NICHE Vehicle Network

OPTIMISATION OF ELECTRIC POWERTRAINS FOR URBAN MOTORCYCLES PROJECT REPORT

Project Partners

REAP Systems Ltd

Agility Global Ltd

Lynch Motor Company Ltd

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Introduction

1.1 Background and Motivation

The electric vehicle powertrain industry has neglected road motorcycles, with developed world industry focus on electric cars and developing world industry focus on electric bicycles and scooters. This project does re-balance this focus, bringing competitive innovations from UK companies to this sector and capturing consumer sales in a global market that is set to undergo 800% growth in the next six years.

Using DEFRA's 2010 greenhouse gas conversion factors, the UK has electricity grid emissions of 618 grams of CO_2 per kWh consumed. Agility's single-battery-pack motorcycle Saietta *(the "Saietta S")* has approximately 4.8kWh of energy capacity and delivers a range of 50 miles for urban riding, giving CO_2 emissions of 60 grams per mile. DEFRA gives a figure of 171 grams of CO_2 per mile for the existing 125cc to 500cc motorcycle fleet, the Saietta S being equivalent to a 500cc conventional motorcycle. This provides a CO_2 saving of 65%. The CO2 emissions are even less when taking the EU as a whole, where the average electricity grid emissions are 446 grams of CO_2 per kWh of electricity consumed. With this figure, the Saietta S provides a greenhouse gas saving of 75% over conventional motorcycles. For the Saietta R, which has an energy capacity of 9.6kWh, the saving is even greater, as the corresponding category of conventional motorcycle *(over 500cc)* produces an average of 225 grams of CO_2 per mile. Replicating the same calculations with the urban riding range of 100 miles gives a CO_2 saving of 73% for the UK electricity grid average and 81% for the EU electricity grid average.

The latest Department for Transport figure for average distance travelled for 125cc to 500cc motorcycles is 2,772 miles per year, leading to an average saving of approximately 308 kg of CO_2 per year per motorcycle. Taken across Agility's first year predicted sales of 500 units, this is a minimum CO_2 saving of 154 metric tons, which is equivalent to the CO_2 sequestered by 59 acres of forest in one year *(United States EPA)*, clearly aligning the project with the carbon reduction theme.

An electric motorcycle powertrain essentially consists of a charger, a battery with battery management system, a motor controller, a motor and a mechanical drive to bring the power to the wheel. Agility has developed a prototype electric urban sports motorcycle called the Saietta, creating a proprietary modular battery module system and gearbox, and using off-the-shelf components for the rest of the powertrain. Due to the focus of the electric vehicle market on electric cars and electric scooters, a number of off-the-shelf components in the powertrain make significant compromises when applied to an urban sports motorcycle. These compromises are not unique to Agility, with global competitors expending significant private and public resource to develop powertrains suitable for urban sports motorcycling. This project provided the opportunity for electric powertrain suppliers to optimise their existing technology for urban sports motorcycling, which is a rapidly growing global market, and to validate this technology on a cutting-edge urban sports motorcycle chassis.

For instance, the smallest EVO electric motor is the AFM-130, which provides 75kW of power and 220Nm of torque, which is far more than necessary for an urban motorcycle. Other motors, such as the range of Lynch or Agni motors provide insufficient torque and power – in the order of 15kW only. By comparison, the Ducati Monster 796 provides 65kW and 79Nm of peak torque.

Similarly, REAPsystems development of battery management systems *(BMS)* has been focused on larger electric vehicles, including boats, cars and underwater vehicles, where space and cost constraints are less demanding or where upfront development budgets for system integration and calibration are much higher. Simpler BMS are available. They are easier to integrate but the scope for calibration is not sufficient for managing the battery with the power levels expected in a sports motorbike.

Battery cost is the main obstacle to commercialising electric vehicles in medium volumes. Isolation test and pre-charge are essential but currently very costly and space-consuming functions. This project allowed REAPsystems to develop a solution, which is fully integrated in their Battery Control Unit. Minimising space requirements, cost and vehicle system complexity but still fulfilling the requirements of REG100.

The Saietta currently has a single gear ratio, which means that a compromise between acceleration and top-speed has to be made. In order to be competitive with conventional motorcycle powertrains, we have biased the compromise towards acceleration, as this is the most important of the two variables in an urban context. However, dual-carriageways and motorways are present within the range of the Saietta in many urban areas in which it will be sold, which means that top speed becomes an important factor for the consumer.

A multi-speed gearbox can enable the Saietta to not only accelerate competitively, but also reach a competitive top speed suitable for consumers who travel on urban motorways and dual-carriageways. There are also likely to be additional gains in range, as the choice of gear ratio will enable the motor to operate in higher efficiency regions of its torque-speed map.

1.1.1 Market Opportunities

A clean-tech research firm, Pike Research, has predicted that the global electric two wheeler market will increase from 17 million units in 2011 to 138 million units in 2017 *(Pike Research Press Release, 18/04/11)*; over 800% growth in six years. It is a globally competitive market, with the majority of sales being electric scooters in Asia. The developed world market, however, is focused on motorcycles due to the higher top speeds and greater range. Pike Research claim that motorcycles will account for 59% of the demand in North America. The Agility Saietta prototype is a fully-functioning and road-legal urban sports bike that will be competing with similarly priced vehicles from American companies Zero and Brammo, the Swiss company Quantya, and the only major manufacturer to have announced a production electric motorcycle, KTM.

These competitors have significantly more resource, which the Advantage Niche Vehicle grant has helped to balance. Brammo has raised $30 million of venture capital *(Southern Oregon Mail Tribune, 23/09/10)* and Zero has recently received a $900,272 grant from the California Energy Commission *(CEC Press Release, 06/10/10)* to develop an optimised electric powertrain. Quantya's financial situaton is not public, but they already produce and distribute the Evo1 Strada in 16 countries. Finally, KTM is a major conventional motorcycle manufacturer with sales revenues in 2009-10 of €591 million *(KTM Financial Report 2009-10)*.

The NVN grant has not only helped increasing the competitiveness and reduce the cost of the end product, the Agility Saietta, but also allowed Lynch Motor Company *(LMC)* and REAPsystems to produce products for a rapidly growing global market. The fact that global demand, particularly from the USA and the EU, dwarfs domestic demand also enables the partners to contribute to reducing the UK trade deficit, which stood at £3 billion in March 2011 *(Office for National Statistics, 11/05/11)*.

Agility predicts first year sales of 500 units. Second year sales will be 700 units and third year sales will be 1200 units. The technology developed can also be applied to Agility's scooter project, which will come to fruition in late 2012 / early 2013. First year sales for the electric scooter are predicted to be 3,600, increasing to 6,000 in 2013-14 and 10,000 in 2014-15.

As the project was focused on optimising existing technology for a new sector, the existing IPR was retained by the respective companies.

1.1.2 Project Extension

A project extension was granted in order to achieve the following:

By providing a top-speed competitive with conventional motorcycles, a multi-speed Saietta would increase Agility's share of the urban motorcycle market in cities where there are significant amounts of higher speed-limit highways. Such markets are particularly prevalent in the USA, as American cities tend to cover a larger area and urban travel is often by highway.

The multi-speed gearbox approach to allowing electric motorcycles to access this market has already been taken by Brammo, an American competitor to Agility. The Brammo Engage, a direct competitor to the Saietta due for release in 2012, will have a 6-speed gearbox to allow it to reach higher top-speeds. The additional funding has allowed Agility to ensure the global competitiveness of the Saietta.

The additional safety features provided by the isolation test circuit included in the new Battery Control Unit *(BCU)* design by REAPsystems will future-proof the Saietta against regulatory requirements, securing access to future electric motorcycle markets. The reduced cost of such features will increase the market acceptance for the motorbike as well as for the REAP battery management electronic products. The integration of those features into the BCU has also reduced the space requirements, reduced the complexity of system design and integration and increased the reliability of the vehicle due to fewer cables and connections. This has increased the market opportunities for REAP electronics. The high reliability due to fewer electrical connections and cables will improve the market acceptance of electric vehicles.

1.2 Project Partners

1.2.1 REAPsystems Ltd - Battery Management Systems *(Project Lead)*

REAPsystems specialise in battery management systems and have produced an off-the-shelf system for a range of applications and industries, based upon their experience in a number of sectors, including underwater vehicles and stationary energy systems. The core knowledge and approach relates back to research conducted by the founder at the University of Southampton. This heritage gives them a rigorous and extensive knowledge and skill base, resulting in their world-leading products. They have a track record of delivering challenging results for customers. In this project, REAPsystems has developed a battery management system for urban motorcycling, reducing the size of the standard units and optimising the electronics.

Dr. Dennis Doerffel from REAPsystems was appointed as project manager for this collaboration. He has 16 years of project management experience and has delivered on many commercial projects for REAPsystems.

1.2.2 Agility Global Ltd - Motorbike Manufacturer

Saietta prototypes have informed the design briefs for the powertrain components and provided test-beds for the developed components.

Agility have provided input requirements from their proprietary battery pack and they have validated the optimised components on Saietta prototypes.

Agility Global Ltd. has a design engineering skill base, with significant automotive commercial experience in the management team. Saietta is their entry to the electric vehicle market, and was launched to great fanfare at the London Motorcycle Show in February 2011. During the launch, 1-2 Google hits per minute were noted about Saietta for several days running, with an estimated 4,000+ people talking about the product online from Moscow to Johannesburg to Los Angeles. The launch at the MCN show was attended by an approximate 1,500 visitors to the Agility stand, including motorcycle celebrities Charley Boorman and Carl Fogerty. Saietta produced 4.5 times the target number of requests for test rides and expressions of interest within 4 days of its release to the public. In terms of proof of market demand, the launch itself was a great success. Since then Saietta has received press coverage in top motoring and pop culture publications in the UK, US, Peru, Spain, Germany, Mexico and Netherlands.

The Agility team is headed by Lawrence Marazzi, who has over twenty years experience in Entrepreneurship and Business Management via successful businesses in Central London and Management Consultancy. Mr. Marazzi also has over a decade of experience in Engineering Development, in companies ranging from Embraer Aerospace who create airplanes in Brazil, Turbo Technics who corner the world market in high speed automobile turbo-charger balancing machines and are a leading specialist turbo manufacturer from the UK, Honeybee Robotics, an American company in New York, who develop space exploration devices used on Mars Rover.

The Agility Team hail from leading UK universities such as Cambridge, Royal College of Art and Hatfield University. The engineering and design departments are among the best in UK cutting-edge development. Their Business Management and Production staff have experience internationally in producing top-quality goods that are created to highest standard, on-time and perfectly priced to maximise customer demand and company profit.

