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Implementation of a Novel Hydraulic Hybrid Powertrain in a Sports Utility Vehicle

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Abstract: Hydraulic hybrid transmissions offer an efficient and high performance alternative to electric hybrid transmission in on-road vehicles. One of the principle benefits of hydraulic over electric hybrids is the higher power density offered by their energy storage media. This enables hydraulic hybrids to capture virtually all of the available kinetic energy from braking. In contrast electric hybrids are often forced to dissipate part of this energy through friction brakes due to the lower power density inherent in their energy storage media. To date various hydraulic hybrid architectures have been investigated and put into production. However as is typically true there always exists room for improvement. This paper details the integration of a novel blended hydraulic hybrid transmission with improved performance and efficiency into a demonstration vehicle. Also included is a discussion of various unique control strategies which were designed for this powertrain as well as a discussion of initial measurement.

Keywords: hydraulic hybrid, blended hybrid, hydrostatic transmission, control

1. INTRODUCTION

There exists a multitude of technologies and approaches aimed at reducing our consumption of fossil fuels in on-road vehicles. Notable examples include the increasingly popular electric hybrid and pure electric powertrains. However less well known technologies such as mechanical (i.e. flywheel) hybrids and hydraulic hybrids offer many benefits over the more conventional electric hybrid approaches. In fact for certain applications hydraulic hybrids have been shown to substantially outperform competing electric hybrid architectures. Much of the difference in fuel economy between these two hybrid technologies can be attributed to the working principles behind their energy storage media. While electric hybrids typically store energy chemically in batteries or electrically in capacitors, hydraulic hybrids store energy mechanically in hydropneumatic accumulators. This mechanical energy storage provides a substantially higher power density for hydraulic hybrids enabling these powertrains to recover substantially more regenerative braking energy than electric hybrids are typically capable of. In one recent investigation the US Federal Transit Administration along with several industrial partners developed a hydraulic hybrid transit bus. During independent testing this hydraulic hybrid bus was able to improve fuel economy by 47% over an identical non hybrid bus and 109% over a conventional transit bus. Perhaps more interesting was the hydraulic hybrid's 29% increase in fuel economy over the best case electric hybrid bus while simultaneously incurring an estimated lifecycle cost 36% lower than an electric hybrid variant (Heskitt et al., 2012). Other key advantages of hydraulic hybrids over electric hybrids include more environmentally friendly construction. Instead of relying heavily on rare earth and toxic elements hydraulic hybrids are constructed predominately out of steel with mineral oil as the working fluid. Hydraulic hybrids also require minimal thermal management and can take advantage of the same type of oil coolers already in place on vehicles. Unlike batteries accumulators do not degrade in performance from use with some accumulator technologies requiring zero maintenance over the vehicle's lifetime. Also unlike batteries accumulators can be fully discharged while servicing or during an accident further improving safety. Finally hydraulic units have a superior torque curve compared to many electric motors with a constant output torque achievable irrespective of unit speed.

Hydraulic hybrids, like electric hybrids, come in three basic varieties: parallel, series, and power split transmissions. While each system architecture has advantages in certain applications they also exhibit distinct drawbacks. Consider a typical series or power split hydraulic hybrid transmission; two key deficiencies in these architectures can be traced back to the fixed connection between the hydraulic units and accumulator. Variable displacement (fluid moved per revolution) hydraulic units typically operate at peak efficiency when their relative displacement is high with respect to their maximum displacement and pressure is moderate. However in both series and power split configurations the hydraulic units are forced to operate at the accumulator's current pressure. This often results in the hydraulic units operating at higher pressures and lower displacements thereby reducing efficiency. A second deficiency linked to this fixed connection between hydraulic units and accumulator is the relationship between maximum unit torque and current accumulator pressure. If a driver commands more torque than can be satisfied at the current accumulator pressure then the accumulator's pressure must be increased by pumping more fluid into the accumulator than is consumed. However due to the accumulator's inherently high capacitance this process can potentially result in a delay on the order of seconds resulting in poor drivability. This is particularly detrimental as it is

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quite important for any new transmission to maintain a similar and positive response and feel to current transmissions if they are to gain widespread acceptance (Johansson and Ossyra, 2010).

