Digital Displacement for Non-Passenger Rail (COF-IPS-03)

Final Report

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Executive Summary

This project studies the feasibility of using Digital Displacement hydraulics in non-passenger rail vehicle applications in order to reduce emissions from diesel powered vehicles and provide more efficient transfer of power from future alternative fuel and electric powered vehicles.

Artemis Intelligent Power is the global leader in Digital Displacement hydraulics – a fundamental innovation which offers a radical increase in efficiency and control for a wide range of applications. It can be delivered as a ‘straight swap’ for conventional hydraulic pumps or can be integrated to bring system-wide benefits including improved control and reduced fuel consumption. Artemis is working closely with majority owner Danfoss Power Solutions to further develop the core technology and bring a number of ground-breaking, sector-specific applications to the rail, off-highway and industrial markets.

The project was completed in two phases, an initial research phase looking at each application area in non-passenger rail, followed by a more in-depth study of three chosen applications. Each of the three applications included a packaging, fuel and carbon saving analysis and business case study:

- Development of a modular drive system concept for small locomotives and track maintenance vehicles – WP6
- Specification of a DD pump hydrostatic cooling system for a large locomotive -WP7
- Investigate pump swap opportunities for road-rail and track maintenance vehicles – WP8

The modular drive system concept for small locomotives and track maintenance vehicles could lead to fuel and carbon reduction around 30% dependant on specific vehicle and duty cycle. Further refinement of this estimate could be made with further input from OEMs and operators.

Specification of a DD pump hydrostatic cooling system for a large locomotive could lead to annual fuel savings corresponds to 2500 – 5000 litres per vehicle and 6 – 13 tonnes of CO2 emissions depending on duty cycle.

The pump swap opportunities for road-rail and track maintenance vehicles that we investigated indicated that fuel savings of 20% could lead to 7,200 litres fuel saved per vehicle per year, corresponding to CO2 savings of around 19 tonnes per year.
Abbreviations

BSFC  Brake-Specific Fuel Consumption
DD    Digital Displacement
DDP   Digital Displacement® Pump
DMU   Diesel Multiple Unit
DVT   Driving Van Trailer
KERS  Kinetic Energy Recovery System
MPV   Multi-Purpose Vehicle
NPV   Net Present Value
RPM   Revolutions Per Minute
TSU   Traction and Supply Unit
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1. Introduction

This report describes a feasibility study into the use of Digital Displacement technologies in non-passenger rail vehicles. The main aims are to reduce emissions from diesel powered vehicles and to provide more efficient transfer of power from future alternative fuel and electric powered vehicles.

Decarbonisation is a fundamental challenge facing all industries and is essential in order to tackle climate change. It means reducing and ultimately eliminating carbon dioxide emissions. In February 2018 the Minister for Rail challenged the rail industry to remove all diesel-only trains from the network by 2040 and to provide a vision for how it will decarbonise.

Although removing diesel-only trains from the network is the long-term goal, there is also a need for technologies that can reduce emissions in the short to medium term, for example, by recovering braking energy or improving transmission efficiency. It is also important to look at the overall picture – particularly in reducing CO2 emissions through modal shift from road freight haulage to rail, which is three times more energy efficient. Aligning with targets for delivery of a green electricity grid, wider electrification of the rail network remains the key enabler for decarbonising the rail network, however, interim solutions are required whilst electrification programmes are rolled out, and to address the decarbonisation challenge for sections of the rail network that may not be wholly electrified.

In addition to carbon dioxide emissions there is also a need to reduce emissions of other damaging exhaust gasses and particulates. In 2012, diesel locomotive emission requirements in Europe were set out in the EU Non-Road Mobile Machinery Directive 97 / 68 / EC Stage III B.

1.1 Digital Displacement Technology

In response to the low part-load efficiencies and limited controllability of conventional high-pressure, oil-hydraulic machines, Artemis Intelligent Power (‘Artemis’ hereafter) has developed a new kind of pump and motor. These Digital Displacement® (DD) machines can be used in many processes which were previously out of bounds to hydraulics and offer energy savings and performance improvements when swapped into most existing applications.
In DD machines, the flow-commutating and displacement-controlling mechanisms of ordinary hydraulic machines are replaced by solenoid-actuated valves that are triggered, as required, by embedded software running in a dedicated electronic controller.

As illustrated in Figure 1, Digital Displacement pumps (DDP), motors (DDM) and pump-motors (DDPM) have been built with powers ranging from tens of kilowatts for industrial and transport applications up to the multi-megawatt scale for a new class of offshore wind-turbine built with Artemis’s J-V partner company Mitsubishi Heavy Industries.

DD machines comprise one or more banks of radial cylinders. In the example of the twelve-cylinder pump, shown on the left of Figure 1, the twelve are deployed as three banks of four cylinders, whilst the design of the 36-cylinder, 3.5 MW motor shown on the right, comprises six banks of six cylinders. The radial format allows valves to be placed around the perimeter of the machine where there is space for generously sized fluid-galleries. Compared with traditional machines, which ‘breathe’ through commutator and port-plate passages near to the shaft, this cuts down the energy losses caused by flow-throttling. Figure 2 illustrates the fundamentals of a single bank of DD pump. In this case, the active low-pressure valve (LPV) and the passive high-pressure valve (HPV) are separate components. In more recent machines, the two functions are integrated into a single screw-in component. In the default idling state (left) the low-pressure valves (LPV) remain open to a surrounding low-pressure volume. If the LPV is closed at bottom-dead-centre (right), the fluid is pressurised and delivered through the high pressure valve (HPV).
If no contribution is required from an individual cylinder of a spinning DD pump or DD motor, its piston cyclically ‘breathes’ fluid in from the low-pressure source and returns it at the same pressure. These ‘idling’ strokes waste very little energy. A DD machine running at rated speed with all cylinders idling consumes less than 0.5% of the machine’s rated power.

Whenever an individual cylinder is needed to contribute actively to the output of the DD pump or a motor of which it is a part, the controller ‘enables’ it, just in time, by ‘firing’ the appropriate valve(s). Full pressurisation then takes place and energy is transferred from shaft to fluid or vice-versa. At any time, the machine can go from idle to full power, or to any fraction of it, within half of a shaft revolution – typically within 20ms.

The plots in Figure 3 compare the measured efficiency of a DD pump across its full load range along with that of a swash-plate pump of comparable flow capacity. It shows why, in many applications including rail, it may be worth examining the case for the replacement of conventional variable-displacement pumps by their DD equivalents.

Figure 3 - Comparative efficiency (hydraulic fluid power divided by mechanical shaft power) of a 96 cc/rev DD pump and swash-plate pump of the similar capacity. The test was conducted at 1500 rpm and a pressure of 200 bar.
DD has other benefits aside from efficiency. Direct digital control of the high-speed solenoids means that many control modes (flow control, pressure control etc.) are readily available and tuneable through software parameters. The technology is very modular and scalable and has been demonstrated at power levels up to 7MW. Like other hydraulic machines, DD machines are compact and robust. Connection of machines with pipes or flexible hoses, rather than driveshafts, gives good flexibility in packaging options. The machines are made primarily of steel with a long service life and are easily recyclable.

1.2 Energy storage

Accumulators

Accumulators can be used to store energy in a hydraulic system in the form of compressed nitrogen gas. They consist of a steel or composite vessel containing either a piston or a flexible bladder. On one side of the piston/bladder is nitrogen gas and the other side is filled with oil connected to the hydraulic system. When oil is pumped in the gas is compressed to store energy. The oil can subsequently be released back into the hydraulic system providing energy to the circuit as the gas expands. This can be used in a hybrid vehicle to store braking energy for example. Accumulators are good at handling high power levels but have a relatively low energy density. They are relatively cheap, have a long service life and are easily recyclable.

Flywheels

Flywheels have a larger energy density than accumulators but are more complex to integrate in a vehicle application. In the case of a hydraulic drive, the flywheel is coupled to a hydraulic pump-motor to store/return energy to the hydraulic system. Carbon fibre flywheels operating at extremely high speed in a vacuum theoretically offer the best energy density but require extreme precision and high levels of manufacturing technology, as well as a large reduction ratio to the motor. Another approach used in
some light rail vehicles, such as Parry People Mover, is a substantial steel flywheel which can be coupled directly to a hydraulic pump-motor without the need for a gearbox.

1.3 Potential Application Areas in Rail

DD pumps and motors can be combined to create a hydrostatic transmission suitable for a vehicle. DD motors operate equally well in either direction of rotation, which is especially important for rail vehicles. Hydraulic accumulators or a flywheel can be added to provide energy storage (e.g. for power smoothing or braking energy capture). A simple schematic of a hydraulic hybrid rail transmission is shown below.

Note that the hydrostatic transmission offers an infinitely variable gear ratio so that the engine can be operated at the optimum speed for the power required. Packaging is very flexible as the engine/pump is coupled to the motor via pipes or flexible hoses. There can be multiple motors or even multiple engine/pumps.

With DMU applications in mind, a version of this transmission was demonstrated by Artemis in 2018 in a converted DVT vehicle, tested at the Bo’ness and Kinneil Railway. It was powered by two JCB 129kW ecoMax engines meeting the latest emissions standards. The hydraulic motors were installed in a bogie. Test results were used to validate a simulation model, and this predicted a fuel saving of around 30% if applied to typical DMU duty cycles.

Figure 5 – Simplified schematic of hydraulic hybrid rail transmission.
DD can also be used to power the auxiliary systems on trains. In 2018 Artemis completed a project with ScotRail to demonstrate using a DD pump to replace the conventional pump powering the hotel loads in a Class 170 DMU. Results indicated a fuel saving of 6.7%. The project led to a follow-on project with Unipart Rail collaborating with Danfoss (who now have a majority share in Artemis) to trial a commercial version of the system. In this study we will investigate the use of DD for auxiliary drives in non-passenger rail vehicles. One area where hydraulics systems are already extensively used is on-track maintenance equipment. This includes rail-borne excavators, rail grinders, tamping machines, ballast cleaners etc. In general, any application which uses a conventional hydraulic pump would benefit from swapping to a DD pump to reduce energy consumption and carbon emissions.

Figure 6 – DVT vehicle equipped with Digital Displacement series hybrid transmission by Artemis in 2018.
Artemis Intelligent Power already has extensive experience in the field of off-road machinery thanks to its work on excavators, fork-lift trucks and wheel loaders. The excavator modification consisted of swapping a conventional swashplate pump with a DD pump. Both simulations and real testing were performed through this project. The image below shows the Artemis DD excavator under test.

1.4 Methodology

Based on Artemis prior knowledge and the scope of the RSSB competition, four main areas were initially identified to be studied in this project:

- Small locomotive transmissions

**Figure 7 - DD pump swap on a 16-tonne excavator.**

**Figure 8 – Tandem pump used for ScotRail Class 170 auxiliary drive project, installed on development rig for testing.**
In the first phase of the project, background research was carried out on each of these areas. This involved identifying and contacting industry stakeholders, attending trade shows and carrying out research online. The research aimed to cover both technical and commercial aspects. Apart from the four main study areas, we also aimed to be open-minded about other opportunities that presented themselves during this phase.

