vehicles

Article

From Microcars to Heavy-Duty Vehicles: Vehicle Performance Comparison of Battery and Fuel Cell Electric Vehicles

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Abstract: Low vehicle occupancy rates combined with record conventional vehicle sales justify the requirement to optimize vehicle type based on passengers and a powertrain with zero-emissions. This study compares the performance of different vehicle types based on the number of passengers/payloads, powertrain configuration (battery and fuel cell electric configurations), and drive cycles, to assess range and energy consumption. An adequate choice of vehicle segment according to the real passenger occupancy enables the least energy consumption. Vehicle performance in terms of range points to remarkable results for the FCEV (fuel cell electric vehicle) compared to BEV (battery electric vehicle), where the former reached an average range of 600 km or more in all different drive cycles, while the latter was only cruising nearly 350 km. Decisively, the cost analysis indicated that FCEV remains the most expensive option with base cost three-fold that of BEV. The FCEV showed notable results with an average operating cost of less than 7 cents/km, where BEV cost more than 10 €/km in addition to the base cost for light-duty vehicles. The cost analysis for a bus and semi-truck showed that with a full payload, FCPT (fuel cell powertrain) would be more economical with an average energy cost of ~1.2 €/km, while with BPT the energy cost is more than 300 €/km.

Keywords: powertrain simulation; EV vehicle performance; vehicle segments; occupancy; payload; drive cycle analysis

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1. Introduction

Energy has always been considered the backbone of any economy around the world. Industrialization and modernization enhanced the rapid growth of the economy, along with the overuse of fossil energy resources, resulting in global warming, air, water, and noise pollution. The transportation sector has struggled to find alternatives that mitigate its externalities leading to an increasing number of vehicles worldwide [1,2]. This accelerated the need to revolutionize the transportation system with more efficient powertrains and energy systems. This path led to the development of emerging technologies in the transportation system, such as battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), and fuel cell electric vehicles (FCEV), substituting internal combustion engine vehicles (ICEV).

According to the European Environmental Agency "Trends and Projections in Europe 2020" report, the overall GHG emission trend had been reduced by 26% by 2019 (EU-28) as compared to 1990, which is below the EU's GHG reduction target for 2020 [3]. However, 1103 Mt CO_{2eq} of the total EU-28 emission, around 23% is generated from the road transportation [4]. With zero tailpipe emissions, offsetting the carbon footprint, and noise pollution, electrification of powertrains has emerged as a worldwide trend. Besides, the possibility of including renewable energy in transportation systems (e.g., green hydrogen, wind, and solar energy) has proved to be essential to reduce the well-to-wheel emissions associated with these alternative technologies. From 2015 to 2020, EV sales rapidly increased from 0.58 million vehicles to 3.24 million units globally, with nearly 1.4 million BEV and PHEV being registered in Europe, 137% more than in 2019 [5,6].

Furthermore, the seamless transition from conventional powered vehicles to fully electric vehicles should include not only the light-duty application but also medium and heavy-duty applications [7]. Studies have been performed formerly with different energy storage systems of EVs [8]. Using a battery as an energy storage system results in the least average energy consumption per kilometer of travel due to higher powertrain efficiency. However, the lower range and requirement of the larger battery pack is a significant disadvantage of BEV [9–12]. As for FCEV, studies have shown that with a single fueling of 5 kg of hydrogen, the vehicle can reach more than 500 km with less refueling time. By contrast, FCEV is less favorable at present [10,13–16], due to its higher average energy consumption per kilometer, fewer refueling stations, and higher capital expenses compared to BEV and ICEV. The ultracapacitor (UC) is also gaining attention as an emerging energy storage option, due to its higher power density (1000–2000 kW/kg). It consists of a fast-charging option and with a much higher capacity of performing charging and discharging cycles, making it a favorable choice in transportation options. It is ideal for applications that require higher energy and that can make frequent recharging options, like EV for public transportation [10,17–19]. The life cycle assessment performed by Sacchi et al. [20] for a series of medium and heavy-duty trucks shows that the fuel cell and battery will become the most promising powertrain options for trucks in 2040 even compared to advanced combustion technologies. Along with this, to identify the optimal vehicle powertrain, it is also essential to evaluate the driving profile and driving pattern of the user. Crozier et al. [21] performed an explicit study on the behavioral analysis of user-profiles in electric vehicles. The study noticeably shows that users tend to travel a distance between 11 to 91 miles on average each day in the UK. The study done by Sun et al. [22] shows the five different types of vehicle usage pattern on a weekday from floating car data in France, with variable averages and distance travelled in a day.

From the literature mentioned above, we can observe that individual studies have been performed to identify the optimal vehicle powertrain; nevertheless, none of them gives a clear idea of how the performance of EV changes with the number of passengers and vehicle segments for different scenarios. Though the powertrain and drive profile influence the vehicle performance, the number of passengers also impacts the EV performance. The operational results claimed by the manufacturers only consider the weight of the vehicle or with one passenger for testing and analysis [23], but in real-world conditions, a light-duty vehicle is entitled to carry up to 500 kg as payload, which can cause considerable changes to its performance.

In this paper, we propose a generic simulation model of EV for different vehicle types to quantify the vehicle performance in an electric powertrain powered by batteries or fuel cells in different usage profiles. The integrated approach covers all vehicle segments from micro-car to trucks, by evaluating the energy and cost performance of BPT and FCPT configurations. It also captures the effects of the described variables: a range from 100–500 km; different driving profiles, including certification drive cycles and real-world drive cycles; different vehicle segments; and different payload mass. This study presents an innovative approach capable of designing tailor-made EV powertrain and energy storage solutions based on user profile requirements.

The paper is structured as follows: Section 2 explain the study and is divided into further segments: Section 2.1 describes the different types of vehicles considered for this study, Section 2.2 explains the considered drive cycles, including real-world and standard drive cycles. Section 2.3 explains the development of the model in Simulink, including the modeling of battery and fuel cell systems. Section 3 presents the results from the simulation process with various vehicle types. The discussion about the results was performed in Section 4. And finally, the conclusions are reached in Section 5.

2. Data and Methods

This research aims to analyze vehicle performance with different powertrain configurations, driving profiles, the number of passengers, and vehicle segments. To accept these parameters as a variable, a highly flexible model is needed. The model should be capable of considering the former parameters as a variable. Facing the need for flexibility and to analyze different scenarios, an already developed Simulink model from a previous study was modified concerning the requirement of this study [9,10]. For this study, the model was revised from a previous model with a customized drive cycle for different analysis and specified vehicle types were replaced with generic vehicle model to study different vehicle types. The model consists of six subsystems, including drive cycle, vehicle model, vehicle physical model, motor system, battery system, and fuel cell system.

2.1. Vehicle Type

For this study, six generic vehicles were considered based on the vehicle types existing in the automotive market. Table 1 shows the different vehicle types, dimensions, and physical properties (corresponding to the average of a sample of available vehicles on the market).

Table 1. Vehicle segment and physical properties.

Vehicle Type	Micro-Car	Urban 4s	Extra-Urban 5s	Shuttle	Bus	Semi-Truck
Mass * (kg)	450	1200	1350	1600	11,000	10,000
Motor power (kW)	13	130	130	60	220	560
Motor torque (N)	100	340	340	360	1200	2600
Max speed (kmph)	60	145	145	60	90	90
Max payload (kg)	150	350	500	1000	4500	27,000

* Mass of the vehicle is considered without energy storage mass.

With the current market trends, micro-cars have been marking their dominance in many of the prominent EV selling countries. Due to its lower energy consumption, higher battery life, ease of use, and convenience, micro-cars are becoming popular among EV users. In China, GM's venture Micro-EV became the most sold EV in August 2020, followed by the Tesla Model 3 during the pandemic [24]. In 2026, the Micro-EV market size is projected to reach USD 5.8 billion based on the Fortune Business Insights forecast [25].

To study the concept of tailored vehicle for individual uses, a four-seater urban vehicle (Urban 4s) is included, which aims to study the real-world performance of compact urban vehicle with a maximum of four passengers instead of five. The smaller vehicle size with its lighter weight compared to the five-seater vehicle helps with reduced energy consumption and possibly longer range and battery life. This hypothesis will be explained later in the analysis stage. For the physical properties, the existing vehicle's type of hatchback is considered for the 4-seater EV.

To compare with most EVs present in the market, a five-seater extra-urban model (Extra-urban 5s) is also considered. The vehicle properties are determined based on the average of the similar EV vehicles (Sedan) present in the market. In addition to this, in the context of the increasing need for promoting the modal shift to mass transit options and of the push for on-demand services, a shuttle model with an electric powertrain is analyzed in the study.

Additionally, due to the significant share of heavy-duty vehicles in the transport sector externalities (430,000 units [26]) and considering this sector has been slower in adopting alternative solutions, heavy-duty vehicles, specifically, the bus and semi-truck, are also included, due to their different specificities in terms of powertrain design and associated mobility patterns.

2.2. Drive Cycle Selection

The drive cycle data influence the simulation outcomes considerably as they represent the operational conditions of a vehicle. The vehicle types described in Table 1 were tested with certified and real-world drive cycles to study their energy performance. WLTP class 3 drive cycle is used as the certified drive cycle for light-duty vehicles [27]. For real-world drive cycle, 2 distinct drive cycles with road grade were extracted from a larger real-world drive cycles sample collected with light-duty vehicles in Lisbon, Portugal [12] (check the Appendix A, Figure A1 (Real-world drive cycle 1 (duration: 1800 s)) for real-world drive cycle 1-RW1 and Figure A2 (Real-world drive cycle 2 (duration: 1880 s)) for real-world drive cycle 2-RW2). Since the Micro-car and Shuttle have limited engine power, the maximum speed they can achieve is lower than the Urban 4s and Extra-urban 5s, so lower speed drive cycles previously obtained for micro-cars were used [28]. Also, the certified WLTP drive cycle is modified for the former vehicles with a maximum speed of 55 km/h. Figure A3 (Real-world drive cycle for micro-car/shuttle (duration: 14,004 s)) shows the real-world drive cycle for Microcar/shuttle (RW_m) and Figure A4 (Modified WLTP class 3 drive cycle (duration: 1800 s)) shows the modified WLTP class 3-drive cycle. Table 2 details the specification of drive cycles used for the analysis of the light-duty vehicles.

Table 2. Drive cycle specifications for different vehicle types.

Drive-Cycles	WLTP C3 Modified	WLTP C3	RW_1	RW_2	RW_m	RW_b	RW_st
Distance (km)	17.6	23.3	17.8	27.1	46.9	71.3	93.83
Av speed (kmph)	31.5	46.5	35.5	51.8	12.1	19.18	30.63
Max speed (kmph)	55.0	131.4	75.0	103.0	53.9	74.9	58.5
Duration (s)	1800	1800	1800	1880	14,010	13,353	11,027
Av positive acc. (m/s^2)	0.50	0.41	0.57	0.48	0.42	0.33	0.10
Av negative acc. (m/s^2)	−0.19	−0.32	−0.45	−0.40	−0.22	−0.27	−0.11
Av positive road grade	-	-	0.025	0.019	0.027	0.037	0.028
Av negative road grade	-	-	−0.020	−0.019	−0.033	−0.033	−0.031

For heavy-duty vehicles, since there are no certification drive cycles, they are only analyzed with real-world drive cycles, which were recorded in previous studies [10,29]. Figure A5 (Real-world drive cycle for Bus (duration: 13,353 s)) represents the real-world drive cycle used for the simulation of bus and Figure A6 (Real-world drive cycle for Semi-truck (duration: 11,027 s)) show the speed profile of the real-world drive cycle used for semi-truck simulations. Table 2 shows the drive cycle specification used for the simulations of the heavy-duty vehicles (RW_b represents the real-world drive cycle for bus and RW_st represents the real-world drive cycle specifications for semi-truck).

