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University of Wales Trinity Saint David - School of Engineering.

Drive-Cycle Requirement Specifications

Hybrid Powertrain and Control (ACEA7007)

2023 - 2024



Figure 1: Tesla Model 3 (Unplugged Performance, 2023)

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2 Introduction

The following paper presents the validation of a drive cycle and a theoretical hybrid Battery Energy - Hydrogen Fuel Cell conversion of a Tesla Model 3.

From 2035 Onwards, the EU has proposed regulations for both cars and vans, allowing 0g CO₂/km in order to decrease greenhouse gasses and global warming [1]. The Intergovernmental Panel on Climate Change has emphasized the critical need to cap global warming at 1.5°C rather than 2°C to mitigate severe environmental impacts. A major driver of these environmental challenges is the extensive use of fossil fuels for energy. In 2018, the global primary energy demand reached 14,282 million tonnes of oil equivalent (Mtoe), with fossil fuels fulfilling 81% of this demand. Notably, the transportation sector alone consumed 2890 Mtoe, representing 20% of the worldwide primary energy demand.

Table 1 shows the vehicle specifications regarding the tesla Model 3 on which this paper is based.

Table 1: Tesla Model 3 Specifications (UWTSD, 2024)

Mass	Kg	1980
Mass Distribution	% F-R	48-52
Wheelbase	m	2.875
CD	~	0.23
Driven Tyre size	Standard	235/35-20
Battery Nominal Voltage	V	360
Battery Capacity	kWh	75
Peak Torque	Nm	639
Peak Power	kW	336
WLTP Range	km	530
WLTP Consumption	Wh/km	166

The Worldwide Harmonized Light Vehicles Test Cycles (WLTC) are used to measure emissions and fuel consumption from light-duty vehicles using chassis dynamometer tests. Class 3, which has the highest power-to-mass ratio, typically includes vehicles commonly driven in Europe and Japan. This class is further segmented into two subclasses based on their maximum speeds: Class 3a for vehicles with a maximum speed less than 120 km/h, and Class 3b for vehicles with a maximum speed of 120 km/h or more [2].

The pursuit of sustainable and efficient transportation solutions continues to drive technological innovations and regulatory changes worldwide. Among the many approaches explored, the integration of fuel cell technology into existing battery electric vehicle architectures presents a compelling pathway toward enhancing energy efficiency and reducing environmental impact. This report delves into a comparative analysis of the manufacturer-stated Worldwide Harmonized Light

Vehicles Test Procedure (WLTP) for the Tesla Model 3 and a bespoke drive cycle developed to validate alternative powertrain configurations. The primary objective of this study is to assess the validity and reliability of a newly created drive cycle in mimicking the WLTP, which is recognized for its rigorous approach to measuring vehicle range and energy consumption under simulated conditions.

This analysis focuses on replacing 50% of the Tesla Model 3's battery capacity with a hydrogen fuel cell system. This modification aims to achieve a comparable WLTP range while adhering to post-2035 vehicle emission standards, which advocate for significant reductions in carbon emissions. The options considered include enhancing the energy delivery efficiency of the fuel cell beyond 50%, potentially removing the battery entirely, or incorporating capacitors to augment the fuel cell or serve as additional energy storage mediums. These changes necessitate recalculating the WLTP drive cycle based on the altered mass and energy characteristics of the new powertrain configuration.

3 Motec + System Efficiencies determination

Recorded Motec Data of a normal in-traffic drive of a tesla model 3 was provided for use in this assignment [3]. The data consisted of a 3h40m drive which covered 82.042km. Figure 2 shows a screenshot of the data in Motec, showing the speed profile.



Figure 2: Recorded Tesla Data Speed Trace (Iatrakis, 2024)

The data initially was aimed to be used to determine energy consumption over the drive, as channels were provided which consisted of energy charged, discharged and remaining charge. The aim was then to calculate the vehicle loads, vehicle resistance, and then energy required and available to be charged at the wheels and compare these values with the measured discharged and charged energy at the battery in order to determine real system consistencies.

Figure 3 shows the calculated resistant forces in Motec. Figure 4 shows the calculations used in Motec of these channels.

