# Electric Motorcycle Power Plant Design Proposal

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# 1 Executive Summary

Electracycle have commissioned Brilliance in Mind to design a power plant for their electric motorcycle project. The design is to consider various battery chemistry types and capacities, as well as the possible inclusion of a Regenerative Brake System (RBS).

The design goals have been defined as:

1. Maximise the range (or distance between charges).
2. Minimise total cost of ownership (over a 10 year period).

As part of the analysis this report considers aspects of motorcycle performance, battery type/size, regenerative braking, battery cooling, and total cost of ownership. This report details the engineering used to assess each of these design sections, considering all variables, constraints, and design goals.

Brilliance in Mind have modelled all possible battery size/type combinations, with and without the RBS. As this report will highlight, some battery combinations are not suitable for reasons of size (too large to fit the chassis), or cost (exceeding the maximum initial capital cost). Based on the results of our modelling we have considered design solutions and made a recommendation for the final design.

Our recommendation is to equip the motorcycle with a **LFP-60 battery with no Regenerative Brake System**. This report shows that this battery configuration provides the lowest operating cost per unit of range ($/km), providing a compromise between the two design goals.

# Table of Contents

# 2 Introduction

Electracycle Pty Ltd has sought submissions on the power plant design for their proposed Electric Motorcycle design. This report has been prepared by Brilliance in Mind to address the various design criteria as nominated by Electracycle (Client Brief Ver. 2.0, 2011), and to recommend the ideal power plant configuration(s).

The report will summarise the technical analysis of the design sections:

1. Motorcycle performance
2. Battery Type and Size
3. Regenerative Braking System
4. Battery Cooling, and
5. Total Cost of Ownership

The system has been modelled to enable a relevant comparison of the options. Possible solutions will be assessed and a final recommendation made in accordance with the nominated design goals.

# 3 Technical Analysis

The technical analysis of this system has been divided into the design sections as nominated by Electracycle. The following is a summary of the engineering science of each section.

## 3.1 Motorcycle Performance

Motorcycle performance is to be assessed on the criteria of total mass, acceleration and range.

The total mass of the bike is the sum of the various components of the system, and can be summarised as:

$$\boldsymbol{m_t = 160kg + m_r + m_b} \qquad \textbf{Equation 1}$$

Where $m_t$ is the total mass, $m_r$ is the mass of the regenerative brake system (if used), and $m_b$ is the mass of the battery unit. 160kg is the combined mass of the passenger, motorcycle and motor. Battery mass is a product of capacity (kWh) and energy density (kWh/kg), and the calculation for battery mass will be discussed in Section 3.2.

The acceleration of the bike can be calculated from the formula:

$$\boldsymbol{a = \frac{224.3}{m_t}} \qquad \textbf{Equation 2}$$

where $a$ is the acceleration (m/s²).

The constant **224.3** is derived from the torque rating of the motor and the radius of the powered wheel. Both of these values have been nominated in the Client Brief and are treated as constants for the purpose of this design.

For example: a motorcycle equipped with a NMC-44 battery and no regenerative braking system will have a total mass of 167.65kg. Using the above formula we calculate an acceleration of 1.34m/s². In practical terms this would accelerate the motorcycle to 60kph in 12.5 seconds.

It is important to note that the variance in battery mass over all battery types/sizes is only 11.1kg. The battery mass alone forms only a small part of the total motorcycle mass (generally between 5 and 10% of the total), and does not have a large effect on acceleration (see Figure 1). As the diagram shows, the variance in time taken to achieve a velocity is relatively small across the range of achievable acceleration figures.

