DEMONSTRATION of a DIGITAL DISPLACEMENT® HYDRAULIC HYBRID BUS

… a globally affordable way of saving fuel

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1. INTRODUCTION

In the automotive context the word ‘hybrid’ refers to the addition to a hydrocarbon-fuelled vehicle of a secondary source of motive power with a coupled two-way energy store. The primary objective is to reduce fuel consumption and carbon emissions for the least additional cost compared with the non-hybrid vehicle. A secondary objective is usually to make the added features more or less transparent to the driver so that the response of the hybrid vehicle to foot and hand commands feels similar to that of the standard model. Hybridisation therefore generally requires some degree of high-level intervention in the control of the engine and of the braking.

Currently the vast majority of hybrid vehicles use electric motors with battery storage. Electric hybrids cars are expensive compared with the standard product and so their adoption has generally been restricted to drivers willing to pay extra for the environmental advantages. Heavier electric hybrids such as city buses are also very expensive and their adoption is almost inevitably dependent upon subsidies to operating companies.

Artemis Intelligent Power and other companies including Parker, Bosch Rexroth and Eaton have been working for some time on another kind of hybrid system where hydraulic pump-motors provide the secondary motive power and gas accumulators provide energy storage. Accumulators are not as energy dense as batteries so this kind of hybrid is not able to do engine-off running for distances as great as electric hybrids. However the comparatively high charge and discharge rates (power density) of accumulators and the high torque capability of hydraulic machines make them ideal for capturing braking energy and the subsequent provision of high acceleration torque. Hydraulic pump-motors and accumulators are largely made of steel with little or no requirement for strategic or exotic materials.

Artemis hydraulic hybrid systems are based on its own Digital Displacement® technology which overcomes three of the limitations of conventional hydraulics – low part-load efficiency, poor controllability and high noise emissions. The company is committed to the commercial development of hybrids that will pay for themselves within two or three years in vehicles such as city buses.

Artemis has previously built a Digital Displacement® series-hybrid vehicle and supports both series and parallel approaches when applied appropriately according to a particular vehicle operating context. Rydberg [1] gives an excellent general treatment of hydraulic hybrids and shares the Artemis view that these have great potential, particularly in the commercial vehicle sector. Kargil [2] has also presented widely on the opportunities afforded through the adoption of hydraulic hybrids.

A paper [3] presented by Artemis at a previous JSAE conference discussed a parallel transmission configuration which involved considerable modification of the driveline. This approach is appropriate for new build vehicles, where maximum fuel saving can be achieved by transferring the high torques associated with rapid, but intense, braking cycles. However there are millions of city buses which are already in service where a cost effective retrofittable solution could make a significant improvement to fuel economy over a vast fleet of vehicles even if the system were limited by a more modest torque level to capture a smaller proportion of the braking energy.

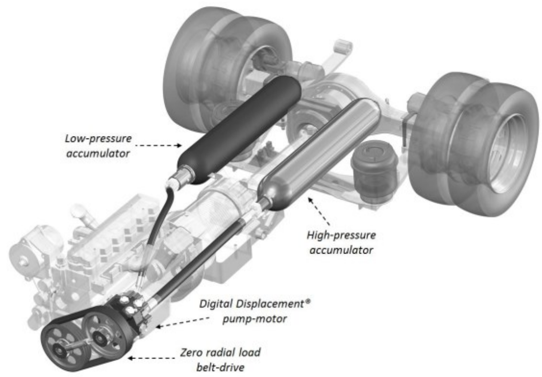

Figure 1: Principal components of the city bus hydraulic hybrid system

This paper describes the implementation of such a system (Figure 1). It discusses the development of the system from conception to the testing of hardware retrofitted to a twelve-year old city bus. The process began with evaluation of the limited packaging space and consideration of the options for transferring torque to and from the driveline. This led to a preferred mechanical layout with a relatively low torque limit imposed by the form of connection to the engine crankshaft. The torque limit, along with data gathered on the same city bus running a local city bus route, provided inputs to a system simulation model. This allowed a gas accumulator energy store to be optimally sized against cost and size and permitted accurate estimates to be made of the potential fuel savings.

