*EVS27*
*Barcelona, Spain, November 17-20, 2013*

# Development of a Dedicated Range Extender Unit and Demonstration Vehicle

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## Abstract

Current focus on the reduction of tailpipe $CO_2$ emissions of road vehicles is increasing the interest in hybrid and electric vehicle technologies. Pure electric vehicles, however, require bulky, heavy and expensive battery packs to enable an acceptable driveable range to be achieved. Extended-range electric vehicles (EREVs) partly overcome the limitations of current battery technologies by having 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.

Over the past 3 years, MAHLE Powertrain has designed and developed an engine specifically for the use as a range extender. Key attributes for the engine have been identified and the appropriate engine technology selected. The resulting design highlights are presented and the development and optimisation of the engine to meet its performance targets is described, along with the resulting performance achieved.

A current production compact-class car was used as a donor vehicle for conversion into an EREV demonstrator to enable verification of the operation range extender unit. The resulting vehicle is intended to reflect likely, near to market, steps to further the wider adoption of electric vehicles in the compact-class passenger car segment. This paper presents details of the EREV demonstrator developed and the Range Extender system integration. Recent activities have focussed on refining the range extender operating strategy to minimise the fuel consumption and NVH performance of the vehicle, as well. The resulting operating strategy for the engine is described and results showing the measured fuel efficiency of the vehicle are presented.

*Keywords: Car, EREV (extended range electric vehicle), EV (electric vehicle), ICE (internal combustion engine)*

## 1 Introduction

Electric vehicles (EVs) can potentially rely on energy provided by a selection of renewable sources which alleviates concerns over energy security and can insulate them from the volatility of oil prices. Additionally, emissions from transportation have been associated with a range of health problems, include, respiratory illnesses and cancer, this coupled with the fact that EVs do not

generate pollutants during usage has fuelled present interest.
However, due to the present capabilities of battery technology, the overall range of such a vehicle is limited [1]. Furthermore, once the battery is depleted relatively long recharging times are currently required before the vehicle is available for use again.
Extended-range electric vehicles (EREVs) overcome many of the short-comings of EVs by having a ‘range extender’ unit, which consists of an on-board fuel converter that converts a fuel, such as gasoline, into electrical energy whilst the vehicle is driving [2]. This enables the battery capacity to be reduced whilst maintaining an acceptable vehicle range. During long journeys, when the battery and fuel tank are both depleted, the vehicle can simply be refuelled in a matter of minutes, in the same way, and using the same infrastructure, as current conventional vehicles. However, it is desirable that for the majority of time the vehicle will operate in a purely electric mode, and that the vehicle is recharged 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.


Figure 1: The range extender unit developed by MAHLE Powertrain

MAHLE Powertrain has developed a dedicated range extender (REx) unit, shown in Fig. 1, to identify the requirements and challenges faced in the development of the components for such future engines. The REx unit design has been focussed on meeting the requirements for a compact-class EREV [3]. In order to enable further development and refinement of the Range Extender system (e.g. NVH attributes of the engine), the unit has been installed into a demonstration vehicle.

A current production gasoline fuelled compact-class car was used as a donor vehicle and converted into an EREV. The all-electric driveline specification was developed to meet the performance criteria set for the demonstrator, matching the acceleration and maximum speed capabilities of the conventional donor vehicle. The resulting vehicle is intended to reflect likely, near to market, steps to further the wider adoption of electric vehicles in the compact-class passenger car segment.
This paper presents an overview of the REx unit concept, design and development phases and the demonstrator vehicle specification and construction. It then focusses in greater details into the development of the operating strategy for the REx unit and the steps taken to minimise the fuel consumption and the optimisation of the NVH characteristics of the vehicle.

# 2 MAHLE REx Unit

The REx engine design has been focussed on meeting the requirements for a compact-class EREV. 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.

## 2.1 REx Unit Concept Selection and Layout

Real world drive logs were analysed to identify usage patterns of such vehicles. Subsequently a driveline model of an EREV was constructed and the power requirements to maintain battery state of charge were analysed. It was concluded that about 30 kW of mechanical power (~27 kW electrical output) was appropriate for this target application [3].
With the most basic of engine performance parameters set by an initial simulation, the type of engine to be used for the REx unit was investigated and specified. An investigation was conducted to identify potential engine types that would suit such an application. These included conventional reciprocating piston engines of all types, rotary engines, gas-turbines, plus some more unconventional engine concepts (e.g. free piston and swash-plate engines). Comparative ranking was employed to quantify the differences between the potential engine concepts using a selection criterion that was weighted based on relative importance to the application. According to the key attributes identified for a range extender, the

criteria with the highest weightings were cost, package size and NVH. Efficiency was not given the highest priority, as for this application it is desirable if the REx unit is not the primary source of propulsive energy.