2.3. Model Development

The developed model consists of six subsystems, including drive cycle, vehicle model, vehicle physical model, motor system, battery system, and fuel cell system. The second-by-second drive cycles defined in Section 2.2 are imported as input signals into the drive cycle subsystem. In the vehicle model, the vehicle specifications were considered based on information presented in Section 2.1. The model enables modification of battery capacity, fuel cell maximum power, and vehicle segment type in this subsystem.

The vehicle physical model subsystem consists of mechanical, mathematical, and numerical expressions to describe the vehicle's physical behaviour, as in other studies in the literature [30]. The traction force required to accelerate the vehicle and deceleration forces are calculated based on the one-dimensional vehicle fundamental motion. That enables calculating the power requirement of the vehicle in each second, based on the drive cycle data and basic vehicle loads forces, as presented in Figure 1.

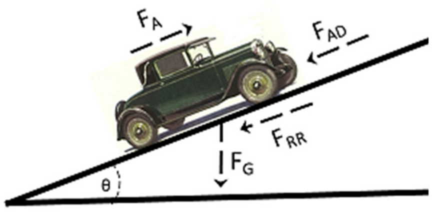


Figure 1. Forces acting on the vehicle.

The total force that is required to move the vehicle is called traction force and is calculated as:

$$F_T = F_A + F_G + F_{RR} + F_{AD} \quad (1)$$

where, F_A is the acceleration force (N), F_G is the gravitational force (N), F_{RR} is the rolling resistance (N), and F_{AD} is the aerodynamic drag (N). The previous expression is expanded as:

$$F_T\ (\mathrm{N}) = (m \times a) + (\frac{1}{2} \times C_d \times \rho \times A_f \times v^2) + (C_r \times m \times g \times \cos\theta) + (m \times g \times \sin\theta) \quad (2)$$

where m is the mass of the vehicle (kg), a is the acceleration (m/s^2), C_d is the drag coefficient, A_f is the vehicle frontal area (m^2), v is the velocity (m/s), C_r is the coefficient of rolling resistance, g is the acceleration due to gravity (m/s^2) and θ is the road grade [9].

The model is designed in such a way that the air density is calculated numerically for each simulation [31]. The rolling resistance is determined based on the average speed of the drive cycle. The experimental results of tire T1071 (modern tire) on ISOr20 road surface (ISO reference surface) at different speeds are taken as a reference to compute the rolling resistance coefficient [32].

In the motor subsystem, a permanent magnet DC motor/generator is numerically modelled. The efficiency curve of the Nissan leaf 80 kW motor is taken as the reference. During forward motion/acceleration, a permanent magnet DC motor (PMDC) is employed as a motor, while during braking/deceleration, the PMDC works as a generator and extracts energy through regenerative braking. Equation (3) represents the power output from PMDC to the wheel during acceleration and Equation (4) represents the regenerative energy production during braking. The power required during each second of the travel is calculated as the sum of power required for acceleration (P_{wheel}), auxiliary power (P_{AUX}), and power loss (P_{loss}), which is represented in Equation (5).

$$P_{wheel}\ (\mathrm{W}) = \frac{F_t \times v}{\eta_m} \quad (3)$$

$$P_{regen}\ (\mathrm{W}) = F_T \times \eta_{regen} \quad (4)$$

$$P_{total}\ (\mathrm{W}) = P_{wheel} + P_{AUX} + P_{loss} \quad (5)$$

where, η_m (%) is the efficiency of the motor and η_{regen} (%) is the regenerative efficiency. It is expected that regenerative efficiency at a particular deceleration point is the same as that motor efficiency at the same acceleration point, however, the maximum regenerative energy production has been limited to 25% of the motor power according to the literature [33,34].

For the battery powertrain (BPT), the total power stored in the battery is defined as the product of voltage (V) of the battery and total current (I) in the battery, as represented by Equation (6). The current injected during charging (regenerative braking) and extracted during discharging (acceleration mode) of the battery is estimated by Equation (7) and terminal voltage, V_t is calculated through Equation (8):

$$P_{bat} = V \times I \quad (6)$$

$$I\ (\mathrm{A}) = \frac{V_t - \sqrt{V_t^2 - 4RP_{wheel}}}{2R} \tag{7}$$

$$V_t = V_{t(t-1)} - V_{drop} \tag{8}$$

where R is the battery internal resistance (Ω) and t is the time in seconds. The resistance of the battery is considered to be 0.1 Ω [35]. The total energy consumed during the drive cycle is assessed by summing the power consumption through each second of the drive cycle. The final total power consumption is estimated by taking the difference of total power consumption to the regenerative energy produced during the journey, as presented in Equation (9).

$$P_T = \sum_{t=1}^{T} P_{total} - P_{regen} \tag{9}$$

The average energy consumption (E_avg) of the vehicle is the amount of energy consumed to reach each unit distance, km, and is calculated as shown in Equation (10). The *Range* (km) of the vehicle is calculated as shown in Equation (11).

$$E\_avg\ (\mathrm{Wh/km}) = {}^{P_t}/_{d} \tag{10}$$

$$Range = {}^{P_{bat}}/_{E\_avg} \tag{11}$$

where d is the distance travelled in the drive cycle (km). It is to be noted that 100% energy capacity available cannot be used, the battery reserves the last 15% of its energy density to prevent full discharge.

State of charge (SOC) is defined as the level of charge of the battery with respect to its capacity. It is presented in percentage: 100% represents fully charged battery and 0% represents empty. *SOC* is calculated at each second by using the coulomb current counting method (see Equation (12)):

$$SOC(t) = SOC(t-1) \pm {}^{I_t}/_{I} \tag{12}$$

where I is the current stored in the battery and it is the current drawn at that particular second.

For the fuel cell powertrain (FCPT), a proton-exchange membrane fuel cell (PEMFC) is modelled based on the polarisation curve of Toyota Mirai 2017, which is taken as the reference [36,37]. The portion of the output power of the fuel cell required to maintain the working condition is termed as the balance of plant (BOP). The fuel cell power (P_{fc}) is then calculated through Equation (13):

$$P_{fc}\ (\mathrm{W}) = \frac{P_{fcp}}{1 - BOP} \tag{13}$$

where P_{fcp} is the maximum output of the fuel cell stack. From the polarization curve, the current and voltage for the power required are estimated. The stack output voltage (V) of the fuel cell is the total voltage produced by the number of cells in the stack (N_c), which is given by:

$$V_{fcp} = N_c \times V_{fc} \tag{14}$$

Fuel cell electrical efficiency is calculated as the ratio of the electric power output to the energy input from hydrogen. The total efficiency of the module can also be calculated as the product of the factors, as shown in Equation (15):

$$\eta = \eta_{th} \times \eta_v \times \eta_F \times \mu_F \tag{15}$$

where η_{th} is the thermodynamic efficiency, η_v is the voltage efficiency, η_F is the faradic efficiency, and μ_F is the utilization factor. The thermodynamic efficiency, faradic efficiency, and utilization factor are assumed as 0.83, 0.9, and 1 respectively [38], and voltage efficiency is calculated by Equation (16), and the fuel mass flow rate of hydrogen is calculated by Equation (17):

$$\eta_v = \frac{V_{fc}}{1.23} \quad (16)$$

$$\dot{m}_{H_2}(\text{gm/s}) = \frac{P_{fcp}}{Q \times \eta} \quad (17)$$

where Q = 120 MJ/kg or 33.33 kWh is the lower heating value/specific energy of hydrogen. Since the power requirements vary each second, the current and voltage produced also change and it will affect the fuel cell operation. In order to intercept that, a DC–DC converter is used with an efficiency of 90%. The range (km) of the vehicle is calculated as:

$$Range\ (\text{km}) = {M_{H_2} \times 33.33 \times 1000}/{E\_avg} \quad (18)$$

For the FCPT, the modelling is performed in such a way that the energy required for the cruise is fully produced through the onboard FC stack, while the energy required for auxiliary consumption is delivered by a secondary battery, which is modelled similar to a battery system for BPT.

2.4. Application of the Model

The simulation model developed for this study is acknowledged as flexible since it enables us to easily modify the number of passengers, various driving profiles, vehicle segment types, and storage options as separate variables. This helps to assess the difference in vehicle performance in different driving scenarios and identify the effects in real-world driving. Through this model, the following analysis was performed.

- Storage capacity assessment per vehicle type for diverse ranges with different payloads: The range is one of the key factors that affect the worldwide sales of EVs. The manufacturers test the vehicle segments with certified drive cycle under strict test conditions and only by considering 1 passenger as the driver. However, in real-world conditions, the performance varies drastically. Users do not follow certified drive cycle accelerations and face diverse road topography profiles, justifying the analysis through real-world drive cycles. Along with this, vehicle payload is aggravated in on-road conditions according to usage patterns, since vehicles can be fully or partially occupied. The vehicles presented in Table 1 are studied for various drive cycles described in Section 2.2 for the different payloads of 150, 250, 350, and 500 kg for light-duty vehicles. For the electric bus, simulations were carried out for 10, 25, 40, and 55 passengers considered as payload, while for the semi-truck 25%, 50%, 75%, and 100% of maximum payload capacity were considered.

From the analysis of existing BEV in the market, the average battery mass of the vehicle is estimated as 32% of the vehicle curb mass without the battery [39,40]. Assuming state of art batteries in forthcoming vehicles, an optimistic value of 35% is considered as the maximum energy storage mass. Furthermore, for bus and semi-truck, the ratio changes to 26% and 42% respectively [41]. Table 3 shows the maximum battery mass for each vehicle segment and respective battery capacity based on the allocated battery mass and also the specifications assumed for the FCPT.

Table 3. Battery specification for vehicle segments.

Vehicles	Vehicle Mass (kg)	Battery Mass (kg)	Battery Capacity (kWh)	Payload (kg)/Passengers (no.)	Fuel Cell Capacity (kW)	H_2 Stored (kg)
Micro-car	450	152	19	150/2	13	3
Urban 4s	1200	424	53	350/4	130	5.6
Extra urban 5s	1350	472	59	500/5	130	5.6
Shuttle	1600	560	70	1000/12	60	5.6
Bus	11,000	2880	360	4500/60	220	100
Semi-Truck	10,000	4160	520	27,000	520	100

The average battery mass is considered as 8 kg/kWh, which is also estimated from the battery pack to weight ratio from the BEV available in the market [10,40]. For fuel cell vehicles, the maximum hydrogen storage in the FCEV at present for the light-duty vehicle is 5.6 kg [42], which is also assumed for the light-duty vehicle simulations. For heavy-duty vehicles, a 100 kg H_2 storage capacity is considered, inspired by the latest long-range heavy-duty vehicle launched by Nikola Motors (Nikola 2 semi-truck) [43]. Based on the hydrogen storage, the model estimates the storage tank mass, in addition to the vehicle mass.

- Average energy consumption per km per person for different vehicle segments: It is to be noted that when we consider bigger vehicle types for transportation, presumably the average energy consumption will be higher than for the other smaller segments. By contrast, analyzing the number of passengers traveled, a five-seater vehicle may have the least average energy consumption for each passenger than a four-seater vehicle, which shows the five-seater vehicle has lesser average energy consumption per person. Although energy consumption per passenger is typically disregarded, it may retain significant importance in the future in the wider adoption of shared vehicle solutions. By analyzing the average energy consumption per person for unit distance, it is possible to identify the optimal vehicle segment selection based on the passengers.

- Powertrain cost analysis on vehicle segments: The cost of the vehicle is one of the important decision factors from the user's point of view before buying an EV. In the market, ICEV gained the title of most affordable vehicles, while FCEV is the most expensive option, considering the same vehicle category, sandwiching BEV in between [10]. However, for BEV and FCEV, the operation and maintenance cost is about 10–20% of the CAPEX, and ICE reaches up to 50%, which makes the total ownership cost almost equal to BEV over the vehicle's lifetime [10]. In this study, powertrain cost analysis is carried out, where the spending for different energy storage options and operation cost is analysed for the whole trip and also for transporting per passenger or unit payload.

