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Optimization of Power Management Strategies for a Hydraulic Hybrid Medium Truck

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This paper investigates development of power management strategies tailored specifically to a medium truck with parallel hydraulic hybrid powertrain. The hydraulic hybrid vehicle (HHV) system is modeled in MATLAB/SIMULINK environment. As the starting point, this study considers rule-based power management strategy adopted from the previous HEV study. Dynamic Programming (DP) algorithm is used to find the optimal trajectories for gear shifting and engine/motor power splitting, assuming that the federal urban driving schedule represents typical use of a delivery truck. Implementable rules are derived from analyzing the optimal trajectories, and it is shown that the changes are to a large extent driven by high power density and low energy density of the hydraulic propulsion system. System behavior demonstrates effectiveness of new strategies in further improving the fuel economy of the hydraulic hybrid truck.

Keywords/Hybrid Hydraulic Vehicles, Power Management, Optimization, Dynamic Programming

1. INTRODUCTION

Global market competition and environmental protection forces are calling for significant improvement of fuel economy of all classes of vehicles. In recent years, fuel consumed by trucks grows at a much faster rate then that of passenger cars. This is a consequence of an increase in the relative number of light trucks and sport-utility vehicles, as well as the higher demand for transportation of goods. In case of trucks, the selection of new technologies is somewhat restricted compared to passenger cars, due to the fact that heavier trucks already use very efficient diesel engines, and that the potential for weight and air drag reduction is constrained by the payload carrying requirements. Hence, advanced hybrid propulsion technologies are critical to achieving future fuel economy goals for trucks.

Due to large mass associated with trucks, hybridization enables regenerating and reusing of significant amounts of braking energy. Consequently, power flows through the hybrid subsystem can be very high. This makes hydraulic propulsion and storage components very attractive for truck applications, since they are characterized by higher power density than their electric counterparts [1]. As the energy storage device, hydraulic accumulator has the ability to accept both high frequencies and high rates of charging/discharging, both of which are not favorable for electro-chemical batteries. However, relatively low energy density of the hydraulic accumulator requires carefully designed control strategy, if the fuel economy potential is going to be realized to its fullest. In this context, parallel hybrid architecture is the most attractive and cost-effective option.

Hybridization raises the question of how to coordinate the operation of primary power source (IC engine) and assistant power source (hydraulic motor) to maximize fuel economy. Earlier studies attempted to use engineering intuition and power distribution calculations to devise control strategies. Buchwald et al. [1] evaluated three different strategies on city buses considering simple vehicle acceleration-deceleration profiles. Wu et al. [2] proposed a strategy for passenger cars based on dividing the accumulator volume into two parts, one for regeneration and the other for road-decoupling. However, in-vehicle operating conditions are varying in a very wide range, often experiencing very rapid transients. Efficiencies of both the engine and the hydraulic pump/motor are functions of their respective operating conditions. Hence, the optimization of control strategies requires careful consideration of duty cycles for a specific vehicle, such as the delivery truck, and goes beyond the ability of engineering intuition.

Dynamic Programming [3] is an approach developed to solve sequential or multi-stage decision problems. The algorithm searches for optimal decisions at discrete points in a time sequence. It has been shown to be a powerful tool for optimal control of various plants [3, 4, 5]. A design procedure of sub-optimal control strategies based on Dynamic Programming (DP) was proposed previously for hybrid electric vehicles by

Lin et al. [5]. For hydraulic hybrid vehicles, this methodology supplies an attractive way to improve understanding of the tradeoffs associated with hydraulic hybrid systems and explore the overall system efficiency.

In this paper, we investigate application of DP methodology for developing power management strategies tailored for the parallel hydraulic hybrid powertrain. Section two describes modeling the hydraulic hybrid truck system in MATLAB/SIMULINK. This is followed by the introduction of the baseline rule-based power management. Next, a Dynamic-Programming algorithm is employed to search for optimal trajectories of gear shifting, engine power command and motor power command. From the results of DP, implementable power management rules are derived and tested in order to demonstrate their effectiveness in further improving the fuel economy of the HHV. Conclusions are offered in the last section.