The results of the selection process showed three competitive concepts; the conventional reciprocating piston engine; the Wankel rotary engine and the micro gas-turbine. All three concepts have distinct merits for use in a range extender power unit application. The rotary engine offers good NVH and a small package volume, however, potentially presents challenges in terms of meeting current and future emission legislation. This is partly due to the lubrication requirement of the rotor tip seals, but also due to the compromised combustion chamber shape. Gas-turbines on the other hand offer low vibration and potentially good noise characteristics coupled with a reasonable package volume, though suffers substantially higher production costs and long development times in comparison to those of both the reciprocating piston and Wankel rotary engine. A reciprocating piston engine offers the potential of low manufacturing cost, reasonable package size and a short development time, but poses more challenges on NVH reduction measures than the other two concepts.

This ranking exercise concluded that the reciprocating piston engine to be the most suitable engine type for the chosen range extender application and the best for a near-term, mass production feasible solution. However, there were still possible variations within this specification. Gasoline and Diesel fuel types were considered as well as 2- and 4-stroke cycles. The 2-stroke cycle was dismissed because of the hydrocarbon emissions problems that may arise from the lubrication systems required. Essentially, this would make direct injection for a 2-stroke engine a likely requirement, increasing the cost of the unit and still not guaranteeing future emissions compliance. A diesel engine was also considered but rejected as the necessary exhaust gas after-treatment systems have drastically increased in complexity, size, weight and cost in recent years due to ever more stringent exhaust particulate and $NO_X$ regulations [4]. In addition to this, the REx engine can be predominantly operated at full load, thus the efficiency benefits of a diesel engine over a gasoline engine is reduced compared with a conventional application.

The next step was to define the basic engine configuration of the gasoline, 4-stroke range extender engine needed. Parametric CAD models were built for 2, 3 and 4 cylinder engines of in-line, Vee and flat (Boxer). The entire concept engine layouts were developed for a swept volume of 0.9 litres, which was derived from the target specific output (10 bar BMEP), maximum engine speed (4000 rev/min) and target power (30 kW). Given the 30 kW target power, the specific output was chosen based on the decision that 10 bar BMEP would be steadily achievable without requiring high levels of inlet or exhaust tuning. The maximum engine speed was limited to 4000 rev/min to maintain acceptable NVH levels.

Key parameters such as total package volume (including a generator), estimated weight and cost were quantified using both CAD data and available empirical data. These estimations were used to rank the concepts relatively, whilst also considering the likely NVH characteristics. The results from the study clearly highlighted the advantages of the in-line 2-cylinder engine for this application. Once the key architectural parameters for the engine had been selected, a concept design was created and resulted in the final concept engine design specifications as summarised in Table 1.

Table1: Key specifications of the range extender unit

| Technical specifications | |
|---|---|
| Layout | In-line 2-cylinder, 4-stroke, gasoline |
| Engine displacement | 0.9 litres |
| Generator | Permanent magnet axial flux generator |
| Maximum power | 30 kW at 4000 rev/min |
| Peak torque | 72 Nm between 2000 and 4000 rev/min |
| Dimensions | 327 x 416 x 481 mm |
| Installation angle | Vertical or horizontal |
| Engine dry weight | 50 kg (70 kg with generator) |

## 2.2 Design Highlights

The overall engine design is targeted at maintaining the lowest production cost to achieve the performance targets within the smallest possible package volume. Given the low rated speed, and moderate specific power output requirements, the engine only requires 2 valves per

cylinder. Similarly port fuel injection is employed for low cost, good NVH and best start-up emissions. In order to minimise overall package, both the generator and the intake and exhaust systems are integrated into the engine structure and closely packaged respectively.
A two bearing crankshaft layout has been adopted, allowing the addition of an internal flywheel between the two cylinders, as shown in Fig. 2. Removing the need for a balancer shaft was viewed as being fundamental to creating a cranktrain with low series production cost and aids in keeping the engine light and compact. Normally for in-line 2-cylinder engines, one or two balancer shafts would be used to compensate for the residual primary forces. Instead, a 180°-540° firing interval was specifically chosen for this range extender application.
One further feature of note is the ability of the engine to be installed at any angle from vertical to horizontal (exhaust side down) with only minor hardware changes (e.g. oil pump pickup pipe). This feature was included to enable the engine to be applied to various EREV layouts. With an EREV, the engine is not mechanically connected to the wheels of the vehicle and thus can be mounted anywhere within a vehicle.
Using the comprehensive best practice competence for design and manufacturing of engine systems and components (e.g. power cell, liners, bearings, intake system, oil pumps and engine castings) within the MAHLE group, right from the initial concept design stages, considerably reduced the engine development time.

