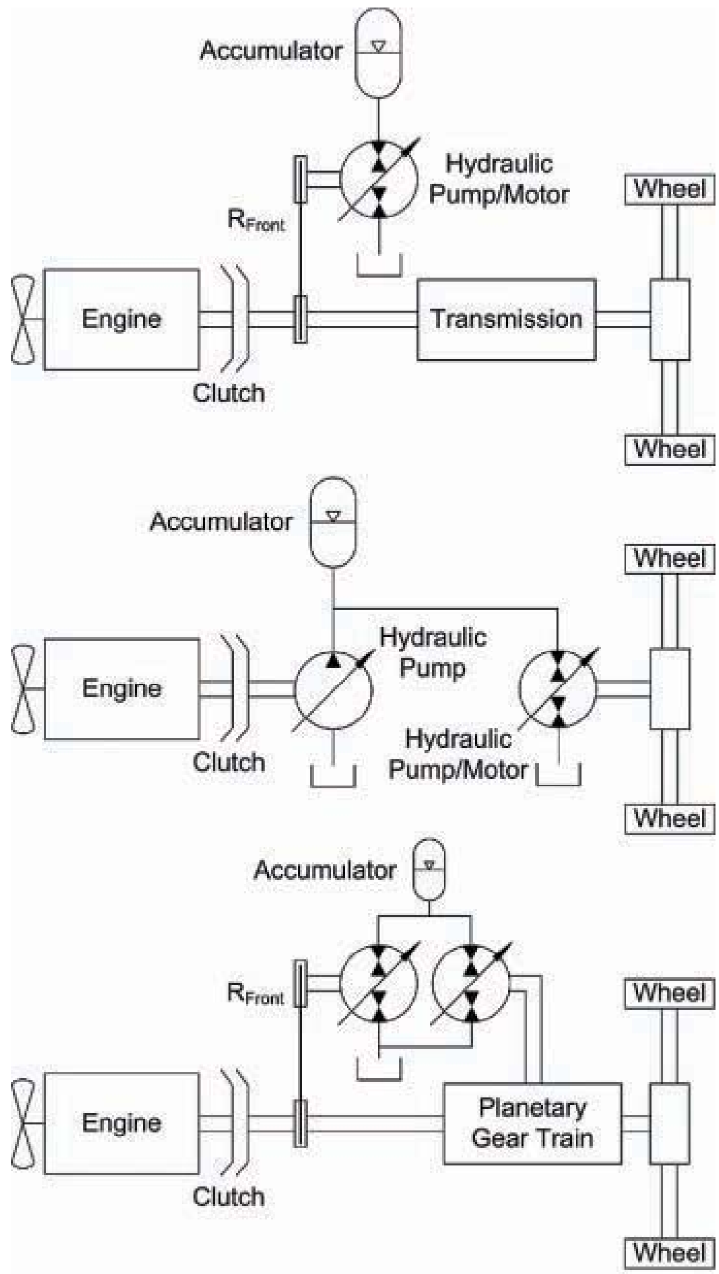
Energy management

BY ANDREW ALLEYNE, TIMOTHY DEPPEN, JONATHAN MEYER, AND KIM STELSON

The transportation sector accounted for 28% of total U.S. energy consumption in 2011. Furthermore, 93% of this consumption is fueled by petroleum and the demand is projected to grow in the coming decades[1]. The need to stem this consumption and reduce greenhouse gas emissions has stimulated the development of hybrid vehicles; here we specifically consider hydraulic hybrids. These vehicles use a high-pressure accumulator for energy storage and pumps/motors to transfer power between the mechanical and hydraulic domains. Energy storage enables the powertrain to partially decouple power generation from demand, allowing for more efficient operation, and the ability to regenerate energy normally lost via mechanical braking. Fluid power has a greater power density than conventional electric technology and the accumulator can be fully charged and discharged safely for many cycles without loss in performance[2]. These characteristics make fluid power particularly attractive for urban driving applications where there are frequent starts and stops. Therefore, research into hydraulic hybrids spans a wide range of applications from heavy-duty vehicles, like city buses, to small passenger vehicles[3-8].

