PROTOTYPING AND PERFORMANCE TESTING OF A HYDRAULIC HYBRID HEAVY COMMERCIAL VEHICLE

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Abstract

Decarbonisation of heavy-duty transport is a globally significant technology challenge. In this study, we have prototyped and tested the performance of a hydraulic hybrid heavy commercial vehicle. The hydraulic hybrid driveline was coupled to a Euro IV four-cylinder Isuzu NPR 400 diesel truck which was equipped with a diesel particulate diffuser and an exhaust gas recirculation system. During regenerative braking events, a working fluid is pumped from a low-pressure reservoir to a high-pressure reservoir. The stored potential energy is available for power assist when the working fluid is discharged from the high-pressure reservoir using a hydraulic motor. An urban drive cycle was designed for testing that featured a high intensity of stopping and starting events that is relevant for the types of trips undertaken by a heavy commercial vehicle. An AVL portable emissions measurement system was used for quantifying gaseous and particle phase emissions species and a Dearborn on-board diagnostic scan tool was used to retrieve data from the trucks electronic control unit. Through using a carbon mass balance technique, average fuel consumption savings of approximately 11% were achieved in hybrid mode through replicated testing on a short urban driving route with a high intensity of stop-start activity. Results for other pollutants in hybrid mode showed reductions in CO of up to 16%, reductions in total hydrocarbons by up to 88% and increases in NO_x by up to 15%. Solid particle number emissions can be reduced by up to 99.6% in hybrid mode by activating the diesel particulate diffuser. Future work on improved control system integration and design optimisations should enhance the ability of this hydraulic hybrid system to reduce fuel consumption and emissions in heavy commercial vehicle applications.

Keywords: hydraulic hybrid, heavy commercial vehicle, fuel consumption, real driving emissions

1. Introduction

The transport sector is a major contributor to greenhouse gas and criteria pollutant emissions in the Australian context. Data from Australia's 2020 National Inventory report (Commonwealth of Australia, 2022) indicates that road transport contributes approximately 19% of total greenhouse gas emissions. Transport-related CO_2 emissions are only exceeded by the electricity generation and agriculture sectors in Australia. Furthermore, total transport-related CO_2 emissions have increased by approximately 14% since 2005 even though the impacts of COVID-19 significantly reduced travel activity in 2020 and 2021 (Commonwealth of Australia, 2022). Reductions in CO_2 emissions from road transport are a key requirement to meet the new federal government's target of a 43% reduction in greenhouse gas emissions by 2030 relative to 2005 emission levels.

While some progress has been made in achieving decarbonisation outcomes by electrifying light duty vehicle fleets, electric vehicles only make up approximately two percent of new vehicle sales in Australia (Electric Vehicle Council, 2022). Even less progress has been made with the electrification of heavy-duty vehicles, although some initial efforts have been undertaken by SEA Electric (https://seaelectricev.com.au/) in manufacturing electric trucks for the Australian market. Foton Mobility (https://fotonmobility.com.au/) are also supplying battery electric trucks and fuel cell electric buses for Australian customers.

As an alternative approach, hybrid vehicles also exist as a transitionary automotive technology until reductions in cost and improved range is possible for electric vehicles or until hydrogen infrastructure is readily available. A key feature of a hybrid electric vehicle is the ability to capture kinetic energy and store it using a battery during regenerative braking events. In this work, we explore a hydraulic hybrid driveline that exhibits an improved capacity to store kinetic energy from regenerative braking events. The origins of this technology date back to patent literature on hydrostatic transmissions in the 1950s and 1960s. Theoretical insights suggest that a hydraulic hybrid vehicle can capture a significantly greater proportion of the kinetic energy from regenerative braking events compared to a battery electric vehicle (Woon et al., 2011). In terms of vehicle development, a collaboration between the Ford Motor Company and the US EPA prototyped a hydraulic hybrid sports utility vehicle (SUV) in the early 2000s (Kepner, 2002). Despite this study, an SUV is not an ideal target vehicle for a hydraulic hybrid installation due to the additional payload requirements. To avoid this limitation, we have converted a Euro IV diesel truck to a hydraulic hybrid prototype and have tested its real driving fuel consumption and emissions performance using a Portable Emissions Measurement System (PEMS).

