models are integrated into the "Strategy" block calculating the appropriate supply electrical values to e.g. traction machine, and the heating, ventilation and air conditioning systems. Depending on the applied driving cycle scenario and the ambience conditions (cold or hot temperatures) the accumulated energy demand of the main auxiliary will be available from measurement data and can be considered in the simulation.

5.4 Input data for the models and driving cycles

Before starting the vehicle simulations, the simulation models must be parametrised and calibrated corresponding to the FCEV and BEV main parameters and measurement data which will be aggregated by IVECO and the EMPOWER consortium. The FCEV and BEV main parameters were derived using specifications of the IVECO base vehicle, which were gained from IVECO internal documentations and data sheets. Additionally, measurement Controller Area Network (CAN) data describing the physical behaviour of the demonstrators and its systems will be recorded during EMPOWER project execution.

A parameter extraction script developed in the numerical computing environment MatLab will be applied to demonstrators CAN data (like vehicle speed, rotational speed and torque of the e-machine as well as voltage and current of the e-machine, the battery and all electrical components) to get relevant parameters for the EMPOWER vehicles and its sub-components. The "Cycle" block (cp. Figure 27) enables to load any driving cycle serving as basis for a simulation run. The "Cycle" block allows e.g. for range tests, to repeat a driving cycle periodically until a break-off criterion is reached. To reflect real-world demonstrators' operation, data can be gained from real-world driving test cycle in WP7 for measuring the energy flows and consumption.

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6 Conclusion and next steps

To give the project consortium of EMPOWER a useful and valuable starting point, various information on both IVECO vehicle demonstrators (FCEV and BEV) were summarised and depicted in this deliverable (D1.1).

An insight into the internal conceptualisation, specification, and initial design of all relevant vehicle systems shall deliver a profound initial basis for the implementation and execution of the EMPOWER project. Additionally, the shown collected information can act as benchmark, but also as aid to calibrate and validate the developed simulation models of the demonstrators, which will be enhanced and used for the initial development of digital twin.

The presented approaches for development of single systems and the overall demonstrator vehicles shall be helpful to show the needed targets of the improved vehicle functionality. The detailed procedures need to be developed and enhanced according to the actual characteristics of the newly implemented components, systems, and modules.

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