Citation for published version:
Turner, M, Turner, J & Vorraro, G 2019, 'Mass Benefit Analysis of 4-Stroke and Wankel Range Extenders in an Electric Vehicle over a Defined Drive Cycle with Respect to Vehicle Range and Fuel Consumption', *SAE Technical Paper Series*, vol. 2019, no. April, 1282. https://doi.org/10.4271/2019-01-1282

DOI:
10.4271/2019-01-1282

Publication date:
2019

Document Version
Peer reviewed version

Link to publication

2019-01-1282

Mass benefit analysis of 4-stroke and Wankel range extenders in an electric vehicle over a defined drive cycle with respect to vehicle range and fuel consumption.

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)
Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone

Abstract

The gradual push towards electric vehicles (EV) as a primary mode of transport has resulted in an increased focus on electric and hybrid powertrain research. One answer to the consumers' concern over EV range is the implementation of small combustion engines as generators to supplement the energy stored in the vehicle battery. Since these range extender generators have the opportunity to run in a small operating window, some engine types that have historically struggled in an automotive setting have the potential to be competitive.

The relative merits of two different engine options for range extended electric vehicles are simulated in vehicle across the WLTP drive cycle. The baseline electric vehicle chosen was the BMW i3 owing to its availability as an EV with and without a range extender gasoline engine.

Two different range extenders were considered; a single rotor Wankel rotary and a 4-stroke reciprocating engine, with the baseline vehicle electric glider mass fixed for all options. Fuel tank capacity was fixed at 9 litres. Baseline EV performance was evaluated on simulated European drive cycles with mass sensitivity conducted before the implementation of each range extender.

Potential options for the optimisation of the range extender operation were considered with respect to their impact on vehicle performance. Total combined fuel efficiency was compared and an assessment of maximum range and vehicle performance was also conducted.

Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) report; indicates that if current trends continue global temperature will reach 1.5°C above pre-industrial levels by around 2040, with zero global net anthropogenic CO2 emissions required by around 2050 to limit warming to 1.5°C [1]. With this in mind the EU's focus on vehicle emissions and the latest implementation of Euro 6, through Commission regulation (EU) 2017/1151 [2] appears justified.

With average CO_2 output from European vehicles sold stalling at around 118g/km from 2016 to 2017 [3], the increased focus on vehicle emissions presents a problem, i.e. how to successfully transition to a zero carbon transport model.

The most likely route forward for the automotive industry to meet this change is in the electrification of the future vehicle fleet. This in itself however presents some challenges, the largest of which for the Original Equipment Manufacturers (OEMs) is the limitations in current battery technology [4]. As demonstrated in Figure 1 the energy density of current battery technology lags far behind that of diesel and gasoline.

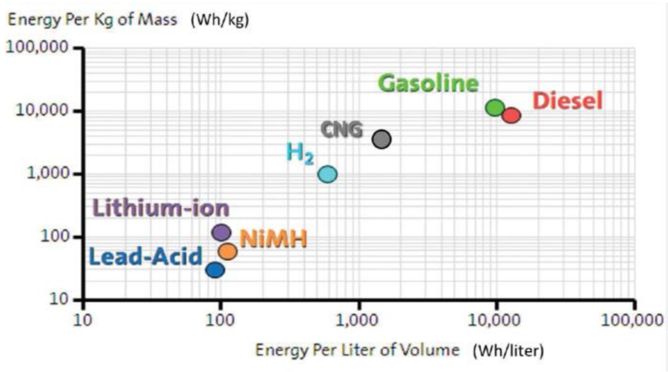

Figure 1 - Comparison of Energy density (by mass and volume) of various storage media (log-log scale) (from [5])

Investigating the link between EV mass size and energy consumption reveals a clear trend between the mass of the vehicle and its corresponding energy consumption per kilometre over the NEDC cycle. Interrogation of the European Environment Agency database of vehicles sold in Europe in 2016 reveals an average energy consumption for the electric vehicle fleet (both hybrid and pure electric) of 144 Wh/km with a corresponding mass in running order [6] of 1753kg [7], the provisional EV vehicle distribution for 2017 can be seen in Figure 2. As indicated by Ribau et al. [4] current lithium ion battery energy storage is somewhere in the region of 35 time heavier than an equivalent gasoline or diesel powered vehicle fuel tank.

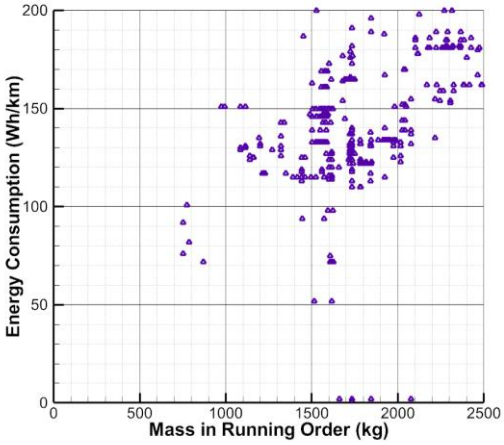

Figure 2 - European Environment Agency provisional 2017 CO2 database - EV (including hybrid) energy consumption and mass in running order [7], negating total fleet volumes.

One solution to this problem is in the hybridisation of electric vehicles, with this paper focused on series hybrids specifically. In a series hybrid vehicle a combustion engine is used as a range extender to convert chemical fuel energy for the explicit purpose of boosting the state of charge in an EV with no mechanical link to the driven wheels, see Figure 3.

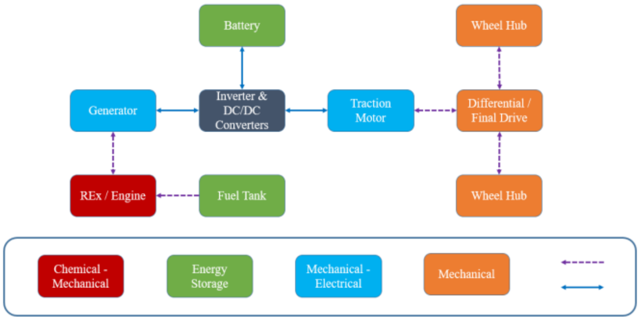

Figure 3 - Generic series hybrid layout (purple dash line indicates chemical or mechanical transport, blue electrical transport)

The duty cycle of a typical directly coupled internal combustion engine (ICE) is considerably different to that of a range extender, with the last often only operating at two or three speed and load points. As a result various combustion engine options are available to vehicle manufacturers. The 4-stroke reciprocating engine is the mainstay of the automotive industry, and is the obvious choice for the majority of manufacturers. In addition, research into 4-stroke reciprocating range extenders (REx) have been on-going for several years [8]-[11].