This research allowed us to conduct an initial analysis of each application area and the conclusions identified which areas were to be investigated in more detail in the second phase of the project.

Trade shows that we attended during the project included:

- Railtex on 14th May 2019. Held at the Birmingham NEC and exhibiting railway equipment, systems and services. It covered all four areas of research for non-passenger rail and has led to several good contacts which are covered in the relevant sections of this report.

- Railworx on 11th June 2019. An outdoor event as part of the larger Plantworx trade show. The visit was not very productive due to heavy rain, many Railworx stands didn’t set-up and there were only about a dozen to start with. It seems that Railworx is a new addition that is not yet established. We did make a couple of contacts which are covered in the relevant sections of this report.

- Rail Live on 19th June 2019. Held at Long Marston rail depot this is an on-site exhibition including live demonstrations. Fortunately, the weather conditions were favourable, and many good contacts were made especially in the track maintenance sector which are covered in this section of the report.

- EXPO Ferroviaria on 2nd October 2019. Held in Milan and exhibiting railway equipment, systems and services including track maintenance equipment and service providers and locomotive manufactures based in Europe. Several contacts were made which are covered in the relevant sections of this report.
Project plan

The Figure 9 below shows the overall project plan that was followed. The plan was regularly reviewed and revised to allow the work packages to be defined after the conclusions of the first phase of the project. The detailed work packages selected for phase two were:

WP6 – Modular powertrain study
WP7 – Locomotive auxiliary drive study
WP8 – Track equipment pump swap study

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Figure 9 – Project plan.
List of stakeholders, meetings and conferences

Artemis presented their work on DD non-passenger rail applications at the following meetings and conferences:

Table 1 - stakeholder meetings and conferences

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The table below shows a list of stakeholder organisations that were of interest and contacted during the project.

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Figure 10 – List of companies of interest.
2. Initial study

2.1 Small locomotive transmissions

Introduction

The nature of this application, as envisaged in the study, is one where wheelset loading is somewhat less than the maximum of 21.5 Tonnes permitted by Network Rail in the UK for RA7 i.e. light axle-load.

The immediately obvious vehicle that this would apply to is shunting locomotives. But there have also been developments in intermodal freight where lightweight, self-propelled, multiple units for freight have been employed in place of conventional heavy locomotives (as will be explored in a separate section). In both cases the driveline configuration is likely to be very similar. A driveline, which uses Digital Displacement hydrostatics, is very likely to be configured in the same way that Artemis opted to drive the DVT (see section 1.3). This is effectively a hydraulic analogue of the common EMU driveline, with an engine-driven pump replacing the generator and a hydraulic motor driving each wheelset via a reduction gear mounted on the wheelset’s axle.

Whilst it was felt that there was very limited technology development needed for this application, there were concerns over the commercial prospects.

Background research

The focus from the start was determining the potential market which could be addressed in conventional shunting engines. To this end we spoke to several manufacturers, both in the UK and in Europe.

Following conversations with shunter manufactures in the UK it became apparent that the number of new shunting locomotives being manufactured was very small. Our collaborator Andy Martlew of DRS informed us that shunting in the UK was largely carried out by time-expired mainline freight locomotives or old British Rail shunters, which very much limited the market for special-purpose small locos. Gmeinder Locomotiven make small numbers of shunters in Germany. Our conversation with their associated company revealed that they had applied their limited R&D budget toward developing battery powered locomotives. They expressed no interest, and had no resources, to explore diesel-hydraulic drivelines. New, low-cost, conventional shunters are available from Turkey, which severely damages the market for producers in high wage countries, eg. Tülomsas DH7000.

Shunting duties are also carried out by rail-road vehicles such as the Unimog road-railer BlueTec 6, which is capable of shunting 1,000 ton loads. This option provides lower cost and fuel use over locomotives as well as the versatility of skipping on and off the rails and onto the highway. This type of commercial vehicle modification will be discussed in more detail in Section 2.5.
How DD could be applied

The small locomotive driveline is envisaged to be a variant of the system Artemis created for the DMU driveline. This would use a commercial diesel engine with a power rating of 100 – 200kW and modern emission controls. It would drive an Artemis E-dyn96 pump, either single or tandem, depending on power rating. The flow from the pumps would be routed to a powered bogie which would have both wheelsets driven by hydraulic motors through a single stage reduction gear. The bogie architecture would be extremely similar to that of an EMU, with the significant difference being the substitution of a hydraulic motor for the electric equivalent. The high torque density of hydraulic machines, coupled with their inherent self-cooling (through the hydraulic fluid), allows the hydraulic machine to be both smaller and lighter for the same torque rating. Regenerative energy storage could be deployed but, given that many freight applications would make little use of this feature, it might be installed only on an as needed basis. The DD driveline is modular, so additional engines and driven wheelsets can be added as required for the desired traction levels needed in the vehicle.

Initial Analysis

Technology analysis

The Artemis modular driveline would package well in a conventional shunter layout, with the compact hydraulic motor easily fitting in next to the wheelset. The conventional single prime-mover could be replaced with several smaller and cheaper high production-volume engines, each mounted in a removable skid that could be slid in from the side, above the frame rails. The skid would be entirely self-contained with the engine driving an Artemis E-dyn96 pump—providing for all necessary functions, such as cooling, exhaust, etc. The skid would be bolted down to the chassis and have only fluid
connections for fuel supply, hydraulic hoses for the transmission and electrical signal and power cabling. This multi-engine approach has been successfully trialled (at least on a technical basis) in the US. Hydraulic transmissions make power sharing between multiple engines very much easier than it would be with mechanical drives. The stop/start nature of shunting operations might also make the use of regeneration attractive, again the system of gas accumulators that we developed for the DVT could be adopted.

The TRL level of the Artemis system for this application is relatively high. The engine-driven pumps will be released as a product very shortly by Danfoss, the majority owner of Artemis. The gas accumulators are well proven. Conventional hydraulic motors of sufficient rating are available from several manufacturers to drive the wheelsets.

A three-cylinder version of what will be a larger 12 cylinder, 500cc, Artemis Digital Displacement motor (needed to complete a full DD transmission) has just completed a test - running successfully for 620 hours at 1000RPM and 350 bar. This machine will need further development to reach production, but is already meeting performance and durability targets.

**Commercial analysis**

As related earlier, there is currently a very small market for shunting locomotives in the UK. The existing suppliers are not of sufficient size to undertake the development of a new product range with this form of driveline. The same would seem to apply to Europe. However, in future, the growth of intermodal hubs means that this market is likely to increase. It is difficult to tell if the market would be big enough to justify the cost of development of new shunter transmissions. Furthermore there may be stiff competition from road-rail solutions such as that shown in Figure 11.

**Environmental impact**

Because of limited commercial prospects, this aspect has not been explored in detail. It is expected that the fuel and carbon reduction inherent in the switch to DD regenerative drivelines would be in the range of 30%. Further, the adoption of clean modern diesel engines would make a significant impact on NOX and particulate emissions.

### 2.2 Light Intermodal Freight (additional area)

During a meeting with DRS, exploring the nature of freight transport in the UK, Andy Martlew stressed the increasing importance of intermodal freight to fill the network capacity arising from the demise of coal. Intermodal freight offers huge benefits in terms of lowering energy usage (1/3rd as compared to road hauled), reducing the volume of lorry traffic on trunk roads and significantly affecting the wear and tear on our highway system. Currently UK rail freight haulage is largely confined to main trunk routes. There should be opportunities to increase the rail freight volume through development of the intermodal network. As approximately 60% of the UK rail network
is not electrified, this spread of freight distribution will need to be powered by non-electric means. The fact that much of the non-electrified system is on the periphery of the network also means that it is likely that smaller trains would be needed to provide the appropriate intermodal services. Containerised freight is a global phenomenon, so this need might well be more widespread than just in the UK.

A potentially promising means of delivering this vision was first demonstrated by the Windhoff CargoSprinter of 1996 and the later, autonomous, Siemens CargoMover of 2002 (which was, in fact, a modified CargoSprinter). These used a driveline similar to the one commonly used in DMUs to propel themselves, as well as unpowered wagons, which carried the intermodal container freight. The type of driveline that Artemis developed for the DVT would have appropriate power and traction capabilities for this type of application on non-electrified rails.

The barrier to the wider adoption of the autonomous CargoMover wagons in the 2000s seems to have been the track control systems in place at that time which were not sophisticated enough to accommodate them. There appears to have been some adoption of these systems in closed networks on mineral extraction facilities. The opinion of DRS is that the network control system remains too limited for this to be adopted in the UK at this present time, particularly in mixed traffic. RSSB is aiming to improve the system’s flexibility and is starting a programme to study how to do this.

Following discussions with operators and manufacturers of this type of vehicle we learnt that in general the technology was successful, except when driving axles were not fully loaded due to wheel slip. Commercially it was a failure, with all but two sets subsequently converted to other on-track equipment uses. Andy Martlew similarly cautioned us on the difficulties of making an economic case for light freight trains like the CargoSprinter.
It is perhaps notable that the vehicle originally developed for this purpose has been in continuous production with over 200 units built to date. The two remaining CargoSprinter sets are in Australia, where they continue to carry freight on a daily basis. Their owner Colin Rees is on record as promoting higher capacity CargoSprinters in 2005. We have contacted Colin and expect to have further dialogue with him. He is still very keen on this technology. It could prove to be easier to introduce it outside of the UK.

2.3 Large locomotives transmissions

Introduction

The Artemis DMU DD transmission, described in Section 1.3 above, has the potential to be scaled up for higher power locomotives. Several engines could be used, with some engines shut down when power demand is low, reducing tick-over losses. In addition, due to an infinitely variable transmission (IVT) system, the engines speed would be optimally controlled for maximum operating efficiency. Some regenerative braking could also be included using accumulators. Auxiliary loads could be powered by energy recovered during braking. The challenge in this application is developing the DD transmission technology readiness level at the multi-MW scale required.

Background research

Our main source of research material in this area was from our collaborator in this project, DRS. They have provided us with information on large freight locomotive specifications for current and earlier generations of freight locomotives that have been popular in the UK over the last 50 years. DRS have also provided some information on more global trends in North America and Europe. Below is a brief description of some more recent UK large locomotives.

The Class 66 was built between 1998 and 2015, there are over 500 of these in the UK and it is the primary freight locomotive in the UK. They were manufactured by GM in the USA, though built in Canada. These vehicles became popular as they were very reliable and economical to operate. Their major weakness was an all DC system with drive to motors equal at all times. In the event of wheel slip, all axles must have their torque reduced. They are limited to 75MPH, particularly by the fact that the traction motors and gearboxes are attached to the axle (rather than bogie). DRS own 19 of these vehicles.