2. MODELING A HYDRAULIC HYBRID VEHICLE (HHV)

2.1 Configuration of the HHV Medium Truck

In this paper, an International 4700 series, Class VI truck is selected as the baseline. The conventional truck has a total mass of 7340kg when fully loaded. In cities, medium-size trucks like the 4700 series undertake most delivery and trash collecting tasks that experience frequent stops-and-goes.

The schematic of HHV truck's powertrain is given in Fig.1. Driven by rear wheels, the HHV truck has two power sources. The primary power source is the same diesel engine as the one used in the conventional truck, i.e. a turbocharged, intercooled, DI Diesel V8, 7.3 L engine with rated power of 157 kW@2400 rpm. Although parallel hybrids offer the opportunity for engine downsizing, it is not adopted here to prevent any adverse effect on vehicle mobility and drivability when accumulator is empty. Given the fact of hydraulic accumulator's low energy density, we cannot expect to get power assistance whenever the drive requires excessive propulsion power.

The Torque Converter (TC), Transmission (Trns), Propeller Shaft (PS), Differential (D) and Driving Shaft (DS) are the same as those in the conventional truck. The hydraulic pump/motor is located behind the transmission for more effective braking regeneration. The hydraulic pump/motor is coupled to a propeller shaft via a transfer case with the gear ratio of two.

The assistant power source is an axial piston pump/motor (P/M) with variable displacement. When pumping, hydraulic fluid flows from low-pressure reservoir to high-pressure accumulator; when motoring, hydraulic fluid flows in reverse direction. The displacement per revolution can be adjusted via swash plate to absorb or to produce desired torque.

The accumulator contains the hydraulic fluid, and inertial gas such as Nitrogen (N_2), separated by a bladder. When hydraulic fluid flows in, the gas is compressed, and its internal energy is increased. When discharging, fluid flows out through the motor and into the reservoir. The reservoir can be regarded as an accumulator working at much lower pressure, e.g. 8.5 bar to 12.5 bar. The State of Charge (SOC) is defined as the ratio of instantaneous fluid volume in the accumulator over the maximum fluid capacity.

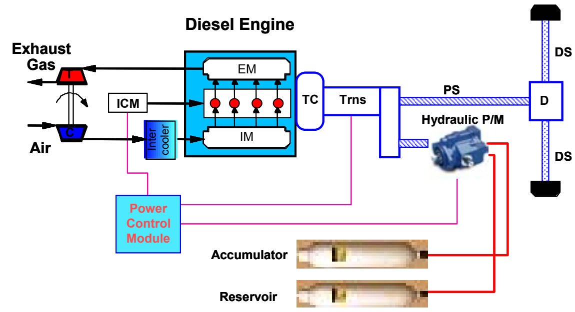


Fig. 1 The schematic of the parallel hydraulic hybrid propulsion system for a 4x2 truck

The size of hydraulic components is configured to absorb sufficient braking energy. The hydraulic pump/motor maximum displacement is 150 ml/rev. Accumulator key specifications are as follows:

Fluid Capacity: 50 liters.
Maximum Gas Volume (SOC=0): 100 liters.
Minimum Gas Volume (SOC=1): 50 liters.
Pre-charged Pressure (SOC=0, at 302K): 125 bar.
Maximum Pressure: ≤ 360 bar.

2.2 Modeling the HHV Medium Truck

The foundation for modeling the HHV system is the simulation of the conventional truck, previously developed at the University of Michigan Automotive Research Center. The simulation is implemented in MATLAB/SIMULINK and named Vehicle-Engine SIMulation (VESIM). It has been validated against vehicle data measured on the proving ground [6]. Lin et al. [7] added electric components and the power management module to create Hybrid Electric VESIM. The hydraulic hybrid is modeled by replacing the modules of electric components with those of hydraulic components, hence generating Hybrid Hydraulic VESIM (HH-VESIM).