4-stroke reciprocating

The majority of research into range extender units has focused on 4-stoke systems with both Lotus and Mahle having created operating prototypes [9][10] in the range of 30kW, with the BMW i3 (a commercially available series hybrid vehicle) operating a parallel twin 4-stroke engine [12]. 4-stroke reciprocating engines have the advantage of a long period of continuous development [13] and as a consequence low cost, in addition to good emission control owing to lambda 1 operation in conjunction with a 3-way catalyst [14].

2-stroke reciprocating

2-stroke reciprocating gasoline engines are conceptually very similar to their 4-stroke siblings. Their thermal efficiency has the potential to be better than their 4-stroke counterparts however their use has been curtailed due to high hydrocarbon emissions and poor oil consumption. They do however offer higher specific power and if designed in conjunction with direct injection and a suitable catalyst offer a potential alternative to 4-stoke piston offerings. Duret et. al. were able to establish a 2-stroke Rotax engine could be modified to meet Euro 6d NOx limits when installed into a suitable series hybrid vehicle [15]. In addition further developments into 2-stroke technology have led to improvements in hydrocarbon emissions [16].

2-Stroke Opposed Piston

The 2-stroke opposed piston engine developed by Achates [17] is currently under development and offers several advantages over typical 2 and 4 stroke piston engines.

As a result of incorporating two pistons into a single cylinder the stroke to bore ratio is increased relative to the ‘single’ piston 2 or 4 stroke. As a result of this plus the absence of a cylinder head the heat losses are reduced, improving thermal efficiency. As with a standard 2-stroke a single combustion event occurs for every 360 degrees of crank rotation so power density is also increased. Furthermore as with all 2-strokes, opposed piston engines have challenges around low load operation and hydrocarbon emissions, something that Achates have been able to overcome with their most recent efforts [18][19].

Wankel Rotary Engine

Of all the alternative combustion engines under review the rotary Wankel engine has seen the most exposure and continued automotive development. Mazda continued to develop and improve their Wankel offering up until 2012 when the last rotary powered vehicle (RX-8) was withdrawn from the market [20]. That being said Mazda recently announced a return to the Wankel rotary engine in 2020 [22]. Outside the automotive industry development and production of the Wankel rotary engine has continued and one of the leading companies, with Advanced Innovative Engineering (AIE) having a range of rotary engines in their product portfolio ranging in output from 5hp through to 120hp [23].

Wankel engines are inherently balanced and light (having no reciprocating parts) which lends them high specific power and good NVH characteristics, however as a result of their elongated combustion chamber and difficulties with sealing, by comparison they suffer from poor thermal efficiency and high emissions [24].

Micro Gas Turbine

Similar to Wankel rotary engines micro gas turbines (MGT) offer advantageous specific power but with relatively poor thermal efficiency. That being said both Capstone [25] and Delta Motorsport have both developed working prototype range extenders based on this concept. Unlike the other ICEs options under review MGTs require no external cooling loop.

Vehicle simulation

Baseline Electric vehicle (BMW i3)

Owing to its availability as both a pure EV and hybrid REx the BMW i3 was chosen as a basis for the model simulation. The model itself was developed using GT-ISE [26] with the vehicle systems specifications detailed below; core vehicle technical specifications are detailed in Table 1. Where reference data was unavailable suitable assumptions were made, also detailed in the subsequent sections.

EU kerb and mass in running order were defined as per EU commission regulation (EU) 1230/2012 [6] with the mass itself taken from the European Environment Agency published database of monitored CO_2 emissions from passenger cars [7]. Mass data for the base vehicle was filtered from the passenger car database to specifically detail the BMW i3 only.

Peak braking capacity was estimated from published performance data in conjunction with published vehicle mass data [27].

Table 1 - Baseline EV Technical Specifications

	Units	BEV	PHEV	Ref
EU Kerb Mass [1]	kg	1245	1365	-
Mass in Running Order [1]	kg	1320	1440	[7]
Front/Rear Axle Distribution	%	47/53	44/56	[12]
Wheelbase	mm	2570	2570	[12]
Drive Configuration	-	Rear Wheel Drive	Rear Wheel Drive	[12]
Drag Co-efficient and frontal area (Cd.A)	- m^2	0.29 x 2.38	0.30 x 2.38	[12]
Tyre Sizes (F/R)	-	155/70R19 F 155/70R19 R	155/70R19 F 175/60R19 R	[12]
Max. mechanical braking torque	Nm	1195 (ea. wheel)	1195 (ea. wheel)	[27]
Fuel Tank Capacity	Litres	-	9 (Europe) 7.2 (USA)	

Primary Powertrain

From published technical information both the continuous and peak power and torque for the prime mover electric motor are available [12]. However the full motor specification is not in the public domain. Using an estimate for the drive wheel rolling circumference at 100 km/h from [28] in conjunction with the published top speed and transmission ratio [12] the maximum motor speed was estimated at 12000rpm. From the available data a maximum power and torque curve was extrapolated (Figure 4).

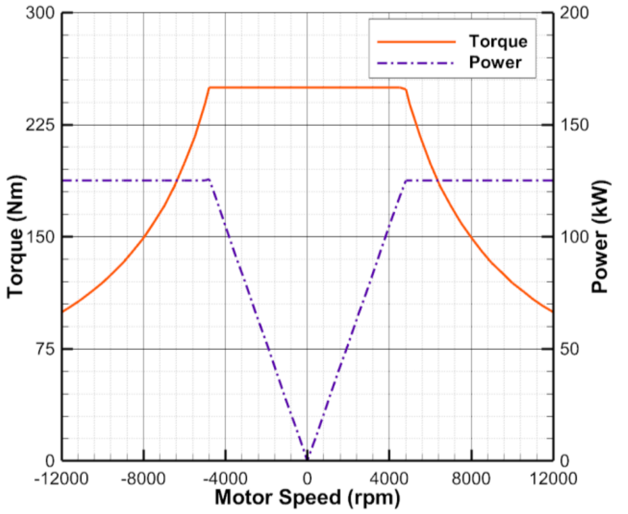

Figure 4 - E-Motor peak power and torque estimation

Further interrogation of the published technical specification revealed the peak regenerative capacity of the motor to be 50kW. Assuming that the peak regenerative capacity of the motor is also constrained by the same peak generating torque seen in Figure 4 the e-motor regenerative capacity was estimated (Figure 5).