Through the development of a new kind of valve, the capability of an existing Artemis industrial pump (the “E-Dyn 96”) was extended to allow it to also operate as a motor. The new pump-motor, along with a gas accumulator system located under the floor, and an electronic controller mounted at the back of the passenger space, were installed in the city bus.

The final stage of the project involved the commissioning, calibration and testing of the hybrid system and the experimental verification of the simulation model. A special duty cycle was developed for the road tests in order to produce a highly repeatable cycle to validate the models predictions. After multiple tests, an average fuel saving of 17% was measured. When the results are applied to the simulation model, with an industry standard duty cycle and the substitution of a more appropriate gearbox, savings of up to 19% are predicted. The inclusion of engine stop-start capability further increases this to 27%.

When the relatively low cost of the hardware installation is considered in conjunction with the fuel savings, it is reasonable to predict a rapid payback for the Artemis hydraulic retrofit system.

2. SYSTEM BACKGROUND

2.1. The vehicle

The vehicle available for retrofit was a twelve-year old city bus which was in active service with the local operator Lothian buses in Edinburgh, UK. Having access to the bus while it was still in service enabled the team to instrument it and record real world performance data on route 12, an Edinburgh service which passes through the city centre and contains a wide range of driving conditions.

Table 1: Vehicle Specifications

Bus model	Alexander Dennis SLF Dart
Year	2002
Mass	8140 kg
Engine Type	135kW, common rail diesel Emissions rating Euro 3
Engine Model	Cummins ISBe 185-30
Gearbox Type	Automatic, with hydrodynamic power splitting
Gearbox Model	Voith DIWA D851.3E

A feature of the transmission is that it has a long hydrodynamic first "gear" which enables it to provide continuous smooth acceleration up to around 20 kph. The challenge this presents in the context of a parallel hybrid is that in a braking event it is not possible to back-drive torque through the gearbox unless it is in second or third gear where lockup is engaged. Had such a vehicle been available, a conventional automatic transmission with lockup in first gear would be more appropriate for this application.

2.2. Defueling the engine

The fuel efficiency of an engine is typically described by a fuel map which relates fuel consumption across the operational range of speed and torque points. Graphically, this three-dimensional data is typically illustrated with a contour, where specific fuel consumption is presented by altitude. A detailed fuel map of the engine was a primary requirement in order to accurately simulate fuelling behaviour, specify system components and develop a control strategy.

Such data is generally not publically available, and in any case typically doesn't cover a defueling scenario when the engine has been back driven. A special dynamometer was built to generate an accurate fuel map from the city bus prior to installation of the hydraulic system, and this was implemented in the system simulation.

2.3. Coupling to the engine

A number of different locations and system architectures were considered for coupling the hydraulic pump-motor to the engine:

- Between engine and gearbox
- 'Drop-box', parallel connection to wheel-side of gearbox
- Gearbox PTO (Power Take Off)
- Engine PTO
- Engine Front End Accessory Drive (FEAD). Mounted on the front end of the engine, passing torque through the crankshaft.

A flat 'pancake' machine between the engine and the gearbox, similar to that developed by Cummins [4] has the potential limitation that it adds overall length to the drivetrain, and could be difficult to retrofit. A drop-box from the output of the gearbox would enable the machine to transmit high torques directly to the wheels, but could be expensive and difficult to retrofit. A system kinematically similar to this, consisting of a tandem, two input, differential has been the subject of a previous Artemis study and demonstrated fuel savings (without stop-start) approaching 25% on a laboratory test rig *(Taylor et al [1])*.

Gearbox PTOs exist on agricultural and specialist vehicles, but are not fitted as standard for bus applications. Engine PTOs are generally designed for lower power accessories such as power steering and fan units, and may also need further qualification for back-driving torque. A front end accessory drive (FEAD) would typically have a torque limit imposed by the manufacturer, and a requirement that radial loads are limited to avoid damaging the engine journal bearing.

Considering final system cost, fuel reduction potential, and the suitability for a retrofit application, a front mounted FEAD system stands out as the most suitable option available.

