Hydraulic Hybrid Powertrain-In-the-Loop Integration for Analyzing Real-World Fuel Economy and Emissions Improvements

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ABSTRACT

The paper describes the approach, addresses integration challenges and discusses capabilities of the Hybrid Powertrain-in-the-Loop (H-PIL) facility for the series/hydrostatic hydraulic hybrid system. We describe the simulation of the open-loop and closed-loop hydraulic hybrid systems in H-PIL and its use for concurrent engineering and development of advanced supervisory strategies. The configuration of the hydraulic–hybrid system and details of the hydraulic circuit developed for the H-PIL integration are presented. Next, software and hardware interfaces between the real components and virtual systems are developed, and special attention is given to linking component-level controllers and system-level supervisory control. The H-PIL setup allows imposing realistic dynamic loads on hydraulic pump/motors and accumulator based on vehicle driving schedule. Application of fast analyzers allows characterization of the impact of dynamic interactions in the propulsion system on engine-out emissions. Therefore, the H-PIL facility allows optimization of the hybrid system for both high-efficiency and low emissions. The impetus is provided by previous work showing that more than half of the soot emissions from a conventional diesel powertrain over the urban driving schedule can be attributed to transients. The setup includes a 6.4L V-8 International diesel engine, highly dynamic dynamometer, Radial piston pump/motors supplied by Bosch-Rexroth and dSPACE real-time environment with in-house developed simulation of the virtual vehicle.

INTRODUCTION

The energy security and climate change concerns provide a strong impetus for development of alternative powertrains. In particular, hybrid propulsion systems enable a significant leap in the fuel economy improvements through utilization of regenerative braking, optimization of engine operation, possible downsizing and start/stop strategies. Hybridization of trucks has a potential for very profound impact, since trucks spend a lot more time on the road, which leads to high annual fuel consumption per vehicle. Until recently, the fuel economy of trucks was unregulated and left up to the market forces, but the recent Presidential memorandum launched a joint EPA and NHTSA effort to establish the fuel efficiency and greenhouse gas emissions standards for medium-and heavy-duty vehicles beginning with model year 2014. While published work provides significant evidence of the fuel economy potential for various hybrid configurations and energy conversion options [***1***,***2***,***3***,***4***,***5***,***6***], the simultaneous minimization of the pollutant emissions represents a next frontier.

Tailpipe emission standards in the United States, and Europe – Euro VI, are becoming ever more stringent in order to reduce the impact of the transportation sector on air quality. They necessitate application of the exhaust after-treatment systems. The typical aftertreatment system comprises a Diesel Oxidation Catalyst, Urea Selective Catalytic Reduction (SCR) and the Diesel Particulate Filter. This increases the complexity, cost and controls challenge for a modern diesel engine powerplant. The flexibility enabled with hybridization creates chances for a synergistic approach, in which the hybrid supervisory control will be augmented to address both emissions and efficiency. The reward will be a possibility to reduce engine-out emissions and with that the size and complexity of the aftertreatment system, thus making the hybrid propulsion more affordable and more likely to penetrate the market in large numbers. This generates motivation for development of novel methodologies, capable of bringing real-world diesel emissions into the hybrid system design and control development process.

Power flows through hybrid subsystems during launch and braking can be very high in a truck due to their large mass. Hydraulic devices, with their high power density and high energy conversion efficiency are very well-suited for hybridization of trucks. In addition, a hydraulic accumulator is capable of accepting high rates of charging and discharging, which is otherwise a challenge for electric batteries. However, the low energy density of hydraulic accumulator needs to be addressed during supervisory controller design. Previous work done by Filipi et al. [***3***] and Kim et al. [***1***] showed excellent fuel economy with the hydraulic powertrain, but uncovered a potential challenge related to the impact of engine transients on emission, if a supervisory control is approached in a traditional way with the sole focus on fuel economy.

Recently researchers [***7***,***8***,***9***,***10***,***11***] have evaluated the effect of transients on diesel engine emissions. Samulski and Jackson [***7***] showed particulate emissions from diesel engines are very sensitive to transient operation and reported an average increase of 47% over steady state. Rakopoulos et al. [***11***] used a two-zone transient diesel engine thermodynamic model to study the effect of load and engine parameters on transient emissions and noted a significant increase in soot production with a step change in load. Based on advanced experimentation for testing under highly dynamic conditions, Hagena et al. [***12***] concluded that transient soot emissions can account for almost half of the total soot emission when an engine is operated over a realistic driving schedule. Transient conditions easily dominate the emission trends for a heavy-duty vehicle, particularly over an aggressive driving schedule like FTP72. Consequently, dealing with transients needs to be part of the overall low-emissions strategy and hybridization offers unique mechanisms for doing so.

The evolution of modeling and simulation tools for a hybrid system enables analysis, optimization of design and control, and subsequent assessments of the fuel economy potential with high degree of confidence [***13***,***14***]. However, predicting the correct composition of the engine exhaust would require 3D Computational Fluid Dynamics (CFD) and chemical kinetics [***15***,***16***] which are prohibitively slow for system level analysis. This led to a decision to bring experimentation into the hybrid system analysis and optimization, by integrating the real engine [***17***] with simulated driveline, vehicle and the driver thus creating an Engine-in-the-Loop (EIL) facility. The research-grade instrumentation in the test cell, including the fast analyzers, enables in-depth measurements. Preserving sufficient fidelity in real-time driveline and vehicle models provides the opportunity to study novel designs and control strategies. Filipi et al. [***17***,***3***] showed that creating a supervisory controller to maximize fuel economy with no consideration for engine-out emissions can lead to an undesirable increase in particulate emissions. An intelligent supervisory controller; designed with multiple objectives, is essential for realizing both efficient and clean vehicles with reduced burden on the after-treatment systems. However, component dynamics have an impact too, thus the Hybrid Powertrain–In-the-Loop (H-PIL) facility is designed to integrate hydraulic components with the engine and provide an opportunity to systematically assess the effects of interactions of real actuators in the driveline. The H-PIL allows studying drivability issues as well.