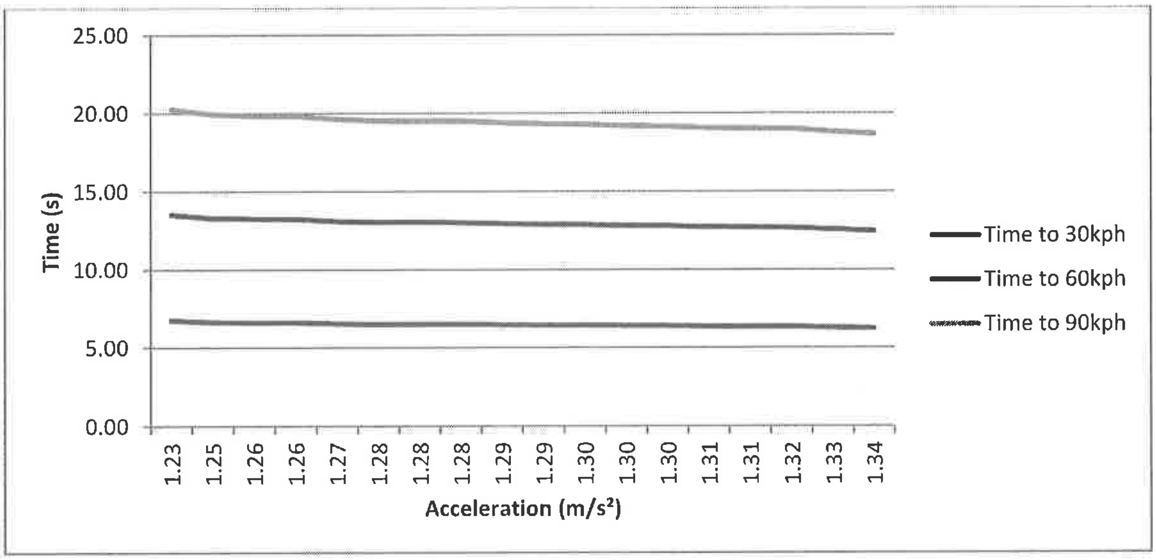


**Figure 1- Acceleration times based on calculated acceleration figures**

Motorcycle range (in km) is a product of the battery capacity and power usage. Electracycle, in the Client Brief (2011), has nominated an average speed of 30kph for urban use. In addition they have supplied the formula to calculate power usage:

$$p = m_t \times v^2 \times f$$

where $p$ is the average power required (W), $v$ is the velocity (m/s) and $f$ the nominated energy usage fraction (12%). This value does not account for the efficiency rating of the motor, meaning that the actual power being drained from the battery will be higher than the value of $p$ calculated from this formula alone.

If we substitute the known values into this formula ($v$ = 30kph or 8.33m/s², $f$ = 0.12), and account for the motor efficiency rating of 90%, the power usage calculation can be simplified to:

$$\boldsymbol{p = 9.26 \times m_t}$$ **Equation 3**

From this we can calculate the motorcycle range (in hours):

$$\boldsymbol{R_t = \frac{c}{9.26 \times m^t}}$$ **Equation 4**

And in kilometres:

$$\boldsymbol{R_d = \frac{c}{9.26 \times m^t} \times 30}$$ **Equation 5**

where $c$ is the battery capacity (W).

It is now clear from Equations 4 and 5 that we can expect range to increase as the battery capacity is increased, and decrease as mass is increased.

As an example, using the previous case of a NMC-44 battery with no regenerative braking system, the range of the motorcycle would be 85.0km (or a running time of 170min).

## 3.2 Battery Type and Size

Electracycle have nominated 3 possible battery chemistry types (NMC, LMO, and LFP) and 3 battery sizes/capacities (4.4 kWh, 6.0 kWh, and 7.5 kWh). This results in 9 possible battery size/type combinations. The final design will need to consider the best combination of these two variables.

As discussed in Section 3.1, the mass of the battery is a contributing factor in the calculations for motorcycle range and acceleration (as a component of total mass, see Equation 1). Mass can be calculated as follows:

$$m_b = \frac{c}{e} \qquad \textbf{Equation 6}$$

where $e$ is the specific energy (or energy density) (kWh/kg), $c$ is the battery capacity (kWh) and $m_b$ is the mass of the battery (kg).

In other words: battery mass is a product of capacity (kWh) and energy density (kWh/kg), with a higher energy density resulting in a lower mass. For example, a NMC-44 battery will have a mass of 7.65kg, but the less energy dense LFP-44 battery will have a mass of 11kg (both having the same capacity of 4.4kWh).

The volume of the battery and optional Regenerative Brake System (RBS) is a primary design restraint, as there is limited space available within the bike chassis to hold the equipment. The maximum available volume ($V_{max}$) is 0.0102m³.

