MCEN4012 ASSIGNMENT 2

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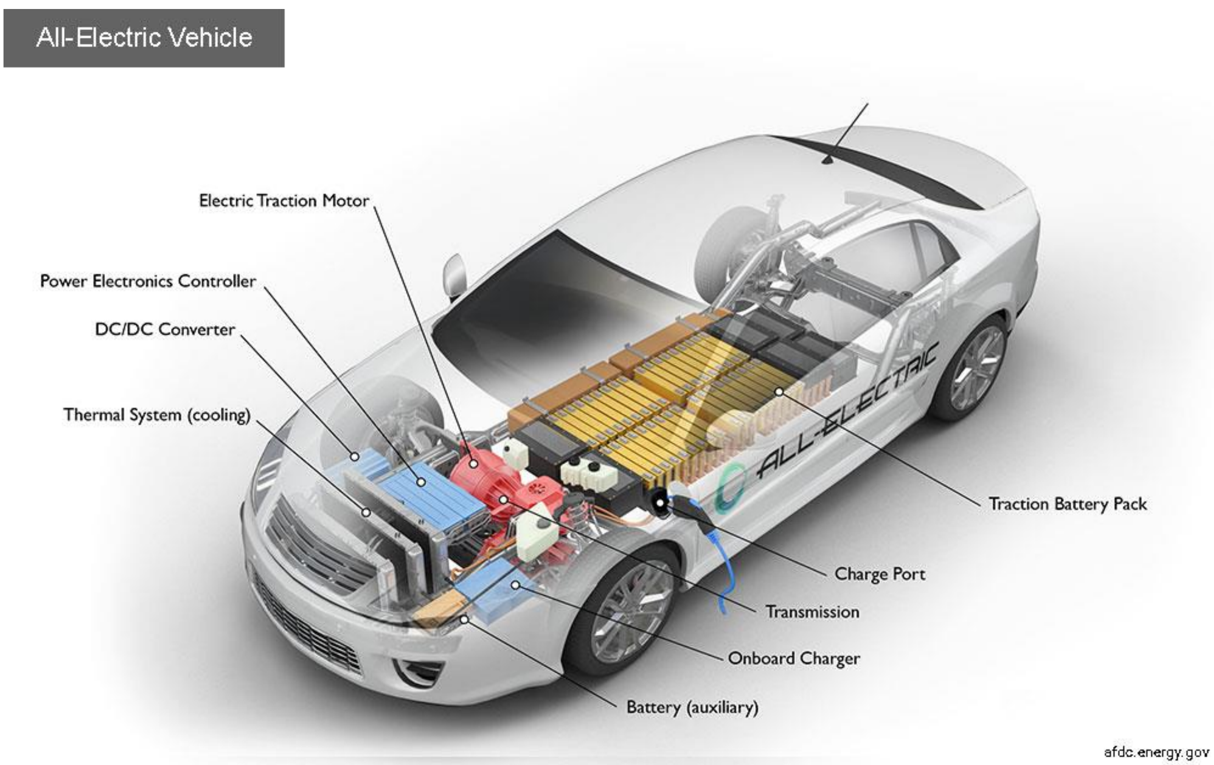

SEMESTER 1, 2022

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Executive Summary

Purpose

The purpose of this report is to define, analyse and simulate a battery electric vehicle (BEC) system designed to achieve specific requirements of 200km travel on one charge in city/urban environments. Further to this, iterative simulation is required to demonstrate the effects of design decisions on the energy efficiency and performance of the BEV system.

Scope

The scope of this document includes all of the subsystems of the BEV system; however, it focuses primarily on the subsystems involved in the electric locomotion of the BEV and the performance of the components that enable this.

Summary

Li-ion NMC type batteries and induction type motors offer optimised characteristics for BEV application however higher efficiencies can be achieved with other types. The trade off comes with increased complexity and cost.

Top Level System Design

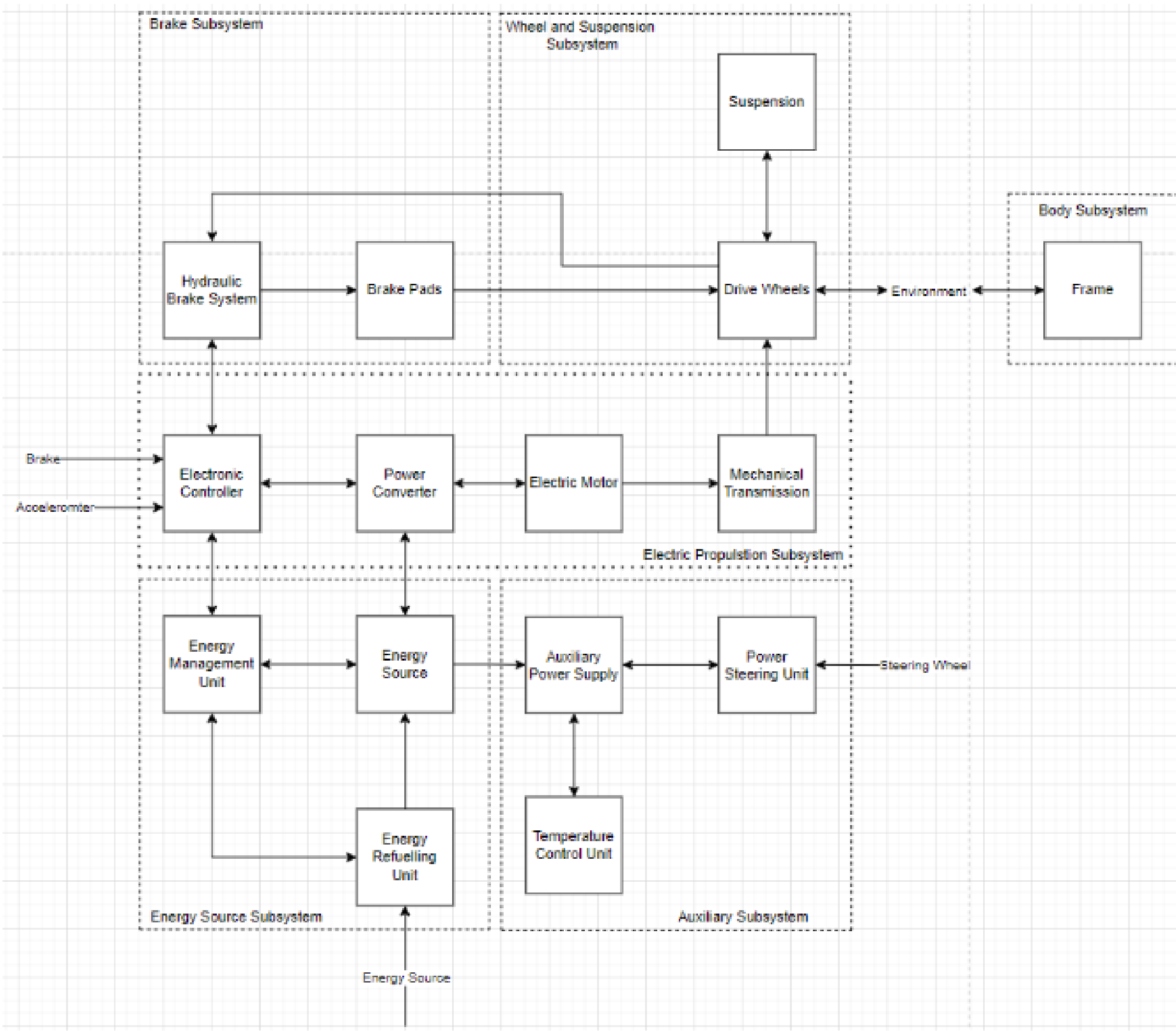


Figure 1 Overall System Design [1][2][3]

Overall System Explanation

The BEV system consists of six major subsystems with co-dependencies and external input/output relationships such as the accelerator and brake pedals, steering wheel and the surrounding environment. The six main subsystems are the energy source, auxiliaries, electric propulsion, brakes, wheels and suspension, and the frame/body of the vehicle. Environmental interactions impact all of these subsystems, for example with temperature and battery performance, however the interactions focussed on in this diagram are between the wheels, frame and the environment predominantly in regard to frictional losses. Specific details for each subsystem and its respective key components are provided in the specifications section in Task 2.

Energy Source Subsystem

This subsystem consists, broadly speaking, of a refuelling unit, energy source and energy management unit. This subsystem's boundaries interface with the electric propulsion subsystem, auxiliary subsystem and an external energy source such as mains power. The purpose of this subsystem is to both take energy from a supply such as mains and manage power to effectively charge and discharge the battery as needed. The battery acts as an energy source to provide power to the power converter of the electric propulsion subsystem and the auxiliary power supply of the auxiliary subsystem. The amount of power provided to each of these sinks from the battery is controlled by the energy management unit.