The paper describes the approach and methods for developing a Hydraulic Hybrid Powertrain–In-the-Loop facility. We begin with a description of the series hydraulic hybrid vehicle (S-HHV) configuration and the challenges related to the integration of such powertrain with the virtual vehicle in the dynamometer test-cell. Next, the experimental setup and features of the key equipment and test instrumentation are discussed in detail. Fast emission analyzers for soot and NO_X, and engine instrumentation for combustion diagnostics during diesel engine transient operation are included, as well as development of the hydraulic circuit for integration of the hydraulic driveline in the test cell using an external power-unit with an open reservoir and fluid cooling. The hybrid supervisory control implementation in the dSPACE system and integration of the electronic systems is documented through discussion of two examples, an open-loop hydrostatic control of the hydraulic Infinitely Variable Transmission, and a closed-loop charge sustaining control of the S-HHV with a large accumulator for energy storage. Results obtained over an urban driving schedule demonstrate the depth of insight enabled with the H-PIL facility, including the impact of the component-level actuation on the system behavior and emissions. The paper ends with summary and conclusions.

INTEGRATING VIRTUAL MODELS WITH A REAL HYBRID POWERTRAIN

The system under consideration is a series hydraulic hybrid, with a V8 medium-duty diesel engine and radial piston hydraulic pump/motors with solenoid controlled valves. This means that no mechanical connection exists between the engine and traction motor, and there is full flexibility in controlling the engine operation. The system has been extensively studied through the simulation work [***1***,***2***] and a first glance at the transient emissions was provided by Filipi at al. [***3***] The work reported here takes the hardware integration a significant step further by including the entire hydraulic driveline and decoupling the engine from the dynamometer. Figure 1 shows a picture of the hardware included in the H-PIL setup at the University of Michigan. The power generation subsystem comprises the V8 diesel engine and the hydraulic pump, shown in the forefront. The propulsion subsystem includes a hydraulic traction motor coupled with a dynamometer, which simulates the vehicle inertia. There is no physical connection between the power generation subsystem and propulsion subsystem except for the hydraulic fluid. The absence of the mechanical connection between the engine and the dynamometer creates a very unique situation related to dynamometer control, and cooperation of the equipment vendor was necessary to allow software updates for the test cell controller and independent control of engine speed and dynamometer speed.

In the H-PIL setup, the diesel engine is instrumented with various pressure transducers, thermocouples, and flow meters, which were directly connected to AVL fast front end modules (F-FEMS) for time-based data acquisition. For crank-angle resolved measurements the Indimaster indicating system was used to capture in-cylinder pressure, fuel injection pressure, and needle lift. These boards communicate with the AVL PUMA Open system, a test cell/engine monitoring and data acquisition system.

Figure 1 – Hydraulic Hybrid Powertrain-in-the-Loop setup

The interface between the key hardware and software components is developed using a dSPACE platform. The dSPACE real-time platform is a modular system with flexible processor arrangement and I/O boards. The dSPACE system simulates virtual components in real-time, communicates with the engine, hydraulics and the dynamometer via a test cell controller, and finally supervises and coordinates operation of the hybrid propulsion. The DS1006 simulates the virtual components in real time, and coordinate the communications between the remaining I/O boards. The custom AVL board interfaces the dSPACE control box with the PUMA system and allows two-way communication between dSPACE and AVL PUMA. The DS2202 is the main I/O board of the system, and is responsible for reading the various pressure sensors, flow sensors signals and controlling the relay to decouple the high pressure accumulator. The DS4302 board allows CAN communication with the pump and motor servo-controllers.

EXPERIMENTAL SETUP

DYNAMOMETER

The 300 kW AVL ELIN series 100 APA Asynchronous Dynamometer simulates the load experienced by the engine based on the signals from the virtual driveline/vehicle and the supervisory controller. The mode of operation utilized in our setup is to maintain rotational speed as close as possible to a commanded value. An embedded dynamometer controller is responsible for minimizing the difference between actual and desired speeds, with the speed command coming from the supervisory controller. A built in torque sensor measures torque and enables safe operating conditions. Dynamometer has a 5ms torque response time, thus being capable of reproducing fast transients that are normally experienced in the real vehicle.

ENGINE SPECIFICATIONS

The engine used in this investigation is a 6.4 L V-8 direct-injection diesel engine manufactured by the Navistar Truck and Engine Corporation. Engine specifications are given in Table 1. The engine is intended for a variety of medium duty truck applications covering the range between Classes IIB and VII.

Table 1 - Diesel engine specifications

Engine Type	**DI 4-Stroke Diesel Engine**
Configuration	V-8, Cam-in-Crankcase, 90°
Bore x Stroke	98 mm x 105 mm
Displacement	6.4 L
Rated Power	261 kW @ 3000 RPM
Rated Torque	881Nm @ 2000 RPM
Compression Ratio	16.5 : 1
Valve Lifters	Push Rod-Activated Rocker Arm
Aspiration	Variable Geometry Dual stage Turbocharger / Intercooler
Fuel Delivery System	High Pressure Common Rail Direct Injection (CRDI)

The engine incorporates advanced technologies to provide high power density while meeting emissions standards when integrated with aftertreatment. A high pressure common rail direct injection (CRDI) system permits the precise control of fuel injection timing, pressure, and quantity, and furthermore allows the use of six injections per cycle. An exhaust gas recirculation (EGR) circuit is used to introduce cooled exhaust gases into the intake manifold in order to decrease NO_X emissions. EGR flow rate is controlled through modulation of the EGR valve and the setting of the variable geometry turbocharger (VGT). The VGT is also used to enhance engine performance, as it reduces boost lag and allows control of the intake manifold pressure. Additionally, an engine starter is used together with two standard 12V engine batteries connected in series to start the engine from stand still. A starter is required as the decoupled engine cannot be started by the dynamometer, and the pump was not setup for motoring.

HYDRAULIC DRIVELINE

The H-PIL facility is designed to simulate two different hydraulic powertrain configurations in the loop with the virtual vehicle. Depending on the desired powertrain configuration, the H-PIL setup can be used to simulate a hydrostatic driveline i.e. infinitely variable transmission, or a full series hybrid with energy storage. In either configuration, the hydraulic pump is connected to the engine and the traction hydraulic motor to the dynamometer, with no mechanical connection in between.

