Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

Collaborative Project

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Author(s):	**Cleef Thackwell (JLR), Matthew Crouch (JLR), Maximilian Wilhelm (JLR)**
Participants(s):	**Walter Vinciotti (PRI), Miguel Carrero (PRI)**
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V1.1	27.09.2019	Final release from JLR to PRI
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V1.3	03.10.2019	Final version for submission

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Abbreviations

4WD – 4 Wheel Drive

BEV – Battery Electric Vehicle

CAD – Computer Aided Design

DSPWM – Discrete Space vector Pulse Width Modulation

EDU – Electric Drive Unit

EPA – Environmental Protection Agency

FeSynRel – Ferrite assisted Synchronous Reluctance motor

HWFET – Highway Fuel Economy Cycle

IFPEN – IFP Energies Nouvelles

IM – Induction Motor

JLR – Jaguar Land Rover

MDL – Motor Design Ltd.

MOSFET – Metal-Oxide Semiconductor Field Effect Transistor

PMSM – Permanent Magnet Synchronous Motor

SiC – Silicon Carbide

SOC – State Of Charge

SVPWM – Space Vector Pulse Width Modulation

SynRel – Synchronous Reluctance

UAQ – Univeristy of l’Aquila

UDDS – Urban Dynamometer Driving Schedule

WLTP – Worldwide harmonized Light vehicle Test Procedure

1 Executive Summary

This report focusses on the integration of the 200kW high power electric drive units designed within the ReFreeDrive project in a Jaguar Land Rover (JLR) vehicle. The results are based on simulations that rely on datasets which have been provided by Motor Design Limited (MDL) in WP3, IFP Energies Nouvelles (IFPEN) and University of l'Aquila (UAQ) in WP4 and complemented by specific datasets related to mechanical and gearbox losses provided by JLR. As the gearbox development wasn't part of the ReFreeDrive project, JLR has provided a dataset for this specific subcomponent based on the assumed gear ratios and gearbox layout corresponding to the target vehicle with the boundary conditions described previously within WP2. Vehicle performance calculations are generated with a JLR-internal vehicle model. Efficiency calculations are generated by the workflow described in Figure 1.

