

Analysis of Real World Data from a Range Extended Electric Vehicle Demonstrator

Jonathan Hall
Mahle Powertrain, Ltd.

Hannes Marlok
MAHLE Powertrain, GmbH.

Michael Bassett
Mahle Powertrain, Ltd.

Marco Warth
MAHLE International, GmbH.

ABSTRACT

MAHLE Powertrain has built a range-extended electric vehicle demonstrator, with a series hybrid configuration. The vehicle is intended to operate predominantly purely electrically. Once the battery state of charge is depleted a gasoline engine (range extender) is activated to provide the energy required to propel the vehicle.

As part of the continuing development of this vehicle, MAHLE Powertrain has recorded data during real world driving, with the aim of further investigating the actual usage a range-extended electric vehicle under non-laboratory test conditions. The vehicle is instrumented with a data acquisition system which records physical parameters, for example coolant temperatures, as well as CAN-based data from the engine and vehicle management systems.

This recorded data has been analysed, using tools developed in-house, to establish the effect of environmental factors such as ambient temperature, human behavioral characteristics and variation in usage patterns on the efficiency and operational behaviour of the range-extended electric vehicle system as a whole. Of particular interest are factors such as the frequency, and duration, of operation of the range extender engine under normal daily usage. The resulting data will guide the design direction and specification, at both component and system level, in future range-extended electric vehicle design and development programmes.

This paper presents an overview of the recorded data and analysis of the key trends identified. The hardware and software systems are briefly discussed and the control strategy is described within the context of the results presented. This paper also demonstrates that both the range extender unit and the traction circuit components have been sized correctly and that a reduction in traction battery pack size, relative to a pure electric vehicle, is both feasible and appropriate.

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INTRODUCTION

Because electric vehicles (EVs) do not generate pollutants during usage, and they can potentially rely on energy provided by a selection of renewable sources, they are the focus of much current interest. However, due to the present capabilities of battery technology, the overall range of such a vehicle is limited in comparison to an equivalent gasoline or diesel fuelled vehicle. Furthermore, once the battery is depleted, relatively

long recharging times are currently required before the vehicle is available for use again. Battery cost, range capability, and also possibly 'range anxiety of the driver', are still viewed as barriers to the widespread adoption of pure EVs.

Plug-in electric hybrids, of which range extended electric vehicles (REEVs) are a subset, overcome many of the short-comings of EVs. REEVs have a 'range extender' unit which consists of an on-board fuel converter that converts a

liquid fuel, such as gasoline, into electrical energy whilst the vehicle is driving. This enables the traction battery storage capacity to be reduced, though still maintaining an acceptable vehicle driving range. For long journeys, when the battery and fuel tank are both depleted, the driver can simply refuel the gasoline tank in a matter of minutes. However, it is desirable that for the majority of time the vehicle will operate in a purely electric only mode, from the battery, and that the user recharges the vehicle when it is not in use (e.g. over-night). Thus, the battery should be sized to cope with the majority of daily usage that the vehicle will encounter, and only rely on the range extender for infrequent, longer, journeys.

MAHLE has developed a dedicated range extender (REx) engine, shown in Figure 1, to identify the requirements and challenges faced in the development of the components for such future engines. The REx engine design has been focused on meeting the requirements for a compact-class REEV. During the concept phase of the project key attributes for the engine were identified and a full evaluation of the different possible layouts for the REx engine was undertaken to assess the most suitable for the intended application.



Figure 1. MAHLE Range Extender (REx) Engine

In order to enable development and refinement of the REx system, it has been installed into a vehicle. A current production vehicle has been fitted with an electric drive-line and the range extender engine. The resulting vehicle is intended to reflect likely near to market steps for REEVs. The REEV specification has been developed with the target of meeting the performance of the conventional baseline vehicle.

MAHLE REEV DEMONSTRATOR VEHICLE

MAHLE has developed a dedicated REx engine to identify the requirements and challenges faced in the development of the components for such future engines. The range extender unit consists of a 2-cylinder gasoline engine, which also houses a fully-integrated electrical generator [1, 2, 3]. The engine is not mechanically connected to the vehicle wheels, but simply generates electrical power whilst the vehicle is driving, which can be used to propel the vehicle or recharge the battery once the battery becomes depleted.

