HORIZON EUROPE PROGRAMME
TOPIC HORIZON-CL5-2022-D5-01-08
Clean and competitive solutions for all transport modes
GA No. 101084046

Zero Emission flexible vehicle platform with modular powertrains serving the long-haul Freight Eco System

ZEFES - Deliverable report

D6.1 Simulation performance of FCEV demonstrators

Funded by
the European Union

Deliverable No.	ZEFES D6.1	
Related WP	WP6	
Deliverable Title	Simulation performance of FCEV demonstrators	
Deliverable Date	2024-06-27	
Deliverable Type	REPORT	
Dissemination level	Public (PU)	
Author(s)	Shantanu Pardhi (VUB) Mohamed El Baghdadi (VUB)	
Checked by	Reinhard Schmid (AVL)	2024-06-19
Reviewed by (if applicable)	Jordi Plana (IDI) Maarten Klijn and Anirudh Balaji (TNO)	2024-06-25 2024-06-24
Approved by	Omar Hegazy (VUB) – Project coordinator	2024-06-27
Status	Final	2024-06-28

Publishable summary

Work package 6 (WP6) focuses on the development, preparation and commissioning of modular heavy-duty hydrogen fuel cell electric vehicle (HD FCEV) demonstrators with state-of-the-art efficiency performance and 500 km minimum daily operational range with battery charge sustenance. As part of task 6.1 (design verification and final specifications using overall FCEV architectural digital twin model), the current report provides a virtual performance evaluation of the planned H_2 HD FCEV demonstrators when running on the intended real-world driving missions with the right payload and ambient conditions. This task provides the ZEFES partners with an initial detailed analysis of the expected mechanical, energetic and thermal cooling behaviour of the upcoming drivetrains before the actual demonstrators are built and employed on the intended use case driving routes. In parallel with the WP4 vehicle digital twin platform, these simulations will give the partners a head start on the operating challenges and possible fine-tuning of drivetrain design, energy management, thermal management and logistics strategies to optimally develop and run these vehicles on the planned ZEFES use case routes. Through precise virtual powertrain representation, the task further supports the capability of simulating the vehicle under different unusual operating conditions such as with very high payloads and extreme hot or cold ambient temperatures, giving insights into the design challenges for these upcoming HD H_2 propulsion technologies.

Given the importance of precise model parameterization to closely simulate the real-world performance of specific FCEV demonstrators on planned driving routes, this task made a stepwise verification of the simulation parameters and results among the WP6 partners, starting with a generic HD FCEV for understanding the required simulation capability, most significant drivetrain aspects and the expected general behaviour of its different subsystems. Initial simulations were made on VECTO long haul and regional delivery driving cycles considering a range of payloads and ambient temperatures, which also helped investigate the expected sensitivity of drivetrain subsystems to changing operating conditions. As WP6 demonstrators' specifications were further finalized, VECTO cycle simulations of the individual FCEVs were verified by the respective ZEFES partners to further assure the expected real-world drivetrain operation. The standard and easily interpretable nature of VECTO cycles could also support the virtual investigation of the demonstrator drivetrain behaviour under different operating conditions and help emulate any major design modifications for improved performance. Once standard simulations were satisfactory, the individual FCEV demonstrators were simulated on the planned ZEFES use case missions comprising real-world European routes with the right payload and ambient temperature. This provided a detailed analysis of the expected H_2 consumption, traction energy expenditure, auxiliary load and cooling requirements as well as the operational challenges and characteristics of individual subsystems specific to these planned FCEV demonstrators and real-world use case driving routes. The model parameterization and simulation capability shown in this deliverable will be further compared and updated with real-world FCEV parameters and driving data, once the use case demonstrations become operational.

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Abbreviations & Definitions

Abbreviation	Explanation
BEV	Battery electric vehicle
CO_2	Carbon dioxide
DC/DC	Direct current to direct current converter
ECMS	Equivalent consumption minimization strategy
EMS	Energy management strategy
EU	European Union
FCEV	Fuel cell electric vehicle
FCS	Fuel cell system
GCW	Gross combination weight
GHG	Greenhouse gas
GIS	Geographical information system
GVW	Gross vehicle weight
H_2	Hydrogen
HD	Heavy-duty
LH	Long haul
NMC	Nickel Manganese Cobalt
PMSM	Permanent magnet synchronous motor
SoC	State of charge
VECTO	Vehicle Energy Consumption calculation TOol

Item	Definition
eDrive	Electric drive including motor and inverter
EMS1	European modular system (configuration 1) Rigid truck + trailer with 25.25 m length and 64 T GCW

1 Introduction

In Europe, heavy-duty road freight currently contributes to about 25% of greenhouse gas (GHG) impact from the transportation sector [1]. In 2019, long haul heavy-duty trucks (HD 5-LH and 10-LH category) together led to about 78% of this CO_2 impact [2]. With the advent of upcoming EU norms aimed at drastically reducing the CO_2 emissions of the newly sold fleet, electrification of these HD commercial vehicle applications features a promising environmentally friendly solution. Fuel cell electric vehicles (FCEVs) offer advantages of battery electric vehicles (BEVs) such as the scope of propulsion energy recuperation during regenerative braking or downhill driving and highly efficient powertrain operation, while also featuring a lower impact on the maximum payload capacity along with a longer range, fast refuelling and less downtime [3]. Renewable hydrogen (H_2) powered FCEVs could thus accelerate the transition towards sustainable HDV electrification until the possible maturity of the BEV technology.

Unlike BEVs, FCEVs feature a multimodal drivetrain with various ways of providing or recuperating traction and auxiliary power at any instant using a combination of the fuel cell system (FCS) and battery pack. Specific combinations of FCS, battery and eDrive dimensions will better suit different HDV applications and will give the best operating outcomes using adapted energy management strategies (EMS). As a part of work package 6 (WP6), ZEFES partners are developing different FCEV drivetrain configurations for specific HDV applications including long haul tractor-trailers and rigid truck plus trailer combinations (EMS1 configuration), which will run on the various investigated long haul, hilly and regional delivery type real-world EU driving missions (WP7). Inside ZEFES WP6 (Modular and efficient long haulage FCHEVs), the main objective of Task 6.1 was 'Verification of final design specifications and virtual performance evaluation of the H_2 FCEV demonstrators' being developed by the individual partner vehicle manufacturers [4]. This deliverable is a report on the virtual performance simulations of the three WP6 FCEV demonstrators while running on the six different ZEFES use case driving missions which were defined by different European long haul routes, logistics operators and payloads [5]. These FCEV simulations will be further verified with real-world tests once the demonstrators are built and employed, which will help in closing the gap between virtual representations and real-world ZEFES use case demonstrations and could then be used for developing intelligent predictive drivetrain management strategies by the vehicle manufacturers and logistics management strategies for the freight operators.

FCEV specifications of some demonstrator vehicles [4], important updates on the WP2 vehicle simulation tool features [6] and precise real-world use case route data [5] are still being finalized and a revision on this report will be made once these upgrades become available.

2 Parametrization approach for FCEV simulations

2.1 Generic HD FCEV VECTO cycle simulation

First, detailed simulations of the above aspects were verified by the WP6 partners for a generic FCEV truck with 40 tonne (T) gross combined weight (GCW) when running on standard VECTO long haul and regional delivery cycles to understand the required simulation capability, most significant drivetrain aspects and the general expected behaviour. Given the ongoing essential updates on the WP2 simulation tool, a complementary MATLAB based FCEV model which also gave electrical subsystem blocks to the WP2 tool is currently used in this activity for assuring the expected powertrain, cooling systems and energy management behaviour, until the former is finalized. Drivetrain layout for this generic FCEV which is also being considered across all other ZEFES WP6 demonstrators is shown in Figure 1. VECTO cycle simulations of the generic FCEV drivetrain including driving route and vehicle speed; power flow across the FCS, battery, eDrive and auxiliary load; battery state of charge evolution (SoC) and H_2 consumption; component temperature evolutions and cooling system load are shown in Figure 2 and Figure 3. Variation of main simulation results including H_2 consumption, average eDrive traction energy requirement and auxiliary load was analysed when carrying a range of payloads under different ambient temperatures to investigate FCEV drivetrain sensitivity to changing operating conditions (some examples in Table 1). In general, GCW (payload variation) was found to have a strong influence on traction energy consumption, whereas ambient temperature had a dominating effect on the overall auxiliary load. Overall, impact of payload variation is obviously higher on the H_2 consumption for the current FCEV truck use case as compared to ambient temperature. The latter is modelled to impact the natural convection and cooling system operation and not only affects the overall auxiliary load but also the traction energy expenditure due to changes in ambient air density (Table 1).

Table 1 VECTO cycle H_2 consumption, traction energy expenditure and auxiliary load for generic HD FCEV: Effect of payload (in tonnes) and ambient temperature in (°C).

VECTO cycles [7]	Vehicle condition	H_2 consumption (kg/100km)			Traction energy (kWh/km)			Avg. auxiliary load (kW)		
	GCW \°C	5	20	35	5	20	35	5	20	35
Long haul (100.2 km)	25 T	6.32	6.12	6.07	1.06	1.04	1.01	3.74	3.83	4.79
	32 T	7.3	7.1	7.02	1.18	1.16	1.13	3.84	3.97	5.05
	40 T	8.49	8.3	8.25	1.33	1.31	1.28	3.93	4.1	5.37
Regional delivery (100 km)	25 T	5.96	5.83	5.77	1.035	1.01	0.99	3.94	3.99	4.84
	32 T	7.12	6.95	6.9	1.185	1.16	1.14	4.08	4.17	5.05
	40 T	8.54	8.39	8.36	1.356	1.33	1.31	4.19	4.32	5.36

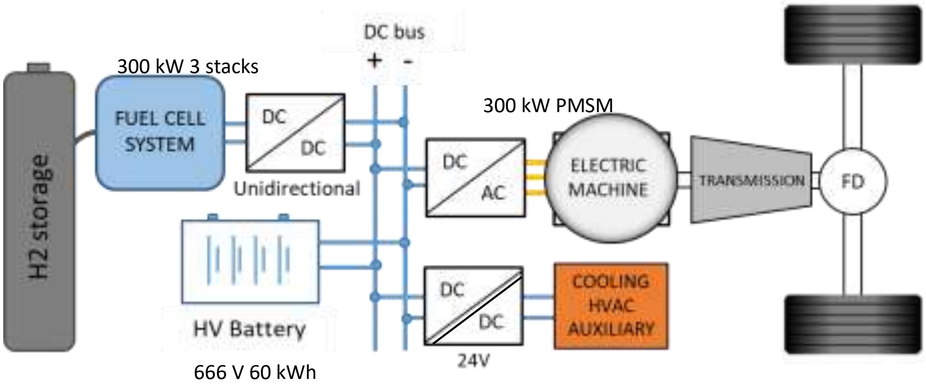

Figure 1 Generic HD FCEV drivetrain layout similar to the other ZEFES demonstrators.

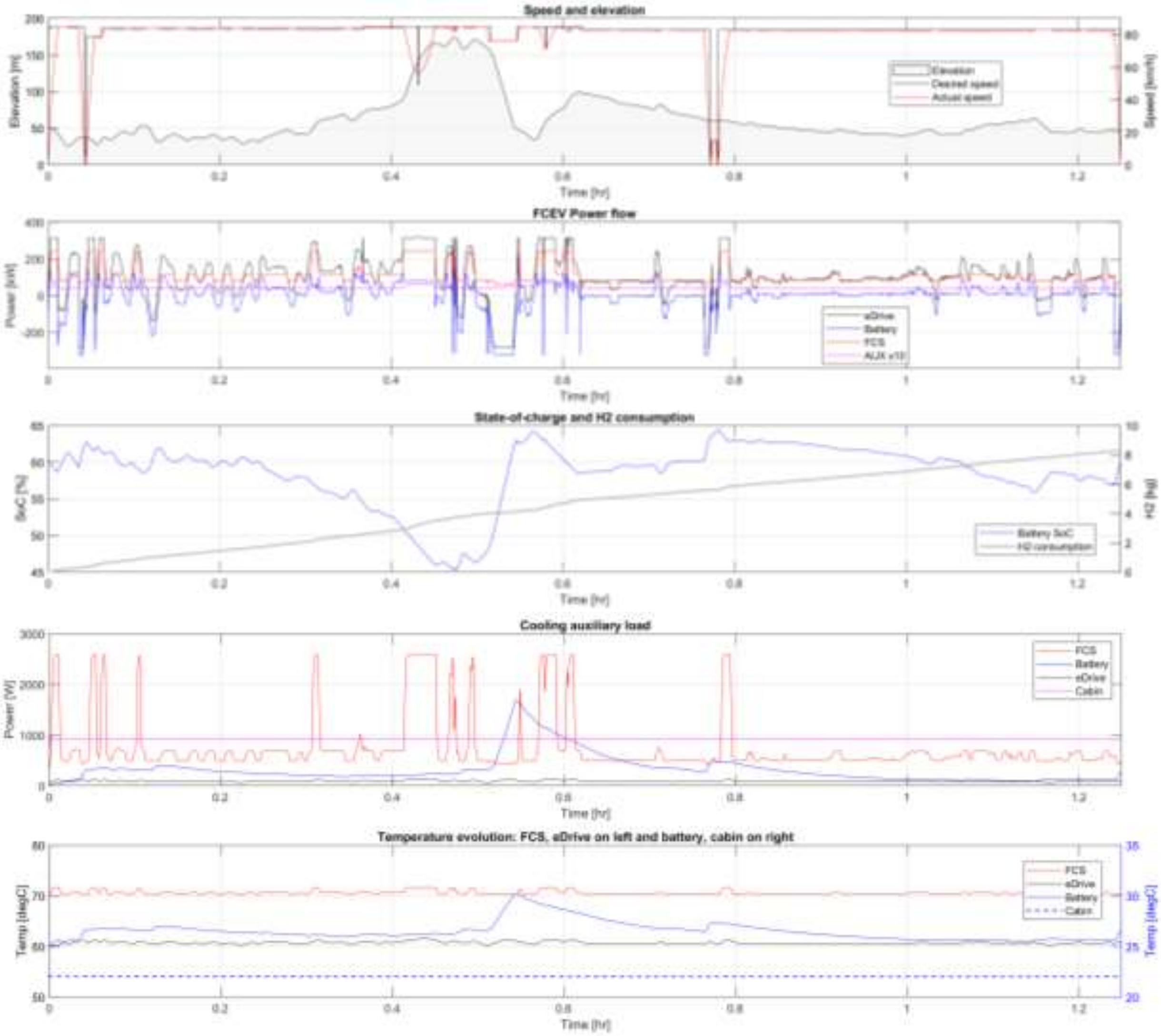

Figure 2 VECTO long haul cycle simulation considering a 40T GCW FCEV and 300 kW eDrive at 20 ^{o}C.