Figure 2: Two bearing crankshaft arrangement with a central flywheel

## 2.3 REx Unit Development

Following the prototype procurement, engine build and an initial break-in period, the performance of the REx unit was initially assessed, with the engine coupled to a dynamometer rather than the generator. The torque and power output of the engine met the performance targets, as can be seen in Fig. 3, with peak power of 30 kW being achieved at 4000 rev/min. It is also seen, that the engine achieves an almost constant BMEP level above the target value set in the desired operating speed range of 2000 to 4000 rev/min. The peak BMEP value of just over 10.5 bar at 2000 rev/min coincides with the peak volumetric efficiency value of 93 %.

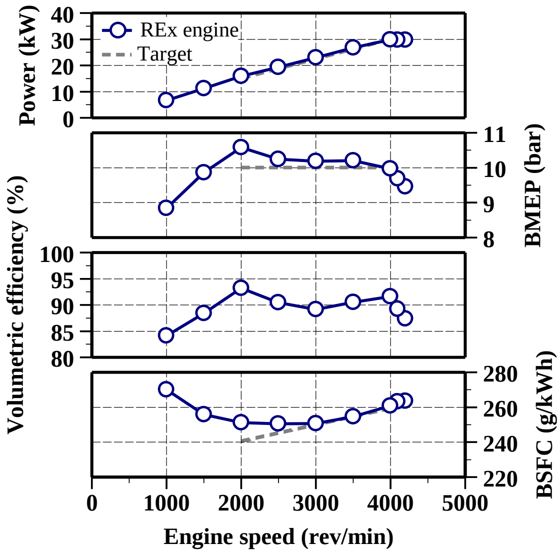



Figure 3: Initial tests results from the MAHLE range extender engine

After the initial break-in and calibration, the unit was tested with the generator in place, disconnected from the dynamometer. The generator has the capability to absorb the torque produced by the engine and is also used to start the engine, meaning that no separate starter motor is required. The control of the generator is managed by an inverter, which is in turn controlled by the engine control unit (ECU). The MAHLE Flexible ECU (MFE unit) is used, with a control strategy developed specifically for the range extender application.
The fuel consumption of the REx unit has been measured, and the total system efficiency map is shown in Fig. 4. A maximum total system efficiency (combined efficiencies of the engine, generator and inverter) of 31 % has been achieved.

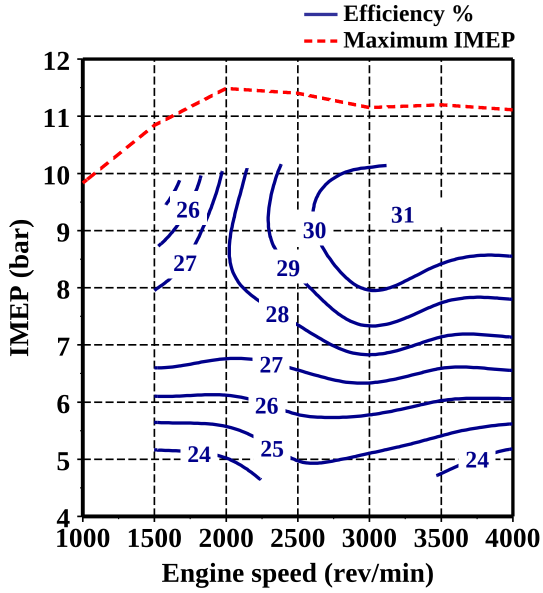



Figure 4: MAHLE range extender unit total system efficiency map

The centrally mounted flywheel layout of the REx engine limits the rotational inertia of the flywheel and the axial-flux generator also has a very low rotational inertia. Additionally, the uneven firing order, selected to removing the need for a balancer shaft, gives no firing events in the 1$^{st}$ revolution of the engine cycle and two firing events in the 2$^{nd}$ revolution of the cycle.

The very low rotational inertia and uneven torque distribution over the engine cycle gives rise to large speed fluctuations during the cycle. Fig. 5a shows measured cyclic speed fluctuations when operating at a cycle average speed of 2000 rev/min and 80 % load. When a constant torque load is applied to the engine via the generator the engine speed can be seen to fluctuate between 2300 and 1560 rev/min across the cycle, giving a peak to peak speed variation of up to 740 rev/min.

A dynamic control strategy for the generator has been devised, where it is switched off during the 1st revolution of the engine cycle and then activated at twice the mean cyclic torque during the 2$^{nd}$ revolution, as depicted in Fig. 5b. Fig. 5a shows the effect of this dynamic torque control strategy on the engine speed and it can be seen from Fig. 5a that the cyclic speed variation is almost half of that observed using constant torque generator control. Further testing has demonstrated that the dynamic torque control of the generator yields similar benefits across the entire operating range of the engine.