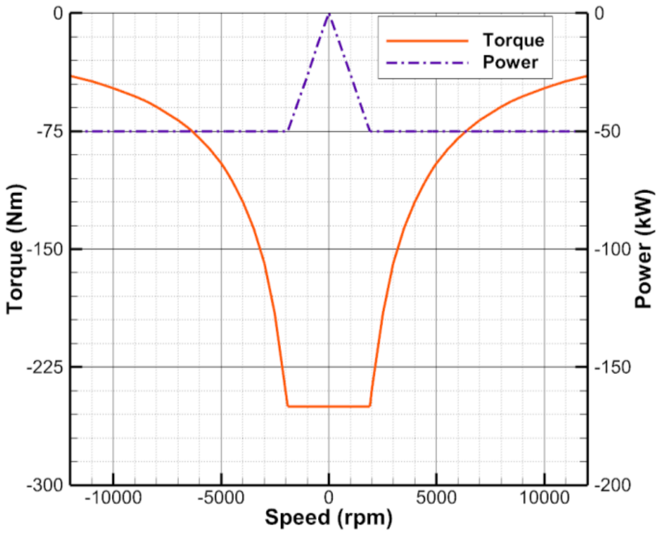

Figure 5 - E-motor peak regen capacity estimation

For the purposes of this model the regenerative calibration of the e-motor was simplified. Below a fixed vehicle speed of 10kph all vehicle braking was handled via the mechanical brake system. Above this speed all events during the drive cycle that required a braking effort below the maximum regenerative capacity of the e-motor were handled exclusively via regeneration. For braking events above this threshold the mechanical braking system was also utilised to meet the vehicle velocity profile specified in the drive cycle.

The baseline vehicle e-motor is connected to the drive wheels via a single gear reduction drive which is fixed at 9.665:1 [12].

EV Glider Battery Assumptions

Both versions of the BMW i3 electric vehicle (EV and REEV) are fitted with the same lithium-ion battery pack. From the available datasheet [12] the high voltage electrical system operates at 353V with the battery system having a maximum capacity of 33.2kWh. However it is also noted that the usable capacity is limited to 27.2kWh (a reduction of 18%). At the system voltage of 353V this equated to a usable battery capacity of 77Ah.

It was assumed that the battery technology implemented in the EV was supplied by Samsung SDI [29]. Further model assumptions included a constant battery temperature of 298K, with the open circuit voltage map extrapolated from the minimum expected cell voltage at 20% and 90% state of charge [30].

Internal resistance was introduced based on the work completed by Jeong et al. [31] with the state of charge limited to 0.8 to account for the difference between total and usable battery capacity.

Range Extender Activation

Range extender operation was based on a simplified representation of the work conducted by Jeong et al. [31]. Engine operation is divided into 4 modes

- Charge depletion – where the range extender does not activate and the battery state of charge (SOC) is permitted to deplete without assistance except through brake regeneration.
- Charge sustain – state of charge high – when the battery SOC drops below 16.5% the generator operates at a fixed engine speed and load of 2400 rpm and 4.6bar (25Nm – 6.3kW)
- Charge sustain – state of charge medium – when the battery SOC is between 13.5 and 15.5% the generator operates at 3600rpm and 7.8bar (40Nm – 15.1kW)
- Charge sustain – state of charge low – with the battery SOC below 13.5% the generator operates at 4500rpm and 10.7bar (55Nm - 25.9kW)

In addition further control criteria were also introduced, e.g. at a SOC above 13.8% the REx was permitted to turn off at speeds below 10.5km/h and would re-activate above 20km/h. Below 13.8% SOC the REx engine would continue to operate.

Baseline NEDC comparison and mass sensitivity.

With the BEV model established, before any mass sensitivity analysis was conducted the model validity was investigated. In support of the European Commission regulation 443/2009, EU member states are mandated to supply detailed information with regard to every vehicle registered in their respective territory. This data is compiled by the commission and published on an annual basis [7]. Included in this dataset is the certified mass in running order of each vehicle along with the official CO_2 and, in the case of electric vehicles, energy consumption per km over the NEDC cycle. A summary of the information relating to the BMW i3 can be found in Table 2.

Table 2 - EEA Provisional 2017 Data - i3 [7]. Where a range was reported the upper and lower limits are displayed

	Units	BEV	REEV
Mass in Running Order	kg	1270~1340	1390~1460
Wheelbase	mm	2570	2570
Front Track	mm	1571	1571
Rear Track	mm	1576~1580	1536~1608
Energy Storage	-	Electric	Petrol/Electric
Rated Engine Power	kW	75~135	28~188
Rated energy consumption	Wh/km	126~143	113~125
Engine Capacity	cm^3	-	647

The energy consumption of the model over the NEDC cycle was compared to the official declared figure for the BEV BMW i3. The model in its BEV configuration averaged 141Wh/km over an NEDC drive cycle, by comparison the official declared figure for the BMW i3 as reported in the 2017 provisional data [7] ranges from 126 and 136Wh/km. This difference could be attributed to a lack of an accurate tyre friction model, or inaccuracies in the assumptions around the traction motor and driveline efficiency. A further possibility is due to the permitted errors within 443/2009, which may have an effect on the declared figure. For example, Commission Regulation (EU) 1230/2012 [6] outlines the permitted deviations for vehicle type approval including a +/- 3% tolerance to the mass in running order of passenger vehicles.

Owing to the potential sources of error in both the declared and simulated figure and owing to the initial focus on mass sensitivity and the relative merits to alternate range extender units this deviation was deemed acceptable. In Figure 6 both the official declared energy consumption and model prediction are highlighted against the EEA provisional data previously discussed.