The hydraulic circuit illustrating the integration of the hydraulic components with the engine and the dynamometer in the H-PIL setup is shown in Figure 2. The setup is fully instrumented with high and low pressure sensors, and flow meter to completely characterize the hydraulic powertrain operation. In addition, the setup includes an oil conditioning unit to simulate different hydraulic oil operating temperatures to assess the impact of viscosity on the hydraulic powertrain. The hydraulic fluid path includes oil filter at different locations to remove any foreign particles from the hydraulic oil, and to protect the system from any debris. The H-PIL setup has two high pressure accumulators in the hydraulic path to act as energy storage and reduce pulsation.

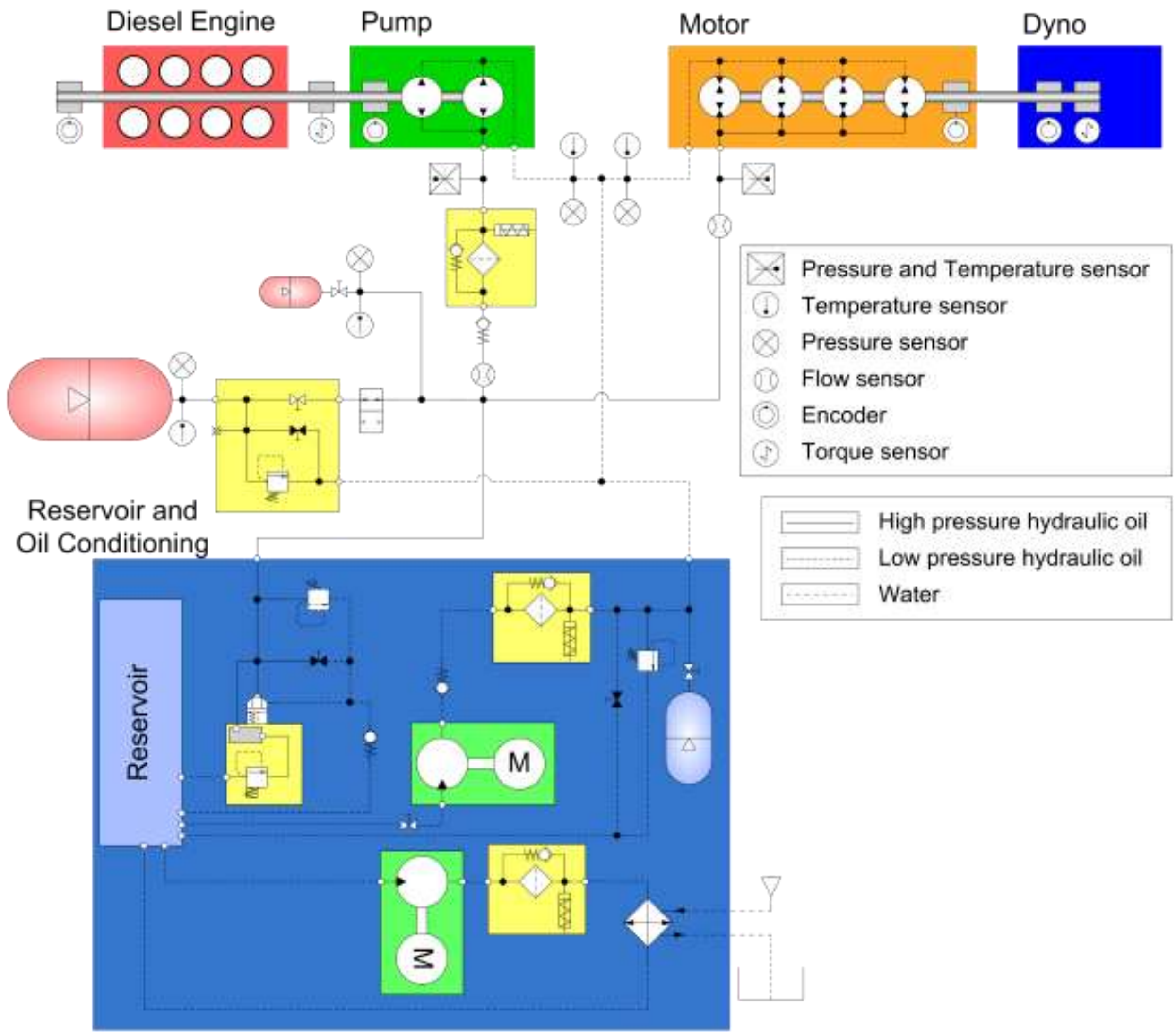

Figure 2 – Hydraulic hybrid powertrain circuit

To maintain safe operating pressures and undesirable damage to the H-PIL setup, the facility is equipped with pressure relief valves at the inlet of the high pressure accumulator and return line to reservoir. The facility is also equipped with a proportional pressure relief valve to dynamically control the maximum operating pressure of the system.

Pump and Motor

The hydraulic pump and motor are high efficiency digital displacement devices developed specifically for mobile application. The hydraulic pump/motor consists of banks of cylinders disposed radially around an eccentric with high and low pressure valves around in the periphery. The core components of a digital displacement pump/motor are the actively controlled poppet valves which guide the flow into, and out of, each cylinder. To maximize the efficiency over a broad range of operating loads, the hydraulic pump/motors alter the number of active cylinders thereby changing the output torque. The digital displacement effectively replaces the port plates and swash plates in conventional hydraulic machines with electronically controlled high speed solenoid valves. This leads to very high operating efficiency in part-load conditions, and unprecedented controllability. The pump and motor specifications in H-PIL are summarized in Table 2.

Table 2 - Hydraulic pump and motor specifications

	Units	Pump	Motor
Displacement	[cc/rev]	96	192
Operating Speed	[RPM]	500-3000	0-2500
Max. Torque	[Nm]	600	1200
Max. Pressure	[bar]	400	400

In the H-PIL, the hydraulic devices are named pump and motor for simplicity. The pump is coupled to the engine, while the traction motor delivers propulsion torque to the dynamometer. The traction motor is reversible and allows regenerative braking in the series hybrid configuration.

Accumulators and Electronic Shut-off Valve

The H-PIL setup comprises two accumulators on the high pressure side. The high pressure accumulators are 38 L and 2 L in size. The large accumulator acts as the energy storage device in the series configuration, while the smaller accumulator dampens the high pressure pulsations during the hydrostatic mode of operation. The large accumulator can be disconnected from the hydraulic path via electronic check valve to simulate hydrostatic driveline with no energy storage.