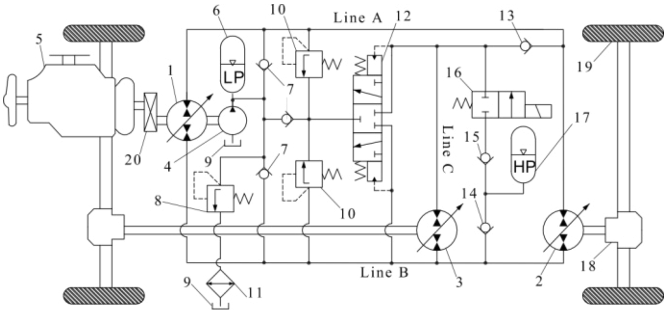
To address these issues and others the authors have proposed and investigated a novel system architecture termed a Blended Hydraulic Hybrid (Sprengel and Ivantysynova, 2012). At a basic level the blended hybrid combines aspects of a Hydrostatic Transmission (HST) and a parallel hybrid while incorporating both passively and actively controlled hydraulic logic elements. In essence this creates a partial separation between power transmission, energy recovery, storage, and reuse enabling the optimization of individual modes of operation. While driving the blended hybrid often operates as a hydrostatic transmission. HSTs operate in a flow (speed) controlled manner with all flow leaving the pump passing through the motors. This arrangement forms an infinitely variable transmission with the transmission ratio a function of relative unit displacements and system pressure a function of load. By not relying on an accumulator to dictate current system pressure HSTs are able to function in an optimal manner at higher displacements and lower pressures thereby increasing efficiency over conventional hybrid architectures. Additionally the inherently stiff nature of hydrostatic transmissions enables rapid changes in system pressure according to driver demand. This creates a more responsive transmission and improves drivability when compared to baseline series and power split based hydraulic hybrids.

Research into the novel blended hybrid began in 2012 with the concept's introduction along with several variations (Sprengel and Ivantysynova, 2012). The blended hybrid's efficiency potential was first evaluated by comparing the proposed architecture with baseline automatic and series hybrid transmissions using Dynamic Programming (DP) to eliminate the influence of control and enable a fair comparison (Sprengel and Ivantysynova, 2013a). Next a top level control scheme was proposed for the blended hybrid in Sprengel and Ivantysynova (2013b). In Sprengel and Ivantysynova (2014a) a power split version of the blended hybrid was proposed and compared to conventional manual and power split transmission using DP. Then in Sprengel and Ivantysynova (2014b) the blended hybrid was constructed, tested, and validated on a Hardware-in-the-Loop (HIL) transmission dynamometer. Finally in Sprengel and Ivantysynova (2014c) a compact SUV was optimally controlled via DP for baseline automatic and manual transmissions, conventional series and power split hydraulic hybrid transmissions, and the novel blended hybrid and blended hybrid power split transmissions. This and prior investigations showed the improvements in fuel economy which the blended hybrid architectures offer over conventional hydraulic hybrid transmissions.

A substantial limit of both simulation and HIL based evaluations is the inability to capture driver feel and perception. This limit was made more poignant through discussions with multiple industry and automotive representatives who said in effect "We know the improved fuel economy is there but how does it feel while driving?" To address this valid concern a full scale blended hydraulic hybrid demonstration vehicle has been constructed at the Maha Fluid Power Research Center located at Purdue University (the authors' research group). This paper will cover some aspects of transmission integration and component packaging before exploring several implementable control strategies and concluding with initial measurement results.

2. BLENDED HYBRID TRANSMISSION

Figure 1 represents the hydraulic circuit for the blended hybrid transmission. Principally the blended hybrid is a hydrostatic transmission with an additional hydraulic unit (Unit 3) connected to the transmission's outputs shaft. Through a combination of check valves Unit 3 can either be connected to the Unit 1 facilitating an increase in the displacement of the hydrostatic transmission or to the High Pressure (HP) accumulator (17) allowing the unit to use power from the accumulator. Check valve (14) connects Line B and the HP accumulator during braking events which enables energy recovery through regenerative braking. Unit 3 can either be connected to a separate axle for four wheel drive applications (as presented here), or to the same axle as Unit 2 for two wheel drive applications. The parallel connection between these two units forms a hydraulic differential enabling the two axles to rotate at different speeds.



1	hydraulic unit 1	2	hydraulic unit 2
3	hydraulic unit 3	4	charge pump
5	engine	6	LP accumulator
7	LP check valve	8	LP relief valve
9	reservoir	10	HP relief valve
11	oil cooler	12	flushing valve
13	check valve	14	check valve
15	check valve	16	enabling valve
17	HP accumulator	18	axle
19	wheels	20	gear box (1.48:1)

Figure 1: Blended hybrid circuit

The blended hybrid can operate in four distinct modes:

Hydrostatic Driving

The blended hybrid operates as a hydrostatic transmission when either the enabling valve (16) is closed, disconnecting the circuit from the HP accumulator, or when the enabling valve is open and the pressure in the HP accumulator falls below that of Line C. In this mode, Unit 1 absorbs the engine power and pumps fluid into Line A. Based on the displacement of Units 2 and 3 part of the flow from Line A will pass through check valve (13) and flow to Unit 3. The displacement of these units and the flow pumped by Unit 1 determine the rotational speeds of the two units.