The hydraulic pump/motor model is an updated version of Wilson's model [8]. The model accounts for both volumetric and torque losses in the pump/motor. Volumetric losses include laminar leakage loss, turbulent leakage loss and the loss due to fluid compressibility. Torque losses include losses due to fluid viscosity and mechanical friction. Model captures dependency of the pump/motor efficiency on the operating mode (pumping or motoring) and operating variables, such as displacement, pressure difference and rotational speed. For example, at smaller displacements (i.e. load), both the laminar leakage and torque losses are relatively larger, thus reducing the pump/motor efficiency.

For the accumulator and the reservoir, the Benedict-Webb-Rubin (BWR) equation is used to consider the real gas properties of nitrogen [9]. The effect of elastomeric foam, used to improve accumulator efficiency, is considered and modeled based on [10].

The internal friction and heat transfer are also included in the accumulator model [8]. Typically, the accumulator average efficiency is within 95~97%.

More details about the diesel engine, driveline, vehicle dynamics and driver modules are available in references [6, 7].

3 INITIAL RULE BASED POWER MANAGEMENT STRATEGY

As a baseline point, the control strategy previously developed for HEV trucks [7] is adopted. It's a rule based strategy, designed with a primary goal of shifting engine operating points to a more efficient region.

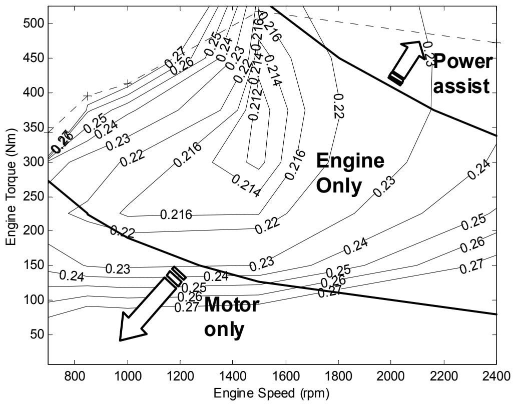


Fig. 2 Diesel engine BSFC map with constant-power lines illustrating the initial power management rules

Fig. 2 illustrates the basic power splitting idea on the engine Brake Specific Fuel Consumption (BSFC) map. The engine operating range is divided into three zones with two constant-power lines (25 and 85 kW respectively). When the total power demand is less than the pre-selected lower bound, the motor provides all the power, as long as there is energy available in the accumulator. Between the lower bound and upper bound, the engine replaces the motor to satisfy the total power command alone. Once the power requirement exceeds the upper bound, motor kicks-in to supply the excess power. In case the power command becomes larger than the sum of the upper bound and the maximum available motor power, engine power output increases to meet the total demand. The purpose of above strategy is to force the engine to operate in the more efficient region.

Since the braking energy is "cost-free", the general splitting rule during braking is to use regenerative braking whenever possible, i.e. whenever the hydraulic pump can supply sufficient negative torque and the accumulator is not full. Friction brakes are activated whenever braking torque requirement exceeds what pump can provide.

In contrast to typical HEV strategies, charging directly with engine power is prohibited due to low energy density characteristic of the hydraulic accumulator. In addition, rather than attempting to sustain the SOC within narrow limits, as it is done with electric batteries, the accumulator state of charge can be allowed to vary from fully charged to completely empty.

The hybrid vehicle duty cycle has a great impact on fuel economy. Since our focus is on the typical delivery truck, all fuel economy numbers are evaluated over the Federal Urban Driving Schedule (FUDS).

4 OPTIMIZATION OF POWER MANAGEMENT STRATEGY

4.1 Formulation of Dynamic Programming Problem

Once system configuration, component design and driving cycle are fixed, the fuel economy depends only on strategy for splitting propulsion power between two power sources and gear shifting logic. Since there is no evidence that the initial power management strategy described in Section 3. is the best, an optimal control problem for HHV is formulated and solved by using Dynamic Programming (DP) algorithm.