Reservoir and Oil Conditioning

A low pressure reservoir is employed in hydraulic hybrids to prevent cavitation in the hydraulic components. Typically the reservoir is similar to an accumulator except that the working pressure is much lower. However, the H-PIL setup uses a different type of reservoir designed to deaerate the hydraulic oil, and serve as an oil conditioning unit. A constant displacement charge pump is used to maintain a low pressure of 5 bar at the inlet of the hydraulic pump. The viscosity of the oil has significant impact on the efficiency of hydraulic components. The reservoir includes a heat exchanger to maintain the desired operating temperature of hydraulic fluid. Figure 2 gives a brief architectural overview of the reservoir.

EMISSIONS MEASUREMENT

Emissions Analyzer

An AVL Combustion Emissions Bench (CEB-II) was utilized to measure engine out exhaust gases. The CEB-II is capable of measuring total hydrocarbons, carbon dioxide (exhaust and intake for EGR), carbon monoxide, nitrogen oxides, and oxygen. Due to long sample lines and limitations of the analyzers, the CEB-II cannot provide insights into instantaneous emissions formation, but it provides accurate cumulative measurement [***9***].

Fast NO_X

To provide insights into the transient emissions produced by the engine, a CLD 500 Fast NO_X analyzer, manufactured by Cambustion Ltd., is utilized. The CLD 500 uses a chemiluminescent detector providing a $T_{90\% - 10\%}$ response time of less than 10 ms for NO_X analysis. To measure exhaust NO_X constituents, a NO_X converter is attached inline prior to the remote sampling heads and convert NO2 species to NO and then measures the total NO_X based on the chemiluminescent principle. The exhaust gases are sampled downstream of the engine turbine to maximize instrument response time [***17***].

Fast Particulate Sizer

Insights into transient particulate emissions are generated with a differential mobility spectrometer (DMS) 500 manufactured by Cambustion Ltd. This instrument measures the number size distribution of particulates between 5 nm to 1000 nm producing 10 Hz data with a 200 ms $T_{10\%-90\%}$ response time. The DMS 500 is also equipped with a two stage dilution system thus enabling extended direct engine out particulate measurement.

The DMS 500 uses the particulate mobility for detection. An electric charge is applied to the diluted particulate samples, which are then introduced into a classifier column with a set of high voltage electrodes – see Figure 3.

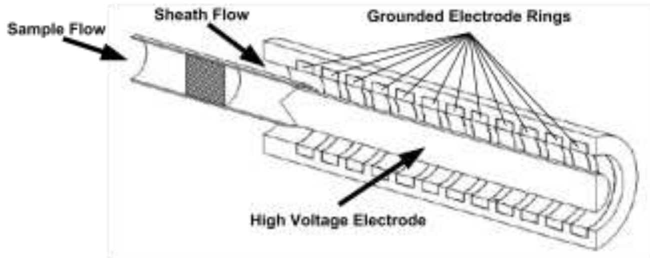

Figure 3 – DMS 500 Classifier Column [*22*]

The mobility of the particle, dependent on the charge to aerodynamic drag ratio, determines the distance the particle will travel before depositing its charge on the detector. The outputs of the detectors produce the spectral data, which can be correlated to mass via Hagena et al. [***9***].

VIRTUAL COMPONENTS

The H-PIL integration requires predictive models of virtual components capable of running in real time.   The transmission, driver, and vehicle models are created in Simulink, using physics based modeling described in [***18***,***17***,***19***].

Table 3 - Vehicle and gearbox specifications [*17*]

	Units	Specifications
1st Gear Ratio	[-]	3
2nd Gear Ratio	[-]	1
Differential Ratio	[-]	2.67
1st Gear Efficiency	[%]	96
2nd Gear Efficiency	[%]	100
Differential Efficiency	[%]	96
Up Shift Speed	[mph]	15.5
Down Shift Speed	[mph]	14.0
Vehicle Mass	[kg]	5112
Wheel Radius	[m]	0.4412
Wheel Inertia	[kg-m^2]	32
Brake Viscous Damping	[Nm-s/rad]	170
Wheel Bearing Damping	[Nm-s/rad]	4.0
Rolling Coefficient	[-]	0.7
Frontal Area	[m^2]	3.58
Coefficient of Drag	[-]	0.7

The transmission is modeled as a two speed gear box. The gear shift logic is devised with consideration of motor efficiency and to prevent gear hunting. The transmission model commands the motor speed through the dynamometer while receiving the measured torque by the dynamometer to accelerate the vehicle, shown in Figure 4. Specifications of the transmission can be found in Table 3.

The transmission model includes a blending function to simulate a realistic shift event. The virtual nature of transmission also enables simulation of other configurations such as a single speed transmission.

The vehicle used in this study is based on the super-HMMWV for all terrain capability with gross vehicle weight of 5 tons. The vehicle model uses an enhanced point mass model with longitudinal and heave motion. The resistive forces were modeled as rolling and aerodynamic drag resistance. The vehicle also contains a brake model, which acts as a coulombic friction device. Vehicle model is described in more detail in [***18***] and Table 3 gives its specifications.

The cyber driver is responsible for maintaining the vehicle speed close to a desired value, by using a proportional integral controller around the vehicle speed. This model is tuned to prevent harsh acceleration/deceleration commands to mimic a real driver. Additionally, the driver model includes preview to compensate for communication lag in the system [***18***]. Figure 4 shows the overview of integrated vehicle/powertrain virtual models to create the Hybrid Powertrain-in-the-Loop system.