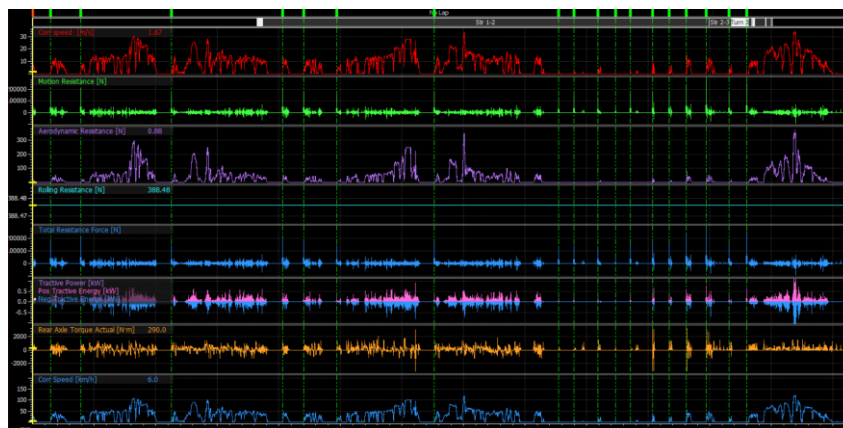


Figure 3: Calculated Resistant Forces (Iatrakis, 2024)

Maths	
Name	Summary
☒ Corr speed [m/s]	'Corr Speed' [km/h]/3.6
☒ Calcd Corr Accel [m/s/s]	derivative('Corr speed ' [m/s])
☒ Motion Resistance [N]	'Mass' [kg] * 'Calcd Corr Accel' [m/s/s]
☒ Aerodynamic Resistance [N]	0.5*'Rho' [kg/m3]*'Coeff of Drag' []*'Frontal Area' [m/s]*sqr('Corr speed ' [m/s])
☒ Rolling Resistance [N]	'Coeff of Rolling Res' []*'Mass' [kg]*'Gravitational Accel' [m/s/s]
☒ Total Resistance Force [N]	'Aerodynamic Resistance' [N]+ 'Rolling Resistance' [N]+ 'Motion Resistance' [N]
☒ Tractive Power [kW]	'Total Resistance Force' [N]*'Corr speed ' [m/s]/1000
☒ Pos Tractive Energy [kJ]	choose('Tractive Power' [kW] > 0, 'Tractive Power' [kW] , 0)
☒ Neg Tractive Energy [kJ]	choose('Tractive Power' [kW] < 0, 'Tractive Power' [kW] , 0)
☒ Power [W]	'Battery Pack Voltage' [V] * 'Battery Current' [A]
☒ Inst Power Regen [W]	choose('Power' > 0, 'Power' , 0)
☒ Inst Power Tractive [W]	choose('Power' < 0, 'Power' , 0)

Figure 4: Calculation Tab Motec (Iatrakis, 2024)

The energy values for charging and discharging recorded in the Motec Data were considered unrealistic because they were found to be twice as high as the expected tractive loads. This discrepancy resulted in calculated system efficiencies of only 52%, significantly below the anticipated 80% [4]. Figure 5 displays the channel reports for energy-related metrics in Motec. Table 2 compares the energy usage data provided by Motec with the calculated tractive energy.

Table 2: System Efficiency Calculation using Motec measured data (Iatrakis, 2024)

Efficiency calc Motec Given Energy Usage				
	Wheel Calc	Motec	Loss	Efficiency
Discharged (kW)	17.070	27.106	10.036	0.630
Charged (kW)	5.230	4.428	0.802	0.847
Total Discharge (kW)	11.840	22.678	10.838	0.522

Battery Energy Info		UWTSD Workshop, Coast Down Test Andrew Noble, Tesla 28/10/2021, Oct 2021 13:13:11, No Lap [220:17.000]	
Battery Energy Capacity [kW]	Min	72.4	
	Max	72.8	
	Avg	72.5	
	Start	72.5	
	End	72.8	
Battery Energy Charged [kW]	Min	13016.910	
	Max	13021.338	
	Avg	13019.630	
	Start	13016.910	
	End	13021.338	
Battery Energy Discharged [kW]	Min	12459.884	
	Max	12486.990	
	Avg	12473.537	
	Start	12459.884	
	End	12486.990	
Battery Energy Remaining [kW]	Min	48.9	
	Max	71.0	
	Avg	60.4	
	Start	71.0	
	End	48.9	
Energy Used Trip [kW]	Min	49.52	
	Max	52.03	
	Avg	50.82	
	Start	49.52	
	End	52.03	

Figure 5: Motec Energy Usage Channel Report (Iatrakis, 2024)

The data provided encompasses the battery pack voltage (V) and battery Current (A) as measured channels. Using these channels, the motor power (W) has been calculated instead of using the provided energy channels. The power has been split up in tractive power (discharged/ negative) and Regenerative Power (Charged/ Positive), the data has then been exported as a CSV in order to perform further calculations.