3. MODELLING AND SIMULATION

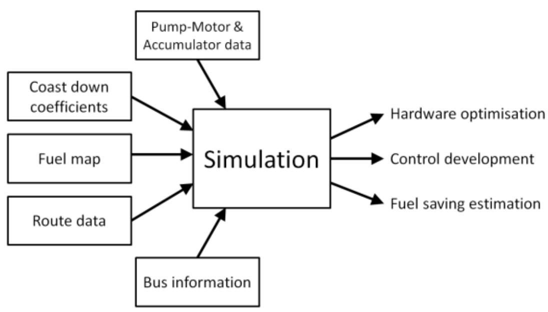

Figure 2: Input parameters required prior to development of the simulation model

3.1. Engine fuelling characterisation

The fuel map of the bus engine was not publicly available, so a custom 30 kW dynamometer was built, which coupled to the engine front end through a cardan shaft. As well as loading the engine, the dynamometer could provide positive torque to offload the engine, thus providing data down to zero fuelling. An accurate fuel measurement system (Max Machinery 710) was used, and this was found to validate the fuel rate reported by the engine control unit (ECU) via the controller area network (CAN). For the region of the fuel map above 30 kW, an existing map for a similar engine was parametrically scaled and then blended with experimental data. Subsequent in-service data collection validated the accuracy of this fuel map to within 0.5%.

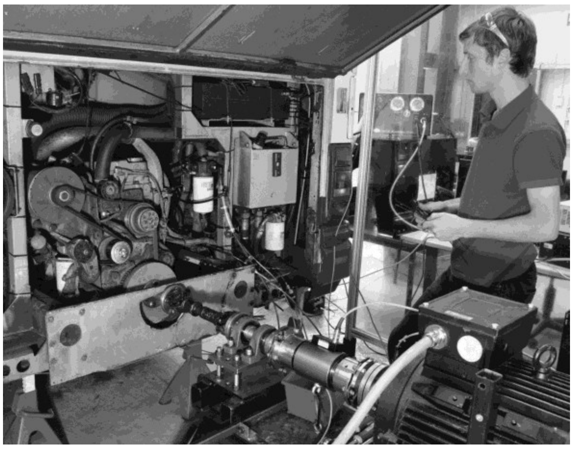

Figure 3: Measuring fuel use with a 30 kw dynamometer connected directly to the crankshaft.

3.2. In-service data collection

The bus was instrumented to collect J1939 CAN data from the engine and gearbox, as well as GPS position and analogue sensors to measure accessory loads.

Data was collected for several weeks driving local operator Lothian Buses's route 12, which is recognised as being representative average of their many routes. Capture of comprehensive vehicle, engine, accessory and route data enabled the vehicle performance to be well characterised across a range of operating conditions.

Bus rolling resistance and aerodynamic coefficients were established experimentally from coast down tests. These were the average of multiple bi-directional runs at speeds up to 70 kph on a straight section of road.

3.3. System model

The engine fuel map and in-service data were used to create a simulation model of the bus using Matlab/Simulink. Analysis of the route showed that 54% of the wheel energy goes into braking.

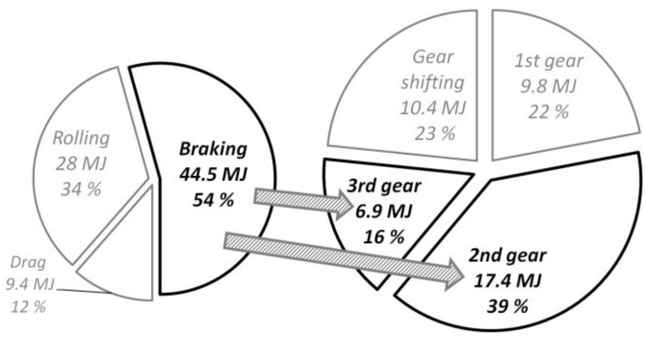

Figure 4: *Left*: From the measured in-service data, 54% of mechanical energy reaching the wheels ended up as braking energy. *Right*: 16% of this braking energy was dissipated whilst the bus was in 3rd gear and 39% whilst it was in 2nd gear. Of the total braking energy, 55% (24.3 MJ) is available to be recovered by the retrofit system.

However, around half of this braking energy is unavailable for recovery by the hydraulic system, since it occurs either during 1st gear (torque converter stage) or during gear shifts, at which times the engine is not rigidly coupled to the wheels.