1.2.3 Lynch *(now: Lees)* Electric Motor Company Ltd - Manufacturer

Lynch Motor Company *(LMC)* have been producing motors and generators for over 20 years and what started out as a small specialist design and manufacturer has now grown into a world renowned product for innovation and quality.

Specialists in the field of low voltage high torque permanent magnet DC motors and generators, all of LMC's products offer the very best in efficiency, low weight and maximum power in the smallest package possible.

Their customer base ranges from individuals wishing to develop there own electric vehicle, boat and sometimes planes, through to large multinational and military organisations. On quite a number of applications LMC are called in at the concept stage to offer their technical assistance on the complete solution.

LMC are passionate about renewable energy and take pride in their achievements with the technology they have developed.

1.3 Project Aim and Objectives

This project is focused on optimising existing technologies for a new market; electric urban sports motorcycling. The key innovation, therefore, is applying UK research and development resource in this sector, giving the partner companies a major advantage in this rapidly growing, global market.

The results of this project are an optimised REAPsystems battery management system and an optimised Lynch electric motor integrated into an electric motorcycle powertrain and validated on a prototype Agility Saietta.

Project Aim and Objectives:

Vehicle System Level Objectives

- Significantly improved acceleration without sacrificing top speed
- Significantly more power from existing battery without sacrificing safety or longevity
- Improved control over individual cells in the battery without sacrificing on consistent driving behaviour
- Significantly improve packaging of battery system and controls
- Improved system reliability
- Added safety features
- Maintain or improve overall cost levels

Battery Management Components Level

Battery Control Unit - BCU

- Significantly reduce size
- Significantly reduce cost
- Ability to offer different packaging options
- Ability to offer custom functionalities, making additional ECUs redundant
- Integrated isolation test circuitry
- Integrated pre-charge circuitry

- Simplified battery control wiring
- Suitable for two parallel battery strings as an option

Cell Monitoring Circuit – CMC

- Significantly reduce size
- Significantly reduce overall battery system size
- Integration into battery modules
- Significantly reduce cost
- Minimise cables and interconnects
- Increased safety redundancy
- Significantly reduce power consumption when idle
- Maintaining robustness
- Ability to log full battery module usage information over battery life

Electric Motor Component Level

- Design larger motor version with more torque and power
- Significantly increase motor performance of existing motor while maintaining its reliability

Muli Speed Gearbox

- Before embarking on a physical gearbox prototype, Agility need to ensure that fitting a multi-speed gearbox into their existing package is feasible. The expected output of a detailed study is a set of detailed designs for a prototype multi-speed gearbox that fits within the existing packaging constraints of the single-speed Saietta.

1.4 Nomenclature

- PCB: Printed Circuit Board
- BMS: Battery Management System
- BCU: Battery Control Unit
- CMC: Cell Monitoring Circuit
- PDU: Power Distribution Unit

Project Development

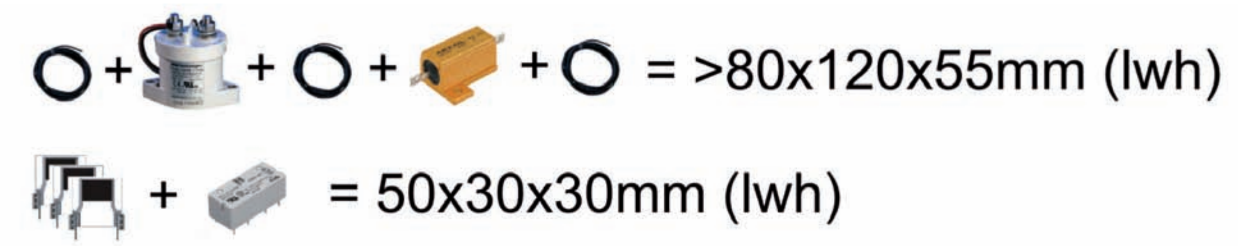
2.1 BMS Optimisation

2.1.1 Pre-Charge Circuitry Integrated into REAP's BCU

For safety reasons, the battery must be disconnected from the motor controller when not in use. This is usually achieved by opening battery contactors. They must be closed again automatically as soon as the ignition is switched on. However, motor controllers have large capacitors on their power input, which will be discharged to 0V when the battery is about to be connected to the motor controller. In order to prevent very high inrush currents and protect the contactors and other components from damage, it is important to charge the capacitors in the motor controller to their operating voltage before closing the contactors. This is referred to as 'precharging'.

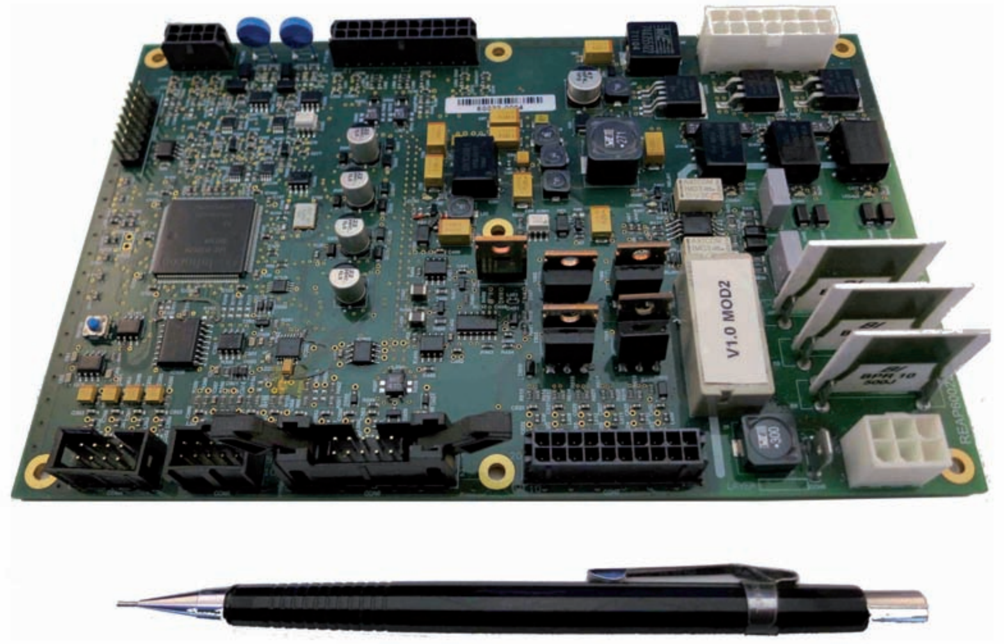
Precharging is usually achieved with an external contactor or relay and a current limiting device, such as a resistor. The external precharge contactor is controlled by an electronic circuit. Sometimes, this circuit simply waits for some time after having closed the precharge contactor before it closes the main contactor. More sophisticated circuits actually measure the battery voltage and the motor controller input voltage in order to determine whether the precharge process was successful. They only close the main contactor if precharge was actually behaving as expected. The later has got the additional advantage that closing the main contactor can be prevented in case of short circuits or open circuits in the electrical circuits.

REAP BCUs use a sophisticated solution for precharge, featuring a number of safety functions and feedback via CAN bus on whether the precharge was successful or why it wasn't. However, the old BCU required substantial external circuitry, using additional space and increasing assembly time for mounting the additional components and wiring them up. The newly developed BCU 1S does not need any external circuitry or any additional wiring since it uses its existing measurement cables. The following diagram demonstrates the key difference.



Considering that the two components for precharge shown in the above diagram are already integrated on the new BCU 1S, the total saving is actually 80 x 120 x 55 *(mm)* = 0.5 litres in volume, not to mention the savings in system complexity, assembly and interconnections with resulting increase in reliability.

The following photo shows REAP's new BCU 1S model:



2.1.2 Isolation Test Circuitry Integrated into REAP's BCU

The battery system in vehicles with combustion engines is usually a 12V system. However, electric vehicles have, in addition to this 12V system, a traction battery. High performance electric vehicles often utilise voltage levels above 60V. Such voltage levels can be lethal to human beings when exposed to the voltage in certain circumstances. The risk increases significantly in case of an isolation fault between the 12V system and the traction battery system. It is therefore good practice to test the isolation between the two battery systems every time the vehicle is used.

Such isolation test circuits are available of-the-shelve. However, such circuits are not very cost effective *(usually in the order of GBP 200.00 per item)* and large in size. The isolation test circuit from Bender for example exhibits the following dimensions: 140 x 60 x 15 *(mm)*.

REAP's new BCU 1S has got an integrated isolation test circuit, using principles derived from the REG100. The BCU uses its existing measurement wires. This not only reduces overall system cost but also eliminates the need for mounting an additional component and its related cabling.

2.1.3 Managing Motor Temperature

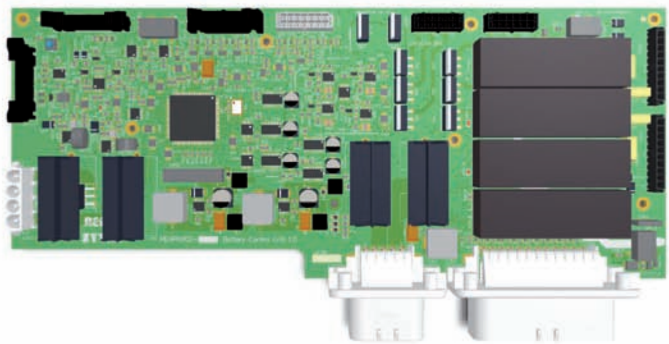
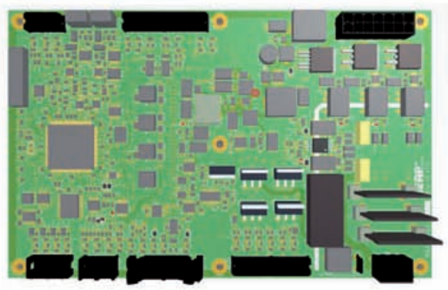
To manage the motor temperature is not a typical BMS feature. However, the REAP BCU has got a very powerful micro-controller and the firmware is not safety critical as all safety critical aspects are dealt with on the Cell Monitoring Circuit level or by the BCU hardware. For that reason, the REAP BCU is perfectly suitable to accommodate additional functions not normally found in BMS. This means that additional electronic controllers can be omitted or replaced with the BCU. Reducing the cost and space requirements of such controllers.

The electric motor is controlled by a motor controller. The BCU only overrides the motor controller if required from a battery perspective. However, the motor controller used in this vehicle is very basic and features no over-temperature protection or control for the motor. Hence, it seemed sensible to implement this functionality into the BCU as part of this project. This leads to better protection of the motor whilst maximising its power and torque capability. More information on this part of the project can be found in a later section.