In Figure 2 and Figure 3, the driver can be seen to follow the distance-based VECTO cycle speed recommendations with controlled acceleration-deceleration (set to around 1 m/s^2) and stops for the recommended duration at the exact stop distance, verifying the capability of simulating real-world distance-based route data received from geographical information systems (GIS) when speed limits, road gradient and expected stop duration are available. Following partner recommendations, power change rate limit of the current 300 kW FCS has been set to 25 kW/s (red), whose effect can be seen on the supporting battery power flow during transients (blue). The optimized FCS power output governed by the EMS (red) remains linear across the VECTO driving mission and only rises or falls under very high change in power demand or regenerative braking (black). Strong relationship between road elevation and battery SoC evolution can be seen for both VECTO long haul and regional delivery cycles. Rise in both power demand for traction and negative power supply during braking can be seen to also increase the overall auxiliary load due to the higher component losses and corresponding cooling requirement. It is important to understand that battery temperature and corresponding cooling auxiliary load rises not only during accelerating/climbing but also during deceleration/descending as can be seen for the long haul cycle. FCS cooling load may be significant at certain times during the driving mission but the average efforts remain low for this electrified system, unlike for a mechanically coupled HD combustion engine cooling system.

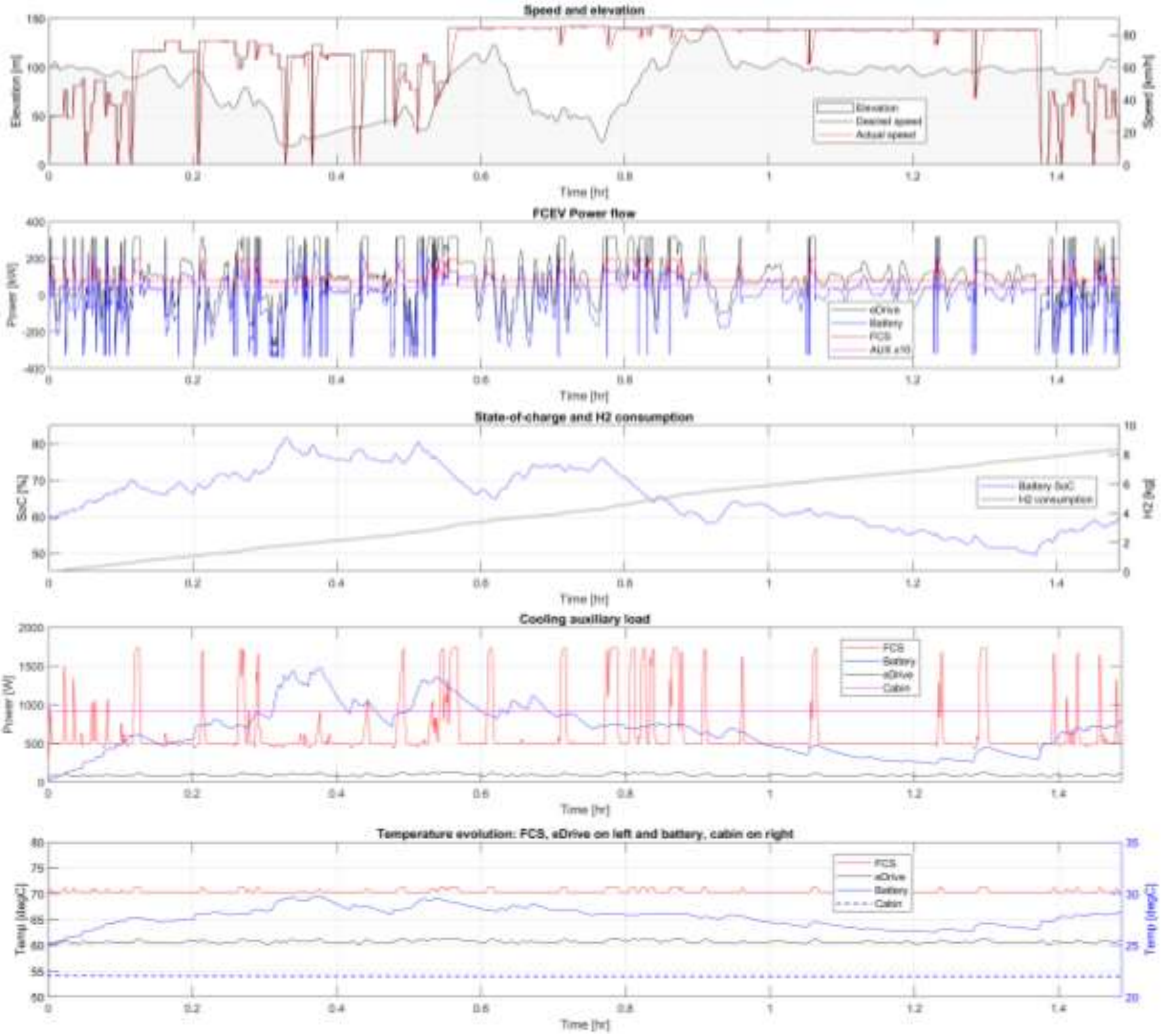

Figure 3 VECTO regional delivery cycle simulation considering a 40T GCW FCEV and 300 kW eDrive at 20 °C.

2.2 Energy management strategy

As mentioned earlier, FCEVs use a multimodal powertrain which features a certain degree of freedom on the usage of FCS and battery for providing or recuperating the total instantaneous traction and auxiliary power. By employing suitable energy management strategy (EMS), this power-split between FCS and battery is typically optimized to improve H_2 fuel efficiency while extending FCS and battery lifetime for minimizing total costs over the vehicle lifespan. The current task considered equivalent consumption minimization strategy (ECMS) based optimized energy management to control FCS power command (P_{fcs}) depending on the total traction - auxiliary power demand (P_{trct},P_{aux}) and the H_2 fuel equivalent battery power costate (λ_{bat}). The ECMS minimizes equivalent consumption (P_{fequi}) of H_2 fuel (P_{H2}) and battery internal power (P_{bat}) at every instant by employing the optimal FCS power command (P_{fcs}).

$$P_{fequi} = P_{H2}(\boldsymbol{P_{fcs}}) + \lambda_{bat} P_{elec}(P_{bat}) \tag{1}$$

$$P_{trct} + P_{aux} = P_{fcs} + P_{bat} \tag{2}$$

Here, P_{H2}, P_{bat}, P_{elec} represent H_2 fuel equivalent power, battery power demand and battery internal power expenditure when accounting for losses. P_{fcs} is subject to the fact that at least the total positive power demand (P_{trct}+P_{aux}) should be satisfied by the combination of FCS and battery power (P_{fcs}+P_{bat}). During braking or load transients, there might be more power for the battery to recuperate than its maximum capacity, in case of which, it is assumed that the extra power is dissipated by means such as a braking retarder or electrical resistor. Figure 4, Figure 5 and Figure 6 show the optimal FCS power commands for the three ZEFES FCEV demonstrator powertrains (Section 3) depending on total power demand and λ_{bat}. This ECMS optimal power command for the three demonstrator powertrains has been pre-optimized offline considering the complete range of power demands and λ_{bat} while aiming for minimization of combined FCS and battery losses. It can also be seen that battery power limit has a substantial impact on the feasible FCS optimal power command, especially during regenerative braking (negative power demands).

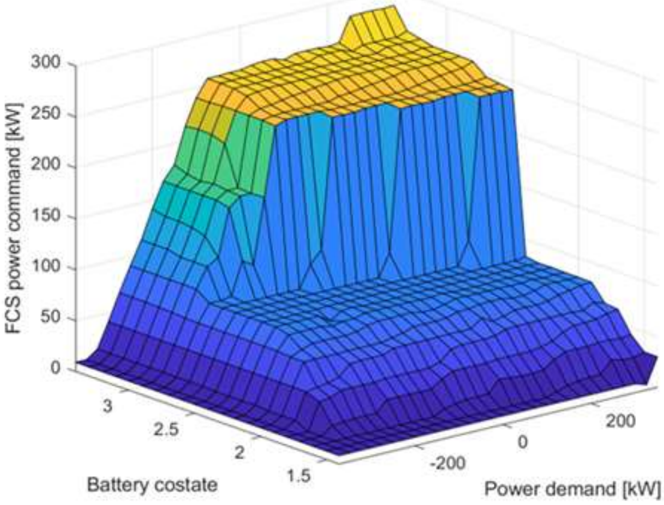

Figure 4 Optimized EMS power command for OEM1 FCEV use case considering a 300 kW FCS and 300 kW battery pack (60 kWh 5C) combination.

For implementation of this optimized ECMS power-split, a single λ_{bat} value is predictively tuned before each driving mission simulation to sustain end-cycle SoC. It is interesting to note that VECTO cycle simulations of the generic FCEV from the previous Section 2.1 showed similar fuel consumption results for both long haul and regional delivery driving missions even if significantly different λ_{bat} values were required to sustain end-cycle SoC (Section 2.1). This is because the long haul cycle is defined by consistent high power expenditure whereas regional delivery involves frequent deceleration-acceleration events with substantial amount of regenerative braking energy recuperation, increasing the importance of H_2 savings over battery power thereby using a low λ_{bat} value. From the EMS perspective, a FCS power change rate limit has also been implemented according to WP6 partners' recommendation to depict energy management operation considering mitigation of FCS ageing and degradation.

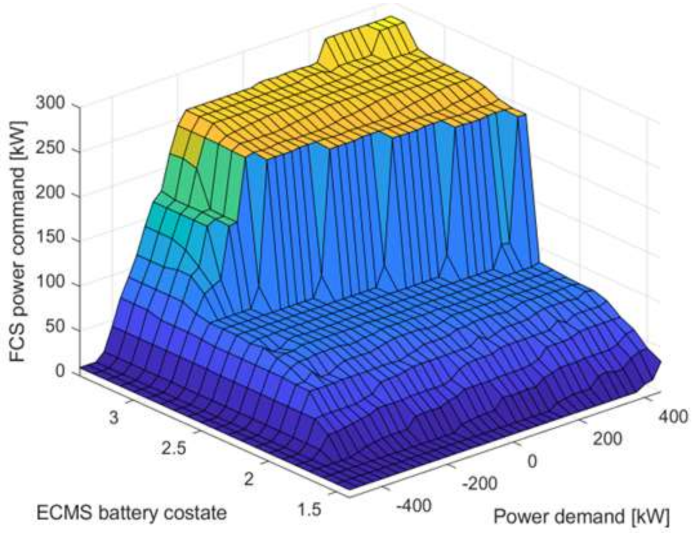

Figure 5 Optimized EMS power command for OEM2 FCEV use case considering a 300 kW FCS and 416 kW battery (416 kWh 1C) combination.

