COMPONENT SIZING STUDY FOR A LIGHT-DUTY SERIES HYDRAULIC HYBRID VEHICLE IN URBAN DRIVE CYCLES

Katharina Baer
Liselott Ericson
Petter Krus
Division of Fluid and Mechatronic Systems
Department of Management and Engineering
Linköping University
Linköping, Sweden
katharina.baer@liu.se, liselott.ericson@liu.se, petter.krus@liu.se

Abstract. *With the focus on energy efficiency for many different kinds of vehicle applications, hybridization is considered a possible solution to reduce fuel consumption. While hybrid electric concepts are already available for passenger vehicles, and also considered for heavier applications, hybrid hydraulic alternatives have been mainly limited to the latter, which benefit most from the higher power density available. To study the different hybrid architectures and applications, a modeling framework for the system design is developed using the simulation tool Hopsan from Linköping University. Previously, the model of a series hydraulic hybrid vehicle was introduced, a light-duty vehicle simulated over two standard urban drive cycles, and its potential for further work established. In this paper, the model is extended by including a simple combustion engine power management to provide for more realistic propulsion of the hydraulic drivetrain, showing the potential to operate a series hydraulic hybrid vehicle's engine in more efficient regions. Additionally, the design is studied concerning the effects of a variation of key component sizes on the accuracy and energy efficiency objectives. Instead of subjecting the system to (multi-objective) optimization, at this stage the individual components' influence is studied, and the objectives are dealt with separately from each other to eliminate the need for compromise between them to gain a better understanding of the interdependencies.*

Keywords: *Series hydraulic hybrid, Hopsan modeling*

1. INTRODUCTION

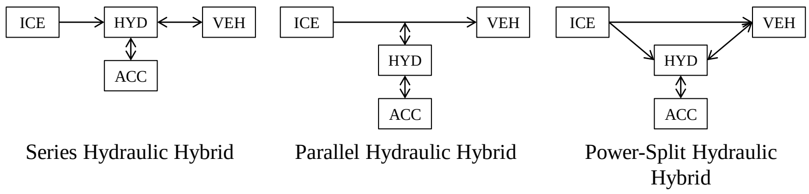
Hybridization of a vehicle's drivetrain aims to improve its fuel efficiency by integrating a second energy form. Thus, it becomes possible to recuperate braking energy, to lower power demand peaks to the engine and consequently to operate the combustion engine more efficiently, and – if considered during the design phase – it can allow for down-sizing of the combustion engine as well. While less common as of now, using hydraulics as a secondary power source can be advantageous over electrics especially due to a higher power density allowing for fast charging and discharging, though at the cost of a lower energy density leading to a shorter range.

Originally, hydraulic hybrid concepts were therefore considered especially suitable for heavy vehicles whose typical drive cycles include frequent stops, such as urban busses and refuse trucks (Yan, *et al.*, 2010; Baseley, *et al.*, 2007), benefitting from the high masses to be accelerated and decelerated in short times. Recent research and development, though, has been extended to passenger and light-weight vehicles as well (e.g. Stelson, *et al.*, 2008; Kim and Filipi, 2007), even leading towards commercially available passenger vehicles with hydraulics announced for the foreseeable future (PSA Peugeot Citroën, 2013).

This paper is part of the development process of a modeling framework for hybrid hydraulic vehicles with the overall goal of studying hybrid hydraulic architectures for different vehicles and duty profiles. The model for a series hydraulic hybrid vehicle previously presented contained a simple constant speed power source supplying the charge pump which can be switched on and off; with the pump operating at either zero or full displacement. Modifications to this power source allow now for different strategies of operation, which will here be limited to the assumption of running the combustion engine in its most efficient operating point. An initial design for a light-weight application is subjected to component size variations to study how those affect key resulting properties. These performance criteria concern whether the vehicle can follow its duty profiles, and whether and to what extent the inclusion of a secondary energy storage shows a potential for energy recuperation as desired. As both are not necessarily correlated, a full design optimization would require handling a multi-objective problem with some form of preferences, and also require more additional design criteria to be considered. Instead, the objectives are treated separately to study the effect of different component sizes.

2. BACKGROUND

Depending on the implementation of the hydraulics in the drivetrain, there are three different basic architectures for hybrid hydraulic vehicles (Fig. 1). Keeping a mechanical connection between the internal combustion engine and the vehicle as in the parallel concept, including some form of gearbox, allows for a more efficient power transfer compared to a series hybrid's continuously variable hydrostatic transmission with inevitable transformation losses. This same mechanical connection, however, prevents a more efficient engine operation due to the dependency between engine and wheel speed. The power-split hybrid aims to combine both architectures' advantages, but requires planetary gearings to split and connect the hydraulic and mechanical paths, making it more complex than the other two alternatives.