Auxiliary Subsystem

This subsystem consists of, but is not limited to, the auxiliary power supply, power steering unit, and temperature control unit. Additional auxiliaries such as adaptive chassis control, lights, wipers, reversing camera, sensors and speaker systems are neglected in this model as the main energy sink from the main battery is considered to be the auxiliary power supply. This subsystem's boundaries interface with the energy source subsystem and take inputs from the steering wheel. The purpose of this subsystem is to take energy from the main battery as needed and convert it to a safe level to power auxiliary assets such as the power steering and temperature control units. As aforementioned, its other purpose is to take the input of the steering wheel and effectively power the steering as needed. The temperature of the main battery and power electronics are controlled by this subsystem in conjunction with cooling/heating systems powered by the main battery. The cabin's temperature is also controlled by this subsystem's temperature control units.

Electric Propulsion Subsystem

This subsystem consists of an electronic controller, power converter, electric motor(s) and optionally a mechanical transmission (some EVs have in-wheel motors to reduce transmission components). In this particular BEV one drive motor will be used with a speed reducing gearbox and differentials. This subsystem's boundaries interface with the energy source, brake and wheel and suspension subsystems, with inputs from both the accelerator and brake pedals. The purpose of this subsystem is to track the response of the vehicle's motion against the user input and handle energy distribution to provide the necessary braking and acceleration required.

Brake Subsystem

The brake subsystem is relatively simple in this diagram, consisting only of the hydraulic brake system and brake pads. This subsystem's boundaries interface with the electric propulsion and wheel and suspension subsystems. The purpose of this subsystem is to apply a braking force to the drive wheels as required by the user, commanded via the electronic controller while tracking the response of the drive wheels to the environment.

Wheel and Suspension Subsystem

This subsystem is comprised of the drive wheels and suspension, with inputs and outputs to the environment through frictional and driving forces. This subsystem's boundaries interface with the electric propulsion and brake subsystems as well as the environment. The purpose of this subsystem is to provide the desired motion of the vehicle controlled by the hydraulic brake system and the mechanical transmission/electric motor. It is worth noting that if in-wheel motors are in use in lieu of a mechanical transmission then vibrational response to disturbances from the environment are important to monitor and respond to via the electronic controller.

Body Subsystem

This subsystem is very self-explanatory consisting solely of the body of the vehicle with its only boundary relation being indirectly linked to the wheel and suspension subsystem via the environment, while also contributing to frictional losses due to drag. The purpose of this subsystem is to house the occupants and some auxiliary assets while providing comfort. Its relation to the environment is predominantly through frictional losses in air resistance, while its relation to the wheel and suspension subsystem is limited to its inertial response to changes in motion in the form of momentum.

Electrical Component Connections

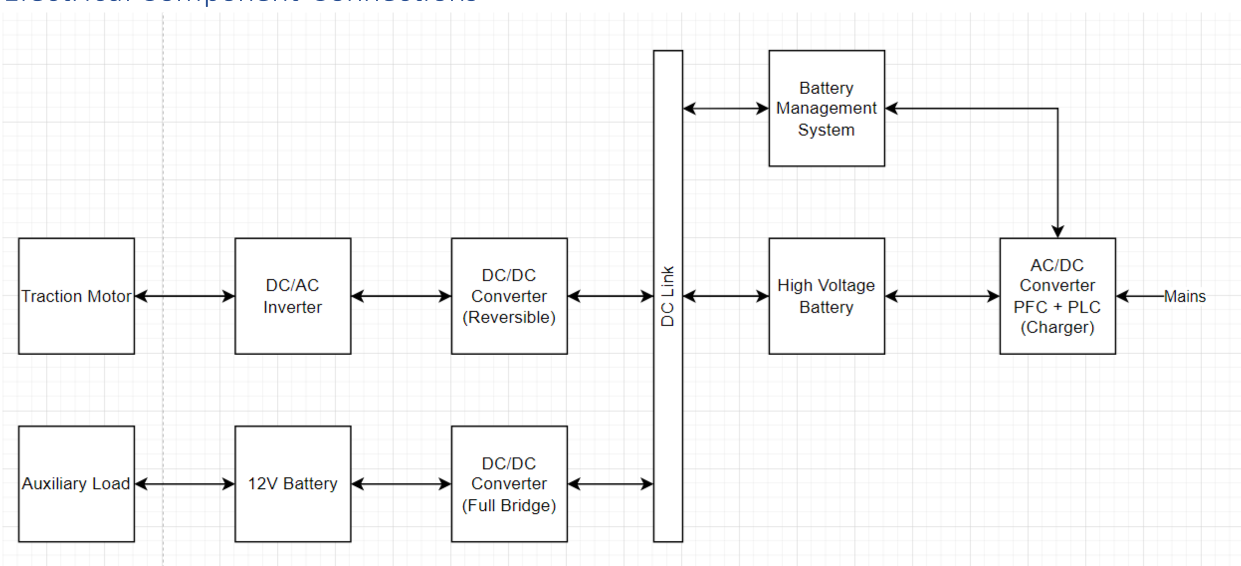


Figure 2 Electrical Component Connections of BEV [4] [5]

Figure 2 shown above depicts the connections of electrical components. The purpose of this diagram is to display how power is controlled, converted and inverted from the sources to the sinks, in this case the mains power/high voltage battery and the traction motor/auxiliary load respectively. It is worth noting that the DC/DC converter that supplies the DC/AC inverter is reversible, meaning it can be used to provide power to the DC link from the traction motor when the vehicle is braking i.e., during regenerative braking.

Initial Simplified Model and Simulation

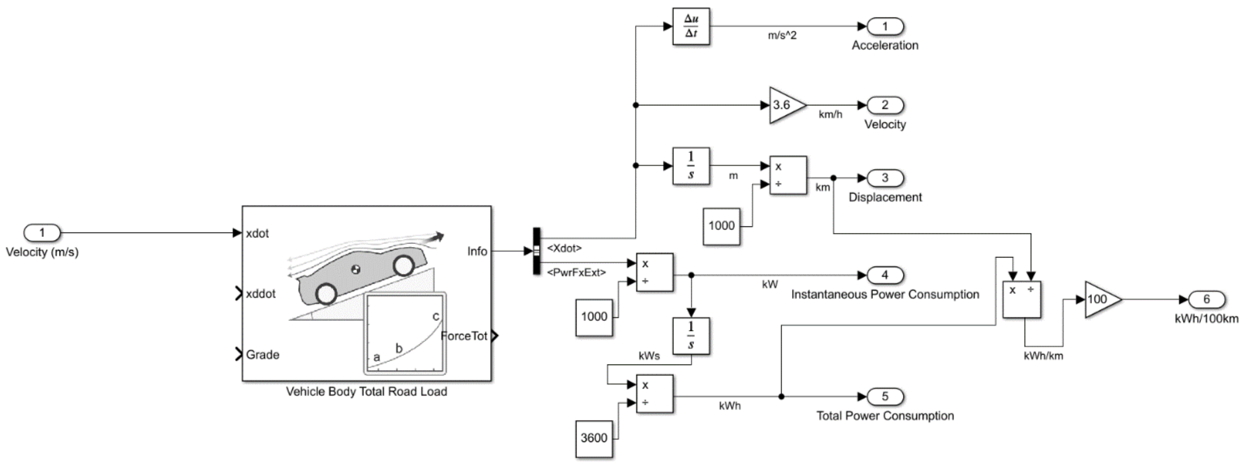


Figure 3 Initial Simplified Vehicle Subsystem Model

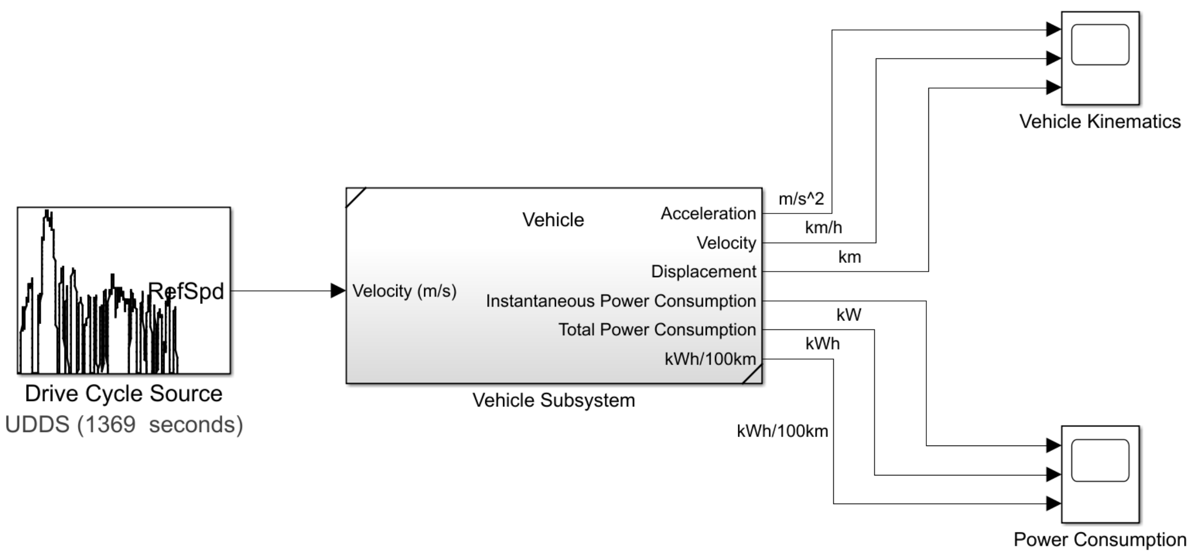


Figure 4 Initial Simplified Vehicle System Model with Drive Cycle

Purpose

The purpose of this initial simplified model of the vehicle was to get an estimate of the power requirements of the traction motor to provide the necessary power to adhere to all relevant drive cycles expected of a common passenger vehicle. Further to this, a suitable battery could be estimated.

