EVS24
Stavanger, Norway, May 13-16, 2009

SHIFTING STRATEGY FOR STEP CHANGE TRANSMISSION VEHICLE – A COMPARATIVE STUDY AND DESIGN METHOD

Ngo Dac Viet[1], Theo Hofman[1], Maarten Steinbuch[1], Alex Serrarens[2]
[1]*Department of Mechanical Engineering, Eindhoven University of Technology PO Box 513, 5600 MB Eindhoven, The Netherlands, email: n.dac.viet@tue.nl*
[2]*Drivetrain Innovations B.V, Croy 46, 5653 LD Eindhoven, The Netherlands*

Abstract

In this paper, gear shifting characteristics of vehicles equipped with an Automated Manual Transmission (AMT) and PowerShift-AMT (PS-AMT) are analyzed and compared in order to study their effects on the fuel economy. A "rapid" upshift strategy proposed for PS-AMT shows that relative fuel saving can be achieved up to 8.5% compared to the case of the AMT with prescribed gear shifting schedule over NEDC. To fully explore potential fuel savings with respect to gear shifting strategy, Dynamic Programming (DP) is utilized for PS-AMT system to derive a globally optimal shifting schedule. Simulation result reveals that relative fuel economy improvement can be reached up 10.7%. A systematic approach is proposed to study a tradeoff between fuel consumption and driveability with respect to gear shifting strategy. The optimization problem of which the cost function consists of fuel consumption, power reserve and shifting cost is formulated and solved for optimal gear shifting strategies by the DP algorithm. In this study, it is found that the fuel saving potential decreases approximately proportional with an increase of the potential accumulated power reserve. This design method is verified through simulations of forward facing dynamic powertrain model. Finally, in order to further improve the fuel saving potential and the driveability, a Hybrid Electric PS-AMT prototype is introduced and design consideration concerning the optimal control strategy is discussed.

Keywords: fuel economy, Automated Manual Transmission (AMT), PowerShift-Automated Manual Transmission (PS-AMT), Hybrid Electric PS-AMT, powertrain.

1 Introduction

In recent years, the sales of vehicles equipped with an Automated Manual Transmission (AMT) is steadily increasing due to the higher economy benefits compared to the Automatic Transmission (AT) vehicles and higher comfort than Manual Transmission (MT) vehicles [1]. The efficiency of the AMT is approximately equivalent with the MT of which efficiency value can approach 97% [2], and is unlikely to be improved any further. Besides, when customer's expectations increase, the AMT still reveals a bad shifting quality due to disengaging and re-engaging the dry clutch during gear shifting. Therefore, the AMT can not further improve the efficiency and driveability over the

MT as of its physical limitations. Continuously Variable Transmission (CVT) itself gives a smooth torque supply to driveshaft, yet it has low transmission efficiency and low torque capacity over a MT and an AMT. Meanwhile, the fuel economy and driveability in vehicle are constantly getting more attentions from both customers and automobile manufacturers. These demands have also been intensified by environmental protection regulations and incentives to invest more in R&D of new transmission system and control algorithms. In an effort to improve driveability and fuel economy of an AMT-equipped vehicle, the PS-AMT is developed and introduced by [1]. This transmission forms an excellent base for both a conventional vehicle and a hybrid electric vehicle (HEV) [1]. The PS-AMT module combines the seamless shifting characteristic of a dual-clutch transmission system with the agility of a conventional single dry clutch AMT transmission. The module transforms a manual transmission into a comfortable and fuel-efficient, lightweight automatic transmission.

Shifting control strategies for vehicle transmissions are still the important issues for design engineers and researchers so far due to the fact that the improvements of powertrain configurations are still expanding. The principle of shifting strategies for CVT-based vehicles are focused on shifting the engine operating points for a certain demanded power towards higher loads and lower speeds to permit more efficient engine behaviour by continuously changing gear ratio. Various control strategies can be found in literatures for both conventional vehicles and hybrid electric vehicles. However, these are beyond the scope of this. Interested readers are referred to [3], [10], [11], [12]. Conventional shift operations for an AT-based vehicle are implemented in form of shift maps. The shifting points are generated based on current vehicle speed and throttle opening. The shift maps are traditionally built either by engineers heuristically based on their experiences and intuitions or by model-based computation [4].