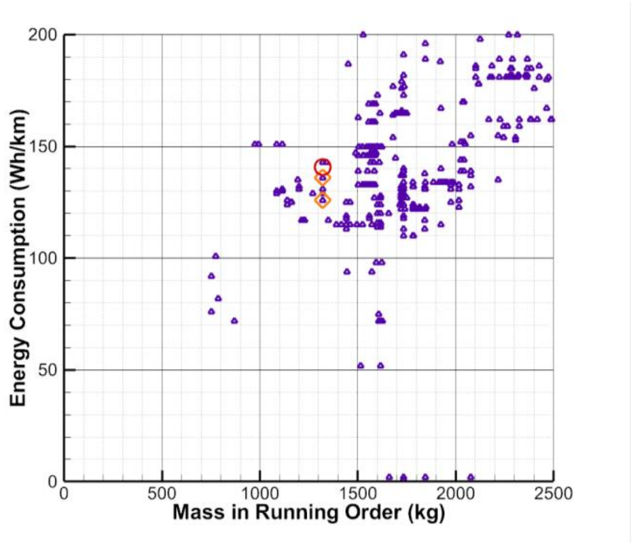

Figure 6 - EEA Provisional EV energy consumption with BMW i3 highlighted (Orange triangle) and model prediction (red circle)

Since the introduction of World harmonised light vehicle test procedure (WLTP) manufacturers are now required to certify their vehicles using a new test cycle designed to more closely represent real world driving conditions (Figure 7). As demonstrated by Simeu and Kim [32] the comparative impact on BEV energy consumption when tested under NEDC versus WLTP was in the region of 18-20%. However subjecting the simulation to the full WLTP cycle results in an energy consumption in the region of 157 Wh/km, an increase of 12%, at present the reason for this discrepancy is not completely clear and requires further investigation. Since the WLTP results for the i3 have yet to be published by the EEA the decision was taken to take the increase of 12% at face value pending a more detailed review.

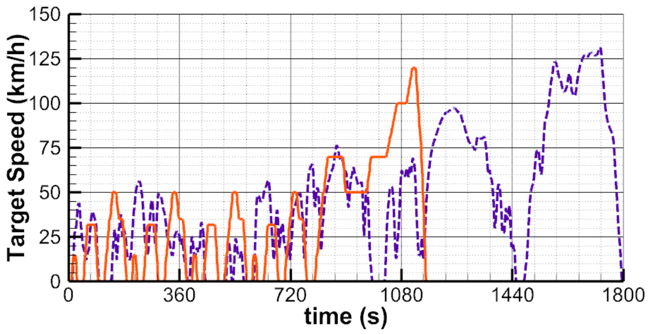

Figure 7 - NEDC and WLTP drive cycles (NEDC - orange solid, WLTP - purple dash)

Mass sensitivity

Once the model was established the impact of a variation to mass was investigated. Using the declared mass in running order of 1320kg (1245kg kerb mass and 75kg driver) as a baseline, the NEDC test was re-run with a vehicle mass ranging from 622.5kg through to 1867.5kg.

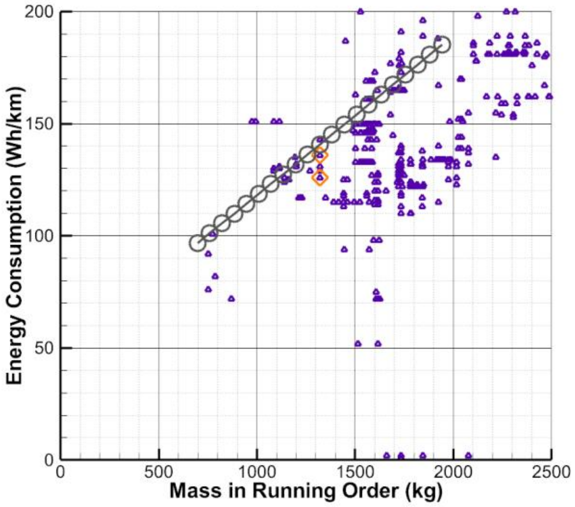

Figure 8 – Impact of mass variation on BEV energy consumption in comparison to EEA provisional 2017 data with BMW i3 highlighted (Orange triangle) and model mass sensitivity (grey circle)

Populating the average NEDC energy consumption onto the EEA dataset reveals that, as expected, the kerb mass of the vehicle has a direct impact on energy consumption over the NEDC cycle (Figure 8). It is also noteworthy that the gradient of the sensitivity curve closely matches the gradient of the EV specific EEA dataset. Applying the average energy consumption of 140Wh/km to the usable energy capacity of the battery (27.2 kWh) suggests a maximum EV range of 193km. This broadly corresponds with the manufacturer released ‘everyday driving’ range data [12] of 200km. Strangely, the same document indicates a range of 300km for the EU cycle, which if the usable capacity of the battery were to be maintained the average energy consumption would need to be in the region of 90Wh/km. The reasoning behind this difference is not immediately clear. Returning to the model, the simulation suggests that a 5% reduction in kerb mass equates to a 3% reduction to energy consumption over the NEDC cycle. On this assumption to achieve a further 50km of range then ~ 400kg of mass reduction would be required.

Comparing the impact of mass on the full WLTP cycle yields a similar trend: reducing the vehicle mass does have a corresponding reduction to energy consumption over WLTP. However it would appear that, in this instance at least, mass has less of an impact on the energy consumption over the test cycle. This could be due to the greater prevalence of transient vehicle speeds in the WLTP cycle compared to NEDC in parallel with vehicle acceleration that more closely matches real world driving conditions. Figure 9 demonstrates the relative difference in mass sensitivity of the two different cycles, the data also suggesting that while the NEDC cycle reveals a fairly linear relationship, WLTP results in a slightly more complex interaction. Again this will be investigated further, however it is reasonable to speculate that while mass seems to have less of an impact in the WLTP cycle the greater concentration of transients in WLTP may negatively affect vehicles with higher mass, along with greater periods of high speed running.

Figure 10 demonstrates the relative difference in estimated vehicle range for both the NEDC and WLTP cycles for a vehicle with different mass. Reducing the vehicle mass by 100kg results in a theoretical NEDC range of 203km (a 5% or 10km increase) while in the WLTP cycle only an 8km (4.5%) benefit is realised (180km vs 172km). Clearly any alternative range extender unit fitted to an electric vehicle will see only small gains from even significant mass savings over a typical 4-stroke reciprocating unit.