Drive Cycles Used

A number of drive cycles exist from organisations including the Environmental Protection Agency (EPA) in the US, the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), the New European Driving Cycle (NEDC) and the China Light-Duty Vehicle Test Cycle (CLTC). It has been found that the EPA's drive cycles are the most accurate to real world conditions, so they were the drive cycles used in this report.

> "EPA ratings of electric vehicles are the most accurate, according to the real-world test results. The EPA range estimates are approximately 11 percent lower than the WLTP range figures. For example, an electric vehicle with 100 miles (or kilometres) of WLTP range is probably going to get an EPA range estimate of around 89 miles (or kilometres), or 11 mi./km less range than the WLTP standard." [6]

There are many drive cycles available from the EPA, however the most appropriate drive cycles to meet the requirements of 200km travel on one charge in city/urban environments were the UDDS and the NYCC drive cycles. Respectively, they represent standard city driving conditions and low speed, stop and go traffic driving conditions. Further to this, higher power drive cycles such as the HWFET and US06 were also modelled to provide a baseline for a more versatile vehicle that can provide sufficient power for highway driving conditions and high acceleration/speed aggressive driving conditions. [7]

Simplifying Assumptions

1. The terrain is assumed to remain flat throughout the course of the drive cycles and is not accounted for as a result.
2. The average mass of current market EVs is taken to be 1940kg [9]. Therefore, this is the total vehicle mass used in this initial model.
3. Windspeed independent of vehicle speed is not accounted for, only the drag induced by the vehicle's speed is considered.
4. Regenerative braking is not accounted for in this first model.
5. Power losses due to inefficiencies in power electronics and auxiliary consumption is not considered.

Parameters

Parameter	Value	Units	Description
b	2.232	Ns/m	Viscous driveline and rolling resistance coefficient left as the default value from the MATLAB Vehicle Body Total Road system block [8]
c	0.389	Ns^2/m^2	Aerodynamic drag coefficient left as the default value from the MATLAB Vehicle Body Total Road system block [8]
g	9.81	ms^{-2}	Acceleration due to gravity
m	1940	kg	Vehicle mass [9]
μ_k	0.015	-	An average value of the frictional coefficient of rolling resistance of the vehicle w.r.t the ground [10]
θ	0	$°\ or\ rad$	Road angle relative to the horizontal (set to zero as per simplifying assumptions)

Variables

Variable	Units	Description
x	m	Longitudinal displacement of the vehicle
$\dot{x}$	ms^{-1}	Longitudinal velocity of the vehicle
$\ddot{x}$	ms^{-2}	Longitudinal acceleration of the vehicle

Simplified Model Kinetics Equations

Equation	Units	Description	No.
$F_{road} = F_N + b\dot{x} + c\dot{x}^2 + mgsin\theta$	N	The total force the road exerts on the vehicle [8]	1
$F_{total} = m\ddot{x} + F_{road}$	N	The total force exerted on the vehicle [8]	2
$P_{total} = F_{total}\dot{x}$	kW	Total tractive input power [8]	3

Simulations

UDDS T = 1400s (standard city driving conditions)

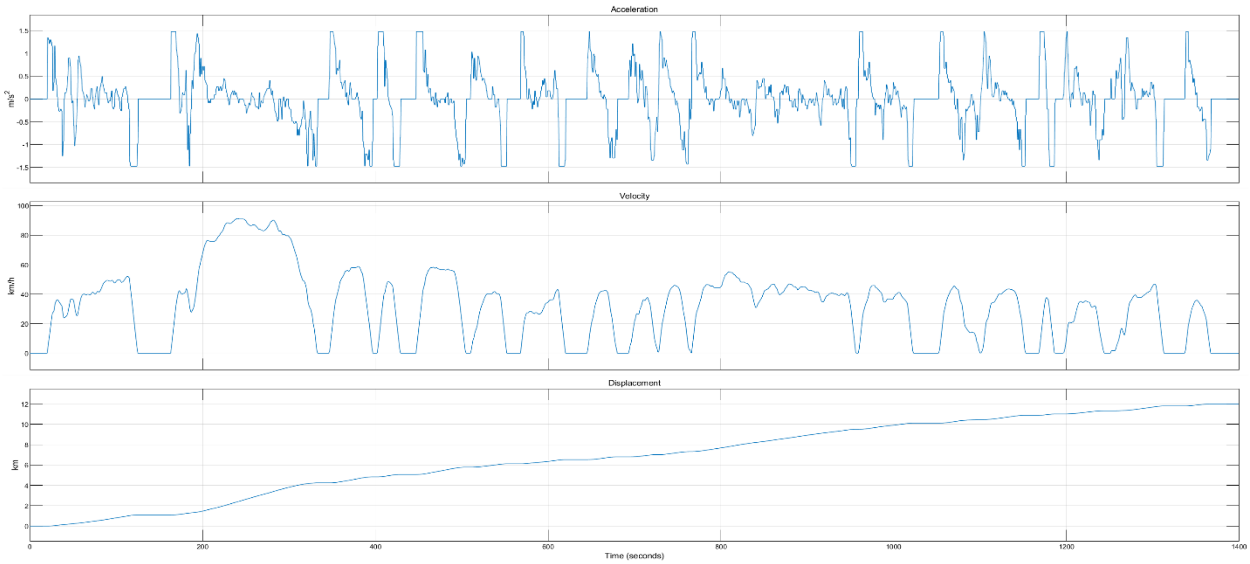


Figure 5 UDDS Kinematics Profile

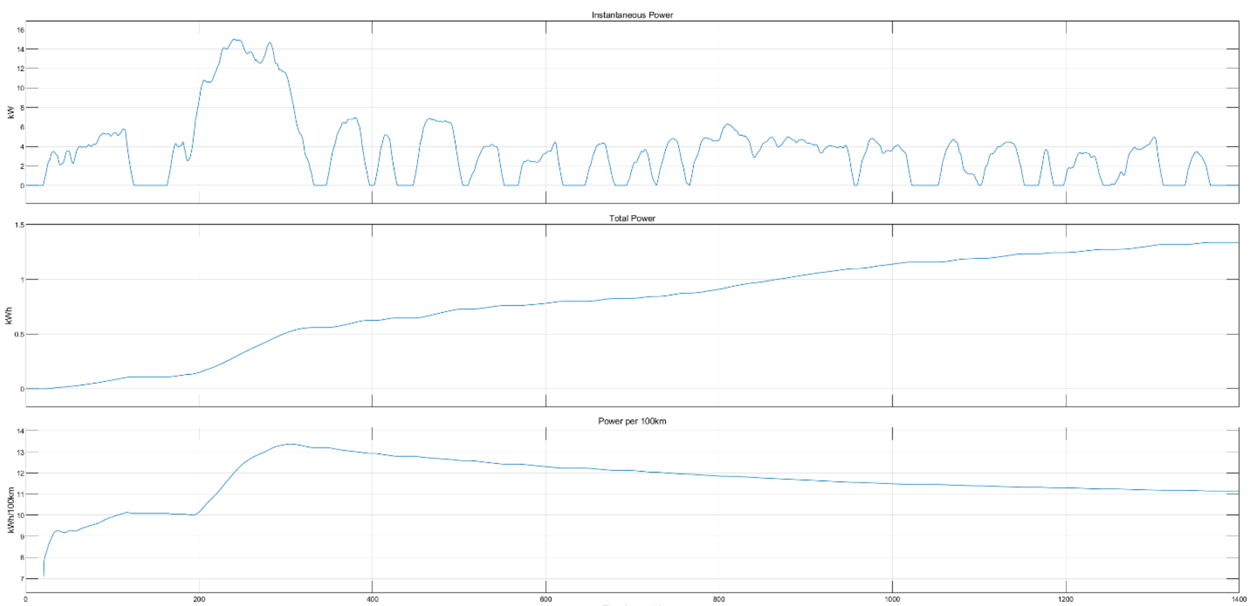


Figure 6 UDDS Power Consumption Profile

NYCC T = 600s (slow traffic stop and go driving conditions)