Due to the advantages of an AMT over a MT and an AT, shifting control strategies for an AMT-based vehicle have been studied and improved so far by researchers. Xiao Yin, et al. [5] proposed a method of combined time-optimal strategy and fuzzy logic strategy for engine control in the gear shifting process for an AMT. It was stated that the proposed control algorithm was capable of reducing the fuel consumption, engine noise, shift jerk and clutch friction losses by means of decreasing engine speed deviation between the controlled target and actual control output and shortening gear shifting time. Yang et al. [6] introduced a method of optimal shift control based on pattern recognition and learning algorithm utilized three dynamic parameters: vehicle speed, acceleration and throttle angle. The simulation results showed that the power and fuel performance were improved. In [7], a fuzzy cruise control system was developed to make gear changing decision for an AMT-base vehicle to increase the automation degree of automotive during cruise mode. The authors proposed controller that generated the set points for throttle opening and shifting points for transmission to maintain the vehicle speed at a predefined value. Shifting schedule is based on shifting map obtained from empirical experiments. Another study about gear shifting strategy in [8] considers engine working conditions and driver's intention. The authors designed a 2-layer fuzzy controller to eliminate unnecessary shiftings occurred when the intention of driver is overlooked or unclear. It was stated that control algorithm resulted in better performance. However, this control algorithm was tested on a self-designed short driving cycle. The authors in [9] proposed an advanced gear shifting and clutch strategy for an AMT-based HEV. The gear shifting maps for each driving mode of the HEV were built considering both the fuel consumption of diesel engine and the efficiency of the induction machine. The controller utilizing the speed control of induction machine and the diesel engine according to the driving conditions claimed a synchronizing at gear shift, reducing shift shocks and shortening the shifting time with minimum shift effort.

It is clear that shifting operation is one of the most frequent controlled operations of the powertrain system. To explore the potential fuel savings of the PS-AMT-based vehicle with respect to gear shifting decision making, initially a "rapid" upshift strategy will be introduced to learn the fuel consumption benefit. Then, a global optimal shifting schedule is derived based on Dynamic Programming (DP) to discover benchmark fuel savings. A systematic approach of determining optimal gear shifting strategy to study the tradeoff between fuel consumption and driveability is proposed based on DP algorithm. "Power reserve" is incorporated in the cost function of optimization problem to study driveability issue quantitatively. This will be compared to that of the AMT powertrain with the pre-described shifting strategy primarily optimized for driveability to justify the shifting design method.

2 Gear shifting strategy analysis

2.1 Powertrain topology

In Fig.1, the AMT powertrain and the PS-AMT powertrain studied in this paper are depicted.

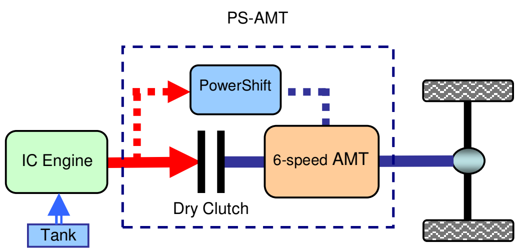

Figure 1: Layout of the AMT/PS-AMT powertrains

The baseline powertrain is based on an AMT as used in small- to medium-sized passenger cars. Then, the PS-AMT [1] is constructed by adding a powershift system which is in parallel with the dry clutch and the 6-speed AMT. The final reduction gear ratio is lumped into the AMT for simplicity. The internal combustion engine is 1.5 Liter Spark Ignition engine with a maximum torque of 145 Nm at 4150 rpm and a maximum power of 80 kW at 6100 rpm. The single dry clutch has a maximum torque capacity up to 215 Nm.

2.2 Transmission gear shifting analysis

In this research, for simplicity, the efficiency of the clutch, transmission and final gear reduction are assumed to be 100%. To calculate the fuel usage, a quasi-static engine map is used. Shifting sequences for an AMT are regulated through the following distinct phases:

(i) slipping to disengage the dry clutch;
(ii) synchronizing the gear-mesh to shift;
(iii) slipping to engage the dry clutch again;

When evaluating the fuel consumption vs. driveability of the AMT powertrain, it is mandatory to consider the entire shifting process time taking about 0.8s–1.0s to properly calculate the fuel consumption. Particularly, during city driving, the transmission must be shifted many times to adjust the vehicle speed to traffic conditions. For the AMT this reduces the driveability significantly due to the many drive torque interruptions during shifting. Particularly for this reason, the AMT vehicle makers usually delay and limit the number of upshifts, which obviously penalizes the maximum achievable fuel economy. In addition, right after shifting, due to torque interruption and resistance forces acting on the vehicle, more torque is required at the wheel to accelerate the vehicle accommodating the reference vehicle speed as desired. That means in some cases of reaching the maximum engine torque, causes the driver to press harder on accelerator pedal which results in a higher fuel consumption.

This opposed to the PS-AMT powertrain, where no torque interruption occurs during the gear upshift and kick-down downshift. The powershift system is activated by a controller that acts as a by-pass unit in order to transmit power and torque to the wheels during shifting. This will improve the driving comfort. Therefore, an amount of fuel will be consumed during the shift since the engine is still combusting during the shifting phase. However, the PS-AMT powertrain enables the "rapid" upshift strategy, which means that upshift triggers are given at a lower engine speed with less shift control effort compared to a conventional AMT of which the shift strategy would do to prevent shift haunting, engine deterioration or stalling conditions.