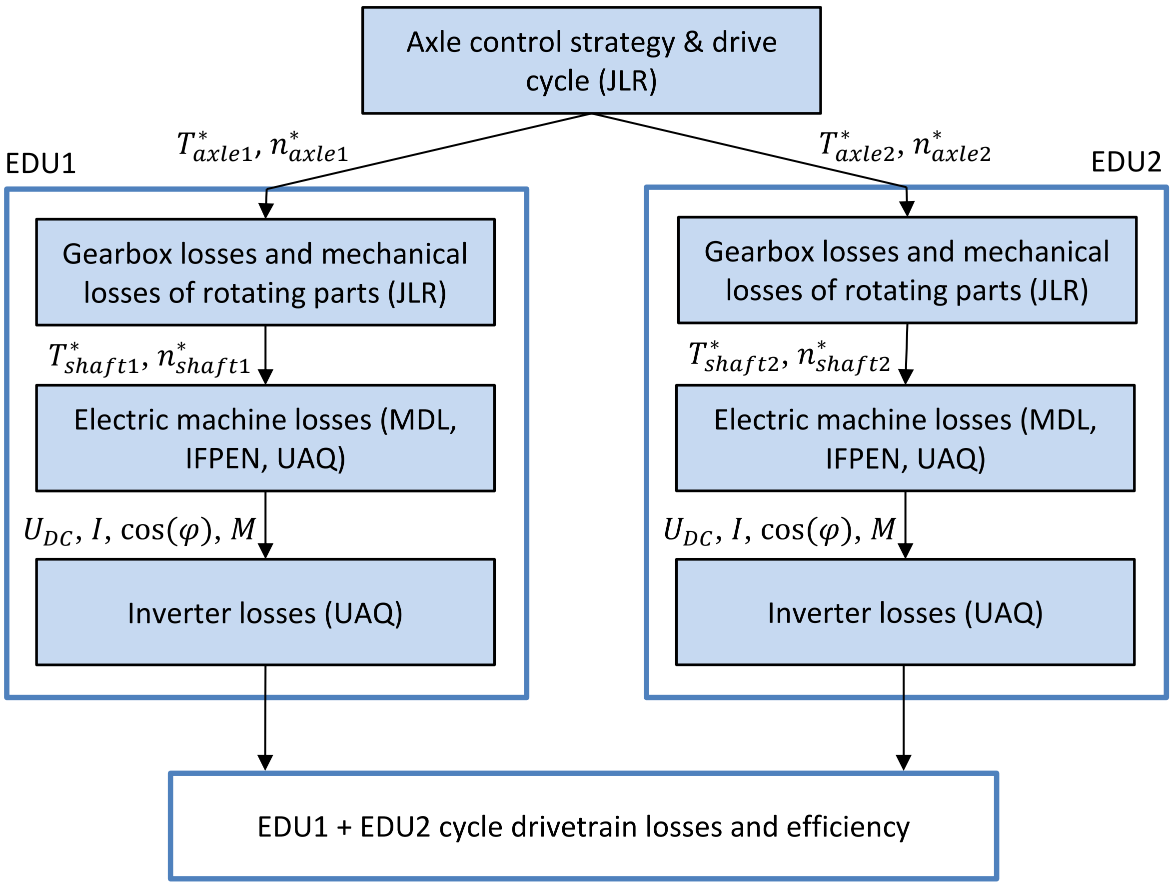

Figure 1: Workflow for generation of drivetrain losses over representative drive cycle and subsequent drive unit efficiency determination

The different outputs will highlight the performance of the three rare-earth free motor topologies at system level when used as dual-axle four Wheel Drive (4WD) propulsion system for high performance Battery Electric Vehicles (BEV) .

The results show that each type of motor technology has a different impact on the behavior of the inverter and the gearbox thus directly impacting the overall system. The ReFreeDrive motors integration potential is described and proven in section 2.1.

In terms of deliverable tracking, delivery month of D5.4 was M24 according to the ReFreeDrive proposal but delivery in M28 was mandatory in order to ensure all design data from the relevant partners was consistent and compliant with the JLR simulation processes. No deviations on content were mandatory to comply with the project proposal and the simulative aspect of the deliverable has been clearly defined previously (no 200kW motor vehicle integration within the project). D5.4 in general will help understand the high-level trade-offs between the different technologies and define a more robust exploitation plan and techno-economic assessment in WP8 as the powertrain efficiencies will directly impact battery cost for a given range.

2 Electric drive unit selection

All the sub-components within WP3, WP4 and WP5 have been designed to ensure compliance with the given vehicle architecture and to ensure the Electric Drive Unit (EDU) comprising the designed motor and inverter as well as an exemplary gearbox layout provided by JLR can be packaged on the front and rear axle of the vehicle without conflicting with the sub-frame. Details of each sub-component assembled within the electric drive unit are provided in the following sections.

2.1 Electric drive unit packaging

In order to avoid conflict with other components of the electric drivetrain and to ensure compatibility with the target vehicle, all the required dimensions of the ReFreeDrive electric drive unit (EDU) have been previously communicated by JLR within WP2. After carrying out the design work-packages WP3, WP4 and WP5, IFPEN and UAQ have generated a final Computer-Aided Design (CAD) layout of the drive unit. By integrating the final CAD into the available package space, JLR has confirmed the unit would not conflict with another drivetrain component and enough space is available to accommodate a two-stage gearbox suitable for the ReFreeDrive motor speed operation range (18,000 – 22,000 rpm). The next sections will focus on the sub-components, giving a short overview of the choice of technologies and their compatibility with a high-performance BEV powertrain.

2.2 Electric motor

Three variants of electric motors free from rare-earth materials have been designed to fit within the housing. A reminder of the motor specifications is listed in Table 1. The choice of motors includes an Induction Motor (IM), a Ferrite assisted Synchronous Reluctance motor (FeSynRel) and a pure Synchronous Reluctance motor (SynRel). All motors were designed to fit within the package defined in section 2.1. Due to different mechanical integrity restrictions, the three motor variants could not be designed for the same speed. The IM is able to withstand centrifugal forces up to 22,000 rpm +20%, the SynRel up to 18,000 rpm +20% and the FeSynRel up to 18,000 rpm +20%.