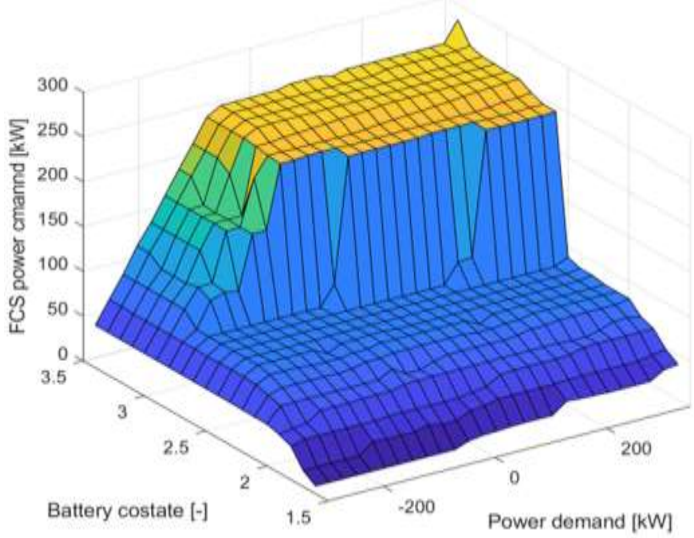

Figure 6 Optimized EMS power command for OEM3 FCEV use case considering a 300 kW FCS and 100 kW battery pack (100 kWh 1C) combination.

As demonstrator specifications were finalized, simulations of the individual FCEV configurations were verified by the involved ZEFES WP6 partners to further make sure that the models closely represented their expected real-world drivetrain behaviour. Standard VECTO cycle simulations were again considered, before simulating the specific real-world ZEFES use case missions with the right payload and ambient temperature, for which the root cause of a deviation would have otherwise been difficult to directly investigate. Finally, simulations of the real-world ZEFES driving missions were shared between the respective WP6 partners to build the precise virtual simulation capability for representing the upcoming FCEV demonstrators under the planned real-world operating conditions. Some of these real-world virtual simulations are discussed below in this report.

3 FCEV demonstrators and use case simulations

The vehicle, drivetrain and cooling system specifications assumed for the three ZEFES HD FCEV demonstrators from OEM1, OEM2 and OEM3 [4] will now be described in the below sections along with their planned European long haul driving missions [5]. System simulation of these FCEVs while running on their respective use case driving routes will then be discussed including real-world desired speed, actual vehicle speed and road elevation; power flow across the FCS - battery and power demand from the eDrive traction and auxiliary load, corresponding battery SoC evolution including end-cycle sustenance and H_2 consumption will also be shown. From the thermal and cooling system perspective, simulated temperature evolutions of the main components such as the FCS, battery, eDrive, cabin and the corresponding auxiliary load as the vehicle travels over the planned use case driving mission will also be investigated.

3.1 OEM1 6X2 rigid truck - EMS1 trailer

The OEM1 FCEV demonstrator is a 28T rigid truck towing a 36T Swedish semi-trailer in EMS1 configuration capable of a maximum total GCW of 64T. The planned driving mission from ZEFES use case OEM1-721 is a fully loaded long haul return trip of 474 kms between Gothenburg-SE and Hofors-SE carrying steel scrap and steel collies. The drivetrain specifications assumed for the OEM1 FCEV demonstrator are given in Table 2.

Table 2 Assumed OEM1 FCEV simulation parameters.

Main drivetrain specifications	
FCS (kW)	300
Battery pack (kWh, kW)	60, 300
Battery current limit (-)	5C
eDrive (kW)	300
Cooling system dimensions	
Max FCS cooling capacity (kW)	450
Max battery cooling capacity (kW)	20
Max eDrive cooling capacity (kW)	68
Vehicle specifications	
Aerodynamic drag [Cd*A] (m^2)	Rigid = 5 (EMS1 = 5.4)
Rolling resistance coefficient (-)	0.005
Number of wheels (-)	Rigid = 14 (EMS1 = 26)
Wheel radius (m)	0.49
Overall wheel rotational inertia (kgm^2)	Rigid = 217 (EMS1 = 403)
Differential ratio (-)	2.31
Differential torque loss (-)	VECTO
Differential inertia (kgm^2)	1.25
Transmission efficiency (%)	98
Transmission inertia (kgm2)	1.45
Transmission no. of gears (-)	3

Table 3 OEM1-721 Gothenburg to Hofors return route: Overall simulation results.

Main results for the OEM1-721 use case (Rigid truck + EMS1 64T)					
Route direction [5] D1.2 ST7.2.1	**H_2 consumption (kg) [Distance (km)]**	**H_2 (kg/100km)**	**End – SoC (%)**	**Traction energy (kWh/km)**	**Avg. AUX load (kW)**
Gothenburg to Hofors	53.83 [473.6]	11.37	59.6	1.714	4.14
Hofors to Gothenburg	49.43 [473.4]	10.44	60.8	1.615	4.07

Table 3 summarizes the H_2 consumption for the fully loaded return journey between Gothenburg and Hofors along with the average eDrive traction energy requirement and auxiliary load. The average traction energy and H_2 consumption are of course much higher for the 64T EMS1 truck compared to the previously discussed 40T generic tractor trailer FCEV (Section 2.1).

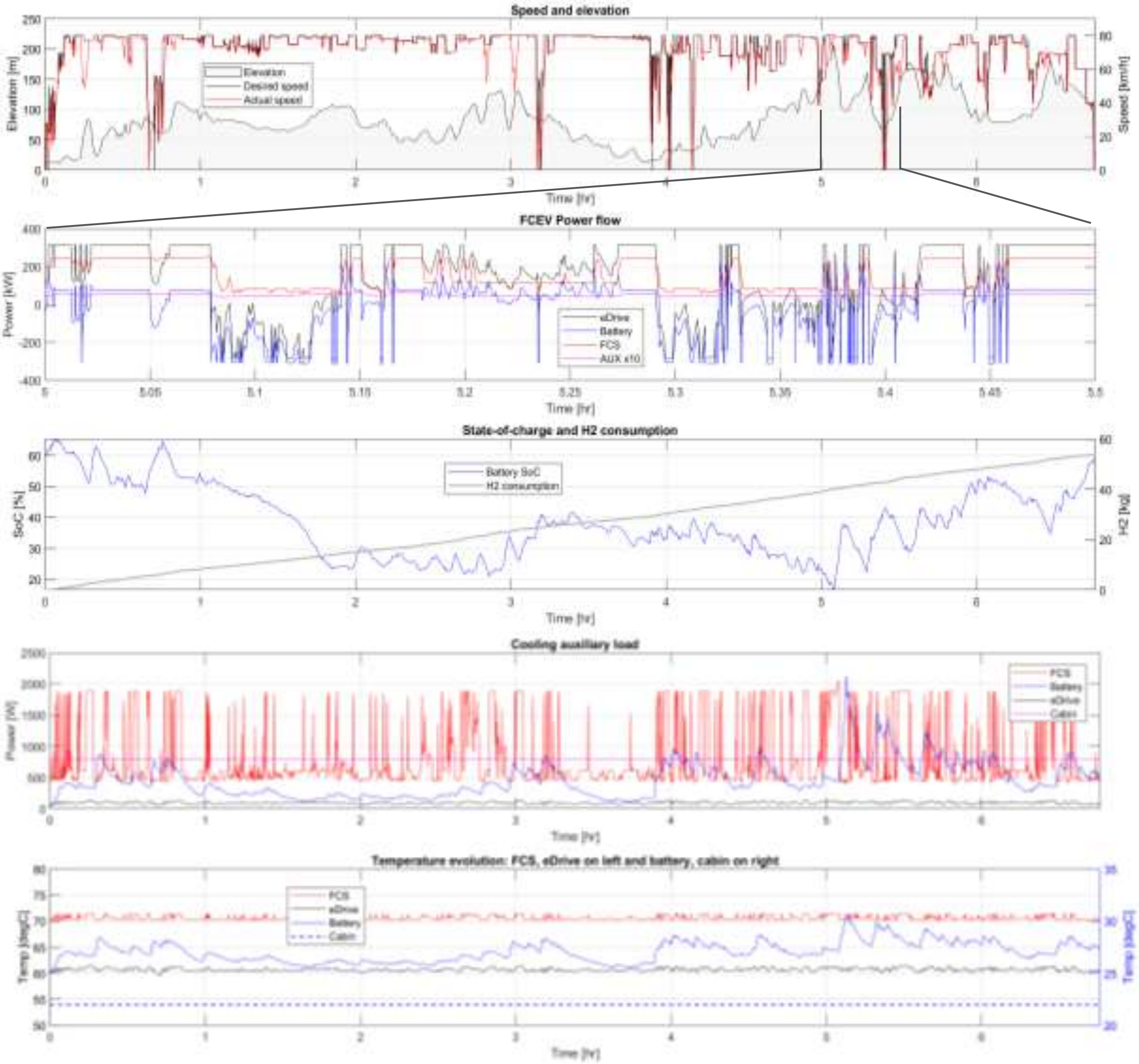

Figure 7 OEM1-721 EMS1 UC (64T GCW) on Gothenburg (12m) to Hofors (114m) 474 km journey simulated at 12°C.

Figure 7 and Figure 8 show vehicle speed profile, road elevation; power flow across FCS, battery pack, eDrive and auxiliary load; battery SoC evolution and cumulative H_2 consumption; FCS, battery, eDrive and cabin cooling efforts and temperature evolution along the long haul driving mission. The driver can be seen to follow the distance based desired route speed considering the assumed eDrive traction capabilities and overall vehicle GCW. The FCS power adapts to changing power demands whose transient requirements are supported by the assumed high power battery pack. For the current energy management strategy using a single battery ECMS costate across the complete mission with end cycle SoC sustaining, the small battery pack is seen to charge and discharge to its maximum capacities. Substantial amount of battery cooling efforts can be seen as the small high power battery supports the large transients in power flow throughout the accelerating, climbing, descending and braking situations.

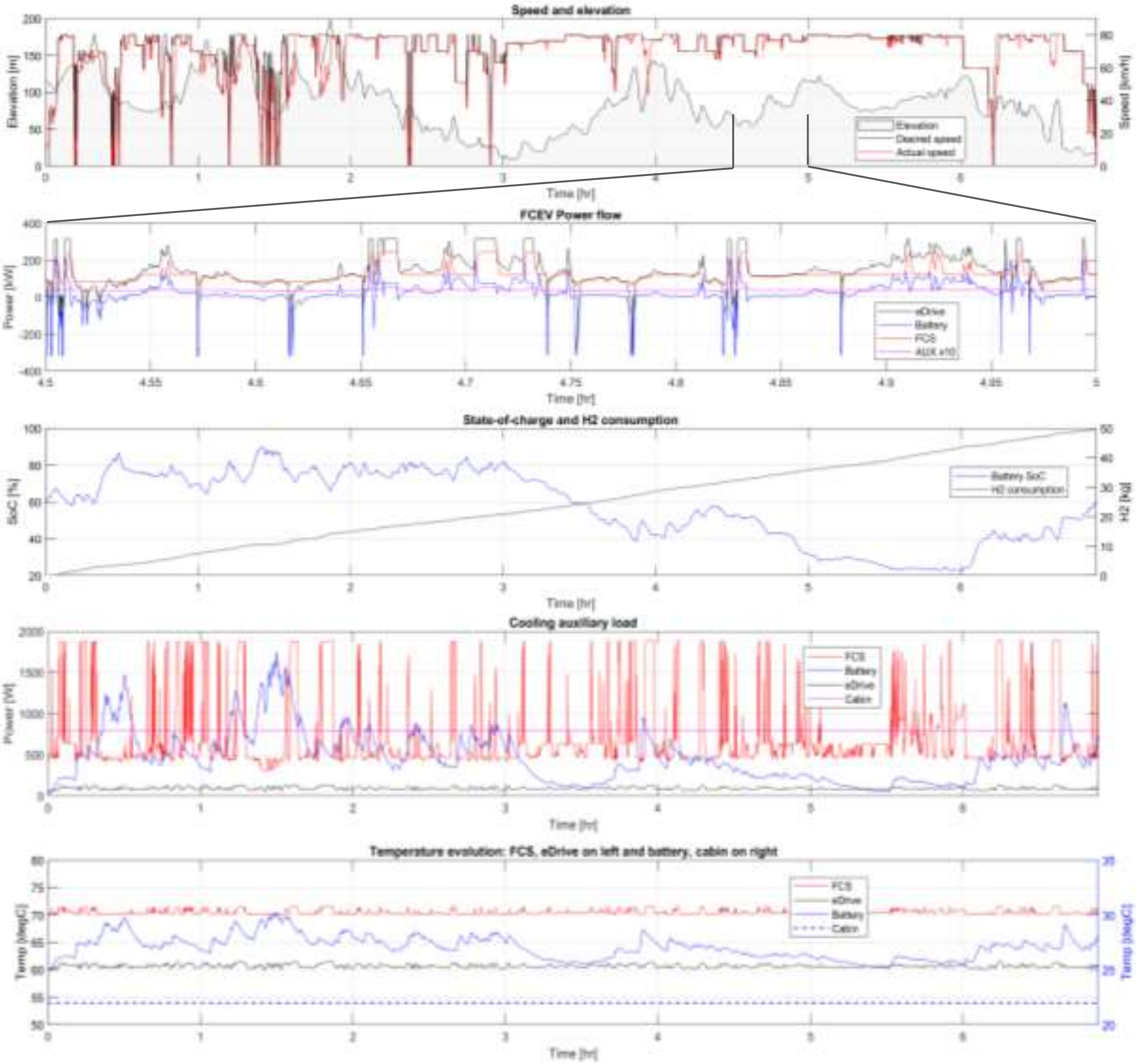

Figure 8 OEM1-721 EMS1 UC (64T GCW) on Hofors (114m) to Gothenburg (12m) 474 km journey simulated at 12°C.