2.3 Rapid upshift strategy

Traditionally, pre-defined shift map is used to generate shift points for transmission based on current throttle position and vehicle speed. In this study, the New European Drive Cycle (NEDC) is chosen as a velocity profile and the accompanied gear shifting schedule is used for determining shifting points, which is hereafter called the *"normal shifting"* as shown in Fig.2 (bottom). It is built at the driveability calibration stage. So, ti does not take into account the varying operating points and operating conditions of the engine to yield out a proper shifting schedule for fuel consumption benefit.

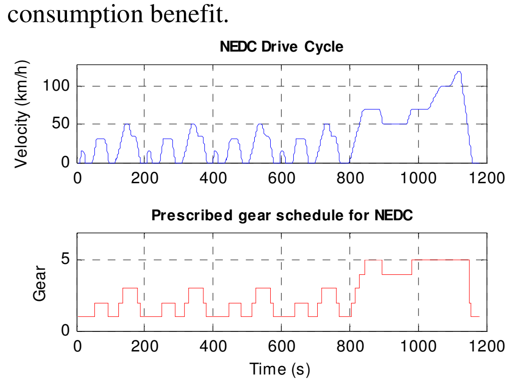

Figure 2: NEDC drive cycle, normal shifting schedule

The fuel efficiency for the powertrain system equipped with a step-change transmission like PS-AMT can be improved substantially by an optimized shifting strategy, wherein its principles can be stated as follows:

- A decision to change gears should be based on the ability of the powertrain to remain in next gear for an acceptable period of time to prevent shift haunting and engine deterioration or engine stalling conditions.
- At low engine speeds, the engine efficiency is higher. When accelerating the vehicle, rapid upshift is desirable to bring back the engine in the optimal Brake Specific Fuel Consumption region.
- Shifting points should be made such that the engine stays as long as possible in the best fuel efficient region.

By utilizing these principles, a shifting strategy that allows rapid upshift for the PS-AMT powertrain is designed. This so-called *rapid upshift strategy* always exams engine operating point and gear position to generate shifting points as early as possible resulting in a higher shifting frequency than the normal shifting strategy for the AMT powertrain would do. Due to torque filling during shifting, the rapid upshift strategy does not cause the performance of a vehicle to deteriorate.

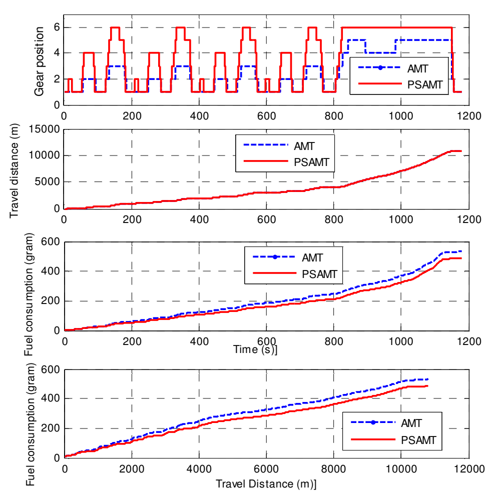

Figure 3: gear position, distance vs. time, fuel consumption vs. time, fuel consumption vs. distance for the AMT with normal shifting and the PS-AMT with rapid upshift.

Forward facing dynamic models of the AMT and the PS-AMT powertrains are built by Matlab/Simulink in which the shifting sequences are incorporated to account for their effects on fuel consumption during shifting. The normal shifting and the rapid upshift strategy are applied for the AMT and the PS-AMT powertrains respectively. The control algorithms will regulate both powertrain systems on the NEDC so that they can end the NEDC with a same long travelling distance.

Simulation results in Fig.3 show the different gear positions of both systems. The PS-AMT powertrain can goes up to the 6th gear and remains for long driving period. Meanwhile, the AMT powertrain operates up to the 5th gear for a shorter driving period. Both of them can travel for a same long distance at the end of cycle but fuel consumption of the PS-AMT powertrain is much smaller compared to that of the AMT powertrain. The relative fuel savings is up to 8.5% in this simulation.

In Fig.4, the engine operating points of the PS-AMT powertrain concentrate at high fuel economy region more than those of the AMT powertrain. This leads to an improvement of fuel economy with respect to rapid upshift strategy. However, there exist some parts of the PS-AMT powertrain operating points far from optimal operating region. The operating points at 200 rad/s and higher are those when the vehicle is driving at highway part in the 6th gear so it can not be further optimized unless the system is hybridization.

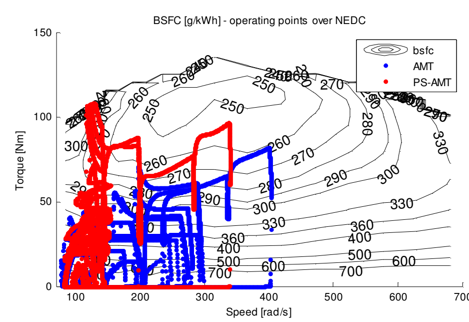

Figure 4: Operating points of theAMT powertrain with normal shifting and the PS-AMT powertrain with rapid upshift over NEDC.