2.1.4 Size Reduction of Battery Control Unit (BCU)

Maximising battery capacity whilst saving space on all components is of premium importance in electric motorbikes. REAP have used their previous BCU as a baseline in order to estimate the size required for the BCU from a technical perspective. Following this, REAP estimated the savings potential using different technologies and careful selection of specifications and features. A size was agreed with Agility, the motorbike manufacturer. From then on, REAP have based all their design decisions on the given space envelope right from the start of the design.

As a result, their newly developed 'BCU 1S' fulfils the challenging space requirements within the electric motorbike. The following table shows the reduction in size from the old to the new BCU.

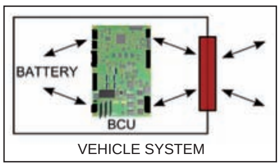
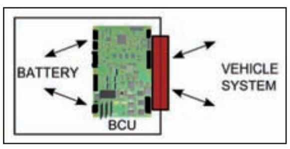
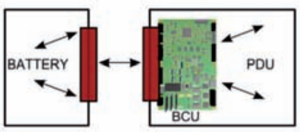
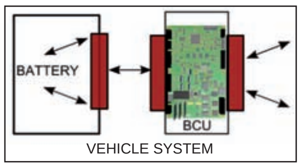
Previous BCU	New BCU 1S
	
290 x 148 x 31 *(in mm)*	187 x 120 x 30 *(in mm)*
Total reduction of almost 50% in volume *(square box envelope)* and area.	

A further reduction in the overall space requirement on a systems level was achieved by integrating several important features into the new BCU design. This is covered in another section.

A significant reduction in BCU size can be assigned to the fact that the previous BCU comprises large IP67 connectors, while BCU 1S has no IP rated connectors. Removing the large IP67 connectors from the equation, the BCU 1S still achieves a reduction of 38% in volume. However, in various applications like for example the Saietta Electric Motorbike, the BCU may be mounted inside a sealed battery box without a need for the large IP67 connectors. So, for such applications, the total saving is indeed 50% in volume.

2.1.5 Maximising Versatility through a Range of Packaging Variants

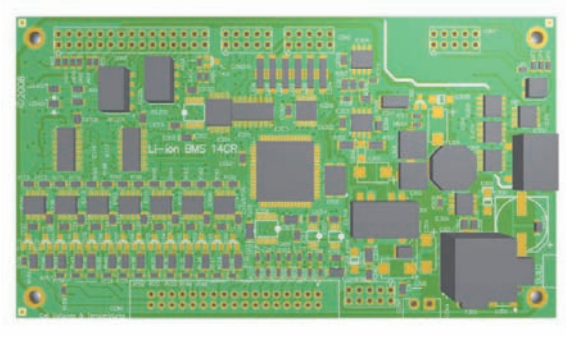
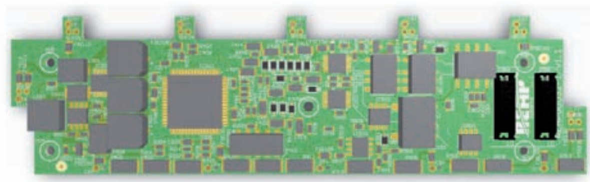
In order to be able to offer components with maximum versatility, the new BCU 1S is designed in such a way that REAP can still offer a variety of mounting and casing options, including IP67. So, the smaller design has only advantages. The following figures demonstrate the different options using variants of the same BCU product BCU 1S:

			
BCU mounted inside the battery. Connections to outside world using customer's connectors or glands.	BCU mounted inside battery on outside wall. Connections to outside world using BCU sealed connector without additional cables and connections.	BCU mounted outside the battery but inside another component, for example PDU. Connections to battery through BCU sealed connector.	BCU mounted in its own housing with sealed connectors for battery and vehicle system connections.

The first option on the left is used for this project in the Saietta electric motorbike.

2.1.6 Size Reduction of Cell Monitoring Circuit (CMC)

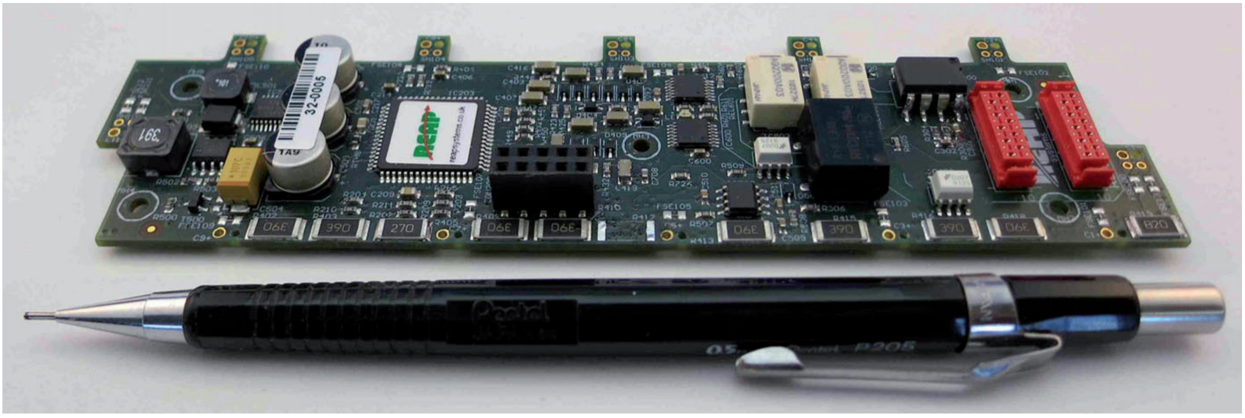
A new, custom Cell Monitoring Circuit 'CMC11' was designed specifically for the battery module used in this motorbike. The following table compares both cell monitoring circuit designs, the older BMS14CR and the new CMC11

BMS14CR	CMC11
	
136 x 76 x 29 *(in mm)*	149 x 41 x 7.3 *(in mm)*
Total reduction of 85% in volume *(square box envelope)* and 40% in area.	

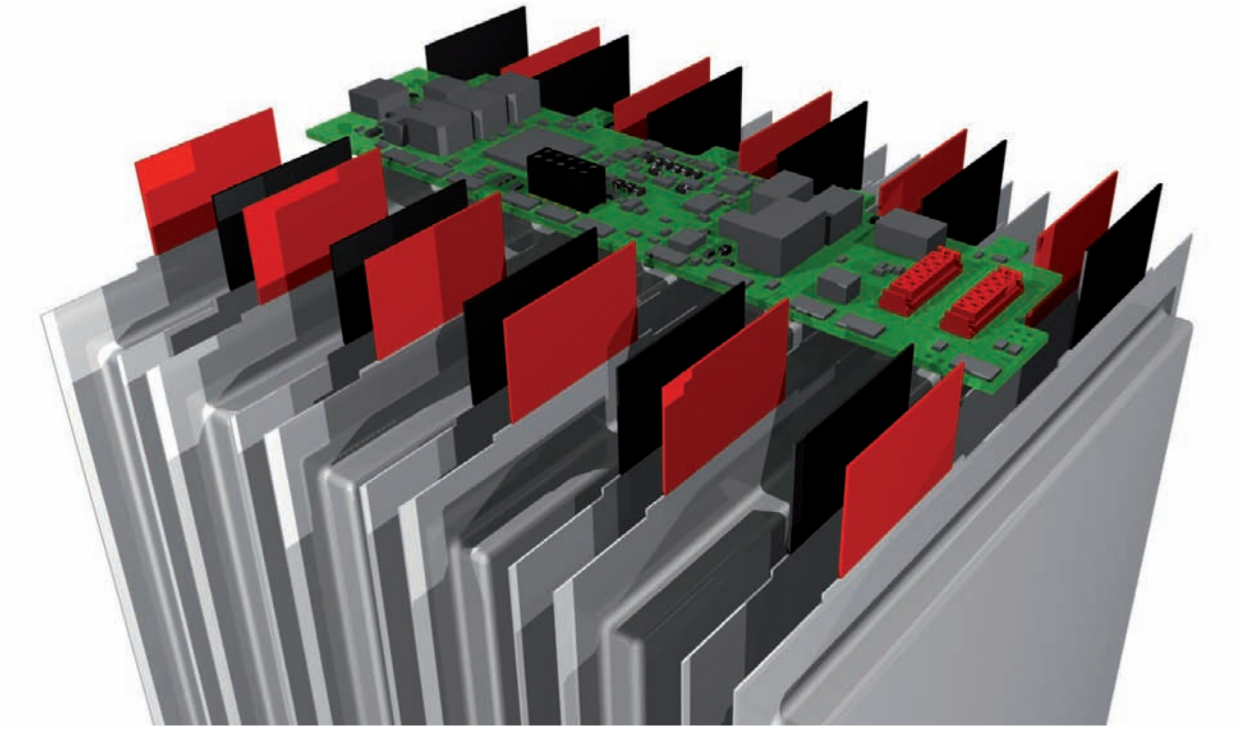
However, more importantly, the CMC was designed in such a way that it can be integrated into the existing battery module design without increasing the size of the battery module. This is covered in another section.

2.1.7 Smart Battery Module with Integrated Cell Monitoring Circuit

One of the project aims was to make the existing battery module smart by integrating as much of the battery management electronics as possible into it without increasing its size or changing its design. This lead to the development of the custom design CMC11, which is specifically optimised for the customer' existing battery module. The functionality and features were based on REAP's existing cell monitoring circuit 'BMS14CR'. The following figure shows the new CMC11 product.



The new CMC11 is already significantly smaller in terms of PCB area if compared with the older BMS14CR. However, the key improvements in terms of size are due its very low profile, specified down to 1mm exact by the customer. Additionally, CMC11 is so narrow that it can be fitted between the terminals of the specific cell type *(EiG, 20Ah)* used in this battery module. The CMC is integrated into the existing battery module without changing the battery module dimensions. The following figure shows this principle.



2.1.8 Reduction in BMS Power Consumption

Due to the growing number of electronic controllers in vehicles, their power consumption has become much more important over the last decade. In combustion engine vehicles, the power consumption whilst in operation *(active)*, is not of primary concern as electrical power is generated in abundance. The power consumption of electronics is of low significance if compared with the lights, fans, air conditioning, etc. However, the power consumption of electronic controllers becomes a major concern whilst the vehicle is parked and switched of *(inactive)*. Small power consumption accumulates over time and can drain and even destroy the 12V battery, for example during a holiday period. The vehicle will not be able to start and the 12V battery may be destroyed and needs replacing.

