Proceedings of the 7th JFPS International
Symposium on Fluid Power, TOYAMA 2008
September 15-18, 2008

OS6-3

OPTIMIZATION OF A PASSENGER HYDRAULIC HYBRID VEHICLE TO IMPROVE FUEL ECONOMY

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ABSTRACT

This paper investigates power management strategies for hydraulic hybrid passenger vehicles. Parallel, series, and power-split architectures are modeled and explored in the Matlab environment using variable efficiency hydraulic pump/motor models. Results are presented using a rule-based strategy with ad hoc selection of engine on/off setpoints for the accumulator and transmission gear shifting. The dynamic programming algorithm is then used to determine the optimal trajectories for engine/hydraulics power splitting for each of the architectures over urban and highway drive cycles. Results are then compared to baseline simulation for improvement. Using the given vehicle parameters, the parallel architecture for both the urban and highway drive cycles was shown to be best. By decreasing the volumetric displacement of the hydraulic pump/motors for the power-split configuration, fuel economy can be improved with a corresponding decrease in acceleration.

KEY WORDS

Key words: Hydraulic Hybrid Vehicle, Power Management, Dynamic Programming, Optimization

NOMENCLATURE

L : Fuel consumption in one time step (g)
k : Time step index
N : Number of time steps in drive cycle
u : Control vector
x : State vector

INTRODUCTION

A major source of global energy consumption is transportation, which consumes approximately 4.8 billion barrels of crude oil per year in the United States, as of 2003. Passenger vehicles consume 2 billion barrels of the total with a value of over $200 billion at $100/barrel [1]. This significant usage of oil for passenger vehicles is the motivation for developing a vehicle that dramatically improves the fuel economy. A promising way to improve mileage is with a hybrid vehicle.

A hybrid vehicle is one that contains two sources of power, with one source most commonly being an internal combustion engine. The other power source can be mechanical in the form of a flywheel, electric in the form of motor/generators and batteries, or hydraulic in the form of pumps/motors and accumulators. The hybrid also allows energy storage during braking.

Currently, mass produced hybrid vehicles for passenger vehicles have been electric hybrids. One reason is the technological advances that have been made in electronics over the past few decades. Also, electric batteries have high energy density, allowing large energy storage. However, a disadvantage of electric hybrids is the low power density of electric motors/generators and batteries.

To overcome this shortcoming, hydraulics should be used in passenger vehicles due to the large power density of hydraulic pumps/motors and accumulators. Also, hydraulic components are inexpensive when compared to their electrical counterparts, especially for state-of-the-art battery packs. Developments are also being made in the area of digital hydraulic valves and higher energy density accumulators, making hydraulic technology look promising for passenger vehicles.

Researchers have previously studied using hydraulics in hybrid vehicles, but most of these have been concentrated on large vehicles such as buses, delivery trucks, and military vehicles. As computing power increased, researchers began developing simulations and trying different control strategies for city buses to improve fuel economy [2]. Research has also been done using models of hydraulic hybrid military vehicles, optimal control theory, and numerical algorithms to determine drive train parameters to minimize fuel consumption [3]. Researchers have also used the dynamic programming technique to optimize the power management strategy for a delivery truck [4] and the design and power management strategy for military vehicles [5]. Very little research has been done on using hydraulics with optimal power management in passenger vehicles.

In this paper, the different types of architectures for hybrid vehicles are explained. The computer model used to obtain simulation results is briefly described, and baseline results using ad hoc parameters are presented. The dynamic programming optimization technique is explained as it relates to each architecture. Optimized results are presented and compared for each architecture for an urban and highway drive cycle. Finally, future modifications are studied.

HYBRID VEHICLE ARCHITECTURES

Regardless of the secondary power source of the hybrid vehicle, three main types of architectures exist: parallel, series, and power split. In this section, the overall operation of each will be described. Figure 1 shows a schematic of each type.