Battery volume can be calculated as follows:

$$V = \frac{c}{e\ \rho} \qquad \textbf{Equation 7}$$

where $\rho$ is the density (kg/m³) and V represents battery volume (m³).

This volume, combined with the volume of the RBS (0.001m³, if chosen), can be no greater than 0.0102m³.

Table 1, below, lists some of the possible battery type/size combinations and the associated volumes. Please note the cells with the red numbers indicate a combination that exceeds the allowable volume.

**Table 1 – Battery Volume Samples**

| Chemistry Type | Capacity (kWh) | Battery Volume ($m^3$) | Combined Battery/Brake Unit Volume ($m^3$) |
|---|---|---|---|
| NMC | 4.4 | 0.0051 | 0.0061 |
| NMC | 6.0 | 0.0070 | 0.0080 |
| NMC | 7.5 | 0.0087 | 0.0097 |
| LMO | 4.4 | 0.0059 | 0.0069 |
| LMO | 6.0 | 0.0081 | 0.0061 |
| LMO | 7.5 | 0.0101 | 0.0111 |
| LFP | 4.4 | 0.0073 | 0.0083 |
| LFP | 6.0 | 0.0100 | 0.0110 |
| LFP | 7.5 | 0.0125 | 0.0135 |

Battery life (in years) is derived from the expected life of the battery (in recharges), and the expected number of times the battery will be recharged.

$$L = \frac{N}{250} \qquad \textbf{Equation 9}$$

Where $L$ is the battery life (in years), and $N$ is the Expected Life (in recharges, as given in the Client Brief Ver. 2.0 (2011)).

## 3.3 Regenerative Braking System

The Regenerative Braking System returns a portion of energy collected in the brakes during deceleration, and returns this energy to the batteries. In other words the battery is recharged during normal driving.

The regenerative brake system effectively adds 17% to the battery capacity, whilst adding mass (3 kg), volume ($0.001m^3$) and cost ($1000) to the overall motorcycle (Client Brief Ver. 2.0, 2011). Modelling has shown that the inclusion of a regenerative braking system does exceed the volume or cost constraints of *some* battery size/types. Table 2 gives an example of this, showing the change in volume and cost for a LMO-75 equipped motorcycle, with and without the brake system.

As we know from above, the increase in mass will have an adverse effect on both range and acceleration (see Section 3.1, Motorcycle Performance). As discussed, the relatively small changes in mass have little effect on real world acceleration. However, modelling does show that the extra capacity will have a positive effect on range. Table 2 shows the effect on range when a regenerative braking system is added to the LMO-75 equipped motorcycle.

**Table 2 –LMO-75 regenerative brake system, cost and volume and range comparison**

| Regenerative Brake System | Volume ($m^3$) | Initial Capital Cost ($) | Range (km) |
|---|---|---|---|
| No | 0.0101 | 15,000 | 139 |
| Yes | 0.0111 | 16,000 | 160 |

Brilliance in Mind have modelled all battery type/size combinations with and without the RBS, enabling a comprehensive assessment of all configurations. Our design solutions and recommendations will therefore take into consideration the potential costs and benefits of including a regenerative braking system.

## 3.4 Battery Cooling System

All battery types produce heat and require cooling to prevent damage or injury. As stated in Dinger et al (2010): a "single battery fire could turn public opinion against electric mobility". All battery types we have considered have a maximum safe operating temperature of 50 C.

To reduce heat build-up within the battery, cooling can be provided through convection with the surrounding air (Moaveni, 2011, p. 321). The battery itself is exposed on 2 sides to open air, providing some cooling. Where the exposed surface area is not enough to cool the battery, cooling fins may be required to provide the additional required area.

Note that for all following calculations, an ambient temperature of 40 C has been assumed. Although the Client Brief gives an ambient temperature range of 0 C to 40 C, using the higher figure will result in the safest results as this will require the smallest increase over ambient temperature to exceed the maximum safe operating temperature. An average velocity of 30kph has been assumed.

The heat generated by a battery can be calculated as follows:

$$Q_H = \left(\frac{p}{48}\right)^2 \times 0.05 \qquad \textbf{Equation 10}$$

where $Q_H$ is the power loss causing internal heating within the battery (W) and $p$ is the power (W, see Equation 3).