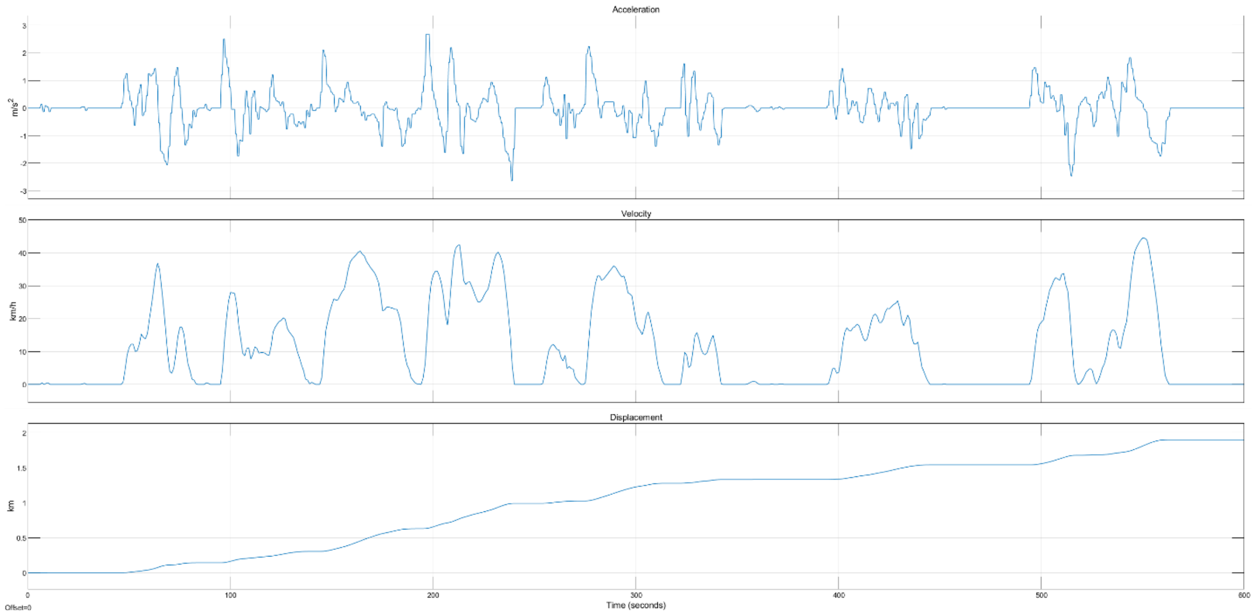


Figure 7 NYCC Kinematics Profile

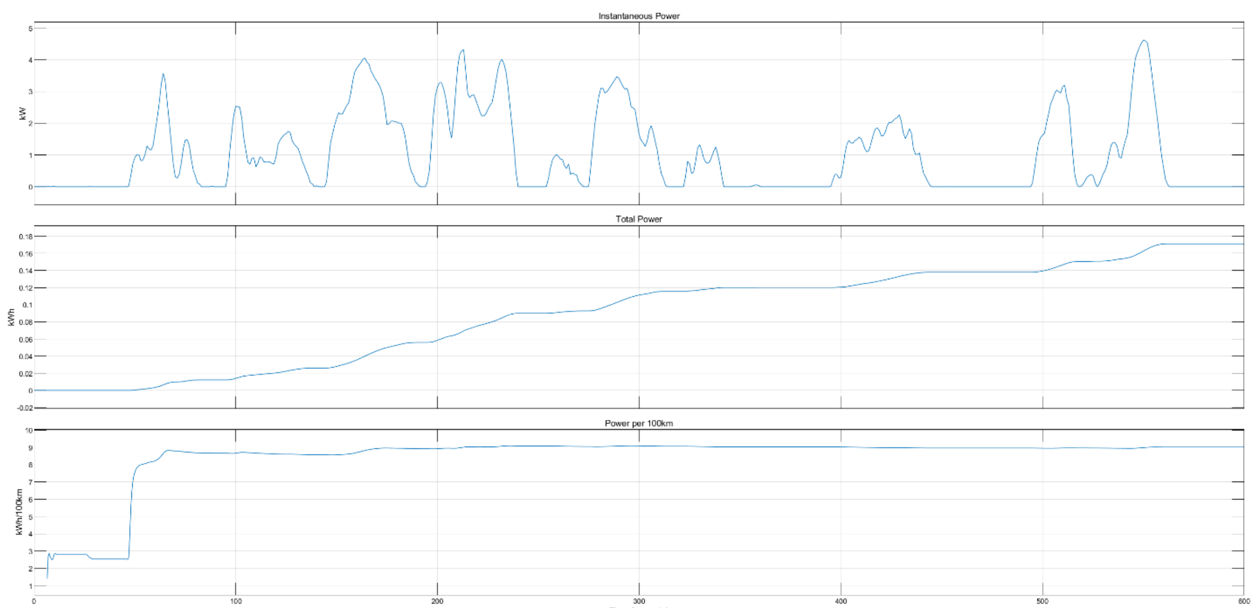


Figure 8 NYCC Power Consumption Profile

HWFET T = 800s (highway driving conditions)

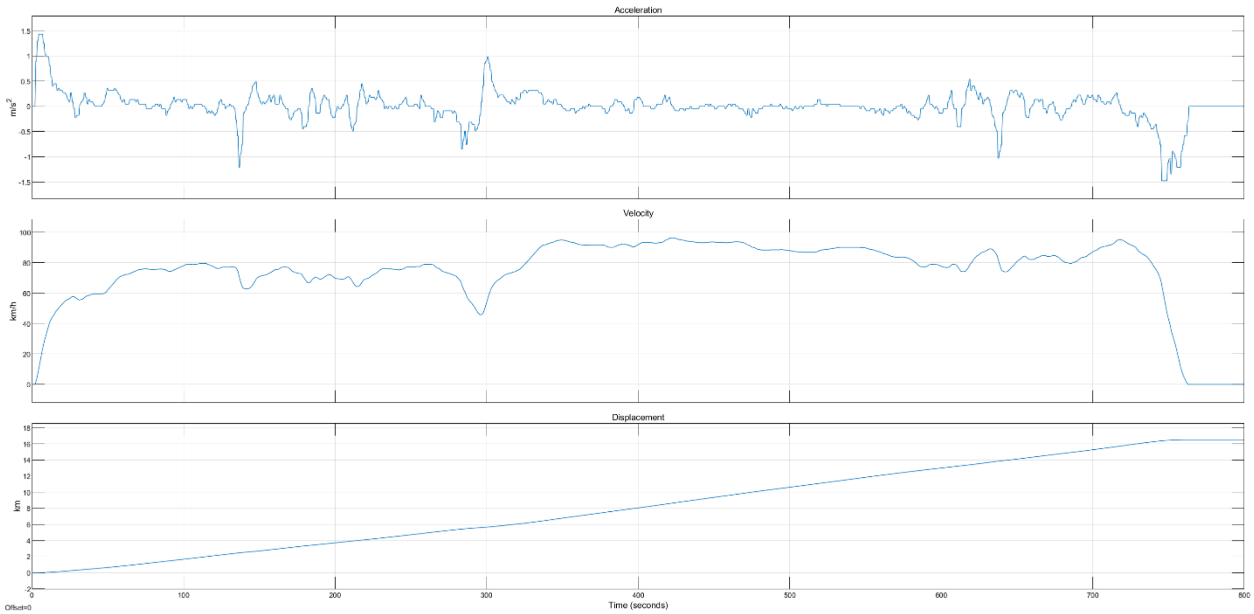


Figure 9 HWFET Kinematics Profile

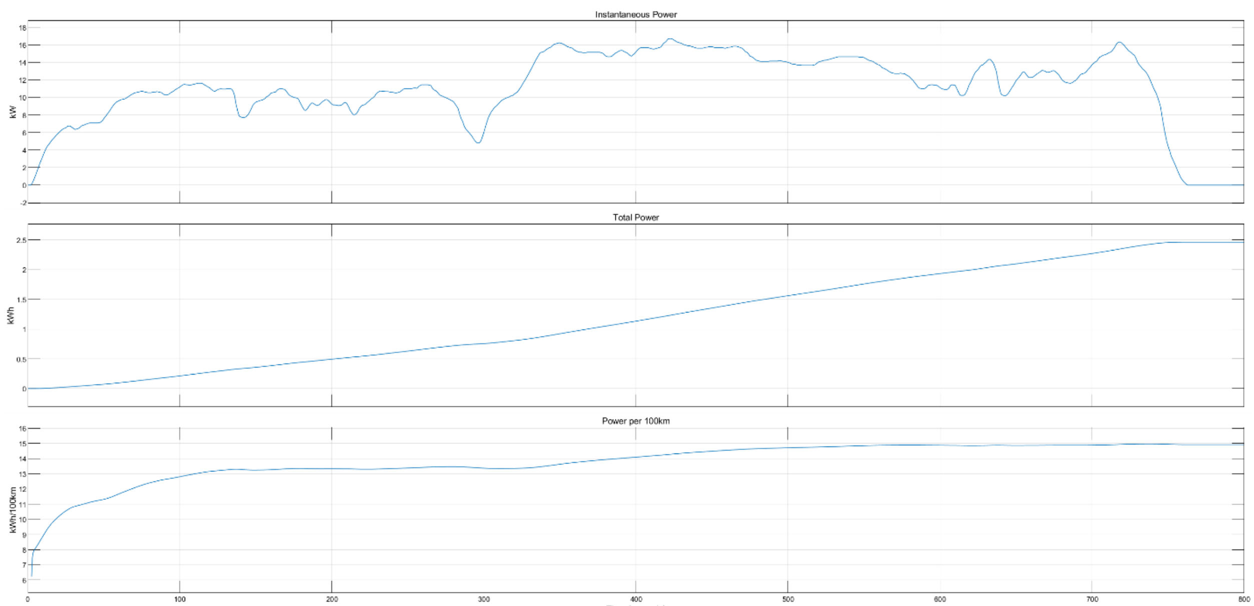


Figure 10 HWFET Power Consumption Profile

US06 T = 600s (high acceleration aggressive driving conditions)