Hybrid Driving

During hybrid driving the entire torque requirement at the wheels is fulfilled by Unit 3 using energy previously stored in the HP accumulator during regenerative braking. This is achieved by opening the enabling valve and commanding Units 1 and 2 to zero displacement. Opening the enabling valve exposes Line C to the pressure in the HP accumulator, whereas setting the displacement of Units 1 and 2 to zero ensures that no power flows through the hydrostatic transmission.

Blended Hydrostatic and Hybrid Driving

During blended hydrostatic and hybrid driving the system combines some characteristics of both the hydrostatic and hybrid modes described above. This mode is achieved when the enabling valve is open along with non-zero displacements of Units 1 and 2. Additionally the pressure in Line C must be greater than that in Line A to ensure that check valve (13) remains closed. In this case, Unit 3 is powered by energy stored in the HP accumulator whereas Unit 1's displacement is adjusted to utilise the engine power to rotate Unit 2. The required torque at the wheels is thus satisfied by a combination of the torque provided by Units 2 and 3. Here the pressure in Line A is a function of the total torque required at the wheels minus the torque provided by Unit 3. When the pressure in Line A exceeds that of line C, and hence that of the HP accumulator, check valve (13) opens and (15) closes. This causes the circuit to convert to a hydrostatic driving mode.

Braking

Regenerative braking is initialized by moving Unit 1 to zero displacement and Units 2 and 3 to some nominal displacement. Oil from Units 2 and 3 continues to flow from Lines A and C to Line B. However as flow cannot leave through Unit 1 the pressure will build until it exceeds the high pressure accumulator's pressure and begins to flow through check valve (14) and into the HP accumulator. Braking torque is a function of the HP accumulator's pressure and both Unit 2 and 3's displacement. As pressure increases Unit displacements are adjusted to achieve the desired level of braking torque. The energy captured during regenerative braking is now available for reuse as needed throughout the cycle.

3. PLATFORM VEHICLE

A 1999 Land Rover Range Rover was chosen as a demonstration vehicle in which to implement the blended hydraulic hybrid transmission. A picture of this vehicle can be found in Figure 2.

Figure 2: Base demonstration vehicle

The SUV demonstration platform was selected in response to several considerations including among others ample seating for four evaluators, large quantities of available kinetic energy during braking, a relatively spacious packaging environment, existing four wheel drive, and less reliance on existing CAN based powertrain control. Select vehicle parameters are located in Table 1.

Table 1: Select vehicle parameters

Axle ratio:	3.54:1	Engine:	136 kW @ 4750 rpm
Tire rolling radius:	0.358 m	Engine:	340 Nm @ 2600 rpm
Frontal area:	2.78 m^2	Fuel:	Gasoline
Drag coefficient:	0.4	GVM:	2780 kg

4. TRANSMISSION DESIGN AND SIZING

Proper transmission design and sizing is critical for balancing system performance with fuel economy. Far too often simulation studies into hybrid vehicles focus on maximizing fuel economy for a specific drive cycle while neglecting the effects on vehicle performance and drivability. While this may go unnoticed in simulation, a poorly performing demonstration vehicle would be immediately apparent to anyone driving. Consequently great care went into ensuring the demonstration vehicle equalled or exceeded the baseline vehicle's performance while simultaneously maximizing fuel economy.

Transmission sizing began by first instrumenting then baselining the current vehicle. These results severed as both performance metrics and a means to validate the vehicle dynamics model to be used in simulation. A high fidelity simulation model was then created in MATLAB Simulink of the vehicle's powertrain including the new blended hybrid transmission. Optimal component sizing for all three hydraulic units and both accumulator's was then conducted through a large scale design of experiments. Here various combinations of unit sizes, accumulator sizes, and accumulator precharge pressures were simulated and compared over the industry standard Urban Dynamometer Driving Schedule. In this study each transmission was optimally controlled using dynamic programming to eliminate the influence of control on fuel economy thereby ensuring a fair comparison. Once completed the combination of unit and accumulator sizes which resulted in the maximum fuel economy, while still meeting or exceeding the baseline vehicle's performance, were selected for the demonstration vehicle. Select transmission parameters are located in Table 2. More details on the transmission design and sizing processes for this vehicle can be found in Bleazard et al. (2015).