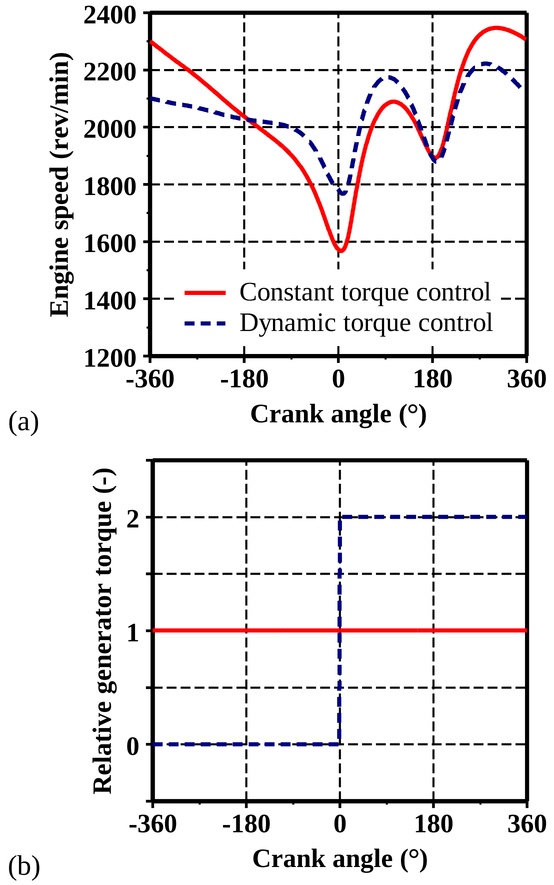



Figure 5: Dynamic generator control strategy (a) Cyclic speed fluctuations; (b) Generator torque switching

Accelerometer measurements of the benefits of the dynamic generator control strategy were taken. The engine was mounted using the configuration intended for the vehicle application. The accelerometer was located on the side of the engine to measure the oscillation of the engine about the axis of the crankshaft. Fig. 6 shows the measured maximum accelerations of the engine for each of the two generator control modes for an operating condition of 2500 rev/min and 50 % load. It can be seen that for both cases the peak accelerations occur at a frequency corresponding to 21 Hz. With the constant generator load control the peak acceleration at this frequency is 1.45 g, whereas with dynamic generator load control the corresponding peak acceleration at this frequency is only 0.90 g. Clearly, as these measurements were taken using the same engine mounting stiffness, any reduction in engine acceleration directly influences the load applied to the vehicle body to restrain the range extender system, thus giving a direct reduction in the vibration detectable to the vehicle occupants.

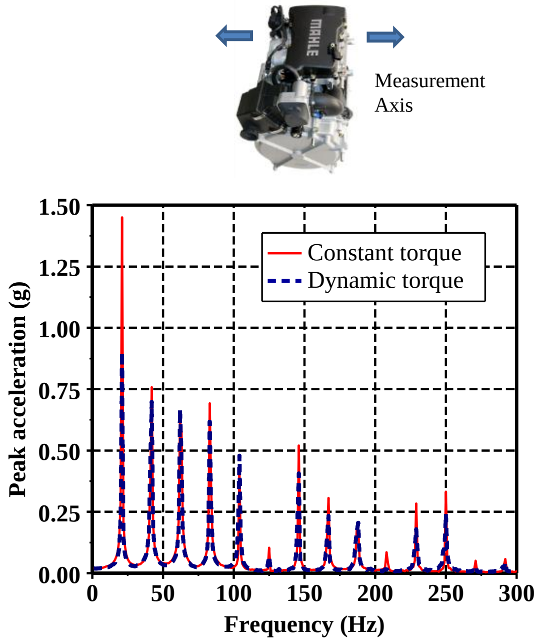



Figure 6: Measured peak accelerations in dynamic and constant generator torque control modes (2500 rev/min, 50 % load)

# 3 EREV Demonstrator

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. The resulting vehicle is intended to reflect likely near to market steps for EREVs. The EREV specification has been developed with the target of meeting the performance of the conventional baseline vehicle.

## 3.1 Vehicle Layout and Construction

In combination with a package study, the performance targets set enabled suitable electric driveline components to be selected and sourced for the EREV demonstrator.

The base vehicle was initially benchmarked for performance, fuel economy and emissions before the original powertrain and drive systems were stripped from the car. A mounting frame was designed to locate the new hardware including the MAHLE range extender engine and the traction system, shown in Fig. 7.

The only component that was moved from the engine bay area for packaging reasons was the 12 volt battery. This was re-located to an area below the rear seat, which was enabled by the reduction in size of the conventional fuel tank. The fuel tank was reduced in capacity to 25 litres because the original volume was considered to be excessive for a range extended electric vehicle. With a 25 litre fuel tank, the combined electric and range extended range of the car is 500 km, based on repeated driving of the NEDC cycle.

