

REAL WORLD POWERTRAIN ANALYSIS

POWERTRAIN AND SUSTAINABILITY

SUPERVISION

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1 INTRODUCTION

The following assessment was developed for the 2nd Term evaluation of the module of Powertrain and Sustainability of the third year – level 6 of the Motorcycle Engineering Degree.

The aim of the presented work is to evaluate 3 sets of vehicle data from distinct types during a known drive cycle that encompasses various road scenarios and environments.

A comparison between the 3 different vehicles will be performed, demonstrating how they differ in certain parameters, such as engine load, drivability, efficiency and performance.

Finally, the author will attempt to model a different vehicle, with a range of different technologies and energy sources, capable of performing the same drive cycle with better overall results.

2 ANALYSIS OF DATA FILES FOR A SPECIFIC DRIVE CYCLE

The author was provided with raw data and calculated channels from three different vehicles types. This data was collected during a 30 km “drive cycle”, including motorway, extra urban, b-road and unclassified road.

The three different vehicles put to the test were:

- Triumph Tiger 800 XC 2011;
- Volvo V40 Cross-Country D2 2016;
- Toyota Aygo 1.0 VVT-I 2016;

Prior to the analysis of the data, the author knew the parameters in which the different vehicles were going to be compared. This was crucial when deciding which data was going to be evaluated and which was going to be dismissed.

Once the data was selected, it was then possible to validate some of the calculated channels by the application software.

The data selected is presented in the following excel sheets: “Task1 – Triumph”, “Task1 – Volvo” and “Task1 – Toyota”.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	FROM DATA		CALCULATED												
2	Frame Number	Frame Time (ms)	Frame Time (delta)	AUX.GPS.SPEED km/h	SAE.RPM /pm	SAE.VSS km/h	CALC.DISTANCE km	CALC.ENGINE_POWER hp	CALC.ACCELERATION_G g	Time (s)	ΔDistance (m)	Distance (m)	Acc (m/s ²)	Force (N)	WD (J)
3	Frame Number	Frame Time (ms)	Frame Time (delta)	GPS Speed	RPM	Wheel Sensor Speed	Distance (km)	Power (hp)	Acceleration (g)						
4	221	18188	113	0	965	0	0.0	21	0	0.00	0.00	0.00	0.00	0.00	0.00
5	222	18307	119	0	965	1	0.0	21	0	0.12	0.02	0.02	0.00	0.00	0.00
6	223	18397	90	0	965	1	0.0	22	0.001	0.21	0.03	0.04	0.01	16.57	0.41
7	224	18423	26	0	965	1	0.0	22	0.001	0.24	0.01	0.05	0.01	16.57	0.12
8	225	18531	108	0	965	1	0.0	22	0.001	0.34	0.03	0.08	0.01	16.57	0.50
9	226	18642	111	0	965	1	0.0	22	0.001	0.45	0.03	0.11	0.01	16.57	0.51
10	227	18662	20	0	964	2	0.0	22	0.001	0.47	0.01	0.12	0.01	16.57	0.14
11	228	18844	182	0	964	2	0.0	22	0.001	0.66	0.10	0.22	0.01	16.57	1.68
12	229	18858	14	0	964	2	0.0	22	0.06	0.67	0.01	0.23	0.59	994.31	7.73
13	230	18831	-27	3	964	2	0.0	22	0.06	0.64	-0.02	0.21	0.59	994.31	-14.91
14	231	18970	139	3	964	2	0.0	22	0.06	0.78	0.08	0.29	0.59	994.31	76.78

Figure 1. Example of excel sheet for Task 1

The order of work performed to analyse and validate the data acquired and calculated was the following:

- All the data prior to the vehicle started moving and after stopping in the end of the drive cycle was deleted;
- The altitude changes were evaluated to investigate the air density changes and possible impact in the powertrain efficiency;