3.2 OEM2 6X2 tractor - semi-trailer

The OEM2 FCEV use case is a 6X2*4 tractor towing a standard European trailer together capable of a maximum GCW of 44T. Considering a payload of 25T and tractor calculated mass of 10.7T, the loaded GCW of this use case for simulations was considered to be 43.2T. OEM2 verified drivetrain specifications used for the following use case missions' simulations are given in Table 4.

Table 4 OEM2 checked FCEV simulation parameters.

Main drivetrain parameters	
Fuel cell system (kW)	300
Battery pack (kWh)	416
Battery current limit (-)	1C
Battery voltage and series strands in parallel (-)	666V, 4
Cell capacity and type	150 Ah, NMC
eDrive (kW)	390 PMSM
H_2 tank capacity (kg)	56
Cooling system dimensions	
Max FCS cooling capacity (kW)	300
Max battery cooling capacity (kW)	7.5
Max eDrive cooling capacity (kW)	90
Vehicle parameters	
Aerodynamic drag [Cd*A] (m^2)	4.63 [8]
Rolling resistance coefficient (-)	0.005
Wheel radius (m)	0.49 [7]
Number of wheels (-)	14
Overall wheel rotational inertia (kgm^2)	217
Differential torque loss (-)	VECTO [7]
Differential inertia (kgm^2)	1.25
Transmission efficiency (%)	98
Transmission inertia (kgm^2)	1.45

The planned fully loaded ZEFES use case driving missions for the OEM2 demonstrator are:

- OEM2-732 - Return trip across the Brenner pass between Verona and Brixen, Italy.
- OEM2-733 - Long haul multi-halt journey between Huelva, Spain and Le Boulou, France while carrying cooled cargo.

Table 5 OEM2-732 main simulation results for Verona to Brixen return journey through Brenner pass.

H_2 fuel consumption for the OEM2-732 (Brenner pass)					
Route [5] D1.2 ST7.3.2	**H_2 consumption (kg) [Distance (km)]**	**H_2 (kg/100km)**	**End – SoC (%)**	**Traction energy (kWh/km)**	**Avg. AUX load (kW)**
Verona to Brixen	16.83 [192]	8.77	59.87	1.49	4.28
Brixen to Verona	8.93 [192]	4.65	60.19	0.83	3.9

Table 5 summarises the main simulation outcomes for the OEM2-732 use case which is a return driving mission between Verona and Brixen, ascending and descending through the Brenner pass. An almost two fold difference in traction energy requirement and H_2 consumption can be seen between the ascending and descending missions on this driving mission even though different speed recommendations were followed, highlighting the influence of road gradient on the energy consumption of HD FCEVs. Although much greater drivetrain efforts were required for ascending (Table 5), higher regenerative braking energy recuperation during downhill descending led to more battery cooling efforts even if the FCS cooling remained low (Figure 9 and Figure 10). This resulted in to only slightly lower average auxiliary load consumption during descending (Table 5).

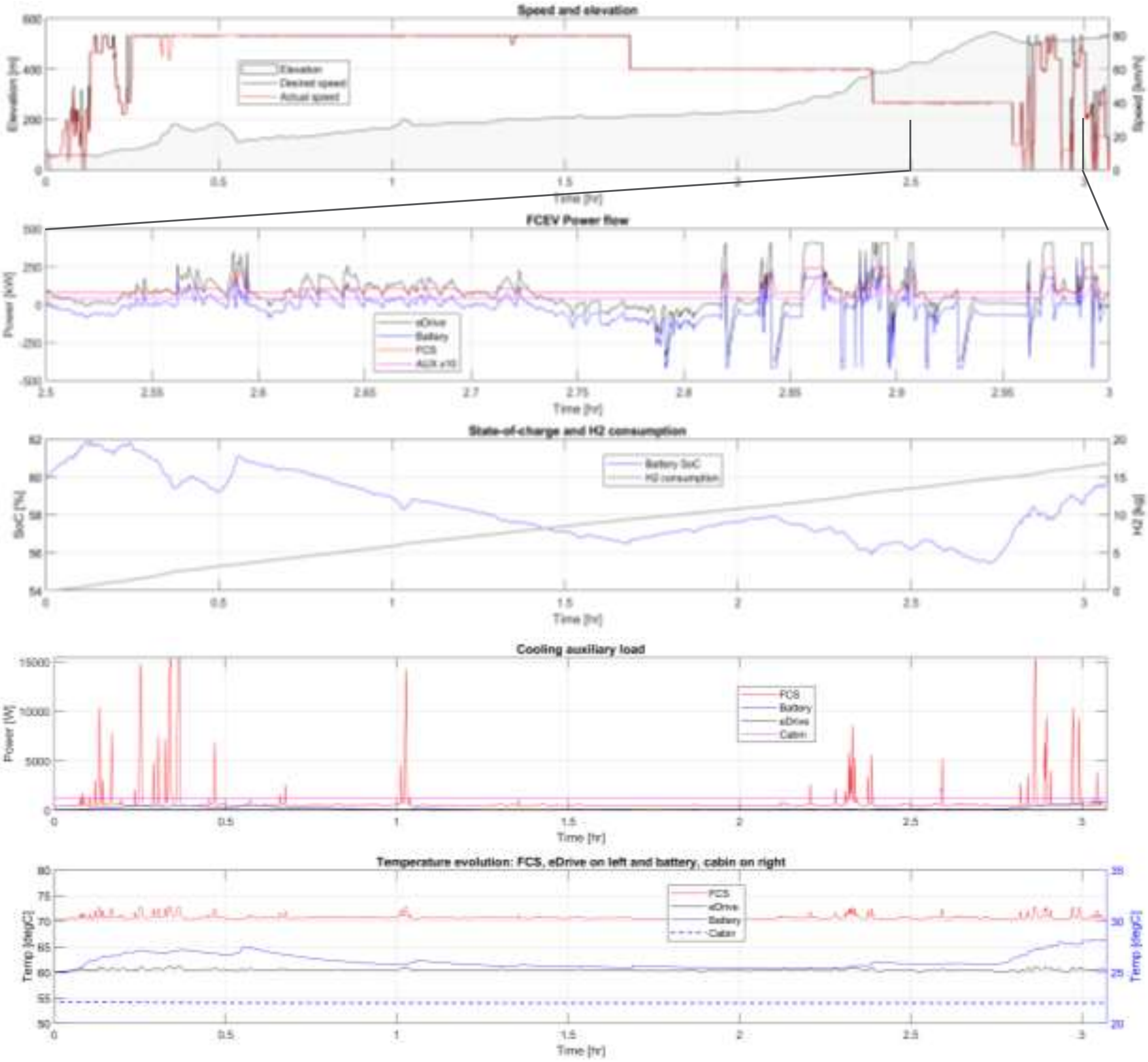

Figure 9 OEM2-732 semi-trailer (42.7T GCW) from Verona (59m) to Brixen (560 m) ascending Brenner pass (192 km) 28 °C.

Beginning from 60%, end-cycle SoC is sustained in both ascending and descending directions, which makes a fair energetic comparison possible. The FCS in ascending case generates much more power also leading to greater cooling efforts, as compared to descending case where both the FCS power output and corresponding cooling efforts are much lower. On the other side, temperature rise and cooling efforts for the battery pack are slightly higher in the descending case than during the ascending journey. An inverse relationship between the road elevation and battery SoC evolution like for the other FCEVs is also evident for the current demonstrator on OEM2-732 use case.

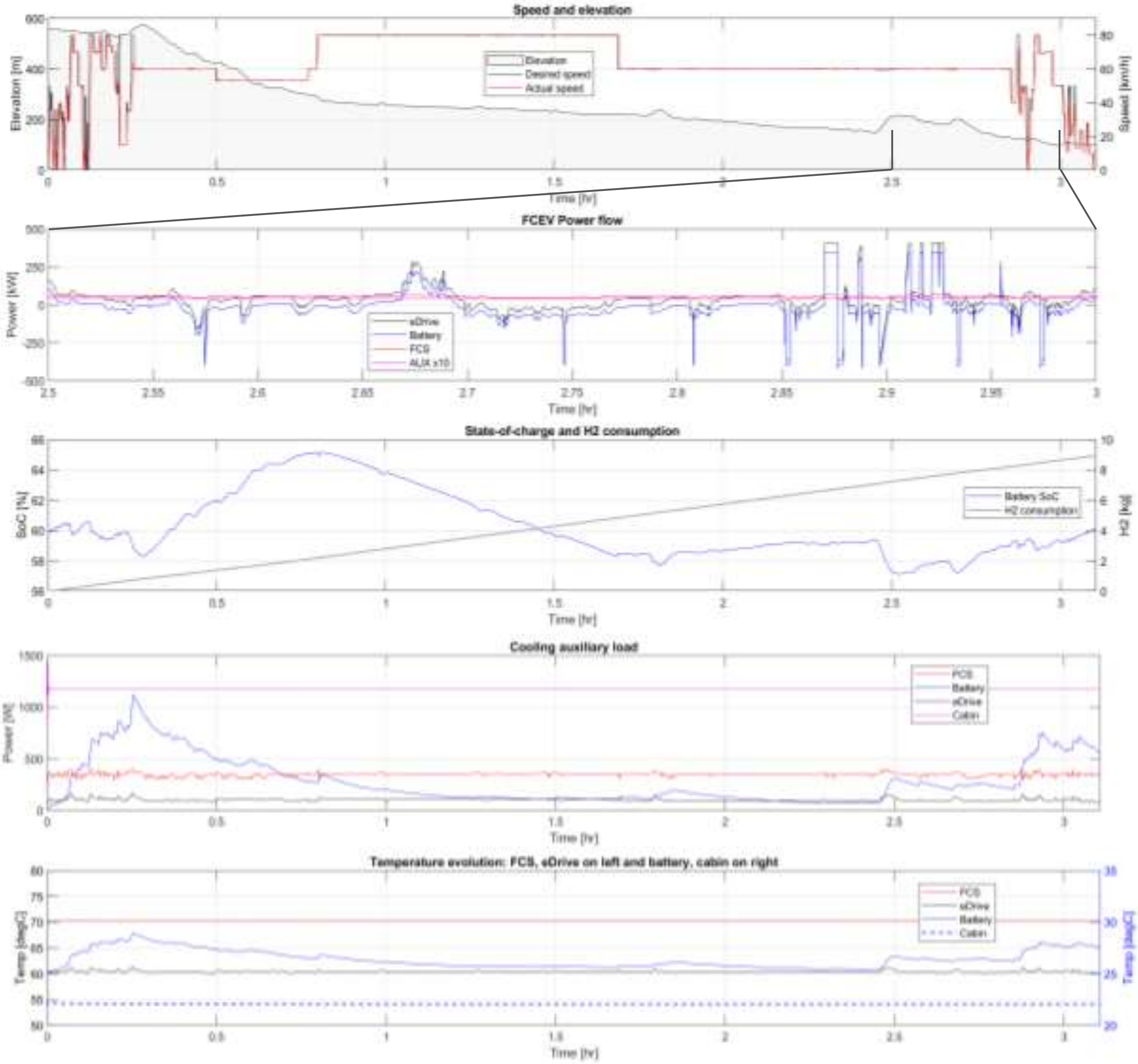

Figure 10 OEM2-732 semitrailer (42.7T GCW) from Brixen (560 m) to Verona (59 m) descending Brenner pass (192 km) 28 °C.

Table 6 summarises the main simulation outcomes of the OEM2-733 driving mission use case with fully loaded FCEV semi-trailer travelling from Huelva, Spain to Le Boulou, France. The overall journey of more than 1450 km was divided into 4 parts considering important halts and H_2 tank limited range.

Table 6 OEM2-733 overall simulation results from Huelva, Spain to Le Boulou, France multi-phase long haul driving mission.

OEM2-733 Huelva, Spain to Le Boulou, France long haul Route, D1.2 ST7.3.3 [5]					
Segments	**H_2 consumption (kg) [Distance (km)]**	**H_2 (kg/100km)**	**End – SoC (%)**	**Traction energy (kWh/km)**	**Avg. AUX load (kW)**
Huelva to Casabermeja (A)	26.17 [313.1]	8.36	59.55	1.36	4.2
Casabermeja to Primafrio (BC)	24.22 [345.1]	7.02	60.36	1.14	4.54
Primafrio to Valencia (D)	16.77 [257]	6.53	60.15	1.12	4.03
Valencia to Le Boulou (EF)	39.37 [536]	7.35	60.1	1.21	3.92

When the traction energy requirement for the driving use case sections was more demanding, such as in case of Huelva to Casabermeja (A) and Valencia to Le Boulou (EF) (Table 6), greater cooling efforts were needed for the FCS compared to the battery pack (Figure 11 and Figure 14) leading to overall lower average auxiliary load (Table 6). On the other hand, hilly driving segments such as Casabermeja to Primafrio (BC) and Primafrio to Valencia (D) led to greater utilization of the battery pack for supporting traction as well as braking power recuperation, which also increased required battery cooling efforts (Figure 12, Figure 13). This resulted in overall slightly higher average auxiliary load (Table 6). Similar to the other simulated FCEV demonstrators and driving mission use cases from this report, an inverse relationship between road elevation and battery SoC evolution was again seen for the current employed EMS where a single battery costate value was used across the complete driving mission to sustain end-cycle SoC.