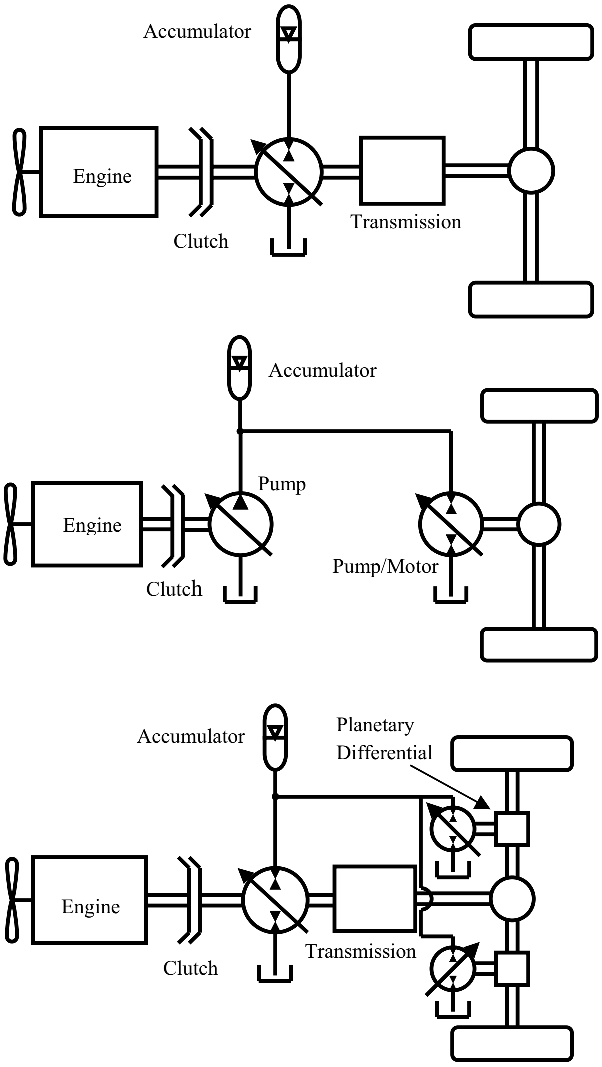

Figure 1 Schematic for the parallel hybrid (top), series hybrid (middle), and power-split hybrid (bottom) configurations

Parallel Hybrid Vehicle

In a parallel hybrid vehicle, the engine shaft is directly connected to a transmission, which is connected to a differential to provide power to each wheel. The hydraulic pump/motors are connected to the drive shaft between the engine and the transmission to provide or absorb power from the accumulator as needed. A clutch is placed between the engine and hydraulic pump/motors so the engine can be decoupled from the road load and the vehicle powered entirely by hydraulics. This allows the engine to be turned off when not needed, and turned back on when the accumulator becomes low. While the engine power does not need to match the load, the engine speed is matched to the wheel speed by the transmission gear ratio, and optimal engine management is not possible.

Series Hybrid Vehicle

In a series hybrid vehicle, the mechanical drive train is removed, and the vehicle is powered purely from hydraulics. The engine shaft is directly connected to a hydraulic pump/motor, which is connected to an accumulator to allow for energy storage. A hydraulic pump/motor is placed at each wheel to provide power and propel the vehicle. A clutch decouples the engine allowing on/off engine management. This architecture not only allows the engine output power to not match load demand, but also the engine speed does not need to match wheel speed, allowing for optimal engine management.

Power-split Hybrid Vehicle

The power-split configuration combines the parallel and series architectures into one. The mechanical drive train is still intact as in the parallel hybrid design, but hydraulic pump/motors are also connected to the drive wheel shafts as in the series hybrid design. This configuration allows for optimal engine management since, even though the engine is coupled mechanically to the drive wheels, the pump/motors at the wheels can be used to make up for the desired wheel speed. The clutch immediately downstream of the engine allows the engine to be decoupled completely from the load as in the parallel and series configurations. The power-split combines the advantages of both the parallel and series configurations: the mechanical drive train enables highly efficient power transfer from engine to wheels of the parallel architecture while maintaining the optimal engine management of the series architecture.

MODELING AND SIMULATION

A model of each type of vehicle architecture is needed to perform the power management optimization and compare results. The model used for the optimization was developed by Van de Ven et al [6], and is briefly explained here for completeness. The model is a backward-facing model with limited dynamics, meaning the power is calculated backwards through the drive train from the wheels to the engine. The model includes aerodynamic drag, rolling resistance, road grade, and inertial forces.

Hydraulic Pump/Motor Efficiency Model

Since optimization relies heavily on the efficiencies of the individual components, having an accurate hydraulic pump/motor efficiency model is essential. The hydraulic pumps/motors used in each configuration are variable displacement. Efficiency is characterized by displacement, operating pressure, angular velocity, and oil viscosity. The model developed by McCandlish and Dorey [7] is used to determine the efficiency at different operating parameters. This requires knowing the volumetric flow and torque data of the pump/motor at different operating conditions, which is mathematically fit to the equations. The volumetric and mechanical efficiency are calculated given the operating pressure, pump/motor angular speed, fractional displacement, and oil viscosity, and the two are multiplied together to calculate the overall efficiency.