The original exhaust system was also replaced with a fully re-engineered system, designed specifically for the characteristics of the MAHLE range extender engine. Exhaust noise is of particular importance in a range extended electric vehicle given the base EV will be quiet in operation. The activation of the range extender engine should not be obtrusive to the vehicle occupants. Numerical simulations were used to specify an exhaust system with the desired noise suppression characteristics to dampen the exhaust gas pulsations and minimise orifice noise.

A comprehensive 1-D analysis of the vehicle cooling systems was carried out to assess the expected heat rejections, based on the various component efficiencies. Furthermore, the pump performance requirements were assessed based on the pressure drop values across the individual components and coolant hoses. The 1-D coolant flow simulation also enabled the optimisation of the heat exchanger layout in the frontend of the vehicle. The heat exchangers were re-sized relative to the original vehicle setup to optimise the balance of heat rejection from each circuit. A special front end cooling pack was manufactured for the vehicle within the package space of the original setup. This resulted in the cooling fan pack position being retained. A fan cowling was sourced from another Audi A1 application, which covered the entire rear of the cooling pack to optimise airflow across the surface when the fan is operational.

The original single-fan layout was retained, which means that the cooling strategy of the vehicle is conducted on a highest-priority basis. This means that the circuit with the greatest cooling requirement at any given time is allocated the highest priority and therefore control over the fan speed. Temperature information from each of the components is fed to the Vehicle Control Unit (VCU) and the VCU to controls the fans. In addition, there are temperature sensors in some of the coolant lines, which are fed directly to the VCU. Moreover, the electrical components typically have their own internal thermocouples measuring critical areas of the electronics (e.g. traction motor stator winding temperature). This temperature information is generally fed to the VCU in CAN format. Many of the components also have their own safety shut-down procedures in the event that safe operating temperatures are exceeded and the VCU has not ordered de-rating or shutdown to occur.

To install the traction battery, it was necessary to cut away the rear of the car in the area of the spare wheel well. A battery mounting cage was designed (to withstand shock loading) using mounting points to the vehicle structure on top of the rear chassis members for best strength. The mounting cage not only holds the battery in normal use, but will also act as a crash structure in the event of a rear-end impact and retain the battery in a roll-over scenario.

The battery charger was mounted alongside the battery pack including a high-voltage service disconnect which provides the ability to physically interrupt the high voltage circuit from the traction battery to ensure safety when working on the vehicle. Despite the sizeable battery and the addition of the charger and service disconnect this arrangement was able to retain the original boot floor height and the complete luggage stowage volume of the base car.

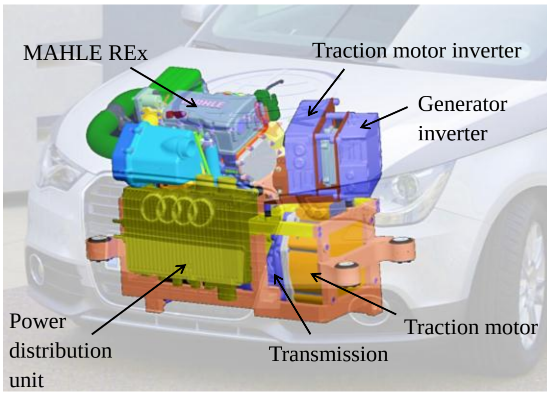



Figure 7: Schematic showing the EREV demonstrator layout

The compactness of the traction motor and transmission enabled the MAHLE REx unit to be installed alongside them within the original engine bay of the baseline vehicle, as shown in Fig. 7. By virtue of its 2-cylinder configuration and fully integrated axial flux EVO Electric generator, the MAHLE REx unit is appreciably shorter than the 1.2 litre, turbocharged, 4-cylinder baseline engine it is replacing. Likewise, the EVO Electric AF-130 traction motor [5] has a very narrow package envelope because of the axial flux configuration used (it is anticipated that the EREV will be about 250 kg heavier than the baseline vehicle). The inverters for the traction motor and the REx unit generator have been packaged above the traction motor and transmission, and these are also shown in Fig. 7. In this location they are close to the respective motor/generator units that they control, as it is desirable to minimise the cable length between the inverter unit and motor to help minimise the radio noise generated, given the high frequency current switching between the inverter and motor. The resulting vehicle installation can be seen in Fig. 8.