The scenario is similar for electric vehicles. When switched on or during charging *(active)*, the 12V battery is constantly recharged from the main battery and the power requirements of the electronic components are almost insignificant in comparison with the power levels for the electric drivetrain – see table below. However, when the vehicle is switched off, this is when power consumption matters most. This is even more pronounced in electric motor bikes because the 12V battery capacity can be smaller by a factor of 4 or similar.

All REAP BMS components have always been designed to minimise power consumption from the 12V battery when the vehicle is not in use. The following table shows the power consumption on the 12V system for active and inactive situations *(active = charging or ignition on)* for REAP's different products.

This is an average value only as exact figures depend on system configuration.

	Inactive Power	Active Power	For Total Bike (Saietta R)			
			Units per Bike	Inactive Power	Active Power	Drain Time when Inactive (12Ah Battery)
BCU	0.03 W	2.80 W	1 each	0.03 W	2.80 W	**200 days** ***(more than 6 months)***
Contactor	0.00 W	1.08 W	2 each	0.00 W	2.16 W	
Current Sensor	0.00 W	0.15 W	2 each	0.00 W	0.30 W	
CMC	0.00 W	0.02 W	6 each	0.00 W	0.11 W	
Total	**NA**			**0.03 W**	**5.37 W**	

The power consumption shown here is for BMS related components only. Other vehicle components may add to this. All figures are approximate. Also they may significantly depend on system configuration.

However, an electric vehicle has got a high cost traction battery in addition to the 12V battery. The BMS does drain power from this traction battery and it can therefore damage it through deep discharge in case the vehicle is not being used for a long period of time. This may specifically apply to electric motorbikes as they may not be used throughout the winter period for example. In order to prevent them BMS from damaging the traction battery, one important part of this project was to minimise the power drain on the traction battery whilst the vehicle is not in use.

The BCU, the contactors and the current sensors are powered from the 12V battery. For this reason, they do not drain the traction battery unless the ignition is switched on. When ignition is on or when the charger is plugged in, the traction battery will recharge the 12V battery through the DC/DC converter with an assumed efficiency of 85%. The following table shows the BMS power drain on the traction battery based on this assumption.

	Inactive Power	Active Power	For Total Bike *(Saietta R)*		
			Units per Bike	Inactive Power	Active Power
BCU	0.00 W	3.29 W	1 each	0.00 W	3.29 W
Contactor	0.00 W	1.27 W	2 each	0.00 W	2.54 W
Current Sensor	0.00 W	0.18 W	2 each	0.00 W	0.35 W
CMC	0.02 W	1.00 W	6 each	0.13 W	6.00 W
Total	NA			0.13 W	12.18 W
Drain Time *(full Battery)*				**> 4 years from full**	**16 days from full**

The power consumption shown here is for BMS related components only. Other vehicle components may add to this. All figures are approximate. Also they may significantly depend on system configuration.

REAP's existing off-the-shelf BMS14CR design was based on different component technologies. The active power consumption was 1.2W - very similar to the new CMC11 design. The quiescent power consumption was only 9 uW - even lower than on the new CMC11. This was due to the lack of **real time clock and data logging capability**, which is featured by the new CMC11. The new CMC11 would be down to the same quiescent power level if the data logging was removed or disabled during off periods. However, the previous BMS14CR design showed a significant drain on the cell voltage measurement wires due to its measurement technology.

The BMS14CR's cell voltage measurement drain increased the total drain on the traction battery to approx. 3.7 Ah/month for a system with 11 cells per module. This would have meant that a fully charged battery in the Saietta R would be completely drained within less than 11 months when being unused. As shown above, the new CMC11 technology increases this time to more than 4 years with the added benefit of a real time clock and data logging at all times. The overall improvement of the new CMC11 technology in terms of quiescent power drain is therefore a factor of more than 4.

2.1.9 Reduction in BMS Cost

The Saietta electric motorbike from Agility is aiming to be an affordable and cost competitive product, which can be a real alternative to production street bikes with combustion engine. Lithium-Ion traction batteries with high energy and power densities are still relatively expensive and to introduce a new product in a niche with relatively small volumes at a competitive price is very difficult.

Battery management systems can add significantly to the cost of the final product. REAP is committed to achieve competitive price levels that will enable their customers to make their products commercially viable. REAP has taken this challenge on when developing the new BCU and CMC. Our approach is as follows:

- Focus on cost right from the beginning of the design phase. Prevent over-specified features or components.
- Adopt higher levels of integration than on previous REAP products. Fewer components result in lower cost and higher reliability.
- Rely on standard components where possible.

- Use suppliers that offer just in time and low MOQ. This reduces stock levels and risk.
- Think outside the box and optimise overall system cost in close cooperation with the customer rather than minimising just individual component cost. The aim is to reduce cost of assembly, wiring, connectors and additional components outside the BMS. System reliability is increased, which reduces risk to REAP and our customers.
- Cost-down exercises in between design iterations. Making sure we understand our cost and can do something about it before the design is fully finished and validated.
- Flexible purchasing options allowing to order and deliver just in time for the volumes required. This follows Toyota Principles and reduces the risk and cost involved in stocking components and circuits, even if the lower prices of higher volumes are tempting.
- Make the product as versatile as possible without significantly increasing the cost. This allows REAP to sell the same product to a range of customer and projects, which will help reducing the cost per piece through volumes.
- For custom products, REAP aims to use common parts. So, that at least the parts can be purchased in higher volumes and hence better prices.

The following cost improvements have been achieved for the new BCU and CMC if compared with the previous designs *(figures based on the volumes predicted for the Saietta motorbike)*.

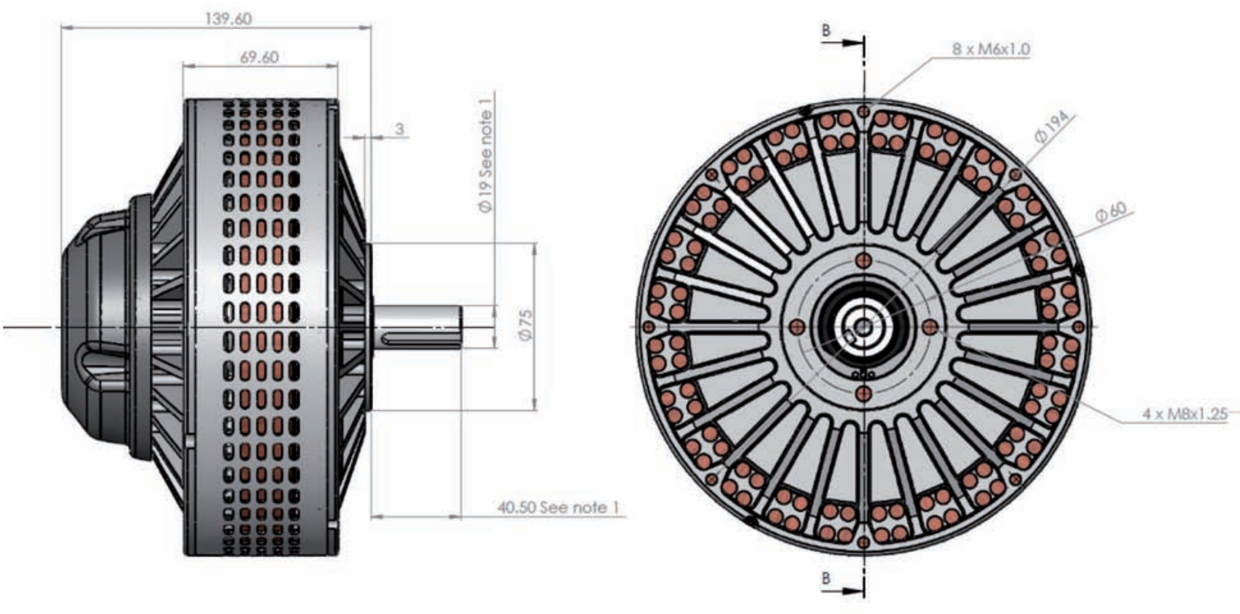
- BCU 1S: Cost improvement of approx. 60% if compared with previous BCU.
- CMC11: Cost improvement of approx. 55% if compared with older BMS14CR product.

2.2 Motor – Performance Optimisation Through Control

The acceleration of the motorbike in urban traffic is mainly determined by the mass of the bike, the motor torque and the gear ratio of the transmission.

The mass of the bike is optimised outside the scope of this project. However, one option analysed in this project is to use a larger and heavier motor – see next section. Another option is to change the gear ratio. However, the gear ratio will effect the top speed when using permanent magnet motors without field weakening. The chosen gear ratio is already optimised for good motorway speed levels. So, the only way to use higher gear ratios without impacting the top speed is by using a two *(or more)* speed gear box. This has been investigated in this project also – see another section.

Finally, one remaining option for improving the acceleration is to increase the motor torque. The motor used in this project is an LMC200D135 from Lynch Motor Company Ltd. This is a permanent magnet brushed DC motor with natural air cooling. The following figure shows this motor.



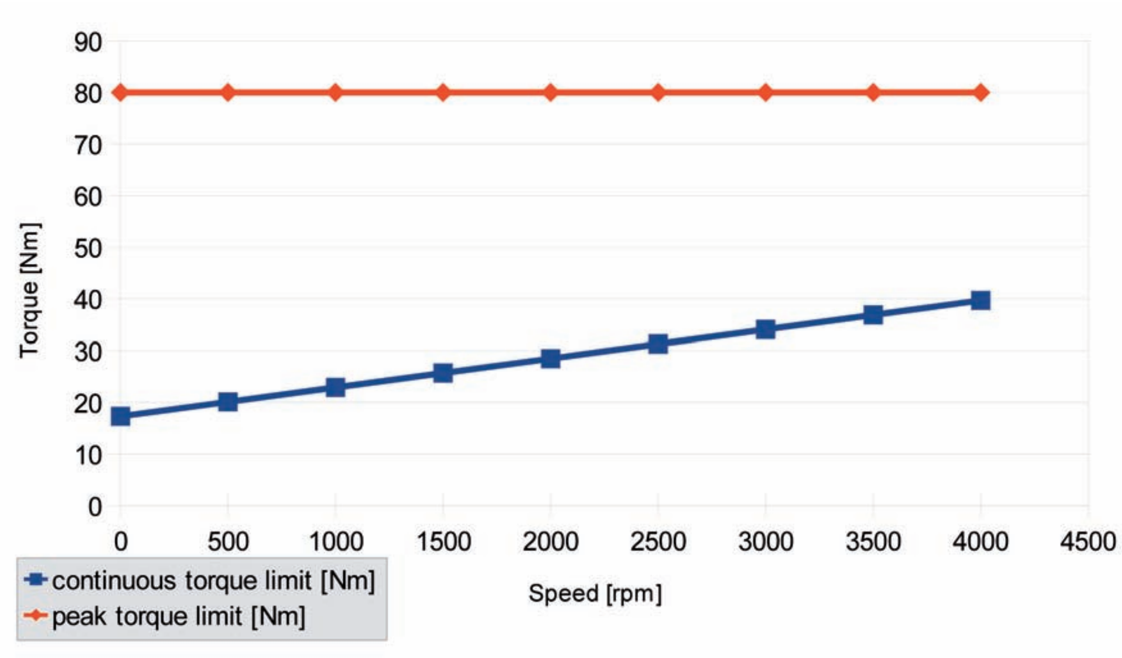
The amount of heat energy produced by the motor is proportional to the losses in the motor. The losses significantly depend on the motor current. The motor torque is virtually proportional to the motor current in this permanent magnet motor. This means the higher the acceleration, the higher the heat energy generated inside the motor.