The objective is to search for optimal trajectories of control signals, $u(k)$, including engine command, hydraulic pump/motor command and gear shifting command to minimize the fuel consumption of the HHV truck over the whole driving cycle, i.e.:

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

where L is fuel consumption over a time segment, N is driving cycle length, and x and u are the vectors of state variables and control signals respectively. In order to match the final value of accumulator SOC with its initial value, a penalty term is added:

$$G = \alpha(SOC(N) - SOC(0))^2 \qquad (2)$$

Hence, the objective of the DP problem can be expressed as follows:

$$\min J = \min_{u} \sum_{k=0}^{k=N-1} L(x(k), u(k)) + G \qquad (3)$$

As a high-fidelity simulation tool, HH-VESIM is not suitable for DP analysis, and model simplification is conducted to reduce computation time. For Hydraulic propulsion sub-system, all dynamics are eliminated. The pressure difference between the accumulator and the reservoir is mapped as a static function of accumulator SOC, while the pump/motor efficiency model is replaced with look-up tables. More details about model simplification and DP algorithm are available from reference [5]. After simplification, only two states remain: the transmission gear number and the accumulator SOC. Based on Bellman's principle of optimality, the DP algorithm is presented as follows [3]:

Step $N-1$:

$$J^*_{N-1}(x(N-1)) = \min_{u(N-1)} \left[L(x(N-1), u(N-1)) + G(x(N)) \right] \qquad (4)$$

Step k, for $0 \le k < N-1$

$$J^*_{k}(x(k)) = \min_{u(k)} \left[L(x(k), u(k)) + J^*_{k+1}(x(k+1)) \right] \qquad (5)$$

After the recursive equation is solved backwards from step $N-1$ to 0, an optimal, time-varying, state-feedback control policy can be obtained.

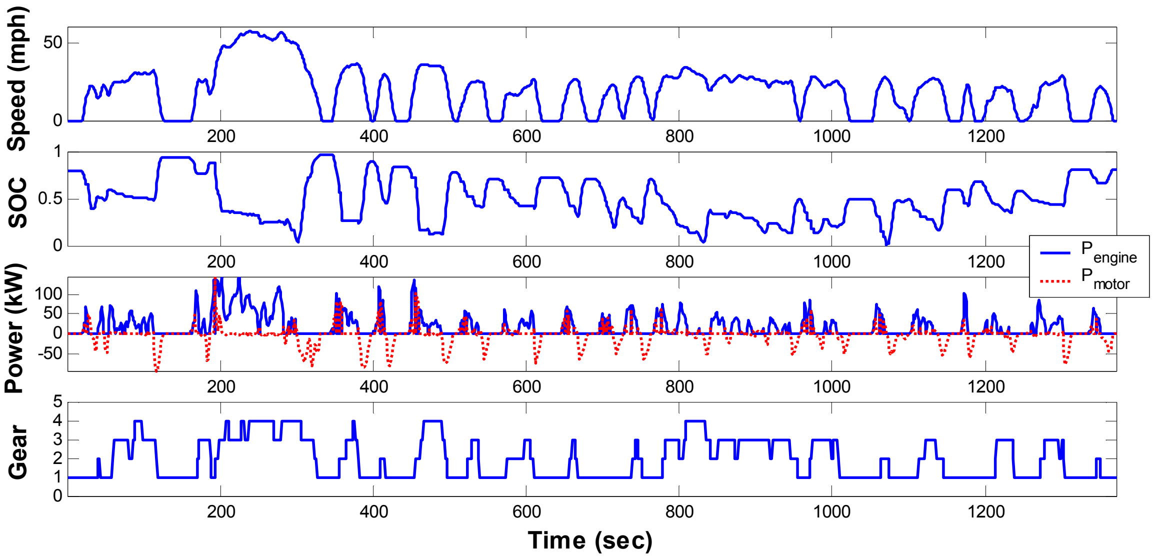


Fig. 3 FUDS cycle and Dynamic Programming results (using the low efficiency pump/motor)