The cost assumptions were based on the literature. Currently, due to the limited vehicle production, the unit FC stack production cost is around 175 €/kW [10]. Increasing the production to 100,000 units/year can reduce the price below 60 €/kW [44]. In this study, mass production of FC units has been considered. As for the fuel price, 0.21 €/kWh is considered as the electricity price and 11.3 €/kg for hydrogen, while the average maintenance cost is considered as 0.018 €/km for both vehicles [10,45]. Hydrogen storage cost is also included in the cost analysis based on the energy storage assumed for these vehicle types [46]. Also, battery cost is estimated as 118 €/kWh presently [46]. Additionally, this study considers the technological growth in the future and it is estimated that the price of hydrogen fuel could be dropped by 60% and reach 6.5 €/kg in 2030 [47]. The battery would also become cheaper, with an estimated cost of 48 €/kWh in 2030 [46].

3. Results

The simulation model developed is tested for various vehicle types with distinct drive cycles for BPT and FCPT vehicles. Initially, the model is validated, and the analysis is carried out. The analysis is performed in two stages: the first stage includes the analysis of light-duty vehicles for distinct driving profiles and payloads and during the second stage the heavy-duty vehicle analysis is performed for both BEV and FCEV configurations.

3.1. Model Validation

The model validation is completed in two steps, initially for BEV and then for FCEV. The validation has been performed and is presented in the previous studies published by the authors [9,10]. WLTP class 3 drive cycle is employed for the validation, the result of the simulation is then compared against the laboratory test results. Seven different vehicle models available in the market from different vehicle manufacturers were tested with the certified drive cycle for the model validation. For FCEV, the simulation results of Toyota Mirai were compared with FTP 75 and HWFET laboratory test results. For heavy-duty vehicles (HDV), the City eGold bus was simulated with the real-world drive cycle and the results were compared with the recorded energy consumption. The vehicle specification such as vehicle dimension, vehicle mass, battery mass, and other parameters are given of the chosen vehicles, and results are tabulated in Table 4.

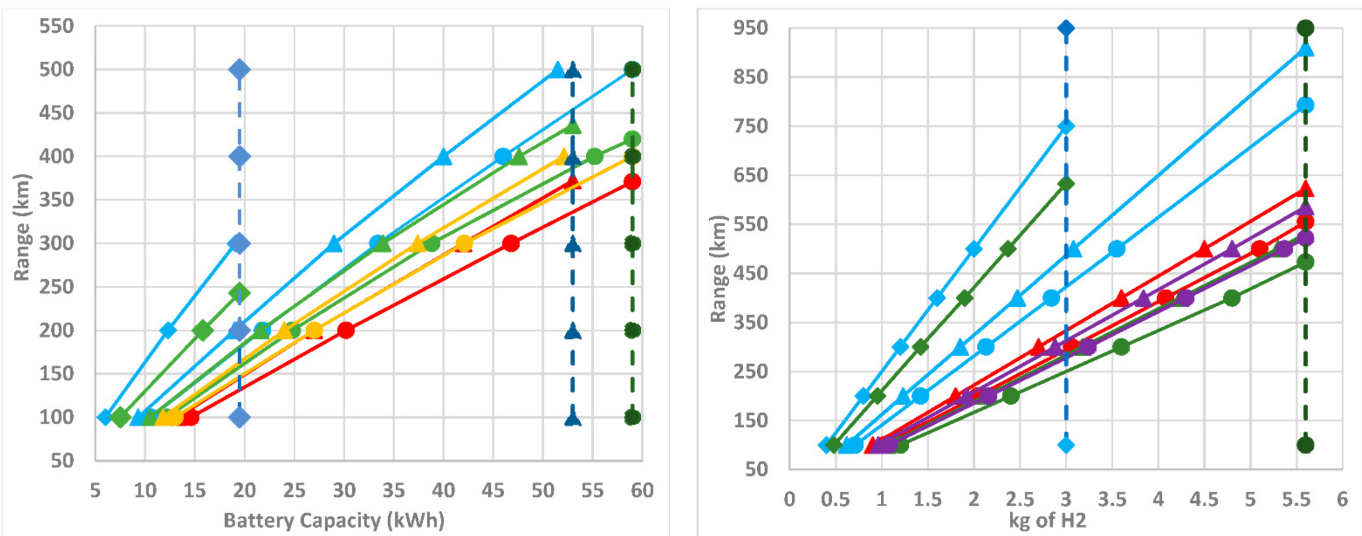
Table 4. Electric vehicle (EV) simulation results (error compared to reference, %).

Vehicle	Energy Consumption (Wh/km)	Range (km)	Battery Rated Energy (kWh) or Hydrogen Stored (kg)
		EV	
Nissan Leaf S	138.6 (−1.7)	288 (1.4)	40.0
Renault Zoe R110	132.5 (0.4)	392 (−0.8)	52.0
Kia Niro	140.2 (3.0)	280 (−3.2)	39.2
Kia Soul EV	145.1 (2.1)	271 (−2.2)	39.2
Hyundai IONIQ	122.1 (−0.7)	313 (0.6)	38.3
BMW i3	129.9 (−2.4)	324 (2.8)	42.0
Mini Cooper	121.9 (−1.7)	267 (1.5)	32.6
City eGold (HDV)	822.5 (−1.1)	103.3	85
		Fuel cell EV	
Toyota Mirai	313.5 (1.3)	528 (4.6)	5.6 (kg of H_2)

The comparisons results showed the simulation model results were reliable with a mean average error of 5% for light-duty vehicles and 2% for heavy-duty vehicles [9,10]. This shows the model is reliable and consistent.

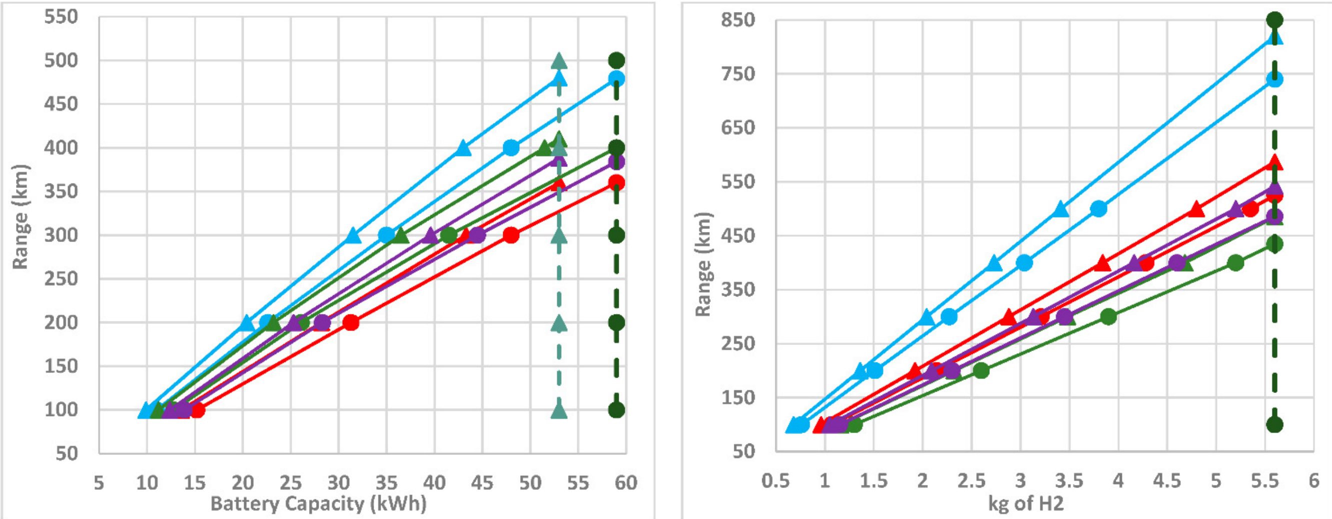
3.2. *Storage Capacity Assessment per Vehicle Type for Diverse Ranges with Different Payload*

The range of EV is one of the critical variables when it comes to EV and, in this analysis, various types of vehicle are simulated with various drive cycles and payloads. It helps to estimate the energy storage requirement (battery capacity or quantity of stored H_2) to reach certain range markers with each powertrain option. For light-duty vehicles, the vehicle is simulated with various payload mass ranges from 150, 250, 350, and 500 kg, which represents 2, 3, 4, and 5 passengers, respectively, along with maximum possible additional weights. Considering the maximum battery capacity and fuel cell specification from Table 3 it is possible to evaluate the energy storage required to transport a payload of 150 kg in different vehicle segments, considering the full BEV or FCEV configurations, following distinct drive cycles, as presented in Figures 2–5. These show the energy storage requirements for the payloads 250, 350, and 500 kg, respectively.



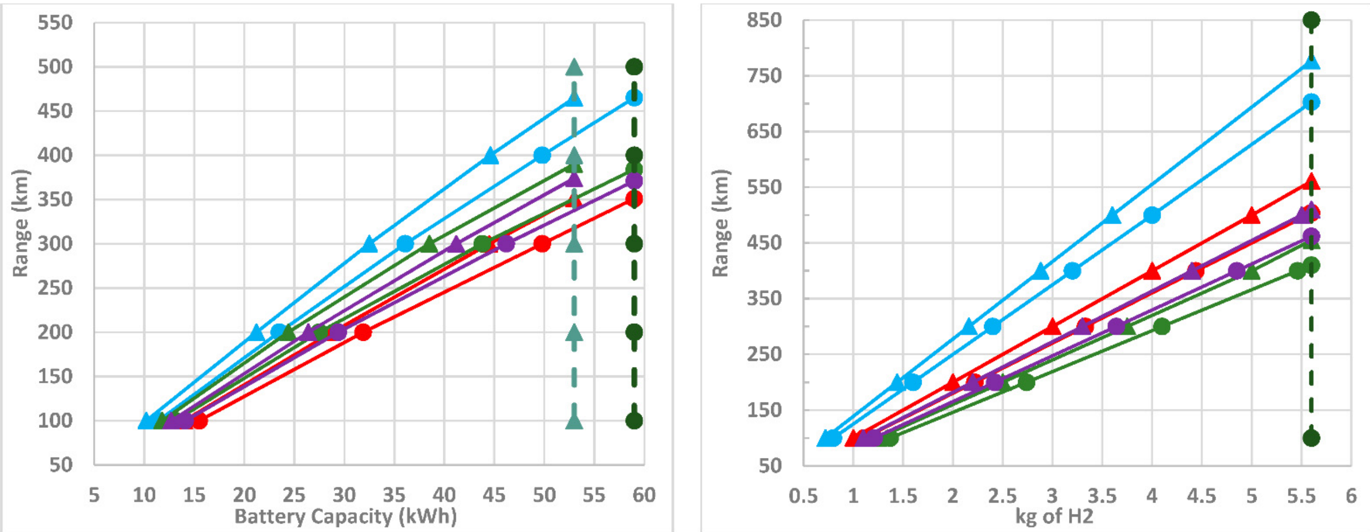
(a) Battery powertrain *(b) Fuel cell powertrain*

Figure 2. Energy storage requirement to transport 150 kg payload with different drive cycles.



(a) Battery powertrain *(b) Fuel cell powertrain*

Figure 3. Energy storage requirement to transport 250 kg payload with different drive cycles.