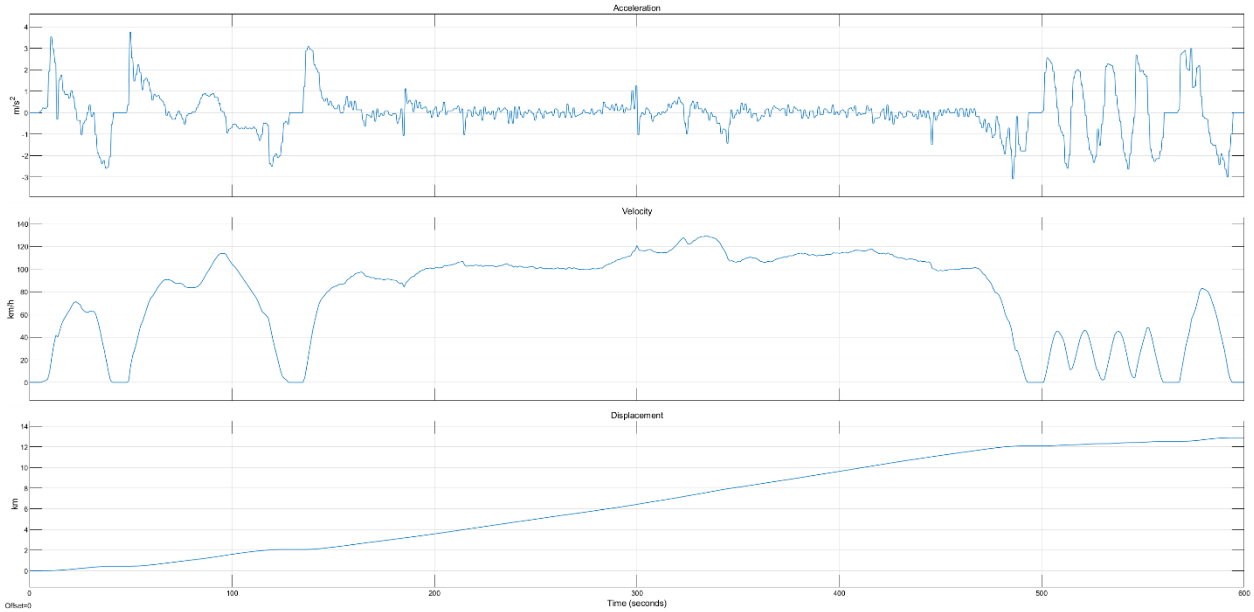


Figure 11 US06 Kinematics Profile

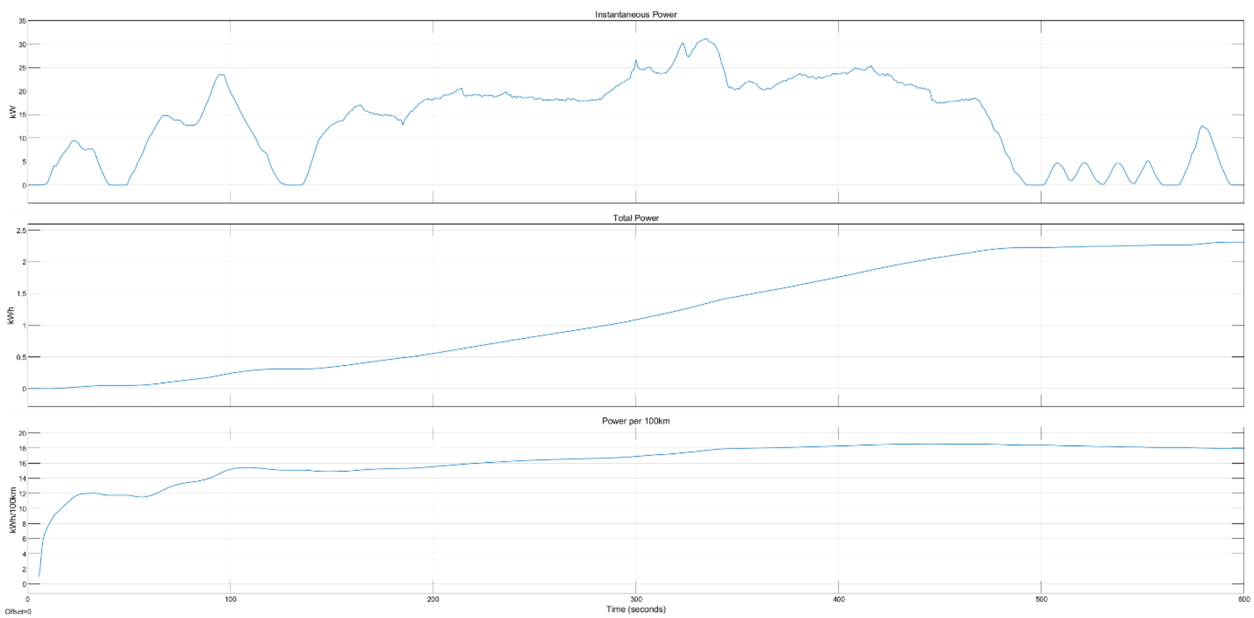


Figure 12 US06 Power Consumption Profile

Results

UDDS

Variable	Value	Unit	Time (s)
Max instantaneous velocity	91.25	km/h	240
Max instantaneous power	15	kW	240
Max instantaneous power/100km	13.37	$kWh/100km$	305.5
Total Power	1.336	kWh	1367.5
Total Displacement	11.99	km	1367.5

NYCC

Variable	Value	Unit	Time (s)
Max instantaneous velocity	44.58	km/h	550
Max instantaneous power	4.616	kW	550
Max instantaneous power/100km	9.088	$kWh/100km$	296
Total Power	0.1711	kWh	563
Total Displacement	1.898	km	563

HWFET

Variable	Value	Unit	Time (s)
Max instantaneous velocity	96.4	km/h	422
Max instantaneous power	16.33	kW	718
Max instantaneous power/100km	14.96	$kWh/100km$	737.5
Total Power	2.462	kWh	761
Total Displacement	16.51	km	761

US06

Variable	Value	Unit	Time (s)
Max instantaneous velocity	129.2	km/h	334
Max instantaneous power	31.12	kW	334
Max instantaneous power/100km	18.65	$kWh/100km$	445.5
Total Power	2.31	kWh	593
Total Displacement	12.89	km	593

Conclusions

From the UDDS drive cycle simulation, the maximum instantaneous power consumption per 100km of travel (P_{100km}) was 13.37kWh/100km with a peak instantaneous power (P_{max}) usage of 15kW at 91.25km/h (v_{max}) . The total power used was 1.336kWh (P_{total}) to cover a displacement of 11.99km (x_{total}) yielding an expected energy consumption of 22.2852kWh to cover 200km. From these results a motor of 15kW rated power would suffice with a battery that can provide 22.2852kWh of energy with the capacity to provide 15kW continuously. Keeping in mind the simplifying assumptions and that the driveline and aerodynamic drag losses were kept as default pre-set values it would be prudent to oversize the motor and battery to 20kW and 30kWh respectively.

From the NYCC drive cycle simulation, P_{100km} was 9.088kWh/100km with P_{max} of 4.616kW at v_{max} of 44.58km/h. P_{total} was 0.1711kWh to cover x_{total} of 1.898km yielding an expected energy consumption of 18.0295kWh to cover 200km. From these results a motor of 4.616kW rated power would suffice with a battery that can provide 18.0295kWh of energy with the capacity to provide 4.616kW continuously. For reasons aforementioned it would be prudent to oversize the motor and battery to 10kW and 25kWh respectively.

From the HWFET drive cycle simulation, the P_{100km} was 14.96kWh/100km with P_{max} of 16.33kW at v_{max} 96.4km/h. P_{total} was 2.462kWh to cover x_{total} of 16.51km yielding an expected energy consumption of 29.8243kWh to cover 200km. From these results a motor of 16.33kW rated power would suffice with a battery that can provide 29.8243kWh of energy with the capacity to provide 16.33kW continuously. As before, it would be prudent to oversize the motor and battery to 20kW and 35kWh respectively.

From the US06 drive cycle simulation, the P_{100km} was 18.65kWh/100km with P_{max} of 31.12kW at v_{max} 129.2km/h. P_{total} was 2.31kWh to cover x_{total} of 12.89km yielding an expected energy consumption of 35.8417kWh to cover 200km. From these results a motor of 31.12kW rated power would suffice with a battery that can provide 35.8417kWh of energy with the capacity to provide 31.12kW continuously. Again, it would be prudent to oversize the motor and battery to 35kW and 40kWh respectively.