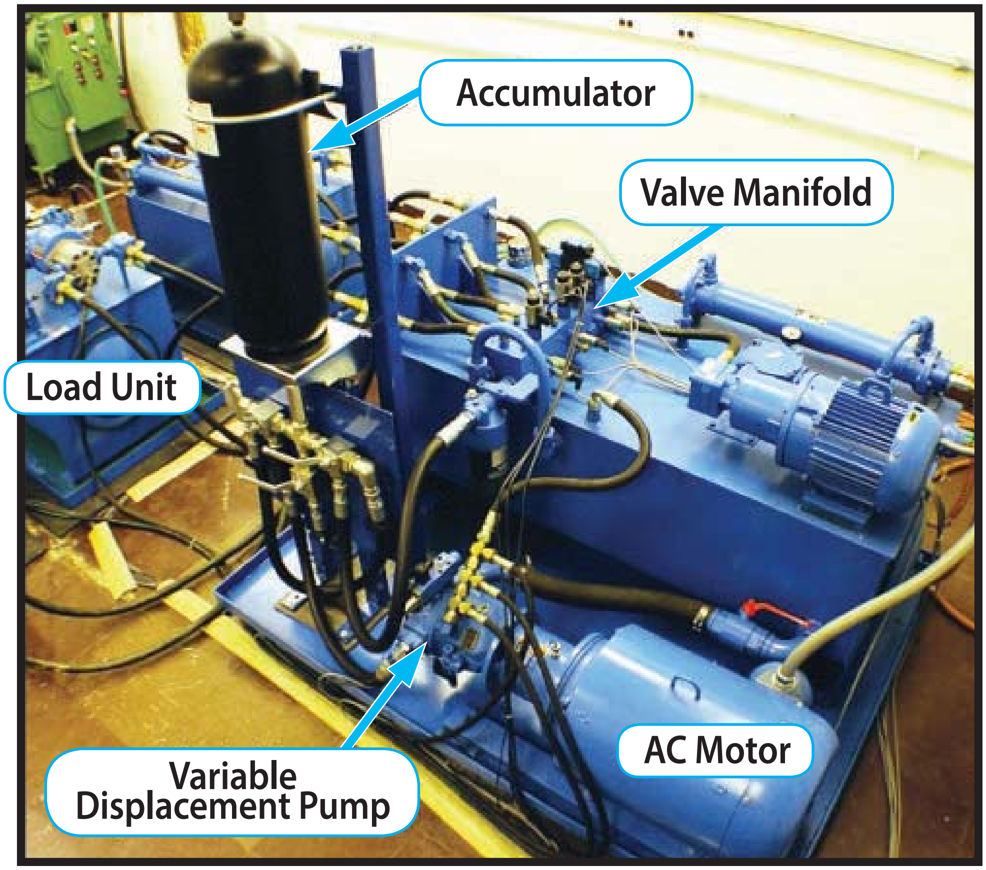


Within the broad class of hydraulic hybrid powertrains, there are three primary architectures: parallel, series, and hydromechanical. The parallel configuration, or power assist, uses a variable displacement pump/motor and accumulator in parallel with a mechanical transmission to store, disperse, and reclaim energy. The advantage of this architecture is that it includes the highly efficient mechanical transmission. However, this connection limits the flexibility when conducting energy management. The series configuration eliminates the mechanical path entirely and replaces it with a hydrostatic transmission that includes an accumulator for power storage. This allows engine operation to be decoupled from desired vehicle speed but the transmission efficiency

in mobile hydraulics

FIGURE 1
Hybrid powertrain architectures (top: parallel, middle: series, bottom: hydromechanical).

FIGURE 2
Augmented Earthmoving Vehicle Powertrain Simulator at the University of Illinois at Urbana-Champaign.



is dominated by the hydraulic components. Finally, the hydro-mechanical, or power-split, architecture utilizes a combination of the series and parallel models. This architecture offers the advantages of both the parallel and series but with additional complexity. These configurations are shown in **Figure 1**.

To realize the potential of the hydraulic hybrid powertrain, a supervisory control strategy is needed to regulate energy generation and distribution. Design of energy management strategies (EMS) for hybrid vehicles has been an active area of research for many years. There are numerous approaches to designing these strategies, ranging from computationally demanding off line optimization techniques to heuristically derived rules[9, 10]. In the context of hydraulic hybrids there are three popular approaches to design of real time implementable EMS's: rule-based, stochastic dynamic programming (SDP), and model predictive control (MPC). Rule based EMS's use a set of rules or logic to control the powertrain[5]. They are typically extrapolated from global optimization assessment performed using deterministic dynamic programming over an assumed drive cycle. Due to the cycle-dependent nature of this derivation, the performance cannot be guaranteed under arbitrary driving. Stochastic dynamic programming uses probability maps in place of an assumed drive cycle to make an estimate of what the vehicle will be required to do in the future and optimizes using this estimate[6, 11]. The benefits of this approach over the rule-based design are that the solution is not limited to a specific drive cycle and a causal control strategy is determined without further analysis of the results. However, this optimization procedure still includes some implicit assumption of the drive cycle and is best suited to applications with relatively well defined travel patterns; for example, refuse trucks or busses. Finally, model predictive control (MPC) uses a model of the system to predict how the powertrain will respond to a sequence of inputs and optimizes the response over a finite prediction horizon[8]. Unlike the rule based and SDP solutions, MPC can be formulated without using any knowledge of the future drive cycle or its statistical nature. One of the primary drawbacks to using MPC is the intense online computation required.