The resulting optimal control trajectory is then used as a state-feedback controller in the simulations to generate the fuel economy result. The simulation results are shown in Fig. 3. Engine power, motor power, and gear trajectories show the optimal control actions to achieve minimum fuel consumption. The SOC trajectory starts at 0.8 and ends around 0.8 to meet the final state constraint imposed in the cost function (Eq. 3). The SOC graph in Fig. 3 is characterized by large fluctuations due to high power flows through the system. However, DP optimized policy maintains SOC within limits, never allowing it to hit either upper or lower bound, and thus enabling unrestricted use of the motor. The fuel economy of the DP-optimized hybrid trucks is more then doubled compared to values obtained with initial rule-based control strategy, as shown in Table 1. Large negative swings of motor power in Fig. 3, indicate effective capturing of braking energy.

4.2 Improvement of Power Management Rules

Since the DP algorithm is forward-looking, i.e. it uses the knowledge of the future driving conditions, the resulting optimal control signals are not applicable in practice. However, the optimal control signal trajectories provide a benchmark for evaluating applicable strategies. By analyzing the DP results, we can get useful hints about how to improve the initial power management rules and derive improved strategies that can be practically implemented.

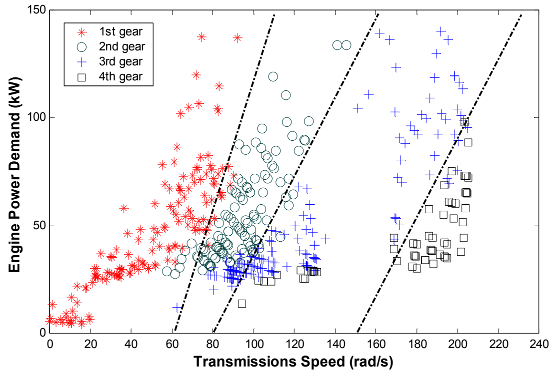


Fig. 4 Transmission gear shifting logic derived from DP

Fig. 4 shows the gear number versus the transmission speed DP results. Points are nicely clustered, making it easy to locate dividing lines that separate different gear numbers. Such dividing lines represent the optimal gear shifting schedule for maximizing fuel economy. At the same time, since DP satisfies the constraint to follow the desired driving cycle, the mobility of the truck is preserved.

Zooming-into DP generated engine and motor power histories during the 400-560 second time segment of the driving schedule, given in Fig. 5, demonstrates how DP splits the total driving power. Clearly, DP attempts to use the motor at the beginning of each vehicle launch, because the motor runs very efficiently at low speeds. Next, DP tends to use the motor and engine exclusively. Switching points during vehicle acceleration can be explained by observing the dotted line showing instantaneous maximum motor power, which depends on motor speed and accumulator pressure. Whenever the total power demand exceeds maximum motor power, propulsion is switched to the engine, and in most cases the engine becomes the only source. The reason for this is found in engine and motor characteristics: both devices have higher efficiencies at higher loads. Load of the hydraulic motor is expressed

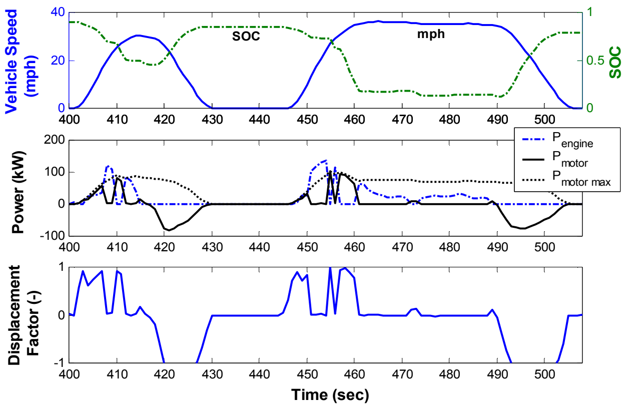


Fig. 5 DP optimized system behavior during the 400~510 second interval of the driving schedule

through a displacement factor, i.e. the ratio of instantaneous displacement to maximum displacement. By switching between the two power sources and avoiding simultaneous use of both the engine and the motor, the DP obviously attempts to keep propulsion components at high-load, high-efficiency regimes. The displacement factor time history shown in the bottom of Fig. 5 demonstrates DP's effectiveness in controlling motor load. Observed behavior is in sharp contrast with the power assist rule in the initial strategy. Finally, analysis of the SOC profile in Fig. 5 indicates that DP ensures: (i) enough accumulator storage space for the future regeneration event, and (ii) appropriate hydraulic energy reserve for next launching.