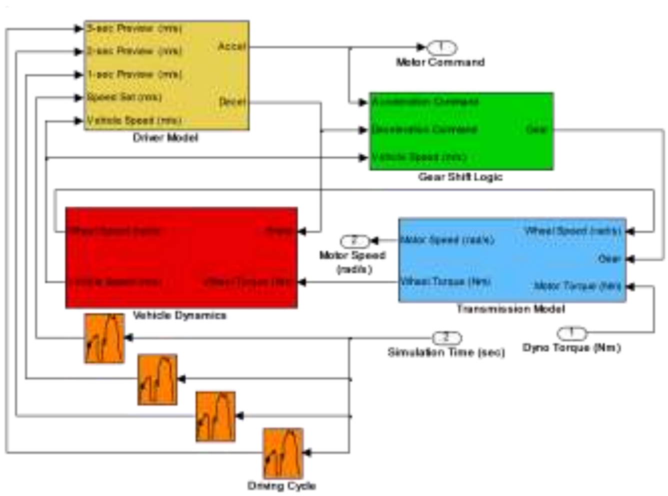

Figure 4 – Virtual components modeled in SIMULINK; Motor Command and Dynamometer Torque signals couple the virtual system with hardware

HYDROSTATIC CONTROL STRATEGY

The H-PIL setup is capable of running in hydrostatic or series hybrid configurations. The hydrostatic operation allows operating the powertrain as an infinitely variable transmission (IVT). The infinitely variable transmission allows the engine to operate independent of the vehicle, which means that the engine speed is completely decoupled from the vehicle speed. The advantage of such a system is that the engine can be operated to minimize fuel consumption. As mentioned before, the hydrostatic power generation subsystem (pump/engine) is connected to the propulsion subsystem (motor/dynamometer) via the high pressure fluid. The system employs a small pulsation accumulator to dampen pressure fluctuations and improve vehicle performance. The hydrostatic driveline operates at very high pressures to increase system performance. Note that regenerative braking is not possible since the hydrostatic configuration does have any energy storage capacity.

The hydrostatic power management controller needs to orchestrate three system components i.e. the hydraulic motor, the hydraulic pump, and the diesel engine to successfully drive the vehicle. The hydraulic motor is controlled directly by the driver as shown in Figure 5. To maintain constant operating pressure, the flow rate through the motor must be matched by the pump. In other words, the power generation subsystem needs to match the power consumed by the motor. A practical approach is to monitor the power out of the motor and to ensure that it equals the power generated by the engine. The control strategy employed in this paper includes a feedforward controller and feedback controller on the system pressure. The feedforward controller estimates the motor power based on motor torque, motor speed and motor operating efficiency. The feedback controller is required to correct for any discrepancy between actual motor power and estimated power. The feedback controller is a PI controller with the error signal obtained by subtracting the filtered high pressure signal, *P1*, from the desired pressure, *P1’*, as shown in Figure 5. The combined estimate is used to calculate the desired engine power, *Pw2’*.

The hydraulic IVT driveline gives an additional degree of freedom in operating the engine. The engine operation can be optimized to maximize the combined efficiency of the power generation subsystem i.e. engine and hydraulic pump efficiency. A combined efficiency map of power generation subsystem is created by combining the engine brake specific fuel consumption map with the pump efficiency map, similar to work done by Filipi and Kim [***12***]. For a given power demand, the engine operating point, i.e. desired engine torque and desired engine speed is calculated from the optimal operation line based on this combined efficiency map, Figure 5. The desired engine torque is converted to an engine throttle command using a lookup table. In order to actively maintain the engine speed at a desired value, the speed demand is compared with the actual engine speed and the error is sent to a PI controller that calculates the pump displacement command.

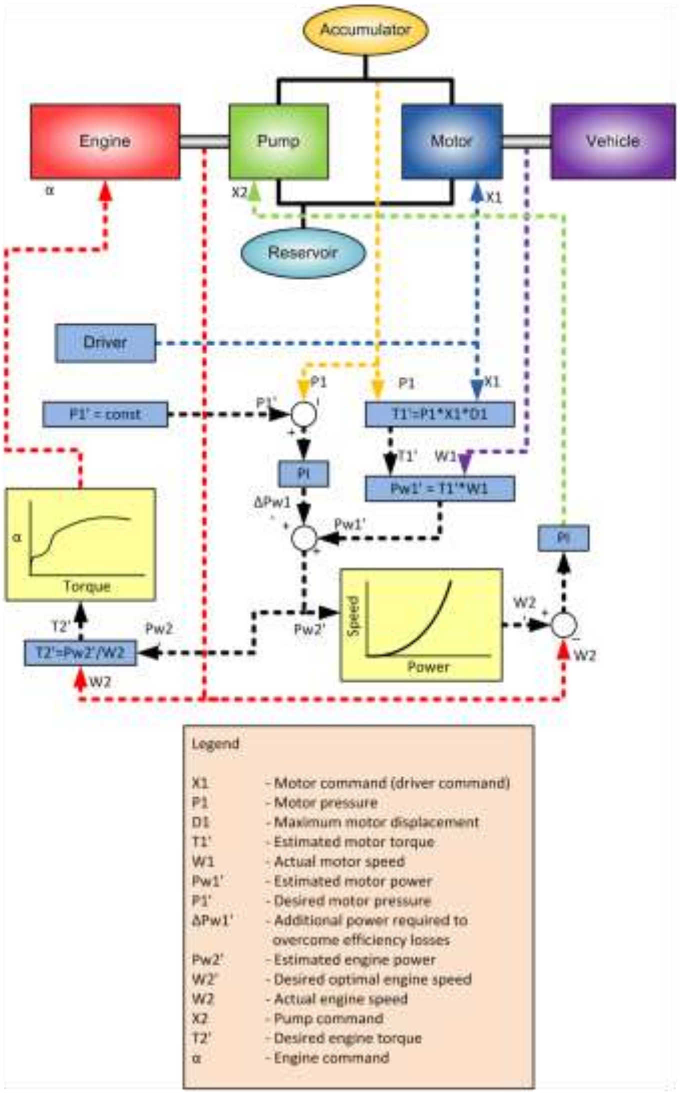

Figure 5 - Applied control strategy for hydrostatic operation

SERIES HYBRID CONTROL STRATEGY

The series hybrid powertrain differs from the hydrostatic by the fact that the high pressure accumulator is much larger, and therefore capable of energy storage. The control of the engine-pump system is much different than in the case of the hydrostatic operation, and the critical control variable becomes the State-of-Charge (SOC) which determines the pressure in the system. Rather than a classic thermostatic control of SOC, we apply a modulated control. A filtered pressure signal from the accumulator is used to estimate the SOC. As the pressure drops past the limit, a PI controller acts on the engine to maintain the desired pressure level, as illustrated in Figure 6.