Table 1: Overview of electric motor properties designed within WP3 and WP4 with electrical boundary conditions at peak operation

Motor variant	IM	FeSynRel	SynRel
DC-link voltage	720 V	720 V	720 V
Max. modulation	0.98	0.98	0.98
Max. current	500 Arms	636 Arms	636 Arms
Required inv. kVA	430 kVA	550 kVA	550 kVA
Peak torque	400 Nm	470 Nm	415 Nm
Maximum speed	22,000 rpm	18,000 rpm	18,000 rpm
Gear ratio	14.90	12.19	12.19
Peak overall power	320 kW	250 kW	290 kW
Peak power @nmax	150 kW	90 kW	80 kW

Based on the availability of a single package envelope, the different motors have been designed with different peak currents i.e. different required inverter kVA-ratings in order to generate an output close to the target vehicle requirement. Therefore, while the SynRel and FeSynRel are using nearly the entire available power from the inverter with 636Arms, the IM only uses 500Arms, in part due the better power factor over the torque-speed envelope. A representation of the three motor topologies is pictured in Figure 2 (taken from WP3 & WP4):

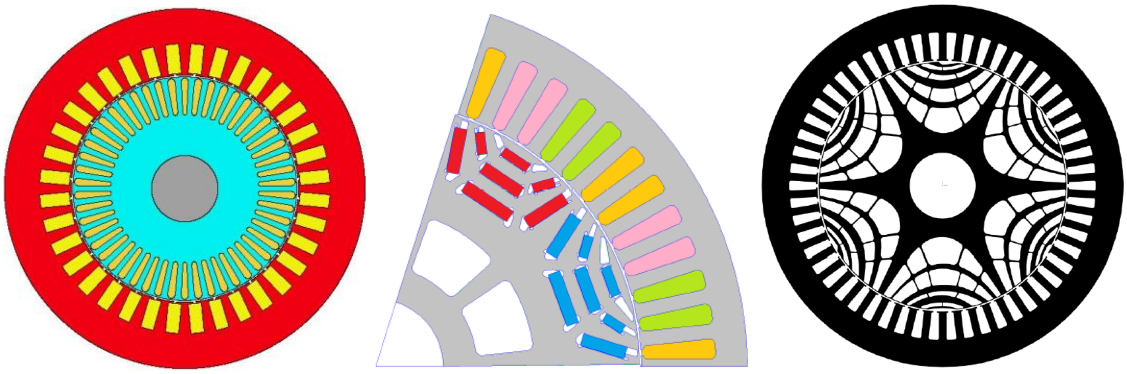

Figure 2: Cross-section of the three rare-earth free electric motors designed within WP3 & WP4: IM (left), FeSynRel (center) and SynRel (right)

The FeSynRel in particular has been designed to withstand irreversible demagnetisation during a transient active short circuit occurrence at a worst-case temperature of -40°C.

For efficiency calculations, the loss components taken into account in the motor maps include:

- For the IM: copper loss (stator & rotor), iron loss and additional stray load loss (provided by MDL – WP2)
- For the FeSynRel: copper loss, iron loss, magnet loss (provided by IFPEN – WP3)
- For the SynRel: copper loss, iron loss, stray load loss (provided by UAQ – WP3)

Note that all the mechanical loss components such as bearing and friction loss are included in the gearbox loss maps and not the motor loss maps. The motor maps provided in this report are purely consisting of electrical losses.

2.3 Inverter

The inverter has previously been designed by UAQ within WP5. All inverter data generated in this report has been provided by UAQ and is calculated based on the hardware used within the ReFreeDrive inverter. The inverter module is capable of withstanding currents up to 636Arms per phase.

Space Vector Pulse Width Modulation (SVPWM) will be implemented by the ReFreeDrive partners during component testing, however, while standard SVPWM-modulation yields a maximum modulation index of approximately 0.91, Discrete Space vector Pulse Width Modulation (DSPWM) would allow this to increase up to 0.98 by reducing the total number of switching events taking place over one electrical cycle and hence reducing any harmful dead-time effects and switching occurrences. Therefore, the maximum available modulation index is set to 0.98 for powertrain simulation purposes as it represents current state-of-the-art and would be used if implemented within the JLR target vehicle.

The DC-link voltage applied to the inverter has been set to 720V for this deliverable. In reality, the DC-link voltage fluctuates depending on the amount of energy drawn by the load and battery State Of Charge (SOC). For simplification purposes, it is assumed that the DC-link voltage remains constant. The value of 720V represents a voltage level close to full battery SOC and a load operation covering a standard certification drive cycle such as the Environmental Protection Agency (EPA) cycle or the Worldwide harmonized Light Vehicle Procedure (WLTP) cycle.