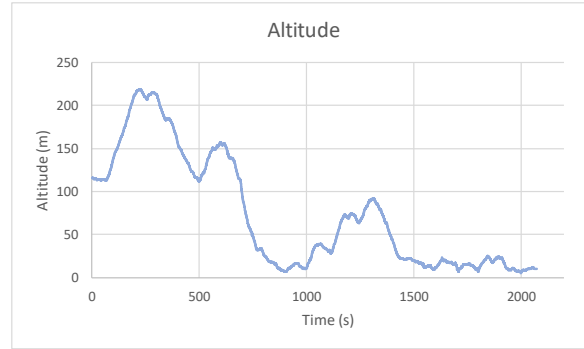


Figure 2. Altitude during drive cycle

During the drive cycle, a maximum altitude of 219m and an average altitude equal to 73m were observed. Because:

$$\rho = \frac{P}{R \cdot T}$$

Where,

- ρ = air density (kg/m³);
- P = air pressure (Pa);
- R = specific gas constant (J/(Kg.K));

It is known that at low altitudes above the sea level the air pressure decreases around 1,2kPa for every 100m, which represents a drop of 2,6 kPa at the maximum altitude of the drive cycle.

Assuming an air pressure at sea level of 100kPa, it can be concluded that the air pressure will drop 2,6% and consequently the air density will be reduced by the same percentage at the maximum altitude in the drive cycle.

- The velocity data from the GPS was then compared against the velocity from the motorcycle wheel sensor.

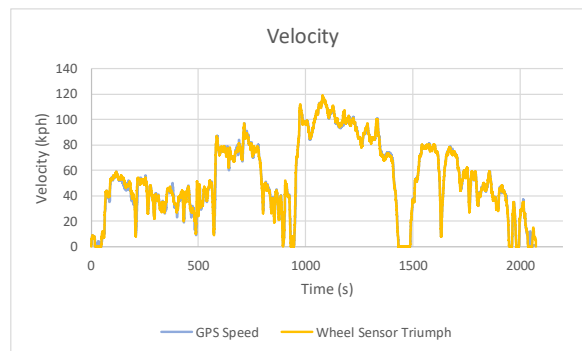


Figure 3. Triumph velocities analysis

As it can be observed in Figure 3, the data from the GPS has the same precision as the values measured from the wheel sensor. As the GPS source was the same for the 3 vehicles, this means that comparing the 3 velocities will give reliable results.

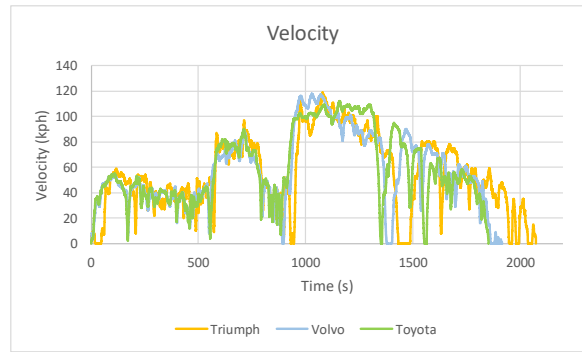


Figure 4. Velocity Comparison

A similar velocity pattern was verified in the 3 different types of vehicles during the same drive cycle.

- The RPM of the 3 vehicles was plotted and the differences observed were the expected, once analysing the vehicles' powertrain specifications.

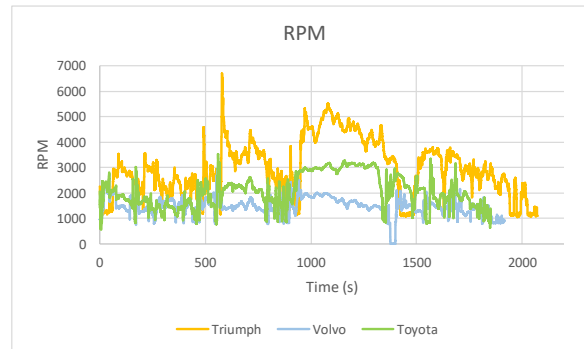


Figure 5. RPM Comparison

- It was then interesting to analyse the calculated channel that outputs the engine's power.