To ensure that the vehicle has the necessary acceleration response and range to accommodate drive cycles such as US06 it would serve to size a motor capable of providing at least 35kW of power continuously to the drive wheels. As a result, neglecting energy reclamation by regenerative brakes, a battery capable of providing 40kWh of energy and at least 35kW continuously would be required to enable a motor of this size to perform at this level.

Further iterative modelling and simulation may sacrifice this performance and range to achieve better efficiency at lower speeds such as those in the UDDS drive cycle by reducing motor and battery size, thus reducing weight and therefore frictional losses.

Traction Motor

From the initial modelling a traction motor capable of generating at least 35kW of continuous power is required. The type of motor is important as different motors have different performance graphs, drivers and efficiencies. Some motors are more desirable for reasons such as improved efficiency but often come with disadvantages such as more complex drivers being required, being less commercially available and costing significantly more than other types of motors. Pictured below in Figure 13 is a table outlining key aspects of different traction motor types.

Characteristics	Motor type			
	DC	IM	PM	SRM
Power density	Low	Medium	Very high	Medium
Efficiency	Low	Medium	Very high	Medium
Controllability	Very high	Very high	High	Medium
Reliability	Medium	Very high	High	Very high
Technological maturity	Very high	Very high	High	High
Cost	Low	Very low	High	Low

Figure 13 Traction Motor Comparison [12]

"[PMSM motors] have a simple construction, high efficiency, and high power density, thus they are suitable to be used as traction motors (common in hybrid vehicles, EVs, and buses). PMSM motors have a higher efficiency compared to IMs. The drawbacks of this type are high costs, eddy current loss in PMs at high speed, and a reliability risk because of the possible breaking of the magnets… [Induction motors] This motor type is very common in EVs because of its simple construction, high reliability, robustness, simple maintenance, and low cost and operation at different environmental conditions. IMs can be naturally de-excited if the inverter faults, an important safety advantage for EVs." [12]

While permanent magnet synchronous motors (PMSM) are more efficient in most regards, their drawbacks make them undesirable compared to an induction motor (IM). As a result, the type of traction motor selected in this report is the IM due to its high technological maturity and low cost.

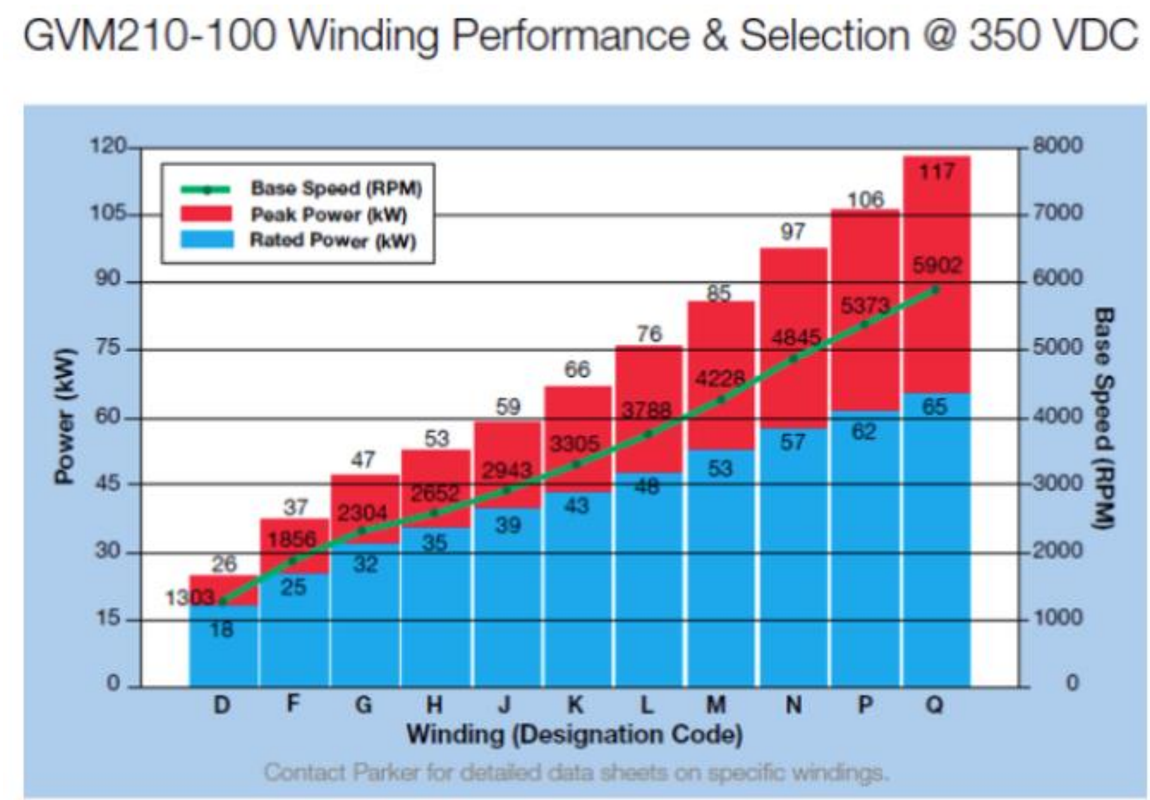
GVM210-100 Performance @ 350 VDC

Parameter	GVM210-100D	GVM210-100F	GVM210-100G	GVM210-100H	GVM210-100J	GVM210-100K
Peak Torque (Nm)	165	166	167	167	167	167
Base Speed (RPM)	1,303	1,856	2,304	2,652	2,943	3,305
Peak Power (kW)	26	37	47	53	59	66
Stall Torque Continuous (Nm)	93	94	94	94	95	95
Rated Torque (Nm)	77	77	78	78	78	78
Rated Speed (RPM)	2,248	3,168	3,878	4,293	4,764	5,272
Rated Shaft Output Power (kW)	18	25	32	35	39	43
Max Continuous Speed (RPM)	2,964	4,119	5,114	5,746	6,375	7,160
Stall Current Peak (Amp RMS)	97	135	169	190	212	238
Stall Current Continuous (Amp RMS)	48	68	85	95	106	119
Coolant Temperature (°C)	60	60	60	60	60	60
Max Winding Temperature (°C)	180	180	180	180	180	180
Winding Temp at Rating (°C)	140	140	140	140	140	140
Rotor Inertia (kg-m^2)	0.01904	0.01904	0.01904	0.01904	0.01904	0.01904
Motor Weight (kg)	35	35	35	35	35	35
Recommended Parker Inverter	MB2	MB2	MA3	MA3	MA3	MA3

Figure 14 Traction Motor Specifications [11]

A suitable motor model series was found, with motors capable of rated shaft output power from 18kW all the way up to 43kW as shown at left in Figure 14

Pictured below in Figure 15 is the performance chart of each of the motors in Figure 14 shown operating at 350VDC corresponding to their winding designation.



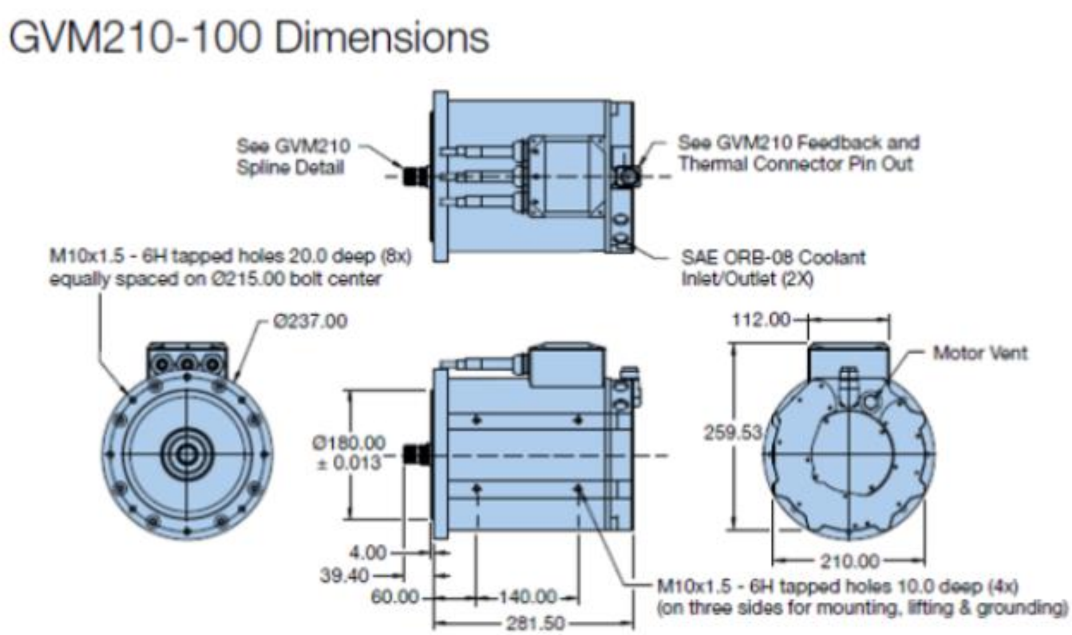


Figure 15 Traction Motor Performance Chart and Dimensions [11]

GVM210-100H Induction Motor Key Specifications

To satisfy the rated power requirement of 35kW continuous rated shaft output power the GMV210-100H was selected. A table of its key specifications is shown below.