3 Optimal shifting control strategy

It is crucial that the shifting strategy can improve the fuel economy dramatically. The authors in [11] already used shift command as one of the control variables for designing of a near-optimal energy management strategy for parallel hybrid electric truck equipped with an AT. This strategy, called an improved rule-based control strategy, was developed based on the optimal results of DP control policy. The DP was applied for the

optimal control problem represented by a cost function of the fuel consumption, and certain selected emissions (i.e., NOx and PM) and state of charge constrain of battery over a drive cycle. From simulation results, they showed that significant emission reduction was achieved at the expense of a small increase in fuel consumption.
However, the most considered emission is CO_2, which in general will be reduced when fuel economy is improved. Therefore, the next step of this research is to develop a systematic approach to study the potential fuel savings with respect to only shift command for vehicle equipped with step-change transmission like PS-AMT. The cost function consisting of fuel consumption, power reserve and shifting cost will be proposed for an optimal shifting control problem to quantitatively analyze trade-offs between fuel consumption and driveability.

3.1 Fuel consumption minimization

To explore how much fuel savings can be achieved over a specific drive cycle with respect to gear shifting strategy, an optimal shifting control problem is formulated as follows:

$$J = \int_0^{t_f} L(x(t),u(t))\,dt = \int_0^{t_f} \underbrace{[T_e.\omega_e.bsfc]}_{fuel\ consumption}dt \qquad (1)$$

Subject to constraints:

$$\dot{x}(t) = f(x(t),u(t)) \qquad (2)$$

$$\begin{aligned} &\omega_{e\_\min} \le \omega_e(t) \le \omega_{e\_\max} \\ &T_{e\_\min}(\omega_e(t)) \le T_e(t) \le T_{e\_\max}(\omega_e(t)) \\ &1 \le n_{gb}(t) \le 6 \end{aligned} \qquad (3)$$

wherein: L is the instantaneous cost of fuel used by vehicle, (2) describes the model of the vehicle system, *x(t)* is the state vector of the system, *u(t)* is the vector of control variables, ω_e is the engine speed, T_e is the engine torque, n_{gb} is the gear position of the transmission.
DP is well known as a powerful tool to solve for an optimization problem with constraints and nonlinearity while obtaining a globally optimal time-variant, state feedback solution. So, it can be used as a benchmark for other control strategies. The technique of DP is based on the recursive programming of Bellman's principle optimality [14].
In this paper, a numerical-based DP approach is used to solve for this finite horizon dynamic optimization problem by discretizing the (1)...(3) with time step of one second as follows:

$$\begin{aligned} J &= \sum_{k=0}^{N-1} L(x(k),u(k)) \\ &= \sum_{k=0}^{N-1} T_e(k).\omega_e(k).bsfc(k) \end{aligned} \qquad (4)$$

Subject to constraints:

$$x(k+1) = f(x(k),u(k)) \qquad (5)$$

$$\begin{aligned} &\omega_{e\_\min} \le \omega_e(k) \le \omega_{e\_\max} \\ &T_{e\_\min}(\omega_e(k)) \le T_e(k) \le T_{e\_\max}(\omega_e(k)) \\ &1 \le n_{gb}(k) \le 6 \end{aligned} \qquad (6)$$

Shift command, the only concerned variable for the optimization problem, is expressed through gear position:

$$n_{gb}(k+1) = \begin{cases} 1, & n_{gb}(k) + shift_{gb}(k) < 1 \\ 6, & n_{gb}(k) + shift_{gb}(k) > 6 \\ n_{gb}(k) + shift_{gb}(k), & otherwise \end{cases} \qquad (7)$$

wherein: the $shift_{gb}(k) \in [-1,0,1]$ is the shift command at time step *k* representing downshift, sustain and upshift respectively.
Then, the DP algorithm is formulated as:

Step N-1:

$$J^*_{N-1}(x(N-1)) = \min_{u(N-1)} \left[L(x(N-1),u(N-1)) \right] \qquad (8)$$

Step k, ($0 \le k < N-1$ *)*:

$$J^*_k(x(k)) = \min_{u(k)} \left[L(x(k),u(k)) + J^*_{k+1}(x(k+1)) \right] \qquad (9)$$

wherein: *N* is the length of drive cycle, $J^*_k(x(k))$ is the optimal cost-to-go function at state *x(k)* starting from time stage *k*. It points out the optimal paths for system under control and the corresponding optimal cost results.
This algorithm is solved backward to find the optimal solution path, which minimizes the cost function for the whole drive cycle.
In order to apply DP for optimization problem, the model of powertrain must be simplified enough to reduce the number of states and capture main fuel consumption characteristics over a long drive cycle. Dynamics of system that are faster than 1 Hz could be ignored. The static model [2] is chosen in this study. The simulation results for the AMT powertrain (baseline) with normal

shifting and the PS-AMT powertrain with shifting schedule from DP results are shown on table 1.