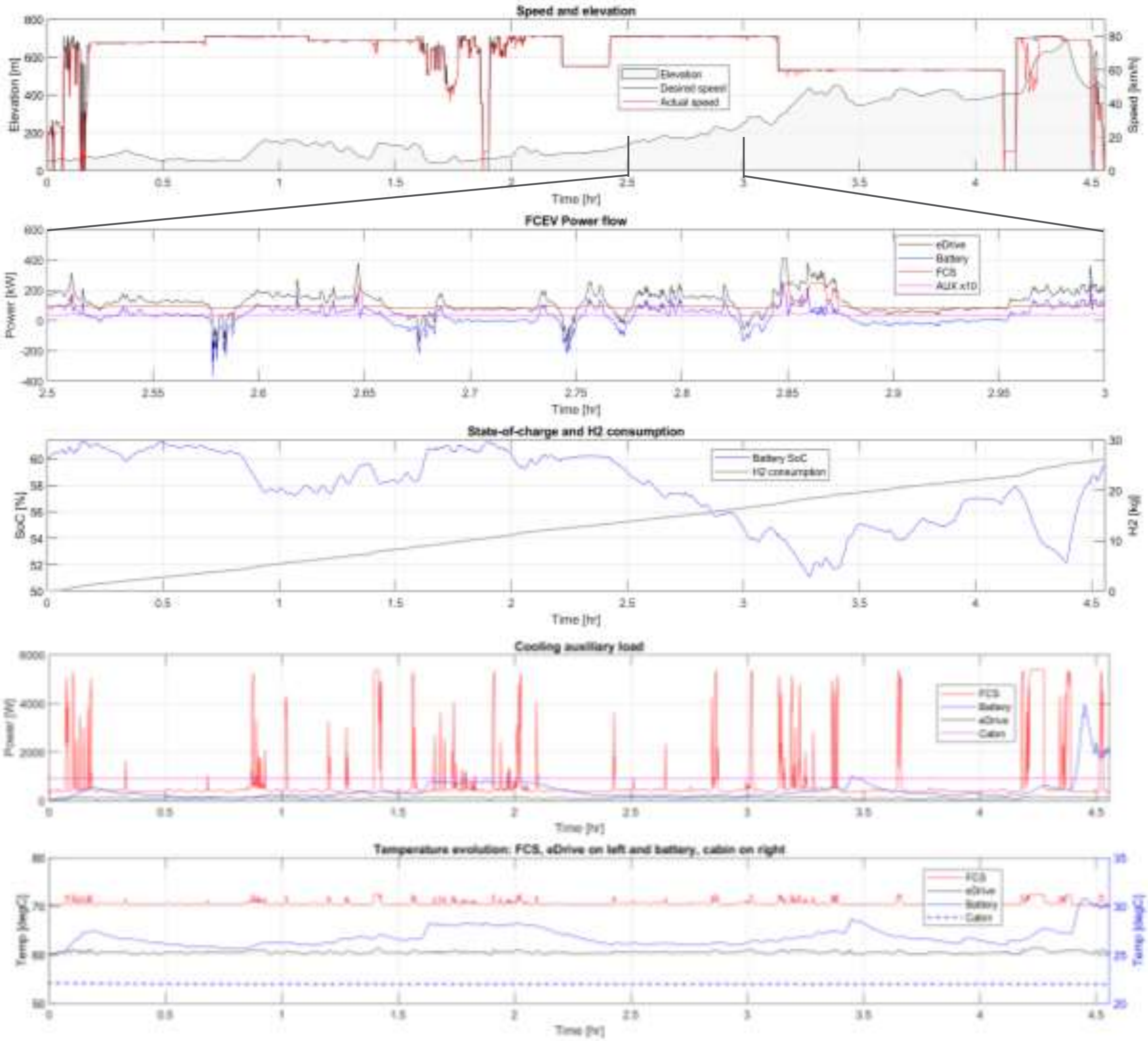

Figure 11 OEM2-733 FCEV semitrailer (42.7 T GCW) from Huelva (54 m) to Casabermeja (440 m) 313 km at 21 ^{o}C.

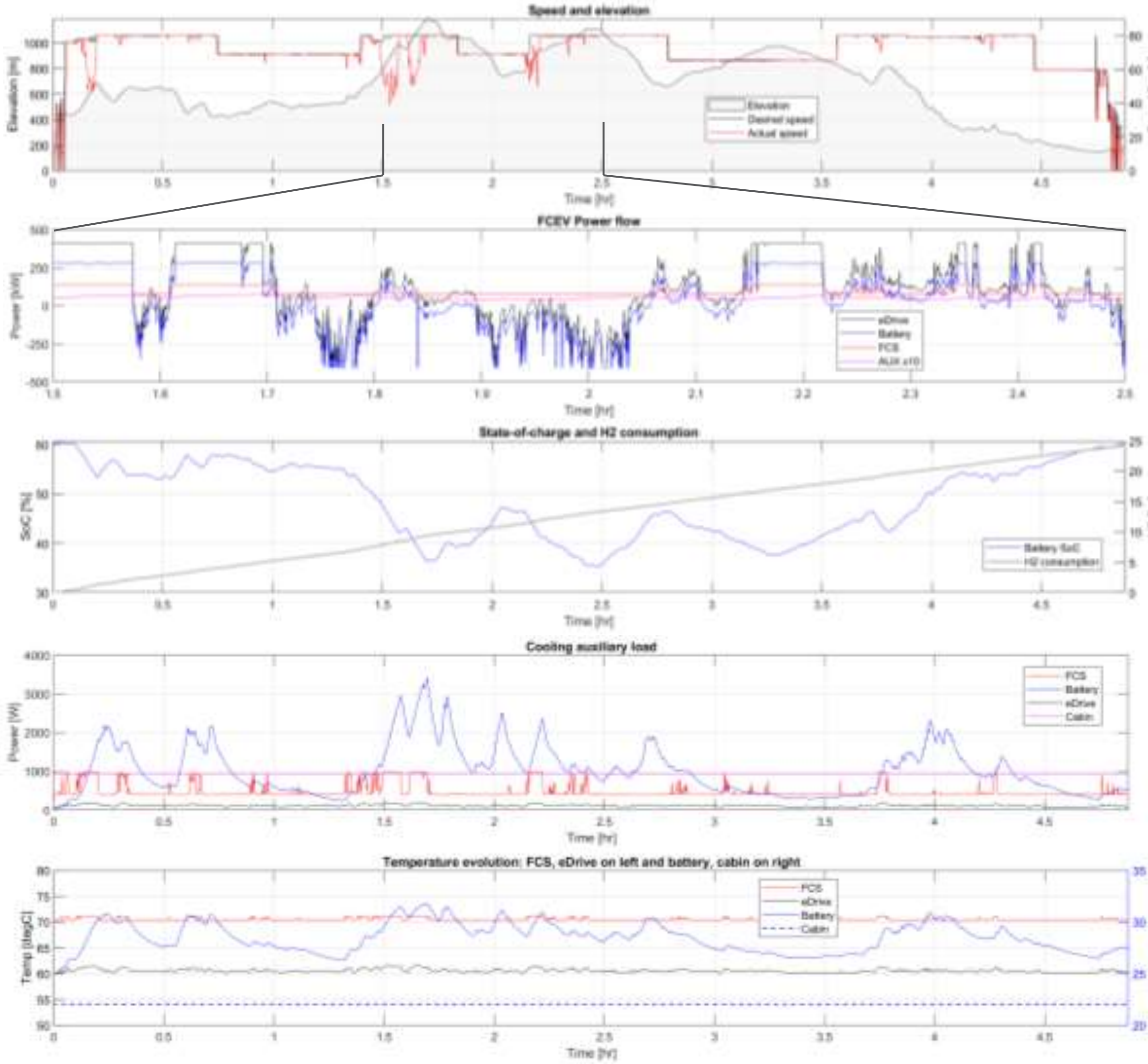

Figure 12 OEM2-733 fully loaded semitrailer (42.7 T GCW) from Casabermeja (440 m) to Primafrio (170 m) 345 km.

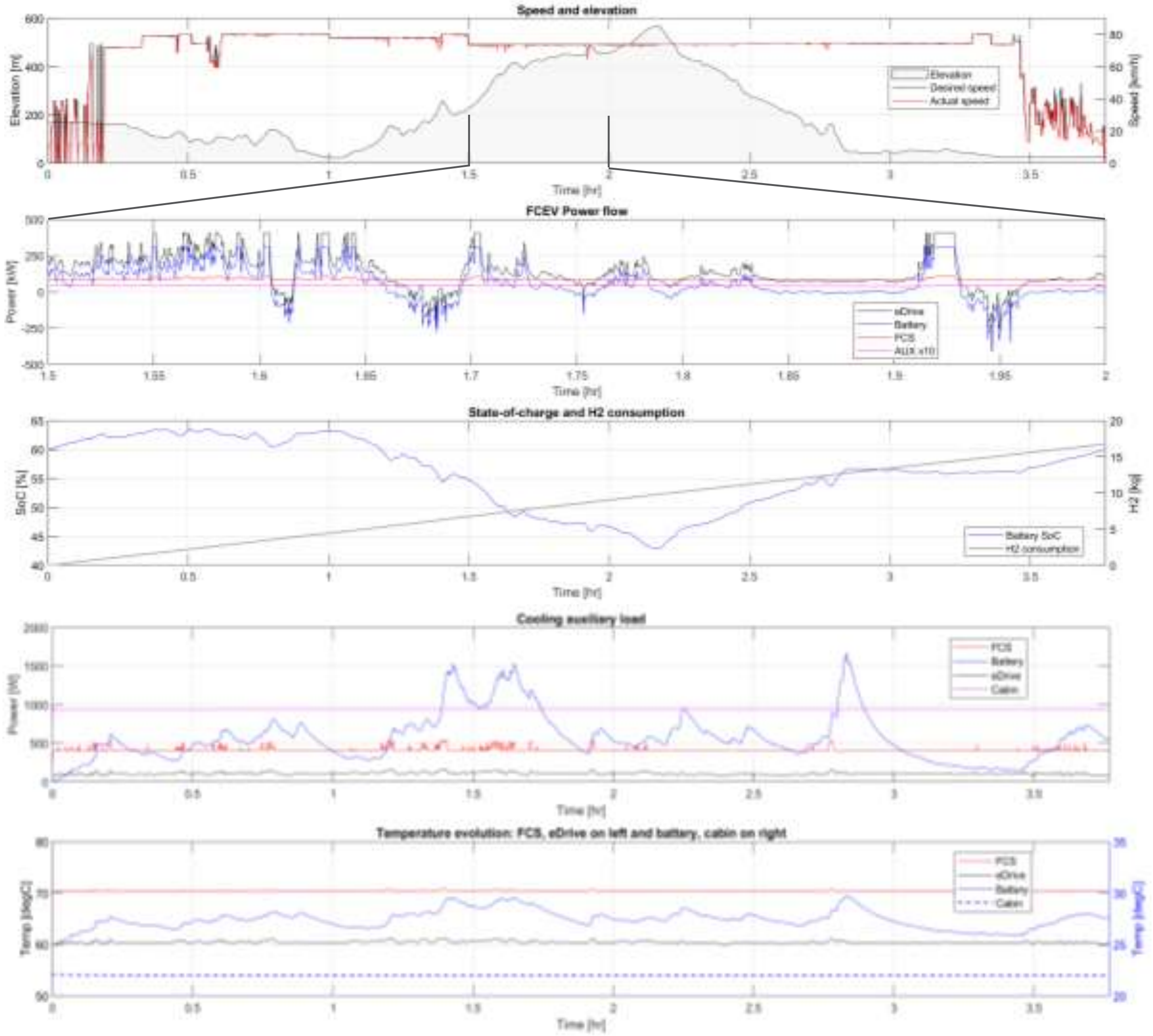

Figure 13 OEM2-733 fully loaded semitrailer (42.7 T GCW) from Primafrio (170 m) to Valencia (15m) 257 km.