Note that Electracycle have nominated a safety factor of **2** for the battery design, and therefore the value of $Q_H$ from above will be doubled when calculating the area required for cooling the battery.

For example, an NMC-44 battery equipped motorcycle with no regenerative braking system will produce 52.2W of heat. The cooling system would therefore need to be designed to dissipate 104 W of heating.

The area of battery fins required for cooling the battery can be calculated as follows:

$$A_r = \frac{(\frac{p}{48})^2}{10000} - 2.(\sqrt[3]{V})^2 \qquad \textbf{Equation 11}$$

where $A_r$ is the total area of cooling fins required (m²), $p$ is the power required to maintain an average speed (W) and $V$ is the volume of the battery (m³, see Equation 7). Please note this formula *does* account for the safety factor mentioned above.

A negative value of $A_r$ would indicate that the cooling provided by the surface of the battery itself is adequate to keep the battery below the maximum safe operating temperature. A positive value will give us the actual area required to be provided by the cooling fins.

In all cases, our modelling shows that cooling fans will be required once the safety factor has been taken into consideration.

## 3.5 Total Cost of Ownership

The total cost of ownership of the motorcycle can be separated into two sections: the initial capital cost, and the ongoing battery replacement costs. For this assessment Electracycle requested that the ongoing costs be estimated for a 10 year period.

The capital cost of the motorcycle is comprised of three parts: the motorcycle and motor, the battery, and the regenerative braking system. As the motorcycle/motor cost is fixed ($6000), the cost of the battery and optional brake system are the only variables.

The formula for calculating total capital cost is as follows:

$$C_t = (C_e \times c) + C_r + 6000 \qquad \textbf{Equation 12}$$

where $C_t$ is the total capital cost ($), $C_e$ is the cost per kWh of the battery ($/kWh), $c$ is battery capacity (kWh), and $C_r$ is the cost of the optional regenerative brake system.

The more energy dense a battery is, the greater the cost per kWh, which in turn is reflected in the total cost of the battery. For example, a low energy density LFP-44 battery will cost $4,400, whereas the more energy dense NMC-44 battery will cost $6160.

The total cost of ownership for a 10 year period is the sum of the initial capital outlay, plus the cost replacing the battery during that time:

$$C_o = (C_e \times c \times \frac{10}{L}) + C_r + 6000 \qquad \textbf{Equation 13}$$

where $C_o$ is the total cost of ownership and $L$ is the expected battery life (in years, see Section 3.2).

For example, a motorcycle with a NMC-44 battery (as above, cost: $4,400) and a regenerative braking system will have a total cost of ownership of $21,000 over 10 years, $13,160 of that figure being the initial capital cost.

# 4 Design Solutions

The possible design solutions for the Electracycle motorcycle must comply with the constraints of initial capital cost (not greater than $15,000) and available space for the battery/brake unit (0.0102m³). The available variables for consideration are the battery size, battery chemistry, and the optional inclusion of the Regenerative Braking System (RBS).

The Brief (Client Brief Ver. 2.0, 2011) nominates the following two design goals:

1. That the total cost of ownership (over a 10 year period) be minimised; and
2. That the range (as a distance between recharges) be maximised.

To some extent, these two variables are conflicting. Our modelling has shown that a motorcycle equipped with a cheaper battery option is likely to have a smaller range; and the battery combination offering the greatest range is likely to be more costly.

Figure 2 displays the total cost of ownership and range for all possible battery types, with and without the RBS. As a comparison, the average ownership cost across all combinations is $22,940, and the average range 120km.