The peak currents of the different electric motors detailed in Table 1 can all be achieved with the ReFreeDrive inverter design.

The inverter loss maps take into account following loss components derived with a loss model and data from the 1,200V Silicon Carbide (SiC) Mitsubishi switches provided by UAQ and used within the project:

- Metal-Oxide Semiconductor Field Effect Transistor (MOSFET) switching losses
- MOSFET conduction losses
- Diode switching losses
- Diode conduction losses

The chosen switching frequency for all simulations is 20 kHz over the entire torque-speed envelope.

2.4 Gearbox (JLR proposal only)

In order to match the speed of the ReFreeDrive electric motor to the required vehicle axle speed, a single-ratio transmission is proposed. For this application, the package space considered allows implementation of a lay-shaft design which is the preferred JLR solution as it offers efficiency benefit over coaxial gearbox designs, for example, despite requiring more volume. The maximum ratio step achievable within a single-stage, commercially available helical gear-set lies between 4 and 5. Hence, given the maximum axle speed required for the target vehicle, an efficient two-stage spur gear would allow an upper limit of approximatively 25,000 rpm on the speed range of the motor, which is within range for all motor variants within ReFreeDrive. Anything above this speed would require a third gear stage which would not be acceptable in terms of cost, packaging and efficiency. The different gear ratios considered for the 3 variants of ReFreeDrive motors are:

- IM: 14.90
- FeSynRel: 12.19
- SynRel: 12.19

Based on JLR's experience with single-speed lay-shaft gear boxes, the loss estimation in the powertrain integration simulations is based on measured gearbox data up to 15,000 rpm which is extrapolated to higher rotational speeds for the purpose of adaptation to ReFreeDrive requirements. The loss maps take into account the contribution of following loss components:

- Bearings (all bearings incl. motor bearings)
- Seals
- Gears
- Oil churning

Any additional windage losses caused by the cooling of the rotor shaft is neglected here, as the cooling concept chosen within ReFreeDrive has not been investigated enough by JLR to assume correct windage loss values.

3 Electric drive unit integration (simulation)

3.1 Performance

The peak performance of the three rare-earth free motors delivered to JLR by MDL, IFPEN and UAQ under the boundary conditions specified in Table 1 are pictured in Figure 3 and **¡Error! No se encuentra el origen de la referencia.**. All motors presumably deliver enough torque to enable vehicle acceleration times from 0 to 100 kph below the target value of 4 seconds. The SynRel stator winding has been rewound with a decrease in the number of turns compared to what has previously been delivered within WP4 to account for a JLR update on the DC-link voltage which has dropped from 800V to 720V. The overall peak power values correspond to the peak output power mentioned in Table 1.