ICE	Internal Combustion Engine	ACC	Hydraulic Accumulator
HYD	Hydrostatic Transmission	VEH	Vehicle

Figure 1. Hybrid hydraulic drivetrain architectures (schematic, compare similarly (Stecki and Matheson, 2005)).

Of the three main hydraulic hybrid architectures, the series hydraulic hybrid concept was chosen as the first to be modeled as its hydrostatic transmission and combustion engine can be treated fairly separately from each other, the focus here still being the hydraulic part of the drivetrain. This independence also allows for more energy-efficient engine management.

In current literature, modeling and optimization of series hydraulic hybrid concepts for passenger vehicles (e.g. Deppen, *et al.*, 2012; Johri and Filipi, 2010) and light- and medium-sized trucks (Kim and Filipi, 2007; Sun, 2010) are frequently addressed. While some focus is upon the optimization of the drivetrain's components (Sun, 2010), much research revolves around power and energy management strategies, respectively, and their optimization (e.g. (Wu, *et al.*, 2004) for a rule-based approach; (Kim and Filipi, 2007) with a thermostatic state-of-charge control; (Johri and Filipi, 2010) utilizing Stochastic Dynamic Programming; (Deppen, *et al.*, 2012) using Model Predictive Control).

3. FRAMEWORK FOR A SERIES HYDRAULIC HYBRID VEHICLE MODEL IN HOPSAN

An earlier version of the model in this paper was presented previously (Baer, *et al.*, 2013) and set up and tested for a light-weight vehicle over two urban drive cycles to confirm its ability to follow the prescribed velocity profile accurately and its theoretical potential for reduced energy input and improved energy efficiency. The simulation model was created in a development release of Hopsan (Eriksson, *et al.*, 2010; Axin, *et al.*, 2010), a multi-domain simulation tool by the Division of Fluid and Mechatronic Systems at Linköping University, which is available for download free of charge. It utilizes transmission line modeling technique (Auslander, 1968) which bases pressure and flow calculations on wave characteristics (Krus, *et al.*, 1990). While the original Hopsan dates back to the 1970s, it has been launched in its current version in 2010 and is being continuously developed further.

The main components the model consists of (Fig. 2) are a one dimensionally-modeled vehicle, a variable pump/motor and a variable charge pump, as well as a gas accumulator. The vehicle is described through its mass M_{veh}, which takes the mass of the main hydraulic components into account, its effective frontal area $c_d \cdot A$, and its effective wheel radius $r_{wheel,eff}$, which includes the actual wheel radius r_{wheel} and the differential gear ratio i_{diff}. An additional gearbox between hydrostatic transmission and vehicle could allow for smaller components and protect the pump/motor against too high shaft speeds, as well as permit a higher maximum vehicle speed for highway driving situations. While included in some models for series hydraulic hybrid vehicles (e.g. Johri and Filipi, 2010), it is not considered as of now. The mass of the main hydraulic components is derived from the data of commercially available products and extrapolated based on the installed displacement. Both hydraulic machines include efficiency models (Rydberg, 1983) factoring in the displacement setting angle, the rotational speed and the pressure difference over the machine. Furthermore, the modeled components allow theoretically for switching the high and low pressure side; this feature, however, is not utilized currently. The accumulator is modeled as being loss-free, assuming an adiabatic process with the polytropic exponent adjusted to the system's pressure level (Rydberg, 1984), and directly connected to the hydrostatic transmission. A combustion engine is not specifically modeled, for the charge pump a constant angular velocity is assumed instead.

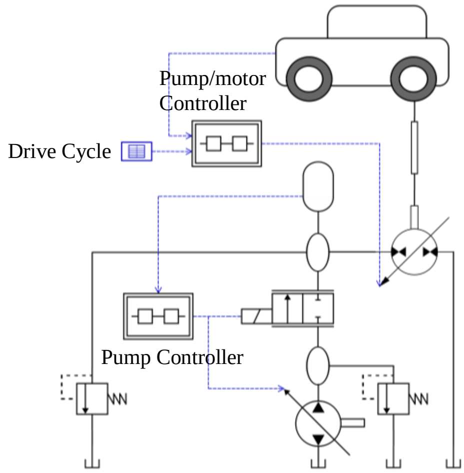


Figure 2. Basic structure of the series hydraulic hybrid model in Hopsan.