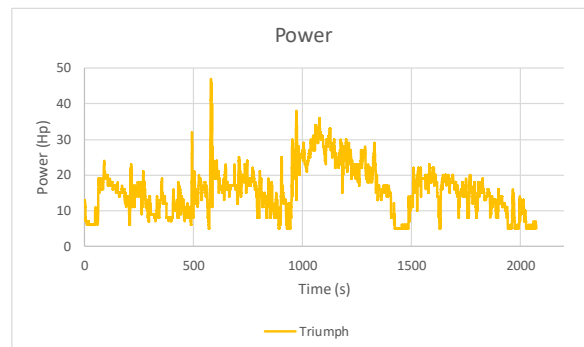


Figure 6. Triumph Power

A relation between the Triumph power output and the and RPM values observed in Figure 5 can be clearly identified. For the maximum RPM value observed during the drive cycle, around 6600 RPM, the Triumph model should be outputting more than 60 Hp according to a real power curve.

It can be concluded that the calculated channel of engine power it is not accurate enough to be used as a reference.

- The calculated channel of distance was plotted and compared for the 3 vehicles, once it was validated resorting to the delta time and velocity raw channels;

$$\Delta x = \left(\frac{v + v_0}{2} \right) t$$



Figure 7. Distance Comparison

The distance travelled by the 3 vehicles followed the same trend during time, which enhances the similarities between drive cycles, as it was already observed in Figure 4, when comparing the velocities.

- The calculation channel of acceleration was also selected to be analysed because of its relevance in further calculations performed in Chapter 3;

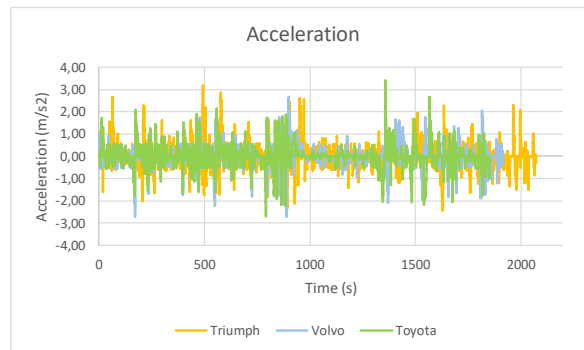


Figure 8. Acceleration Comparison

Even though this calculated channel wasn't validated by the author, it was assumed as correct because of its dependency to the velocity and time channels that were already validated. No further conclusions could be taken from the figure above, Figure 8.

3 COMPARISON OF THE 3 VEHICLES OVER THE DRIVE CYCLE

In the previous chapter the raw data and calculated channels from the 3 different vehicles were compiled, processed and the selected calculated channels were validated. It was now possible to carry out a comparison between the vehicles over the asked parameters in the assignment.

The Triumph, Volvo and Toyota were then assessed in terms of engine load, drivability, efficiency and performance over the drive cycle.

Before addressing those parameters, the author compared some of the vehicles' specifications and performed a fuel/energy analysis.

Table 1. 3 Vehicles Specs and Fuel analysis

Model	Triumph	Volvo	Toyota	Units
Bore	0,074	0,082	0,071	m
Stroke	0,0619	0,0932	0,084	m
Max Power	69,1	88	51	kw
	9300	4500	6000	RPM
Mass	300	1691	955	Kg
Volume S	2,66E-04	4,92E-04	3,33E-04	m3
Vol Eff	1	1,1	1	
Density Air	1,167	1,167	1,167	Kg/m3
FUEL ANALYSIS				
Density	770	832	770	Kg/m3
Fuel Ratio	13,23	13,05	13,23	
Mass	2,18E-05	4,50E-05	2,73E-05	Kg/cyl
LHV	4,34E+07	4,26E+07	4,34E+07	J/Kg
Energy	948	1916	1184	J/cyl
Power Engine	220,3	287,4	177,6	kW
Efficiency	31%	31%	29%	
Fuel Economy	4,7	4,7	4,7	L/100km
	0,047	0,047	0,047	L/km
	3,62E-05	3,91E-05	3,62E-05	Kg/m

Starting by comparing the drivability, the vehicles were assessed in relation to the number of seats, luggage and tank capacity.