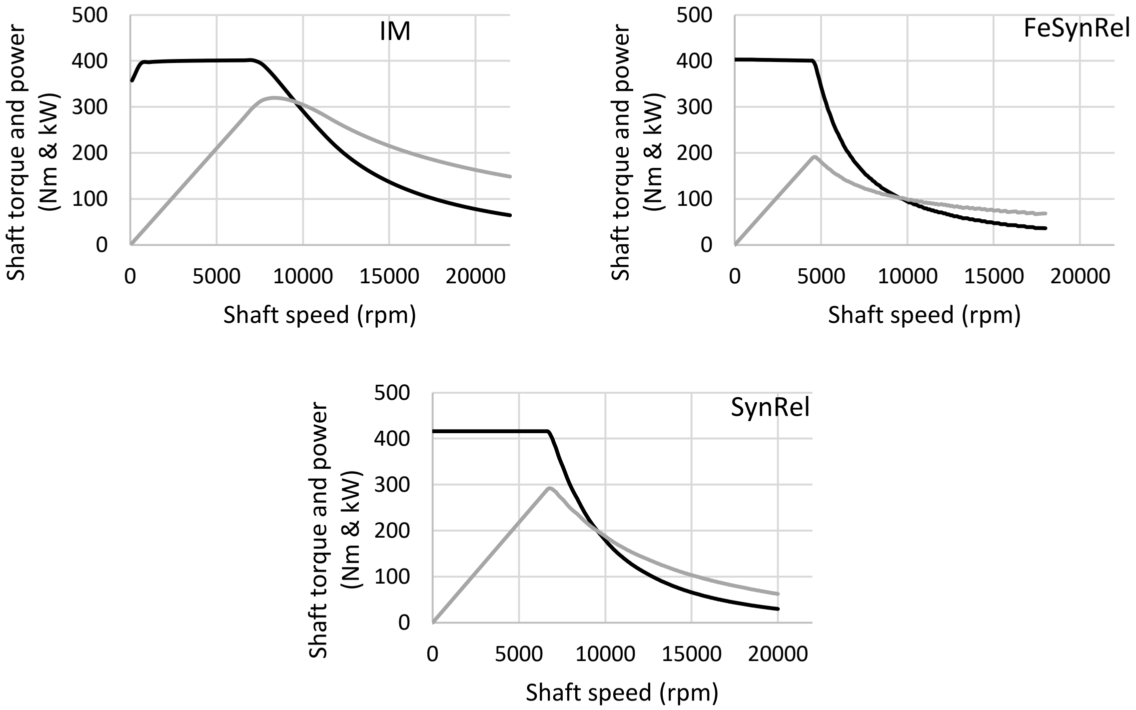

Figure 3: Peak motor shaft performance characteristics of the IM, the FeSynRel and the SynRel

3.2 *Efficiency*

The efficiency maps of each subcomponent have been calculated according to the loss datasets. Overall, the IM has a smaller 96%+ efficiency area owing to additional rotor cage losses and lower efficiency at low speeds due to the additional magnetising current required. The inverter efficiency maps all show efficiencies in excess 98% as the speed increases. Coupled to a FeSynRel or an IM, the inverter even achieves efficiencies in excess of 99% due to motors enabling operation under higher power factors than the SynRel. Most of the gearbox efficiency region lies around 97%, with the 98% region strongly dependant on the gear ration chosen i.e. the maximum operating speed of the motor. It can be seen that higher speed motors may decrease the gearbox efficiency for a given operating point. The subcomponent efficiency maps are detailed in Figure 4, Figure 5 and Figure 6.

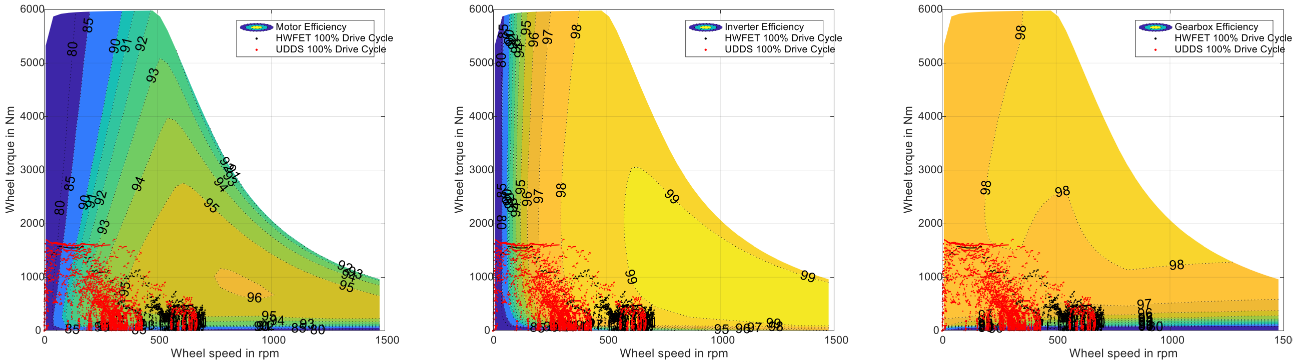

Figure 4: Efficiency map of each subcomponent within the IM EDU: motor (left), inverter (center) and gearbox (right)

