Improvement of Fuel Economy in Power-Shift Automated Manual Transmission through Shift Strategy Optimization – An Experimental Study

D.V. Ngo*, T. Hofman*, M. Steinbuch*, A. Serrarens**, L. Merkx**
* Department of Mechanical Engineering, Eindhoven University of Technology
PO Box 513, 5600 MB Eindhoven, The Netherlands
Corresponding author email: d.v.ngo@tue.nl
** Drivetrain Innovations B.V, Croy 46, 5653 LD Eindhoven, The Netherlands

Abstract -- **In this paper, an optimal gear shifting control strategy based on Dynamic Programming (DP) for a vehicle equipped with a Power-Shift Automated Manual Transmission (PS-AMT) is proposed in order to explore the potential fuel savings. Simulation results on the city part of the New European Drive Cycle (NEDC), called ECE cycle, reveal that the relative fuel economy improvement can be reached up to 15.4% by applying DP shifting strategy compared to the case of applying a prescribed gear shift schedule. A forward facing dynamic power train model and control system are designed and developed for the prototype PS-AMT vehicle in order to validate the system modeling and shifting algorithm implementation. The test results of the prototype vehicle on the roller bench show that 11.2% improvement of fuel economy is achieved. It can be concluded that significant potential fuel savings can be obtained by optimal gear shift control and the proposed design method is consistent.**

I. INTRODUCTION

Innovations for vehicular powertrain system are currently on the "hot" spot of automotive industry to improve fuel economy, performance and to adapt to stringent regulations of governments about vehicle emissions. Therefore, shifting control strategies for vehicle transmissions are important issues for design engineers and researchers to attain high efficient drivetrain systems. Shifting strategies for Continuously Variable Transmission (CVT)-based vehicles are focused on moving the engine operating points, for a certain demanded power, towards higher loads and lower speeds. This will permit more efficient engine behaviours by changing the gear ratio at infinite step for best suiting. Various control strategies can be found in literature for both conventional vehicles and hybrid electric vehicles. However, these are beyond the scope of the research presented in this paper. Interested readers can be referred to [3], [4], [8], [10]. Conventional shift operations for Automatic Transmission (AT)-based vehicles are usually implemented in the form of shift maps. The shifting points are generated based on current vehicle speed and throttle opening. The shift maps are traditionally built based on heuristic, intuitive knowledge of engineers from empirical experiments.

Due to the advantages of an Automated Manual Transmission (AMT) over a Manual Transmission (MT) and an AT, shifting control strategies for an AMT-based vehicle have been studied and improved by researchers. The authors in [11] 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. Another study of fuzzy cruise control system was developed to make gear changing decision for an AMT-base vehicle to increase the automation degree of vehicle during cruise mode. The shifting schedule was based on a shifting map obtained from empirical experiments; see [9]. The authors in [12] 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. Another study about the gear shifting strategy, see [5], considered engine working conditions and driver's intention. The authors designed a 2-layers fuzzy controller to eliminate unnecessary shifting occurred when the intention of driver is overlooked or unclear.

Gear shifting strategy is a key factor to improve fuel economy for step-change transmission vehicles. Previous study, see [6], shows that optimal shifting strategy can reduce fuel consumption for conventional vehicle significantly. However, the shifting strategy still affects the driveability. Interactions between these two performance criteria can be found in [7]. In this paper, an optimization problem for designing shifting strategy to minimize the fuel consumption over a drive cycle is formulated. Dynamic Programming is used to find a global optimal solution. And more importantly, experimental tests on the roller bench for a prototype PS-AMT vehicle are performed to validate the system model, control algorithm and the gearshift design method.

II. POWERTRAIN TOPOLOGY AND SHIFTING CHARACTERISTIC

A. *Powertrain topology*

In an effort to improve the driveability and the fuel economy of an AMT-equipped vehicle, a PS-AMT is developed and introduced by Drivetrain Innovations Company. This transmission forms an excellent base for both

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a conventional vehicle and a hybrid electric vehicle (HEV). The PS-AMT combines the seamless shifting characteristic of a dual-clutch transmission system with the agility of a conventional single dry clutch AMT transmission. The transmission transforms a MT into a comfortable and fuel-efficient, lightweight automated transmission. Interested readers can be referred to [1].