The simulation included detailed models of the gas bladder accumulator, Digital Displacement® pump-motor, and hybrid system controller. The model of the gas bladder accumulator is based on the Benedict-Webb-Roubins [5] equation of state, with coefficients from Otis & Pourmovahead [6, 7]. Its ability to accurately predict accumulator round-trip efficiency was experimentally confirmed in a separate Artemis study.

This system model allowed fuel saving to be estimated, and parameters such as accumulator volume and gas pre-charge (Figure 5) to be optimised prior to procurement of components.

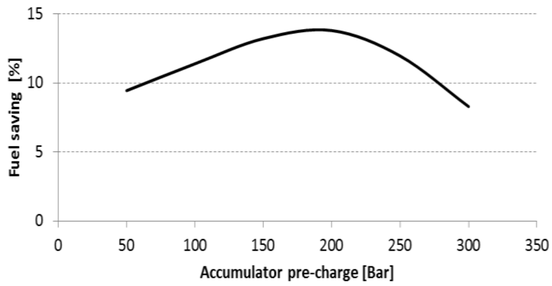

Figure 5: A parameter sweep of accumulator pre-charge pressure to find the optimum.

4. THE HYBRID SYTEM AS BUILT

4.1. Pump-motor specification

The machine selected for this project was an advanced version of a new industrial pump, the "E-dyn 96", with the addition of motoring functionality. Table 2 lists its outline specification. It is a compact, power dense machine, which comfortably exceed the maximum allowable torque on the front end of the engine crankshaft.

Table 2: Specification of the E-dyn 96 pump-motor as built for the bus retrofit.

Swept Volume	96 cc/rev
Speed range	200-2500 min^{-1}
Peak flow	170 litre/min
Peak Pressure	350 bar
Peak Power	140 kW (190 hp)
Peak Torque	530 Nm
Mass	60 kg

4.2. Belt drive

A number of locations in the driveline were considered for connection of the hybrid system before the FEAD option was chosen. The packaging space in the engine bay was limited, with only 70 mm of axial length available between the engine crankshaft and the rear bumper, and existing ancillaries occupying much of the space surrounding the engine. The system also needed to be able to deliver peak torque without putting new side loads on the crankshaft, to avoid potential damage of the crankshaft journal bearing and consequent voiding of the engine manufacturers warranty. A simple belt drive capable of delivering the required torque would typically have an associated side force of around 5 kN when pre-tensioned.

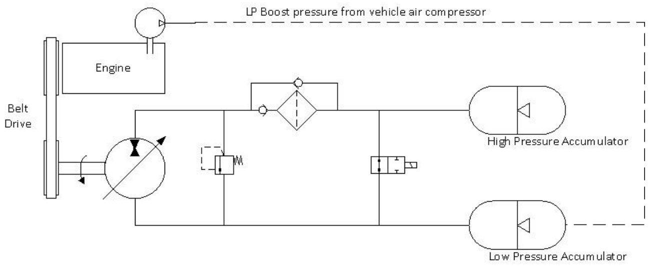

Figure 6: Hydraulic schematic. Note the low component count, enabled by the Digital Displacement® pump-motor directly control flow and pressure.

The final solution arrived at was to resolve all side loads internally, using a sprung strut between the two pulleys to provide the belt tensioning force. The pump-motor was mounted on a pivoting bracket on the side of the engine. By compressing the spring via a threaded adjuster, the rod expands, pivoting the pump and applying the appropriate tensile pre-load to the belt. A helpful feature is that the belt pre-tension can be accurately defined by measuring the compression of the spring. The forces are neatly resolved within the FEAD assembly, without applying any side-loads to the engine or Pump-Motor crankshafts.

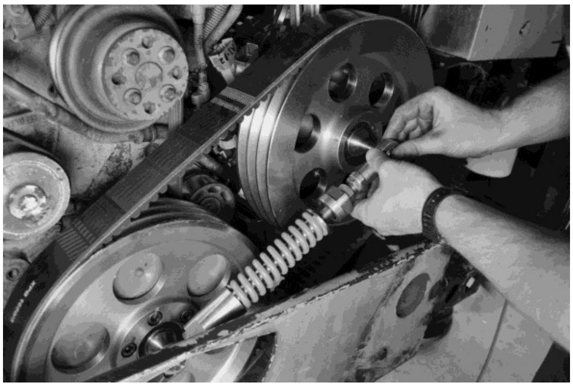

Figure 7: The belt-drive is spring tensioned to prevent the hybrid system from imposing any additional radial loads on the engine crankshaft.