The displacement setting angle of the pump/motor is set through a PI-controlled velocity feedback, comparing the current vehicle speed to the reference velocity of the drive cycle. The propulsion of the system depends on the state-of-charge of the hydraulic accumulator, which is calculated based on the current gas volume (Wu, *et al.*, 2004): if the current state-of-charge is lower than a lower boundary (SoC_{low}), the pump's displacement setting is fully opened and charges the system, until an upper boundary (SoC_{high}) is reached, causing the displacement setting angle to be closed (compare to Kim and Filipi, 2007). Thus, it is modeled to switch the propulsion on and off. However, it does not allow for a more controlled pump flow beyond maximum or zero.

Two resulting properties were specified, representing the accuracy in following a prescribed drive cycle and the energy recuperation potential, respectively. The accumulated relative velocity error (ARVE, Eq. (1)) puts the accumulated velocity deviation over time in relation to the total distance covered by the drive cyle, x_{max}, a low value corresponding to little deviation from the drive cycle. The adjusted energy input ratio (EIR_a, Equ. (2)) is the ratio of the energy input into the system over the full drive cycle to the system's energy demand. The energy input into the system has to be corrected by energy content of the accumulator at the end of the drive cycle, as an empty accumulator is assumed at the start. The system's energy demand includes losses in the hydraulic path of the drivetrain. Thus, EIR_a focuses on how much the possibility of energy recuperation can lower the energy input. The lower this ratio becomes, the more of the system's energy demand can be met by energy recuperated in the accumulator instead of energy provided by the system's propulsion. It should be noted that for the optimization of the whole system it will be relevant to reduce the hydraulic losses as well.

$$ARVE = \int_t \left| v_{ref} - v_{veh} \right| dt / x_{\max} \tag{1}$$

$$EIR_a = \left(E_{in,system} - \Delta E_{acc}\right) / \left(E_{in,veh} + E_{loss}\right) \tag{2}$$

As test application, a light-weight vehicle (see Tab. 1 for the vehicle parameters) was simulated over two urban standard cycles, the EPA Urban Dynamometer Driving Schedule FTP-72 (UDDS FTP-72) and the New York City Cycle (NYCC) (United States Environmental Protection Agency, 2013). These velocity profiles differ in length, maximum velocity, maximum acceleration, and general driving profile (see Tab. 2).

Table 1. Light-duty vehicle parameters.

Vehicle Property	Individual Value	Combined Value
Vehicle mass M_{veh} (half-loaded, without additional components)	2700 kg	-
Frontal area A	3.75 m^2	1.78 m^2
Aerodynamic drag coefficient c_d	0.475	
Wheel radius r_{wheel}	0.33 m	0.1 m
Differential gear ratio i_{diff}	3.3 [-]	

Table 2. Drive cycle characteristics.

Drive Cycle Property	UDDS FTP-72	NYCC
Length	1369 s	598 s
Maximum velocity	25.4 m/s (= 91.3 km/h)	12.38 m/s (= 44.6 km/h)
Average velocity*	10.8 m/s (= 38.9 km/h)	4.9 m/s (= 17.6 km/h)
Maximum acceleration*	1.48 m/s^2	2.68 m/s^2
Total distance covered*	12.0 km	1.9 km