Table 2: Select blended hybrid transmission parameters

Unit 1:	100 cc	Max pressure:	450 bar
Unit 2/3:	75 cc	HP accumulator volume:	32 l
Charge:	27 cc	LP accumulator volume:	40 l
Low pressure:	30 bar	HP accumulator pre-charge:	130 bar

5. HARDWARE IMPLEMENTATION

Implementing the blended hydraulic hybrid transmission in the demonstration vehicle required first removing the existing automatic transmission as well as the transfer case and fuel tank. Once complete a CAD model was created of the vehicle's chassis and underbody to define packaging constraints. Transmission components were then modeled in CAD and positioned to ensure everything would fit in the limited space available. Finally fixturing and supporting members were designed to form one cohesive packaging assembly. A CAD render of the transmission packaging is located in Figure 3. It is worth noting the dual purposes of constructing this hybrid vehicle as both technology demonstrator and research platform. Consequently much of the hardware integration was focused on ease of construction as well as simplifying future modifications. If this architecture were to go into series production then many of the components would be condensed down into a single transmission assembly.

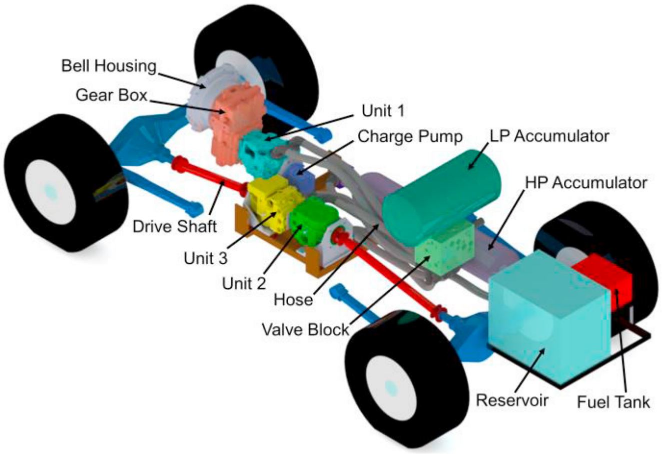


Figure 3: Demonstration vehicle CAD render

Select modifications to the base vehicle included replacing the existing fuel tank with a smaller version fitted with zero spill quick disconnects. This configuration enables accurate gravimetric fuel consumption measurements between cycles. These alterations and others can be seen in a picture of the vehicle's underbody (Figure 4).

A custom bell housing and flywheel adapter plate were machined to couple the engine and pump drive (gear box). A speed reduction of 1.48:1 was chosen to address the wide range of operating speeds seen in typical gasoline engines. However if a diesel engine or bent axis unit were used this speed reduction would be unnecessary. A supporting frame with vibration dampers was created for the pump drive to which both Unit 1 and the charge pump were attached. Units 2 and 3 were mounted in roughly the same space that the transfer case had previously occupied. This ensures that the drive shafts connecting units and axles function properly over the full suspension travel. Throughout the vehicle vibration dampers were installed at each location where the transmission was attached to the vehicle in order to minimize structure borne noise propagation to the vehicle's occupants.