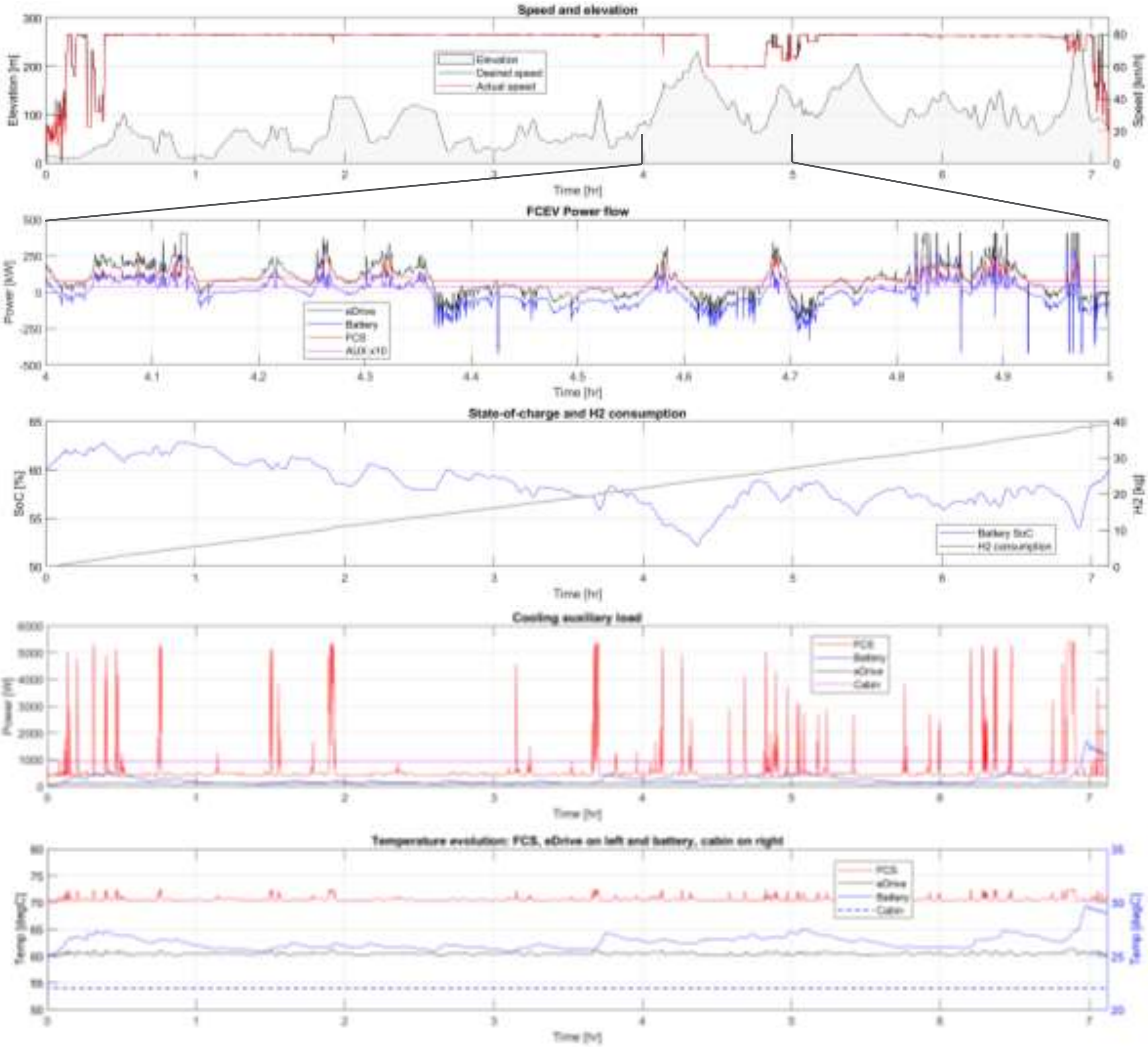

Figure 14 OEM2-733 fully loaded semitrailer (42.7 T GCW) from Valencia (15 m) to Le Boulou (55 m) distance 536 km.

3.3 OEM3 6X2 tractor - semi-trailer

The OEM3 FCEV demonstrator is a 6X2*4 tractor towing a standard 7.5T European trailer with a combined maximum GCW capacity of 44T. Considering a payload of 22T and tractor vehicle mass assumption of 13.42T, the simulated GCW of this use case was found to be 42.9T. The drivetrain simulation assumptions for the OEM3 FCEV demonstrator for this report are given in Table 7 below.

Table 7 Assumed OEM3 FCEV simulation parameters.

Main drivetrain parameters	
FCS (kW)	300
Battery pack (kWh, kW)	98, 98
Battery current limit (-)	1C
eDrive (kW)	300
H_2 tank capacity (kg)	58
Cooling system dimensions	
Max. FCS cooling capacity (kW)	450
Max. battery cooling capacity (kW)	7.5
Max. eDrive cooling capacity (kW)	68
Vehicle parameters	
Aerodynamic drag [Cd*A] (m2)	5.135
GVW with 25 tonne payload (kg)	42920
Rolling resistance coefficient (-)	0.005
Wheel radius (m)	0.49
Number of wheels (-)	14
Overall wheel rotational inertia (kgm^2)	217
Differential ratio (-)	2.31
Differential torque loss (-)	VECTO
Differential inertia (kgm^2)	1.25
Transmission efficiency (%)	98
Transmission inertia (kgm^2)	1.45
Transmission no. of gears (-)	3

Table 8 OEM3-761, OEM3-762 and OEM3-763 overall simulation results.

Route use case (D1.2 ST7.6) [5]	**H_2 consumption (kg) [Distance (km)]**	**H_2 (kg/100km)**	**End – SoC (%)**	**Traction energy (kWh/km)**	**Avg. AUX load (kW)**
OEM3-761 Istanbul to Kocaeli	9.16 [91]	10.07	59.6	1.28	4.97
OEM3-761 Kocaeli to Istanbul	9.35 [87.7]	10.66	59.8	1.3	4.96
OEM3-762 Kalsdorf > Maria-Lanzendorf	12.32 [190.6]	6.46	59.9	0.97	4.26
OEM3-762 Maria-Lanzendorf to Kalsdorf	15.57 [190]	8.19	60.2	1.17	4.42
OEM3-763 Milan to Santa Palomba	45.8 [604.2]	7.58	60.8	1.16	4.28
OEM3-763 Santa Palomba to Milan	47.65 [605.5]	7.87	60	1.17	4.52

Three different routes have been considered by the ZEFES driving mission use cases:

- OEM3-761 - Regional delivery between Istanbul (iDO port of Pendik) and Kocaeli (OEM3 plant)
- OEM3-762 - Hilly route between Kalsdorf and Maria-Lanzendorf, Austria
- OEM3-763 - Long haul between Milan and Santa Palomba, Italy

Table 8 summarizes the main simulation outcomes including H_2 fuel, average traction energy and auxiliary load consumption for the fully loaded FCEV demonstrator while running on these planned use case driving missions including the return journeys. Regional delivery mission (OEM3-761), showed the highest specific traction energy and H_2 consumption as well as auxiliary load, which can be related to both the demanding nature of the driving mission with frequent start-stops and high speeds and also the slightly higher ambient temperature. Downhill driving mission (OEM3-762) from Kalsdorf to Maria-Lanzendorf leads to overall lesser H_2 fuel and tractional energy consumption as compared to the slightly uphill return journey. Long haul mission (OEM3-763) with lesser number of start-stops, road elevation changes and slightly lower average vehicle speed led to the least overall specific energy consumption.

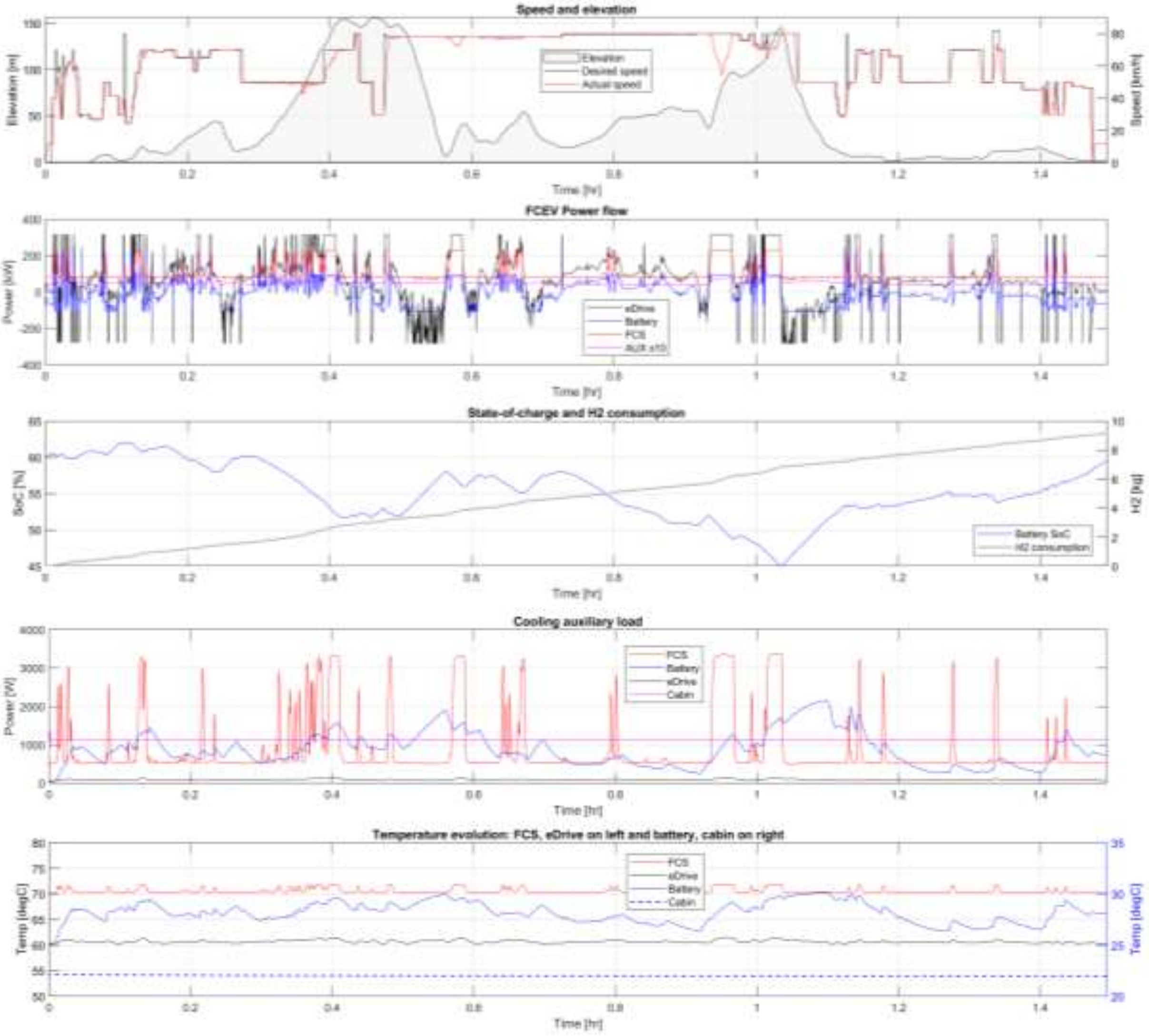

Figure 15 OEM3-761 fully loaded semitrailer (42.9 T GCW) Istanbul to Kocaeli 91 km at 28°C.

As seen for the other FCEV use cases discussed in this report, an inverse relationship is seen between road elevation and SoC evolution across the driving missions due to the choice of the predictive EMS with single ECMS costate for end-cycle SoC sustaining (Figure 15 to Figure 20).