Table 2. Drivability Comparison

DRIVABILITY COMPARISON				
Model	Triumph	Volvo	Toyota	Units
Number of seats	2	5	4	
Luggage Capacity		335	168	L
Tank Capacity	19	62	35	L

As it can be observed at Table 2, the Volvo is clearly the best option in all the parameters observed. It is able to transport the largest amount of people. The luggage capacity is twice the size of the other car option and the motorcycle as standard doesn't offer luggage capacity. Finally, the tank capacity is where the Volvo stands out, being able with its 62L to cover 1.8 times more distance than the Toyota and 3.4 times more than the motorcycle for the same fuel economy.

The Volvo could have been the best option out of the three vehicles in terms of drivability, but when doing a performance analysis, this outcome is not observed.

Table 3. Performance Comparison

PERFORMANCE COMPARISON				
Model	Triumph	Volvo	Toyota	Units
Engine Performance	86,5	44,7	51,1	kW/L
Overall Performance	0,230	0,052	0,053	kW/Kg

Two different performance comparisons were evaluated – Engine and Overall Performance.

- $Engine\ Performance = \frac{MaxEngine\ Power\ from\ Specs(kW)}{Engine\ Displacement(dm^3)}$
- $Overall\ Performance = \frac{MaxEngine\ Power\ from\ Specs\ (kW)}{Vehicle + Driver\ Weight\ (Kg)}$

Analysing the results from Table 3, the superior performance of the Triumph motorcycle is observed over the other cars. Not only the power developed by the engine over its displacement is almost twice as much as the one from the cars, but also the overall performance of the Triumph is 4.4 times superior to its competitors. This difference is related with the discrepancy of overall mass between the vehicles - 215 kg for the Triumph, more than 1500 kg for the Volvo and close to 900 kg for the Toyota.

The results for the engine load and efficiency comparison were the following:

Table 4. Engine Load & Efficiency Comparison

ENGINE LOAD & EFFICIENCY COMPARISON				
Model	Triumph	Volvo	Toyota	Units
Mean Engine Load	130,3	607,0	388,0	N
Mean WorkDone	188,4	730,8	452,8	J
Mean Fuel Energy	1570,6	1665,8	1570,6	J
Drive Cycle Efficiency	12%	44%	29%	

Having in consideration the mass difference between vehicles and that all 3 vehicles had a similar velocity and acceleration profile during the drive cycle, it was evident that the mean engine load would follow the same pattern as the mass difference. Where,

$$Engine\ Load\ (N) = (mass\ of\ vehicle + driver) . accelereation$$

(The mean engine load was only calculated for positive values of acceleration)

The results for the efficiency of each vehicle during the drive cycle were once again the expected. Because of the same fuel economy figure for all vehicles (around 50 mpg) and the difference in engine loads/work done, it was then anticipated the biggest efficiency around the drive cycle for the Volvo. With the same amount of energy provided by fuel, the Volvo was able to accomplish the same drive cycle having to move a much bigger mass.

The calculations performed were the following:

$$WorkDone (J) = Mean [Force . \Delta Distance]$$

$$Mean Fuel Energy(J) = fuel\ economy(Kg/m).LHV_{Gasoline}$$

$$Drive\ Cycle\ Efficiency = \frac{Mean\ Work\ Done}{Mean\ Fuel\ Energy}$$

4 “IDEAL” VEHICLE FOR THE 60KM DAILY COMMUTE

In this chapter it is proposed to model an ideal vehicle for a 60 km commute, using one of the previous analysed vehicles as a start point.