To demonstrate the capabilities of the hydraulic hybrid powertrain, coupled with energy management, experimental results for a series hardware-in-the-loop hydraulic hybrid powertrain are presented. This test system, shown in **Figure 2**, uses an electric motor to emulate an IC engine and a resistive hydraulic load unit to emulate vehicle driving loads. For this energy management strategy an objective function is used which balances minimization of losses within each of the actuators (engine, variable displacement pump, and throttling valve)[8]. Through a simulation study it was found that focusing on

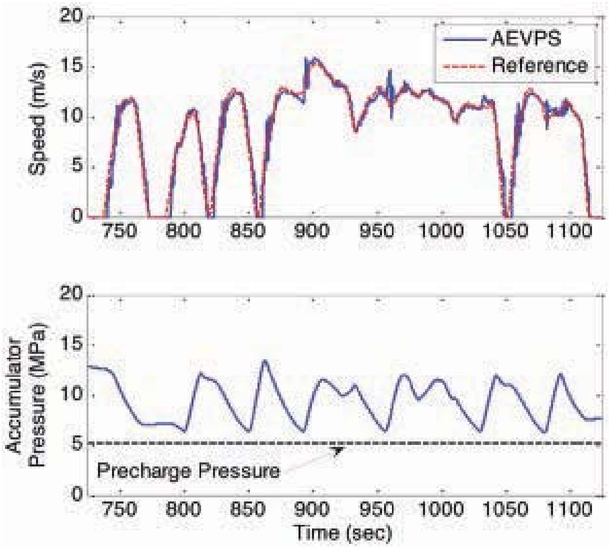


FIGURE 3 Experimental powertrain response for AEVPS with MPC in urban driving.

stops and large acceleration/braking power demands. To take advantage of the additional flexibility offered by energy storage an energy management strategy is needed. Since the opportunities and challenges of fluid power are different than those of electrical power, unique control strategies are needed and a summary of common EMS design methods for hydraulic hybrids was presented. When designing these strategies it is important to take a system wide perspective and consider all of the actuators within the powertrain. Through a case study with MPC it was observed that a 27% reduction in fuel consumption could be achieved by accepting tradeoffs in individual component efficiencies as opposed to just maximizing engine efficiency. This case study also highlights the importance of having well a designed energy management strategy if one is to maximize benefit of the hybrid powertrain. ■

any one actuator would not minimize overall fuel consumption. Rather, a combination of penalizing losses in the pump and valve led to the lowest overall fuel consumption as shown in **Table 1**[8]. **Figure 3** shows the experimental response of the powertrain. Note that the accumulator is repeatedly charged and discharged throughout the drive cycle, which is feasible due to the high power density and robustness of the gas charged accumulator.

There is potential for hydraulic hybrid vehicles to offer a cost effective solution to the need for increased efficiency in transportation systems. The high power density of fluid power makes it a natural choice for energy storage in urban driving environments where there are frequent starts/

FUEL CONSUMPTION	(kg)
Engine Only	1.51
Pump Only	1.32
Valve Only	1.20
Best Case	1.10

TABLE 1 Simulation results for weighting different component efficiencies.

ABOUT THE AUTHORS

ANDREW ALLEYNE received his B.S.E. from Princeton University in 1989 in Mechanical and Aerospace Engineering and his M.S. and Ph.D. degrees in Mechanical Engineering in 1992 and 1994, respectively, from the University of California at Berkeley. He joined the University of Illinois at Urbana-Champaign in 1994 where he currently holds the Ralph M. and Catherine V. Fisher Professorship in the College of Engineering. He is the recipient of the 2008 ASME Gustus L. Larson Memorial Award and is also a Fellow of ASME. His research interests are a mix of theory and implementation with a broad application focus.

TIMOTHY DEPPEN completed the combined B.S./M.S. program in the Mechanical Science and Engineering department at the University of Illinois at Urbana-Champaign in 2009. He received the Mechanical Science and Engineering Outstanding Scholar Fellowship in 2008. In the summer of 2012 he was selected to participate in the Naval Research Enterprise Internship Program. Currently, he is expected to complete his doctoral program as part of the Alleyne Research Group at the University of Illinois at Urbana-Champaign in May 2013. His research interests include energy management, model predictive control, optimal control, and modeling of multi-domain energy systems.

JONATHAN MEYER graduated with high honors from the Milwaukee School of Engineering with a Bachelor of Science degree in mechanical engineering and a minor in mathematics in May 2006. He immediately began to pursue his doctorate in mechanical engineering at the University of Minnesota and is expected to complete his degree in summer 2013. He is also an adjunct faculty member at the University of St. Thomas in St. Paul, MN, teaching mechanical engineering courses and labs. His research interests include energy management, stochastic optimal control, and modeling fluid power systems for mobile applications.

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