* approximated

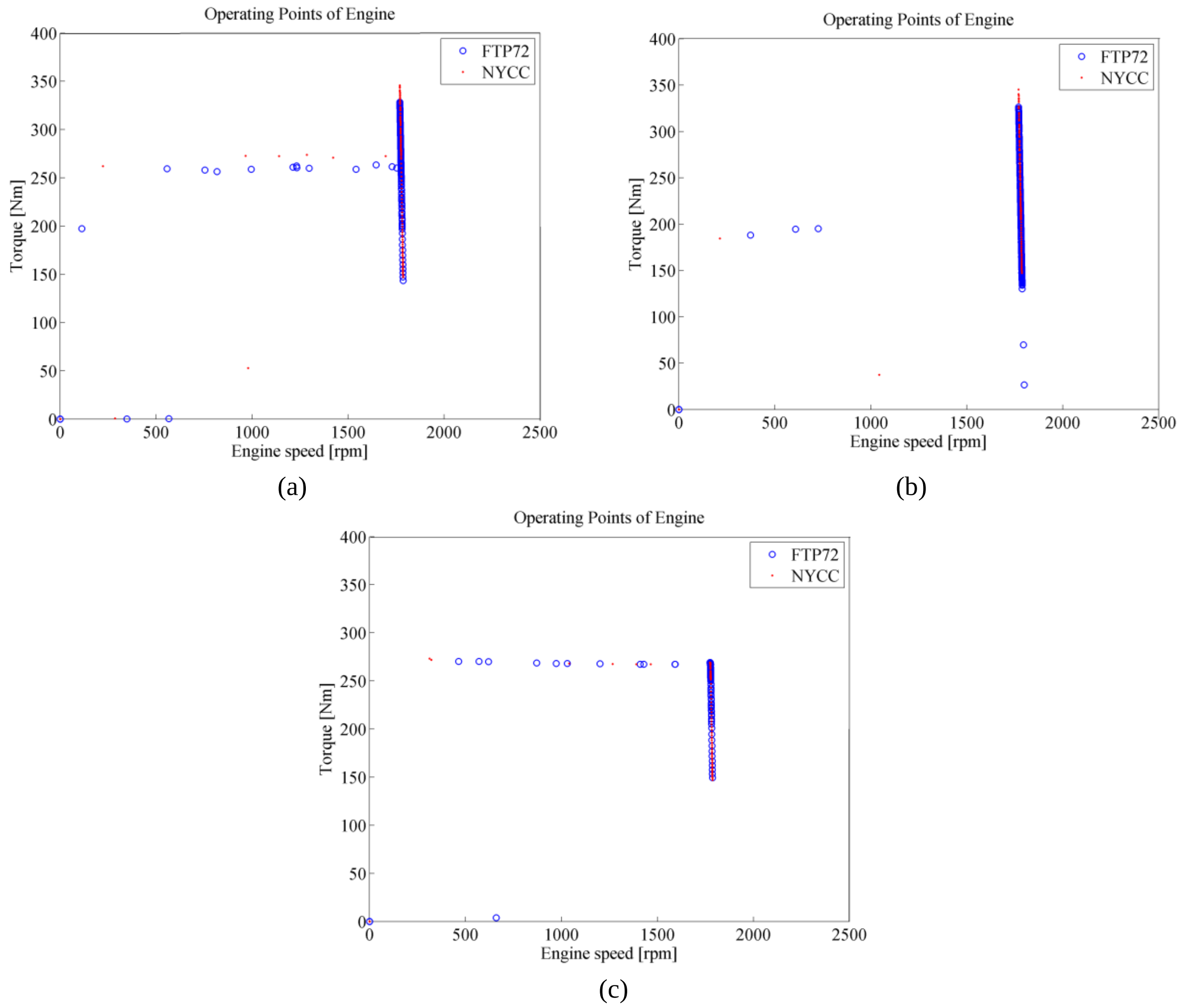
For the modeled vehicle and drive cycles, sufficient accuracy could be achieved, and the system indicates a potential for energy recuperation. It is to be pointed out that the intention is not to compare the two drive cycles to each other, but rather to expose the vehicle configuration to different driving requirements.

4. INFLUENCE OF SOME PROPULSION STRATEGIES ON THE ENGINE'S OPERATING POINTS

The internal combustion engine in the previous design was reduced to a constant speed source providing the required torque for the hydraulic pump at either full or no displacement, effectively canceling out the pump's variability of displacement. Because of the varying pump pressure – and consequently – load torque, the engine visits a wide range of operating points, especially operating in less efficient points when under a low load (see Fig. 3(a)). Torque variations stem from different pump pressures; operating points of a lower speed than targeted and torque outliers are transient. A wider span between the state-of-charge parameters, which are responsible for the pump's actuation, yields even further-spread operating points due to a larger difference between lowest and highest pump pressure (see Fig. 3(b) with a lowered SoC_{low} compared to the default parameters).

As a series hybrid allows more than the other concepts for a highly efficient combustion engine operation independent from the current wheel speed, this initial propulsion strategy is not desirable. To operate the combustion engine more efficiently, the most intuitive alternative is to run it for as much as possible in its most efficient point, the so-called "sweet spot", with a defined speed and torque. If both speed and torque are kept (close-to-)constant by adjusting the pump's displacement setting according to the current pressure level in the system, it is possible to reduce the range of visited points (Fig. 3(c)). Torque variations then stem mostly from the start-up phase when the system pressure is lower than in the normal operating range due to the assumption of a discharged accumulator at the beginning of each drive cycle.

Through appropriate system control and dimensioning of the internal combustion engine, a more fuel-efficient operation can be achieved once fuel consumption in the individual operating points is integrated in the component model, and engine and hydrostatic transmission are matched. It has to be pointed out, though, that while for the individual combustion engine component a power management strategy aiming at its "sweet spot" yields a high efficiency, the full system's most energy-efficient operation does not necessarily have to concur with this, as other components' lower efficiencies could potentially reverse the engine's positive effect (Kim and Filipi, 2007; Johri and Filipi, 2010; Deppen, *et al.*, 2012).