We had an opportunity to be shown around one of these vehicles during a tour of the DRS Carlisle depot. Engine to wheel efficiency is estimated to be 82% by operators. The industry will be looking to replace these vehicles in the next 10 to 20 years.
The Class 70 was built between 2008 and 2017. They were manufactured by GE in the USA. These vehicles were fitted with AC-AC drives which can regenerate braking energy to drive auxiliaries, however excess energy is not stored but dumped as heat through brake resistors. The AC-AC drive system allows individual axle torque control, providing a massive advance in traction technology. DRS have never operated the Class 70 locomotive.

The current UK fleet of Class 68 vehicle were built between 2013 and 2017. They were manufactured by Stadler Rail (previously Vossloh Rail). These vehicles fitted with four
AC-AC driven axles and blended rheostatic electropneumatic braking. 34 vehicles are operating in the UK by DRS.

The Class 88 is a dual mode version of the Class 68 also manufactured by Stadler in Spain. These units can operate either by overhead lines or by using an onboard diesel engine, the body shell and much of the equipment is the same as the Class 68.

Both the Class 68 and the Class 88 were designed for higher speed and lighter loads (lower torque) than previous locomotives due to change in typical loads, a move from heavy coal to lighter high value commercial goods. Vehicle components were selected for their compactness and lower weight. This also explains the move from 6 axles to 4 axles.

Vehicle layout

All but the most recent locomotives had the same general layout of drive train. A large diesel engine driving one or more electrical generators or a high voltage electrical system sitting amidships and large cooling radiators to one end of the power unit standing vertically and longitudinally in a parallel configuration such that they drew air in from the sides of the loco and expelled it upwards from a cavity between the two radiators. At the other end of the power unit, varying levels of control and power electronics cabinets are located. Fuel tanks and batteries are sited on the underside of the vehicle. The figure below shows the layout of a Class 88 dual mode locomotive.
Powertrain

The four or six axles of UK freight locomotives can be loaded at 21 tonnes each to comply with rail limits. A design friction coefficient of 0.37 is envisaged in dry conditions between wheel and rail. The means a maximum usable tractive force of 79 kN per axle, the wheels generally being 1100mm in diameter giving a maximum torque at the axle of 44 kNm. This effectively defines the requirements of the driveline. There is no value in having any more torque available beyond the limit of adhesion. The brake discs tend to be attached to either side of the wheel pans, which means that they are out of the way of the drive equipment in the centre of the vehicle.

Modern locomotives mount the traction motor to the bogie frame. The weight of the motor is carried entirely by the bogie frame, to which it is rigidly attached. The axle is driven through a flexible coupling at the final drive. The far end of the gearbox is suspended from the bogie frame to allow the gearbox to move relative to the bogie mounted drive motor. This arrangement reduces the un-sprung weight on the wheels and therefore reduces wear. For the Class 68, the gear ratio between electric motor and axle is 4.25:1.

Operations

Reliability and maintainability are very important. The early BR locomotives tended to make the engines and other components difficult to access, modern designs have all the
components mounted in detachable rafts, or modules that can be accessed easily for a quick swap.

Fuel cost is the freight operator’s second biggest cost - salaries being first. So, any reduction in fuel use will be seen in a very positive light as margins tend to be very tight. It is cheaper to run electric locomotives than diesel ones due to fuel costs.

Accelerating the vehicle up to speed as quickly as possible is very important to operations and achieving this is where a lot of the cost comes from. Two locomotives may run on one train set to achieve acceleration and top speed requirements.

It was surprising to learn that the aerodynamic resistance of intermodal trains can be severely impacted by the gaps between containers. This means that freight train locomotives are often running at full power throughout their journey.

How DD could be applied

The powertrain layout of a diesel-electric locomotive is very similar to that of the DD powertrain. In that in the simplest conversion the same engine would drive a large pump or series of pumps through a splitter gear box replacing the electric generator. The electric traction motors would be replaced by hydraulic motors, the final drive gear ratio would be lower than it is currently however, the package could be the same.

To take full advantage of a DD transmission and produce further carbon reduction, as well as reduced engine cost, there is the potential to make a hydraulic version of the Gen-set locomotive. The large diesel engine can be replaced with several smaller engines. Several engines could be used in one locomotive, with some engines shut down when power demand is low, reducing tick-over losses. In addition, due to an infinitely variable transmission (IVT) system, the engines speed would be optimally controlled for maximum operating efficiency. Smaller engines are more readily available at lower cost and see much more development and regulation to reduce emissions. The figure below shows the layout of a DD series hydraulic hybrid locomotive powertrain.
Further efficiencies can be achieved with the addition of accumulator bank for braking energy storage and regeneration. This energy can be made available for power boosting, engine off traction or auxiliary hydrostatic drive systems, fan drives etc.

**Alternative Fuels**

Note that the IC engine(s) powering the DD transmission can run off alternative lower-carbon fuels such as LPG, CNG, biodiesel or BioDME\(^1\).

**Initial Analysis**

**Technology analysis**

Artemis powertrain technology configuration options include parallel and series hybrid designs and power-split designs. For the parallel hybrid design the engine and hydraulic pump motor are connected in parallel to store and recover energy using accumulators. However, the duty cycle of freight locomotives doesn’t usually have enough stop-start to make this worthwhile. For the series hybrid design, as shown in Figure 18, the wheelsets are powered by hydraulic motors and several small engines are used to power DD pumps on each engine. Accumulator storage of hydraulic braking energy is also an option. The power-split design does not lend itself well to locomotive applications, as it uses a mechanical drive in parallel to the hydrostatic one which is very complex to install in multi powered bogie axle configurations.

Advantages of the DD series hybrid system include low cost, reduced weight (due to high power density of hydraulic machines), excellent controllability and improved efficiency. Components are made from readily available recyclable material.

Cost of development for a powertrain suitable for the large locomotive application would be significant, as currently the components needed for this scale of system are
not available. However, Artemis has developed and fully tested larger systems and therefore it is quite feasible to develop suitable pumps and motors.

**Commercial analysis**

- **Market size**
  - There are around 700 large diesel freight locomotives in the UK and the rail freight has grown by 3% since 1997 [source Rail Delivery group]. Network Rail have stated that over the next decade, they expect rail freight demand to grow by at least 30 per cent, the equivalent of 240 additional freight trains a day, and by as much as 140 per cent over the next 30 years. Growth is also seen in other comparable European counties, Germany, Italy and Netherlands. Around the world rail freight is dependent on infrastructure, however there is clearly a large market especially in North America.
  - Rail freight tonnage as a percent of total moved by country [referenced sources from Rail Freight Transport article Wikipedia]:
    - Russia: about 12% in 2016
    - Japan: 5% in 2017
    - USA: 40% in 2009
    - China: 8% in 2016
    - EU28: less than 20% of all "inland traffic" in 2014

- **Buying patterns**
  - As discussed above, in the UK there are over 500 Class 66 locomotives that are coming to an end of their lives in approximately ten years. With a typical lifespan of 30 years. There is also a challenge set by UK government to remove all diesel only trains by 2040.

- **Competition**
  - Current transmission types include dual-mode and electric traction. For non-electrified lines current competition includes: diesel-electric, battery-powered electric, hydrogen fuel electric.
  - A DD hydraulic transmission can offer:
    - Engine benefits:
      - Saves fuel
      - Downsizes engine
      - Improves productivity
    - Suitable for use with alternative fuels
- Battery-electric benefits:
  - Reduces battery capacity
  - Reduces electric machine rating
  - Reduces charging requirements

- Barriers to entry include cost of retrofitting, OEM development strategies already investing heavily in electric drives, readiness level of the DD technology at large locomotive scale.

- Alignment with overall strategy, Artemis would need to develop this scale of transmission and look for other applications that could benefit from this scale of system.

2.4 Auxiliary Drives

In addition to propelling the vehicle, engines on many rail vehicles also drive auxiliary loads. These can include cooling fans, alternators, compressors and work functions for track machinery. This section considers typical auxiliaries on freight locomotives.

Background research

Our research in this area comes mainly from two areas; discussions with DRS about the design of the Class 68 locomotive and our previous work with ScotRail on auxiliary drives for DMUs.

Diesel locomotives require cooling blowers and radiator fans to cool the engine, hydraulic oil, traction motors, alternator and inverters. This would also be the case for locomotives running off alternative fuels such as biodiesel or LNG.
The fans and blower can be driven either by electric motors or hydraulic motors. EMD & GE use electric fan drives as standard. Other builders vary in their choice of drive technology but generally hydrostatic drives are used to save weight and size. On the Class 68 a hydraulic system was chosen for reasons of lower mass and cost. The figure below shows the hydrostatic circuit to drive the radiator fans and blower on a Class 68 locomotive:

Figure 19 – Schematic of hydraulic system used to drive fans and blower on the Class 68.

- The pumps are fixed displacement, geared to run at about 1.5x engine speed.
- The blower pump handles approx. 65kW peak, and the fan pump handles approx. 75kW peak.
- The traction/alternator blower is driven by a fixed displacement motor, equipped with an electronically variable bypass valve to regulate the speed.
- Two radiator fans are driven by fixed displacement motors, connected in parallel. One of these has a bypass valve which regulates the speed of both by providing a parallel flow path.

Note that all flow through the bypass valves represents wasted energy in this system.

On the Class 68 the air compressor is driven electrically. It is rated at approx. 23kW producing around 2400 litres/min @ 10 Bar. It might be possible to drive this hydraulically instead.

The UK has 34 Class 68 locomotives. There are over 500 Class 66 vehicles in the UK – the UK’s primary locomotive. The industry is looking to replace these vehicles in the next 10 years.
How DD could be applied

In the simplest approach a DD pump could be fitted instead of a conventional pump. For example, in the Class 68 system described above each pump could be replaced by a DD pump which can vary its output flow. There would be no need to use bypass valves, saving energy. Flow losses in the hydraulic system would be reduced, saving further energy. The pump itself would be more efficient. The system could be designed to interface with the existing control signals so that significant changes to the vehicle control system are not needed.

A more ambitious approach could include using DD motors to drive the fans or other auxiliaries like the air compressor.

Initial Analysis

Technology analysis

Hydraulic auxiliary drives are already preferred by many manufacturers for reasons of weight, size and cost. Boosting the energy efficiency and improving control with DD could further improve the appeal of a hydraulic solution.

Suitable machines are already available from Danfoss at a high TRL, so the overall development cost is low.

Commercial analysis

Based on the Class 170 auxiliary drive project where we swapped a conventional pump with a DD pump, we would expect a payback period of 1-3 years.

Environmental impact

There is good potential to make a worthwhile saving in fuel consumption and carbon emissions. The technology is applicable to vehicles powered by some alternative fuels. Components are primarily made of steel and readily recyclable.