Figure 6 shows the calculated power channels. Using the CSV data in excel, the sum of the instantaneous positive power and instantaneous negative power was calculated in order to determine the charged and discharged battery energy over the full measurement cycle.



Figure 6: Calculated Power Channels (Iatrakis, 2024)

Table 3 shows a comparison between the calculated energy required, regenerative energy at the wheels and the calculated battery discharged and charged energy. The calculated system efficiencies derived from these values are more realistic than table 2 and are assumed as feasible to be used in the author's further drive cycle calculations.

Table 3: Efficiency calc using calculated battery energy usage (Iatrakis, 2024)

Efficiency calc				
	Wheel Calc	Motec Calc	Loss	Efficiency
Discharged (kW)	17.070	21.780	4.710	0.784
Charged (kW)	5.230	4.416	0.814	0.844
Total Discharge (kW)	11.840	17.364	-5.524	0.682
Efficiency full Cycle	0.682			

The collected data has also been exported in order to use the speed profile as an 'extra' drive cycle in order to compare to the WLTP drive cycle.

4 WLTP Validation

In order to validate calculated results to stated results of the Tesla Model 3's WLTP range and consumption, MatLab was used in order to 'simulate' range and consumption. The WLTP Class 3 drive cycle speed profile was provided [3], tractive and resistant forces were calculated at the wheels, using the previously calculated drivetrain efficiencies, battery drain and charge was determined.

4.1 Considerations and Limitations

The following part shortly discusses the method of calculation and which forces have been considered for the validation of the WLTP drive cycle and the limitations involved. No formulas are shown in this document as the whole calculations and extra descriptions are available in the submitted MatLab script. It is important to point out the tesla has a nominal battery capacity of 72Kwh [3], this is not considered in the drive cycle calculations, but as the same battery capacity is used across all comparisons this is an accepted limitation and will not influence the comparisons made.

Resistive forces:

- Aerodynamic resistance force, calculated using provided aerodynamic specifications (table 1).

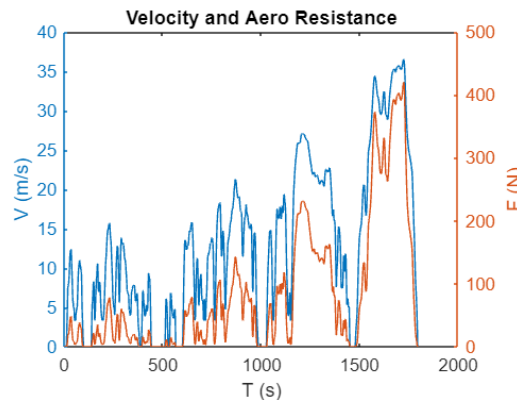


Figure 7: Calculated aerodynamic forces and WLTP speed profile. (Iatrakis, 2024)

- Rolling resistance, assumed at 2% rolling resistance coefficient [5].
- Acceleration Resistance.

Using the total resistive force, the wheel torque required, tractive energy required at the wheels and energy recoverable at the wheels can be calculated when following the WLTP 3 Driving cycle.

Using the previously calculated system efficiencies, the energy drained and charged at the battery can be calculated. The energy drained over one driving cycle is calculated by assuming that resistive forces (if not speed-dependent) and system efficiencies remain constant throughout the cycle. From this, the full range and energy consumption can be calculated based on the battery's capacity. It's also assumed that all braking energy can be regenerated and none is taken by braking power.

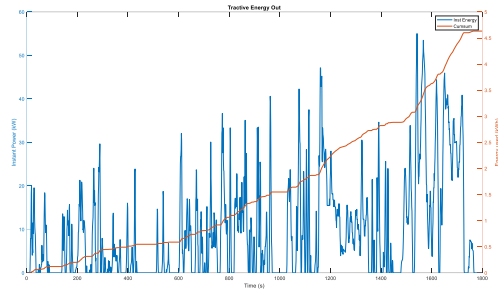


Figure 8: Calculated Instantaneous Energy required & CumSum (Iatrakis, 2024)

Figure 8 shows the instantaneous energy required at the wheels throughout the drive cycle, together with the cumulative sum.