(a) (b) (c)

Figure 3. Operating points of combustion engine with constant target speed and default controller parameters (a) and lowered SoC_{low} (b), respectively, and constant target speed with adjusted displacement setting angle (c).

5. COMPONENT SIZE VARIATIONS

The initial components and some of the system's parameters are given in Tab. 3. While the previously presented results were promising, and the additional weight through the hydraulic components was taken into account, the system configuration is potentially oversized for a comparably small vehicle. Especially the accumulator shows potential for down-sizing without compromising on either accuracy or energy efficiency.

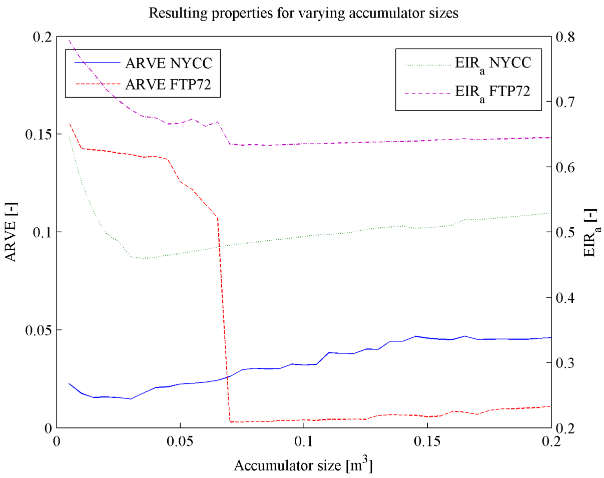
Table 3. Series hydraulic hybrid light-duty vehicle component sizes.

Component Size/Parameter	Value
Hydraulic pump displacement D_p	$100 \cdot 10^{-6}$ m^3/rev
Hydraulic pump/motor displacement D_{pm}	$150 \cdot 10^{-6}$ m^3/rev
Hydraulic accumulator volume V_{0acc}	0.1 m^3
Constant pump (engine) speed	1800 rev/min
Maximum system pressure	33 MPa
Upper boundary state-of-charge SoC_{high}	0.71
Equivalent pressure for SoC_{high}	20 MPa
Lower boundary state-of-charge for SoC_{low}	0.55
Equivalent pressure for SoC_{low}	16 MPa

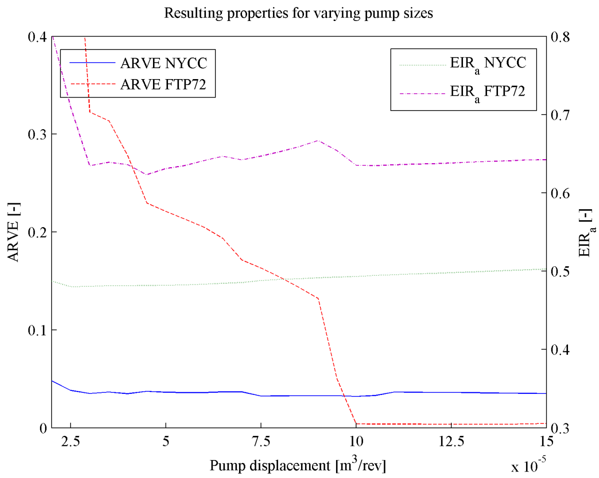
In this chapter, the effects of variation of one or more of the key components' sizes will be studied. The goal at this stage is neither to achieve an optimal configuration, nor to find a design satisfying multiple objectives. Instead, the properties introduced in chapter 3.2 will be considered separately. The following sections deal with the variation of the component sizes individually (section 5.1) while keeping the default values from Tab. 3, and the simultaneous variation of accumulator size and hydraulic machines' displacements (section 5.2). The effect of smaller components on system parameters other than the vehicle's mass including the hydrostatic transmission, e.g. higher allowed maximum pressure or pump shaft speed, has not yet been considered.