Table1: Fuel consumption for AMT base-line (normal shifting) vs. PS-AMT (DP shifting) over NEDC

	Fuel consumption (gram)	Improvement (%)
AMT (baseline) *normal shifting*	513.79	-
PS-AMT *DP shifting*	458.76	10.7

It can be seen that the relative fuel savings is up to 10.7% by applying DP to gear shifting strategy. Compared to the case of rapid upshift strategy in previous section, 2.2% of relative fuel savings can be improved further.
Simulation results in Fig.5 show that transmission is controlled to upshift as early as possible. This DP shifting strategy can be considered as the "smart" rapid upshift strategy because of shifting points are varied with respect to gear positions and engine operating points. However, DP is just applicable for only specific drive cycle meanwhile the rapid upshift strategy designed in previous section can be applied for other drive cycles in principle.

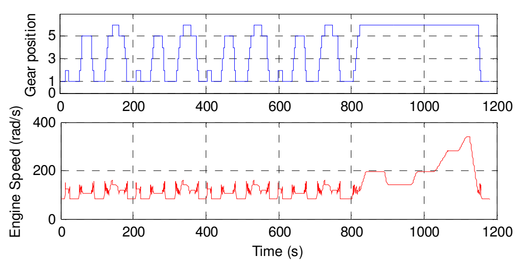

Figure 5: DP gear shifting and corresponding engine speed for PS-AMT powertrain

3.2 Fuel consumption and driveability optimization

It is revealed that gear shifting strategy obtained from DP algorithm is considered as the globally optimal solution so that the total fuel consumption is minimized over NEDC. However, there exists a question of finding what the penalty is and how much it is in contrary with the fuel economy improvements.
Under optimized gear shifting schedule, engine operating points tend to gather around the best fuel efficient region. As a results, the so called *torque reserve* ΔT_e defined by a difference between actual engine torque T_e and maximum engine torque T_{eWOT} (Wide Opening Throttle – WOT) tends to decrease compared to that of normal shifting schedule. So, the *power reserve*, defined by product of actual engine speed ω_e and torque reserve ΔT_e will tend to change. The driveability in broad view is determined by the instant availability of power when pressing the accelerator pedal. In other word, power reserve can be used as a measure of the driveability.
Therefore, the cost function is re-proposed to study the tradeoff between fuel consumption and driveability of PS-AMT powertrain as follows:

$$J = \int_0^{t_f} [\underbrace{T_e.\omega_e.bsfc}_{fuel\,consumption} + \underbrace{\upsilon.(\Delta T_e.\omega_e)^{-1}}_{driveability}]dt \qquad (10)$$

wherein:

$$\Delta T_e = T_{eWOT} - T_e$$

The fuel consumption and accumulative power reserve of the AMT powertrain system with normal shifting on NEDC is chosen as a baseline for all comparisons hereinafter. The simulation results are shown on table 2.

Table 2: Baseline result of AMT Powertrain

AMT (baseline) *normal shifting*	FC (gram)	Acc. PR (kJ)
	513.79	15446

Note: FC - Fuel Consumption; Acc. PR – Accumulative Power Reserve

The weighting factor υ in (10) is varied to study the sensitivity between driveability and fuel consumption. Its values are selectively chosen as:

$$\upsilon \in \{0, 500, 1000, 1500, 2000, 3000, 4000, 5000\} \qquad (11)$$

DP algorithm is still applied for optimization problem of PS-AMT system in the same manner in section 3.1 to find out optimum values and optimal gear shifting schedules.

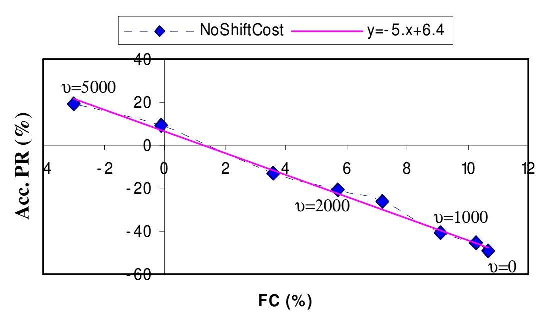

Figure 6: Fuel economy versus accumulative power reserve.

Fig.6 shows the tradeoff in fuel consumption and accumulative power reserve improvements. When $\upsilon = 0$, the case corresponds to the fuel economy only problem of 10.7% improvement and -49.3% deficit of accumulative power reserve. Increasing υ leads to a decreasing of fuel economy and a increasing of accumulative power reserve. When $\upsilon = 5000$, fuel economy is degraded by 3% meanwhile accumulative power reserve is improved by 19.5%. However, there is a small improvement region of both fuel economy and accumulative power reserve when υ is properly chosen somewhere between [3500, 4000].