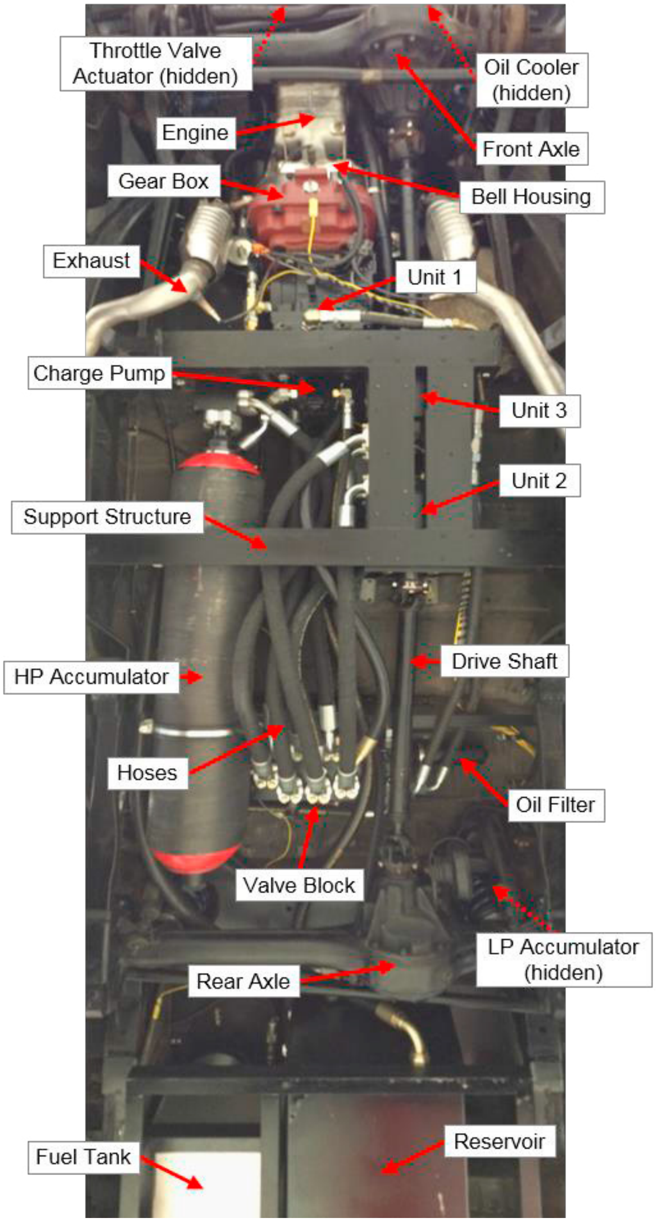


Figure 4: Demonstration vehicle underbody

Both high and low pressure accumulators were constructed using composite materials to minimize weight and improve performance. The low pressure accumulator is composed predominantly of carbon fiber while the high pressure accumulator features a steel shell wrapped in aramid fiber. To maximize energy storage efficiency the high pressure accumulator's gas volume was filled with foam which minimizes thermal losses and the associated energy dissipation. The accumulators, hydraulic units, and various other hydraulic components were connected by hoses to a centralized valve block. This compact valve block houses the majority of valves and sensors while providing connections between the various hydraulic components.

Traditionally engines found in on-road vehicles produce torque in response to the driver's throttle command whereas engines used in off-highway applications operate under closed loop speed control. However several of the blended hybrid's modes of operation are better suited for use with a speed controlled rather than torque controlled engine. To address this issue an actuator and associated engine speed controller was installed on the engine replacing the mechanical link between throttle pedal and throttle valve.

Position sensors were added to the throttle and brake pedals in order to capture driver inputs into the powertrain. While regenerative braking is normally used during vehicle deceleration the original friction brakes remain as a safety precaution. In interest of safety it is desirable to have only one brake pedal for both systems. This was accomplished by increasing the brake pedal's travel such that roughly the first 3 cm of pedal travel is only sensed electronically and used to control regenerative braking. However as the brake pedal is further depressed the friction brakes are activated in the normal manner.

In addition to the pedal position a number of other sensors were incorporated into the car including engine speed, vehicle speed, lateral and yaw accelerations, brake pressures, transmission pressures, and transmission temperatures among others. These sensors were linked to a real time controller which provided powertrain data acquisition and control. A simplified schematic of information flow can be seen in Figure 5.

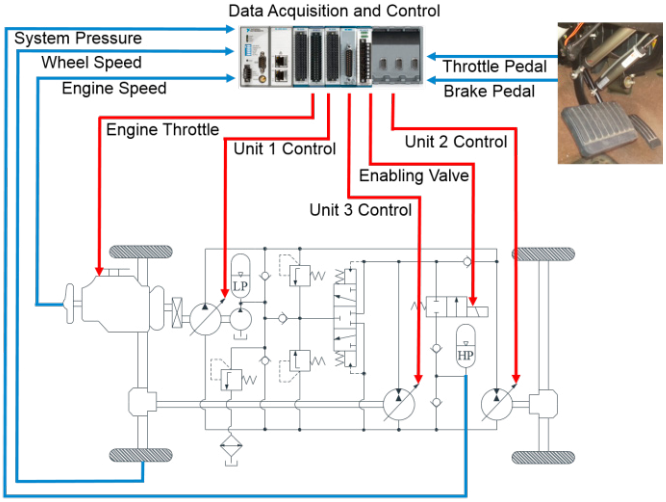


Figure 5: Sensors and information flow

6. CONTROLLER DEVELOPMENT

Exploring driver feel and perception was a principle impetus behind the construction of the blended hydraulic hybrid demonstration vehicle thus developing control schemes with good drivability was essential. As discussed in Section 2 the blended hybrid operates in four distinct modes of operation: hydrostatic driving, hybrid driving, blended hydrostatic and hybrid driving, and braking. Controls for each of these four modes of operation are briefly discussed here. While control methods for hydraulic hybrid driving of off-highway vehicles have been investigated in the past, the control of HSTs for on-road vehicles is unique to this study. Hydrostatic transmissions are widely used in off-highway applications however they are used almost exclusively in conjunction with speed controlled engines. At a basic level HSTs can be thought of as simple input-output systems with an infinitely variable transmission ratio. When an HST is coupled to a speed controlled engine the loop closed around engine speed propagates through the transmission resulting in a certain output shaft speed. The driver of these off-highway transmissions thus directly control vehicle speed by adjusting the transmission ratio, engine speed set point, or both. This is in stark contrast to drivers of on-road vehicles who control the engine's combustion torque which is propagated through the transmission to the wheels.