5.1 Single parameter variation

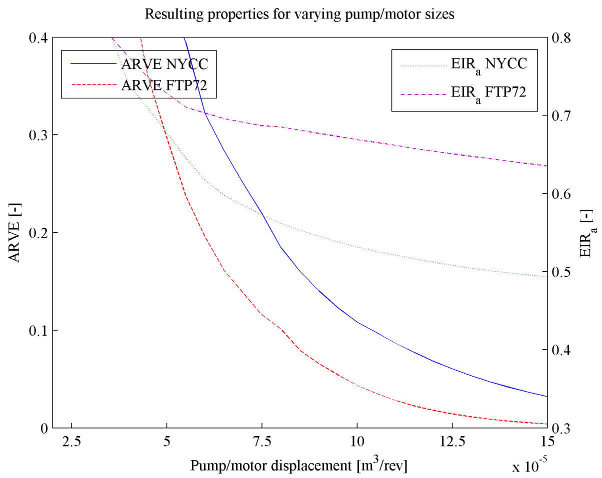
Figure 4 contains the results for varying only one of the main hydraulic components sizes, while keeping the sizes of the other components as well as the system and controller parameters constant. Only the total vehicle mass varies depending on the component's weight.



(a)



(b)



(c)

Figure 4. Individual component size variation: accumulator volume (a), pump displacement (b), and pump/motor displacement (c) for both drive cycles and resulting properties.

As expected, the accumulator size can be reduced without compromising much on both objectives even when the hydraulic machine sizes are not adapted (Fig. 4(a)). The installation of more pump displacement (Fig. 4(b)) and hence higher hydraulic charge power leads to increased losses in the system and a higher total vehicle weight, thus resulting in decreased energy recuperation potential. The absence of volumetric and other limitations for the size of the components used would lead to a maximally sized pump/motor in an energy efficiency-oriented optimization (Fig. 4(c)). Lastly, the study of more than one drive cycle proves to be valuable, as the UDDS FTP-72 cycle's accuracy is less robust towards decreased component sizes due to higher velocities over longer periods, while the NYCC's profile is characterized by high accelerations but short distance and low maximum velocity, leading to its energy recuperation potential to be affected more easily due to a comparably low total energy demand.

5.2 Multiple parameter variation

The previous section does not touch upon interdependencies between the component sizes which have to be expected. Even without a concrete limit or penalty on the components' combined volume in place, the goal of the component sizing has to be a light, compact and hence less expensive drivetrain without compromising too much on the afore-mentioned objectives of accuracy and energy recuperation. Two systems are compared in the following considerations, one of which contains the original accumulator of 0.1 m^3, while for the second the accumulator gas volume has been reduced even below what has been suggested in Fig. 4a. For each system, the displacements of the hydraulic machines are varied simultaneously, and the resulting properties evaluated for each system design.

As stated before, the vehicle's ability to follow the Urban Dynamometer Driving Schedule FTP-72 is more affected by accumulator size variation. With a lower energy storage capacity (Figure 5), the system's accuracy decreases less than before when using a smaller pump/motor, while an under-sized pump leads to considerably higher accumulated velocity deviations. From the plots it can also be seen that while the original pump and pump/motor sizes' result is worse for a smaller gas accumulator, it is however possible to find a design with the same pump and a decreased pump/motor displacement with satisfying accuracy. It appears that part of the pump/motor's size depends on the machine to be matched to the discharge flow of the accumulator, which is lower with a smaller oil volume stored.

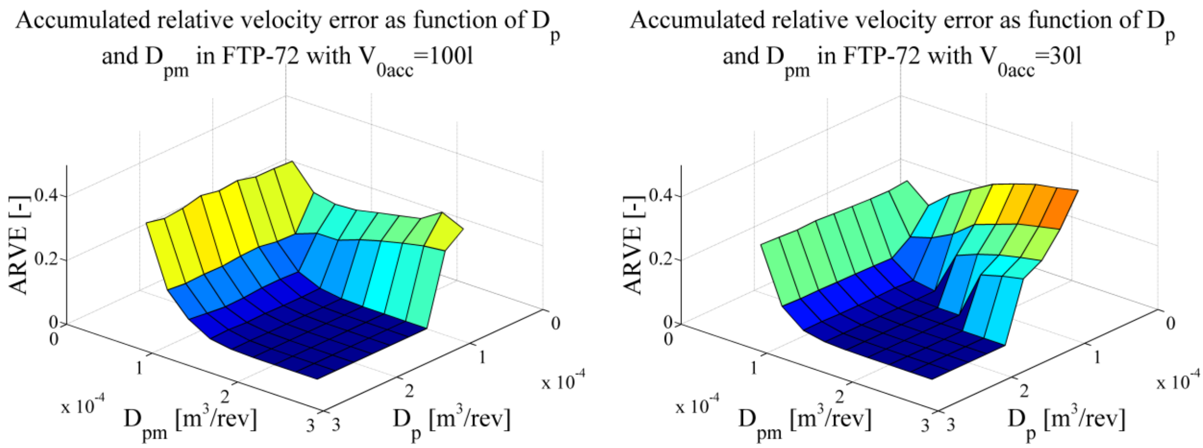


Figure 5. Hydraulic machine size variation for two different accumulator sizes.
Accumulated relative velocity error in Urban Dynamometer Driving Schedule FTP-72.