(a) Battery powertrain *(b) Fuel cell powertrain*

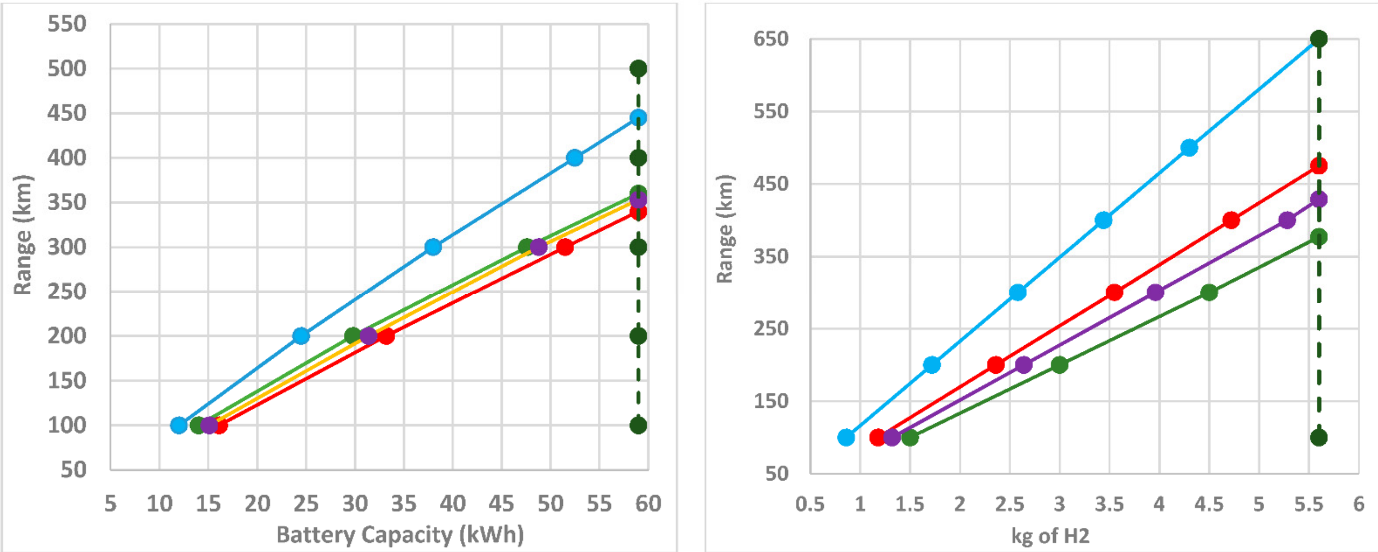
Figure 4. Energy storage requirement to transport 350 kg payload with different drive cycles.

The vehicles were simulated to reach a range marker of 100 km, 200 km, 300 km, 400 km, and 500 km and the results are plotted from Figures 2–5. The simulations are extended to analyze the maximum range that can be traveled with the assigned energy storage capacity and are restricted after the vehicle reached its maximum possible distance with the maximum possible storage capacity.

Figure 2 shows the storage required for the transportation of two passengers for a Micro-car. We can observe that a Micro-car can reach an average distance of 270 km with an average energy consumption of 74 Wh/km. Whereas, Urban 4s or Extra-urban 5s vehicle reaches a higher cruise range of 430 km and 445 km with average energy consumption of 124 and 140 Wh/km, respectively. This points that the Micro-car would be ideal for 2 passengers, satisfying the drive cycle requirements and least energy consumption, and the state of art charging techniques give added advantages in reduction of charging time to a 13-kWh battery than for 53 or 59 kWh batteries.

Figures 3 and 4 show the simulation results of vehicles transporting payload of 250 and 350 kg respectively. For payloads of 250 kg and 350 kg or 3 and 4 passengers, the Urban

4s and Extra-urban 5s vehicles can cruise almost to the same range, however, the Urban 4s transports the same passengers with lower energy consumption. For a payload of 500 kg, only the Extra Urban 5s vehicle type is simulated and Figure 5 shows the simulation results.



(a) Battery powertrain (b) Fuel cell powertrain

Figure 5. Energy storage requirement to transport 500 kg payload with different drive cycles.

Legends: WLTP red.—Micro-car; WLTP red.—Urban 4s; WLTP red.—Extra-urban 5s; WLTP C3—Urban 4s; WLTP—Extra-urban 5s; RW_m—Micro-car; RW1—Urban 4s; RW1—Extra-urban 5s; RW2—Urban 4s; RW2—Extra-urban 5s; Micro-car—max capacity; Urban 4s—max capacity; Extra-urban 5s—max capacity.

On the other hand, looking at to FCPT for two passengers (Figure 2), a Micro-car can reach an average range of 690 km with 3 kg of hydrogen and 13 kW FC stack, while the Urban 4s and Extra-urban 5s vehicles with 5.6 kg of hydrogen and 130 kW FC stack reach an average distance of 660 and 590 km, respectively. The Micro-car reached a higher range of 690 km, due to its lower acceleration profile and total vehicle mass. Considering Urban 4s and Extra-urban 5s, the lower overall mass and same FC stack capacity and fuel stored, the Urban 4s can reach higher distances than the Extra-urban 5s. A similar trend can be observed from the results with different payloads in Figures 3–5.

Table A1 shows in detail the average energy consumption, range, and regenerative braking energy produced for different vehicle segments with distinct drive cycles for variable payloads. Comparing FCPT and BPT, we can observe that for longer distances, battery capacity has to be increased and at a certain point. Due to chassis load capacity and safety factors, the battery capacity cannot be increased. This limits the range of BEV to 400 km or less with real-world drive cycles. By contrast, FCEV only requires extra fuel space, which has less influence on total vehicle mass and the chassis load capacity and thus can easily achieves 600 km range and more with real-world drive cycles.

The simulation was equally performed for the shuttle, bus, and semi-truck. Figure 6 shows the simulation results of the shuttle vehicle, considering a payload of 1000 kg or a total of 12 passengers. It can be seen that, with a maximum allowed battery capacity of 70 kWh, the vehicle can only move up to an average of 270 km, while with the FCPT the vehicle can drive 80 km more only with assumed H_2 storage of 5.6 kg. Considering the application of the vehicle, assuming extra hydrogen storage with FCPT is practically executable and explainable, the vehicle can reach a longer range without any burden to the existing total vehicle mass.

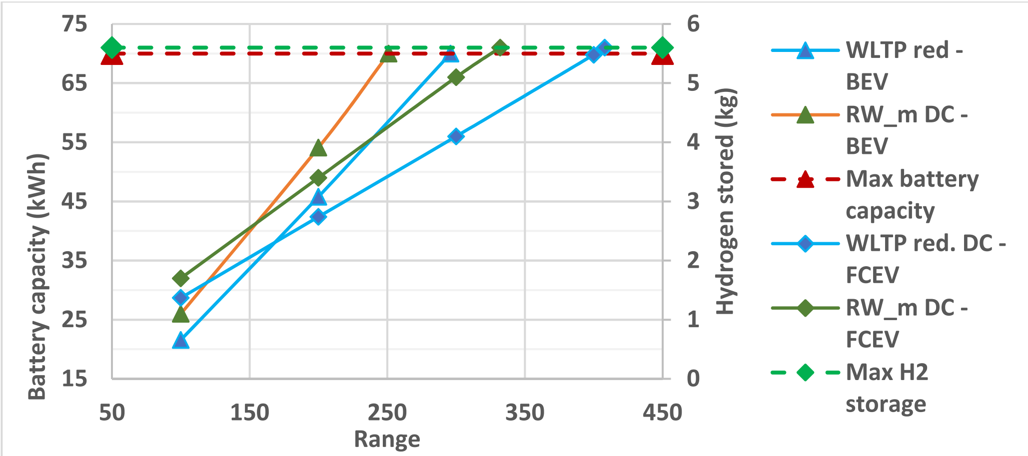


Figure 6. Energy storage requirement to transport 12 passengers (1000 kg equivalent) with different drive cycles.

For the bus, the simulation is carried out with a variable number of passengers. The payload is considered as 10, 25, 40, and 55 passengers accordingly. Figure 7 shows the simulation results obtained, showing that with the maximum battery capacity of 360 kWh, the bus can only travel to 315 km with 10 passengers and up to 250 km with a maximum capacity of 55 passengers. As for the FCPT, 100 kg of H_2 enables the vehicle to cruise for 1300 km with 10 passengers and to 980 km with 55 passengers, which is almost four times the range than the BEV configuration.

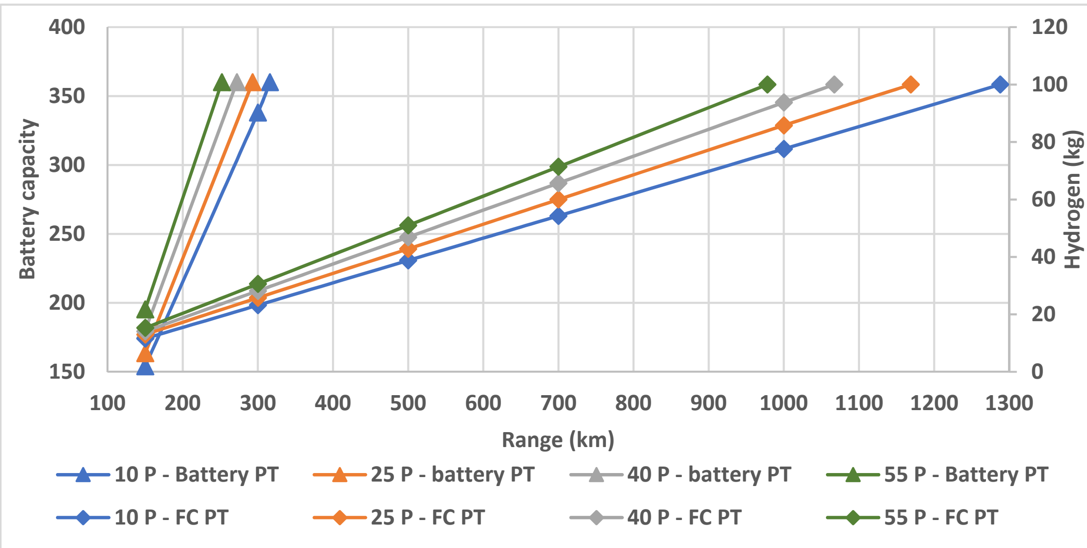


Figure 7. Energy storage requirement for the electric bus to transport passengers.

Considering the distance of the drive cycle (73.1 km) and assuming full capacity throughout the journey and three trips per day, the full BEV configuration would require a recharging event after each day. In the FCPT, refueling is only required once in 4 days, or after 13 trips. This analysis shows the advantages of the requirement of FCPT in bus or heavy-duty vehicles.

For the semi-truck, the simulations were carried out for various payloads: 25%, 50%, 75%, and 100% of the maximum payload capacity. Figure 8 shows the simulation results of the model for the various payload with the real-world drive cycle.

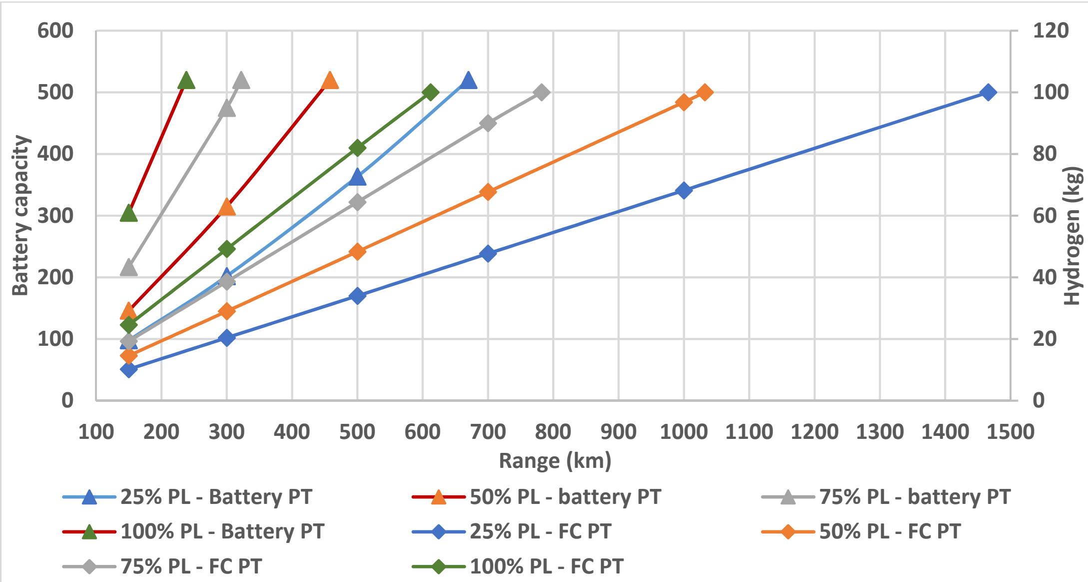


Figure 8. Energy storage requirement for semi-truck to move freight.