The motor temperature will increase if the generated heat energy exceeds the heat energy removed through cooling. The amount of cooling in this naturally air cooled motor is limited. It depends on the motor speed. The higher the speed, the higher the amount of cooling. This means that the continuous torque levels that can safely be produced by the motor depend on the motor speed and the ambient temperature. The higher the motor speed and the lower the ambient temperature, the more torque and hence acceleration can be produced. The following table shows the rated current levels of the motor as a function of motor speed. This is for an ambient temperature of 20ºC.

Motor Speed	Continuous Motor Current Limit
4,000 rpm	200 A
3,500 rpm	185 A
3,000 rpm	170 A
2,500 rpm	160 A

All values approximate only.

However, the above restrictions are due to cooling limitations and resulting overheating of the motor. For short time, it is possible to use the motor at much higher peak currents and obtain much higher torque levels. Acceleration can simply be improved by using this peak current capability from the same small motor instead of employing a larger version of that motor. The peak capability can be as high as 5 times compared to the continuous torque capability. However, for this project, a factor of 2 was assumed sufficient. This means twice the torque and hence acceleration capability. The following figure demonstrates the improvement potential.



However, strict temperature control must be implemented in the system in order to prevent the motor from overheating and permanent damage. The most suitable temperature measurement type and location in the motor was determined on dynometer tests and smooth closed loop controls were implemented in the BCU firmware using its spare temperature measurement inputs. Following that, the stability and smoothness of controls where successfully validated on further dynometer tests.

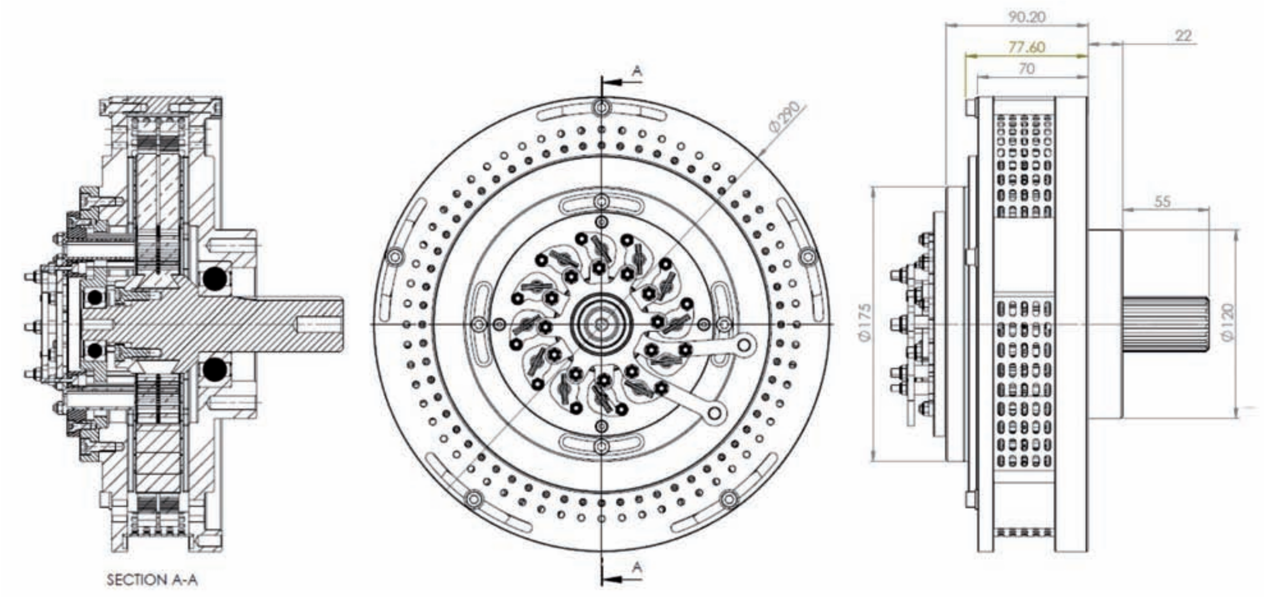
However, road testing revealed that the natural cooling was not sufficiently cooling the motor down between acceleration runs as can be typically expected in urban driving pattern. This insufficient cooling lead eventually to high motor temperatures through 'ratching-up effects', which in return limited the available motor performance. Further investigations or tests could have improved the situation through more heat resistant materials or better cooling. However, these were not within the scope of this project due to time and budget limitations. Instead, a larger motor was chosen for the bike.

2.3 Motor – Performance Increase with Larger Motor Design

The development of a larger motor was initiated as part of this project. The motor promises to produce more than twice the torque continuously if compared with the smaller version described earlier. The following table summarises the key data of this motor.

Continuous current	300 A
Peak current	600 A
Speed constant	30 rpm/V
Maximum voltage	144 V
No of poles	12
Burst speed of motor	5,000 rpm

The motor was designed and drawn. Various parts were manufactured and most tooling was made. However, the production of prototypes had to be delayed due to non-technical issues and was therefore no feasible any more within the time-scales of the project. The following figures show the design of the larger motor.



2.4 Agility – Improvements on Saietta Motorbike

2.4.1 Validation Introduction

The project's aims were to improve on the drive train performance from baseline options. These aims have clearly been achieved, through better BMS controls, increased motor performance potential, improved motor arrangement options and increased safety protocols. The Gearbox feasibility study has shown the availability of further increased performance which could be confirmed through prototyping and on-board validation.

2.4.2 Constants Maintained During Testing:

- Overall Transmission Ratios
- Tyre Rolling Diameters
- Non-Motor Driveline components Rotational Moments of Inertia *(RMOI)*
- Wheels and tyres RMOI
- Vehicle Frontal Areas *(Including keeping Protective Clothing and Rider constant)*
- Vehicle Aerodynamic Coefficient of Drags
- Vehicle Test Masses *(Note: Difference between CENEX and Baseline)*
- Test Location
- Time Between Runs

2.4.3 Uncontrolled Variables

The following may or in some cases most certainly will have influenced the outcome of these tests. The effect of heavy rain and wind on performance was particularly noticeable – De-rating was reduced and available performance increased – whilst concurrently traction was reduced. It is recommended that an indoor location be identified if future studies of this kind need to be carried out in inclement winter weather to minimise variables.

Test Surface dry coefficient of friction ≈ 0.65 – 0.72*

(*Dependent on temperature/dust/other surface contaminants/and road surface macro and micro-form.)

Test Surface wet coefficient of friction ≈ 0.3 – 0.5**
(**Note: due to largely inclement weather through Q1 and early Q2 2012, a number of the tests were carried out with Wet Test Surface coefficient of friction ≈ 0.4 . Where a test was a wet weather test this has been indicated on the data.)

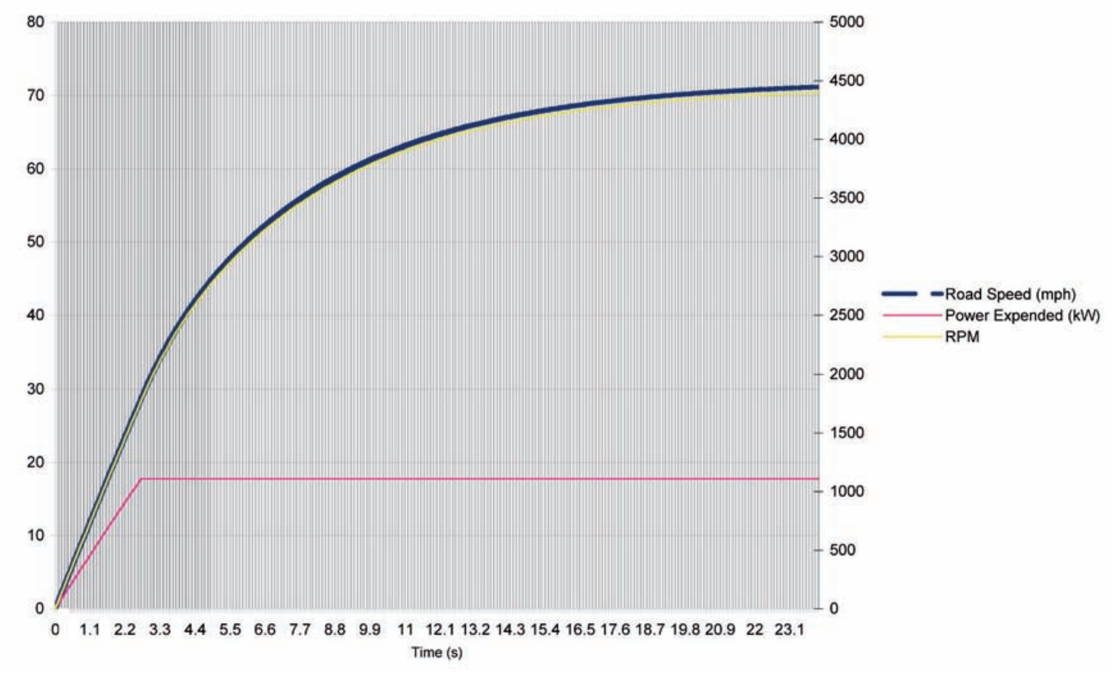
Temperature***
(***Note: The BMS control system for Motor De-rating is primarily basing level of De-rating on motor temperature as measured by thermistors on/in the motors, and both the Lynch CENEX motor and the Baseline motor are air-cooled. As such variations in ambient temperature had a significant affect on De-rating and thus performance.)