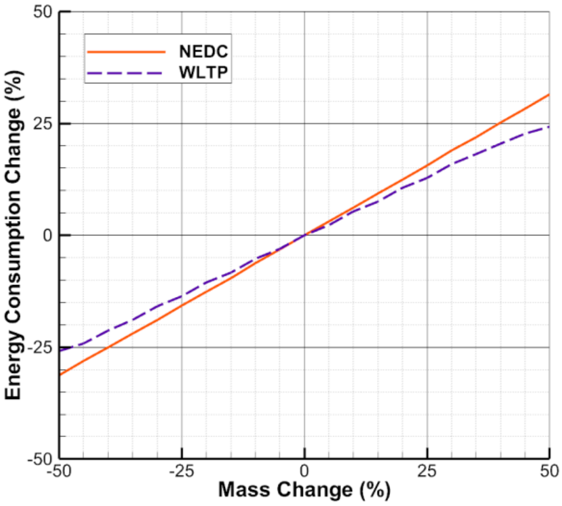

Figure 9 - Mass sensitivity comparison between the NEDC (orange solid) and WLTP cycle

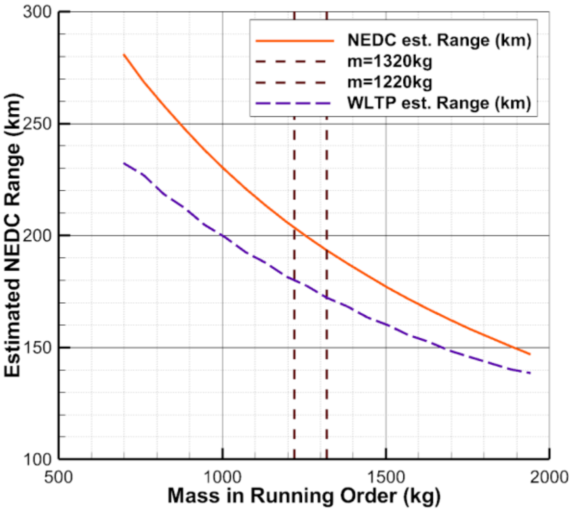

Figure 10 – Prediction of NEDC and WLTP range with respect to mass in running order [6]. NEDC range (orange solid), WLTP range (purple dash).

Range Extender Options

Several possible range extender units were considered for further review, as detailed previously, however owing to available experimental data the initial simulation study was limited to that of the Wankel rotary engine. The micro gas turbine and especially the opposed piston remain of significant interest and will be explored in more detail in a later paper.

4-stroke Range Extender Internal Combustion Engine

The REEV variant of the baseline vehicle is equipped with a parallel twin 4-stroke internal combustion engine with a capacity of 647cc (Table 3)

Table 3 - Baseline vehicle range extender engine specification [12]

Displaced volume	647 cc
Stroke	66 mm
Bore	79 mm
Compression ratio	10.6:1
Number of Valves per cylinder	4
Peak output (@ rpm)	28kW (5000)
Peak torque (@ rpm)	56Nm (4500)
EU emission compliance	EU6

Based on the peak torque and power figures published an approximation of BMEP across an engine speed range of 750 to 5500rpm was created (Figure 11). Furthermore an appropriate brake specific fuel consumption map was estimated from work conducted by Mahle and Lotus on their range extender programmes [8]-[10].

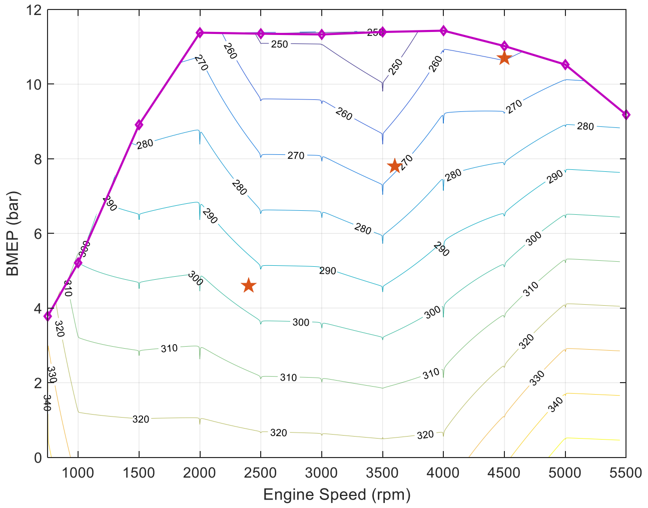

Figure 11 - Maximum BMEP and BSFC estimation for 4-stroke REx engine with the 3 operating points highlighted (orange)

Wankel Rotary Engine

As part of the Westfield led APC and Innovate UK project ADAPT the engine manufacturer Advanced Innovative Engineering (AIE) with the assistance of the University of Bath, are developing their 225cc Wankel rotary engine for use as a hybrid vehicle range extender. As previously discussed Wankel engines are typically light with low levels of friction, however they often struggle with low load emissions. The intricacies of Wankel engine operation will not be covered here (instead please refer to [24][33] for an explanation of the Wankel rotary engine and [20][21] for a more focused study of the engine investigated in this study).

The rotary engine under investigation is AIE's 225CS engine [23] which has a rated power of 30kW, almost exactly the same as the parallel twin engine the i3 employs. Basic engine geometry and port timing can be found in Table 4. Characterisation of AIE 225CS is currently underway and both the peak BMEP and BSFC at lambda 1 operation is represented in Figure 12. Saving the question over exhaust emissions for later review, minimum BSFC for this engine was recorded at 292g/kWh around 50g/kWh higher than the best reported by [8]-[10].

Table 4 - AIE (UK) Ltd. 225CS engine geometry and port timing

Definition			**Units**
Generating Radius	69.5		mm
Eccentricity	11.6		mm
Offset/Equidistance	2		mm
Width of Rotor Housing	51.941		mm
No. of Rotors	1		
Total Displacement	225		cc
Mass (excluding ancillaries)	10		kg
Compression Ratio	9.6:1		
Port timing			
Port	Opens	Closes	Units
Intake Port	71 BTDC	60 ABDC	degrees
Exhaust Port	69 BBDC	57 ATDC	degrees
Effective Port Overlap	128		degrees