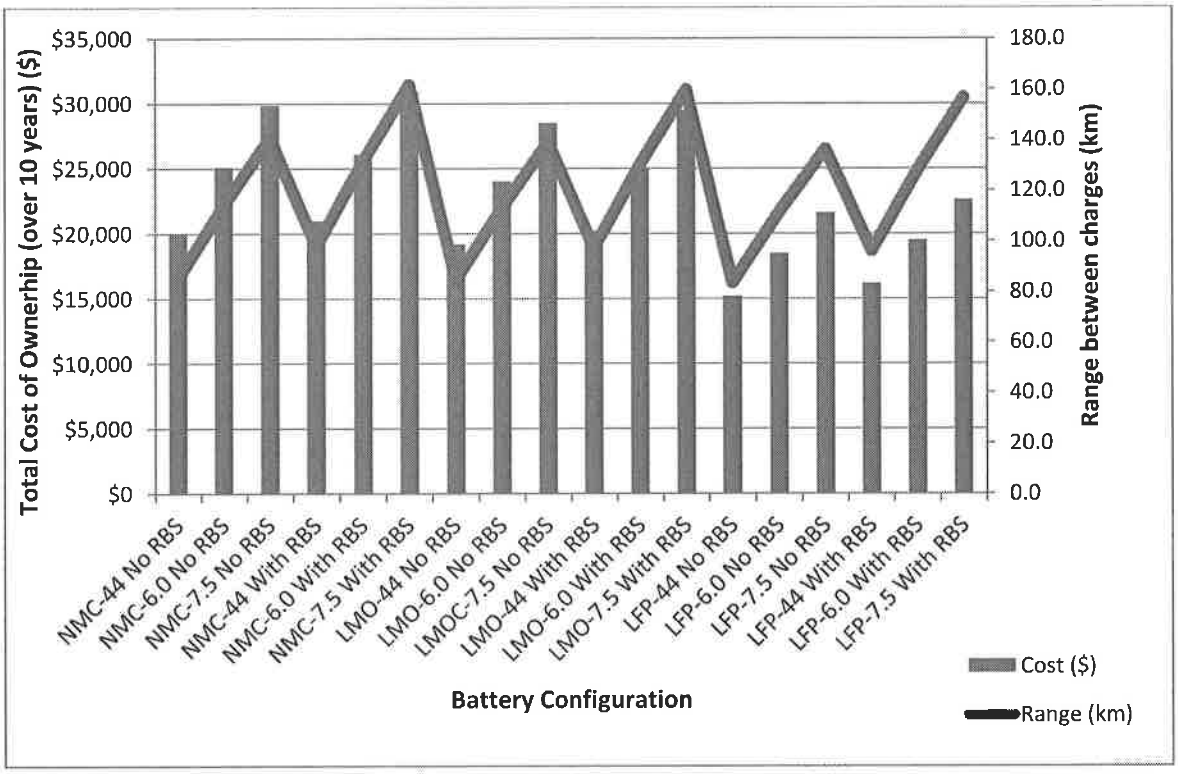


**Figure 2- Total Cost of Ownership and Range Between Charges**

Firstly we will consider the option with the lowest total cost of ownership: the LFP-44 battery with no RBS. This combination will result in a motorcycle with a total cost of ownership of $15,170, well below the average. This motorcycle, however, has the lowest range of all the options we have modelled, at 83km.

At the other end, the option with the largest range would be the NMC-75 battery with RBS. This motorcycle would have a range of 162km (almost double the previous example). However, the total cost of ownership for this motorcycle would be $30,860 of 10 years. More importantly, the initial capital cost of this motorcycle would be $17,500, exceeding the $15,000 limit nominated by Electracycle.

The configuration with the largest range that also meets the space and cost design constraints is the LMO-75 battery with no RBS. This motorcycle will have a range of 138.8km and a total cost of ownership of $28,500.

Our modelling suggests that the ideal solution will be a compromise between range and cost. To enable a comparison we have elected to model a Cost/Range ratio. This ratio will be a direct comparison between total ownership cost (over 10 years) and the range of the motorcycle between charges. Effectively this creates a value for cost ($) per range (km) (or $/km). Figure 3 compares the Cost/Range ratio for all available battery configurations.