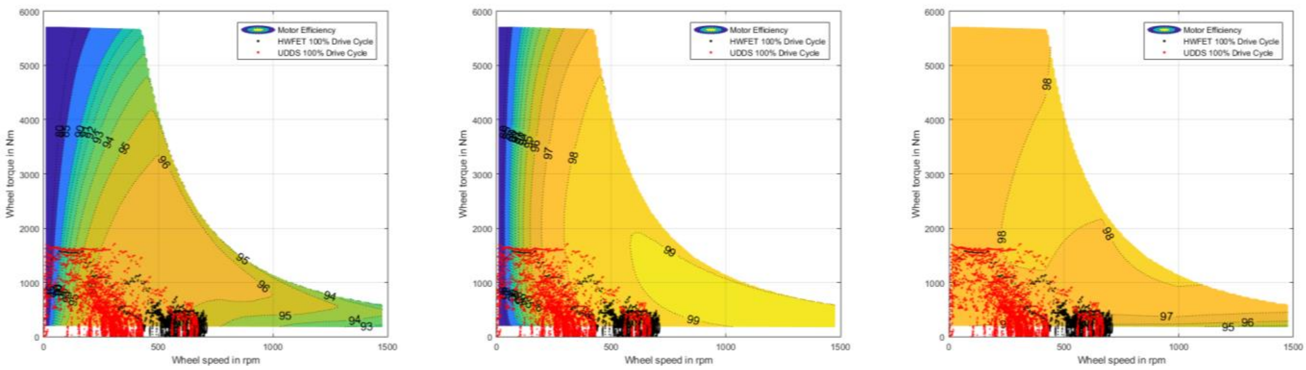

Figure 5: Efficiency map of each subcomponent within the FeSynRel EDU: motor (left), inverter (center) and gearbox (right)

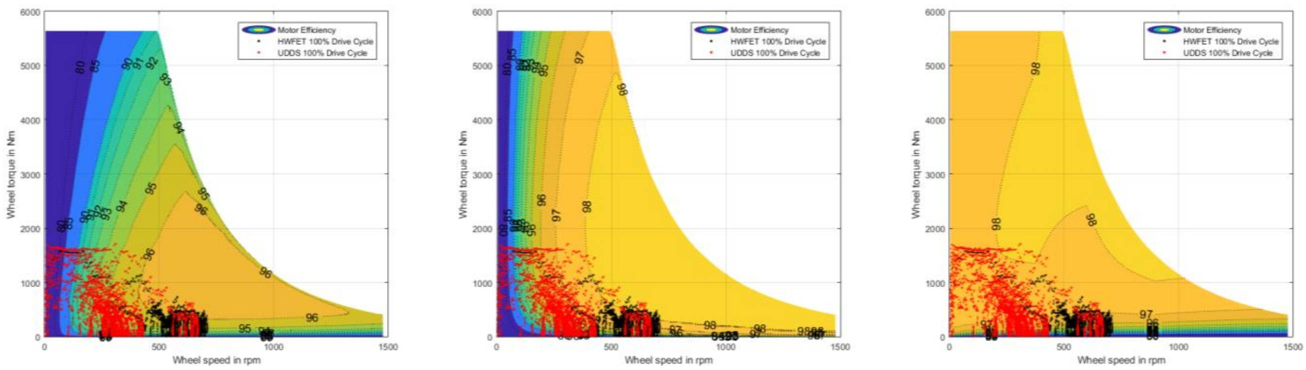

Figure 6: Efficiency map of each subcomponent within the SynRel EDU: motor (left), inverter (center) and gearbox (right)

4 Powertrain integration (simulation)

In this section, the separate loss maps will be combined together into a single EDU loss map. An appropriate EPA drive cycle, broken down into Urban Dynamometer Drive Schedule cycle (UDDS) and Highway Fuel Economy cycle (HWFET), will then be used to calculate the total EDU energy consumption over that cycle taking into account the target vehicle parameters and vehicle architecture from section 2 i.e. a 4WD vehicle comprising one EDU per axle. The total energy output in relation to the energy input after the cycle will yield a representative powertrain efficiency for a qualitative comparison between the rare-earth free motor variants within the EDU and how they affect the overall powertrain performance. In addition to the powertrain efficiency, the 0-100 kilometre per hour (kph) times (incl. launch accounted for with an additional 0.2s) and the 80-120 kph times will be simulated with the corresponding vehicle model.

4.1 Drive cycles and dual electric drive unit control strategies

The efficiency of the electric drive unit was calculated over the United States EPA drive cycle. This drive cycle is a weighted average of the low speed UDDS and the high speed Highway HWFET. These drive cycles are shown in Figure 7.