4.3. Energy storage accumulators

Gas accumulators have several features which make them well suited to energy storage in hybrid vehicle applications. They are power dense, enabling capture of high-power braking events, and are commonly used in industrial processes, so are available at low-cost. They have few moving parts, are very robust and capable of high cycle life.

The timing of a typical stopping event means that the process is close to adiabatic. A bus does not wait for long at the stop, so heat generated during the compression phase of the cycle does not have time to escape before being recaptured in the expansion phase.

The rate of heat loss from an accumulator, its thermal time constant, can be further reduced by using insulated, foam-filled accumulators. Measurements made by Artemis show that on a typical cycle a conventional accumulator has a round-trip efficiency of around 94%.

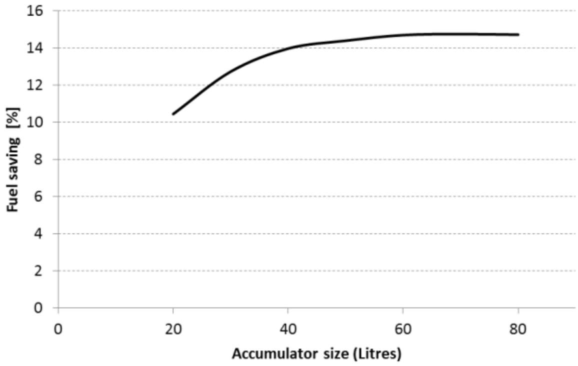

Figure 8: Accumulator volume optimisation. Diminishing returns are seen above around 40 litres.

Sizing of the accumulators is dictated by the energy available in a braking event; the aim being to capture as much of the energy as possible during braking, and use it again before the next event. The simulation model predicted diminishing returns above 40 litres.

4.4. Control and integration

The nature of Digital Displacement® means that high bandwidth (10 - 20 ms) control decisions are implemented directly on the pump-motor. This enables accurate flow and pressure control to be achieved in harmony with the engine without need for additional external control valves. Consequently the hydraulic circuit is simple, keeping hydraulic system and maintenance costs down.

Low-level control of valve timing was realised using the "AMC2" - a proprietary control unit developed by Artemis for vehicle and industrial applications. Implementation of the top level control algorithm and communication between the engine ECU and subsystems on the J1939 CAN network were done by a small PC, running Simulink code compiled to run in real time. Developing and testing the control system in a model based design environment such as Simulink is convenient and efficient, enabling rapid iteration and fine-tuning of the control strategy during testing.

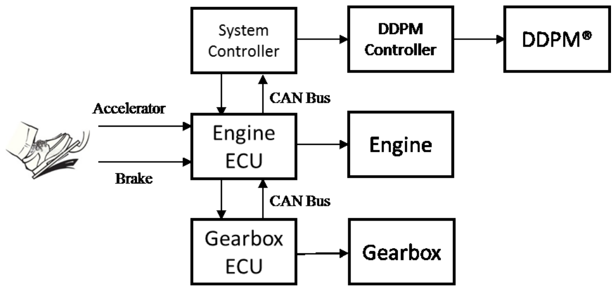

Figure 9: Communication between hybrid vehicle sub-systems

5. ROAD TESTING

5.1. Testing methodology and justification

One of the challenges presented by the bus that was available for this demonstration is that the gearbox has a long hydrodynamic first gear up to speeds of approximately 20 kph. When the gearbox is in 1st gear, it is not possible to capture braking energy, because it cannot back-drive torque from the wheels to the engine. A 'saw-tooth' drive cycle was developed which closely matches the MLTB acceleration and deceleration rates, but keeps the transmission engaged in either second or third gear. The aim of the test was to quantify fuel savings in the current system, validate this against the simulated result, and then use the simulation to project fuel savings on a modern Euro VI vehicle with a more appropriate transmission.