Parameter	GVM210-100H
Peak Torque (Nm)	167
Base Speed (RPM)	2,652
Peak Power (kW)	53
Stall Torque Continuous (Nm)	94
Rated Torque (Nm)	78
Rated Speed (RPM)	4,293
Rated Shaft Output Power (kW)	35
Max Continuous Speed (RPM)	5,746
Stall Current Peak (Amp RMS)	190
Stall Current Continuous (Amp RMS)	95
Coolant Temperature (°C)	60
Max Winding Temperature (°C)	180
Winding Temp at Rating (°C)	140
Rotor Inertia (kg-m²)	0.01904
Motor Weight (kg)	35
Recommended Parker Inverter	MA3

Figure 16 GMV210-100H Specifications [11]

Additional Key Parameters

Parameter	Value	Unit	Description
Cost	7392.00	$ AUD	Unit cost [11]
Volume	0.017489	m^3	Unit volume
Power to Weight Ratio	1	kW/kg	Power to weight ratio

Inverter

The inverter recommended for the chosen traction motor is a Parker MA3 series inverter [13]. From the user manual for MA3 series inverters, the specifications of MA3 series Parker Inverters are shown below [11]. Given the rated voltage, current and power requirements of the traction motor selected the most suitable inverter is the MA3-40-0225.

Input Voltage – DC Bus Ratings

Inverter	Operating Range (Vdc)	Nominal (Vdc)	Undervoltage Trip (Vdc)	Overvoltage Trip (Vdc)
MA3-40-xxxx	210 - 400	320	205	410
MA3-60-xxxx	315-600	480	310	615
MA3-80-xxxx	420-800	640	410	820

Output Ratings

Inverter	Continuous Current (A rms)	Peak Current (A rms)	Continuous Power (kW)	Peak Power (kW)
MA3-40-0225	130	225	54	93
MA3-40-0325	185	325	77	135
MA3-40-0400	225	400	93	160

Figure 17 MA3 Series Parker Inverter Input/Output Specifications [13]

Description	MA3-40			MA3-60			MA3-80		
	225 Arms	325 Arms	400 Arms	225 Arms	325 Arms	400 Arms	225 Arms	325 Arms	400 Arms
Voltage Operating Range	205 - 400 VDC			310 - 600 VDC			410 - 800 VDC		
Nominal Voltage	320 VDC			480 VDC			640 VDC		
Peak Current Output	225 Arms	325 Arms	400 Arms	225 Arms	325 Arms	400 Arms	225 Arms	325 Arms	400 Arms
Continuous Current Output	130 Arms	185 Arms	225 Arms	130 Arms	185 Arms	225 Arms	130 Arms	185 Arms	225 Arms
Peak Power	93.5 kW	135 kW	160 kW	155 kW	225 kW	270 kW	187 kW	270 kW	325 kW
Continuous Power	54 kW	77 kW	93.5 kW	90 kW	128 kW	156 kW	108 kW	154 kW	187 kW
Switching Freq (PMAC)	4.0 kHz			4.0 kHz			4.0 kHz		
Switching Freq (Induction)	2.0 - 4.0 kHz			2.0 - 4.0 kHz			2.0 - 4.0 kHz		
Efficiency	97%			97%			97%		
Control Voltage Range	7 to 32 VDC			7 to 32 VDC			7 to 32 VDC		
Max Control Current @ 7 V	8 ADC			8 ADC			8 ADC		
Min Control Current @ 32 V	0.7 ADC			0.7 ADC			0.7 ADC		
Max Inrush Current	18.9 ADC			18.9 ADC			18.9 ADC		
Weight	35 lbs/15.9 kg			35 lbs/15.9 kg			35 lbs/15.9 kg		
Operating Temperature	-40°C to 55°C			-40°C to 55°C			-40°C to 55°C		
Storage Temperature	-40°C to 85°C			-40°C to 85°C			-40°C to 85°C		
Protection	IP65			IP65			IP65		
Control Type	Speed/Torque			Speed/Torque			Speed/Torque		
Feedback	Resolver			Resolver			Resolver		
Communication Protocol	CANopen			CANopen			CANopen		
Cooling Options	Water/Glycol or Hydraulic Oil (Alternate cooling configurations are available. Please contact us with special requirements.)								
Flow Rate max (min)	2 gpm/7.6 lpm (1 gpm/3.8 lpm)			2 gpm/7.6 lpm (1 gpm/3.8 lpm)			2 gpm/7.6 lpm (1 gpm/3.8 lpm)		
Max Pressure	30 psi/2.07 bar			30 psi/2.07 bar			30 psi/2.07 bar		
Max Inlet Temperature	55°C			55°C			55°C		
Certifications	CE and UL pending (Consult factory)								

Figure 18 MA3 Series Parker Inverter Specifications [14]

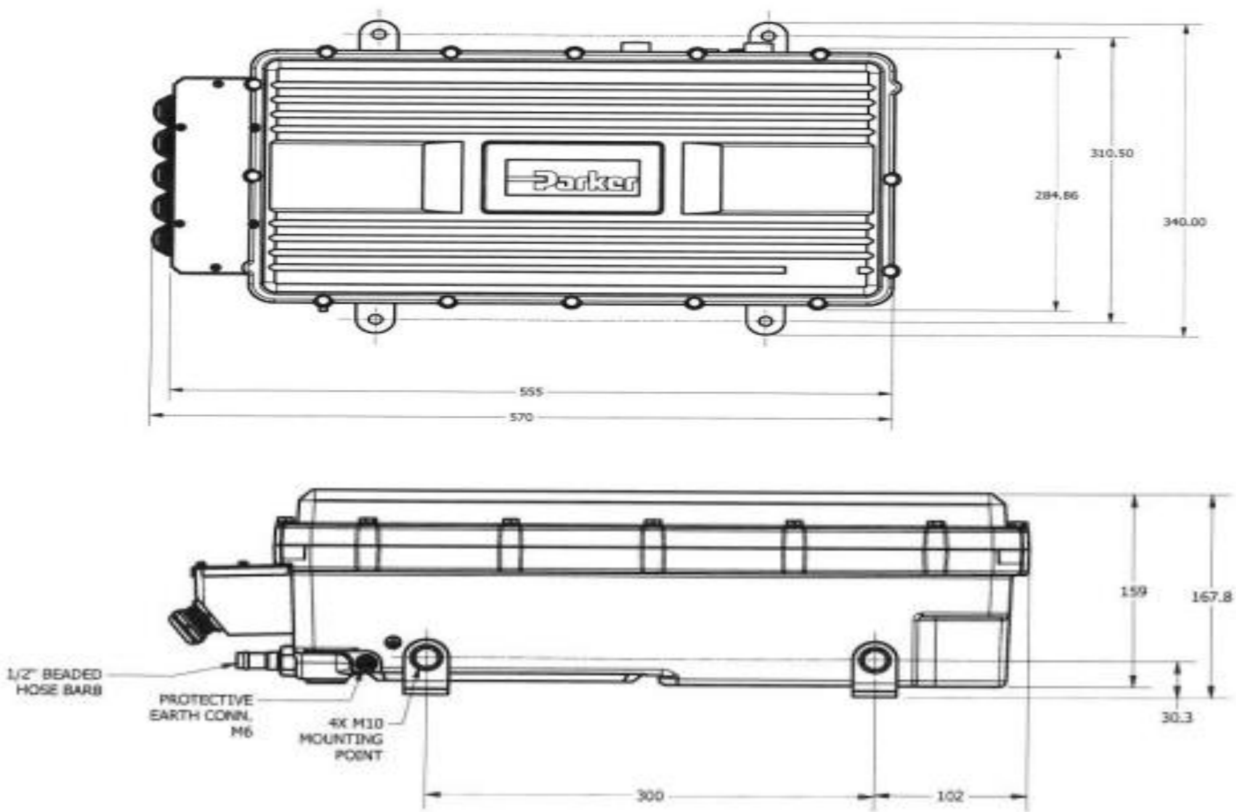


Figure 19 MA3 Series Parker Inverter Dimensions [13]

Additional Key Parameters

Parameter	Value	Unit	Description
Mass	16.8	kg	Unit mass
Volume	0.0325	m^3	Unit volume
Cost	Quote	$ AUD	Requires quote

Battery

There are many types of batteries with various properties that make them desirable such as specific energy, specific power, small size and low cost however there are drawbacks such as heating/cooling requirements as well precautionary safety measures which adds mass, complexity and power consumption. It had been found that lithium ion batteries had the highest specific energy, thus they could store the equivalent charge of a much larger lead acid battery in a considerably lower mass of batteries. [15] A comparison of major battery types and sub-types of lithium ion batteries is shown.