OPTIMIZATION VIA DYNAMIC PROGRAMMING

Once the system configuration, components, and drive cycle are fixed, the fuel economy of the vehicle depends only on the strategy for power splitting between the two sources and the transmission gear. The optimal control problem is formulated and solved by using the dynamic programming algorithm [8]. This is a powerful technique for solving optimal control problems for nonlinear, constrained dynamic problems since the true optimal solution is found.

The dynamic programming algorithm is based on Bellman's principle of optimality, which states that if a sequence of decisions is optimal, each subsequence must also be optimal. Using this principle, the algorithm can start at the end of the drive cycle, go one step back and find the optimal trajectory, go another step back and find the optimal trajectory, and continue this process until the beginning is reached.

The formulation of the problem for the hybrid vehicle is as follows. The objective is to find the optimal trajectory of control signals u(k), which include engine command and gear shifting, to minimize the fuel consumption of the vehicle over an entire drive cycle. Mathematically, this is given in Eq. (1).

$$\min_{u(k)} J = \sum_{k=0}^{N-1} L[x(k), u(k)] \tag{1}$$

In Eq. (1), L is the fuel consumption in one time segment, N is the number of time segments, x is the state vector, which includes vehicle speed and accumulator state of charge, and u is the control vector, which includes engine command and transmission gear ratio.

The optimal cost at time step N-1 is:

$$J^*_{N-1}[x(N-1)] = \min_{u(N-1)} L[x(N-1), u(N-1)] \tag{2}$$

For all other time steps, the optimal control is found by minimizing the total cost.

$$J^*_k[x(k)] = \min_{u(k)} \{L[x(k), u(k)] + J^*_{k+1}[x(k+1)]\} \qquad 0 \le k < N-1 \tag{3}$$

Once the equation is solved backwards from step N-1 to 0, a lookup table is formed in which, given the state of charge of the accumulator at a time step, the optimal control is found to minimize fuel consumption. Then, given the initial state, the optimal control can be found from the lookup table, the model is executed to find the state the next time step, and this can be propagated forward in time until the end of the drive cycle is reached. The resulting optimal control trajectory is then simulated to obtain the fuel economy result.

RESULTS

In this section, results are presented from the dynamic programming optimization for each type of architecture for an urban and highway drive cycle. To compare the optimization results to determine the amount of improvement in fuel economy, a baseline simulation is executed for each type of architecture.

Baseline Simulations

For the baseline simulation, control parameters were chosen using physical intuition about the system. For the parallel configuration, the control parameters are the engine state and the transmission gear ratio. To determine engine state, a constant lower and upper setpoint was determined based on the accumulator pressure. When the pressure falls below the lower setpoint, the engine will turn on to refill the accumulator, and above the upper setpoint the engine will turn off and run purely on hydraulics. For this simulation, the lower setpoint is 60% of the full pressure and the upper setpoint 90% of the full pressure. The gear shifting setpoints of the transmission were chosen to take advantage of the full speed range of the engine and hydraulic pump/motor. If the engine is on, the gear shifting point is when the engine speed equals 3000 rpm, corresponding to a vehicle speed of 12.9 m/s. If the engine is off, the gear shifting point is when the hydraulic pump/motor equals 3600 rpm, corresponding to a vehicle speed of 15.5 m/s. Using this strategy produced a fuel economy of 7.4 L/100km (31.8 mpg) for an urban drive cycle and 5.11 L/100km (46 mpg) for a highway drive cycle.

For the series configuration, the control parameters are the engine state and engine speed. The engine state is determined as described for the parallel configuration above. The engine speed is determined by operating at the most efficient point, corresponding to a speed of 2200 rpm. This can be done since the displacement of the hydraulic pump/motor attached to the engine can be varied as the operating pressure changes. The displacement of the hydraulic pump/motors at the wheels is fixed due to the specified wheel speed, operating pressure, oil viscosity, and efficiency, and therefore is not a decision variable. This strategy produced a fuel economy of 4.42 L/100km (53.2 mpg) for an urban drive cycle and 5.6 L/100km (42 mpg) for a highway drive cycle.