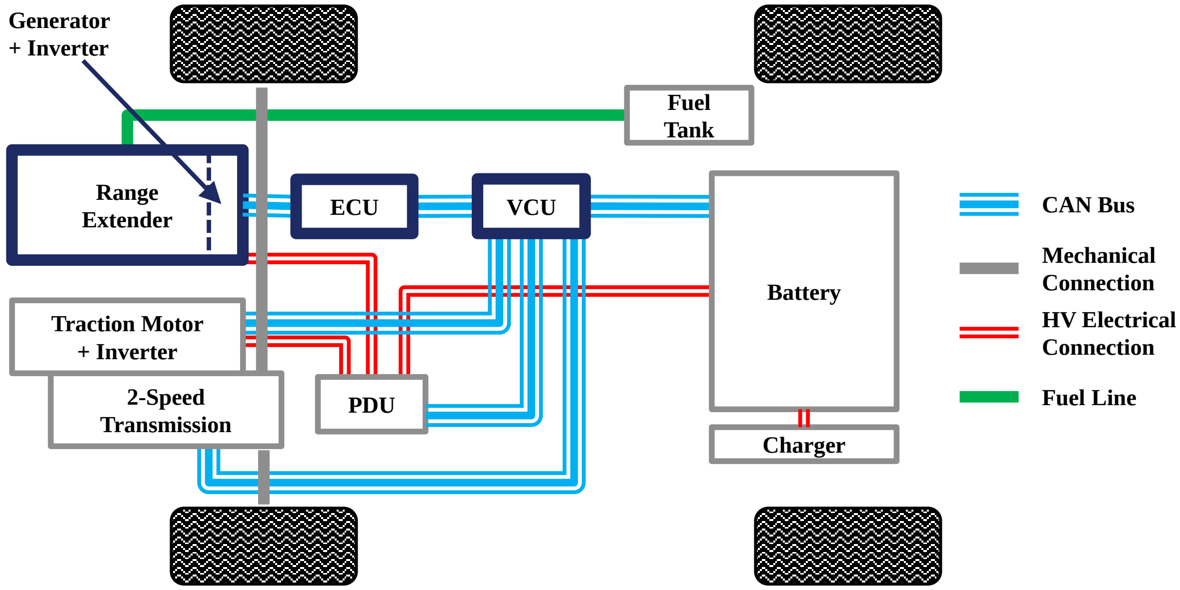
The motor and generator inverters are fed with DC power from the high-voltage battery pack via a power distribution unit (PDU), which is installed at the front of the engine bay behind the original vehicle cooling pack. The PDU also incorporates a DC to DC converter which generates a 12 volt supply to maintain the vehicle’s standard battery, which is used to feed all of the low voltage systems retained from the baseline vehicle. The PDU also supplies a high voltage feed for the electrical cabin heater and electrical air-conditioning compressor.

Figure 8: Vehicle installation

## 3.2 Control System Architecture

All components are controlled by a master vehicle control unit (VCU), which has been developed in-house by MAHLE Powertrain using the MAHLE Flexible ECU (MFE) as a basis. This is the same base unit used to control the engine but with a different control structure developed from a clean sheet to control the electric vehicle and interface with the required vehicle sub-systems. The system architecture for the demonstrator vehicle is shown schematically in Fig. 9.

The REx engine and generator are both controlled by the engine control unit (ECU), whereas the remainder of the EREV systems are controlled by the master vehicle control unit. When required, the REx ECU receives a charge request from the VCU. The ECU switches on the generator inverter, 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.




ECU: Engine Control Unit, VCU: Vehicle Control Unit, PDU: Power Distribution Unit

Figure 9: Schematic of the EREV demonstrator system architecture

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, when this point has been reached, the ECU sets the engine speed and power output, as 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 empirically [6]. The ECU monitors the engine, generator and inverter temperatures and limits the output power of the unit if required; also the ECU will monitor for system errors and sends an error report to the VCU if necessary. Once the VCU charge request ends the ECU will control the engine shutdown and switch off the electrical systems to the generator and inverter.

## 3.3 REx Operating Strategy

The operating strategy of the range extender engine has been devised to maximise the fuel economy of the vehicle, whilst maintaining an acceptable NVH characteristic. Additionally, intra-cyclic speed fluctuations have been minimised to ease the burden on the engine management system and enable repeatable control characteristics.

Previous studies indicated that low load and low speed operating points were best for achieving catalyst light-off, whilst minimising the cumulative tail-pipe emissions levels prior to light-off being achieved [6]. Testbed simulations of NEDC test cycle operation indicated that the emissions levels of the engine could be kept to around 30 % of the Euro 6 limits.