Figure 9 shows the instantaneous recoverable energy at the wheels and the cumulative sum.

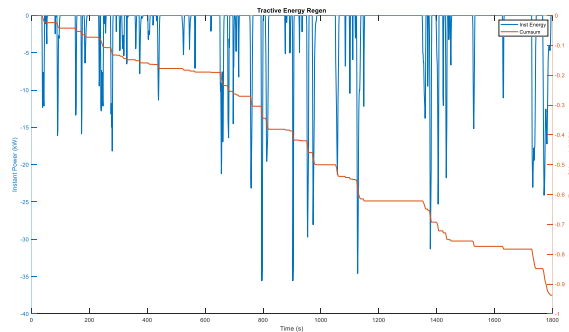


Figure 9: Calculated Instantaneous recoverable (braking) energy + CumSum. (Iatrakis, 2024)

Figure 10 shows the net energy out of the battery over one WLTP cycle, assuming no braking energy is performed by the brakes, recharging and system efficiencies have been considered.

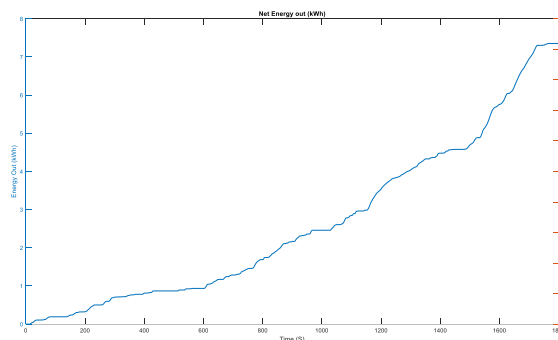


Figure 10: Calculated Cumulative Energy Used over one WLTP Cycle. (Iatrakis, 2024)

Figure 11 shows the energy stored in the battery at each point of the driving cycle, only one initial driving cycle is plotted.

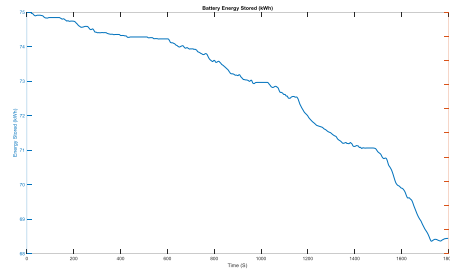


Figure 11: Calculated Energy Stored in battery over one WLTP cycle from full charge. (Iatrakis, 2024)

Table 4: Rated and Calculated WLTP results Comparison. (Iatrakis, 2024)

	Rated WLTP	Calculated WLTP	Calculated Motec
Consumption WLTP (kWh/100km)	15.7	28.55	18.46
Calculated Range (km)	527	262.67	406.30

Table 4 shows a comparison between the calculated and stated results [6] for a WLTP cycle, compared is also the calculated results using the measured data as a speed profile. There is a large difference, this is mainly expected due to the used system efficiencies as the calculated energy usage also provided for entertainment, heating etc. The stated WLTP mileage by tesla also notes 'up to 527km', where the WLTP stated range likely assumed perfect conditions and minimal extra energy usage. Though the results can be used to compare with the following work considering a change in powertrain structure. The calculated results from the measured results come closer to the WLTP rated statement. Since the calculation method for both the measured speed profile and WLTP speed profile are exactly the same, this shows the variance between different speed profiles, acceleration harshness etc more accurately. The measured data is 'softer' on acceleration and has a lower average speed than WLTP. Figure ... shows a comparison. It is expected that manufacturer consumption and mileage stated numbers are between 20% lower and 60% higher in reality [7,8], although the comparison between a less demanding calculated speed profile and the WLTP speed profile, shows more major discrepancies in the WLTP stated numbers.

Though the WLTP Test is more representative than the previous NEDC test, it is still a laboratory executed test, allowing manufacturers to 'optimise' the vehicle for that test, using special test drive modes; air conditioning; transmission optimisation; using different tyres for testing than for real-world sales; etc. Manufacturers also tend to exploit the flexibility of the way of testing, and are allowed to state a certain % decrease in WLTP mileage [8].

Even though the results are not as expected compared to Tesla's stated WLTP results, the calculation method is deemed feasible for use in the following part, comparing the 'Fuel Cell converted' Tesla.

5 Battery – Fuel Cell Conversion

The following part encompasses a theoretical conversion of the tesla model 3 to replace 50% of the battery capacity with a fuel cell.