While the author's cannot say whether or not a speed controlled on-road vehicle would possess acceptable driveability, it is a safe assumption that it would yield a substantially different driving experience. Thus it was decided that the best way to ensure a positive driving experience was to replicate the feel of a traditional on-road vehicle. Prior work by Sprengel and Ivantysynova (2013b) proposed allowing the driver to control the engine's combustion torque while an integrated controller adjusted the transmission's ratio to balance performance with fuel economy. While this approach has the benefit of producing a familiar driver feel it was decided that for the first iteration of vehicle controls the engine should remain in speed control through all modes of operation. The intent was to ensure smooth transitions between the various modes of operation however switching to torque control during HST driving will be investigated in future studies.

Reproducing the feel of a torque controlled powertrain using a speed controlled system requires first analysing the typical relationship between throttle pedal motion and vehicle speed.

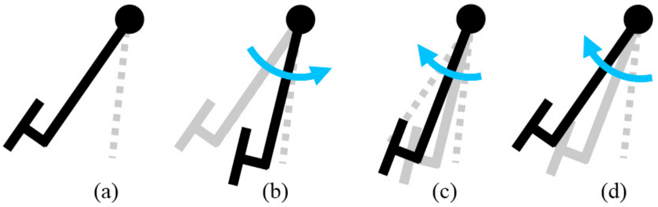


Figure 6: Throttle pedal positions

Figure 6 (a) shows a throttle pedal in its nominal positon. When the vehicle is at rest manual transmissions produce no output torque while automatic transmissions produce some output torque due to the torque converter. Once the throttle pedal is depressed (b) the engine begins producing torque as function of engine speed and pedal position which is propagated through the powertrain. The vehicle will accelerate based on vehicle dynamics until the propulsive torque is balanced with the vehicle's resistive torque (aerodynamic drag, rolling resistance, grading force, etc.). When the pedal position is decreased (c) the vehicle will either continue to accelerate or begin to decelerate depending on the vehicle's current speed and external loads until a torque balance is once again reached. Finally once the throttle pedal returns to its nominal position (d) the vehicle speed will decrease aided by engine braking and other resistive torques.

Imitating this response with the blended hybrid's speed controlled hydrostatic transmission begins by sensing the throttle pedal's position. Using a simplified powertrain model the driver's throttle input is converted into a torque which is propagated through the transmission's current ratio before being applied to a vehicle dynamics model (Figure 7). This 1D vehicle dynamics model determines the driver's desired acceleration which is then integrated to determine desired vehicle speed based on current speed and commanded engine torque.

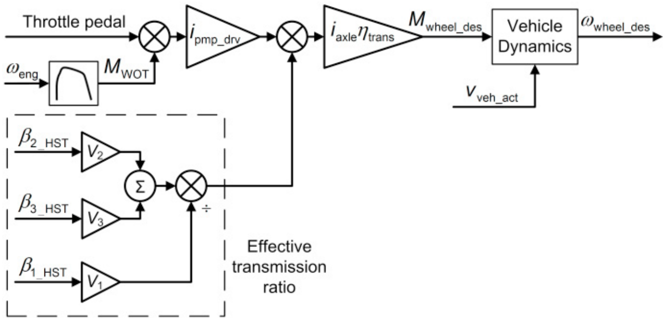


Figure 7: Desired vehicle speed

Approximant unit displacement are then calculated based on desired vehicle speed and current engine speed (Figure 8).

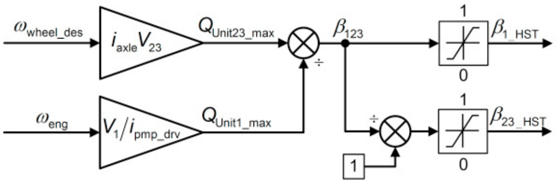


Figure 8: Full HST driving controller

One important component of this control strategy is that it remains completely open loop and feed forward in nature. The driver's throttle command is converted into a desired vehicle speed which is then acted upon. However as the driver has no knowledge of this internal control signal its exact magnitude is not critical. Rather the driver perceives the vehicle's actual speed and will adjust their throttle input accordingly. It is quite important for drivability that the transmission responds rapidly to changes in the driver input. For example if the actual vehicle speed is lagging behind the internal vehicle speed command and the driver releases the throttle pedal then the vehicle should immediately begin decelerating. However if a closed loop feedback term (e.g. PI) was included in the controller then the vehicle could potentially continue increasing in speed until the commanded speed was reached before finally beginning to decelerate. Obviously this is undesirable as the transmission controller's main task is to respond instantaneously to driver commands, not to follow some arbitrary reference cycle.