2.4.4 Results

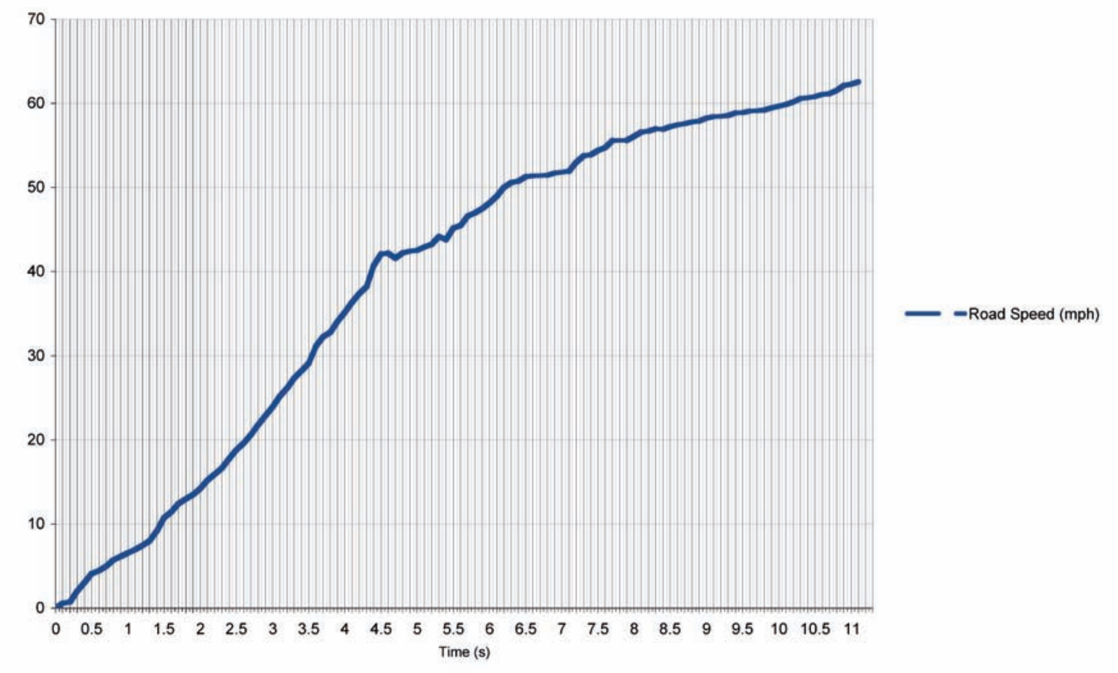
Below are graph results for various set ups. Predicted performance values were generated from analyses which took into account: motorcycle characteristics, motor characteristics, transmission characteristics, ambient and surface conditions, and other factors.

Note:
The convention used in this report in the numerical names of motor set ups is for the 1st number to indicate the Kilowatt *(Kw)* limit. The 2nd number indicates current limit in the set specification.

2.4.5 Baseline S Spec 18-400 Predicted Performance Graph:



Performance of Saietta with Baseline LMC (before project)
Acceleration: 0-60 mph in 9.4 seconds. Top Speed at 71 mph.

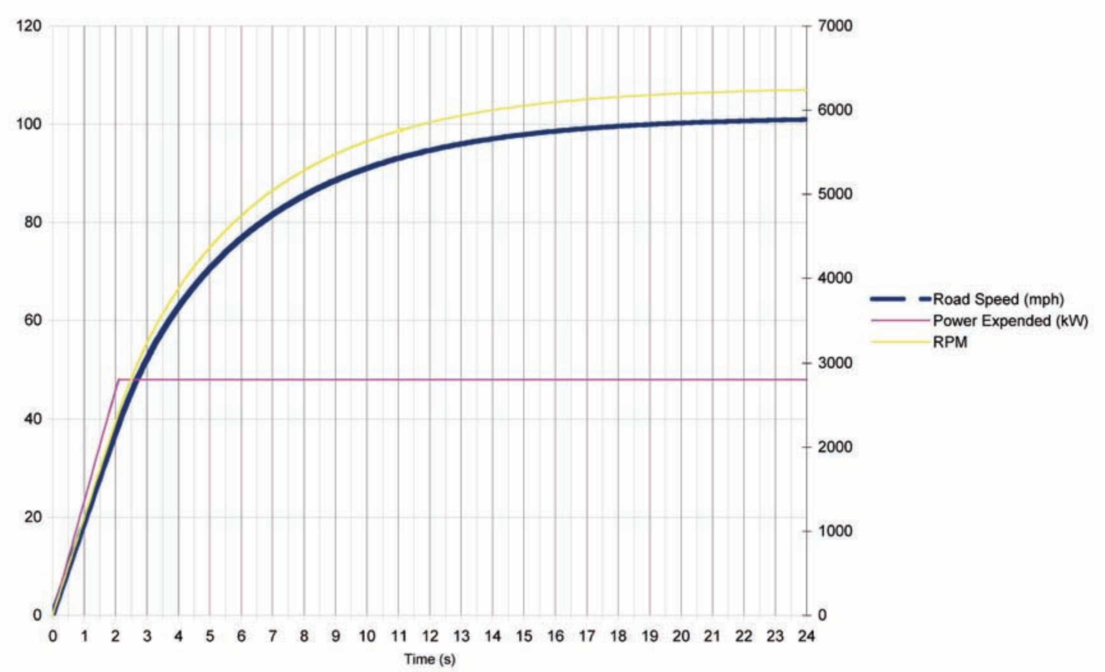


Lynch 18-400 Measured Performance Graph
Power Limit 18 Kw, Current Limit 400 Amps (A)

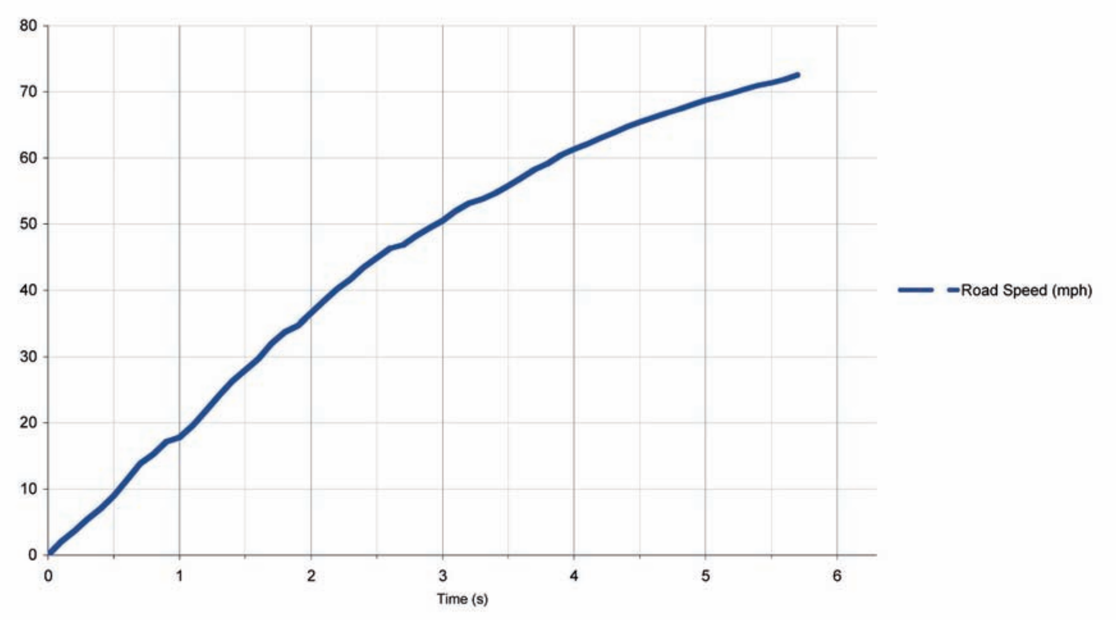
2.4.6 Baseline R Spec Motor Predicted Performance:

Top speed predicted at 67.7 mph without further temperature control or other performance management.

Top speed measured at 67.67 mph in London traffic with motor RPM limit of 4186 at motorway speeds. Acceleration measured at 0-60 mph in 3.9 seconds.