5.1 Conversion

The idea presented is using a hydrogen fuel cell in order to charge the battery with a constant current after the battery drops past a certain percentage drain.

Considerations in the vehicle are removing 50% of the battery mass. Table 5 shows the tesla model 3's battery pack weight/ size specifications [9]. Assuming removing half the battery pack's capacity removes 50% of the mass and volume, the freed space and weight can be used for a hydrogen system.

Table 5: Tesla Battery Pack Specs (EVshop.eu, 2024)

Tesla gross weight (kg)	1980	kg
Tesla battery pack weight	480	kg
Tesla battery pack size	0.4	m ³

The author has chosen an approach of sourcing an existing fuel cell for installation into the model 3.

Toyota produces a complete fuel cell package which includes the main components (fuel cell stack and components that handle air supply, hydrogen supply, cooling and power control) [10] (figure 12). The compact package with all components means no extra space or high amounts of modifications are necessary to build the infrastructure for the extra components, just the fuel cell, hydrogen storage tank and connections between.

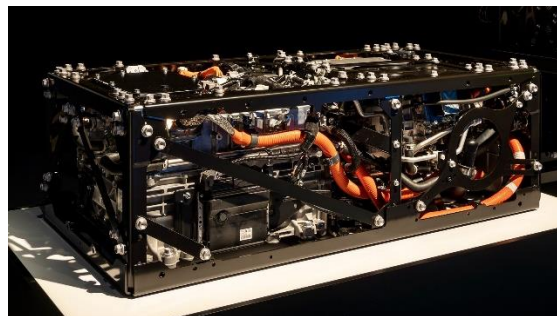


Figure 12: Toyota TFCM2-F Fuel Cell (Toyota, 2024)

The fuel cell size and weight specifications are given in table 6. Together with the Toyota Mirai Hydrogen Tank unit sizes and weight. The Fuel Cell has a 0.12m³ higher volume than the battery volume taken away and is planned to be placed in front of the rear motor, where the battery volume will be removed (Figure 13). Toyota's flagship Hydrogen vehicle, the 'Mirai' uses two compressed hydrogen storage tanks of 60l and 62l volume storing a total of 5kg hydrogen at 87.7MPa filling pressure [11]. The 60L tank at 43kg weight, housing 2.45kg of hydrogen is assumed to house enough energy to supply the Tesla Model 3 in order to increase range compared to stock. The Hydrogen tank is to be placed behind the rear seat above the rear motor (figure 13). This is in order to minimise modifications

required to the vehicle as the front end houses more of tesla's components and can keep storage space. Placing the tank in the rear also limits connection distance required between the filler cap, tank, and fuel cell module.



Figure 13: Tesla Model 3 Drivetrain (Etherelington, 2022)

Using these components, a 42kg increase in weight compared to the stock Tesla Model 3 is found.

Table 6: Fuel Cell physical specs (Iatrakis, 2024)

Fuel Cell Weight	240	kg
Fuel Cell Size	0.33	m ³
H2 storage tank Size	60	l
H2 Tank Weight	43	kg
Hydrogen storable	2.45	kg
Tesla Gross weight	1980	kg
Updated H2 Tesla Weig	2023	kg

5.2 Drive Cycle Considerations

The drive cycle is recalculated using the new vehicle specifications.

The new mass is considered for the acceleration resistance.

2.45kg of gaseous hydrogen is stored for conversion to electric energy by the fuel cell stack. An energy density of 33.6kwh/kg is assumed for hydrogen [12].

The fuel cell stack conversion efficiency between fuel cell and battery is assumed at 62% [13]. System efficiency between the battery and motor remains the same as before.

The tesla model 3 had a starting battery capacity of 75kWh, which has been halved. Considering the fuel cell system efficiency, 51kWh is available to be fed into the battery.

With the higher weight, the energy required for a drive cycle is now increased, although the energy available is increased, increasing range. Once the battery charge drops below 80%, the fuel cell will feed the average consumed usage. This has also been incorporated into the MatLab script. Table 7 shows a comparison between the calculated consumptions and ranges, consumption has increased 1.65% due to the increased range, whereas a 13.87% increase in range us

calculated, thus reaching the goal of creating a fuel cell conversion with the same or more range.