Other auxiliary drive applications - Active suspension

Liebherr has developed a hydraulic active suspension system for passenger trains. They currently use electrohydraulic actuators, however this system could be simplified and made cheaper by using DD auxiliary pumps. Liebherr claim that their active suspension can massively decrease damage to the trains and rails, while increasing passenger comfort and allowing trains to go faster. In freight train applications the suspension system could also move wagons up, down and sideways which could help with loading. However, even with the cost reductions that can be made by applying DD technology to this system it is unlikely that the system would be commercially feasible for freight trains.
2.5 Track Machinery

On-track equipment is used for a variety of construction and maintenance tasks on the railway. This includes tampers, grinders, stone blowers, cranes and excavators for example. Almost all of these already use hydraulic systems, making this an interesting application area for Digital Displacement.

Background research

Our initial research on track machinery involved attending several trade shows, contacting relevant companies and online research. Details of the trade shows attended and stakeholder contacts made are provided in section 1.4.

Our conclusion from the research was that there are two main types of on-track equipment:

- Road or off-road equipment which has been converted for rail by fitting rail wheels in addition to the standard wheels/tracks. These vehicles are typically hydrostatically propelled on the railway and may also have hydrostatic work functions. Examples include excavators, elevated work platforms and personnel carriers. Some examples are shown below.
Figure 21 – Deployable rail wheels (with hydrostatic propulsion) installed on a converted tracked excavator

Figure 22 – Road vehicle adapted for road-rail use by addition of rail wheels with hydrostatic propulsion

- Purpose-built machines for rail use only. These include tamping machines, stone blowers, rail grinders etc. They typically have hydrostatic propulsion and complex hydraulic work functions. Tampers in particular, have very powerful and sophisticated hydraulic systems as shown below.
We found that some rail-only vehicles are based on a common platform such as the modular system developed by Windhoff.

We also found, in discussions with Windhoff, that there is a trend to reduce noise and emissions in sensitive areas through use of electrification. We noted that battery powered hydraulic equipment places even greater demands for efficiency in the hydraulic system to prolong battery life and reduce cost.
On track plant is rather specialised and there is a relatively small fleet of a wide range of vehicle types. According to rail record there are 153 vehicles with head-codes, broken down as follows:

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</tr>
<tr>
<td>Miscellaneous</td>
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Note that this list excludes a lot of road-rail equipment.

**How DD could be applied**

Since a lot of track machinery already uses hydrostatic transmissions and work functions, introducing Digital Displacement technology is relatively easy. Simply replacing the existing hydraulic pump with a DD pump would improve efficiency and reduce carbon emissions. It would also bring advantages of improved control via software and improved productivity (more power available from the same engine). The benefit would be especially large in high power applications such as tampers and stone-blowers. Hydraulic energy storage using accumulators could be beneficial for tamping machines.

Evidence for the claims about efficiency and productivity improvement comes from Artemis work on a JCB excavator where we replaced the conventional pump with a DD pump. The simulations and tests performed on the modified excavator showed benefits in both productivity and fuel consumption. Two modes were implemented, an ‘efficiency mode’ which shown up to 21% fuel saving and productivity improvement of 10%, and a ‘productivity mode’ where 28% productivity improvement and 10% fuel saving were recorded in comparison to the traditional hydraulic transmission. Further improvements could be made considering an optimisation of the hydraulic circuit or by incorporating an energy recovery system.

The MPV (Multi Purpose Vehicle) developed by Windhoff is an interesting application. It could be equipped with a DD hydrostatic transmission, with auxiliary outputs from the pump available to support various work functions.

There is a trend towards bi-modal equipment which runs off either diesel or electric power. The output of two Digital Displacement pumps can be easily combined so one could be driven by an engine and the other by an electric motor.
For battery powered equipment energy consumption is very important. DD would improve energy consumption and reduce carbon emissions. It would increase the life of batteries and reduce their capital cost.

Initial Analysis

Technology analysis

The simplest approach to introducing DD to this market would be to directly swap the conventional pumps for DD pumps bringing improvements in energy efficiency and carbon emissions. Further refinement could bring improvements to productivity and controllability. Suitable DD machines will soon be available from Danfoss at a high TRL. DD pumps can provide multiple independent outputs per machine with software-selectable control modes, which can dramatically simplify system design.

DD motors could be combined with DD pumps to form a transmission to propel a vehicle. This would enable use of accumulators to store braking energy. Suitable motors are currently under development.

Tamping machines could be a good target vehicle for further analysis due to the high-power requirements and need for multiple hydraulic services. Tamping machines could benefit from KERS especially smaller ones where the tamping tools are not able to move forward/backward independently (the train needs to stop at every sleeper). The KERS also allows for faster acceleration which allows the machine to work faster and cause less disturbance to rail traffic. The MPV platforms developed by Windhoff could be another good application, with a DD transmission for propulsion and auxiliary outputs for work functions.

Commercial analysis

Based on Artemis experience in other applications, fuel savings of 20-40% could be expected. Typically, this leads to a payback period of 1-3 years depending on the duty cycle. The development cost of introducing DD to a vehicle which already has hydraulic pump(s) should be relatively small.

We expect that Danfoss’ introduction of DD pumps to the marketplace will gradually see them replace conventional pumps in many applications such as off-road machinery. This will subsequently benefit the road-rail industry whose products are based on off-road machinery.

The overall market size is quite small as these machines are rather specialised. As referenced above there are approximately 153 large track machinery vehicles in the UK.

A barrier to entry could be the perception that DD is a new and relatively untested technology (by comparison conventional hydraulics has not changed much in the last 50 years). In the on-track equipment sector reliability is seen as key, and fuel cost/carbon emissions are a secondary issue. Another barrier could be the need to gain certification for any product introduced to the rail industry. On the other had the on-track
equipment market fits well with the Danfoss/Artemis strategy to introduce DD pumps to
off-road applications.

Environmental impact
The percentage reduction in carbon emissions is likely to be quite high for some vehicle
types (estimated around 40% for tampers for example). However, the number of
vehicles is relatively low, limiting the overall benefit of any one class of vehicle.

2.6 Initial conclusions
The project set out to examine four possible application areas for Digital Displacement
hydraulics. Unsurprisingly, at the end of the first part of the programme, the outlook
changed somewhat. On the disappointing side, some of the applications have limited
commercial potential and so would not motivate the development of a specific product.
More encouragingly, some applications, such as the driving of compressors and cooling
fans, can benefit immediately from access to the Danfoss E-dyn96 which is planned for
commercial launch in the very near future. The E-dyn96 will immediately reduce fuel
use in both new and refurbished vehicles. More significantly, at least one of the
applications could enable very positive changes to lighter rail vehicles (for a variety of
purposes) in the UK, and elsewhere.

Shunting locomotives and on-track vehicles are made in such small numbers that
individually they do not present an attractive commercial opportunity. But, given that
they all could advantageously use a very similar modular drivetrain, there is an opening
to develop a drive system for the 10 Tonne axle which can be universally applied to a
range of different vehicles. The detailing of this modular drive system was taken
forward as part of the second phase of the programme.

The E-dyn96 machine can replace conventional hydraulic pumps in a variety of vehicles
and applications. It can drive cooling fans and compressors in heavy locomotives, giving
a significant reduction in parasitic power – perhaps around 5% of overall fuel
consumption. For auxiliary drives very little modification to the existing hydraulic system
will be necessary, making the benefit available not only for new build but also as a part
of a refurbishment. This application was taken forward as part of the second stage of the
study.

The E-dyn96 machine can also be adopted in equipment which has been primarily
designed for non-rail applications but fitted with road-rail drive wheels. Typically, these
vehicles have PTO drives on their transmissions onto which can be fitted an E-dyn96
pump. This pump can provide improved drive performance on the rails, while also
providing hydraulic power through multiple independent services for different vehicular
functions. Danfoss has relationships with many OEMs which build this type of off-road
equipment and so could hope to influence the purchasing choices of their buyers. This
application was also taken forward in the second phase of the project and look at ways to justify this initiative, by providing numbers and specifications.

Of the four initial application areas, large locomotives seem furthest away. On the technology front, the concept can be carried over from the DMU driveline, but the motors required to achieve the 44 kN.m torque at the wheel-set axle represent a significant developmental hurdle. The number of locomotives produced in the western world is not huge, so from a commercial point of view this doesn’t look to be an exciting prospect either. Neither of these are definitive barriers, so in the second phase of the project we mount a watching brief.

3. Modular powertrain study

3.1 Introduction

The driveline that Artemis developed for the DVT prototype (see section 1.3) has the potential to address several other markets as discussed in section 2.1. As well as the benefits already mentioned, the use of DD pumps and motors used in this powertrain design unlock performance improvements such as high-bandwidth control of wheel slip.

This driveline could be adapted for on-track machines such as tampers, rail laying equipment, ballast cleaners, multi-purpose service vehicles, etc. It would be particularly appropriate where vehicles have both transport and working modes – each at extreme ends of the speed range. It can also be used in small shunting locomotives, where maximum torque per wheelset is limited to 20 kN.m. The same driveline architecture can be up-scaled to match mainline freight locomotive torques, but some of the advantages start to reduce. For example, there are fewer inexpensive commercial diesel

Figure 25 - Australian variant of the Windhoff CargoSprinter container transporter originally imported by Colin Rees Transport.
engines at larger sizes – so the economic driver for this end of the propulsion system becomes less obvious. The Artemis pumps and motors could be made at multi-MW scale, but this introduces a new development hurdle. So, whilst large locomotive applications are possible, and might even be advantageous in the longer term, they are not the obvious place to start.

The same drive layout could be used in self-propelled freight wagons, such as those trialled by Windhoff and Siemens with the CargoSprinter and CargoMover concepts of the 2000s. While both of those attempts have failed to get established, it still seems a good way to reduce articulated lorry traffic whilst also making a four-times reduction in CO2 production on the basis of freight mass carried. It would appear that the reason for the lack of success for these initiatives has been fundamentally due to the economics of operating on a legacy driven rail network – where path costs have priced short trains off the rails. This is unfortunate as the freight equivalent of a DMU has the potential of carrying intermodal containers much closer to their destination, so reducing both road congestion and damage whilst also saving CO2.

In the UK there is a particular problem limiting the expansion of intermodal freight. The rail network, having been largely built during the Victorian era, suffers from restrictions in the loading gauge. Containers are, by definition, uniform in their dimensions, and uncomfortably tall relative to the earlier UK gauges. Fortunately, electrification has brought with it a concerted effort to increase the loading gauge, so as to permit intermodal freight over a much larger portion of the network. Even still, the outer sections of the network, which are not likely to be electrified, are least likely to be cleared for larger loading gauges and these are exactly the lines where non-electric propulsion will be needed.

The originator of the TruckTrain concept, Phil Mortimer, has developed a different economic model for short, high speed, freight trains which can inter-operate with passenger trains. Phil ran a trial of Windhoff multi-purpose vehicles from the south coast of the UK to Birmingham to test the TruckTrain concept and found that there was also at least one significant technical challenge to be resolved. The wheel loading in the single tractor unit was insufficient to prevent wheel slip. As a result, his concept has evolved to include self-propelled wagons.