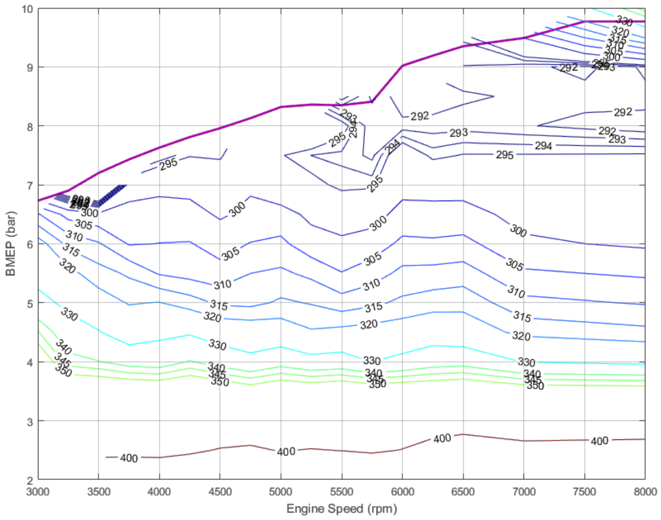

Figure 12 - AIE (UK) Ltd. 225CS Peak BMEP (bar) in purple and BSFC (g/kWh). Note - Data above 6500 rpm extrapolated from adjoining data

Mass Comparison

The REx installation for both the parallel twin and a theoretical Wankel engine were analysed and the breakdown of mass was estimated (Table 5). While it is reasonable to assume that the mass of the cooling, exhaust and ancillaries for both engines will be similar (since both have a power output in the region of 30kW) where the two power plants differ is in the core engine mass, owing to the fact that the rotary engine has no valve train or reciprocating components.

Table 5 - Estimated mass breakdown for Parallel twin (I2) and Wankel rotary engine (estimated from [34])

Vehicle Subsection	**Mass 647cc I2**	**Mass 225CS - Rotary**	**Units**
Frames and Mounting	3	3	kg
Base Engine	45	15	kg
Engine Cooling*	11	11	kg
Air Intake System	5	5	kg
Engine Control (ECU) and Harness	4	4	kg
Exhaust System (incl CAT.)	13	13	kg
Fuel System (incl 9 litres fuel)	15	15	kg
Power generation (electrical generator)	27	27	kg
Generator ECU	3	3	kg
Total	126	96	kg

*i3 engine cooling shared with battery and traction motor

REx Vehicle Simulation

In order to understand the relative merits of differing REx units a suitable baseline needed to be established with the existing parallel twin engine; Each simulation was run twice with the battery state of charge differing at the start of each cycle:

- CD - Charge Depletion – in this run the battery state of charge starts at 80% (for this model this is assumed to be fully charged) this results in both the NEDC and WLTP cycle completing with no range extender activation.
- CS - Charge Sustain – in this run the battery state of charge begins at 16.5%, the threshold at which the REx operation begins to support the battery.

Firstly the model simulation was updated to reflect the different mass and coefficient of drag the REx equipped i3 is purported to have (Table 1) before being subjected to the NEDC and WLTP cycle. Next the vehicle was updated to reflect the reduced mass that the Wankel REx would benefit from and the test cycles re-run to capture both the average energy and fuel consumption in both charge depletion and sustain modes. A summary of the overall average energy and fuel consumption results can be seen in Table 6.

As seen previously an increase in vehicle mass corresponds with an increase in energy consumption as measured at the battery terminals. Interestingly the quoted range for the REx i3 over ‘everyday driving’ is up to 330km [8], taking this figure at face value would suggest that the i3 REx is designed around an EV range of ~200km [12] and a CS petrol range of 130km. Given that the i3 has a fuel tank capacity of 9 litres this equates to an average fuel consumption of 6.92 l/100km. Given that the model simulation currently predicts an average fuel consumption figure of 4.9 and 5.8 l/100km clearly the model engine controller requires further refinement. This was to be expected considering the REx controller was based upon a simplified version of the one detailed in [31].

Table 6 - Average energy and fuel consumption over NEDC and WLTP cycle for BEV and REx variants of i3 plus i3 REx with reduced mass (equivalent to 225CS REx)

		BEV Ref.	**i3 REx**	**i3 REx (reduced mass)**	**Units**
Kerb Mass		1245	1365	1334	kg
Mass in Running Order		1320	1440	1409	kg
NEDC	**CD Energy Consumption***	140.0	148.8	146.6	Wh/km
	CS – Energy Consumption*	-	20.5	19.9	Wh/km
	CS – Fuel Consumption	-	4.9	5.7**	l/100km
WLTP	**CD – Energy Consumption***	158.0	165.7	163.6	Wh/km
	CS – Energy Consumption*	-	21.8	10.6	Wh/km
	CS – Fuel Consumption	-	5.8	6.5**	l/100km

*measured at battery terminal

**estimated fuel consumption with 225CS rotary range extender

In order to compare the performance of the 225CS with that of the parallel twin the REx power request profile was generated from both the NEDC and WLTP cycle at a mass in running order of 1409kg. In Figure 13 the difference in the REx power profile from the model at both 1440kg and 1409kg over the NEDC cycle is recorded. One can notice that for NEDC the REx power profile is almost identical for the two vehicle masses, the only real deviation is during the last high speed portion of the cycle where the heavier vehicle moves to 15kW slightly earlier. By comparison in the WLTP cycle (Figure 14) there is greater deviation; not only does the REx activate and transition to the higher power state later, at one point it also does not activate at all.

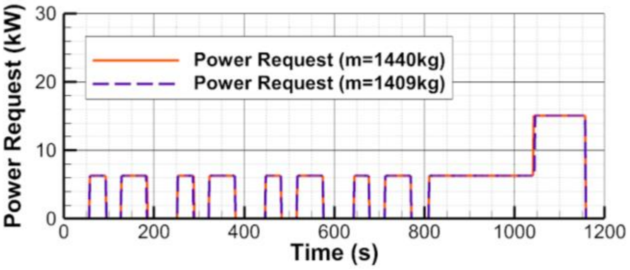

Figure 13 - Rex Power Demand over NEDC cycle (m=1440kg and 1409kg)

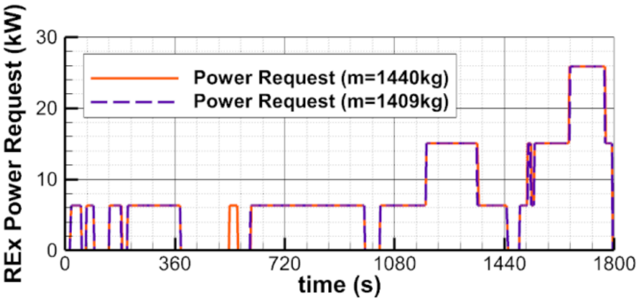

Figure 14 - WLTP Rex power demand (m=1440kg and 1409 kg)

The next step was to select suitable speed and load points for the 225CS that match the power loads modelled with the parallel twin (I2) REx. For the three charge sustain modes the power demand were as follows.