The REx unit design has been focused on meeting the requirements for a compact-class REEV. In order to enable development and refinement of the NVH attributes of the REx system, the system has been installed into a vehicle. A current production vehicle has been fitted with an electric drive-line and the range extender engine, as shown in Figure 2. The resulting vehicle is intended to reflect likely near to market steps for REEVs. The REEV specification has been developed with the target of meeting the performance of the conventional baseline vehicle.

The controller has been applied to both the low level engine control (ECU) and the vehicle control unit (VCU), with the VCU controlling both the electric drivetrain and the REx unit operating strategy. Separate controllers were used for the ECU and VCU operations to provide a level of separation in the controller, and also allow the architecture of the system to be configured in a way that reflects the architecture envisaged for production applications.



Figure 2. MAHLE Powertrain Range Extender Vehicle

The demonstrator vehicle was configured with all engine and traction elements except the high voltage battery packaged in the engine bay that had previously housed the 1.2L four cylinder engine in the donor car, as shown in Figure 3.

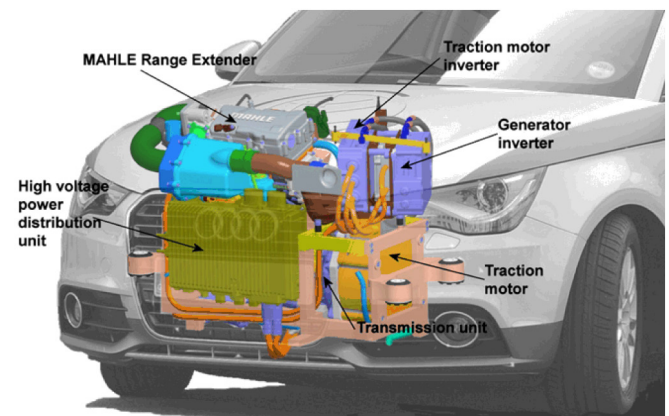


Figure 3. Engine bay arrangement MAHLE range extender demo car

The system architecture for the demonstrator vehicle is shown schematically in Figure 4. The REx engine and generator are both controlled by the ECU. The remainder of the vehicle systems are controlled by a separate VCU. The ECU functionality has been separated from the VCU so that the complete system could be a relatively simple addition to an electric vehicle.

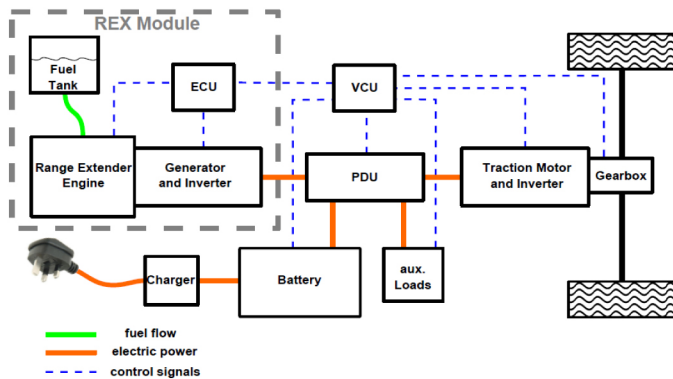


Figure 4. REEV demonstrator system architecture

The engine ECU receives a charge request from the vehicle control unit, at which point the ECU switches in the generator inverter and fuel pump and sets the engine throttle to starting position. The ECU then sends a request to the generator to spin the engine at starting speed. Fuelling is initiated once engine starting speed is achieved and the engine sensors and ECU have determined the engine crank angle. The engine is then run at the catalyst light-off speed and is loaded by the generator at the light-off engine load for a pre-defined period, until the exhaust catalyst conversion is achieved. At this point the engine operation is set to the engine speed and power output requested by the VCU. The engine operating point (speed and load) to achieve minimum cumulative total exhaust emissions prior to catalyst light-off being achieved has been determined by testing, as described by Bassett *et al.* [3]. The ECU monitors the engine, generator and inverter temperatures and will limit the output power of the unit if necessary; also the ECU will monitor for system errors and will send an error report to the VCU if necessary. Once the VCU charge request ends the ECU will control engine shutdown and switch off the electrical systems to the generator and inverter.