By changing the gear shifting strategy, the expected fuel consumption benefit can be obtained at a certain loss or even benefit of accumulative power reserve by an approximated linear slope factor -5.

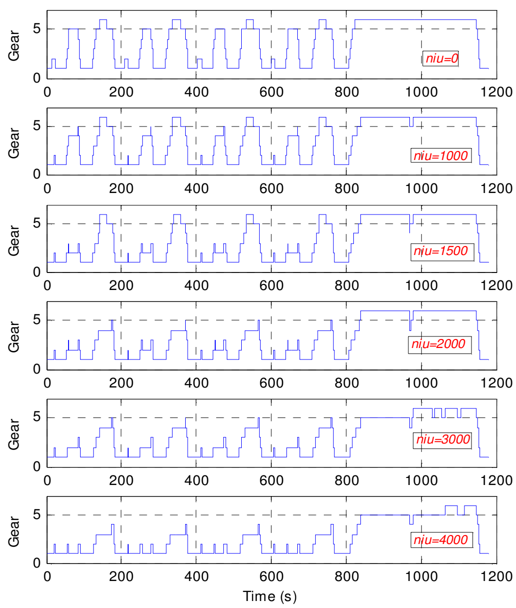

Figure 7: DP gear shifting schedules for optimization problem of fuel economy and driveability.

Simulation results in Fig.7 show that at certain value of υ, the transmission tends to shift at higher frequency and some un-wanted shift points occur which will effect the driveablity of vehicle.

3.3 Fuel consumption, driveability and shifting cost optimization

It is obvious that eliminating the frequent shifting features in the optimal shifting schedules obtained in section 3.2 means driveability will be improved. To approach that target, the cost function is again re-proposed by adding the shifting cost as follows:

$$J = \int_0^{t_f} [\underbrace{(T_e.\omega_e.bsfc)}_{fuel\ consumption} + \underbrace{\upsilon.(\Delta T_e.\omega_e)^{-1}}_{driveability} + \underbrace{\beta.abs(shift_{gb}(t))}_{shifting\ cost}]dt \quad (12)$$

wherein: β stands for weighting factor of the shifting cost.

For every specific value of υ, the value of β is varied to determine which will result in less frequent shifting schedule but assure a small change or un-change of fuel consumption and accumulative power reserve. The sensitivity study of fuel consumption and accumulative power reserve to shifting cost is neglected. This will be future research.

Table 3: Optimization results for PS-AMT powertrain

υ	β	Improvement (%)	
		FC	Acc. PR
0	0	10.7	-49.3
500	0.2	9.6	-42.1
1000	0.1	8.8	-39.4
1500	0.2	6	-21.7
2000	0.2	4.8	-17.2
3000	0.1	3.5	-12.8
4000	0.05	-0.1	9
5000	0.1	-2.6	18

Table 3 shows the selective values of β for every value of υ and the corresponding improvements in fuel economy and accumulative power reserve when the optimization is solved by DP.

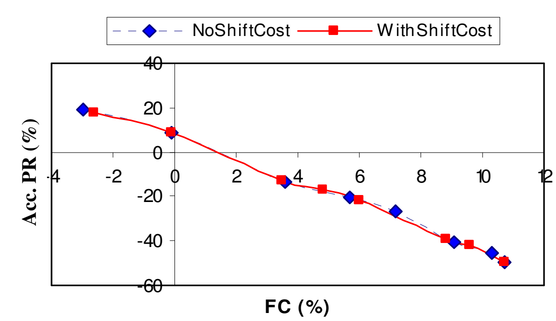

Figure 8: Fuel economy versus accumulative power reserve.

Fig.8 depicts sensitivity between fuel consumption and accumulative power reserve for both cases of “no shifting cost” and “with shifting cost". It is observed that they are almost disposed on the same curve.

The optimal shifting schedules are illustrated on Fig. 9. The control algorithm significantly eliminates the unexpected shifting points that result in the "nice" optimal shifting schedules.

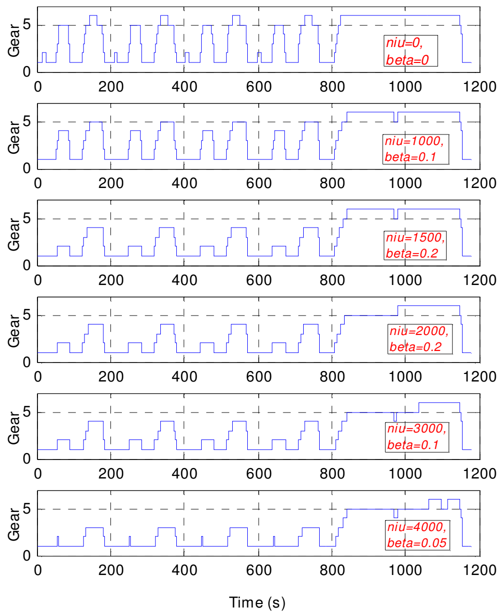

Figure 9: DP gear shifting schedules.