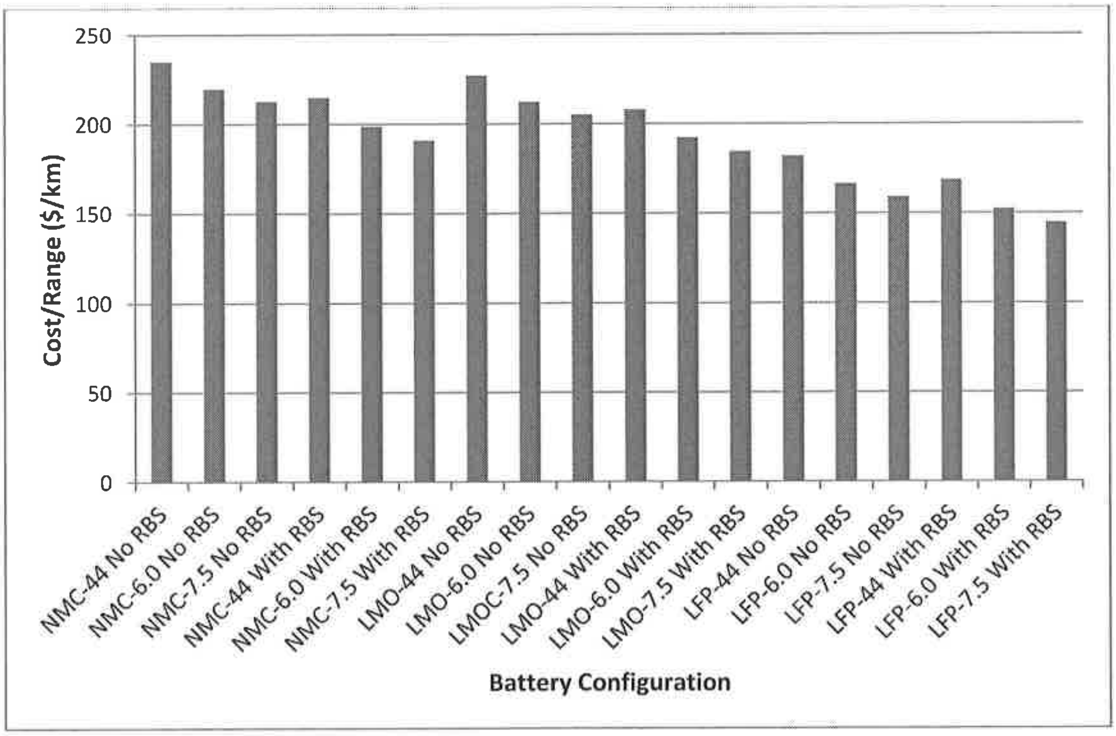


**Figure 3 – Cost/Range comparison between all battery configurations**

Please note that this figure displays the Cost/Range ratio of all configurations, and does not consider the design constraints of cost and battery volume that will need to be met in the final design.

# 5 Recommendation

As discussed in Section 4, we have elected to use a Cost/Range ratio to select the battery configuration. This value represents the cost (as an overall cost of ownership) per range (in kilometres between recharges). This represents a compromise between the two primary design goals set down in the Client Brief (Ver. 2.0, 2011).

Our recommendation is to equip the motorcycle with a LFP-60 battery with no Regenerative Brake System (RBS) (see Table 3).

**Table 3 – Design Recommendation**

| Type | RBS | Total Bike Mass (kg) | Battery/RBS Volume ($m^3$) | Acceleration ($m/s^2$) | Time to 60kph (s) | Range (km) | Initial Capital Cost ($) | Total Cost of Ownership (10 years) ($) | Area of battery fins required ($m^2$) |
|---|---|---|---|---|---|---|---|---|---|
| LFP-60 | No | 175 | 0.0100 | 1.28 | 13 | 111 | 12,000 | 18,500 | 0.021 |

This configuration represents the lowest Cost/Range ratio of all options that fit within the design constraints. Note there are several options with a lower Cost/Range ratio that are deemed not suitable due reasons of size (too large to fit the chassis) or cost (initial capital cost exceeding $15,000).

It is interesting to note that the recommended design does not include the RBS. Although the inclusion of a RBS does in fact improve the Cost/Range ratio over a similar battery without the RBS, our modelling indicates that the LFP-60 without the RBS still represents a better compromise over other suitable configurations.

In summary: we have thoroughly modelled all parts of the motorcycle power plant design, and recommend to Electracycle that the LFP-60 battery without RBS represents the best compromise of the nominated design goals, within the given constraints.

# 6 References

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