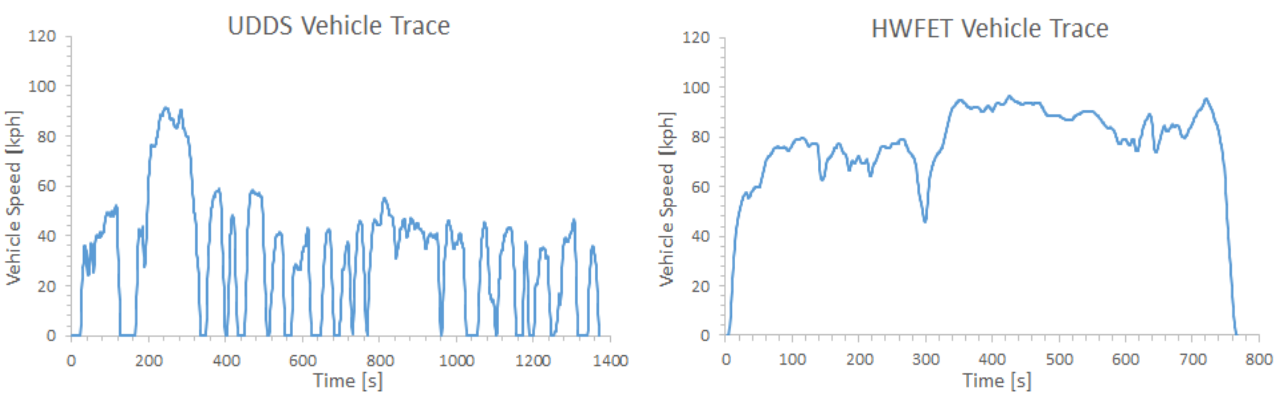

Figure 7: Vehicle trace for the low-speed (left) and high-speed (right) components of the EPA drive cycle

Due to the high peak performance capability of the EDU, the legislative drive cycles' torque and speed traces sit well within the peak performance envelope. These traces are plotted over the SynRel eMachine efficiency map in Figure 8. The left plot in Figure 8 shows the UDDS (red) and HWFET (black) traces at 50% load, utilising an equal torque split between the front and rear EDUs. The right plot shows the trace at 100% load on one EDU. The advantage of this torque split strategy is that the EDU is operating closer to its peak efficiency region while the other EDU is 'free-wheeling'. Unlike a Permanent Magnet Synchronous Motor (PMSM), the rare-earth free machines will not produce electromagnetic losses at no-load and negligible switching losses in the inverter.

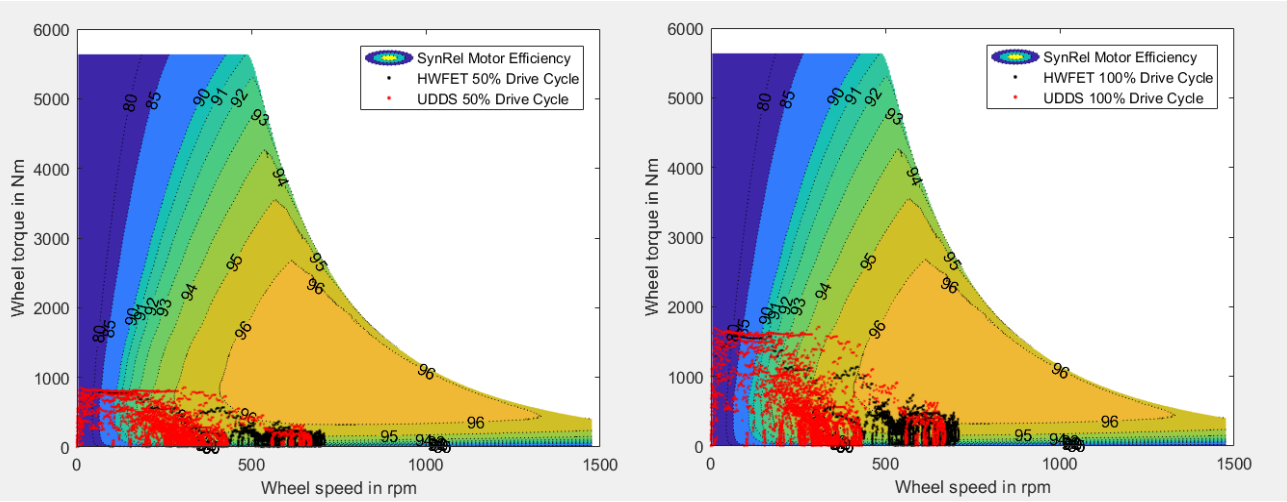

Figure 8: EPA drive cycle torque/speed traces plotted over the pure-SynRel eMachine efficiency map

In reality, torque split ratios never correspond to exactly 50/50 or 100/0 over the cycle. However, for simplification purposes of the simulation these ratios have been used to assess the best drive strategy to be considered for optimum efficiency.