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

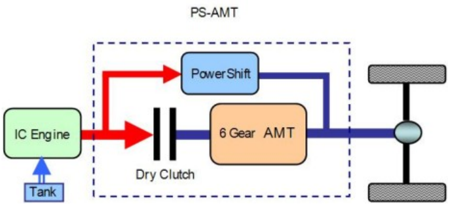

Figure 1: Layout of the AMT/PS-AMT powertrains.

The baseline powertrain is based on an AMT as used in small- to medium-sized passenger cars. The PS-AMT is constructed by adding a powershift system which is in parallel with the dry clutch and the 6-speed AMT. The vehicle parameters are given in the appendix A.

B. Transmission gear shifting analysis

The entire shifting process time of a step-change transmission usually takes about 0.8s–1.5s. During city driving, the transmission must be shifted many times to adjust the vehicle speed to traffic conditions. For the AMT powertrain system, 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 up-shifts, which obviously penalizes the maximum achievable fuel economy.

However, in the PS-AMT powertrain, no torque interruption occurs during the gear up-shift 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 driveability and comfort. In addition, due to the torque filling, the PS-AMT powertrain enables the "rapid" up-shift strategy. Up-shift triggers can be done at a lower engine speed with less control effort for engine during shifting. Meanwhile, for conventional AMT, shift actions should be triggered at high engine speed to avoid shift haunting, engine deterioration or stalling conditions.

III. OPTIMAL SHIFTING CONTROL STRATEGY AND VALIDATIONS

A. Problem formulation

Assuming that clutch is not included to the drivetrain (or no clutch operation) during shifting, the gear ratio can be changed continuously. Given a drive cycle $v(t)$, an optimization problem for the transmission shifting strategy is formulated as follows:

Problem 1: Find the optimal control law $u^*(t)$ that minimizes the fuel cost function over the entire drive cycle with time length t_f.

$$J_1 = \int_0^{t_f} L(x(t),u(t))\,dt = \int_0^{t_f} \dot{m}_f(x(t),u(t))\,dt \tag{1}$$

wherein: $\dot{m}_f\big(x(t),u(t)\big)$ denotes the fuel rate used by vehicle.

subject to constraints:

- the powertrain system dynamics:

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

wherein: $x(t)$ is a state variables which are a gear ratio $r_g(t)$and engine torque $T_e(t)$; $u(t)$ is the control variable which is the rate of change of gear ratio $\dot{r}_g(t)$; $f(x(t),u(t))$ is the system dynamics representing a longitudinal motion of vehicle.

- the control variable $\dot{r}_g(t)$:

$$\delta r_{g\_min} \le \dot{r}_g(t) \le \delta r_{g\_max} \tag{3}$$

$$\int_0^{t_f} \dot{r}_g(t)dt = 0 \tag{4}$$

wherein: δr_{g_min} and δr_{g_max} are the lower bound and upper bound on the rate of change of gear ratio which are defined by the drivetrain's characteristics.

- the state variable $r_g(t)$:

$$r_{g\_min} \le r_g(t) \le r_{g\_min} \tag{5}$$

$$r_g(t) = r_g(0) + \int_0^t \dot{r}_g(t)dt \tag{6}$$

wherein: r_{g_min} and r_{g_min} are the minimum and maximum on the gear ratio.

- the state variable $T_e(t)$ and engine speed $\omega_e(t)$ which are bounded by physical limitations:

$$\begin{aligned} &T_{e\_\min}(\omega_e(t)) \le T_e(t) \le T_{e\_\max}(\omega_e(t)) \\ &\omega_{e\_\min} \le \omega_e(t) \le \omega_{e\_\max} \end{aligned} \tag{7}$$

Generally speaking, the problem (1)-(7) can be solved by using the Pontryagin's Minimum Principle to obtain the global optimal solution. However, utilizing that method to derive such a global optimal solution is out of scope of this paper. Moreover, the powertrain topology studied in this paper has a 6-gear AMT and the gear ratio is discrete value. The derivative of gear ratio with respect to time cannot obtain. Therefore, numerical optimization problem is formulated based on the discretized model of the powertrain system. Then, a numerical Dynamic Programming (DP), see [2], is applied to solve the global optimal solution for this finite horizon dynamic optimization problem.