From Figure 8, it can be observed that with the BPT, with the maximum load, the vehicle can only reach up to 240 km with a battery pack of 520 kW while with half load, the vehicle can reach up to 450 km. While presenting a similar trend for the FCPT, the truck can cover a distance of 612 km with a full load and 1030 km with a half load. Table A1 shows in detail the average energy consumption, range, and regenerative braking energy produced for different vehicle segments with distinct drive cycles for variable payloads.

This study shows the influence of payload mass on the vehicle performance and range of the vehicle. This shows that the type of service and mobility patterns to be performed are crucial variables that influence the decision to choose an adequate energy storage option.

3.3. Average Energy Consumption per km per Person for Different Vehicle Segments

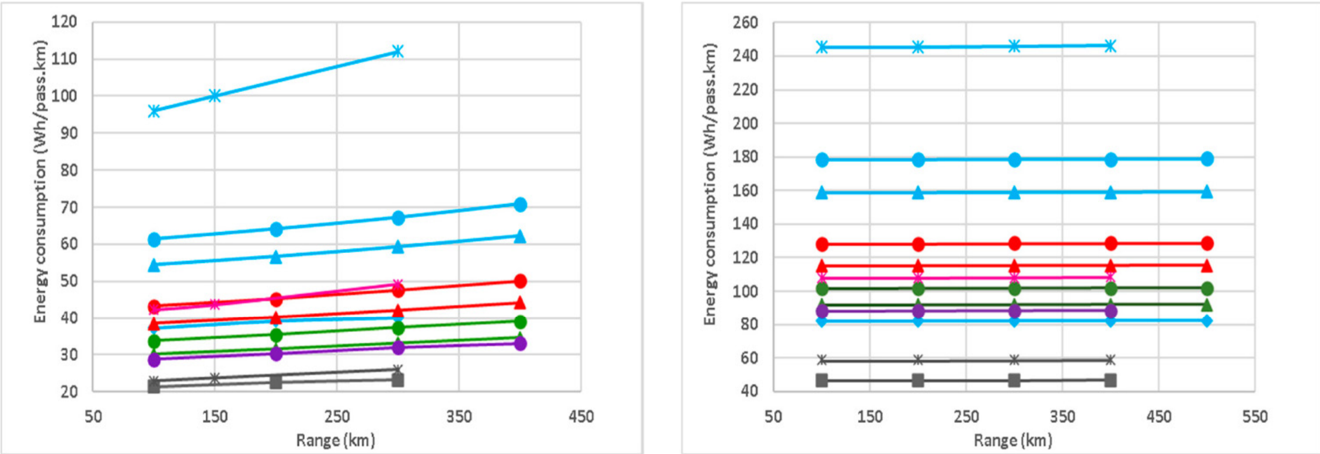
This study aims to analyze the average energy consumption/km for each passenger transported, to identify the most efficient transportation mode. As we observed in the reduction of range with the increased number of passengers, this study validates how beneficial it is to have an extra passenger compared to having an extra vehicle on the road.

Figure 9 shows the average energy consumption/km per passenger for the above-specified vehicle types. The average energy consumption data from the real-world drive cycle simulation is used for this analysis.

Initial observation shows both BPT and FCPT have a similar trend with the average energy consumption/km for each passenger. Looking into the results, we can observe that for two passengers, the Micro-car is the optimal vehicle with the least energy consumption compared to other vehicle types. Considering the Urban 4s and Extra-urban 5s, Urban 4s only consumes less energy for different payload scenarios. However, for mass transportation of passengers, that shuttle is much more efficient than using multiple vehicles of any other category.

While including the bus in this analysis, the results show that with 25% of the capacity, i.e., with 10 passengers, the energy consumption per passenger is the highest among the other vehicles. Having an occupancy of 45%; with 25 passengers, the average consumption is nearly equal to that of Urban 4s and Extra-urban 5s. Though, with full occupancy of 55 passengers, the energy consumption is the least.

Considering the two different powertrains, unquestionably BPT consumes less energy due to its high tank-to-wheel efficiency. The low efficiency and wastage of regenerative energy due to the smaller secondary battery in FCEV reduce the potential of acquiring the fullest regenerative braking energy potential.



a) Battery powertrain *b) Fuel cell powertrain*

Legends: Micro-car – 2P ; Urban 4s – 2P; Extra-urban 5s – 2P; Urban 4s – 3P; Extra-urban 5s – 3P; Urban 4s – 4P; Extra-urban 5s – 4P; Extra-urban 5s – 5P; Shuttle – 12P; bus – 10P; bus – 25P; bus – 55P

Figure 9. Average energy consumption per passenger/km in a full battery electric vehicle (BEV) (**a**) and fuel cell electric vehicle (FCEV) (**b**) configuration.

This analysis shows that fewer passengers can promote a lighter vehicle, such as Micro-car, which has better performance characteristics than a light-duty EV. On the other hand, choosing a five-seater car for four people would not be ideal, as the simulation results show that the Urban 4s and Extra-urban 5s vehicles can reach the same range, but Urban 4s vehicle consumes lesser energy per passenger. In terms of powertrain, FCPT is superior to BPT by providing a longer range with easier refueling procedure, even though BPT has the least energy consumption.

3.4. Powertrain Cost Analysis on Vehicle Segments

The previous study in Sections 3.2 and 3.3 showed despite the lower energy efficiency than its counterpart, FCEV can reach almost double the range of BEV. Even though this is a significant part, the number of FCEV vehicles in the market is not even 1% compared to the BEV in the market. This is justified by the higher purchase costs of FCEV and also the lack of hydrogen refueling stations. Nonetheless, the recent European push for green hydrogen towards the decarbonization of society may help to alleviate some of the barriers in the transition to hydrogen. In this analysis, the average energy cost spent to cover a unit distance with a different powertrain is estimated for the vehicle segments.

Table 5 shows the cost associated with traveling to a targeted distance with different powertrains. The base price is defined as the initial energy storage price requirement to reach 100 km. For BPT, the cost of battery capacity required to reach 100 km is calculated and, for further travel, the additional battery cost is estimated for each additional kilometer. As for the FCPT, unit cost includes the fuel cell stack cost and fuel cost to reach an initial 100 km and, for further travel, only fuel is required, thus the hydrogen cost.

From an initial glance through the results, it can be observed that the base price of the BPT for microcar is nearly one-third that of the FCPT. While looking on to the energy expense to cover a 1 km distance in addition to the base expense, BEV owners have to pay more when compared to FC vehicle owners. This is because, for BPT, an additional battery has to be mounted along with the energy cost, while for FCPT, only fuel cost is included and the higher net calorific energy value of hydrogen (33.33 kWh/kg [48]) help to reduce the cost further down. Further studies were performed to analyze the cost breakdown for the transportation of each passenger with different vehicle types in BEV and FCEV configuration as shown in Table 6.

Table 5. Cost analysis with battery powertrain and fuel cell powertrain (in euros).

Payload (kg)	Veh.	Battery Powertrain (BPT)				Fuel Cell Powertrain (FCPT)				
		Base Price (100 km)	**200 km**	**300 km**	**400 km**	**Base Price (100 km)**	**200 km**	**300 km**	**400 km**	**500 km**
150	Micro	888.4	9.8	10.2		2637	0.07	0.07	0.07	0.07
	4s	1574.0	16.2	17.7	18.1	11,514	0.14	0.14	0.14	0.14
	5s	1727.7	18.5	19.6	20.3	11,515	0.15	0.15	0.15	0.15
250	4s	1609.4	17.3	18.0	18.9	11,515	0.15	0.15	0.15	0.15
	5s	1798.6	19.0	20.2	20.9	11,516	0.16	0.16	0.16	0.18
350	4s	1656.7	17.5	18.6	19.7	11,516	0.16	0.16	0.16	0.16
	5s	1834.0	19.4	21.2	21.4	11,517	0.17	0.17	0.17	0.18
500	5s	1905.0	20.2	21.7	22.2	11,519	0.19	0.19	0.14	-
1000	shuttle	3075.3	33.2	36.9		7321	0.21	0.21	0.23	-
700	Bus	10,955.9	145.0	145.0		31,790	0.90	0.89	0.90	0.90
1750		11,207.4	162.5	162.5		32,800	1.00	1.00	1.00	1.01
3850		13,526.9	191.0	191.0		31,817	1.17	1.17	1.17	1.17
6750	Semi-truck	7488.4	82.0	82.0		49,779	0.79	0.79	0.79	0.79
13,500		10,632.8	133.0	133.0		49,812	1.12	1.11	1.12	1.12
27,000		21,578.3	289.1	289.1		49,887	1.87	1.87	1.87	1.87

Note: It is assumed that vehicle segments with the same specification are employed and thus the cost apart from the powertrain is the same for both battery and fuel cell EV. Abbreviation: Micro—Microcar; 4s—Urban 4s; 5s—Extra Urban 5s.

Table 6. Cost analysis per passenger with battery powertrain and fuel cell powertrain (in euros per passenger).

Payload (kg)	Veh.	Battery Powertrain (BPT)				Fuel Cell Powertrain (FCPT)				
		Base Price (100 km)	**200 km**	**300 km**	**400 km**	**Base Price (100 km)**	**200 km**	**300 km**	**400 km**	**500 km**
150 kg	Micro	444.2	4.9	5.1		1318.6	0.04	0.04	0.04	0.04
	4s	787.0	8.1	8.9	9.0	5756.9	0.07	0.07	0.07	0.07
	5s	863.8	9.2	9.8	10.2	5757.7	0.08	0.08	0.08	0.07
250 kg	4s	536.5	5.8	6.0	6.3	3838.3	0.05	0.05	0.05	0.05
	5s	599.5	6.3	6.7	7.0	3838.8	0.05	0.05	0.05	0.06
350 kg	4s	414.2	4.4	4.6	4.9	2879.0	0.04	0.04	0.04	0.04
	5s	458.5	4.9	5.3	5.3	2879.3	0.04	0.04	0.04	0.04
500 kg	5s	381.0	4.0	4.3	4.4	2303.7	0.04	0.04	0.03	-
1000	shuttle	256.3	2.8	3.1		610.1	0.02	0.02	0.02	-
700	Bus	1095.6	14.5	14.5		3178.9	0.09	0.09	0.09	0.09
1750		448.3	6.5	6.5		1272.0	0.04	0.04	0.04	0.04
3850		245.9	3.5	3.5		578.5	0.02	0.02	0.02	0.02
6750	Semi truck **	1109.4	12.1	12.1		7374.6	0.12	0.12	0.12	0.12
13,500		787.6	9.9	9.9		3689.8	0.08	0.08	0.08	0.08
27,000		799.2	10.7	10.7		1847.7	0.07	0.07	0.07	0.07

** for semi-truck, powertrain expense per ton is calculated instead of per passenger. Abbreviation: Micro—Micro-car; 4s—Urban 4s; 5s—Extra Urban 5s.

Table 6 shows the energy cost breakdown per passenger/km and we can see that the base price of the powertrain goes down for unit passengers as with more passengers. Considering the full capacity of the bus, BPT costs 246 €/km as the base cost, while with fuel cell the base cost becomes 578 €/km, which is comparable. In addition to this, taking into consideration the fuel expense for the rest of the journey, it can be estimated that the FCPT bus becomes more economical than its counterpart accounting for the total operating lifetime.

For the semi-truck, instead of the cost to travel unit distance with 1 passenger, the cost for transporting 1 ton to unit distance is estimated. From the results, it can be observed that at full load, the base price per ton of cargo is 50% more with FCPT in trucks, while transportation cost per km apart from the powertrain cost is cheapest at 7 cents/km. While considering half load, the base cost is almost triple, however, sizing the FC stack to transport the corresponding load drastically reduces this base cost. However, it requires personalized FC stack sizing, which reduces the flexibility to transport wide payload ranges.