Unfortunately, these features are not practically applicable, because, unlike the DP algorithm, we do not know the future. In addition, very frequent switching between the motor and the engine would be unacceptable from the drivaeability standpoint. Hence, new rules have to be derived from ideas described in the previous paragraph. As an example, attempting to use only the motor to launch the vehicle should ensure frequent motor operation at high-load/low-speed, as well as emptying of the accumulator in preparation for the next braking event. Accounting for constrains imposed by motor power limits, as well as availability of energy in the accumulator, leads to the following improved rules:

$IF\ SOC > 0,$

$P_{motor} = min(P_{command}, P_{motor\ max})$

$P_{engine} = P_{command} - P_{motor}$

$Else,$

$P_{engine} = P_{command}, P_{motor} = 0$

In summary, whenever there is energy available in the accumulator, controller will call upon the motor to satisfy the total power demand. If the power requirement is more than what motor can provide, the engine will supplement the motor power. If the accumulator is empty the engine becomes the sole power source. These rules should capture the main features of the DP results in a very simple and easily implementable way.

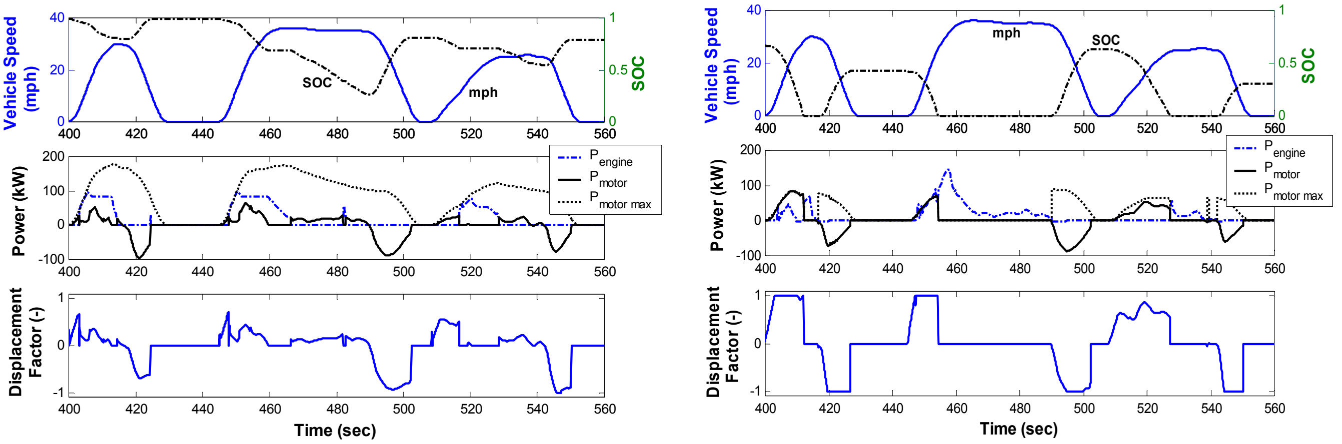
4.3 Discussion of Results

The overall simulation results are summarized in Table 1. For each vehicle configuration, and power management option, two cases are simulated; one with High Efficiency Pump/Motor (HEPM) and the other with Low Efficiency Pump/Motor (LEPM). Hybridization significantly improves truck's fuel economy (FE) over the city driving schedule. Even with the initial rules, which were never optimized for HHV, the fuel economy expressed in miles per gallon (mpg) improved 32.3% (for HEPM) and 15.6% (for LEPM) compared to the conventional vehicle.