The key performance targets and characteristic attributes of the REEV demonstrator are summarised in Tables 1 and 2.

Table 1. REEV demonstrator performance targets

Parameter	Units	Base vehicle	REEV target
0-100 km/h acceleration time	s	11.7	12.0
Maximum speed	km/h	180	145
Grade ability	%	—	20
Maximum speed on 6 % grade	km/h	—	90
Pure EV range	km	—	>60

Table 2. REEV demonstrator key attributes

Parameter	Units	Value
Kerb mass	kg	1450
Frontal area	m ²	2.3
Aerodynamic drag coefficient	-	0.32
Tyre rolling resistance coefficient	N/1000N	0.012
Traction motor peak power (continuous)	kW	100 (55)
Battery pack capacity	kWh	14
System voltage (nominal)	V	350
REx unit power output (mechanical)	kW	30
Max total REx system efficiency	%	31

RANGE EXTENDER CONTROL STRATEGY

The REx unit control strategy monitors the battery state of charge (SOC) and, under normal vehicle usage, does not run, allowing the vehicle to be operated as a purely electric vehicle. When charging from an electricity outlet is not possible, or a continuous journey greater than the purely electric range of the vehicle is required, the REx unit is enabled. The operating strategy selected for the REx unit is to sustain the SOC of the high voltage battery rather than to recharge it. This strategy has been adopted to give the best tail-pipe CO₂ figure for the vehicle. Vehicle testing using the new European Drive-cycle (NEDC) has yielded an electric-only range of 67 km, and a weighted CO₂ figure of 42 g/km.

The NEDC is the current legislative cycle used for the assessment of fuel economy in the European Union, which is an 11 km cycle that takes 1180 seconds to complete, at an average speed of 33.7 km/h. The test procedure for a plug-in hybrid is defined by Regulation 101 [5] and involves performing two sampled NEDC tests, one starting with a fully charged battery and the other one starting with the battery in the depleted state. The depleted battery state is achieved by running the hybrid vehicle over repeated NEDC cycles until its internal combustion (IC) engine starts. The declared fuel consumption is then based on a weighted average of the results of these two tests, where the weighting is a function of the electric range capability of the vehicle.

The weighting factor for the tailpipe CO₂ emissions is given by the following equation:

$$M = (D_e.M_1 + D_{av}.M_2)/(D_e + D_{av}) . \quad (1)$$

Where:

M = mass emission of CO₂ in grams per kilometer

M_1 = mass emission of CO₂ in grams per kilometer with a fully charged electrical energy/power storage device

M_2 = mass emission of CO₂ in grams per kilometer with an electrical energy/power storage device in minimum state of charge

D_e = vehicle's electric range, according to the procedure described in Annex 9 of R101 (repeated NEDC cycles until engine starts)

D_{av} = 25 km (assumed average distance between two battery recharges)

Assuming that the vehicle does not generate any CO₂ emissions when running in electric mode, then the value for M_1 will be zero. It can be seen that the weighting factor favours vehicles that can operate further in pure electric mode.

The REEV demonstrator vehicle has been tested over repeated NEDCs to determine the achievable range prior to the first starting of the range extender engine. Figure 5 shows the battery SOC variation during these repeated cycles. The operating strategy of range extender is to deplete the battery as far as allowable (20 % SOC) before starting the engine. It can be seen from Figure 11 that an electric range of 67 km was achieved before the engine fired.