2. Methods

2.1. Prototyping of the hydraulic hybrid truck

An Isuzu NPR 400 diesel truck (Table 1) was converted to a parallel hydraulic hybrid driveline by HRDS Technologies as part of this study. Key features of the hydraulic hybrid driveline (Table 2) include a hydraulic pump/motor, a high-pressure accumulator and a low-pressure accumulator which are illustrated in Figure 1. Both accumulators were piston-based. During regenerative braking events, kinetic energy is stored as potential energy by pumping a working fluid from the low-pressure accumulator to the high-pressure accumulator using the hydraulic pump. To launch the vehicle, the hydraulic motor pumps the working fluid from the high-pressure accumulator to the low-pressure accumulator to provide power assist.

Table 1. Specifications of the diesel truck converted to hydraulic hybrid technology.

Item	**Specification**
Model	Isuzu NPR 400
Gross Vehicle Mass (kg)	7500
Cylinders	4
Capacity (L)	5.193
Bore × stroke (mm)	115 × 125
Maximum power (kW/rpm)	114/2600
Maximum torque (Nm/rpm)	419/1600
Compression ratio	17.5
Fuel injection	Common rail
Aspiration	Turbocharged
Emissions certification	Euro IV
After-treatment	Exhaust gas recirculation and diesel particulate diffuser
Australian Design Rule	80/02

Table 2. Specifications of the parallel hydraulic hybrid driveline.

Item	**Specification**
Hydraulic pump type	Axial piston, variable displacement, hydraulic motor
Hydraulic pump capacity (cm^3)	210
Hydraulic pump maximum power/speed (kW/rpm)	480/3000
Accumulator uncompressed volume (L)	32
Accumulator maximum pressure (MPa)	35
Oil reservoir volume (L)	120
Control system	Programmable logic controller with engine throttle position in a closed loop

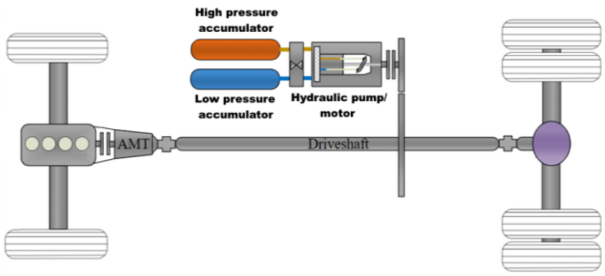

Figure 1. Powertrain architecture for the hydraulic hybrid driveline. Figure adapted from Zhou (2021) with permission.

2.2. Portable Emissions Measurement System testing methods

The methods described in the text below were developed by Walker et al. (2020) and applied in a subsequent study by Smit et al. (2022). Real driving fuel consumption and emissions testing was performed with an AVL MOVE system consisting of an AVL 493 Gas PEMS iX, an AVL 496 Particle Number (PN) PEMS and a 2.5-inch AVL 495 exhaust flow meter. The Gas PEMS recorded emissions data for CO_2, CO, NO, NO_2, methane (CH_4), non-methane hydrocarbons (NMHC; propane equivalent) and oxygen (O_2) at 10 Hz. In terms of measurement principles, CO_2 and CO were quantified using non-dispersive infrared spectroscopy. NO and NO_2 were quantified with non-dispersive ultra-violet spectroscopy that enabled simultaneous quantification of both species without the need for a catalyst or ozone generator. Hydrocarbons were quantified with a flame ionisation detector with accompanying needs to supply burner fuel and gas during tests. The PN PEMS made measurements of solid PN concentration after removing volatile material with a catalytic stripper. The PN PEMS uses the principle of electrostatic precipitation to detect particles which is achieved by firstly assigning a unipolar charge to particles using a corona discharge technique followed thereafter by the precipitation of particles in a Faraday cage and the measurement of electrical current with an electrometer. The nominal sensing range of the PN sensor is for particles between 23-300 nm which constitutes most of the nucleation and accumulation modes in the particle size distribution (Kittelson, 1998). Gravimetric measurements of particulate matter were not made since particles were not collected onto filters that could be weighed. Fuel consumption was determined using a carbon mass balance technique (European Commission, 2013). An illustration of the PEMS installation is provided in Figure 2.