Battery type	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Specific Power (W/kg)	Mass of battery for EV to run a 100 km with 20 kWh/100km	Mass reduction compared to previous battery
Lead - Acid	35-40	80-90	285	500 – 600 kg	0 %
Ni- MH	50-70	100-140	200	300 – 400 kg	36.36 %
ZEBRA (Na-NiCl2)	100	160	170	200 kg	42.86 %
Li-ion	150-200	250-400	260	100 – 140 kg	40 %

Figure 20 Battery Type Comparison [15]

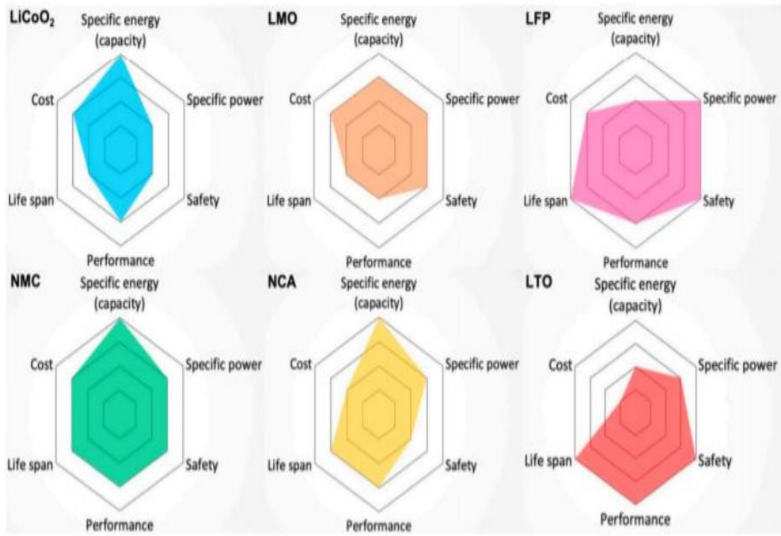


Figure 21 Li-ion Battery Type Comparisons [15]

Summary Table

Lithium Nickel Manganese Cobalt Oxide: $LiNiMnCoO_2$. cathode, graphite anode Short form: NMC (NCM, CMN, CNM, MNC, MCN similar with different metal combinations) Since 2008	
Voltages	3.60V, 3.70V nominal; typical operating range 3.0–4.2V/cell, or higher
Specific energy (capacity)	150–220Wh/kg
Charge (C-rate)	0.7–1C, charges to 4.20V, some go to 4.30V; 3h charge typical. Charge current above 1C shortens battery life.
Discharge (C-rate)	1C; 2C possible on some cells; 2.50V cut-off
Cycle life	1000–2000 (related to depth of discharge, temperature)
Thermal runaway	210°C (410°F) typical. High charge promotes thermal runaway
Cost	~$420 per kWh[1]
Applications	E-bikes, medical devices, EVs, industrial
Comments 2019 Update:	Provides high capacity and high power. Serves as Hybrid Cell. Favorite chemistry for many uses; market share is increasing. Leading system; dominant cathode chemistry.

Figure 22 Li-ion NMC Battery Type Summary [16]

From the main battery technology comparison table in Figure 19, Li-ion stands out as the battery technology most suitable for BEV applications with its high specific energy and specific power. From the radar charts in Figure 20, lithium nickel manganese cobalt oxide (NMC) type batteries offer a battery profile favourable to BEV application by providing very high specific energy while still providing well rounded qualities such as high specific power, safety and long lifespan. Finally, from the summary table in Figure 21 some typical parameters of NMC Li-ion batteries including cost/kWh offer a meaningful baseline of values for this specific type of battery.

Battery Requirements, Selection and Specifications

From the simplified initial model, a battery capable of providing 40kWh of energy and up to 35kW of power continuously is required. Going with the NMC Li-ion battery technology, the following specifications and relevant graphs of an LIR18650 2600mAh EEMB manufactured cell provide the information needed to calculate the total mass of batteries to achieve these requirements. [17]

5.1 Capacity（25±5℃）	Nominal Capacity: 2600mAh (0.52A Discharge, 2.75V) Typical Capacity: 2550mAh（0.52A Discharge, 2.75V） Minimum Capacity: 2500mAh (0.52A Discharge, 2.75V)
5.2 Nominal Voltage	3.7V
5.3 Internal Impedance	≤ 70mΩ
5.4 Discharge Cut-off Voltage	3.0V
5.5 Max Charge Voltage	4.20±0.05V
5.6 Standard Charge Current	0.52A
5.7 Rapid Charge Current	1.3A
5.8 Standard Discharge Current	0.52A
5.9 Rapid Discharge Current	1.3A
5.10 Max Pulse Discharge Current	2.6A
5.11 Weight	46.5±1g
5.12 Max. Dimension	Diameter(Ø): 18.4mm Height (H): 65.2mm
5.13 Operating Temperature	Charge: 0 ~ 45℃ Discharge: -20 ~ 60℃
5.14 Storage Temperature	During 1 month: -5 ~ 35℃ During 6 months: 0 ~ 35℃

Figure 23 LIR18650 2600mAh EEMB Standard Specifications [16]

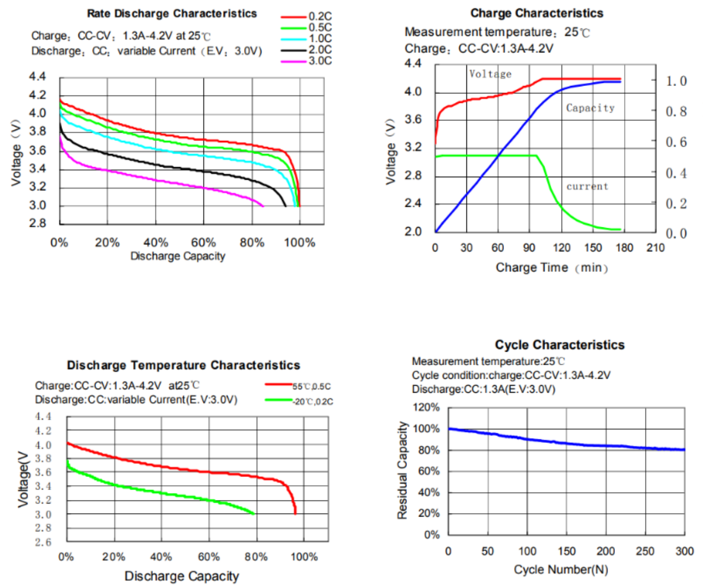


Figure 24 LIR18650 2600mAh EEMB Charge/Discharge Characteristics [16]

Additional Key Parameters

Parameter	Value	Unit	Description
Volume	0.01734	L	Unit volume
Cycle Life	300	-	@ 100% DOD 20% residual capacity loss
Cost	1.70	$ AUD	Unit cost [18]

The recommended C-rate can be taken as being 0.5C with the rated rapid discharge current of 1.3A. This means that an excess of battery cells will be required to satisfy the instantaneous power requirements of the initial simplified model which will inadvertently result in a significantly increased range as the energy capacity will be greater with more cells. However, this also results in an increased mass of the battery which increases frictional losses. The benefit of choosing this cell is its low cost, high technological maturity and high commercial availability.

Battery Size Calculation

Maximum rated cell power output at maximum rated C-rate of 0.5 i.e., at rated rapid discharge current of 1.3A:

$$P_{cell} = P_{nom} - P_{heat}$$

$$P_{cell} = V_{nom} \cdot I_{CC} - (I_{cc}^2 R_{internal})$$

$$P_{cell} = 3.7V \cdot 1.3A - (1.3A^2 \cdot 0.07\Omega)$$

$$P_{cell} = 4.6917W$$

Number of cells required to satisfy 35kW instantaneous power requirement:

$$N_{cells} = \frac{P_{battery}}{P_{cell}}$$

$$N_{cells} = \frac{35{,}000W}{4.6917W}$$

$$N_{cells} = 7460$$

Mass of batteries required:

$$m_{battery} = N_{cells} \cdot m_{cell}$$

$$m_{battery} = 7460 \cdot 0.0465kg$$

$$m_{battery} = 346.89kg$$

Resultant volume of batteries:

$$V_{battery} = N_{cells} \cdot V_{cell}$$

$$V_{battery} = 7460 \cdot 0.01734L$$

$$V_{battery} = 129.356L$$

Resultant energy capacity of battery:

$$E_{battery} = N_{cells} \cdot E_{cell}$$

$$E_{battery} = N_{cells} \cdot C_{nom} \cdot V_{nom}$$

$$E_{battery} = 7460 \cdot 2.6Ah \cdot 3.7V$$

$$E_{battery} = 71.765kWh$$

Total cost of battery and cost per kWh:

$$Cost_{battery} = N_{cells} \cdot Cost_{cell}$$

$$Cost_{battery} = 7460 \cdot \$1.70\ AUD$$

$$Cost_{battery} = \$12{,}682\ AUD\ or\ \$176.72\ AUD\ per\ kWh$$

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