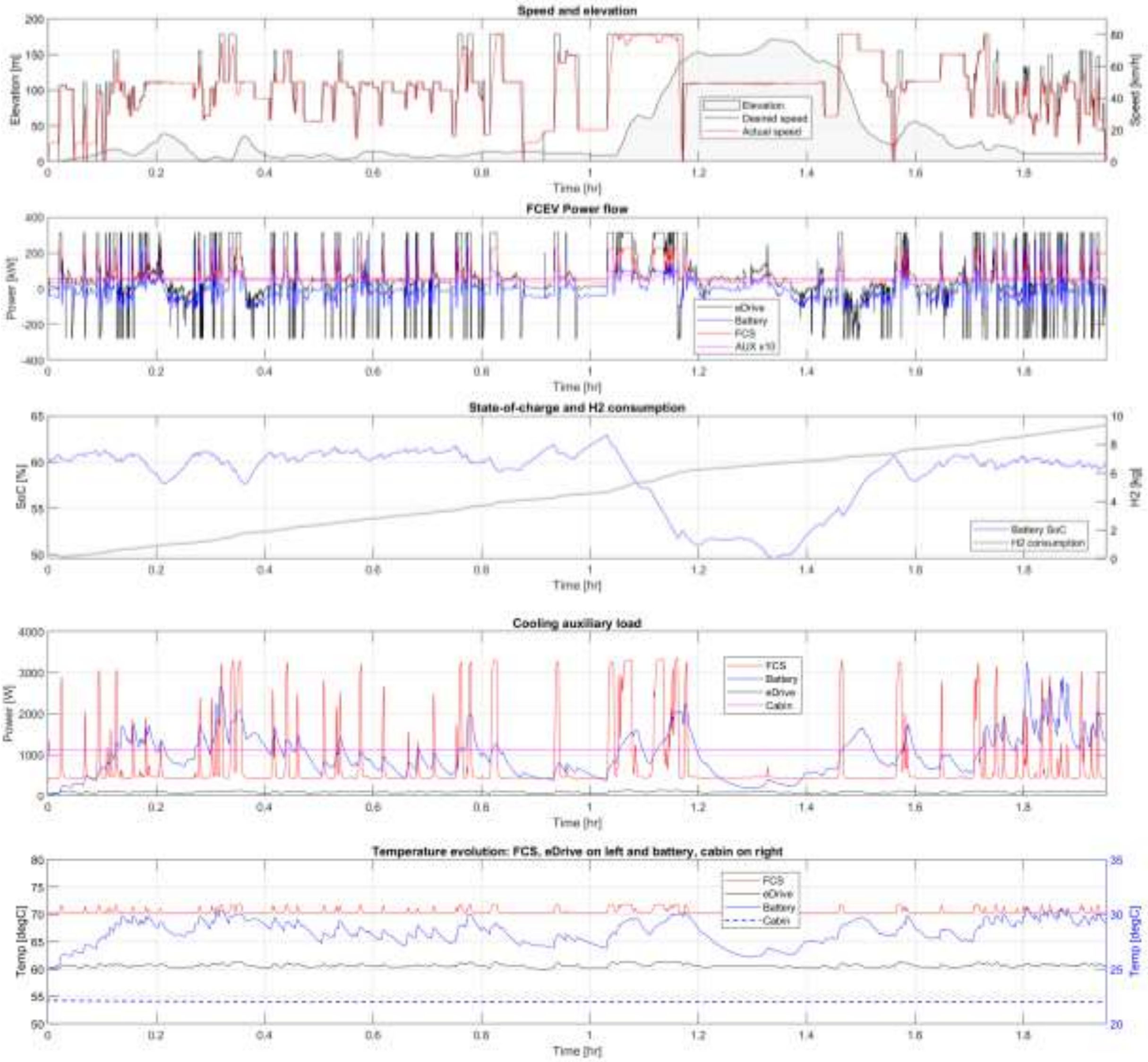

Figure 16 OEM3-761 fully loaded semitrailer (42.9 T GCW) from Kocaeli to Istanbul (87.6 km) at 28 ^{o}C.

Different route data was obtained from the real-world GIS source for the OEM3-761 return trip resulting in a different desired speed profile, road elevation and corresponding powertrain behaviour. It is still interesting to note that for the current regional delivery use case (OEM3-761), the overall energy consumption for the same start and end points remains almost the similar even when using a different driving routes (Table 8).

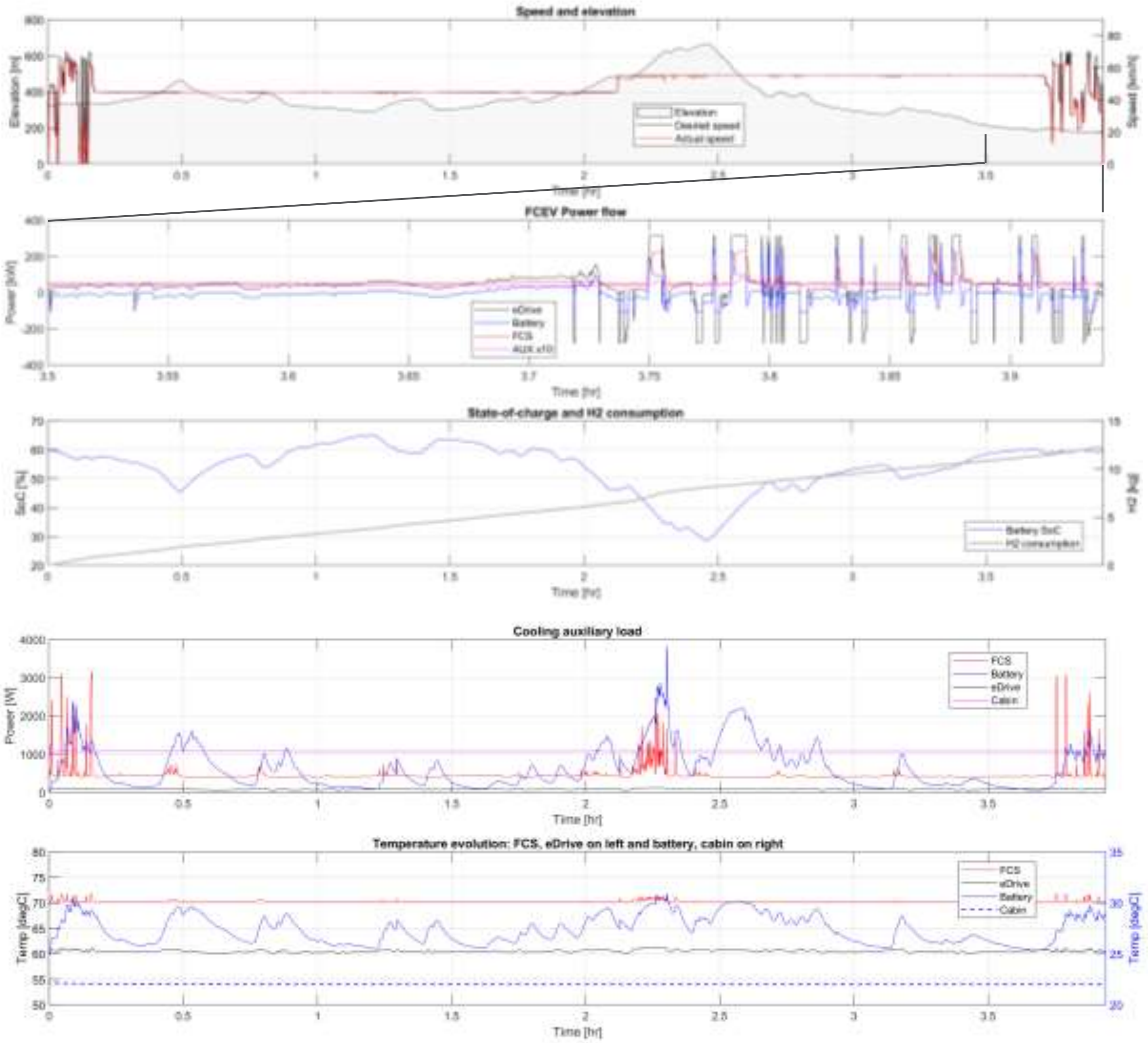

Figure 17 OEM3-762 fully loaded semitrailer (42.9 T GCW) Kalsdorf (324m) to Maria-Lanzendorf (171m) 26^{o}C (190.6 km).

Greater FCS utilization in high speed ascending sections of the OEM3-762 use case (Maria-Lanzendorf to Kalsdorf) leads to higher FCS cooling auxiliary load compared to the return descent.

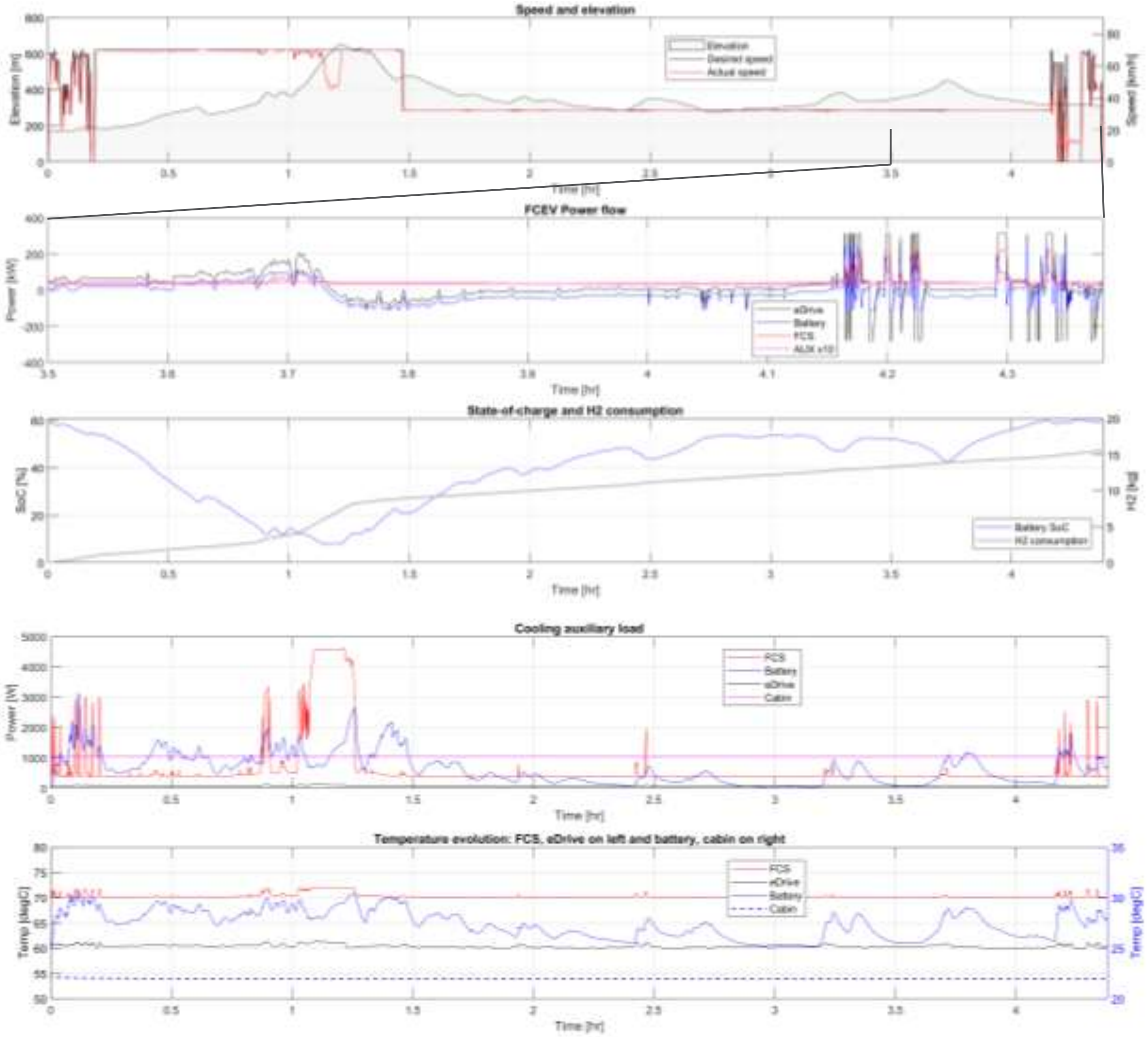

Figure 18 OEM3-762 fully loaded semitrailer (42.9 T GCW): Maria-Lanzendorf (171m) to Kalsdorf (324m) 26^{o}C (190.6 km).

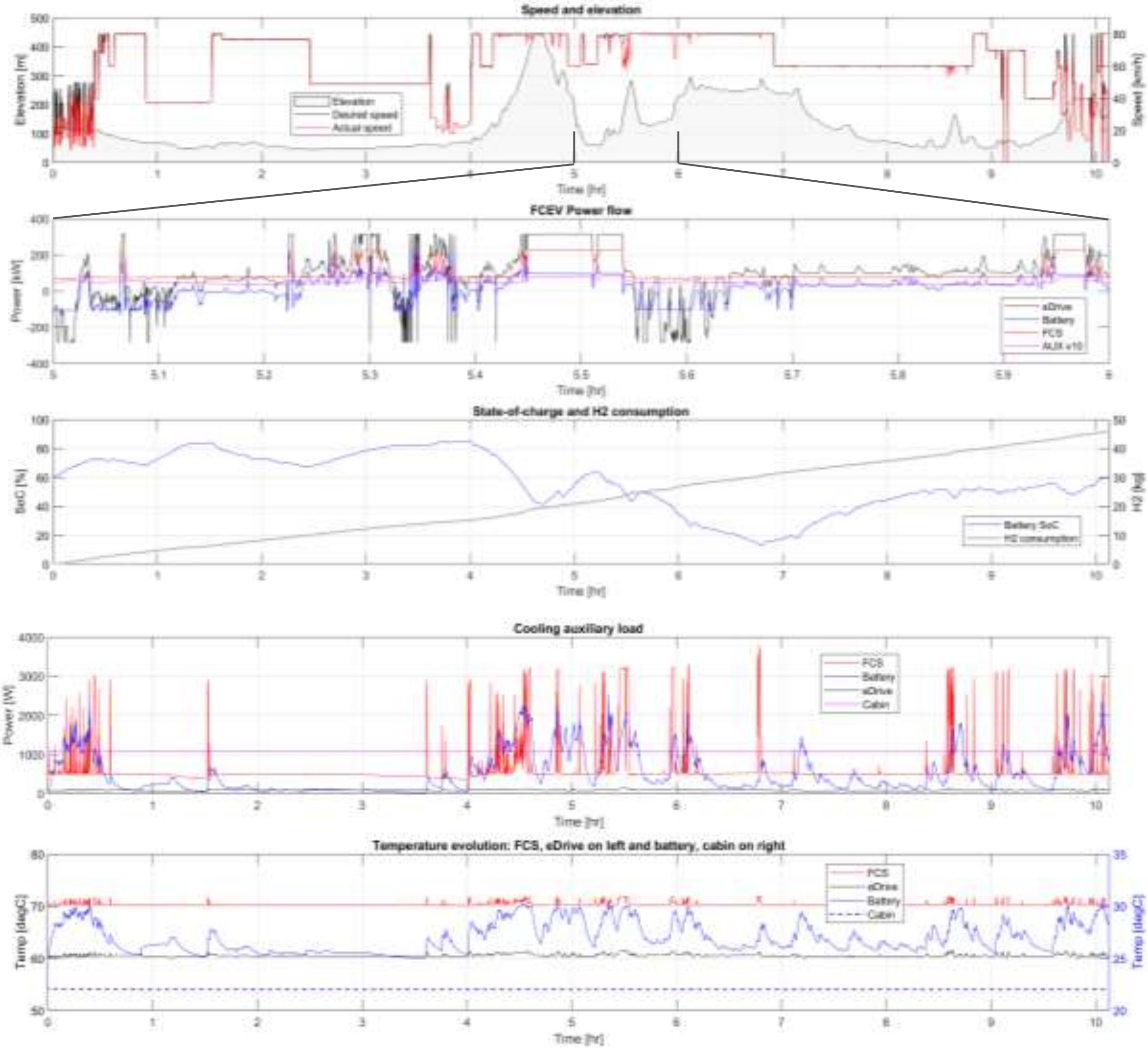

Figure 19 OEM3-763 fully loaded semitrailer (42.9 T GCW) Milan (120m) to Santa Palomba (160m) 27°C (605 km).