- High SOC – 6.3kW
- Medium SOC – 15.1kW
- Low SOC – 25.9kW

In Figure 15 it can be seen that constant power lines overlaid onto the 225CS BSFC map, with the aim to select three speed and load points on these curves to minimise brake specific fuel consumption and maximise efficiency. Going one step forward also displayed is one potential target operating curve for the 225CS which broadly tracks through a curve of best efficiency (with respect to fuel consumption) which could be incorporated into future improvements to the model. For the purposes of this study however Table 7 details the 225 REx load points selected for the three charge sustain modes that matches the I2 operating modes.

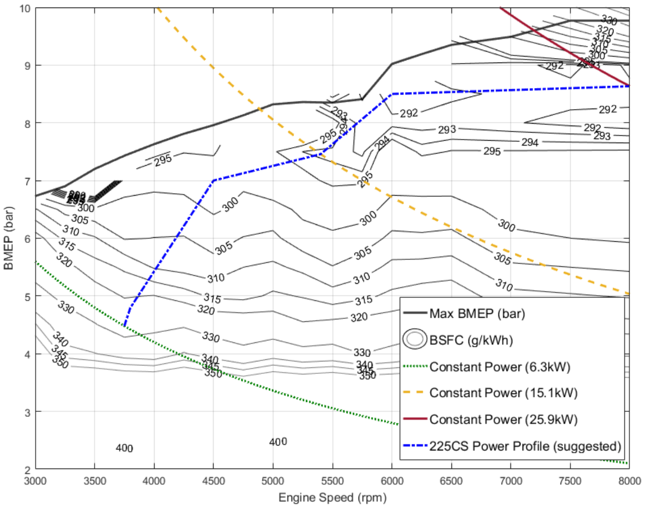

Figure 15 - 225CS BSFC map with constant power lines at 6.3, 15.1 and 25.9kW

Table 7 - 225CS Charge sustain modes

Charge Sustain Mode	**Engine Speed (rpm)**	**BMEP (bar)**	**Power (kW)**
High State of Charge	3750	4.48	6.3
Medium State of Charge	5400	7.46	15.1
Low State of Charge	8000	8.63	25.9

Mapping the 225CS to the power profile generated by the i3 reduced mass model, average fuel consumption for a theoretical 225CS powered i3 series hybrid vehicle across the NEDC and WLTP can be seen in Table 6.

Conclusions/Summary

Throughout this investigation we have been able to replicate and estimate the level of energy consumption for the vehicle modelled (BMW i3) to a reasonable level of accuracy. The model was also able to demonstrate the impact that vehicle mass has on both the energy consumption and predicted range over both the NEDC and WLTP cycles. Taken at face value the results suggest that priority should be given to maximising the vehicle efficiency as opposed to minimising mass if energy consumption and range are of the highest priority. It stands to reason however that vehicles will have differing use cases and requirements in which reducing mass can and will have a significant benefit.

Even though a simplified range extender engine model was introduced the relative merits and challenges associated with alternative range extender units (in this case the Wankel rotary ICE) were established. Wankel engines have both a mass and NVH advantage over reciprocating units, but as this paper demonstrates significant vehicle mass savings are needed to realise an appreciable improvement in both average energy consumption and total vehicle range. In this example if the 225CS were to have equivalence to the parallel twin that it would replace, it would need to achieve an operating thermal efficiency very close to current reciprocating piston engines. To quantify that statement, using the same REx control strategy present in the model and all the model assumptions currently in force, the 225CS efficiency would need to improve by somewhere in the region of 12%, achieving a minimum BSFC of at least 260g/kWh.

The preliminary investigation has successfully identified areas for improvement in the model along with the next area of development. Full integration of the Wankel engine model along with both the opposed piston and micro gas turbine are a priority. In addition the development of the engine control strategy for both the original i3 and alternate REx units will allow further model correlation against the published vehicle figures, and then lead into research focused on the optimisation of the REx unit to maximise vehicle efficiency and minimise (or eliminate) vehicle emissions. Supporting the APC and Innovate UK project, the model will now be adapted to model the Westfield vehicles currently being developed. In parallel experimental research around the Wankel rotary engine to improve both efficiency and emissions (focusing on direct injection [20] along with an exhaust expander, will feed back into the model.

References

1. Allen M., Babiker, M., Chen, Y., et. al., “Global Warming of 1.5 °C” IPCC Report SR15. http://www.ipcc.ch/report/sr15/
2. EU Commission, “Commission Regulation (EU) 2017/1151 f 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Commission Regulation (EC) No 692/2008.” *Official Journal of the European Union L 175/1 Vol 60 2017* ELI: http://data.europa.eu/eli/reg/2017/1151/oj
3. European Environment Agency, “No Improvements on average CO2 emissions from new cars in 2017,” Published 23 April 2018, Accessed October 2018, https://www.eea.europa.eu/ds_resolveuid/4e68ccf3e4334a3cae4e13d1c9e172dc
4. Ribau, Silva, Brito, and Martins. (2012). Analysis of four-stroke, Wankel, and microturbine based range extenders for electric vehicles. Energy Conversion and Management, 58, 120-133. Doi: https://doi.org/10.1016/j.enconman.2012.01.011
5. Morey, B., “Future Automotive Fuels and Energy”, SAE International, Warrendale, PN, 2013, ISBN 978-0-7680-7502-1, doi: 10.4271/T-128
6. EU Commission, “Commission Regulation (EU) NO. 1230/2012 ‘Implementing Regulation (EC) No 661/2009 of

the European Parliament and of the Council with regard to type-approval requirements for masses and dimensions of motor vehicles and their trailers and amending Directive 2007/46/EC of the European Parliament and of the Council,'" *Official Journal of the European Union* L 353/31 Vol 55 2012. Doi: http://data.europa.eu/eli/reg/2012/1230/oj