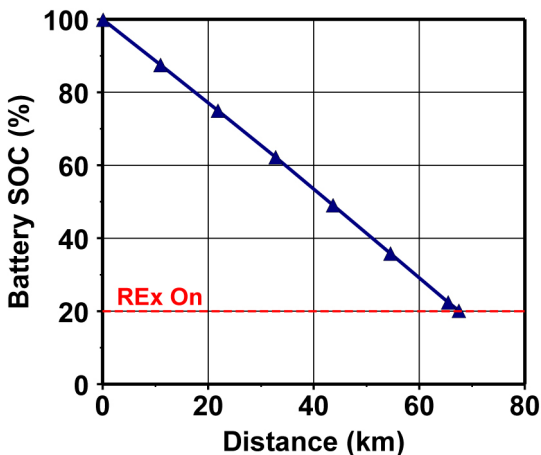


Figure 5. Battery state of charge (SOC) variation during range test over repeated NEDC operation

A further NEDC test has been performed to establish the weighted tail-pipe CO₂ performance of the MAHLE REEV demonstrator. The cycle commences with the battery in its fully depleted state (20 % SOC). The range extender has been controlled using an operating strategy which follows the principle outlined in Figures 9 and 10. Figure 6 shows the resulting range extender power output and battery SOC during the drive cycle.

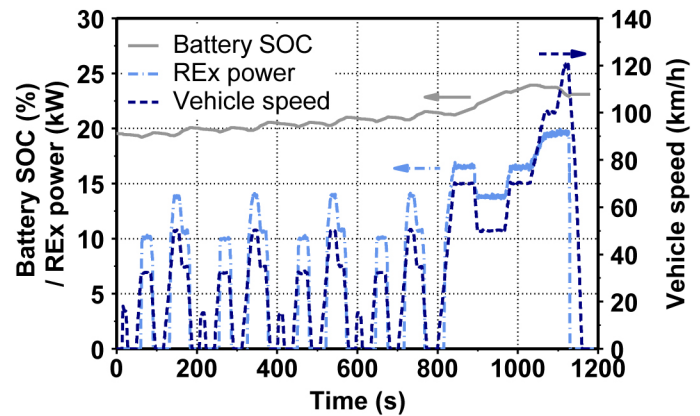


Figure 6. Battery SOC variation and range extender power output during depleted battery NEDC test

The weighted tailpipe CO₂ emissions of the MAHLE REEV, based on the R101 [5] weighting factor, is 42 g/km which represents a significant reduction over that of the baseline vehicle. The MAHLE REEV has a 25 litre fuel tank, which gives the vehicle a 430 km extended range capability, and a combine EV + extended range of almost 500 km.

The strategy adopted for the range extender engine means that the engine does not generally run below a vehicle speed of 20 km/h. This is mainly to mask any noise, vibration and harshness (NVH) aspects that may become intrusive compared to the near silent electric vehicle operation. Using this strategy the operation of the REx unit is virtually imperceptible to the vehicle occupants due to road and wind noise, with the only real indication that the REx unit is operating being the engine speed and power indications on the dashboard and driver display.

The ability of the engine to maintain the battery's state of charge is dependent on driving style and road conditions. If the battery continues to deplete with the engine running the operating point of the engine is moved to compensate. If the battery SOC has achieved a suitably low percentage, e.g. a high proportion of driving in heavy traffic has resulted in the 20 km/h limit for engine operation rarely being reached; the activation speed reduces so that the REx unit will be activate at lower road speeds to prevent the over depletion of the battery.

The REx unit power request is intended to meet the average tractive power demand of the vehicle, based on instantaneous vehicle speed, with an additional percentage added for hotel loads and transient power requirements. The vehicle road load curve is shown in Figure 5, along with the corresponding engine power and engine speed operating lines.