It was then decided to adopt the Triumph motorcycle as a start point, even though it was proven in the previous chapter as the least efficient vehicle during the drive cycle. The lightness, easy flow through traffic, easy parking due to its dimensions and the interest of the author in motorcycles were the reasons behind this decision.

Once the start point was defined, a range of different technologies to improve the efficiency and reduce costs of the 60km commute were implemented. The changes operated range from the substitution of the combustion engine by an electric motor and the introduction of a kinetic energy recovery system (KERS) to recover a portion of the vehicle's energy under braking. It was decided not to include stop-start systems because there is no consumption of energy once the electric motor is stopped and additionally there was only one time the vehicles stopped during the drive cycle.

Starting the analysis by looking at the energy required from the battery package to accomplish the 60 km commute.

Table 5. Electric Energy

Electric Energy		Units
Total Distance	60000	m
Fuel used	2,17	Kg
Energy Output	3,0E+07	J
Battery Capacity	8,21	kWh

Where,

$$Fuel\ used\ (kg) = Total\ distance\ (m) \cdot fuel\ economy\ (kg/m)$$

$$Energy\ Output\ (J) = Fuel\ used\ (kg) \cdot LHV_{Gasoline}\ (J/kg) \cdot Engine\ Efficiency$$

$$Battery\ Capacity\ (kWh) = \frac{Energy\ Output\ (J)}{3600} \cdot 10^{-3}$$

By calculating the energy of the fuel that was transformed in kinetic energy to move the motorcycle during 60 km, 30 MJ, it allowed the author to calculate the battery capacity required to power the same motorcycle if using an electric powertrain – 8,21 kWh.

Then, the author introduced a KERTS system to be able to recover part of the vehicle's energy under braking and determine by how much the battery capacity could be reduced.

Table 6. KERS Analysis

+ KERS		Units
WD - Braking	-3,4E+06	J
WD - Rear brake	-1,7E+06	J
Battery Saved	-0,47	kWh
Battery Capacity KERS	7,74	kWh

Firstly,

$$WorkDone_{Braking}(J) = \sum Force_{Braking} \cdot \Delta Distance$$

Where,

$$Force_{Braking} = (mass\ of\ vehicle + driver) \cdot acceleration_{negative}$$

Energy will be recovered by using the electric motor as a generator, while the motorcycle is under braking. Once the rear wheel is the only wheel connected to the motor, the energy recovered will be approximately ½ of the total Work Done under braking.

Consequently, the energy capacity recovered under braking by the real wheel will be the following:

$$Battery\ Capacity_{Saved}(kWh) = \frac{WorkDone_{Rear\ Brake}(J)}{3600} \cdot 10^{-3} = 0,24kWh$$

So,

$$Battery\ Capacity_{with\ KERS}(kWh) = Battery\ Capacity_{no\ KERS} - Battery\ Capacity_{Saved} = 8,21 - 0,24 = 7,97\ kWh$$

The powertrain efficiency is another factor that makes the electric motor an “ideal” option for the 60 km commute, instead of the combustion option.

Table 7. Powetrain Efficiency

Powertrain Efficiency		Units
Gas Engine	31%	
Electric Motor	92-98%	
Final Battery Capacity	8,14	kWh

With the technology change operated, an increase in the powertrain efficiency from 31% to more than 92% can be observed. Even though it is relatively high, it does not reach 100% efficiency, meaning that the battery capacity will have to be increased from 7,74 kWh to a final battery capacity of 8,14 kWh to be able to feed the electric motor during the 60 km commute.

The “ideal” vehicle will also have reduced running costs and will be environmentally friendly.