4.2 *Performance*

Under the previously defined electrical boundary conditions and vehicle parameters, acceleration simulations have been run with one ReFreeDrive motor on each axle (mixed motor technologies such as an IM on the front axle and a FeSynRel on the rear axle won't be considered within this deliverable). The outputs of which are detailed in Table 2.

Table 2: Acceleration times of the three motor variants when assembled within an EDU and on each axle of the target vehicle

	IM	FeSynRel	SynRel
0-100 kph time	3.28 s	3.62 s	3.4 s
0-100 kph launch time	3.48 s	3.82 s	3.6 s
80-120 kph time	1.84 s	2.27 s	2.09 s
Maximum G-force	0.97 G	0.95 G	0.94 G

4.3 Efficiency

All rare-earth free EDU variants were run over the drive cycle described in section 4.1. The results are summarised in Table 3.

Table 3: Powertrain efficiencies for different motor variants with different axle split control strategies

Efficiency	50/50 torque distribution			0/100 torque distribution		
	HWFET	UDDS	EPA	HWFET	UDDS	EPA
IM	84.8 %	85.9 %	85.4 %	86.1 %	86.3 %	86.2 %
FeSynRel	88.4 %	88.6 %	88.5 %	88.7 %	89.0 %	88.9 %
SynRel	84.8 %	84.2 %	84.5 %	86.5 %	85.3 %	85.8 %

The gearbox losses stand in line with what would be expected as in general, considering a single wheel torque/speed operating point, the motor requiring the highest speed at that point will generate more friction loss than its counterpart, as friction loss tends to increase exponentially with speed. Therefore, the gearbox losses of the EDU with the induction motor (22,000 rpm) are higher than those of the SynRel (18,000 rpm) or the FeSynRel (18,000 rpm).

For the inverter, one can see a clear relationship between the required kilovolt-ampere (kVA) ratings from Table 1 and inverter loss. Indeed, the inverter loss will tend to be higher when more current is required from the load. As the SynRel is using the full inverter current capability of 636Arms to deliver its peak torque, the inverter subsequently operates in regions generating higher conduction losses, as these are proportional to approximately the square of the switching current (i.e. directly related to the motor phase current). In that sense, the SynRel generates the highest inverter loss, followed by the IM (which requires a peak current of 500Arms) and the FeSynRel.

The high electric motor loss generated by the SynRel is a result of the increased motor current required to drive a specific operating point compared to other motor types. As the torque created by this motor is solely made up of a reluctance component, more current is needed to drive a torque level of a motor in which a permanent magnet torque component is added to the reluctance torque component as for example in the ferrite assisted SynRel motor. The tendency of the SynRel to achieve lower power factors also adds to the fact that more copper loss will be generated in the stator windings, hence increasing the loss component over the drive cycle. Even though the SynRel generates more loss than the other variants, it is be the most cost-effective solution in terms of materials and manufacturing, although followed closely by the FeSynRel given current prices of ferrite magnets. This makes the choice of technology an actual trade-off between cost – peak performance – and efficiency that the system requirements shall decide upon.

In general, a 0/100 torque distribution between both axles (i.e. having the vehicle drive in 2wd mode over the cycle) will exhibit fewer overall losses than having both motors operate simultaneously. This can be achieved as the torque required over the cycle in a 0/100 torque split configuration lies well below the peak performance capability of the motor, as already described in section 4.1. With the motors developed within ReFreeDrive it is therefore advised to operate a single axle when the vehicle is cruising and use the second axle for higher torque demand and continuous high-speed operation to avoid derating on one EDU.

5 Conclusions

This report has given an overview of how the different motors and the inverter designed within the ReFreeDrive project would behave when integrated into the powertrain of the JLR target vehicle. It shows that the different motors all influence the behavior of the other components such as the inverter and the gearbox differently. Implementing the rare-earth free motors with a 0/100 torque split, or only operating in 4WD when necessary will benefit the system efficiency the most. Base on that torque split, powertrain efficiencies between 85.8 % and 88.7 % can be achieved.