The hybrid mode controller determines desired transmission torque in the same way as the HST controller. Although here the effective transmission ratio calculation uses the same unit displacements as would be commanded if the transmission were operating as a HST. This ensures the same transmission response and feel is obtained regardless of whether the powertrain is operating in HST or hybrid modes. However instead of converting this desired torque into a velocity the hybrid mode controller calculates the appropriate Unit 3 displacement to achieve the desired torque based on current accumulator pressure (Figure 9).

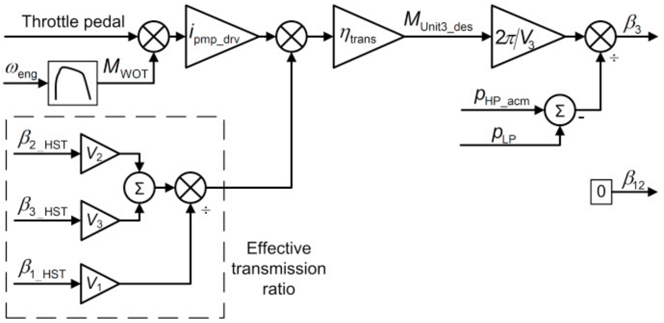


Figure 9: Hybrid mode controller

Combined HST and hybrid driving control uses aspects of both previously discussed control schemes. The hydrostatic transmission formed by Units 1 and 2 begins with the same desired speed controller shown in Figure 7. However unit displacements are now calculated using only the flow from Units 1 and 2 rather than from all three units as seen previously (Figure 10).

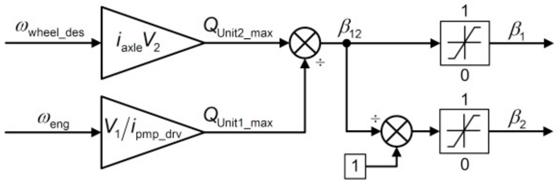


Figure 10: HST controller for combined HST hybrid driving

In the combined HST and hybrid driving mode Unit 3's displacement is calculated in the same manner as the full hybrid mode with the exception that Unit 3 is commanded to provide only half of the desired transmission torque. Providing half of the desired torque is a straight forward way to divide torque between the two transmission segments though it may be improved through a more advanced power management scheme.

Regenerative braking control uses brake pedal position and accumulator pressure as the primary controller inputs. During braking, accumulator pressure rises as more energy is captured. However as braking torque is a function of both unit displacement and accumulator pressure this inevitable increase in pressure must be taken into account. An arbitrary mapping was created to relate brake pedal position to desired braking torque. From here the required Unit 2 and 3 displacements are calculated based on desired braking torque and current accumulator pressure (Figure 11).

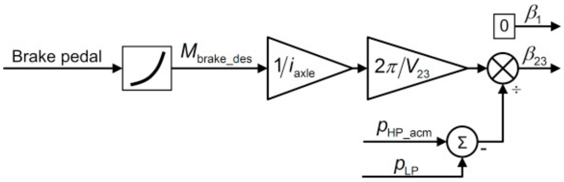


Figure 11: Regenerative braking controller

There exists several areas of control for the blended hybrid transmission which are quite important though not covered here. Among others these include techniques to smoothly shift between the various modes of operation. Also important is a supervisory power management controller which determines when to shift between the various modes of operation as well determining the current engine operating point. These control strategies will be discussed in depth in future works as their influence on drivability is refined.

7. MEASUREMENTS

Preliminary measurements taken during vehicle shakedown testing show an initial implementation of the control strategies presented in this paper. For these measurements the driver commanded a simple acceleration and deceleration driving event to demonstrate all four modes of operation (Figure 12).