Table 7: Calculated consumption EV vs EV + FC (Iatrakis, 2024)

	Battery	Battery + Fuel cell	Diff
Useable Energy available (kWh)	75	88.5	15.25%
Consumption 1 cycle (kWh)	6.642	6.7535	1.65%
Consumption WLTP (kWh/100km)	28.55	29.03	1.65%
Calculated Range (km)	262.67	304.97	13.87%

6 Useability improvements/ deteriorations + drive cycle comparison

The conversion keeps the car weight comparable to the degree where a difference in handling isn't expected, as most mass will stay where it was as the vehicle was designed. Some boot space (60l max of the 425L stock [14]) will be lost due to the H2 Fuel tank placement but this is accepted as the vehicle wasn't designed to house the extra infrastructure required to run on hydrogen. Electric-ICE hybrid vehicles also tend to lose boot space due to usual placement of the battery pack in the rear of the car.

Following tables show the prices assumed for hydrogen fuelling at a fuelling station in 2023 [15], together with the average household electricity cost in 2023 [16] and the average fast charging station price in March 2024 [17].

Table 8: Energy Cost at pump comparison (Iatrakis, 2024)

Energy Cost Assumed	
H2	11.86 £/kg
normal electric cost	0.27 £/kWh
fast charge public	0.81 £/kWh

A clear difference is visible between running cost when vehicles are fast charged. The currently high hydrogen cost/kg also increases the running cost of the EV + H2 vehicle a lot compared to the EV.

Table 9: Calculated running costs (Iatrakis, 2024)

Running Cost Comparison				
	Full EV	Full EV Fast Charge	EV + H2	EV + H2 Fast Charge
Full charge cost	20.25	60.75	39.182	59.432
£/km WLTP	0.077	0.231	0.128	0.195
£/km Motec	0.050	0.150	0.083	0.127

Useability of the 2H vehicle is still low because of the little amount of fuelling stations currently available, 6 hydrogen filling stations are currently open for public use in the UK, dropping from 10 in 2022 [18]. Germany itself currently has 92 filling stations open [19]. Whereas 59.000 electric charging points are available for public use in the UK [20].

Refuelling the hydrogen tank at a station requires only 3-5 minutes[21], offering a substantial benefit over traditional battery charging. In contrast, supercharging a Tesla Model 3 takes 15-20 minutes and significantly accelerates wear on the battery pack [22].

However, FCEVs have a well-to-wheel efficiency of only 30% in passenger cars, significantly lower than the efficiency of around 70% of BEVs [4]. The conversion and storage of hydrogen is currently very energy inefficient, generating greenhouse gasses. The usage of composites for fuel tanks also poses challenges in recycling, though not as high as for battery Ev's.

Recycling fuel cell systems leads to a substantial reduction in greenhouse gas (GHG) emissions, while the recycling of batteries results in a smaller yet still

noteworthy decrease. Nonetheless, despite higher emissions during production and disposal, all battery electric vehicles (BEVs) demonstrate a lower global warming potential (GWP) over their lifetime compared to fuel cell electric vehicles (FCEVs). This advantage is primarily due to lower emissions during the operational phase. Hydrogen generated from fossil fuels without carbon capture, or using electricity derived from fossil fuels, results in high upstream emissions. Furthermore, the tank-to-wheel efficiency of FCEVs is generally lower than that of BEVs. As a result, FCEVs might only achieve a lower use phase GWP than BEVs in regions where the electrical grid relies heavily on carbon-intensive sources, more so than the hydrogen production mix. This scenario could occur, for instance, if green hydrogen is imported. Conversely, green hydrogen produced using a renewable electricity mix generally performs less efficiently in reducing GWP compared to direct usage of renewable electricity in BEVs [23,24]

7 Conclusion

The principal aim of this paper was to present the validation of the WLTP drive cycle in order to 'simulate' the driving cycle using a hydrogen fuel cell conversion to replace 50% of the Tesla's battery capacity. Results showed that the WLTP range and consumption stated numbers are likely inaccurate by optimising testing conditions and results through flexibilities in the WLTP testing and analysis procedure. The validation conversion was deemed successful in the manner of using the theoretical capabilities of the fuel cell system applied to charge the battery pack in order to increase the range compared to the initial tesla configuration. Current infrastructure doesn't allow for usage within the UK due to shortage in fuelling stations, High well to wheel energy requirements for hydrogen and an overall well to end of life emissions still being higher than battery electric vehicles deems hydrogen fuel cell vehicles currently unfeasible. Running costs are currently also steeper than battery electric vehicles. Cost of the hydrogen conversion was not considered as price of the components used wasn't available.

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