Fig. 10 shows the measured system efficiency for the range extender unit cross-plotted against the cyclic speed fluctuations observed. Lines of constant power are also shown in Fig. 10. From this it is possible for each power output, to identify an operating point that offers the highest overall system efficiency. For example, for 10 kW power output the highest system efficiency that can be achieved is ~27.5 % and this occurs at an engine speed of just under 2000 rev/min and an IMEP of 7.8 bar, as shown in Fig. 10. However, at this operating point the cyclic speed fluctuation is almost 400 rev/min per cycle. Only relatively small sacrifices in total system efficiency are observed for reductions in engine load, allowing the cyclic speed fluctuation encountered to be minimised. Again, taking 10 kW power output as the example, by operating at 2750 rev/min and 6.0 bar IMEP the cyclic speed fluctuation is reduced to about 200 rev/min, as shown in Fig. 10, and the overall system efficiency is only reduced by 1.0 % compared to the 10 kW peak efficiency point.

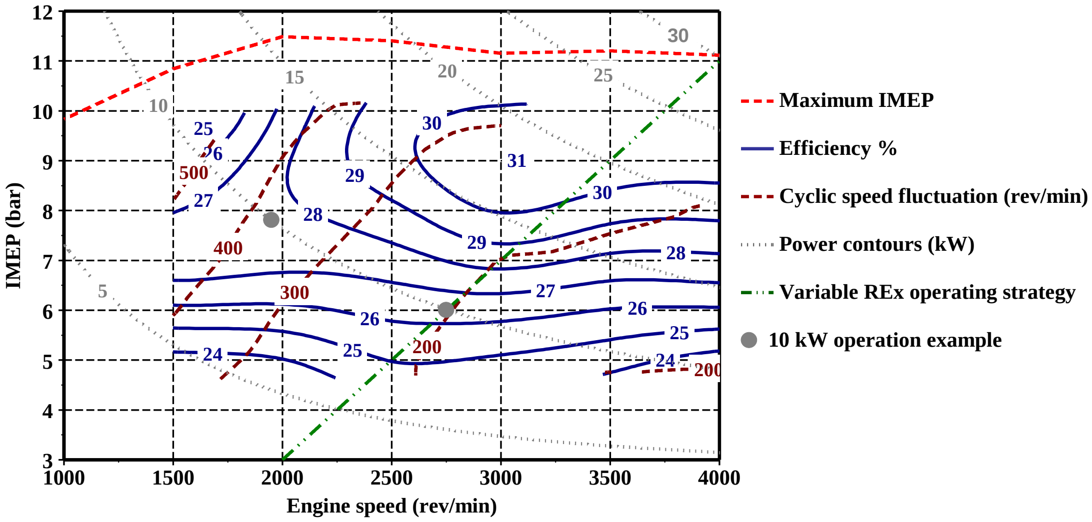



Figure 10: REx unit operating strategy (example)

An example of a possible variable speed and load operating line for the range extender engine is also shown in Fig. 10, with the power output of the unit being modulated by operating the engine along this line. This operating strategy also has the additional benefit of simultaneously reducing the engine intake and exhaust orifice noise at lower power outputs.

To minimise the declared vehicle $CO_2$ emissions based on the European test procedure it is desirable to achieve as high an electric operating range as possible and to minimise the $CO_2$ emissions measured in the minimum battery state of charge test. This drives a strategy that does not start the range extender unit until the battery has reached the minimum allowable State of Charge (SOC), to maximise the EV range, and also does not recharge the battery during normal operation, but simply sustains it at the minimum SOC. This is because any energy that is added to the battery during the minimum state of charge test is not credited by the test procedure, but creates additional $CO_2$ emissions whilst being generated.

Therefore the proposed operating strategy for an EREV would be, for example, to activate the REx unit once the battery SOC falls to a predefined threshold value, at a power only slightly above the instantaneous road load power requirement (modulated slightly based on instantaneous battery SOC). Fig. 11 shows the road load power requirement of the demonstrator vehicle, along with the proposed REx unit power output and resulting REx operating speed based on the strategy shown in Fig. 11. When battery SOC allows, it is planned to avoid range extender operation at power demands below 3 kW (or 20 km/h), however at low SOC levels the REx unit will have to be activated and operated at 3 kW in order to avoid further battery depletion due to continued low speed driving.

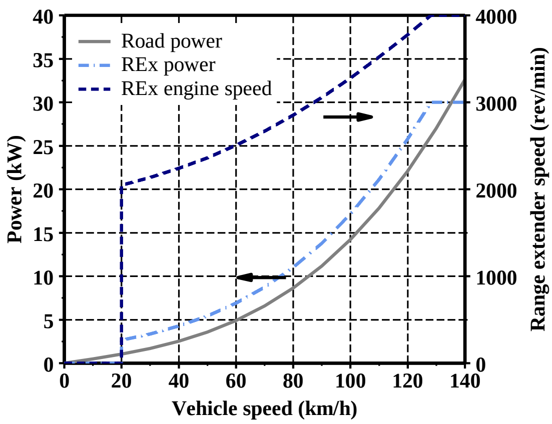



Figure 11: Vehicle road power requirement and proposed REx unit operation

## 4 Initial Vehicle Test Results

The MAHLE EREV demonstrator has been tested over repeated NEDCs to determine the achievable battery powered range prior to the first starting of the range extender engine. The operating strategy of range extender is to deplete the battery as far as allowable (in this case 20 % SoC) before starting the engine. It can be seen from Fig. 12 that an electric range of 67 km was achieved before the engine fired.