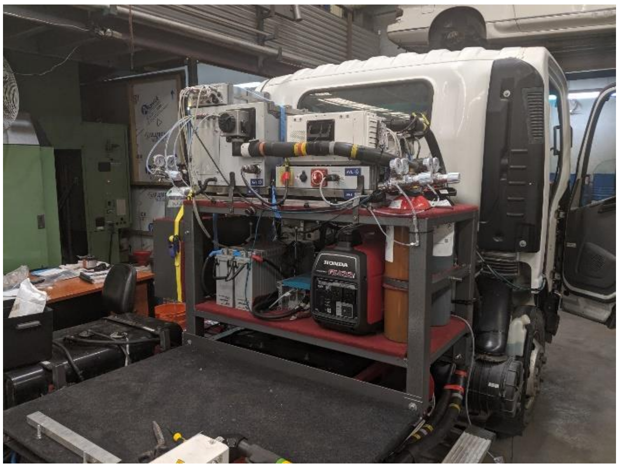

Figure 2. PEMS installation on the hydraulic hybrid truck.

A Global Positioning System was deployed to collect positional information including latitude, longitude and elevation and this was complemented by a meteorological sensor that recorded temperature, relative humidity and barometric pressure during tests. In terms of quality control for measurements, pre-tests for each PEMS test involved performing a system purge and leak check, followed by zero and span calibrations as well as zeroing of the exhaust flow meter. A system purge followed by zero and span drift checks were performed after each PEMS test.

2.3. Test routes

Real driving emissions testing was conducted in Picton NSW from Spring 2019 through to Summer 2020, but was curtailed somewhat by the Black Summer bushfires and subsequent floods. Two test routes were adopted in this study. The first route (Figure 3) was a short urban driving route with a maximum speed of 60 km/h that was 5.1 km long and took about eight minutes to complete. This test route was designed to reproduce the high intensity of stopping and starting driving conditions that would be encountered in deliveries undertaken by a heavy commercial vehicle, for which a hybrid driveline is expected to yield reductions in fuel consumption and emissions. The urban drive cycle was executed five times with a given driveline architecture before switching between conventional diesel or hybrid mode.

The second test route (Figure 4) was a rural test route with a maximum speed of 90 km/h that was 16.6 km long and took 21 minutes to complete. This test route was used as a control test where benefits from a hybrid driveline are not expected due to the lack of stop and start driving conditions. This drive cycle was executed twice per test but only in conventional diesel mode and not for hybrid mode. For this reason we don’t present the rural driving data in this paper.

Figure 3. Short urban test route. Source: Google Maps.

Figure 4. Rural driving test route. Source: Google Maps.

2.4. Data analysis protocols

Data used for the determination of fuel consumption and emissions factors were corrected to dry conditions using ISO 16183 (International Standards Organisation, 2002) and were corrected for zero and span drift using a linear drift correction model. NOx emissions were also corrected for ambient conditions using ISO 16183. Engine maps were prepared (Figure 5) to compare the performance of the hydraulic hybrid system to conventional diesel operation under both cold running and hot running conditions.

3. Results and Discussion

Summary statistics for replicated tests conducted on the short urban cycle are presented in Table 3 for both conventional diesel operation as well as hydraulic hybrid operation. Averaged across two tests, fuel consumption and CO_2 were reduced by approximately 11%, CO was reduced by 16%, total hydrocarbons were decreased by 88%, while NOx was increased by 15%. Hybrid operation also reduced solid PN by up to 60%. When the Diesel Particulate Diffuser was active, solid PN was reduced by 99.6%.

The engine maps in Figure 5 plot engine speed versus the equivalence ratio, or the fuel-to-air ratio (Heywood, 2018) with fuel consumption appearing as a filled contour representing a third variable. Under fuel-rich combustion conditions at high load the equivalence ratio achieves its maximum value. Hot running conditions were assumed to commence when the coolant temperature exceeded 70 °C for the first time in a test.