There are two differences between this strategy and that of the hydrostatic powertrain. First, the engine power demand of the series hybrid is solely based on the pressure information, as compared with the hydrostatic that uses a feed forward estimation from the driver command and vehicle speed. Secondly, the desired pressure value, *P1'*, is usually much smaller than that of the hydrostatic powertrain. This is desired to maintain sufficient storage capacity for a typical regeneration event. The low pressure operation and large variations of pressure have significant impact on the motor control logic. A dual strategy can be adopted by using the powertrain in hydrostatic mode during high performance situations, and as a series hybrid during milder driving conditions and braking events.

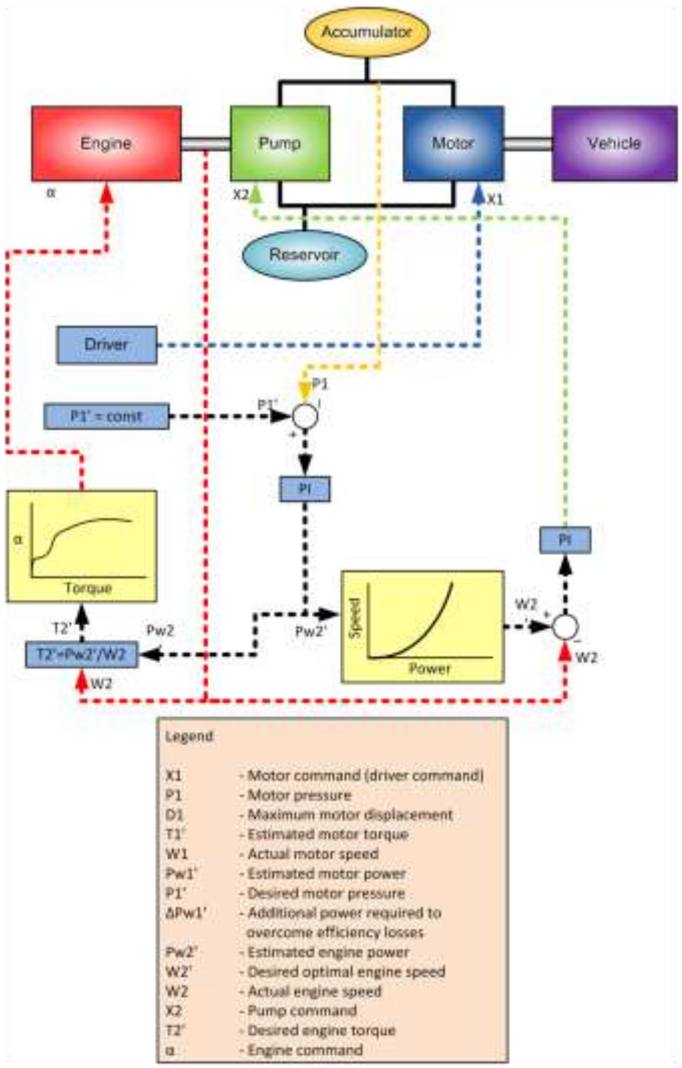

Figure 6 – Control strategy for series hybrid operation

POWERTRAIN-IN-THE-LOOP INITIAL RESULTS

HYDROSTATIC RESULTS

The hydrostatic powertrain behavior is investigated by simulating the super-HMMWV operation over the scaled FTP72 driving cycle. A half-scaled velocity profile is used to avoid extreme operating conditions in the early stage of work with prototype hydraulic units. The results in Figure 7 show that the hydrostatic powertrain acts as an infinitely variable transmission. The engine operates in the load following mode, but the speed and torque points are chosen independent of the vehicle velocity. The engine torque and speed are determined to provide the demanded power with the best possible efficiency. Since the measurement of the torque at the flywheel is not possible, the torque of the power generation subsystem is estimated using the pump. The pump torque $T_{estimated}$ is estimated using the equation below:

$$T_{estimated} = \eta \cdot x_{pump} \cdot D_{pump} \cdot p \qquad (1)$$

where η is the efficiency of the hydraulic pump, x_{pump} is the displacement command, D_{pump} is the total pump displacement and p is the system high pressure.

Figure 7 illustrates that the hydrostatic system is capable of maintaining the pressure relatively close to a desired level, but significant pressure fluctuations could not be avoided (Figure 7a). This phenomenon occurs because small changes in accumulator gas volume lead to large pressure fluctuations making the system very stiff. In the ideal case the hydraulic flow consumed by the motor would equal the flow provided by the pump. However, physical delays in the system and control dynamics cause pressure oscillations. Sudden increase of the motor power demand typically leads to a pressure drop – see Figure 8. Intuitively, one might want to increase the stiffness of controller to improve the response, but this must be done carefully since the system is highly nonlinear. The pressure oscillations in the system also affect the calculation of predicted pump torque, hence the high frequency oscillations noticeable on the blue line shown in Figure 7c. While the controller enables following the overall power demand, high frequency fluctuations and engine dynamics will have an impact on engine-out emissions, as shown in the closing part of this section.

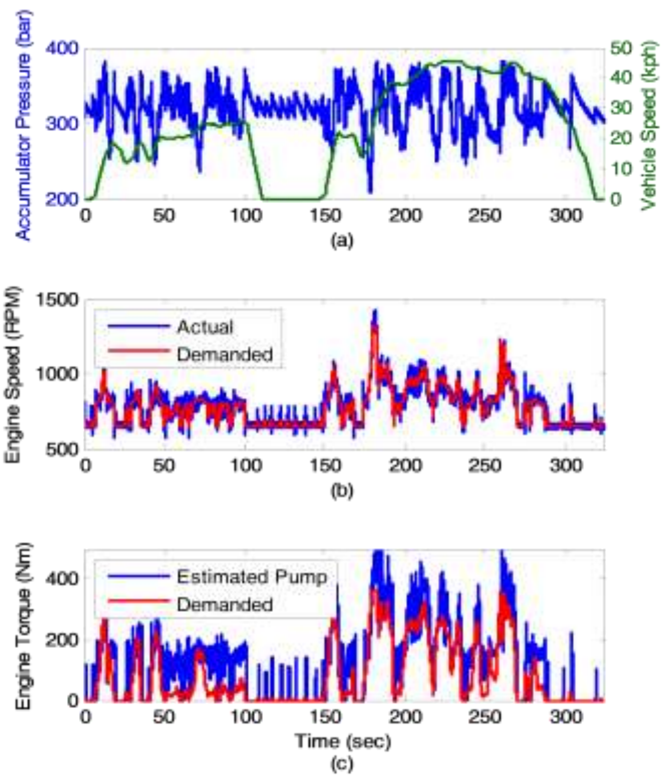

Figure 7 – Time-histories of selected key variables in the hydrostatic powertrain system over a driving schedule segment: (a) The accumulator pressure and vehicle velocity, (b) the actual and denuded engine speed, and (c) the estimated pump torque and demanded engine torque