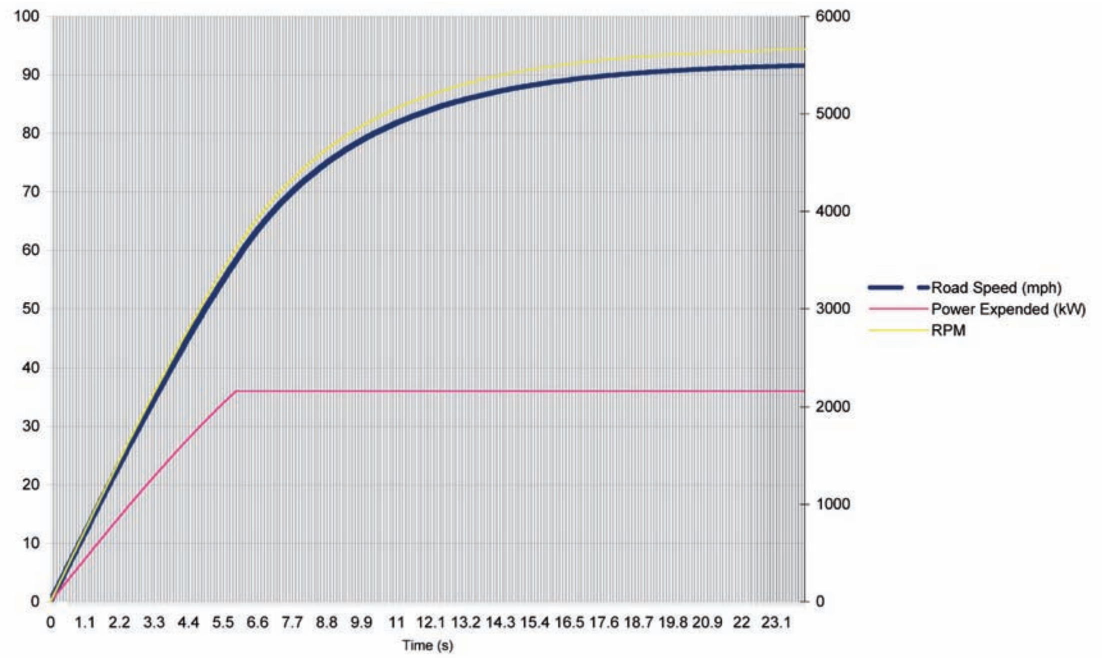
Baseline Motor Measured Performance



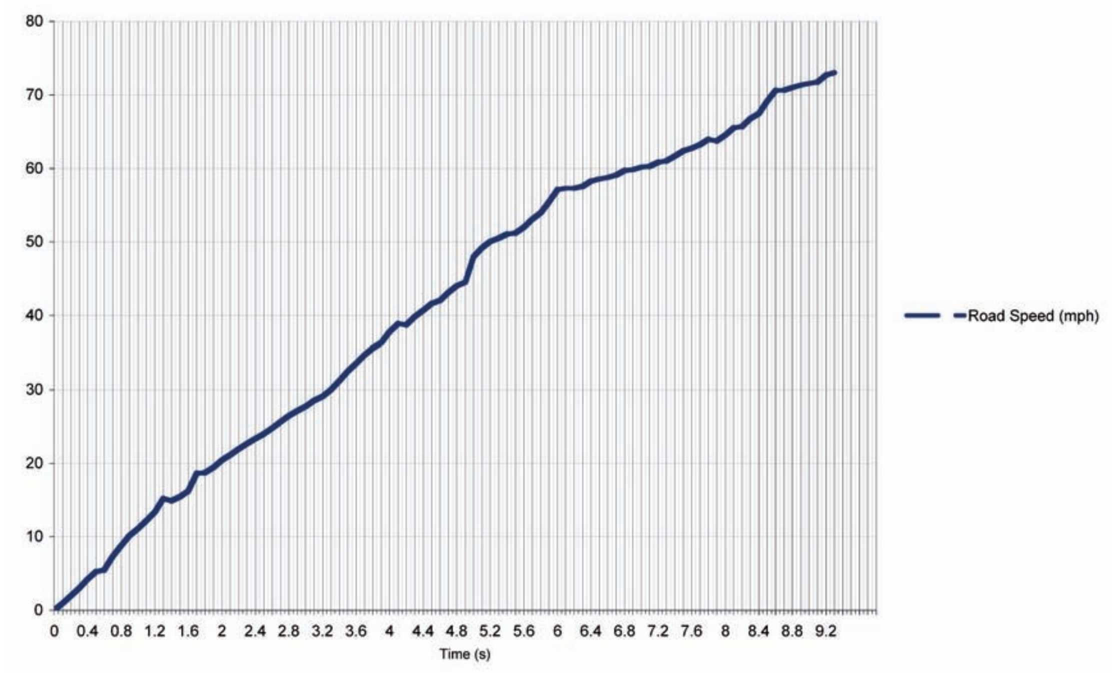
Baseline R Spec Motor Measured Performance

2.4.7 Performance with thermistors for temperature control on S Spec Motor at various thermistor settings

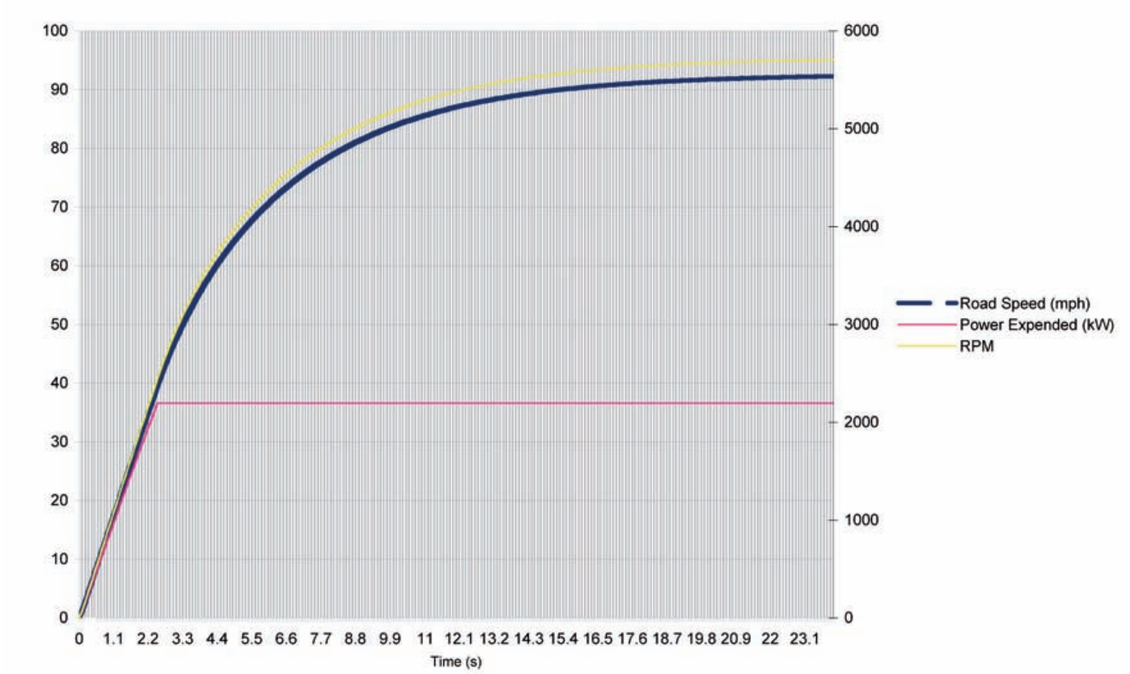
The BMS is successfully controlling the electrical current which the motor receives as a function of thermistor output and BMS reaction. This is protecting vulnerable motor components and allowing significantly higher performance for monitored and controlled intervals. As acceleration runs are continued, more de-rating occurs until performance is no longer optimal due to the heat capacity of the motor. This has shown us a way that we can install forced air cooling to achieve the correct performance over longer periods with an S spec motor closely monitored through thermistors and the REAP BMS.



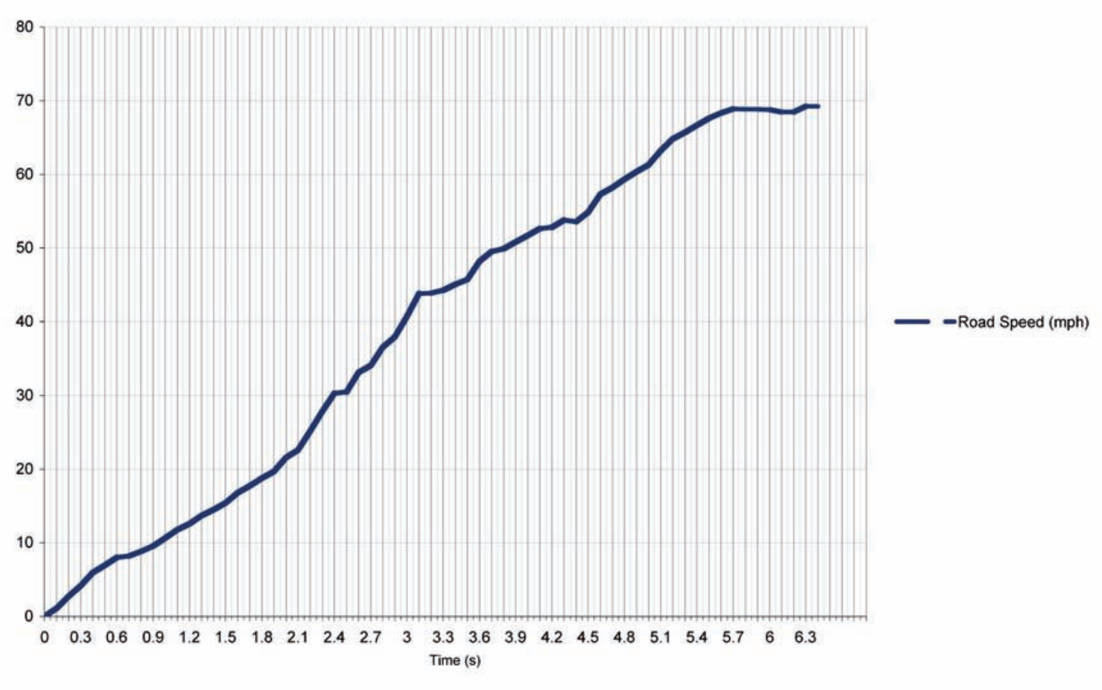
Lynch 36-400 Predicted Performance Graph
Power Limit 36 Kw, Current Limit 400 A



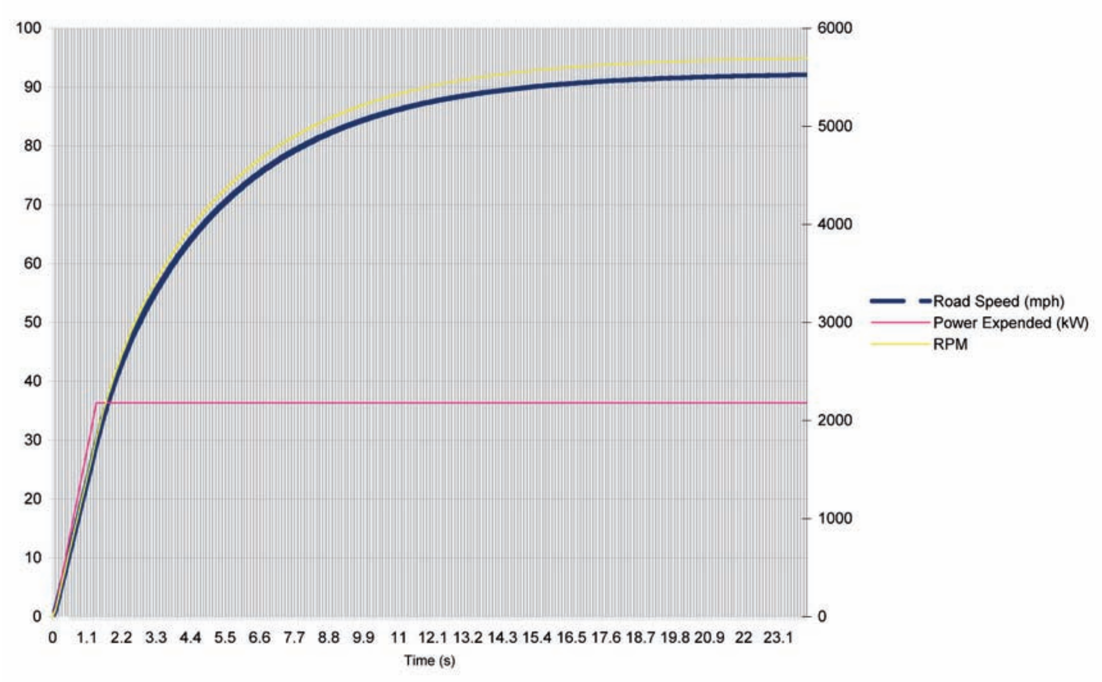
Lynch 36-400 Measured Performance Graph
Power Limit 36 Kw, Current Limit 400 A