The engine maps show that significant fuel consumption savings are present under hot running conditions when the hydraulic hybrid system is activated. Under high power conditions in the engine map (i.e. in the top right corner), hot running conditions for conventional diesel operation achieve fuel consumption rates up to 6 g/s. In contrast, hybrid mode achieves a maximum rate of fuel consumption of 3.5 g/s under high power conditions due to power assist from the hydraulic system which does not consume fuel. Reduction in fuel consumption are also achieved under cold start conditions but are not as pronounced as those achieved under hot running conditions.

An alternative way of viewing the fuel consumption savings is through comparing speed-dependent emission factors for CO_2 in diesel and hybrid mode (Figure 6). This comparison is based on the principle that CO_2 emissions constitute the vast majority of carbon present in the exhaust. This comparison shows that the hybrid system is capable of reducing fuel consumption within each of the speed bins from 0 km/h through to 60 km/h. Fuel consumption savings are particularly pronounced in the 0-10 km/h speed bin since the hydraulic hybrid system is able to provide assistance with launching the vehicle from 0 km/h.

The reductions in fuel consumption in hybrid mode are also achieved due to the opportunity to use a more optimal gear shifting strategy. The availability of power assist from the hydraulic hybrid system enables a higher gear to be selected earlier in a drive cycle due to the additional torque generated by the hydraulic motor. Shifting to a higher gear moves the engine to a more efficient operating point in the engine map which offers fuel consumption savings in addition to the savings in fuel due to using stored potential energy from the hydraulic system. An improved gear shifting

Table 3. Fuel consumption and emissions results summary under conventional diesel and hydraulic hybrid mode. * Denotes that the Diesel Particulate Diffuser was not activated for the test. Summary statistics are presented as the mean ± the standard deviation (std) from two replicated tests.

Mode	**Fuel economy (l/100 km)**	**CO_2 (g/km)**	**CO (g/km)**	**THC (g/km)**	**NOx (g/km)**	**PN (#/km)**
			Euro 4 limit			
			0.74 g/km	0.46 g/km (THC + NOx)	0.39 g/km	
Diesel run 1 (hot start)	15.8	412.8	0.41	0.015	2.37	1.4×10^{10}
Hybrid run 1 (cold start)	15.2	397.3	0.36	0.023	2.93	5.5×10^{9}
Diesel run 2 (cold start)	16.5	429.3	0.55	0.22	2.44	3.7×10^{12} *
Hybrid run 2 (hot start)	13.6	354.1	0.45	0.005	2.58	2.1×10^{10}
Diesel (mean ± std)	16.1 ± 0.47	421.1 ± 11.6	0.48 ± 0.1	0.12 ± 0.14	2.40 ± 0.05	N/A
Hybrid (mean ± std)	14.4 ± 1.15	375.7 ± 30.6	0.41 ± 0.07	0.014 ± 0.01	2.75 ± 0.25	$1.15 \times 10^{10} \pm 1.12 \times 10^{10}$