Accepting the possibility of price reduction in the future for battery, hydrogen fuel cost and electricity price reduction, the base price and cruise expense for unit distance are expected to reduce even further. Figure 10 shows the variation in the price range for different vehicle types against the results in Table 5.

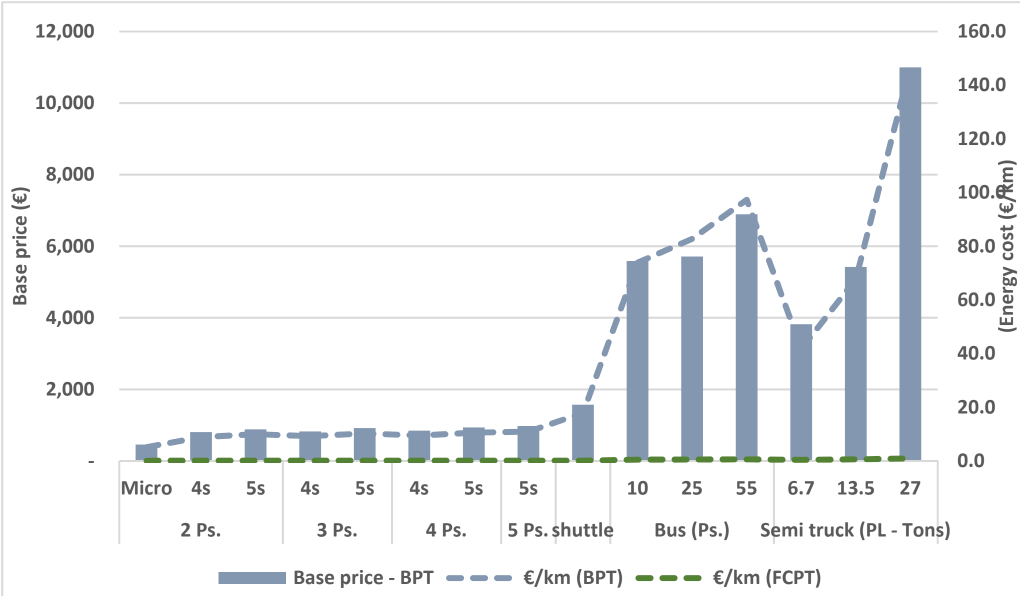


Figure 10. Cost analysis with reduced battery pack and fuel price (fuel cell powertrain (FCPT) base price is not included).

Figure 10 shows cost analysis with reduced battery pack and fuel prices. It is to be noted that the base price of FCPT is not included. This is due to that the fuel cell stack price solely depends on the number of units produced and since the technology is still at its initial development phase, the future production cannot be estimated and thus the stack price. A well-developed battery sector enables us to estimate the battery production for the future and thus the cost. From the results, it can be observed that the reduction in battery price nearly cut down the base price and cruise expense/km by half. Nonetheless, it can be seen that the reduction of hydrogen price reduces the cruise expense even further down by 50%, and enables semi-trucks with a full load to cruise under 1 €/km.

Soon, when vehicles become customized based on storage requirements, this slight change in price for each kilometer will generate a broader difference in the vehicle's CAPEX. Assuming these favorable conditions, this will increase the unit FC stack production, which will reduce the cost even further from 60 €/kW, which can bring down the base price of FCEV.

4. Discussion

This study aims to assess BPT and FCPT vehicle performance in real-world conditions, evaluating range and energy consumption for various vehicle segments with real-world drive cycles and with variable payloads. A simulation model was developed in MATLAB using Simulink, by defining different vehicle type models and dimensioning the efficiency of the various components involved. This enables estimating the energy consumption under different real-world driving conditions. The model was previously validated [9] and ensured reliability with an error of 5% for light-duty vehicles and 2% for heavy-duty vehicles.

The results from Sections 3.2 and 3.3 indicate that choosing vehicle segments based on the number of passengers results in the least energy consumption. For two passengers, a

Micro-car is advised with energy consumption less than 60% compared to other vehicles, along with the least energy consumption per passenger. While for three and four passengers, the Urban 4s is suitable with a maximum range same as Extra-urban 5s, with less energy consumption; and for five passengers the Extra-urban 5s is adequate. The result showed Urban 4s and Extra-urban 5s vehicles can reach almost a similar distance with their respective full battery capacity, which shows that choosing the proper vehicle segment helps to reduce the CAPEX, OPEX, and battery charging time. Also, the result showed it would be beneficial to consider a medium-duty vehicle for a group of passengers rather than employing multiple light-duty vehicles. To transport more than 25 passengers, the bus would also be a better option, while having multiple shuttles can also be considered.

Considering the different powertrain options, the FCPT showed remarkable results compared to BT, where the former reached an average range of 600 km or more in all different drive cycles with full fuel capacity, while the latter only cruised nearly 350 km on average. On analyzing the operational cost based on powertrain selection for unit distance, FCEV remains the most expensive option with a base cost two to eight-fold that of the BEV based on vehicle types. However, FCEV showed remarkable results with an average operating energy cost between 7 cents/km to 2 €/km, where BEV cruise energy cost ranges between 10 €/km to 290 €/km in addition to the base cost. Also, it is worth noting that considering full occupancy in bus, the base cost per person for FCPT would be just 60% more when compared to BPT, and taking the operating cost into account, FCPT would be more economical. Real-world drive cycles testing with variable payload showed that the FCPT would be ideal for a heavy-duty vehicle for long-range operations against its cost as with full payload capacity, even though the base cost is 50% more with FCPT than BPT, the operational cost is around 1.2 €/km for FCPT compared to 300 €/km with BPT.

5. Conclusions

This paper presents an assessment of vehicle performance in real-world conditions with variable payloads despite the claims from the vehicle manufacturers. This difference in claimed vehicle performance to real-world performance will open opportunities for other vehicle segments which are considered as the model for this study. Consequently, these different vehicle types must be seen as complementary (and not competitive) according to usage and payload requirements, meaning that we may be transitioning to more tailor-made and not generalized solutions. In the future, manufacturing customized vehicles would improve the support from the automotive sector towards sustainable goals. Subsequently, this work provides guidelines to all the former mentioned forecasts towards a more sustainable automotive industry.

Future work will be performed in accounting for the volumetric constraints related to the hydrogen storage and thermal management requirements associated with these systems, which are not accounted for in this paper.

Author Contributions: Conceptualization, P.B., S.S.; methodology, P.B., S.S.; software, S.S.; validation, S.S.; formal analysis, P.B., S.S.; investigation, S.S.; data curation, S.S.; writing—original draft preparation, S.S., P.B., A.M., F.M.; writing—review and editing, S.S., P.B., A.M., F.M.; supervision, P.B., A.M., F.M.; project administration, A.M., F.M.; funding acquisition, A.M., F.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

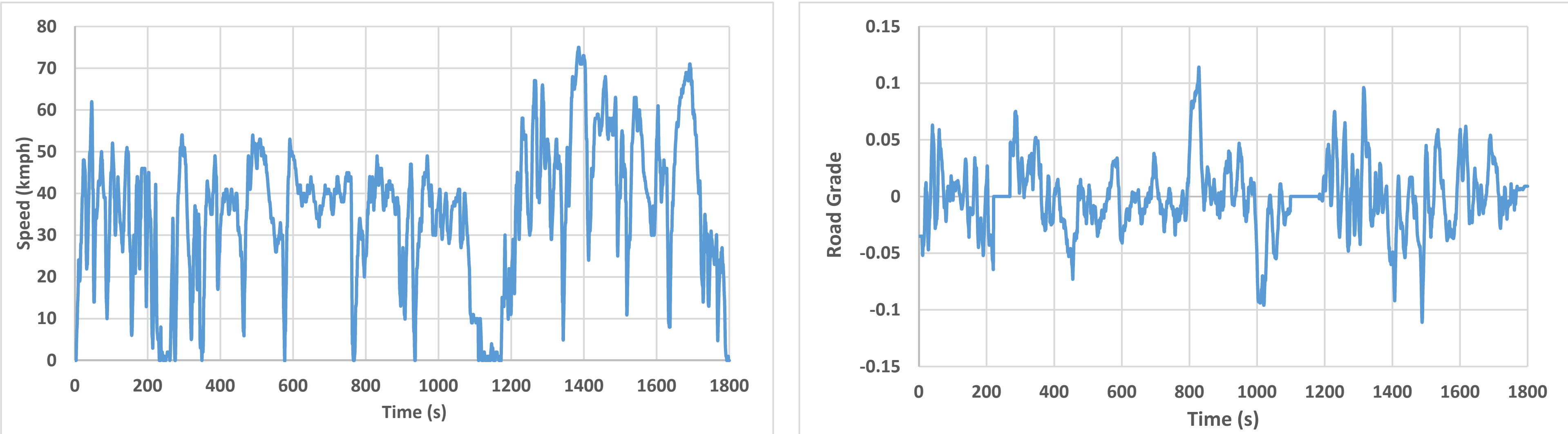

Figure A1. Real-world drive cycle 1 (duration: 1800 s). Real-world drive cycle 1 (RW1) for light-duty vehicles (Urban 4s and Extra-urban 5s).

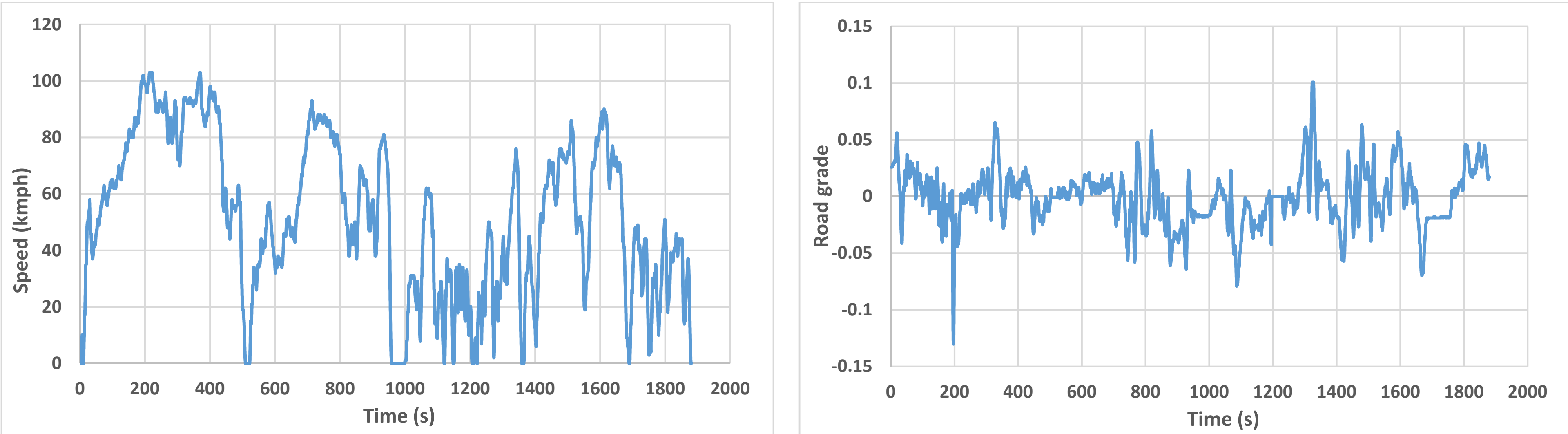

Figure A2. Real-world drive cycle 2 (duration: 1880 s). Real-world drive cycle 2 (RW2) for light-duty vehicles (Urban 4s and Extra-urban 5s).