The impact of system stiffness is also seen during engine idling conditions, when the motor does not produce any power. During this period the system pressure can drop due to internal leakage, thus requiring the engine to engage and pressurize the system. The internal leakage occurs due to the minute flows required for actuation of valves and imperfect sealing in some of the valves incorporated in the complex laboratory setup. This behavior can be seen in the pressure plot of Figure 8a from 100 to 150 seconds. Maintaining constant pressure during this period was found to be particularly difficult owing to the nonlinear behavior of the engine at low loads. While it will be easier to maintain pressure in the compact vehicle system, relaxing the pressure threshold and tuning of the gain during idle-only conditions can also help mitigate this problem.

The engine emissions of the hydrostatic powertrain are plotted in Figure 9. These plots show the difference between steady state and actual emissions. The difference between the quasi-steady estimates and measured instantaneous particulate mass concentrations are quite remarkable. In fact, the actual cumulative soot emission is 1.8 times higher than the estimate based on a steady-state trace shown in Figure 9b. After every onset of a power ramp-up there is a sharp spike of particulate emissions several times higher than the baseline steady-state estimates. These transient traces can easily dominate the overall emissions over a driving schedule with lots of stop-and-go, hence the fast analyzers are an indispensible tool for analysis and optimization of the hybrid control strategy. In case of a hydrostatic strategy, tight control on system pressure can be traded off for reduced transient emissions. Another direction is to add the energy storage and create a hybrid system capable of eliminating drastic transients all together, as discussed in the next sub-section.

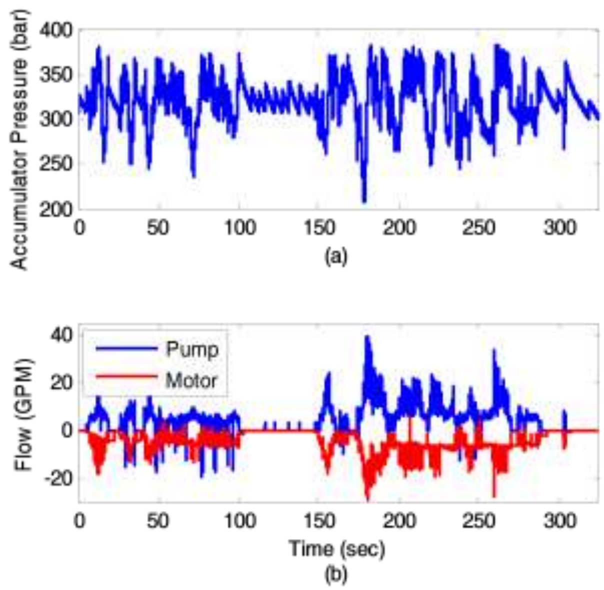

Figure 8 – Pressure and flow rate histories for the hydrostatic powertrain test over a segment of the driving schedule (a) Accumulator pressure, and (b) pump and motor hydraulic fluid flow rates

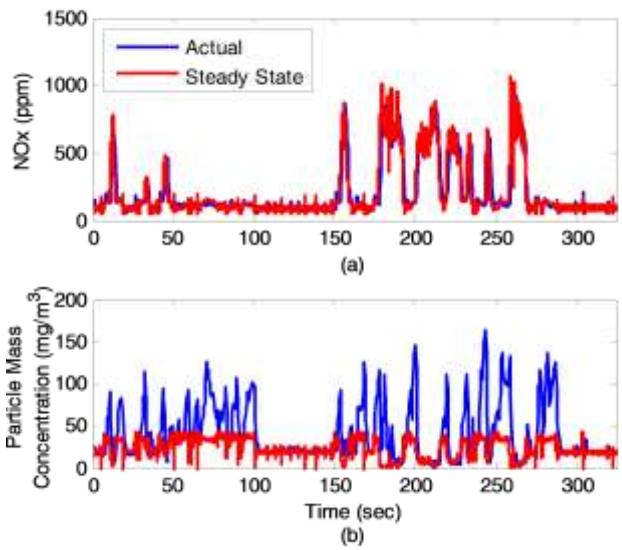

Figure 9 – Instantaneous engine-out emissions with hydrostatic control strategy over a segment of the driving schedule: (a) actual and steady state NO_X, and (b) actual and steady state particle mass concentration

SERIES HYBRID RESULTS

The response of series hydraulic configuration is significantly different from the hydrostatic operation. This can be attributed to a charge sustaining strategy described earlier, and the presence of a large energy buffer (38L hydraulic accumulator) in the hydraulic circuit. The large accumulator dampens the pressure oscillations in the hydraulic circuit and acts like a low pass filter on the pressure signal. The engine control strategy is based on the feedback of high pressure, therefore a smooth pressure signal results in milder engine transients. This can be seen from the high pressure trace and engine speed trace in Figure 10a and Figure 10b. The rise in pressure during periods 100-110 sec and 280-340 seconds illustrates the ability of the system to capture the energy during a regeneration event. The filtering effect of the accumulator also results in lower noise in pump torque estimation for the series hydraulic configuration.