Both the adjusted energy input ratio of the Urban Dynamometer Driving Schedule FTP-72 and the accumulated relative velocity error over the New York City Cycle are robust towards the accumulator size variation. The energy recuperation potential when driving the latter cycle with a smaller accumulator (Fig. 6) is slightly improved, especially for small pump and pump/motor, and can be explained through the lower total vehicle mass, the effect of which is more pronounced for this velocity profile in comparison to the FTP-72 cycle.

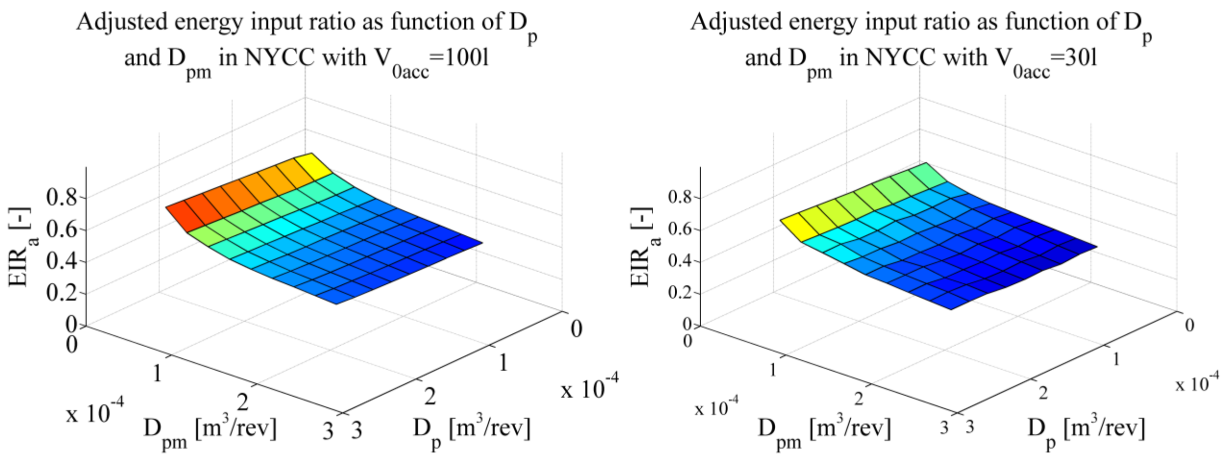


Figure 6. Hydraulic machine size variation for two different accumulator sizes.
Adjusted energy input ratio in New York City Cycle.

6. CONCLUSIONS

In this paper, the existing series hydraulic hybrid model was modified to show the possibility of focusing the combustion engine's operating points on a smaller range with the potential of more fuel-efficient driving. For the future, this allows in combination with fuel consumption data for more complex and more energy-efficient control strategies. The light-weight vehicle design was studied concerning the effect of its main hydraulic components' sizing, particularly in terms of down-sizing without compromising on the accuracy, i.e. drivability, and the effect of energy recuperation over urban drive cycles. It was shown that especially an initial design's accumulator size could be greatly reduced (without claiming optimality), and the consequences for the pump and pump/motor size choices were pointed out.

Besides the hydraulic component sizes (and their masses), further component and system specific parameters will have to be studied and considered for the design, such as the system's maximum pressure, the operating speeds of pump and pump/motor, the pump/engine control and its parameters, the pump/motor controller and others, including their interdependencies amongst each other and with the hydraulic components. Increased operating speed of the hydraulic components would allow for smaller installed displacements and vice versa; with smaller machines and a smaller accumulator volume the system's maximum pressure could be increased, etc.

Besides the core resulting properties mentioned above, others objectives and requirements play a role in the system design as well. Restrictions such as the volume of the additional components installed and additional costs, as well as minimum performance requirements not covered by the current drive cycles (such as gradeability and driving at higher or maximum velocities) need to be considered. While highway-driving may have less potential for energy recuperation due to less frequent acceleration and braking, the vehicle's drivetrain might need to be designed for this task as well.

7. REFERENCES

Auslander, D.M., 1968. "Distributed System Simulation With Bilateral Delay-Line Models". *Journal of Basic Engineering*, Vol. 90, No. 2, p. 195-200.