7. Monitoring of CO2 emissions from passenger cars – Regulation (EC) No. 443/2009. Last modified 11 June 2018. https://www.eea.europa.eu/ds_resolveuid/2635d82b91f043f1ab1b0e1d3b48813c
8. Turner, J., Blake, D., Moore, J., Burke, P. et al., "The Lotus Range Extender Engine," *SAE Int. J. Engines* 3(2):318-351, 2010, https://doi.org/10.4271/2010-01-2208.
9. Bassett, M., Thatcher, I., Bisordi, A., Hall, J. et al., "Design of a Dedicated Range Extender Engine," SAE Technical Paper 2011-01-0862, 2011, https://doi.org/10.4271/2011-01-0862.
10. Bassett, M., Hall, J., OudeNijeweme, D., Darkes, D. et al., "The Development of a Dedicated Range Extender Engine," SAE Technical Paper 2012-01-1002, 2012, https://doi.org/10.4271/2012-01-1002.
11. Jocsak, J., White, D., Armand, C., and Davis, R., "Development of the Combustion System for General Motors' High-Efficiency Range Extender Ecotec Small Gas Engine," *SAE Int. J. Engines* 8(4):1587-1601, 2015, https://doi.org/10.4271/2015-01-1272.
12. Technical Specifications for the BMW i3 (94Ah), valid from 07/2016. PDF. Accessed 24/09/2018. https://www.press.bmwgroup.com/global/article/attachment/T0259598EN/359587
13. Heywood, J. (1988). Internal combustion engine fundamentals (McGraw-Hill series in mechanical engineering). New York ; London: McGraw-Hill.
14. Trattner, A., Pertl, P., Schmidt, S., and Sato, T., "Novel Range Extender Concepts for 2025 with Regard to Small Engine Technologies," *SAE Int. J. Alt. Power.* 1(2):566-583, 2012, https://doi.org/10.4271/2011-32-0596.
15. Duret, P., Venturi, S., Sciarretta, A., Foxhall, N. et al., "Potential of a Production DI Two-Stroke Engine Adapted for Range Extender and Motorcycle Applications," SAE Technical Paper 2017-32-0082, 2017
16. Romani, L., Balduzzi, F., Ferrara, G., Bosi, L. et al., "Experimental Investigation on the Potentiality of a GDI System Applied to a Two-Stroke Engine: Analysis on Pollutant Emission and Fuel Consumption Reduction," SAE Technical Paper 2018-32-0047, 2018, https://doi.org/10.4271/2018-32-0047.
17. Achates Power, "Achates Power – Fundementally better engines" Published 2018. Accessed 26/10/18 https://www.achatespower.com
18. Redon, F., Kalebjian, C., Kessler, J., Rakovec, N. et al., "Meeting Stringent 2025 Emissions and Fuel Efficiency Regulations with an Opposed-Piston, Light-Duty Diesel Engine," SAE Technical Paper 2014-01-1187, 2014, https://doi.org/10.4271/2014-01-1187.
19. Naik, S., Redon, F., Regner, G., and Koszewnik, J., "Opposed-Piston 2-Stroke Multi-Cylinder Engine Dynamometer Demonstration," SAE Technical Paper 2015-26-0038, 2015, https://doi.org/10.4271/2015-26-0038.
20. Peden, M., Turner, M., Turner, J., and Bailey, N., "Comparison of 1-D Modelling Approaches for Wankel Engine Performance Simulation and Initial Study of the Direct Injection Limitations," SAE Technical Paper 2018-01-1452, 2018, https://doi.org/10.4271/2018-01-1452.
21. Vorraro, G., Turner, M., Turner, J.W.G., "Testing of a Modern Wankel Rotary Engine – Part I: Experimental Plan, Development of the Software Tools and Measurement Systems," SAE International Powertrains, Fuels and Lubricants Meeting (In Press)
22. Mazda rotary engine to return as EV range-extender – Published 2-Oct-2018. https://www.mazda-press.com/eu/news/2018/mazda-rotary-engine-to-return-as-ev-range-extender-/
23. Advanced Innovative Engineering (UK) Ltd. Published 2018, Accessed 26/10/2018. https://www.aieuk.com
24. Ansdale, R.F., (1969), "The Wankel RC Engine – Design and Performance" Iliffe Books Ltd – London
25. Capstone Turbine Corporation (CPST), published 2018, accessed 26/10/2018. https://www.capstoneturbine.com/
26. Gamma Technologies, "Engine and Vehicle Simulation" Published 2017, accessed 26/10/2018 https://www.gtisoft.com/
27. Motortrend BMW i3 Test – 0-60 mph 6.4 seconds, Braking is unmatched. Last modified Jan 2015. https://insideevs.com/motor-trend-bmw-i3-test-0-60-mph-6-4-seconds-braking-unmatched/
28. Tire Data Calculator accessed 24/09/2018 - http://paws.kettering.edu/~amazzei/tire_calculator.html
29. The new 2017 BMW i3 (94 Ah): More range paired to high-level dynamic performance. BMW Press Release – PDF. Accessed – 11/10/2018, published – 1/5/2016. https://www.press.bmwgroup.com/usa/article/attachment/T0259560EN_US/385774
30. PushEVS.com - Samsung SDI 94 Ah battery cell full specifications. Published 5/4/18. Accessed 11/10/2018 https://pushevs.com/2018/04/05/samsung-sdi-94-ah-battery-cell-full-specifications/
31. Jeong, J., Lee, W., Kim, N., Stutenberg, K. et al., "Control Analysis and Model Validation for BMW i3 Range Extender," SAE Technical Paper 2017-01-1152, 2017, https://doi.org/10.4271/2017-01-1152.
32. Kamguia Simeu, S. and Kim, N., "Standard Driving Cycles Comparison (IEA) and Impacts on the Ownership Cost," SAE Technical Paper 2018-01-0423, 2018, https://doi.org/10.4271/2018-01-0423.
33. Yamamoto (1971), "Rotary Engine", Toyo Kogyo Ltd – Japan
34. Real OEM, "BMW parts catalogue", accessed 1/9/2018 Undisclosed Internet Source

Contact Information

Matthew Turner

Department of Mechanical Engineering
University of Bath
Claverton Down
Bath BA2 7AY UK

m.turner@bath.ac.uk

Acknowledgements

Thanks to Innovate UK and Advanced Propulsion Centre UK for their support and funding for this research. Thanks also to the University of Bath's partners in the APC project; Westfield Cars, Advanced Innovative Engineering (UK) ltd., GEMS, and Saietta. Thanks also to Gamma Technologies for the use of their simulation platform GT-ISE.