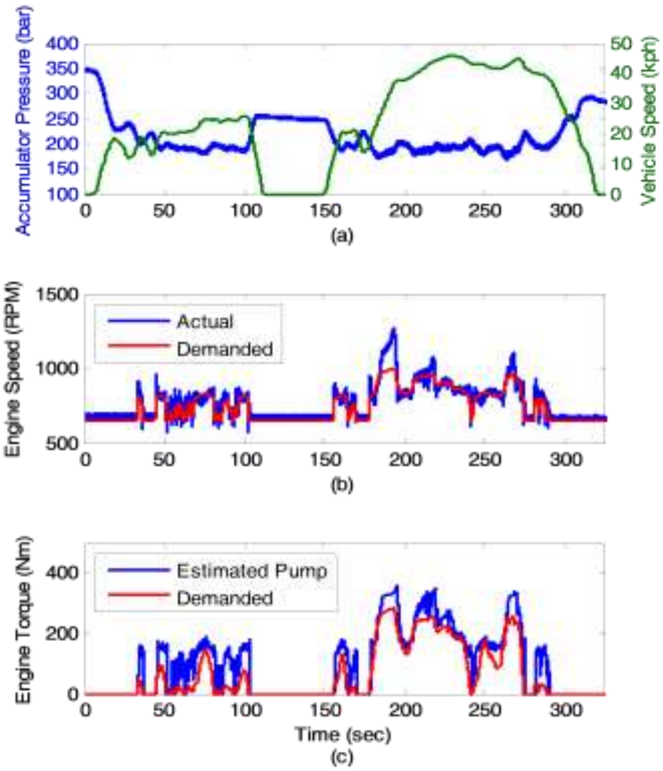

Figure 10 – Time-histories of selected key variables in the series hybrid propulsion system over a driving schedule segment: (a) accumulator pressure and vehicle velocity, (b) actual and demanded engine speed, and (c) estimated pump torque and demanded engine torque

The gradual reduction of system pressure during the idling period (110-150 sec) is present in this configuration also. However, due to the larger energy storage of the series system, the pressure does not fall below the lower threshold and does not require the engine to reengage. Thus, there are no undesirable fluctuations and engine transients.

The series hydraulic hybrid configuration posed a unique challenge related to engine speed control, which was not encountered with hydrostatic operation. The series control strategy tries to maintain a prescribed pressure level, just above the pressure threshold, during normal operation. The threshold is selected to ensure desired performance, and yet allow full energy recuperation during a typical braking event. Since the maximum load torque from the pump is proportional to system pressure, the reduced torque during the 180-200 sec period led to engine speed exceeding the target value. Simply, the resistive torque was not sufficient to keep the engine at low speed. This is an illustration of the detailed insight available from the setup incorporating real hardware. The results indicate the need to either increase the size of the pump or to adjust the pressure threshold value, even if it means a small sacrifice of regeneration capacity.

The smoother operation of engine with series hydraulic powertrain results in lower engine-out emissions and transient spikes can be avoided, Figure 11. Similar to results in Figure 9b for the hydrostatic system, the difference between the quasi-steady estimates and measured instantaneous particulate mass concentrations are quite remarkable. The smoother engine operation results in overall reduction in engine-out emissions compared to hydrostatic operation. Quantitatively series operation results in 23.7% reduction in NO_X and 9.2% reduction in particle mass concentration over hydrostatic operation. Transient spikes of soot emission are much less frequent. The series operation can result in further reduction of emissions with advanced control strategies designed with transient emission objectives [***20***], [***21***].

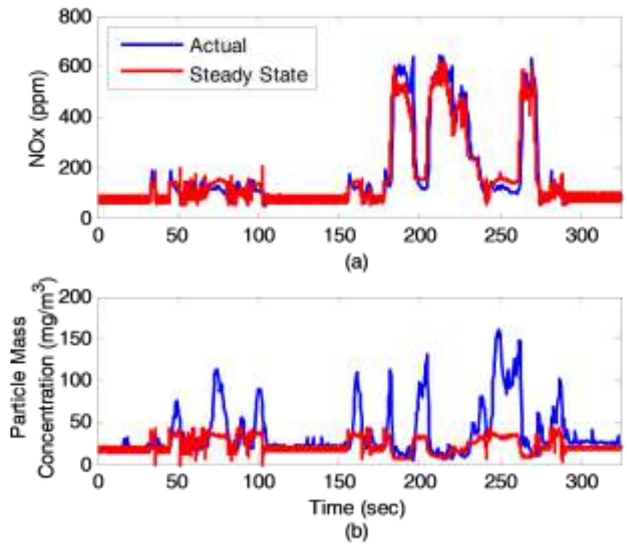

Figure 11 – Instantaneous engine-out emissions for series hybrid powertrain over a segment of the driving schedule: (a) actual and steady state NO_X, and (b) actual and steady state particle mass concentration

CONCLUSION

This paper describes the integration of the real engine and hydraulic driveline with a virtual vehicle and a cyber driver to create a Hybrid Powertrain-In-the-Loop setup. The configuration of the hydraulic –hybrid system and details of the hydraulic circuitry developed for the H-PIL integration are presented. Unique challenges are described, including the separate control of the power generation sub-system and the motor-dynamometer sub-system in the test cell.

Next, models of virtual components and software and hardware interfaces between the real components and virtual systems are developed. Implementation of the real-time models, software interfaces and implementation of the powertrain controller is achieved on a dSPACE platform. The V8 medium-duty diesel engine is fully instrumented for detailed insight into the combustion, performance and emissions during dynamic operation. The hydraulic components are instrumented with pressure and temperature sensors, as well as flow meters for monitoring and control. Hydraulic system integration and supervisory control is discussed for the two possible configurations: hydrostatic and a series hybrid with a 38L accumulator.

The H-PIL setup allows imposing realistic dynamic loads on hydraulic pump/motors and accumulator based on a vehicle driving schedule. Application of fast analyzers allows characterization of the impact of dynamic interactions in the propulsion system on engine-out emissions. Therefore, the H-PIL facility provides detailed insight into dynamic interactions in the complex hybrid system comprising real devices and actuators, and evaluation of strategies aimed at achieving both high-efficiency and low emissions. The initial test results demonstrate the advantage of the series hybrid configuration related to its ability to capture the braking energy during a typical regeneration event, and also provide much smoother engine operation without sharp transients that can lead to spikes in soot emissions.

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ACKNOWLEDGMENTS

The financial support for this research has been provided by the State of Michigan 21st Century Jobs Fund in partnership with the Bosch-Rexroth Corporation. In addition, the authors wish to acknowledge technical interactions with Simon Baseley and Ed Greif, both from Bosch-Rexroth. Lastly, the authors would like to thank AVL, and in particular Christian Schyr, for their technical support in the process of decoupling the engine from the dynamometer.