In his view, these trains will be able to operate many hours per day, have extremely fast turn-around at their destination and be able to reliably participate in the logistics business – where deliveries can be timed and perishable goods, such as fresh food, can be carried. In his opinion, such an infrastructure would be beneficial in every sense, but is so far stymied by the legacy thinking of the network operator, which continues to make this approach uneconomic.

If this were to change, then the Artemis DVT driveline could be incorporated into self-propelled low bed wagons, such as the W H Davis SuperLow45. Variants of these
wagons, with operator cabs could be located at each end. The engines, which would be too tall to fit under the extremely low deck, could be fitted inside narrow transverse housings above the deck at each end of the wagons.

The TruckTrain concept is extremely promising and could also be employed in many locations across the world, particularly where there is no electrification. However, for the purposes of this study at least, it seems to be too steep a mountain to climb. There are simply too many obstacles to allow a realistic business case to be developed.

The same form of drive can be used in on-track equipment, where it could double its duties to power hydraulic work functions. When vehicle speeds are low, the bulk of the hydraulic capacity is freed up to service other functions – such as tampers. One feature of the DD machine is its ability to split its output and provide controlled power flows - to different loads at different pressures. The key challenge in developing this market is the diverse range of on-track machines, each with different functional demands. The relatively small number of each type also makes it difficult to justify developing bespoke products. However, it is envisaged that a universal modular drive system could be offered that would satisfy many of these applications.

3.2 How DD can be applied

The universal modular propel system has been developed with a 40 Tonne single self-propelled vehicle in mind. Its specification has arisen from consultation of existing on-track equipment performance metrics, from specification sheets provided by Colas Rail for the TSU and ballast regulator vehicles.

The system envisaged utilises commercial diesel engines in the 80 – 240 kW range, driving either single or tandem Danfoss DDP096 pumps (the commercial version of
Artemis E-dyn 96 pump) with outputs that can be separated, for work function duty at low propel speeds. Such machines generally are diesel-powered and so the only significant difference on this side of the drive would be the swapping out of conventional hydraulic machines and the integration of overall engine control to allow for more efficient – and quieter operation of the engine(s). DD wheel-motor machines would drive the wheel-sets, as in the DVT described in section 1.3. These would be sized to provide sufficient torque during the work mode and a high enough RPM rating to allow for maximum transport speed. A small hydraulic reservoir, flow switching manifold block and filter would additionally be required to complete the system. Regenerative energy storage could be deployed on an as needed basis. The DD driveline is modular, so additional engines and driven wheelsets can be added as required for the desired traction levels needed in the vehicle.

The approach for applying DD in this application can be considered in two phases, these could be completed as retrofit solutions or could be incorporated into new build development.

**Phase one – pump only swap**

This would be the most straightforward modification requiring minimal modification to the existing hydraulic system. The pumps supplying the propel part of the circuit are likely to be a closed-circuit type, where fluid flows continuously through the system from pump to motor and back with only case drain oil returning to the reservoir. This type of system is commonly used in vehicle drivetrain control. Direction and speed of vehicle movement is all done by controlling the direction and velocity of fluid in the pump. The DD pump is an open circuit design where the fluid flows through the system, then returns to the reservoir. Fresh fluid is then drawn from the reservoir and pumped through the system. In an open circuit system, the pump passes fluid through a directional valve which directs it to wheel motors as required. Low pressure returns flow back to the reservoir.

**Phase two - complete DD powertrain**

A complete DD powertrain with DD pumps powering DD wheel-motors driving the wheels as described in sections 1.3. Accumulator energy recovery would be an option. The following sections in this report discuss how a full DD system could replace the current hydraulic system for two examples of track maintenance vehicles.

### 3.3 On track machine applications

A presentation of the project work at the Freight Technical Committee meeting, RSSB, Derby and through contacts from the University of Huddersfield, discussions were started with Colas Rail who own and operate track maintenance machines. Colas Rail provided headline technical details of two vehicles they believed would be possible
applications for a powertrain packaging and fuel saving study. The Robel Traction and Supply Unit (TSU) and the Plasser and Theurer Ballast regulating machine (USP 5000 RT).

TSU
The TSU is used to pull and provide auxiliary power to track maintenance trains. The TSU also contains a maintenance and repair workshop along with a staff kitchen and welfare facilities. An example three-car train can include an open-bottomed mobile maintenance unit equipped with track maintenance tools fed by electrical, pneumatic and hydraulic power from the TSU and an intermediate wagon for transporting materials and equipment and fitted with a 2-tonne crane. The maximum speed of the vehicle is 96km/h.

The vehicle is driven hydrostatically with 4 driven axles powered by two Deutz 520 kW diesel engines and an auxiliary power unit (3rd engine) powered by a Deutz 160 kW diesel engine. Each of the main engines power 7 pumps via a distribution gearbox, 2 variable displacement pumps for propel, 2 variable displacement pumps for auxiliaries, 2 gear pumps and one vane pump also for auxiliaries. The power pack drives a further 4 pumps, 1 variable piston pump for low speed drive (0-1.25 mph), 1 gear pump for auxiliaries and 2 further variable displacement piston pumps for auxiliaries.

USP 5000 RT
A ballast regulating machine (also known as a Sweeper) is a track maintenance machine used to shape and distribute the gravel track ballast that supports the ties in rail tracks. The USP 5000 RT is powered by a 440kW diesel engine that drives four hydraulic pumps.

Figure 27 - Robel Traction and Supply Unit, TSU.
through a splitter gearbox (2 double variable displacement pumps through shafted and driving small gear pump for the propel functions, 1 double fixed displacement pump and one triple fixed displacement pump driving auxiliary functions). Three wheelsets are

powered by variable displacement motors through a two-speed gearbox. The maximum speed of the vehicle is 96km/h, brushing mode speed is 4 km/h and in ploughing mode is 18 km/h.

The figure below shows the estimated the possible layout of the USP 5000 RT hydraulic circuit.
Technology analysis

The Artemis modular driveline would package well in a conventional track maintenance machine layout, with the compact hydraulic motor easily fitting in next to the wheelset. The conventional large diesel single engine could be replaced with several smaller and cheaper high production-volume engines, each mounted in a removable skid that could be slid in from the side, above the frame rails. The skid would be entirely self-contained with the engine driving a DDP096 pump—providing for all necessary functions, such as cooling, exhaust, etc. The skid would be bolted down to the chassis and have only fluid connections for fuel supply, hydraulic hoses for the transmission and electrical signal and power cabling. This multi-engine approach has been adopted in the US and are known as ‘genset’ locomotives. Hydraulic transmissions make power sharing between multiple engines very much easier than it would be with mechanical drives. The stop/start nature of track maintenance operations might also make the use of regeneration attractive, again the system of gas accumulators that we developed for the DVT could be adopted.

The TRL level of the Artemis system for this application is relatively high. The engine driven pumps are available commercially from Danfoss, the majority owner of Artemis. The gas accumulators are well proven. Conventional hydraulic motors could be used to drive the wheelsets with some modifications to the hydraulic circuit to function with the open circuit DD pumps. However, a three-cylinder version of what will be a larger 18-cylinder, 720 cc, Artemis DD motor (needed to complete a full DD transmission) has recently completed initial performance tests - running successfully for 620 hours at 1000 RPM and 350 bar. This machine (M720) will need further development to reach production but is already meeting performance and durability targets.

The Artemis modular driveline is very flexible in how it can be packaged, as components are connected by pipes or hoses. This means that the engine mounted pumps can be located above or below the vehicle sole bar as required. Energy storage accumulated can also be located where space is available.

It is common for track maintenance vehicles to have their engines mounted above the sole bar, however the Artemis modular driveline could free up this space by locating a series of smaller engine driven pumps below the sole bar to replace the single large engine that would not package well in this location. The figure below shows one possible layout of an under solebar Artemis modular drivetrain.

The DD motor being developed for the Artemis modular power train is the M720. This is based on proven 40cc/cylinder size components, with 3 banks and 6 cylinders. Providing 4 kN of torque at shaft, 628 kW of power at 1500rpm. The figures below show the M720 machine design and overall size.
The M720 motor packages well in the bogie frame, see figure below. The weight of the motor can be carried entirely by the bogie frame, to which it is rigidly attached. The axle is driven through a flexible coupling at the final drive. The far end of the gearbox is suspended from the bogie frame to allow the gearbox to move relative to the bogie mounted drive motor. This arrangement reduces the un-sprung weight on the wheels and track degradation.

Figure 30 - Artemis modular drivetrain packaged below sole bar.

Figure 31 - M720 18x 40cc/cylinder DD motor – sizes in mm.
Environmental impact

It is expected that the fuel and carbon reduction inherent in the switch to DD regenerative drivelines would be in the range of 30%. Further, the adoption of clean modern diesel engines would make a significant impact on NO, and particulate emissions.

3.4 Large locomotive powertrain application

A component sizing study was completed to determine the size of a DD drivetrain required for the large freight locomotive market. The Class 68 vehicle was selected as a case study, as this is a modern diesel freight locomotive operating in the UK and could potentially replace the aging freight locomotive fleets, primarily composed of Class 66 type vehicles.

The layout of the powertrain would comprise of multiple engines driving DD pumps, connected to larger bogie mounted DD wheel-motors connected to the wheelsets through a final drive gearbox; similar in layout to the smaller modular drivetrain discussed in the previous section.

Technology analysis

The Class 68 diesel locomotive uses an electric transmission, with a 1.0 MW ABB electric motor on each of the four axles (used to transmit up to 600 kW). Developing up to 79kN
of tractive effort per axle. The Class 68 weighs approximately 85 tonnes, 21.5 tonnes per axle. Assuming a coefficient of friction of 0.37 between the rail and the wheels, the train would lose traction at 77kN tractive effort per axle, giving a total of 308 kN. This shows that large locomotives are designed to be able to reach their maximum tractive effort limit and therefore we need to size our transmission system to be able to develop maximum torque the vehicle can exert before the vehicle will slip. The motors also need to be able to rotate fast enough to allow the locomotive to reach its maximum speed, which is 160 km/hr for the class 68.

The TRL of the Artemis system at this scale is relatively low. The closest high TRL system is the 40cc/cylinder motor which currently has a maximum speed of 1500rpm and would require a final drive ratio of 2.5:1 to achieve a speed of 120 km/hr (faster than Class 66’s but slower than the Class 68). However, to achieve the specified tractive effort, 78 cylinders or 13 banks of 6 cylinders would be required at each axle, which is not a practical option.

Packaging study

Packaging this size of motor would be very challenging. One option is to install two up-stroked (43cc/cylinder) 6 bank machines per axle, one per wheel. Based on the design of the current 3-bank technology demonstrator machines available, we can assume that such a machine would be at least 750mm long. Clearance between the wheels is approximately 1350 mm and could allow fitting of a coupling, final drive and motor. More difficult is mounting two machines per axle, especially when considering the gearbox and motor bogie mounting points required.