Since the power-split configuration is a combination of the parallel and series architectures, the control parameters are a grouping from each and include engine state, engine speed, and transmission gear ratio. The engine state is the same as the parallel and series architectures, using the constant fixed lower and upper setpoints of accumulator pressure. The engine is also operated at its most efficient point as in the series configuration. However, the transmission gear ratio is chosen differently than in the parallel configuration. The transmission gear is chosen to minimize the speed of the hydraulic pump/motors connected to the drive wheels. This is done to maximize the power flow through the highly efficient mechanical drive train and minimize the power through the hydraulics. This strategy resulted in a fuel economy of 7.97 L/100km (29.5 mpg) for an urban drive cycle and 5.88 L/100km (40 mpg) for a highway drive cycle.

Optimization Results

The dynamic programming algorithm is now implemented for each type of architecture. For the parallel configuration, two control variables are used, engine state and transmission gear ratio. The equations given in section 4 are used to determine the optimal trajectories. The results for both the urban and highway drive cycles are shown in Figure. 2.

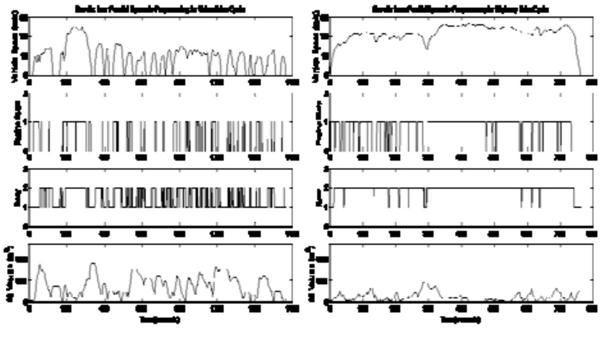

Figure 2 Dynamic programming results for the parallel hybrid configuration over an urban (left) and highway (right) drive cycle

The transmission gear ratio for the highway drive cycle is almost constant in 2nd gear, while for the urban drive cycle it fluctuates much more due to the higher vehicle speed during the highway drive cycle. Also, while both never reach a full accumulator state of charge, the highway drive cycle utilizes the accumulator less due to limited regenerative braking. The optimized results gave a fuel economy of 3.46

L/100km (68 mpg) for the urban drive cycle and 4.5 L/100km (52.3 mpg) over the highway drive cycle, a significant improvement over the baseline results.

For the series configuration, the two control variables are engine state and engine speed (if the engine is on). Applying the dynamic programming algorithm gives the results shown in Figure 3.

The results show when the engine is on, the engine speed is fairly constant around 2000 rpm, especially over the highway drive cycle. This is to utilize the efficient operating region of the engine. Also, the optimized results use the full volume of the accumulator for both drive cycles. This is due to the fact that the vehicle is a purely hydraulic drive train. The highway drive cycle does not fill the accumulator at the end of the cycle, however, since the optimization algorithm knows the end of the drive cycle is approaching. The optimized fuel economy for the urban drive cycle is 3.77 L/100km (62.3 mpg) and 5.10 L/100km (46.1 mpg) for the highway drive cycle, an improvement over the baseline result.

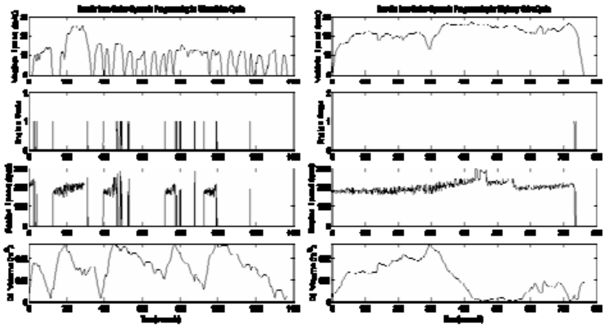

Figure 3 Dynamic programming results for the series hybrid configuration over an urban (left) and highway (right) drive cycle

Finally, the dynamic programming algorithm is applied to the power-split configuration, which has control variables of engine state, engine speed, and transmission gear ratio. The results are shown in Figure 4.

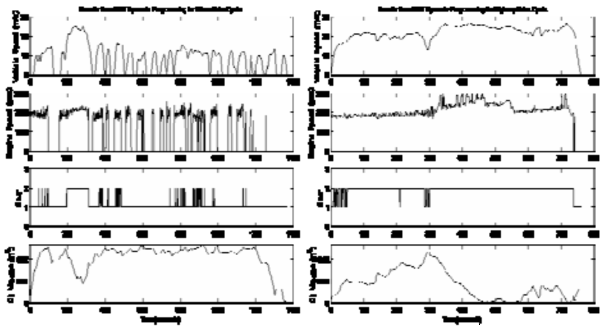

Figure 4 Dynamic programming results for power-split configuration over an urban (left) and highway (right) drive cycle

The results are very similar to those for the series hybrid, especially for the highway drive cycle. The engine speed is still operating near 2000 rpm, but more fluctuations exist in the transmission gear ratio. One interesting results is the high average state of charge of the accumulator over the urban drive cycle. The hydraulic pump/motors at the wheel are operating at a relatively slow angular velocity at low displacement, so the optimization forces the operating pressure higher to improve the efficiency of these pump/motors. The optimized fuel economy for the urban drive cycle is 7.17 L/100km (32.8 mpg) and 5.38 L/100km (43.7 mpg) for the highway drive cycle. The results for all architectures for the urban and highway drive cycles are shown in Table 1.