3.4 Gear shifting verification

The obtained optimal gear shifting schedules are now applied for the vehicle's forward facing dynamic model on the NEDC to verify the design method. Simulations are performed by Matlab/Simulink.

Table 4: Forward model simulation results for the baseline AMT and the PS-AMT powertrains.

AMT (baseline) *normal shifting*	FC (gram)	Acc. PR (kJ)
	534.75	15,636

PS-AMT		Improvement (%)	
υ	***β***	FC	Acc. PR
0	0	10.2	-49.8
1000	0.1	8.9	-39.8
2000	0.2	4.9	-17.2
3000	0.1	3.7	-13
4000	0.05	0.0	7.6

The results on table 4 show that there are differences of outputs for the baseline between backward and forward facing models (refer to table 2). This is apparent due to the different natures between backward and forward modelling methods and the differences of time step for simulation of DP algorithm and the forward simulation method. However, the relative improvements of fuel consumption and accumulative power reserve of these forward facing model simulations nearly coincide with that of backward model simulations (compared to table 3).

4 Hybrid Electric PS-AMT Powertrain

The PS-AMT forms an excellent base technology for parallel hybridization. Its high efficiency, torque-filling capabilities and faster 0-100 km/h acceleration which is up to 1.5 s quicker than a dry-DCT for small- to medium-sized vehicles, lowers the demand for electrical assist methods normally offered by hybrid drive trains. This reduces power and energy specifications of electric power parts [1], [13].

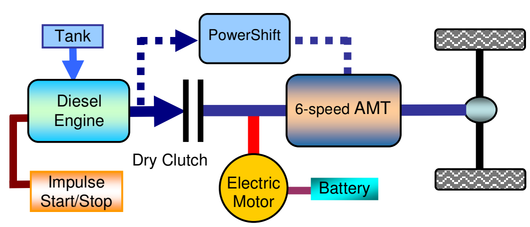

Figure 10: Hybrid Electric PS-AMT powertrain.

The Hybrid Electric PS-AMT prototype in progress of development by DTI b.v. [1] is shown on Fig.10. This new hybrid system consists of a 1.3Liter turbocharged diesel engine, a highly efficient AMT including DTI's powershift technology, a peak 12 kW side-mounted electric machine and a low-cost impulse start/stop system. The electric machine is driven and powered by power electronics and a Li-ion battery pack mounted in front. This prototype aims at cost-effective hybrid system to realize a fuel economy target between 3-3.5 L/100km and CO_2 emission below 100g/km [13].

Energy management system based on optimization control problem is a key to achieve those excellent results. It decides, which electric motor modes (braking mode, charge mode, motor mode and motor assist mode) will be used and controls the impulse start/stop system. During the charge and the motor assist modes, the optimal power-split ratio between diesel engine and electric machine is derived from the optimization control problem. Concurrently, the optimal gear shifting strategy is designed to increase the average combustion efficiency of the engine. Fast responses of engine impulse start/stop and smart recovery of braking energy that is reused to launch the vehicle electrically at moderate drive-off demands to keep engine far away from low efficiency areas are feasible means to reduce fuel consumption.

5 Conclusions

Shifting strategy for a step change transmission vehicle plays a crucial role in improving the fuel economy. A rapid upshift strategy applicable independent of the vehicle use or selected drive cycle, is proposed for the PS-AMT powertrain. It can relatively save fuel consumptions up to 8.5% compared to the baseline of the AMT powertrain with the normal shifting strategy over the European drive cycle (NEDC). Dynamic Programming-DP shifting algorithm for the PS-AMT powertrain proves that it is the best rapid upshift strategy in terms of the fuel economy with relative fuel savings up to 10.7% compared to the baseline. Tradeoff between the potential fuel savings and the accumulative power reserve over the whole drive cycle is quantitatively studied by incorporating the power reserve quantity into the cost function and the corresponding optimal gear shifting schedules are obtained. Forward facing model simulations prove and verify the consistency of gear shifting design method. This method is not only applicable for the PS-AMT powertrain, yet also for a step-change transmission powertrain in exploring the relation between fuel economy and accumulative power reserve (driveability).

Electric hybridization for the PS-AMT powertrain in small- to medium-sized passenger cars will improve much more the fuel economy, CO_2-emission reduction and the driveability, which will be future research.

Acknowledgments

This study is part of “Euro Hybrid” which is a research project of Drivetrain Innovations Company, together with the Eindhoven University of Technology, The Netherlands. The project is financially supported by SenterNovem.