Development of a higher speed and higher pressure machine could be another approach, 450 bar and maximum speed of 2250rpm could increase power to maintain the 40cc cylinder size, however, 6 banks per machine would still be required. Figure 34 below shows the difficulty of packaging this solution.

Figure 33 - Packaging two up-stroked (43cc/cylinder) 6 bank machines per axle, one per wheel.
Alternatively, a ring-cam machine configuration could provide a better solution for this application. This type of machine can deliver high torque in a more compact package. These types of machines are usually designed for low-speed, however the pistons could retract when they are not needed for efficiency by pressurising the crankcase, i.e. at higher speed when power is limited. The sketch in Figure 35 below shows the ring cam motors sized to provide the required torque and speed for this application. This could be explored further if the market demand was found. Cost of development for a powertrain suitable for the large locomotive application would be significant, as currently the components needed for this scale of system are not available. However, Artemis has developed and fully tested larger systems and therefore it is quite feasible to develop suitable pumps and motors. However, given the level of development of electric traction alternatives, it is difficult to imagine large freight locomotive powertrain demand.

![Figure 35 - Concept design of ring cam DD traction motors, showing approximate size of motors.](image)

**Environmental impact**

Because of level of development required to scale up the DD powertrain to large locomotive scale, this aspect has not been explored in detail. It is expected that the fuel and carbon reduction inherent in the switch to DD IVT drivelines would be in the range of 30%. Further, the adoption of clean modern diesel engines would make a significant impact on NOx and particulate emissions. The technology would also allow improved efficiency of spark ignition engines through the reduction of transient engine loading. These engines could run on CNG -which produces very little in the way of emissions other than CO₂.

**Proposal for further work**

Artemis could further develop the modular powertrain for suitable track machine applications. Discussions with owners, operators and manufactures have been initiated. We would require access to more technical detail on these vehicles and their duty cycles to allow us to carry out packing and fuel saving studies in more detail.
Tamping machines are a promising application due to the high-power requirements and need for multiple hydraulic services. Tamping machines could benefit from KERS especially smaller ones where the tamping tools are not able to move forward/backward independently (the train needs to stop at every sleeper). The KERS also allows for faster acceleration which allows the machine to work faster and cause less disturbance to rail traffic.

4. Class 68 Auxiliary Drive Study

4.1 Introduction

This section considers the hydrostatic cooling fan drive system of the Class 68 freight locomotive and the benefits that might be seen through a direct pump swap to two DDP096 pumps (Danfoss commercial E-dyn96 pumps). A brief description of the system is given in section 2.4. The current setup utilises fixed displacement pumps, and flow regulating valves to control the fan speed. The proposed Artemis circuit would take advantage of efficient, DD pumps, removing the high losses caused by unnecessarily high flow rates, and the use of restrictive control valves.

The aim is to initially demonstrate, through high level simulation, that this reconfiguration would yield significant savings. Discussions with DRS about collecting cooling system and vehicle data are currently ongoing. A set of real-world data will validate the results shown in this section.

4.2 How DD could be applied

In the simplest approach a DD pump could be fitted instead of a conventional pump. For example, in the Class 68 system described above, each pump could be replaced by a DD pump which can vary its output flow. There would be no need to use bypass valves, saving significant amounts of energy as a result. Flow losses in the hydraulic system would be reduced, producing further savings. The pump itself would be more efficient.

The system could be designed to interface with the existing control signals so that significant changes to the vehicle control system are not needed.

A more ambitious approach could include using DD pumps to drive other auxiliaries like the air compressor.

Hydraulic auxiliary drives are already preferred by many manufacturers for reasons of weight, size and cost. Boosting the energy efficiency and improving control with DD could further improve the appeal of a hydraulic solution.

Suitable DD pumps are already available commercially from Danfoss, so the overall development cost is low, involving mainly system integration.
4.3 Analysis

The power developed in the pumps must be high enough to overcome circuit losses and still drive the load at the desired operating point. Fluid friction and part geometry are responsible for pressure loss in hose lengths and elements (filters, valves, coolers), with further valve losses as a result of flow restriction. By directly controlling pump displacement, regulating valves become redundant, circumventing associated losses and circuit flow rate is reduced as necessary (pressure loss in hose lengths and fittings is proportional to flow rate squared).

Based on available information, conditions can be deduced for each throttle notch, including engine fuel consumption rate and engine speed. Artemis bench tested the pumps and motors currently used in the system to determine their displacements, and with a known gear ratio, pump output flow was calculated. With assumptions made about the operating characteristics of various components, and data available for the specific fuel consumption an accurate, backward facing system level simulation was achieved.

Pressure drops in hoses and fittings were determined using standard equations (e.g. Darcy-Weisbach equation) and hydraulic circuit dimensions provided by DRS. Some component parameters and pressure loss relations in circuit elements were based on parts assumed to perform similarly to the actual system components as more detailed information was not available.

The conventional circuit was assessed, and then so was the direct pump swap circuit, omitting the bypass valves, and appropriately modifying calculations to apply to the DD configuration. Each throttle notch condition was given 3 associated states; engine cooling fans running at 0%, 50%, and 100% (a simplifying assumption).

Figure 35 – Sankey diagram illustrating savings possible through implementation of DDP for the operating state of throttle notch 3, engine cooling fans at 50% speed.
Figure 36 illustrates one operating condition (throttle notch 3, engine cooling fans at 50% speed) for the conventional circuit. The Sankey diagram visually allows the flows of power through the cooling system to be displayed when operated conventionally and when operated by DD pumps. The left-hand edge of the diagram represents the power entering the system from the engine. The red areas display the power lost from the systems on the left-hand side from the conventional system and on the right-hand side from the DDP system. The green areas show the DDP system savings. The blue area shows the power used to drive the fans; note that the fan power required is proportional to the cube of the fan speed.

In the conventional circuit, the flow output from the pumps is much higher than required, and even though the flow bypasses the motors, it all still passes through hoses, fittings, and elements, generating large amounts of friction, and high power loss. The variable displacement DD pump reduces circuit flow rates, and thus eliminates most of this power loss. By restricting the flow path with valves, power is again lost due to a pressure differential between the valve ports, and all the excess flow not required by the load passing through the bypass valves. All this power is recoverable when DD pumps are employed, and the valves are removed. The DD pumps will, in this case, together require 9.25 kW less than the conventional pumps, and the pump losses are reduced by about 50%, bringing the overall savings to 10.2 kW for this particular operating point, which results in a required power input that is 82% lower for the DD circuit.

The cooling circuit with two E-dyn96 pumps would draw less power from the engine than the existing circuit, allowing for a reduction in fuel consumption for a given drive cycle. Using data for CAT C175-16 engine brake-specific fuel consumption at different speeds, and assumptions for fuel density and cost, the overall fuel and financial savings per hour are calculable. Duty cycle data was made available to Artemis by DRS for their fleet of Class 68 freight locomotives. However, the nature of the DRS Class 68 cargo meant that over a year, the vehicles can spend less than half their time operating. The potential for this application is best highlighted when applying the Class 68 duty cycle to Class 66 annual operational hours data that was made available, which is more representative of general freight vehicle applications. This gives a means for calculating expected annual fuel savings through employment of a DD cooling circuit for general UK freight vehicle operation. Using the example in Figure 36, an hourly saving of £1.06 can be predicted at current prices. This happens to also be approximately the median value for all 27 states considered. Figure 37 below shows a collapsed view of the simulation output calculating fuel savings for each operating state and estimates annual fuel savings for the 3 fan states considered.

The top half of Figure 37 displays the power losses in the initial circuit and the Artemis DD pump circuit to determine the power savings expected in the areas discussed, and the corresponding annual savings for a 7000 operating hours per year, using the fuel
consumption and kilowatt savings. Each state has an hourly and annual saving, which represent the predicted savings for a vehicle spending 100% of its time in this state. The bottom half of the figure applies the Class 68 duty cycle data to the annual savings (a weighted average) and predicts an overall annual saving. It also shows the range of expected hourly savings for the three ICE cooling fan operating points.

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<td>Losses in components (kW)</td>
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<td>0.52</td>
<td>8.92</td>
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<td>9.69</td>
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<td>Sub total (kW)</td>
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<tr>
<td>Power saving (kW)</td>
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<td>0.64</td>
<td>6.52</td>
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<td>Percentage reduction in inlet power</td>
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<td>0.75</td>
<td>5.09</td>
<td>0.97</td>
<td>6.12</td>
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<tr>
<td>Annual saving (kW)</td>
<td>1705.7</td>
<td>74052.5</td>
<td>4498.7</td>
<td>45695.5</td>
<td>5312.6</td>
<td>81042.9</td>
</tr>
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<td>Fuel consumption (g/kWh)</td>
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<td>185.14</td>
<td>63.84</td>
<td>185.14</td>
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<td>£ 8.03</td>
<td>£ 14.47</td>
<td>£ 8.05</td>
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</tr>
<tr>
<td>Exhaust</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>litres of fuel</td>
<td>130.88</td>
<td>19469.20</td>
<td>345.19</td>
<td>10102.34</td>
<td>407.64</td>
<td>18233.88</td>
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<tr>
<td>Financial savings (£)</td>
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<td>£ 9981.52</td>
<td>£ 207.11</td>
<td>£ 6497.00</td>
<td>£ 264.58</td>
<td>£ 10960.95</td>
</tr>
</tbody>
</table>

| Operating Hours / yr | 7000.00 |
| Fuel Density (g/L) | 832 |
| Fuel Cost (£/L) | £ 0.60 |

| Annual Savings Fan 100% | £1,860.33 | 3100.6 L | 8.19 |
| Annual Savings Fan 50% | £3,016.24 | 5027.1 L | 13.27 |
| Annual Savings Fan 0% | £2,054.20 | 3423.7 L | 9.04 |

| Hourly Savings Fan 100% | £0.01 to £1.81 | 3.81% to 13.71% |
| Hourly Savings Fan 50% | £0.03 to £2.05 | 17.24% to 56.5% |
| Hourly Savings Fan 0% | £0.03 to £1.47 | 11.38% to 68.03% |

Figure 36 – A collapsed view of savings per operating state.

With the current set of data, hourly savings of approximately £1 are expected, though with a less time spent inactive or idling, this could easily be increased to approach £2 per hour. Equally the carbon savings will be increased in a similar manner.

The annual savings in idle states are modest when compared to those with higher power requirements. The mean annual operational hours for the Class 66 vehicles considered was around 5000 hours, though it is not unreasonable to look towards the higher end of vehicle use – almost half of the vehicles looked at showed 5500 – 7000 hours a year. Considering these cases, the annual savings are expected to be between £1500 - £3000 dependent on the duty cycle, which corresponds to 2500 – 5000 litres of fuel, and 6 – 13 tonnes of carbon dioxide emissions. If all freight diesel freight locomotives in the UK were to adopt the technology savings of around 7000 tonnes of carbon could be made (an average of the annual saving figures for 100, 50 and 0% fan use, 10 tonnes of CO2 x
700 vehicles). The technology is also applicable to passenger DMUs and Artemis has found that a saving of nearly 10,000 litres of fuel per vehicle per year can be made.