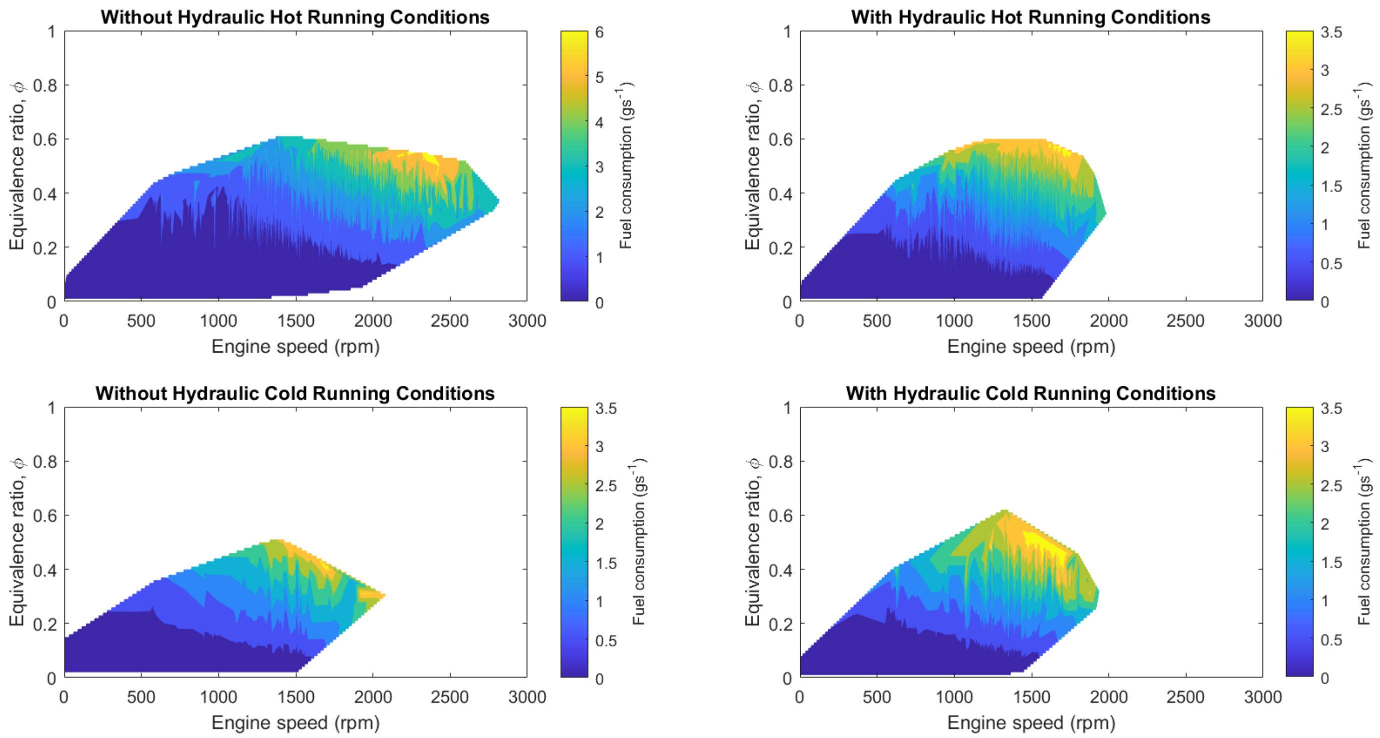

Figure 5. Engine maps for fuel consumption during both hot and cold running conditions for conventional diesel operation and for hybrid mode.

strategy also has benefits for emissions which is reflected by the reductions in CO and total hydrocarbons due to operating the engine at a more efficient point in the map. A disadvantage of this approach is that NOx emissions are increased due to the increased in-cylinder flame temperature under high load conditions (Heywood, 2018).

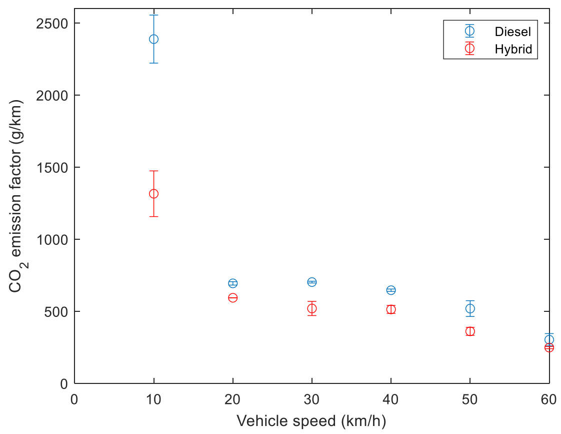

Figure 6. Speed-dependent emission factors for CO_2 in diesel and hybrid mode derived from the urban test route. Data are binned according to speed based on 1 Hz emission data. Data are pooled across cold start and hot running conditions.

4. Conclusions and future work

In this study, we have successfully prototyped a hydraulic hybrid heavy commercial vehicle and have tested its real driving fuel consumption and emissions performance using an urban drive cycle. In hydraulic hybrid mode, this heavy commercial vehicle achieves:

- fuel consumption reductions of 11%,
- reductions in CO by 16%,
- reductions in hydrocarbons by 88%,
- reductions in solid PN by 99.6%,
- increases in NOx by 15%.

Future research efforts will target improved fuel consumption and emissions performance (especially for NOx) by developing a more advanced control system that optimises the performance of the driveline components such as the hydraulic motor and the accumulators.

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