Optimized gear shifting schedule modified based on DP results, further improves fuel economy, but only slightly (see Table 1). However, implementation of new power splitting rules in addition to modified gear shifting, leads to FE improvements of 47.4% (HEFFM) and 27.8% (LEFFM). Hence, even though practical new rules can not achieve nearly the same levels of fuel economy produced by the DP algorithm, they enable a very dramatic increase of HHV's ability to realize its fuel saving potential. In case the HHV is configured with the low efficiency/low cost motor the FE improvement is almost doubled with the new power management strategy compared to initial rules.

Fig. 6 shows the differences between the initial and improved power management strategy and helps us explain the efficiency gains with new rules. With the initial strategy, the hydraulic motor operates predominantly with the small displacement factor (see Fig. 6a, bottom). With improved strategies, the hydraulic motor frequently operates with a much higher displacement factor level, often reaching full-load conditions, as shown in Fig. 6b, bottom. The combination of high-load/low-speed leads to most efficient motor operation. In addition, frequent use of the motor for vehicle acceleration often depletes the energy in the accumulator, which prepares the system for the next regeneration event. Therefore, situations where SOC hits the upper limit and prevents further regeneration are avoided; an example simulated with initial rules is seen in Fig. 6a, around 425 seconds into the driving schedule.

The results in Table 1 indicate the critical role of regeneration and effective re-use of the regenerated energy. Total regenerated energy captured during braking reaches similar levels in all cases, except for DP calculations. However, reused energy varies significantly with both efficiency of components (HEPM vs. LEPM) and power management. If HHV



(a) Initial Rule Based

(b) Improved Rule Based

Fig. 6 Illustration of system behavior with different power management strategies during the 400~560 second interval

Table 1 Summary of Simulation Results

Configuration	Conventional	Initial Rule		Initial Rule + Improved Shifting		Improved Rule		Dynamic Programming	
P/M Efficiency	NA	High	Low	High	Low	High	Low	High	Low
mpg	10.39	13.75	12.01	14.08	12.40	15.32	13.28	18.37	14.34
mpg Improve.	NA	32.3%	15.6%	35.5%	19.3%	47.4%	27.8%	76.8%	38.0%
Regen. Energy (kJ)	NA	9748	9700	9652	9736	9459	9656	10013	10458
Reused Energy (kJ)	NA	6034	3187	5963	3229	7476	4524	8491	5134
Reused / Regen.	NA	61.9%	32.9%	61.8%	33.2%	79.0%	46.9%	84.8%	49.1%

(HEPM) with initial rules is compared to the HHV (HEPM) with optimized rules, the jump from 6034 kJ to 7476 kJ of reused energy can be attributed directly to the control strategy forcing the motor to operate in more efficient regimes. The reused and regenerated energy are obtained as integrals of motoring and pumping power over the whole driving cycle. Therefore, all losses in the accumulator/reservoir, pump and motor are considered. The ratio between reused energy and regenerated energy, shown in the last row of Table 1, illustrates the effectiveness of the energy conversion in the hydraulic sub-system. It should not be confused with so called wheel-to-wheel efficiencies, since the ratio does not account for losses in the driveline and friction braking. The new power management allows increase of the ratio from 62% to 79 % for the HEPM configuration, and from 33% to 47% in case of LEPM configuration.

5 CONCLUSIONS

An optimal control problem for power management of the Hydraulic Hybrid Medium Truck System is formulated and solved by using Dynamic Programming (DP) algorithm to minimize the fuel consumption. The results of forward-looking DP optimization are used to extract sub-optimal rules implementable in the practical controller. The new rules differ significantly compared to typical HEV strategies. The improved rules enable frequent use of the hydraulic motor as the sole power source during acceleration. This forces its operation at high-loads / low-speeds, a combination providing highest efficiency. In addition, frequent use of the motor for vehicle acceleration often depletes the accumulator charge, thus preparing the system for the next regeneration event. Depending on the efficiency of the hydraulic pump/motor, the practical control strategy derived from DP results enables fuel economy increase of the HHV truck over the conventional counterpart between 28% and 48%.

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