Figure 38 below graphically represents the results in Figure 37. What is made clear is how much the savings would improve as the vehicles spend more time in higher power states.

![Figure 38 - Potential increase in annual savings for higher power duty cycles at ICE fan speeds of 0%, 50%, 100%.](image)

Artemis is working with DRS to establish a data collection plan that will validate these results and remove the remaining assumptions. The potential exists for annual savings or around £10,000 for demanding duty cycles, for example, when more time is spent at a higher notch level. For the current UK rail system freight vehicles spend a vast majority of their time in idle, conceivably waiting for track to become available. A rail system that allows higher power duty cycles, will open the door to much larger savings – other countries (Canada, for example) prioritise freight vehicles. Figure 39 illustrates the considerable amount (about two thirds the total) of time UK freight vehicles spend either off or idling, even for the highest operational hours provided.
Calculation assumptions

As previously mentioned, assuming operating conditions with engine cooling fans at 0%, 50% and 100% speed, is a simplification. Their speed is continuously variable and an accurate duty cycle of their operation would require logging fan data over an extended period or developing a detailed model of the control system. A plan to collect a full set of data is in progress with DRS and outlined in section 0.

Also, the rotational inertia of the fans is unknown, but if the system is assumed to be operating at steady state, the acceleration of this load can be ignored, and the pressure drop across the motor at various speeds depends only on the motor.

The assumptions still present in this analysis leave the results open to some change. However, cooperation with DRS has allowed for the refinement of calculations, and as many assumptions as possible have been eliminated.

4.4 Packaging study

As a direct pump swap, the proposed reconfiguration is straightforward. The size of the DD pumps is not so large that the vehicle interior should need any modification, and other associated changes primarily involve the removal of valves and connecting hoses. The E-dyn96 pump is shorter than the current pumps, but the body is wider. As seen in Figure 40, the size difference poses no issue for the ICE cooling pump, however the
blower pump is in an enclosed space, and so fitting the DD pump would require a standoff from the gearbox to allow the pump to clear the surrounding obstructions.

Figure 39 - Left: Blower Pump. Right: ICE Cooling Pump.

Fall back mode

As noted previously, the nature of the DD pumps means that a loss of electrical power, normally stops the machine from pumping. This conflicts with the current default response, ensuring that in the event of signal failure or a broken cable, the hydraulic motors are driven at full speed to provide emergency cooling. If the DD system is to have this same default, a separate backup power supply may be necessary to ensure the pump runs at full displacement in the event of a failure. Alternatively, Artemis are developing a valve modification which defaults the pump to an emergency pumping mode upon loss of power, rather than defaulting to idling. This system is currently being developed for other applications that also require this mode of operation.

4.5 Environmental impact

Burning a litre of diesel produces around 2.62 kgs of carbon dioxide, so the annual fuel savings calculated would correspond to annual CO2 savings for the vehicle life. Using the available duty cycle data, an annual emissions reduction of 5 to 15 tonnes of CO2 per vehicle could be expected, though with a more demanding duty cycle this could increase to perhaps 30 or 35 tonnes. The technology could be applied for new build but also to retrofit existing vehicles which have significant remaining life.
4.6 Business Case

Benefit Cost Analysis (BCA)

In this section, we present the benefit cost analysis (BCA) of Artemis’s DD pumps as a cost effective and sustainable innovative technology to make significant performance and reliability improvements in the rail freight sector in the UK. The main objectives of the BCA are to examine in monetary terms the benefits and costs of DD technology applications for non-passenger rail.

In this progress report, we focus the study and the BCA on the retrofitting of DD pumps to replace existing conventional auxiliary drive pumps on Class 68 locomotives. However, several vehicles in Europe use hydrostatic drives for the auxiliary system (due to the space/weight benefit). The BCA will consider the vehicle’s expected remaining service life and explore how various scenarios for refitting these locomotives with DD pumps will impact on operational efficiency, in particular fuel consumption, and reduction in carbon emissions.

The BCA will provide a detailed financial analysis using the payback period and net present value (NPV) techniques to determine the short and long term viability of swapping existing auxiliary pump systems with DD variants. The payback period measures an investment worth in a short time span, whereas the NPV appraises an investment over its entire estimated life and sums up the streams of future costs and benefits to the same base date by converting them to present values. We use an expected service life of 30 years for each Class 68 locomotive for discounting the cash flows, thus covering both the UK Government rail decarbonisation targets of 2030 and 2040. As the locomotives have already been in use, the 30-year analysis period is adjusted for an average of 5 years, giving a remaining service period of 25 years for calculating the NPV. Thus, 2020 is the start year and to represents the base date for calculating the NPV.

As shown in the NPV layout Figure 41 below, the BCA is structured around the reduction of emissions and fuel consumption as these are the major benefits and the most directly measurable from the DD systems. The costs include initial outlay, general operating costs (e.g. fuel consumption) and regular maintenance costs (e.g. labour and small part replacement costs). The BCA is carried out by estimating annualised future cash flows in real terms (i.e. costs and benefits at a common price level to eliminate the impact of general inflation) of the DD pump swap, over the useful life of the locomotive and converting those cash flows into present values using the recommended real discount rate of 3.5%* for the proposed DD pump swap project. These discounted present values are then totalled in order to calculate a net total benefit of the project, i.e. its NPV. Given the long time horizon based on the expected useful life of a Class 68 locomotive, the payback period is expressed as the number of years it would take to recoup the investment in the DD pump system and is calculated for each overhaul cycle when a pump renewal is required.
Figure 40 - NPV layout for business case analysis.

### Net Present Value Analysis

#### Artemis DD technology application: Locomotive Auxiliary Drive

| Period (in years) | Year | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| **Costs**        |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| **A.**           |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1 Capital costs  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Pump (i.e. cost of the unit to the loco-operator) | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| vs. Cost of DD pump / Artemis selling | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Differential cost | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Installation cost of DD pumps | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| **B.** Expected benefits |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1 Fuel cost savings | Current fuel cost | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| vs. Fuel cost with DD pump | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Differential cost | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| **Total Benefits** | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |

#### Discounted Cash Flow Analysis

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<td>Discount factor</td>
<td>1 0.97 0.93 0.90 0.87 0.84 0.81 0.79 0.77 0.74 0.71 0.69 0.66 0.64 0.61 0.59 0.57 0.54 0.52 0.50 0.49 0.47 0.45 0.44 0.42 0.41</td>
</tr>
<tr>
<td>Present Values</td>
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</tbody>
</table>

**NPV @ 3.5%** 0
Details of the final analysis results are not shown in this report for confidentiality reasons, however, the results from this work were encouraging showing a potential payback period of 3-4 years for the 50% fan load example duty cycle shown in Figure 37. *The 3.5% is the Social Time Preference Rate (STPR) recommended in the UK for public sector and long term projects such as rail investment projects[1-4]. The 3.5% discount rate in real terms is considered as the reference parameter for the real opportunity cost of capital in the long term for this type of project.

Market

This initial analysis, based on the UK rail freight market, will help promote new markets for more efficient locomotives through sustainable innovative technology in the rest of Europe and their uptake around the world. Rail freight in general is in need of finding ways to address existing operational and system weaknesses, achieve better energy savings and greater carbon emission reductions. Moreover, as freight by road is less efficient and costlier than by rail, in the longer term, improving the efficiency of freight locomotives would help achieve much wider economic and other benefits such as road decongestion, reducing HGV emissions as more freight is transferred to rail. As HGV operators in the UK and elsewhere lose business to rail freight, they would be forced to improve load utilisation of their vehicles further and, consequently, the reduction of empty HGVs on the road network will result in additional decongestion and reduction of carbon emissions. There will also be a significant reduction in infrastructure maintenance cost if HGV traffic is reduced as road life is a function of the axle load. An NVF Committee Vehicles and Transports report suggest that this is to the 4th power 8.

By demonstrating that worthwhile gains can be made in reducing the carbon emissions of freight locomotives, and that these can be realised without a significant financial cost, it is envisaged that existing relationships with vehicle manufacturers can be leveraged to explore how DD technology can be deployed more widely to support the decarbonisation of the railways.

At the time of writing we aware of 44 locomotives in the UK are operating hydrostatic cooling systems – 34 Class 68 vehicles, and 10 Class 88 vehicles - all operated by DRS. There are over 500 Class 66 vehicles in the UK – the UK’s primary locomotive. Class 66 operators will be looking to replace these vehicles at the end of their remaining life, which may be in 10-20 years. If the results of this study show sufficient fuel saving, carbon reduction it will encourage the manufactures of new vehicles to fit a Digital Displacement hydrostatic cooling system as standard. It should also provide an incentive for Class 68, Class 88 operators to consider retrofitting Digital Displacement technology into their vehicles.

In addition to analysis of the UK market size in respect to the number of diesel locomotives operating hydrostatic cooling systems, the project team also reached out to European railway stakeholders in a bid to quantify the corresponding European market.
size. In addition to enquiring with Freightliner and DRS, contact was made with the following stakeholders:

The UK Private Wagon Federation (PWF), DB (UK), DB (GmbH), CAF, Stadler, UNIFE and the Community of European Railway and Infrastructure Companies (CER).

Unfortunately, it proved difficult to obtain data relating to the number of vehicles operating hydrostatic drives in the European market. The only firm response received from DB (GmbH) was an indicative figure of 800 diesel vehicles operating in Germany with hydrostatic drives that may suitable for pump swap.

This figure is encouraging as it would suggest that if all EU member states were considered, then a relatively large market size could exist, perhaps within the realm of a number of thousands of units.

**Incentives**

Neither the UK Government, nor the ORR have indicated that they are to publish plans to incentivise decarbonisation of the railways and therefore it is unlikely that subsidies for the retrofitting of technologies to reduce carbon emissions will materialise any time soon. For high traction power demand applications such as freight locomotives, the extension of overhead electrification remains the preferred strategic option for rail decarbonisation. However, extensive electrification will take time and not all routes will likely satisfy business case requirements for implementation and hence the adoption of interim decarbonisation solutions such as DD technologies will primarily be incentivised by the limited number of alternative solutions to decarbonise high powered locomotives.

**4.7 Proposal for further work**

As previously mentioned, assuming operating conditions with engine cooling fans at 0%, 50% and 100% speed, is a simplification. Their speed is continuously variable, and to obtain an accurate duty cycle of their operation the next step would be to conduct data logging of fan operation data over an extended period.

An in-service trial of a DD pump swap would prove the performance and robustness of the technology and allow a back-to-back fuel saving measurement.

More detailed information around the duty cycle and costs for pump production, retrofitting and maintenance would also enable the business case modelling to be further refined.