Figure 10: The hybrid bus during testing on a local airfield

5.2. Test results

A total of nine drive cycles were conducted with energy capture enabled and another nine with it disabled. On average these showed a saving of 17%. The difference between actual and simulated fuel saving was an average of 0.3%, whilst other characteristics, such as gear-change timings, also matched the simulation. This provided additional confidence in the model.

5.3. Predicted savings on future vehicles

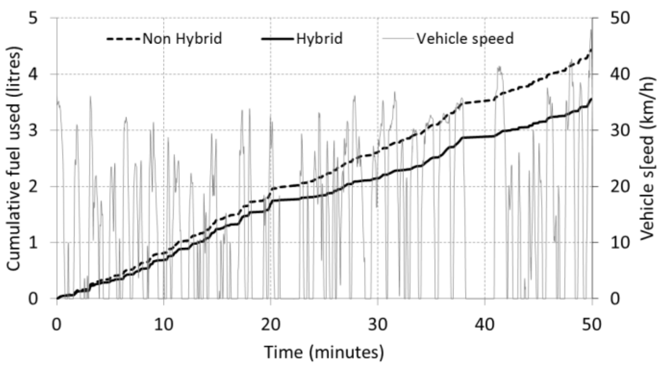

Figure 10: Simulated fuel saving on the MLTB cycle with a conventional automatic transmission and stop-start functionality

Using the validated simulation model, the system performance on two different duty cycles could be investigated. The duty cycles investigated were:

- Lothian buses Route 12 (LB 12); a representative local route, recorded by Artemis with detailed instrumentation.
- "Millbrook London Transport Bus" (MLTB); a repeatable, representative cycle developed by Millbrook and Transport for London, based on London route 159. *TFL, 2011 [8]*.

The model of the current bus showed moderate fuel savings with both Route 12 (5.1%) and MLTB (7.3%). This is because a large proportion of braking energy (Figure 4) is only available when the bus is in first gear, a region that cannot be captured with the current gearbox.

The model was re-run with a number of realistic enhancements to investigate performance in a bus with a conventional automatic gearbox.

- Next generation Digital Displacement® machine with higher operational limits (420 bar motoring up to 2300 min^{-1});
- Conventional automatic gearbox with lockup in first gear;
- Stop / start – switching the engine off when the vehicle is stationary, and using the high torque of the hydraulic pump-motor to restart

These showed very promising fuel saving predictions, up to 27%, as shown below.

Table 3: Cumulative fuel saving predictions

Drive Cycle	*Current Bus*	*Improved motoring valves 420 bar, up to 2300 min^{-1}*	*Conventional Automatic Transmission*	*Stop/ Start*
MLTB	7.3%	11.1%	19%	27%
LB 12	5.1%	8.2%	12%	20%

7. SUMMARY

A retrofittable hydraulic hybrid system using a Digital Displacement® pump-motor was developed and installed on a city bus. Challenges encountered relating to packaging the system onto the bus were overcome using a novel internally reacting belt drive arrangement. The large operating range of the torque converter mode in the transmission reduced the systems potential to recover braking energy in the test bus. However, a transmission capable of capturing braking energy down to low speeds was investigated numerically.

A detailed Simulink model of the vehicle was developed to enable parameters such as gearbox replacement to be investigated. This model was then validated with real world tests - predicted and measured fuel consumptions were in close agreement.

The validated model predicts that a hydraulic hybrid with a conventional automatic transmission and stop-start capability is capable of fuel savings of up to 27% on the MLTB route cycle. The project enabled core Digital Displacement® hardware to be developed, and many of the technical obstacles relating to system integration to be addressed. This paves the way for a follow-up project with a more mature Digital Displacement® machine and a demonstration vehicle with a more appropriate transmission.

6. FUTURE PLANS

There is a significant global market for conventional diesel buses, and it is likely that hybrid offerings will only be able to disrupt this if they can demonstrate realistic payback times without relying on government subsidies. With its low cost and significant fuel savings, the system described here would deliver a subsidy free return on investment in around two to three years. It therefore seems worth-while to develop the system further.

Artemis plan to implement the engine mounted parallel hybrid concept discussed here in a modern Euro 6 vehicle to gain in-service experience and demonstrate the high fuel savings expected with a conventional automatic transmission.

ACKNOWLEDGEMENTS

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