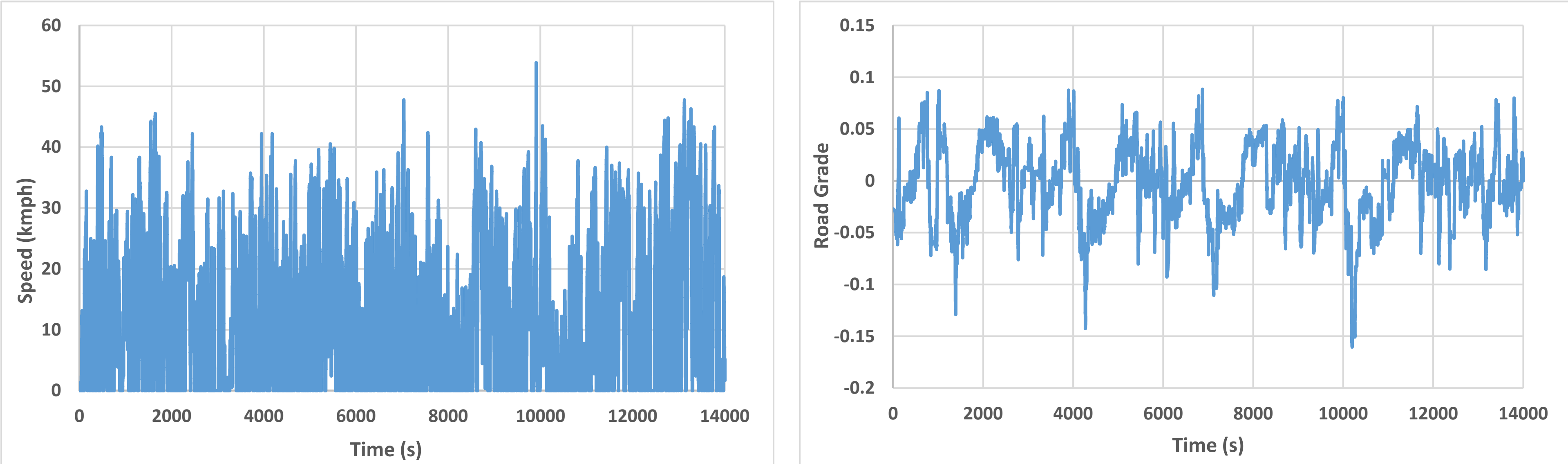

Figure A3. Real-world drive cycle for micro-car/shuttle (duration: 14,004 s). Real-world drive cycle (RW_m) for Micro-car/Shuttle vehicle.

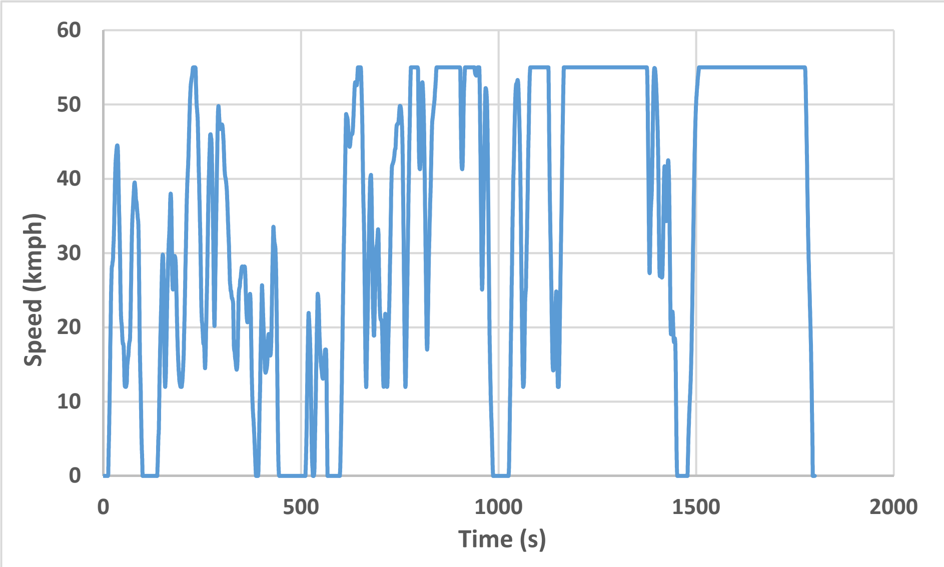

Figure A4. Modified WLTP class 3 drive cycle (duration: 1800 s). Modified WLTP class 3 drive cycle for Micro-car/shuttle (maximum speed limited to 55 kmph).

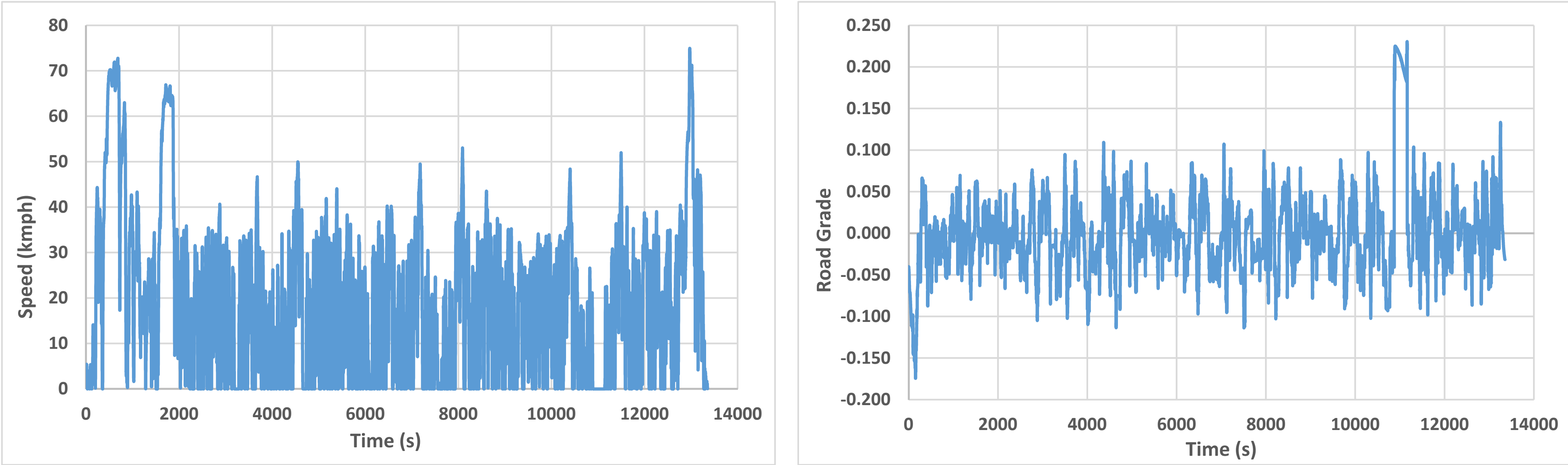

Figure A5. Real-world drive cycle for Bus (duration: 13,353 s). Real-world drive cycle (RW_b) for Bus.

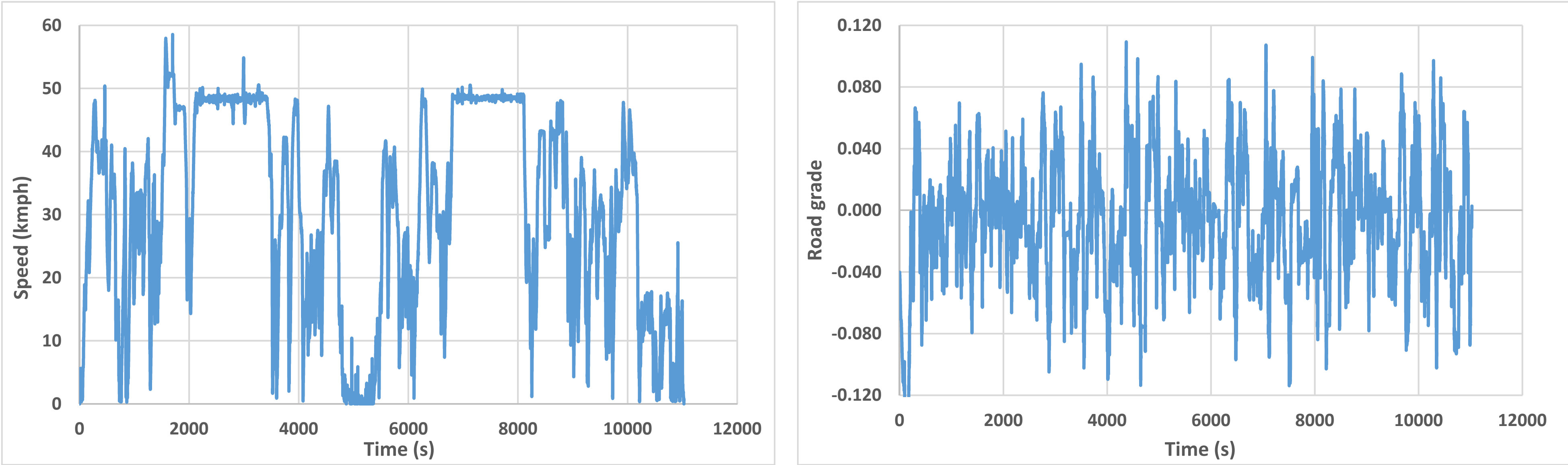

Figure A6. Real-world drive cycle for Semi-truck (duration: 11,027 s). Real-world drive cycle (RW_st) for semi-truck.

Table A1. Simulation results of different vehicle segments with distinct drive cycles.

PL	Drive Cycle	Power Train	100 km				200 km				300 km				400 km				500 km			
			Veh	A	B	C		A	B	C		A	B	C		A	B	C		A	B	C
150	WLTP red.	BEV	Micro car	58.51	0.12	6	Micro car	60.93	0.13	12.3	Micro car	63.57	0.13	19.1	Micro car	-	-	-	Micro car	-	-	-
		FC		133.8	0.12	0.4		133.9	0.12	0.8		134	0.12	1.2		134.1	0.12	1.6		134.3	0.12	2
	RW_m	BEV		74.65	0.84	7.5		78.45	0.94	15.8		80.21	0.98	19.5/243 km		-	-	-		-	-	-
		FC		164.5	0.88	0.48		164.6	0.88	0.95		164.7	0.88	1.42		164.8	0.88	1.9		164.9	0.88	2.37
	WLTP red.	BEV	Urban 4s	91.53	0.47	9.3	Urban 4s	94.08	0.51	19	Urban 4s	96.73	0.54	29	Urban 4s	99.66	0.576	40	Urban 4s	102.7	0.62	51.5
		FC		197.5	0.45	0.62		197.5	0.48	1.23		197.6	0.45	1.85		197.7	0.45	2.47		197.8	0.45	3.08
	WLTP C3	BEV		130.8	0.66	13.3		134.8	0.74	27		139.1	0.81	42		142.3	0.87	53/372 km		-	-	-
		FC		287.5	0.62	0.9		287.6	0.62	1.8		287.7	0.62	2.7		287.8	0.62	3.6		287.9	0.62	4.5
	RW 1	BEV		102.5	1.35	10.5		107.2	1.44	21.6		112.7	1.54	33.9		119	1.65	47.6		121.5	1.69	53/436 km
		FC		333.7	0.65	1.06		333.9	0.65	2.12		334.2	0.65	3.8		334.4	0.65	4.24		334.7	0.65	5.3
	RW 2	BEV		115.5	1.28	11.8		119.8	1.37	24		124.6	1.49	37.4		130.1	1.61	52.1		-	-	-
		FC		302.1	0.79	0.96		302.3	0.79	1.92		302.5	0.79	2.88		302.6	0.79	3.84		302.9	0.79	4.8
	WLTP red.	BEV	Extra Urban 5s	104.6	0.53	10.6	Extra Urban 5s	107.7	0.56	21.8	Extra Urban 5s	111	0.6	33.4	Extra Urban 5s	114.6	0.65	46	Extra Urban 5s	118.5	0.69	59.5
		FC		226.7	0.49	0.71		226.8	0.49	1.42		226.9	0.49	2.13		227	0.49	2.84		227.1	0.49	3.55
	WLTP	BEV		145.8	0.74	14.6		150.3	0.82	30.2		155.2	0.9	46.8		159.9	0.96	59/371 km		-	-	-
		FC		321.9	0.69	1.02		322	0.69	2.04		322.1	0.69	3.06		322.3	0.69	4.08		322.5	0.69	5.1
	RW 1	BEV		116.4	1.48	12.2		122.1	1.59	24.8		128.7	1.69	38.8		136.7	1.8	55.2		-	-	-
		FC		374.7	0.69	1.2		374.9	0.7	2.4		375.2	0.7	3.6		375.5	0.7	4.8		375.7	0.7	5.6/473 km
	RW 2	BEV		129.4	1.39	13		134.6	1.51	27		140.3	1.63	42.1		147	1.765	59		-	-	-
		FC		339.2	0.85	1.08		339.4	0.85	2.16		339.6	0.85	3.24		339.8	0.85	4.3		340	0.85	5.37