Discussions with DRS are ongoing regarding the vehicle configuration for data collection. Whilst beyond the scope of this project, both Artemis and DRS see benefit in logging vehicle data over an extended operating period. This will validate current saving predictions and prove the feasibility of the system. An initial assessment of the vehicle
has been conducted, and along with data that is already logged by the vehicle, further instrumentation has been considered.

If access to the in-built telemetry system is not possible, a plan is in place to fit instrumentation and use a data acquisition system to collate this data. Figure 42 below shows the proposed additional sensor configuration if required. However, the data that is already being recorded by the vehicle’s telemetry system should be sufficient to either directly measure, or calculate the parameters required and provides a sufficient dataset for eliminating the remaining assumptions.

![Figure 41 - Proposed Sensor Configuration.](image)

5. **Track equipment pump swap**

5.1 **Introduction**

As discussed in section 2.5 on-track equipment is used for a variety of construction and maintenance tasks on the railway and almost all these already use hydraulic systems, making this an interesting application area for DD. The following study is split into two sections, road-rail machines and rail-only on track plant.

Industry presentations and networking events have led to discussions with owners and operators of track machinery including Network Rail, Colas Rail and manufacture Plasser and Theurer and Rail-Road vehicle convertors G.O.S Engineering and Rexquote. This has provided access to some technical details of track machines and their operation.
5.2 Road-rail machines

How DD could be applied

These vehicles are based on off-highway machines and are fitted with rail wheels that are powered by the vehicle’s existing hydraulic system. This class of vehicle is typically diesel-powered as it is required to operate in remote areas far from electric power supplies. The high power requirement of these machines make them unsuitable for battery power options with technology currently available.

The simple application of a DD Pump in place of a conventional pump can deliver significant fuel savings and productivity benefits, whilst also acting as an enabler for more radical future development. The figure below shows the basic hydraulic layout of a converted Rail-Road excavator.

![Figure 42 - Basic Road-Rail excavator layout](image)

Figure 42 - Basic Road-Rail excavator layout, (1) engine driven tandem pump (2) control valve block, (3) boom rams, (4) dipper ram, (5) bucket/accessory ram, (6) swing motor, (7) track travel motors, (8) Rail wheel motors, (9) Rail wheel rams.

Technology analysis

Artemis has already converted a 16-tonne excavator for off-highway construction applications. This vehicle was chosen because, as standard, it is fitted with an 80 cc/rev tandem pump that is close in displacement to the DDP096 tandem machine. The excavator’s negative flow control system (or ‘Negacon’) is also common across many excavators in this size range.

The hardware modifications to the excavator were limited to a pump swap only, see figure below for the excavator pump installation. No other changes were made to the hydraulic system or engine.
Side by side testing of the modified excavator and a standard excavator showed that when the modified excavator was operating in ‘efficiency mode’ a fuel saving of up to 21% and productivity improvement of 10% is possible. In ‘productivity’ mode, a 28% productivity improvement was recorded along with a 10% fuel saving. These results are validated with reference to the higher efficiency of the DDP and improved control system which allows the engine to run closer to its torque limit. Further improvements of the hydraulic circuit, reducing delivery losses, have improved efficiency and in a follow-on project fuel savings of 30% have now been proven.

Artemis and Danfoss are now working with the Advanced Propulsion Centre to combine the DD pump installation with energy recovery techniques, it is predicted that fuel saving of up to 50% will ultimately be achieved.

**Commercial analysis**

A 16-tonne excavator has a consumption of approximately 152 l/8hr shift for a trenching duty cycle. If this could be reduced by 20% following a simple pump swap, it would save 5472 litres per year (assuming 180 shifts per year). Assuming a red diesel price of £0.60 this equates to a financial saving of £3283 per year. Therefore a 1-2 year payback is expected for the tandem pump required.

Artemis and Danfoss are already working with off-highway construction vehicle OEMs with an aim to fit DD pumps in new-build vehicle hydraulic systems, including excavators. This may be a better route to applying DD technologies to the Road-Rail market as opposed to fitting DD pumps as part of a Rail-Road conversion of an off-highway construction machine.
Environmental impact

Burning a litre of diesel produces around 2.62 kgs of carbon dioxide, so the annual fuel saving calculated for the Road-Rail 16-tonne excavator would correspond to an annual CO2 saving of about 14.3 tonnes for example given above for the vehicle life, which maybe 10 – 15 years. The technology could be applied to new builds but also to retrofit existing vehicles which have significant remaining life.

5.3 On track plant

How DD could be applied

This class of vehicle is typically diesel-powered in order to maximise the routes on which it can be used. Battery power is unlikely to be practical in the near future because of the very high-power consumption required for the work functions. Hydrostatic propulsion is widely used in these vehicles because it provides flexible packaging and good low-speed control. Work functions are also typically hydraulically driven because of the controllability, robustness, power-density and flexible packaging.

Since these vehicles generally already have hydraulic propulsion and work functions, introducing DD machines to this market should be relatively simple from a technical perspective. Existing conventional hydraulic pumps could be swapped with DD pumps for an immediate boost in efficiency and reduction in CO2 emissions. This could be applied as a retrofit to existing vehicle designs.

If DD was applied to a new vehicle design, the following benefits could also be realised

• Direct digital control – many control valves could be eliminated, simplifying the hydraulic circuit, reducing losses and saving money.

• High bandwidth, accurate control – the performance of the machine could be improved.

• Multiple independent outputs from each DD machine – one DD machine can potentially replace several conventional machines.

• Regeneration and energy storage – some of the motion profiles used in these machines would benefit from energy capture and reuse. This is enabled by DD pump-motors and accumulator energy storage.

Technology analysis

The simplest approach to introducing DD to this market would be to directly swap the conventional pumps for DD pumps; bringing improvements in energy efficiency and carbon emissions. Changes to hydraulic system architecture could bring further improvements to productivity and controllability. Suitable DD machines will soon be available from Danfoss at a high TRL which will make this possible at scale. DD pumps
can provide multiple independent outputs per machine with software-selectable control modes, which can dramatically simplify system design.

DD motors could be combined with DD pumps to form a transmission to propel a vehicle (as outlined in Section 4). This would enable use of accumulators to store braking energy, as has been demonstrated with the modified DVT. Suitable production-intent motors are currently under development.

Tamping machines are a promising application - due to the high-power requirements and need for multiple hydraulic services. The MPV platforms developed by Windhoff could be another good application, with a DD transmission for propulsion and auxiliary outputs for work functions. As an example, a tamper-liner machine is considered in a study by Padovani et al. It involves eight types of predominantly hydraulic actuators: two traction motors, two work-head cylinders, four squeeze cylinders, four vibrating motors, two hook-clamp cylinders, two jack cylinders, two liner cylinders, and one bias cylinder. There are five further types of secondary hydraulic actuators that perform occasional tasks by modifying the machine’s configuration (two slew cylinders, two traverse motors, and a buggy-lift cylinder), contribute to the vehicle’s dynamics (four suspension cylinders), and cool the engine (a fan motor). Auxiliary functions, such as the pneumatic system and the electric system, are also part of the machine.

Figure 44 - Plasser 08-16/90ZW tamping machine.

In principle the pumps supplying any of these functions could be replaced by DD pumps, reducing energy consumption and improving controllability.
Commercial analysis

Evidence for the claims about efficiency and productivity improvement comes from Artemis work on a JCB excavator, where we replaced the conventional pump with a DD pump. The simulations and tests performed on the modified excavator showed benefits in both productivity and fuel consumption. Two modes were implemented, an ‘efficiency mode’ which shown up to 21% fuel saving and productivity improvement of 10%, and a ‘productivity mode’ where 28% productivity improvement and 10% fuel saving were recorded in comparison to the traditional hydraulic transmission. Further improvements could be made by changing the hydraulic system architecture to take full advantage of the DD pump’s capabilities and/or by incorporating an energy recovery system.

A Plasser 08-16/90ZW has a consumption of approximately 200 litres per 12-hour shift. If this could be reduced by 20%, it would save 7,200l per year (assuming 180 shifts per year). Assuming a red diesel price of £0.60 this equates to a financial saving of £4320 per year. Therefore a 2-3 year payback is expected for the 2-3 pumps required.

A barrier to entry could be the perception that DD is a new and relatively untested technology (by comparison conventional hydraulics has not changed much in the last 50 years). In the on-track equipment sector reliability is seen as key, and fuel cost/carbon emissions are a secondary issue. Another barrier could be the need to gain certification for any product introduced to the rail industry. On the other hand, the on-track equipment market fits well with the Danfoss/Artemis strategy to introduce DD pumps to off-road applications.
Environmental impact

Burning a litre of diesel produces around 2.62 kgs of carbon dioxide, so the annual fuel saving calculated for the Plasser 08-16/90ZW would correspond to a CO2 saving of about 18.9 tonnes per year. The vehicle life is typically 15-20 years. The technology could be applied for new build but also to retrofit existing vehicles which have significant remaining life.

DD machines have a long life and the pumps are recyclable at the end of their life. DD offers a viable way to reduce the carbon emissions of yellow plant without requiring huge investment in alternative technologies or changes in work practices. It could be used with alternative fuels such as biodiesel or LPG.

6. Conclusions and next steps

Following the feasibility study on the modular DD powertrain, the next step would be to further develop the DD M720 motor, which has been identified as the traction motor required for the powertrain. Development would include production and performance validation testing to bring the pump to commercial readiness. In addition, a more detailed packaging and fuel saving study for a target vehicle would be completed. Ideally, this study would be done in collaboration with a vehicle OEM and operator.

Initial results from the Class 68 auxiliary drive study predict significant fuel savings and carbon reduction could be achieved, if duty cycle assumptions are correct. The next steps would be to collect data from a vehicle in-service to get a more detailed understanding of the cooling system duty cycle to validate the model assumptions. Additionally, a more detailed packaging and business case study can be completed. This would be followed by a pump swap trial on a vehicle in service to prove the predicted savings as well as the performance and reliability of the technology. This would ideally be with the assistance of DRS, who are operating the target vehicle.

Initial results from the feasibility study for swapping DD pumps in track maintenance machines are predicting significant fuel savings and carbon reduction. More detail on the track machine hydraulic circuit and duty cycles are required to provide accurate predictions. Artemis would like to follow up initial discussions on pump swap opportunities with vehicle OEMs and operators and also with Road-Rail maintenance machine convertors. Danfoss are already preparing to enter the off-highway construction machine market with their commercially ready DD pump.
7. **Dissemination**

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<th>Organisation</th>
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<td>planned for June 2020</td>
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8. **References**

a Road wear from Heavy Vehicles - an overview, Report nr. 08/2008, NVF committee Vehicles and Transports.


d Driverless freight train, The Engineer, [https://www.theengineer.co.uk/driverless-freight-train/](https://www.theengineer.co.uk/driverless-freight-train/)
8 Rail Industry Decarbonisation Taskforce, Final Report to The Minister for Rail, July 2019.

h From discussions with Colin Rees Transport and Direct Rail Services Ltd.