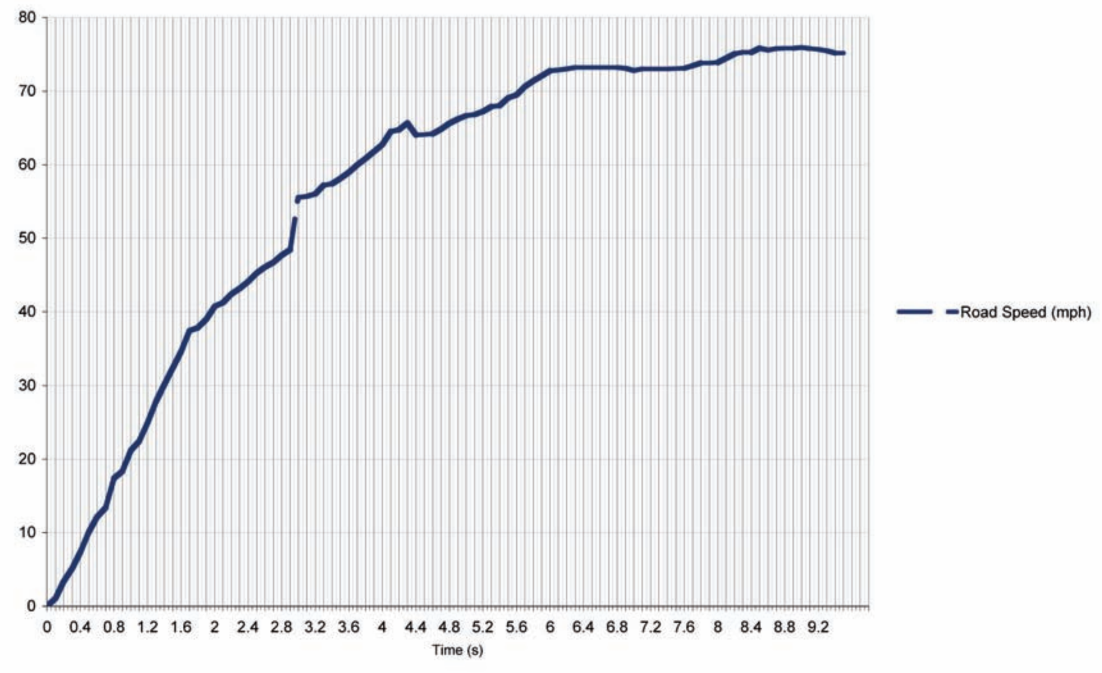
Lynch 36-600 Predicted Performance Graph
Power Limit 36 Kw, Current Limit 600 A



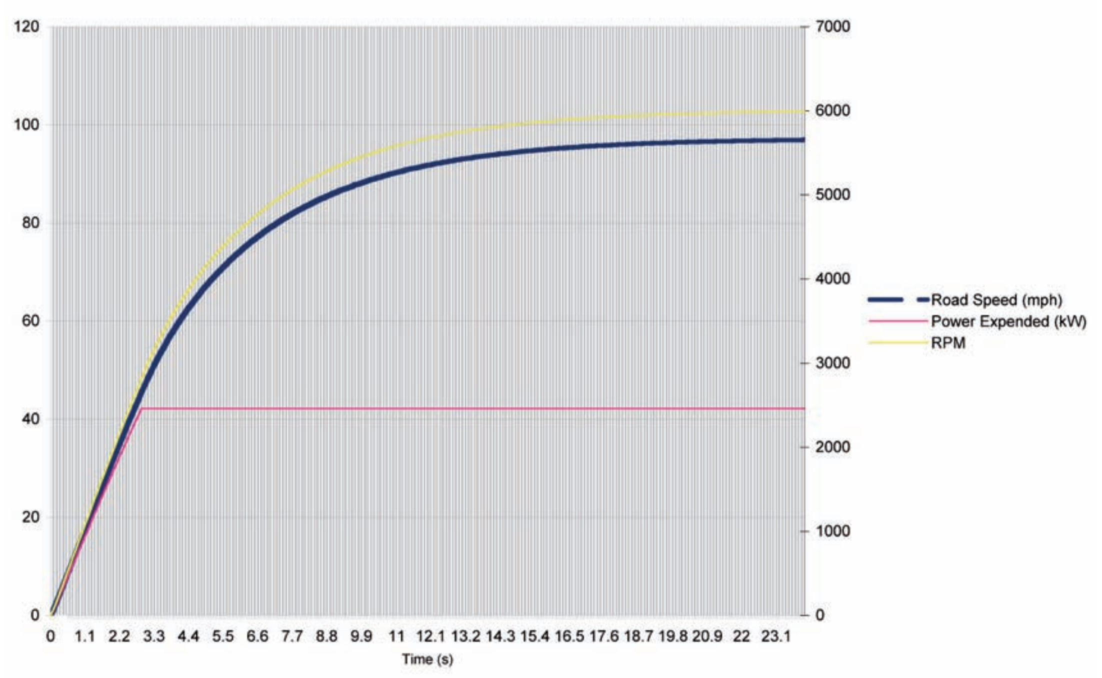
Lynch 36-600 Measured Performance Graph
Power Limit 36 Kw, Current Limit 600 A



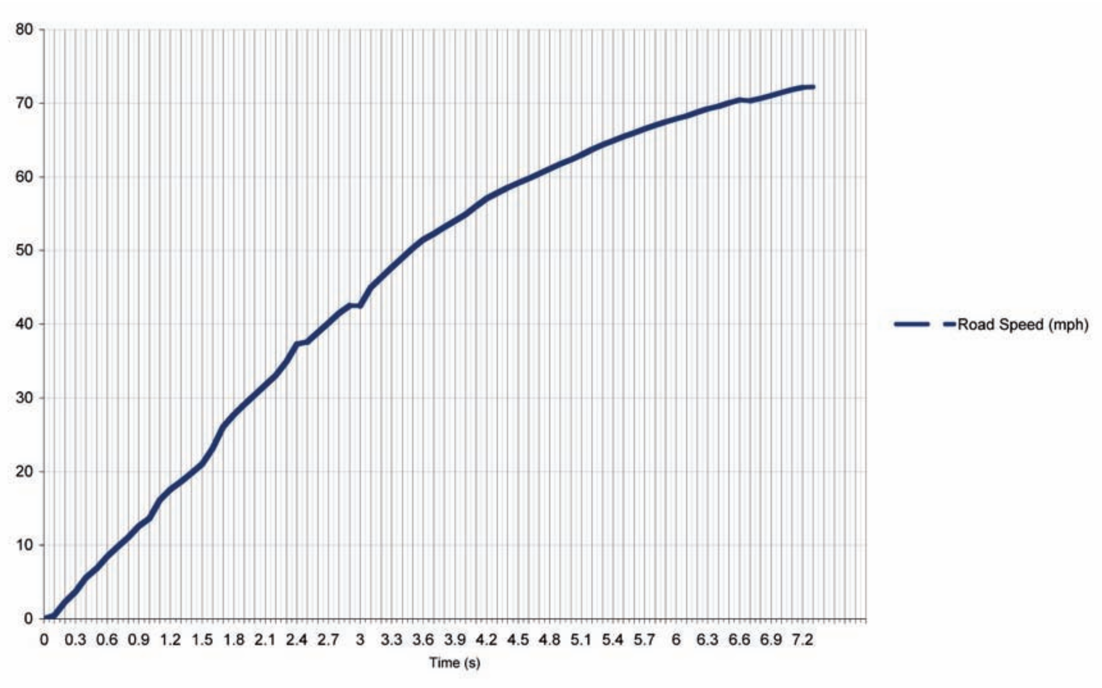
Lynch 36-800 Predicted Performance Graph
Power Limit 36 Kw, Current Limit 800 A



Lynch 36-800 Measured Performance Graph
Power Limit 36 Kw, Current Limit 800 A



Lynch 42-600 Predicted Performance Graph
Power Limit 42 Kw, Current Limit 600 A



Lynch 42-600 Measured Performance Graph
Power Limit 42 Kw, Current Limit 600 A

Agility has been going through road testing on the Saietta motorcycle. The road testing sessions average 4-8 hours per session, at 4 sessions per week. We have gone through various types of testing cycles. Importantly, while driving in London traffic at normal road conditions, we attempted to run the battery flat, but in 6 hours only consumed half of the battery capacity. In a separate motorway test, lasting 4 hours, we were able to consume 82% of the battery, going 80 miles, riding at maximum speeds on motorways and larger roads around London.

There have been additional minor wiring changes ongoing in order to determine the optimal set up during production for ease of manufacture and avoidance of any unplanned electrical issues. The regeneration settings have been turned down in order to avoid rear wheel lock under heavy braking. Our next tests will be with altered brake wiring to discover if this eliminates the issue and regen can be brought back up.

Pre Test Data UCL:

Discharge testing was undertaken at University College London during the early part of the second half of the Cenex project. We needed to test battery discharge current rates. 3 modules were tested. Some of the resulting issues were balance related. This was remedied at the next dyno session by acquiring a power supply to re-charge the low module in line with the other two.

Main Testing:

Dynamometer test carried out from 20-24 February. Tests on the LMC motor went well, and good information was available as a result, as well as information about the entire drive train – not just the motor and Battery Management System *(BMS).*

2.4.8 Validation Conclusions

The REAP BMS has made a huge improvement to the motorcycle performance overall. Because there is a much more intelligent monitoring of the battery, we are able to use much more of the capacity of the power in the drive train. The BMS allows us to discharge a greater proportion of the stored energy without risk of deep discharge. In other words, it acts as a safety net for the drive train which allows more stored energy to be used for increased performance safely and effectively.

It is clear that our studies of a multi speed gearbox would allow a significant performance increase and efficiency as a result of reduction in current required for equal levels of acceleration. We were able to achieve these gains within the tight confines of our package envelope. The design is predicted to weigh well within target objectives. We feel strongly that a follow along prototyping project with a gearbox would be very beneficial.

Acknowledgements

All project partners wish to thank CENEX – Niche Vehicle Network for making this project possible through their funding. Special thanks also goes to Rob Anderson from CENEX for his continued understanding and support. Also many thanks to Viv Stephens from CENEX for helping resolve difficult situations.

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Cenex
Holywell Park
Ashby Road
Leicestershire
LE11 3TU

Tel: 01509 635 750
Email: nvn@cenex.co.uk

www.nichevehiclenetwork.co.uk

Office for Low Emission Vehicles
Advantage West Midlands
www.advantagewm.co.uk
cenex
Technology Strategy Board
Driving Innovation