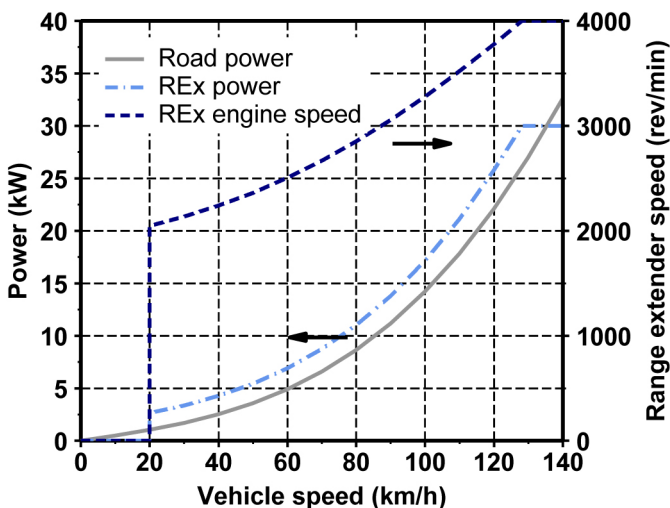


Figure 7. Range extender operating speed and power

The engine operating strategy adopted varies REx engine speed as a function of the vehicle speed. As shown in Figure 7 the VCU controls the output power of the engine during an NEDC cycle with depleted battery to maintain the SOC of the battery.

BENEFITS OF REX TECHNOLOGY FOR VEHICLE ARCHITECTURE

Paradoxically, the integration of a REx engine into an electric vehicle serves to remove range anxiety for the driver, yet also enables the reduction in capacity of the battery pack. This is enabled because of the higher overall range of the vehicle when combining the electric-only and gasoline-assisted operation modes, the ability to re-fill the fuel tank in minutes rather than hours and restore vehicle range provides a practical solution to the problem of exhausting the on-board electrical power storage. Furthermore, the REx unit also enables full utilization of the battery pack capacity without the risk of the vehicle becoming stranded.

It is therefore no longer necessary to use a large battery pack of the size typically fitted to electric-only vehicles. Current market electric only vehicles often use a Lithium Ion battery pack with a capacity of around 20-22 kWh in order to provide the driver with a usable range of around 100 km (based on the NEDC cycle). A REEV does not need an electric only range of this magnitude because of the ability to provide extended range using the REx unit.

This enables a REEV to be designed with an electric-only range which covers only the daily usage for a high percentile of the market without additional electrical range to cover for abnormal journeys. It has been shown [1] that 50 % of daily usage in the UK is less than 50 km. Using the NEDC as a basis, simulation was used to calculate that a 14 kWh battery pack would provide an electric only range sufficient to allow more than 50 % of drivers to carry out all normal journeys on electrical power alone. The REx engine is available on demand

to provide flexibility and allow the car to be used when unexpected trips or longer weekend journeys are required and also to compensate for reduced electrical range in winter conditions.

MEASURED DRIVECYCLE EFFICIENCY

The REEV demonstrator vehicle has been tested under controlled conditions over a number of drive cycles including the NEDC, World Harmonised and Artemis cycles. The results of these tests are shown in Table 3.

Table 3. Drivecycle electrical consumption test results for the REEV Demonstrator

Cycle	Electrical energy consumption (kWh/km)
NEDC	0.13
World Harmonised Cycle	0.14
Artemis	0.16

It can be seen that the electrical consumption of the vehicle when driven on the NEDC is 0.13 kWh/km, which is comparable to the most electrically efficient market EVs when also tested over the NEDC (BMW i3 = 0.129 kWh/km [7], Nissan Leaf = 0.15 kWh/km [8]). Comparatively, the energy usage per unit distance increases for the World Harmonised Cycle and Artemis cycles. This is a reflection of the higher speed residency of those cycles.

It has been established that the Artemis cycle is particularly representative of driving in real conditions in central Europe [1]. On this cycle, the REEV demonstrator has been measured with an electrical consumption of 0.16 kWh/km, which is expected to better represent the energy consumption of the vehicle when used in real driving conditions. It is also expected that the energy consumption will increase in real driving conditions due to the higher hotel loads anticipated. For example, the electrical cabin heating or cooling is not enabled during the controlled conditions of any of the tests listed, but will be required during real driving.

REEV CO₂ EMISSIONS

It must be recognized that even though the tailpipe CO₂ emissions of an EV, or REEV operating in EV mode, are zero, the generation of the electricity used to propel then vehicle is normally achieved using at least a partial contribution from methods which use fossil fuels and have a CO₂ contribution.

The published [9] carbon content of the UK national electricity grid is 455 g/kWh CO₂ including distribution and transportation losses. Using this figure it has been calculated that the equivalent CO₂ output of the REEV demonstrator when driven