For the OEM3-763 long haul driving mission using a single EMS battery costate to assure SoC sustaining, the inverse relationship between road elevation and battery SoC evolution gets constrained by the EMS as the SoC approaches battery nonlinearity and its upper and lower limits.

While the battery supports transient power flow, a significant change in FCS steady power delivery can be seen when more power is required as the battery power capacity is limited (1C current limit).

Greater FCS and battery cooling efforts can be seen as the vehicle travels through the demanding hilly part of the route.

Slightly different to-and-fro vehicle speed profiles can be seen for the OEM3-763 long haul driving mission from the collected GIS route data due to changes in traffic speed (Figure 19 and Figure 20), which still lead to similar H_2 fuel and traction energy consumption results (Table 8).

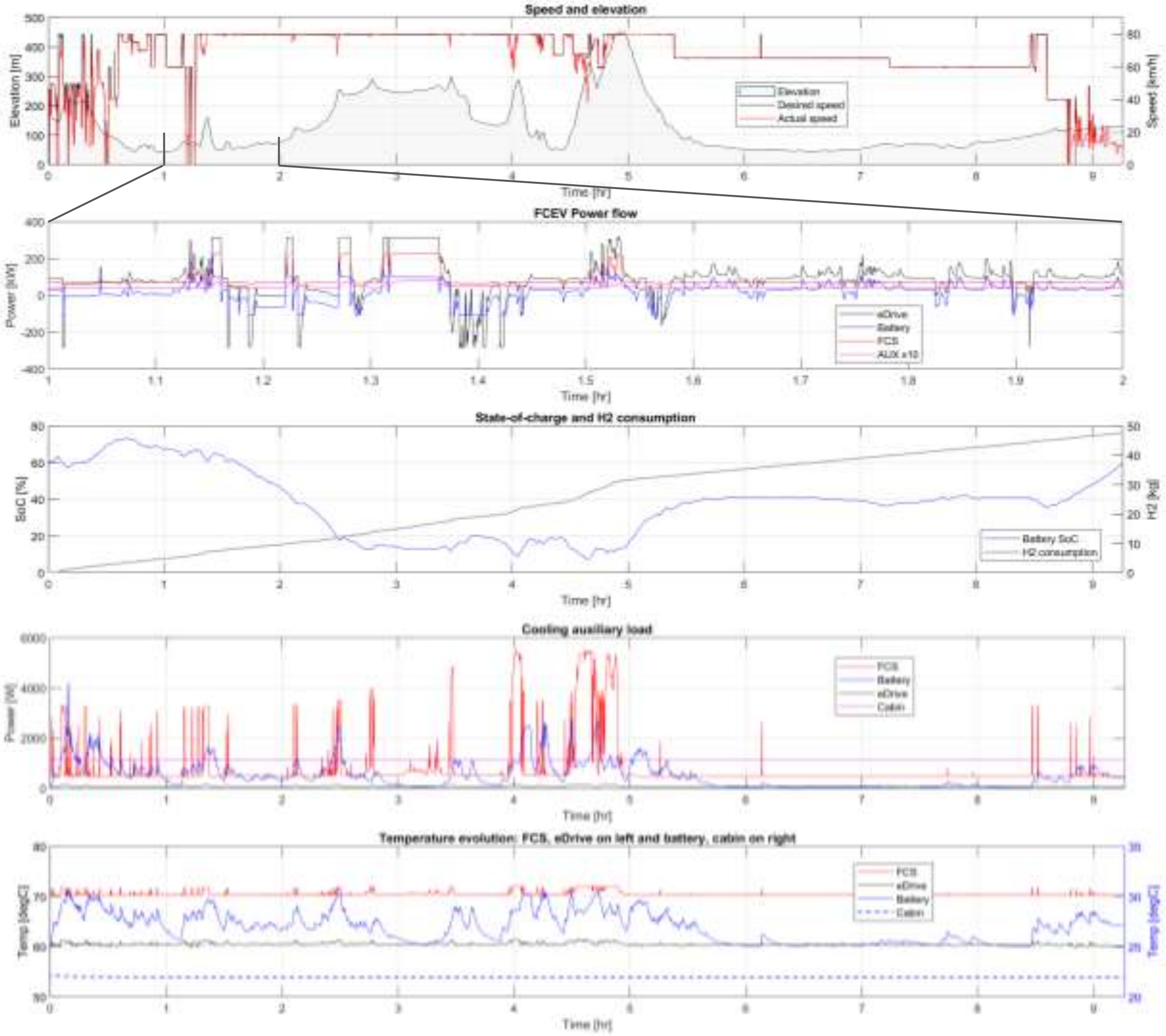

Figure 20 OEM3-763 fully loaded semitrailer (42.9 T GCW) from Santa Palomba (160m) to Milan (120) 27 °C (605 km).

4 Conclusion and Recommendation

As part of task 6.1, this report verified the expected drivetrain specifications and discussed the simulated performance of the three upcoming WP6 HD FCEV demonstrators while running on the planned WP7 use case driving missions with the right payload and ambient temperature. By building the capability to closely simulate the planned FCEV demonstrators, this task provided a detailed analysis of their expected H_2 consumption, traction energy expenditure, auxiliary load and cooling requirements on the ZEFES real-world driving missions. This simulation ability can now also be used to assess operational challenges and characteristics of individual HD FCEV drivetrain subsystems under extreme real-world operating conditions. When simulating the long distance driving missions such as OEM1-721 (474 km), OEM3-763 (605 km) and OEM2-733 (up to 536km) long haul, all three ZEFES use cases showed the capability of running more than 500 kms on such real-world routes with a single H_2 tank refill while carrying full payload.

The simulation activity included matching the right longitudinal vehicle dynamics and driver behaviour for following the distance-based geographical route speed and gradient data; implementing demonstrator specific optimized ECMS power split between the FCS and battery pack for supplying the required eDrive traction and auxiliary load power and precisely representing the expected impact of payload and ambient temperature on H_2 consumption, propulsion energy and auxiliary load expenditure. Effect of the driving route on the evolution of battery SoC and components' temperature with corresponding cooling system load was also investigated. Right model parameterization, which was the key to closely simulating real-world route performance of the planned ZEFES FCEVs was accomplished through a stepwise validation of simulation results by the WP6 partners including standard VECTO cycle simulations of a generic HD FCEV followed by those of the actual demonstrators, and finally the analysis on the actual driving mission simulations. This developed simulation capability with sensitivity to varying payloads and ambient conditions will also help the partner manufacturers in estimating mechanical, energetic and thermal performance of their demonstrators when they will be employed on these planned freight missions.

The next steps will include validating this FCEV demonstrators' real-world simulation capability in WP7, once the vehicles start operating on the planned ZEFES driving missions. As the demonstrators run through seasonal changes and day-night operation with different payloads, the sensitivity of the simulation and its parameters to ambient temperature and payload load could be further calibrated. Once the simulations have been validated against real-world driving data, they could be directly used to verify the mechanical, energetic and thermal behaviour of the planned demonstrator drivetrains under any other operating situations which could help adapt the drivetrain design, onboard energy, thermal and logistics management strategies to gain better real-world performance.

An updated second version of this deliverable is planned (by M24) when the complete drivetrain specifications of the planned ZEFES FCEV demonstrators are available along with precise driving mission route data and updated WP2 simulation model as the current results make generalized assumptions when simulating some of the FCEV use cases and use basic driving mission data.

4.1 Contribution to project (linked) Objectives

The deliverable presents detailed virtual simulations of the H_2 FCEV use cases on the planned ZEFES driving missions, simulating the expected performance of these drivetrains under real-world payload and ambient temperature conditions. This simulation capability could give the project partners a head start on the expected drivetrain behaviour and technical challenges before running the actual demonstrators on the planned driving missions supporting insights into any technical upgrades or modifications that may be required. As such, this deliverable contributes to objective 1, improving modular Heavy Duty (HD) Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs).

4.2 Contribution to major project exploitable result

This deliverable could support technical development and upgrades of FCEV demonstrators' design, energy management, thermal management and logistics management strategies following detailed simulation outcomes of the actual real-world driving mission use cases.
It is helping to investigate robust powertrain design including running under extreme operating conditions such as running with very high payload, extreme hill climbs, hot and cold ambient temperatures.

The real-world route detailed FCEV simulation capability built through this task is currently supporting model based development of real-time implementable optimal energy and thermal management strategies which will use predictive route data to minimize H_2 fuel consumption while extending FCS and battery lifetime, thereby reducing total costs over vehicle lifespan.

Apart from the vehicle performance simulation activity described in this report, following on the co-design optimization tool from WP2, WP6 task 6.1 also conducted some other studies related to:-

1. Lifetime costs and carbon footprint optimization of FCEV powertrain for long haul truck (right sizing of FCS, battery and eDrive) considering onboard tractor space constraints due to the required H_2 tank size, vehicle mass impact, ageing degradation of FCS and battery pack and cooling requirements with their effect on aerodynamic drag.
2. Real-time implementable optimal FCEV powertrain energy management and battery thermal management strategies.

These exploratory advancements will be further demonstrated in the upcoming ZEFES conference and journal article dissemination.

5 Risks and interconnections

5.1 Risks/problems encountered

Risk No.	What is the risk	Probability of risk occurrence[1]	Effect of risk[1]	Solutions to overcome the risk
1	Delay in planned FCEV demonstrator specifications from some WP6 partners due to availability and/or confidentiality issues	2	2	Considering assumed FCEV drivetrain parameters where planned specifications are missing. This may lead to a deviation in the simulation behaviour, requiring a second update on the current deliverable once the actual specifications become available.
2	Delay in real-world use case driving mission route data from WP7	1	2	Using as an alternative external sources to get route distance-based data.
3	Delay in essential updates on the WP2 vehicle simulation tool to be able to simulate the FCEV demonstrators	1	2	Having complementary vehicle simulation models if needed until updates on the WP2 vehicle simulation tool become available. Simulation parameters finalized through such an approach should lead to the same results when using the final WP2 vehicle simulation tool.
4	Comparable reference vehicle data missing	2	2	Real-world driving mission simulation results including system behaviour and H2 consumption (kg/100km), traction energy requirement (kWh/km) and average auxiliary load (kW) give sufficient insights into the expected performance.
5	TTW efficiency cannot be fairly calculated and compared as precise powertrain dimensions and	2	2	Specific H2 consumption and other simulation results give a good indication of powertrain efficiency

	subsystems characteristics are not fully known and are still being finalized			especially for the simulated real-world ZEFES driving missions.

[1] Probability risk will occur: 1 = high, 2 = medium, 3 = Low

5.2 Interconnections with other deliverables

This deliverable builds further on the technical requirements defined in D1.1 and the defined use cases in D1.2. Also the deliverables D2.2 and D2.3 on the vehicle design optimization and sizing and feasibility considerations.

6 References

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7 Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner short name	Partner Full Name
1	VUB	VRIJE UNIVERSITEIT BRUSSEL
2	FRD	FORD OTOMOTIV SANAYI ANONIM SIRKETI
4	KAE	KASSBOHRER FAHRZEUGWERKE GMBH
5	REN	RENAULT TRUCKS SAS
6	SCA	SCANIA CV AB
7	VET	VAN ECK TRAILERS BV
8	VOL	VOLVO TECHNOLOGY AB
9	ABB	ABB E-MOBILITY BV
9.1	ABP	ABB E-MOBILITY SPOLKA Z OGRANICZONAODPOWIEDZIALNOSCIA
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