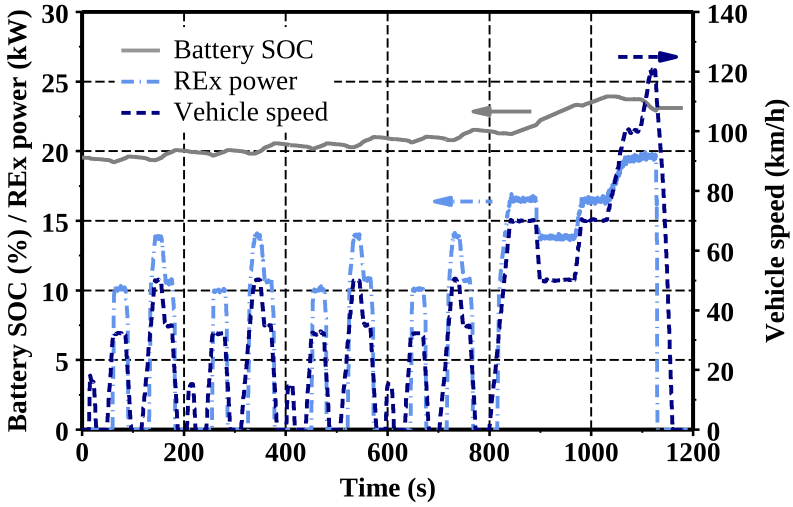



Figure 12: Battery state of charge (SoC) variation and range extender power output during depleted battery NEDC test

A further NEDC test has been performed to establish the weighted tail-pipe $CO_2$ performance of the MAHLE EREV 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 Figs. 10 and 11. Fig. 12 shows the resulting range extender power output and battery SoC during the drive cycle.

The weighted tailpipe $CO_2$ emissions of the MAHLE EREV, based on the R101 [7] weighting factor, is 42 g/km which represents a reduction of over 60 % in comparison to that of the baseline vehicle.

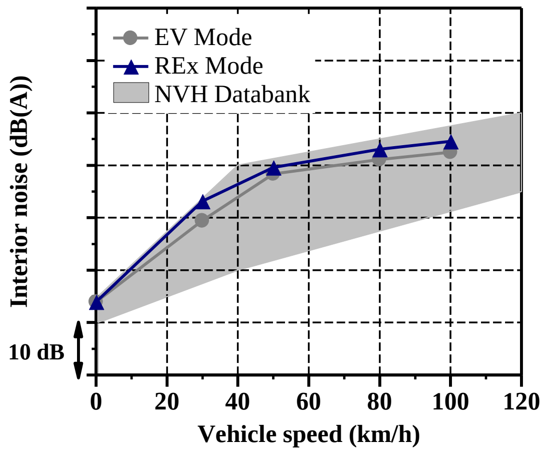



Figure 13: Vehicle interior noise measurements

Fig. 13 shows the measured interior noise of the demonstrator whilst operating in pure EV mode (REx off) and with the REx unit activated. The interior noise of the demonstrator in pure EV mode is on the higher side of our database of recorded data, this is believed to be due to the stiffer suspension settings that have been applied due to the increased weight compared to the baseline vehicle. The REx operating strategy follows that described in Figs. 10 and 11 and it can be seen from Fig. 13 that the interior noise of the vehicle is not appreciably different with the REx unit on or off and based on feedback from numerous demonstration drive conducted with the vehicle, the operation of the REx unit is imperceptible to the driver.

## 5 Summary

MAHLE Powertrain has designed and developed an ultra-compact 30 kW Range Extender engine to address the range issues associated with compact class pure electric vehicles. A demonstration EREV, based on a current production gasoline engine vehicle, has also been designed and constructed to further investigate and assess the special characteristics of this technology.

The aim of this work was to assess and demonstrate the characteristics and capabilities of the MAHLE range extender unit in a real vehicle application. The design and realisation of the vehicle has been completed and initial testing has shown the vehicle achieves a low $CO_2$ figure of just 42 g/km, with good NVH characteristics and a total driving range of 500 km.

## Acknowledgments

The authors would like to acknowledge the efforts of the engineering team at MAHLE Powertrain in Northampton, without whom the project would not have been possible.

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[7] E/ECE/324-E/ECE/TRANS/505 Regulation No 101 Rev 2, Annex 8. 29th April 2005.


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