Table A1. *Cont.*

PL	Drive Cycle	Power Train	100 km				200 km				300 km				400 km				500 km			
			Veh	**A**	**B**	**C**		**A**	**B**	**C**		**A**	**B**	**C**		**A**	**B**	**C**		**A**	**B**	**C**
250	**WLTP red.**	**BEV**	Urban 4s	98.11	0.53	9.9	Urban 4s	101	0.57	20.4	Urban 4s	104.2	0.6	31.5	Urban 4s	107.4	0.64	43	Urban 4s	110.3	0.68	53/480 km
		FC		218.4	0.46	0.68		218.4	0.46	1.36		218.5	0.46	2.04		218.6	0.46	2.73		218.7	0.46	3.41
	WLTP	**BEV**		135.6	0.75	13.6		139.8	0.82	28.2		144.3	0.9	43.4		147.1	0.95	53/360 km		-	-	-
		FC		303.7	0.66	0.96		303.9	0.66	1.92		304	0.67	2.88		304.1	0.66	3.84		304.3	0.66	4.8
	RW 1	**BEV**		109.8	1.49	11.2		115.2	1.59	23.2		121.4	1.69	36.5		128.6	1.8	51.5		-	-	-
		FC		365.3	0.66	1.16		365.6	0.66	2.32		365.8	0.66	3.48		366.1	0.66	4.64		366.3	0.66	5.6/485 km
	RW 2	**BEV**		121.4	1.41	12.4		126.1	1.524	25.3		131.5	1.64	39.6		136.7	1.75	53/388 km		-	-	-
		FC		326.4	0.8	1.05		326.6	0.8	2.09		326.9	0.8	3.13		327	0.8	4.16		327.3	0.8	5.2
	WLTP red.	**BEV**	Extra Urban 5s	109.3	0.58	11	Extra Urban 5s	112.6	0.62	22.6	Extra Urban 5s	116.1	0.66	35	Extra Urban 5s	119.9	0.7	48	Extra Urban 5s	123.2	0.74	59/478 km
		FC		242.6	0.5	0.76		242.6	0.5	1.51		242.7	0.5	2.27		242.8	0.5	3.04		242.9	0.5	3.8
	WLTP	**BEV**		150.7	0.83	15.2		155.5	0.91	31.3		160.6	0.99	48.4		163.9	1.1	59/360 km		-	-	-
		FC		339.1	0.72	1.07		339.2	0.72	2.14		339.3	0.72	3.21		339.5	0.72	4.28		339.6	0.72	5.35
	RW 1	**BEV**		124.1	1.62	12.8		130.4	1.72	26.1		138	1.83	41.5		147	1.96	59		-	-	-
		FC		406.9	0.71	1.3		407.1	0.71	2.6		407.5	0.71	3.9		407.7	0.71	5.2		408	0.71	5.6/435 km
	RW 2	**BEV**		135.7	1.53	13.9		141.3	1.65	28.3		147.7	1.78	44.5		153.7	1.89	59/384 km		-	-	-
		FC		363.9	0.86	1.15		364.1	0.86	2.3		364.3	0.86	3.45		364.6	0.86	4.6		364.7	0.87	5.6/486 km

Table A1. *Cont.*

PL	Drive Cycle	Power Train	100 km				200 km				300 km				400 km				500 km			
			Veh	A	B	C		A	B	C		A	B	C		A	B	C		A	B	C
350	WLTP red.	BEV	Urban 4s	101.7	0.58	10.2	Urban 4s	104.8	0.61	21.22	Urban 4s	108	0.65	32.5	Urban 4s	111.8	0.69	44.6	Urban 4s	114	0.71	53/465 km
		FC		230.4	0.47	0.72		230.4	0.47	1.44		230.6	0.47	2.16		230.6	0.47	2.88		230.7	0.47	3.6
	WLTP	BEV		139.3	0.82	14		143.6	0.89	28.8		148.3	0.97	44.5		150.9	1.01	53/351 km		-	-	-
		FC		316.8	0.7	1		316.9	0.7	2		317	0.7	3		317.1	0.7	4		317.3	0.7	5
	RW 1	BEV		115.7	1.56	11.8		121.6	1.69	24.4		128.3	1.79	38.5		135.6	1.9	53/390 km		-	-	-
		FC		389.9	0.67	1.25		390.2	0.69	2.5		390.5	0.67	3.75		390.8	0.69	5		390.9	0.69	5.6/454 km
	RW 2	BEV		126	1.52	12.7		131.2	1.64	26.4		137	1.76	41.2		141.8	1.85	53/374 km		-	-	-
		FC		345.4	0.81	1.1		345.6	0.81	2.2		345.8	0.81	3.3		346	0.81	4.4		346.2	0.81	5.5
	WLTP red.	BEV	Extra Urban 5s	112.9	0.63	11.4	Extra Urban 5s	116.4	0.67	23.5	Extra Urban 5s	120.1	0.71	36.1	Urban 5s	124.2	0.75	49.8	Extra Urban 5s	127	0.78	59/465 km
		FC		254.8	0.51	0.8		254.9	0.51	1.6		255	0.51	2.4		255	0.51	3.2		255.2	0.51	4
	WLTP	BEV		154.5	0.89	15.5		159.4	0.97	31.9		164.9	1.1	49.8		167.8	1.1	59/351 km		-	-	-
		FC		352.3	0.75	1.11		352.4	0.75	2.22		352.5	0.75	3.33		352.7	0.75	4.44		352.9	0.75	5.56
	RW 1	BEV		130.1	1.71	13.1		137.2	1.82	27.5		145.6	1.94	43.8		153.7	2.04	59/384 km		-	-	-
		FC		432.1	0.72	1.37		432.5	0.72	2.74		432.7	0.72	4.1		433.1	0.72	5.46		433.2	0.72	5.6/410 km
	RW 2	BEV		140.6	1.64	14.1		146.7	1.76	29.4		153.5	1.89	46.2		158.9	1.98	59/371 km		-	-	-
		FC		383.2	0.87	1.21		383.5	0.87	2.42		383.7	0.87	3.64		383.9	0.87	4.85		384.1	0.87	5.6/462 km

Table A1. *Cont.*

PL	Drive Cycle	Power Train	100 km				200 km				300 km				400 km				500 km		
			Veh	A	B	C		A	B	C		A	B	C		A	B	C		A	B	C
500	WLTP red.	BEV	Extra Urban 5s	118.5	0.69	12	Extra Urban 5s	122.2	0.73	24.5	Extra Urban 5s	126.3	0.78	38	Extra Urban 5s	130.7	0.82	52.5	Extra Urban 5s	132.7	0.84	59/445 km
		FC		273.3	0.52	0.86		273.4	0.52	1.72		273.5	0.52	2.58		273.6	0.52	3.44		273.7	0.52	4.3
	WLTP	BEV		160.3	0.98	16.1		165.6	1.1	33.2		171.4	1.15	51.5		173.8	1.2	59/340 km		-	-	-
		FC		373.4	0.78	1.18		373.6	0.78	2.36		373.8	0.78	3.55		374	0.78	4.72		374.1	0.78	5.6/475 km
	RW 1	BEV		139.9	1.86	14		148.1	1.97	29.8		157.7	2.09	47.6		164.1	2.17	59/360 km		-	-	-
		FC		470.3	0.74	1.5		470.7	0.74	3		471.1	0.74	4.5		471.3	0.74	5.6/377 km		-	-	-
	RW 2	BEV		148.5	1.78	15.1		155.2	1.916	31.4		162.6	2.05	48.8		167	2.12	59/353 km		-	-	-
		FC		412.6	0.88	1.32		412.9	0.88	2.64		413.1	0.88	3.96		413.4	0.88	5.28		413.4	0.88	5.6/429 km
1000	WLTP red.	BEV	Shuttle	216.5	0.69	21.6	Shuttle	226.3	0.68	45.8	Shuttle	236.3	0.71	70/296 km	Shuttle	-	-	-	Shuttle	-	-	-
		FC		464.5	0.62	1.37		464.7	0.62	2.74		464.9	0.62	4.1		465.2	0.62	5.48		448.5	0.64	5.6/408
	RW	BEV		257.3	4.84	26		270.6	5.19	54.1		278.5	5.38	70/251		-	-	-		-	-	-
		FC		561.3	4.68	1.7		561.7	4.68	3.4		562.1	4.68	5.1		562.2	4.68	5.6/332 km		-	-	-

A—Average energy consumption (Wh/km); B—Regenerative energy generated (kWh); C—Energy storage required (For BEV—kWh of battery; for FCEC—kg of H_2).

Table A2. Simulation results for heavy-duty vehicles.

	Range		150			300			500			700			1000		
Veh.	**PL**	**Power Train**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Bus (220 kW FC)	**700**	**BEV**	1000	27.71	154	1121	29.93	338	1136	30.18	360/316 km	-	-	-	-	-	-
		FC	2455	16.42	11.6	2458	16.42	23.2	2462	16.42	38.8	2465	16.42	54.3	2471	16.45	77.6
	1750	**BEV**	1092	29.43	163.5	1229	31.57	360/293 km	-	-	-	-	-	-	-	-	-
		FC	2704	16.61	13	2707	16.62	25.8	2711	16.62	42.8	2715	16.62	60	2721	16.63	85.8
	2800	**BEV**	1194	31.07	180	1326	32.84	360/272 km	-	-	-	-	-	-	-	-	-
		FC	2961	16.77	14.1	2965	16.78	28.2	2969	16.79	46.9	2974	16.79	65.7	2981	16.79	93.8
	3850	**BEV**	1301	32.53	195.2	1427	34.01	360/252 km	-	-	-	-	-	-	-	-	-
		FC	3230	16.93	15.3	3234	16.93	30.6	3239	16.93	51	3244	16.93	71.4	3252	16.95	100/978 km
Semi-truck	**6750 (25% PL)**	**BEV**	646.6	52.15	98	673.4	54.75	202	723	58.46	363.5	775.3	61.87	520/670 km	-	-	-
		FC	2156	14.87	10.2	2158	14.87	20.4	2160	14.88	34	2162	14.88	47.7	2164	14.88	68.2
	13,500 (50% PL)	**BEV**	959	70.9	146	1035	73.8	315	1135	77.15	520/458	-	-	-	-	-	-
		FC	3061	15.55	14.6	3063	15.55	29	3067	15.55	48.34	3069	15.55	67.7	3073	15.55	96.82
	20,250 (75% PL)	**BEV**	1427	85	216.8	1586	88.38	475	1615	88.94	520/322	-	-	-	-	-	-
		FC	4038	15.9	19.3	4041	15.9	38.6	4045	15.9	64.4	4049	15.9	90	4051	15.9	100/782 km
	27,000 (100% PL)	**BEV**	2030	95.89	304.8	2179	97.9	520/238 km	-	-	-	-	-	-	-	-	-
		FC	5160	16.17	24.6	5165	16.17	49.2	5171	16.18	82	5175	16.19	100/612 km	-	-	-

Note: In some simulation, instead of the required energy storage, the following format is used; {520/238 km}. It implies with the max possible storage capacity (i.e., 520 kW), only 238 km can be travelled. (Example taken from semi-truck simulated for 300 km targeted range with 100% payload capacity).

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