Improvements to power-split configuration

The optimized results show the power-split configuration being significantly worse for fuel economy than the parallel and series architectures. The main reason is that the hydraulic pump/motors are oversized for this application. Using the same coefficients for the loss terms in the pump/motor models, the maximum displacement of the pump/motors can be decreased, and the fuel economy over an urban drive cycle can be recalculated. These results are plotted in Figure 5. As the maximum pump displacement is decreased, the fuel economy improves.

Table 1 Summary of results for the urban and highway drive cycles

Configuration	Urban Drive Cycle			Highway Drive Cycle		
	Baseline (l/100km)	**Optimized (l/100km)**	**Percent Improvement**	**Baseline (l/100km)**	**Optimized (l/100km)**	**Percent Improvement**
Parallel	7.4	3.46	53.2%	5.11	4.5	11.9%
Series	4.42	3.77	14.7%	5.6	5.1	8.9%
Power-Split	7.97	7.17	10.0%	5.88	5.38	8.5%

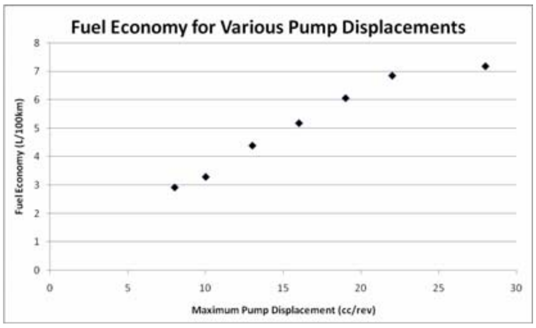

Figure 5 Plot showing fuel economy for various hydraulic pump/motor sizes

Figure 6 shows the time to accelerate to 100 km/h for the pump sizes above. As the maximum displacement decreases, the time to accelerate increases since the hydraulics are not able to add as much power to the drive train.

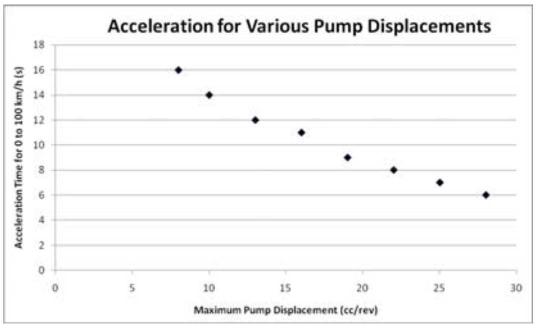

Figure 6 Plot showing acceleration performance for various hydraulic pump/motor sizes

To balance fuel economy and performance, the results above were used to determine two different sizes of the hydraulic pump/motors, one size at the engine and a smaller size at the wheels. A size of 19cc/rev was chosen at the engine since this gave the desired acceleration, while a size of 10 cc/rev was chosen at the wheels for the improved fuel economy. This led to a fuel economy of 4.2 L/100km using dynamic programming while maintaining a zero to 100 km/h acceleration time of 9.0 seconds.

CONCLUSION

By optimizing the control strategy used for hydraulic hybrid vehicles, improvements can be made in fuel economy. In this paper, three different configurations were studied over an urban and highway drive cycle. For each configuration and drive cycle, improvement was made in the fuel economy by optimizing the control strategy. The most significant improvement for both drive cycles was in the parallel configuration. The optimized results also showed that the parallel configuration obtains the best fuel economy for both the urban and drive cycle, with the power-split being the least efficient. However, it should be noted that the hydraulic pumps/motors used are oversized for a passenger vehicle and therefore are operating at low, inefficient displacement, especially at the wheels. When lower displacement pump/motors are used, the fuel economy can be improved while maintaining performance.

ACKNOWLEDGEMENTS

This work was performed within the Engineering Research Center for Compact and Efficient Fluid Power (CCEFP), supported by the National Science Foundation under Grant No. EEC-0540834.

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