Axin, M., Braun, R., Dell'Amico, A., Eriksson, B., Nordin, P., Pettersson, K., Staack, I. and Krus, P., 2010. "Next Generation Simulation Software using Tranmission Line Elements". In *Fluid Power and Motion Control 2010*, Bath, United Kingdom.

Baer, K., Ericson, L. and Krus, P., 2013. "Modeling of a Series Hybrid Hydraulic Drivetrain for a Light-Duty Vehicle in Hopsan". In *Proceedings of the 13th Scandinavian International Conference on Fluid Power - SICFP2013*. Linköping, Sweden.

Baseley, S., Ehret, C., Greif, E. and Kliffken, M.G., 2007. "Hydraulic Hybrid Systems for Commercial Vehicles". In *Proceedings of the SAE 2007 Commercial Vehicle Engineering Congress and Exhibition*. Rosemont, IL, United States.

Deppen, T.O., Alleyne, A.G., Stelson, K.A. and Meyer, J.J., 2012. "Optimal Energy Use in a Light Weight Hydraulic Hybrid Passenger Vehicle". *Journal of Dynamic Systems, Measurement and Control*, Vol. 134, No. 4.

Eriksson, B., Nordin, P. and Krus, P., 2010. "Hopsan NG, A C++ Implementation using the TLM Simulation Technique". In *Proceedings of the 51st Conference on Simulation and Modelling*. Oulu, Finland.

Johri, R. and Filipi, Z., 2010. "Low-Cost Pathway to Ultra Efficient City Car: Series Hydraulic Hybrid System with Optimized Supervisory Control". *SAE International Journal of Engines*, Vol. 2, No. 2, p. 505-520.

Kim, Y.J. and Filipi, Z. 2007. "Simulation Study of a Series Hydraulic Hybrid Propulsion System for a Light Truck". In *Proceedings of the SAE 2007 Commercial Vehicle Engineering Congress and Exhibition*. Rosemont, IL, United States.

Kim, Y.J., 2008. *Integrated Modeling and Hardware-in-the-Loop Study for Systematic Evaluation of Hydraulic Hybrid Propulsion Options*. PhD thesis, University of Michigan, Ann Arbor, MI, United States.

Krus, P., Jansson, A., Palmberg, J.-O. and Weddfelt, K., 1990. In *Proceeding of the 3rd Bath International Fluid Power Workshop*. Bath, United Kingdom.

PSA Peugeot Citroën, 2013. "Hybrid Air, an innovative full hybrid gasoline system". <http://www.psa-peugeot-citroen.com/en/inside-our-industrial-environment/innovation-and-rd/hybrid-air-an-innovative-full-hybrid-gasoline-system-article>.

Rydberg, K.-E., 1983. *On Performance Optimization and Digital Control of Hydrostatic Drives for Vehicle Applications.* PhD thesis, Linköping University, Linköping, Sweden.

Rydberg, K.-E., 1984. "Gas-Charged Accumulators as Energy Storage Devices in Hydrostatic Drives". In *Energy and Environmental Systems - Ees '84: Proceedings IASTED Symposium*. Nice, France.

Stecki, J. and Matheson, P., 2005. "Advances in Automotive Hydraulic Hybrid Drives". In *Proceedings of the 6th JFPS International Symposium on Fluid Power*. Tsukuba, Japan.

Stelson, K.A., Meyer, J.J., Alleyne, A.G. and Hencey, B., 2008. "Optimization of a Passenger Hydraulic Hybrid Vehicle to Improve Fuel Economy". In *Proceedings of the 7th JFPS International Symposium on Fluid Power*. Toyama, Japan.

Sun, H., 2010. "Multi-objective optimization for hydraulic hybrid vehicle based on adaptive simulated annealing genetic algorithm". *Engineering Applications of Artificial Intelligence*, Vol. 23, No. 1, p. 27-33.

United States Environmental Protection Agency, 2013. "Dynamometer Driving Schedules". Last updated 6 Feb. 2013 <http:// http://www.epa.gov/nvfel/testing/dynamometer.htm>.

Wu, B., Lin, C.-C., Filipi, Z., Peng, H. and Assanis, D., 2004. "Optimal Power Management for a Hydraulic Hybrid Delivery Truck". *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility*, Vol. 42, No. 1-2, p. 23-40.

Yan, Y., Liu, G. and Chen, J., 2010. "Integrated Modeling and Optimization of a Parallel Hydraulic Hybrid Bus". *International Journal of Automotive Technology*, Vol. 11, No. 1, p. 97-104.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.