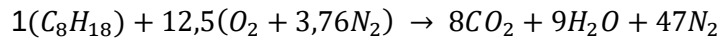
Table 8. Running Cost

Running Cost		Units
Fuel	1,22	£/L
Electric Energy	0,125	£/kWh
Fuel Used	3,44	£
Electric Energy Used	0,97	£
Cost Saving	2,47	£

As it can be observed in Table 8, the running costs during the 60 km commute of the electric motorcycle were reduced by 3.5 times when compared to the combustion option. This is mainly a result of the difference between prices of fuel per litre and energy in kWh. As a result, to perform the same 60 km distance, the electric motorcycle will have a cost of £0,97 when compared to the combustion motorcycle at £3,44.

In terms of CO₂ emission during the studied commute, the “ideal” vehicle with the electric powertrain offers no emissions per kWh consumed, which sets this vehicle already as a better option when compared to the combustion engine.

The emissions of CO₂ for the combustion option during the commute are the following:



- Mass of CO₂ in the current blend = 8 * (12+2*16) = 216 kg of CO₂

$$\frac{\text{Mass of } CO_2}{\text{Mass of fuel}} = \frac{352}{(12 * 8 + 18)} = 3.09$$

- So, for each kg of fuel burned, 3,09 kg of CO₂ are produced.
- With the amount of fuel used, already stated on Table 5, in the 60 km commute the combustion motorcycle will be responsible for the emission of 6,71 Kg of CO₂;

5 MOTORCYCLE SPECIFICATIONS FOR 2028

Assuming the author as a Technical Director of a motorcycle company and following the recent political trend of several countries with propositions to ban petrol and diesel vehicles in coming years in order to reach a set goal of zero carbon emissions, it was decided to propose the production of a 100% electric motorcycle for the year of 2028.

Not only an electric model will follow and benefit from political measures but will also represent great economical benefits for the clients of the future model. As proven in the previous chapter on Table 8, there will be a cost saving of £2,47 per 60 km commute. Considering that this drive cycle will be repeated for five days a week during the 52 weeks on a calendar year, the client will end up saving around £642 per year.

In terms of overall specifications, it was decided to keep most of the Triumph specifications. This way it will be possible to offer the client the same ergonomics, sensations and performance, while benefiting from lower running cost and a zero-carbon emissions vehicle.

For the powertrain, the objective was to use an electric motor with the same performance as the Triumph, while retaining the gearbox in order to offer the same torque figures at the rear wheel.

To do so, the Triumph performance during the drive cycle was investigated to in order to identify the maximum power values used.

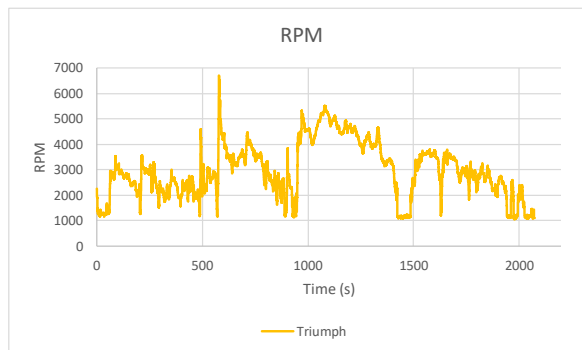


Figure 9. Triumph RPM during drive cycle



Figure 10. Triumph real power curve

After analysing the RPM values from the Triumph motorcycle during the drive cycle and comparing those to a real power curve of the engine, the following conclusions about the power used during the drive cycle were taken:

Table 9. Power used by Triumph during drive cycle

Triumph Engine Analysis		
Max Power	69,1	kW
	9300	RPM
Max Torque	79	Nm
	7850	RPM
During Cycle		
Max Power	65	Hp
	48,4	kW
	6500	RPM
Torque	71,1	Nm

Once identified the maximum power and torque figure utilized by the motorcycle during the drive cycle it was possible to choose the best suited electric motor.

The best electric motor suited for the 2028 electric motorcycle was the EMRAX 268, which presented the following specifications.