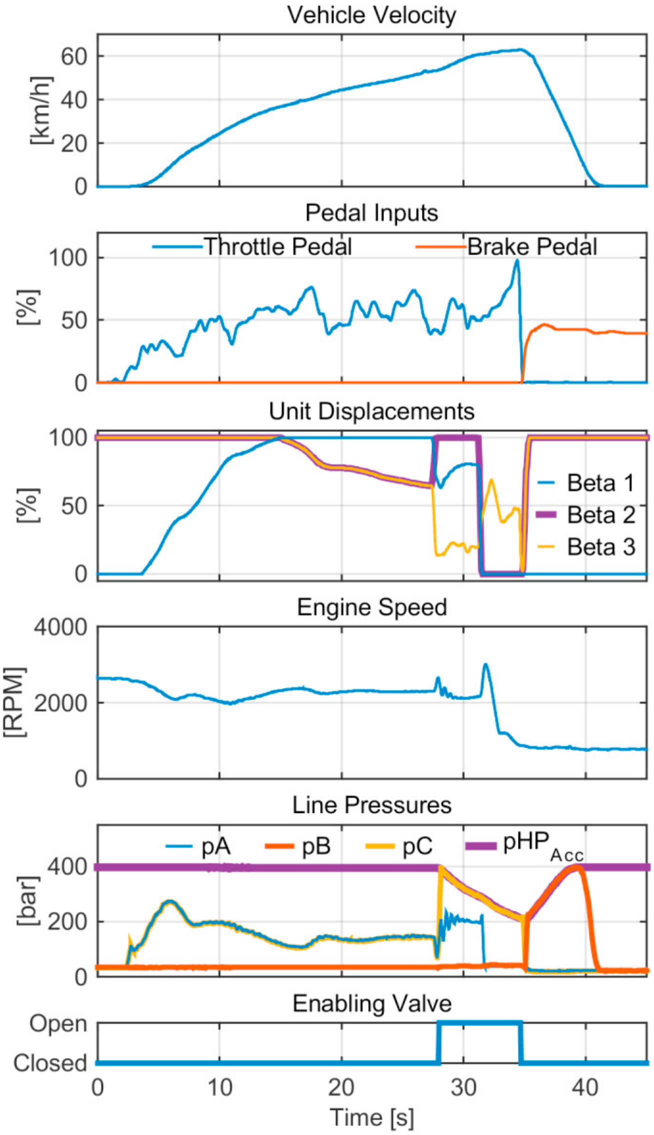


Figure 12: Blended Hybrid Measurement Results

In the beginning of the acceleration event from approximately 5 seconds to 27 seconds the transmission is operated in hydrostatic mode. The driver's commanded torque from the throttle pedal was fed through the desired vehicle speed model and the HST controller which resulted in hydraulic unit displacements that properly accelerated the vehicle. During hydrostatic driving Lines A and C are at the same pressure and flow from Unit 1 is absorbed by Units 2 and 3.

Following the hydrostatic acceleration the transmission enters the blended mode at approximately 27 seconds. During this time the enabling valve is open and power is split between Unit 2 in hydrostatic control, and Unit 3 which is exposed to the pressure in the high pressure accumulator through Line C. The displacement of Unit 3 is determined by the hybrid mode controller to meet a portion of the desired demand coming from the driver. Unit 1 and 2 are operated as a hydrostatic transmission in speed control. The oscillation seen in Line A pressure is due to oscillations in the engine speed.

At approximately 32 seconds the transmission switches to full hybrid mode. The enabling valve stays open during this event while Units 1 and 2 go to zero displacement. The hybrid mode controller is utilized to ensure that the driver demand is met by Unit 3 with power coming from the high pressure accumulator.

At 35 seconds the driver commands a deceleration event through the brake pedal. This command is fed through the regenerative braking controller which determines Unit 2 and 3 displacement based on the current accumulator pressure. Unit 1 is set to zero displacement and Units 2 and 3 begin pumping high pressure fluid into Line B and the high pressure accumulator. During this event the driver command resulted in full displacement of the hydraulic units. With these units in pumping mode the kinetic energy of the vehicle is stored in the high pressure accumulator as the vehicle decelerates for later use.

8. CONCLUSIONS

This paper presents an overview of the integration and testing of a novel blended hydraulic hybrid transmission in a demonstration vehicle located at the Maha Fluid Power Research Center. Included in this work is a description of the modifications which went into converting the automatic transmission based vehicle into a novel hydraulic hybrid demonstration vehicle. Unique control schemes were then proposed for each of the blended hybrid's distinct modes of operation. This paper concludes with initial measurement results highlighting the blended hybrid's operation during a typical driving event.

The blended hybrid architecture has been under investigation since first being proposed by Sprengel and Ivantysynova in 2012. During this time multiple studies have been conducted which have predicted the improvement in fuel economy and performance which the blended hybrid offers over conventional hydraulic hybrid architectures. The blended hydraulic hybrid architecture has also been validated on a hardware-in-the-loop transmission dynamometer which demonstrated the concept's feasibility. However this is the first study which presents the blended hybrid in a fully functional demonstration vehicle. Initial driver perception is quite good and the authors are confident that the blended hybrid will achieve a feel similar to conventional vehicles as controller development progresses albeit with improved fuel economy.

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