References

[1] DTI b.v., *Technical documents of PowerShift System*, www.dtinnovations.nl

[2] L. Guzzella, A. Sciarretta, *“Vehicle Propulsion Systems, Introduction to Modeling and Optimization”*, Springer, 2nd ed., 2007, XII, 338 p. 202 illus.

[3] Pfiffner R., Guzzella L., *"Optimal Operation of CVT-Based Powertrains"* 2001, Int. Journal of Robust and Nonlinear Control, Vol. 11, pp. 1003-1021.

[4] Shushan Bai, Joel Maguire, Kim Daekyun, Huei Peng, *“Dynamic Programming Based Motor Vehicle Shift Map Generation”*, World Automotive Congress, October 2006, Yokohama, Japan.

[5] Xiaofeng Yin Dianlun Xue Yun Cai, *“Application of Time-Optimal Strategy and Fuzzy Logic to the Engine Speed Control during the Gear-Shifting Process of AMT”*, The 4th International Conference on Fuzzy Systems and Knowledge Discovery, volume: 4, on page(s): 468-472, 2007.

[6] Zhigang Yang Changxiu Cao Yugang Su , *“A method of optimal shift control based on pattern recognition and learning algorithm”*, Proceedings of the 4th World Congress on Intelligent Control and Automation, on page(s): 955- 959 vol. 2, 2002.

[7] Qin, G., Ge, A., Zhao, J., Lee, J., *“Cruise control of automated manual transmission vehicle”,* IEEE Computing Control Engineering, 2003, 14(2), 18–21.

[8] B Mashadi, A Kazemkhani, and R Baghaei Lakeh, *“An automatic gear-shifting strategy for manual transmissions”*, Proc. IMechE Vol. 221 Part I: J. Systems and Control Engineering, IMechE 2007.

[9] Hyeoun-Dong Lee, Seung-Ki Sul, Han-Sang Cho, Jang-Moo Lee, *“Advanced Gear-shifting and Clutching Strategy for a Parallel Hybrid Vehicle”*, IEEE Industry Applications Magazine**,** Volume: 6, Issue: 6, page(s): 26-32, 2000.

[10] Jong-Seob Won, Langari, R., Ehsani, M., *“An energy management and charge sustaining strategy for a parallel hybrid vehicle with CVT”*, IEEE Transactions on Control Systems Technology, Volume: 13, Issue: 2, page(s): 313- 320, 2005.

[11] C. C. Lin, H. Peng, J. W. Grizzle, and J. M. Kang, *“Power management strategy for a parallel hybrid electric truck”,* IEEE Trans. Control Syst. Technol., vol. 11, no. 6, pp. 839–848, Nov. 2003.

[12] T. Hofman, *"Framework for combined control and design optimization of hybrid vehicle propulsion systems"*, PhD Thesis, 2007, Eindhoven University of Technology.

[13] A. Serrarens, R. van Druten, W. van Liempt, N. Weel, P. Kumar, L. Römers, D.V. Ngo, *"Light hybridization of diesel powertrains : the most cost-effective route towards 120g/km CO2 and below"*; VDI2008 Innovative Powertrain Systems, Nov, 2008, Germany.

[14] D. P. Bertsekas, *"Dynamic Programming and Optimal Control, 2nd edition"*, Vols. I and II, Athena Scientific, 2002.

Authors

Ngo Dac Viet received the M.Sc. degree in Mechanical Engineering from Sungkyunkwan University, South Korea in 2007. Since May, 2008 he has been a Ph.D. candidate with Control Systems Technology group, Eindhoven University of Technology, The Netherlands. His research interests are modelling and control of hybrid vehicle propulsion systems.

Theo Hofman received the PhD degree in Mechanical Engineering, Eindhoven University of Technology, The Netherlands, in 2007. Since then, he has been a postdoc researcher at the section Control Systems Technology, Eindhoven University of Technology. His research interests are modeling, design and control of hybrid vehicle drivetrains. He is currently a member of the IEEE Vehicle, Propulsion and Power (VPP) International Program Committee. He also an Associate-Editor of the Int. J. of Hybrid and Electric Vehicles.

Maarten Steinbuch received the Ph.D. degree from Delft University of Technology, The Netherlands, in 1989. Since 1999, he has been full professor of the Control Systems Technology group of the Mechanical Engineering Department of Eindhoven University of Technology. His research interests are modelling, design and control of motion systems and automotive powertrains. He is now an Editor-in-Chief of IFAC Mechatronics, a scientific director of the Centre of Competence High Tech Systems of the Federation of Dutch Technical Universities.

Alex Serrarens received his PhD degree from Eindhoven University of Technology, The Netherlands, in 2001 in the field of powertrain control of passenger cars with CVT. Currently, he is business partner within Drivetrain Innovations b.v. (DTI) which is a licensing and contract-research center on automotive powertrains, transmissions, and components.