Table 10. Emrax 268 specifications

	Mechanical		Electrical	
	Type:	Axial flux motor / generator	Maximal battery voltage:	550 (HV) / 350 (MV) / 120 Vdc (LV)
	Casing diameter:	208 mm	Peak power (at 6000 RPM):	68 kW
	Axial length:	85 mm	Continuous power*:	up to 41 kW
	Dry mass:	9,1 kg (AC) / 9,3 kg (CC) / 9,4 kg (LC)	Peak torque:	140 Nm
	Stator cooling:	air (IP21) / combined (IP21) / liquid (IP65)	Continuous torque*:	up to 80 Nm
	Mounting:	Front: 6x M8 threaded holes Back: 8x M8 threaded holes	Efficiency:	92-98%



Figure 11. Emrax 268 motor

As it can be observed in the Table 10, the *EMRAX 268* has the power and torque figures to match the Triumph engine during the drive cycle, is lightweight and works at a low voltage of 120V, which is safer than other higher voltage solutions. (Link for the motor website in Chapter 6 References)

Once the motor was selected it was then time to choose the motor controller, that is responsible for all the interactions between the batteries, motor and throttle and that also works as an inverter, to convert the DC current of the batteries to AC of the motor.

It was then decided to use the *emDRIVE 500*, which is developed and produced in the same country as the motor, performing at the same voltage as the motor and the maximum power allowable is within the range of the motor selected.

Table 11. emDrive 500 specifications



Figure 12. emDrive 500 Controller

CONTROLLER SPECS		
Model	emDrive 500	
Voltage Range	30-120	V
Power Rating	60/110	kW
Weight	4,9	Kg
Cooling	Liquid	

After carefully investigation, the cells chosen to be used in the 2028 electric motorcycle were the LG 18650 – HG2, which offer one of the best relations in the market between capacity, discharge and weight.

Table 12. LG 18650 – HG2 Specifications



Figure 13. LG 18650 – HG2 cells

CELL SPECS		
Model	LG 18650-HG2	
Voltage	3,6	V
Capacity	3	Ah
Discharge	20	A
Weight	0,047	Kg
Price	3,24	£

Finally, when the author had decided the motor and cells to use in the 2028 model, the battery pack could be specked.

Table 13. Final battery specifications

BATTERY PACK SPECS		
Motor Voltage	120	V
Motor Power	41	kW
Capacity needed	8,14	kWh
Series	34	
Capacity / Parallel	360	Wh
Parallels needed	23	
Power Final	55,2	kW
Capacity Final	8,28	kWh
Nº of cells	782	
Weight	36,8	Kg
Price	2533,68	£

Some considerations about the calculations:

- $Series = \frac{Voltage_{Motor}}{Voltage_{cell}}$, (result was round up to get an integer number);
- $Parallels = \frac{Battery\ Capacity\ needed(kWh)}{\frac{Voltage_{Motor}(V)}{CellCapacity(Ah)} * 10^{-3}}$, (result was round up to get an integer number);

- Maximum possible power outputted from the current battery pack:

$$Maximum\ Power\ (kW) = Discharge_{cell}(A) . Parallels . Voltage_{Motor}(V) . 10^{-3}$$

- Final battery pack with the current cell arrangement (34 series by 23 parallels):

$$Final\ Battery\ Capacity\ (kWh) = Capacity_{cell}(Ah) . Parallels . Voltage_{Motor}(V) . 10^{-3}$$

- As observed in Table 13, the final battery pack will end up having 782 cells, weighting approximately 36,8 Kg and it will cost around £2533.

6 REFERENCES

- <https://emrax.com/e-motors/emrax-268/>
- <https://www.emdrive-mobility.com/portfolio/emdrive-500/>
- <https://eu.nkon.nl/rechargeable/li-ion/18650-size/lg-18650-hg2-without-warning.html>