Problem 2: Find the discrete optimal control law $u^*(k)$ to minimize the fuel cost function over the entire drive cycle *N*:

$$J_2 = \sum_{k=0}^{N-1} L(x(k),u(k)) \cdot \Delta t \quad (8)$$

subject to constraints:

- longitudinal motion dynamics:

$$x(k+1) = f(x(k),u(k)) \quad (9)$$

- state variable of gear position $n_g(k)$:

$$1 \le n_g(k) \le 6 \quad (10)$$

- control variable of shift command $u_g(k)$:

$$u_g(k) = \begin{bmatrix} -1 & :\text{downshift} \\ 0 & :\text{sustaining} \\ 1 & :\text{upshift} \end{bmatrix} \quad (11)$$

$$\sum_{k=0}^{N-1} u_g(k) = 0 \quad (12)$$

- state variable of engine torque $T_e(k)$ and engine speed $\omega_e(k)$:

$$\begin{aligned} T_{e\_\min}(\omega_e(k)) \le T_e(k) \le T_{e\_\max}(\omega_e(k)) \\ \omega_{e\_\min} \le \omega_e(k) \le \omega_{e\_\max} \end{aligned} \quad (13)$$

The shift command, the only concerned variable for the optimization problem, is expressed through the state variable of gear position as follows:

$$n_g(k+1) = \begin{cases} 1, & if \quad n_g(k)+u_g(k)<1 \\ 6, & if \quad n_g(k)+u_g(k)>6 \\ n_g(k)+u_g(k), & \text{otherwise} \end{cases} \quad (14)$$

For reasons of acceptable driveability, the set of discrete shift command values is chosen as $u_g(k) \in [-1,0,1]$ to avoid a large variation of engine speed for a certain shift at a certain time step *k*. One gear down or up-shift or sustaining for each time step of one second are reasonably, because the average shifting time for an Automated Manual Transmission (AMT) is typically one second. Note that the clutch losses during shifting have been left out of consideration.

Then the DP algorithm is formulated as:

Step N:

$$J^*_{2\_N} = 0 \quad (15)$$

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

$$J^*_{2\_k}(x_i(k)) = \min_{u(k)=\Omega \in u_g(k)} \left[L(x_i(k),u(k)) + J^*_{2\_k+1}(x_j(k+1)) \right] \quad (16)$$

wherein: $J^*_{2\_k}(x_i(k))$ is the optimal cost-to-go function for every movement of $u(k)$ at state $x_i(k)$ of time stage k to state $x_j(k+1)$ of time stage *k+1*. 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. The static model, see [2], is chosen in this study. Driveline's dynamics faster than 1Hz could be ignored to simplify the system.

B. *Simulation results*

The drive cycle chosen for this study is the ECE drive cycle which typically represents the velocity profile of vehicle in European urban traffic roads. The accompanied gear shifting schedule is used for determining shifting points, which is hereafter called the "*normal shifting*", see Fig. 2.

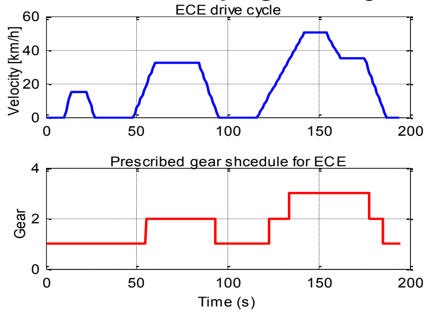

Figure 2: ECE cycle; "*normal shifting*" schedule.

The simulation results for the baseline (PS-AMT powertrain) with *"normal shifting"* and the PS-AMT powertrain with shifting schedule from DP results are shown in table 1.

TABLE1

FUEL CONSUMPTION OVER ECE

	Fuel consumption (gram)	Improvement (%)
PS-AMT (baseline) *normal shifting*	53.36	-
PS-AMT *DP shifting*	45.16	15.4

Simulation results in table 1 show the relative fuel savings is up to 15.4% by applying DP to gear shifting strategy. Simulation results in Fig.3 show that transmission is controlled to up-shift as early as possible. This DP shifting strategy can be considered as the "*rapid*" up-shift strategy.

In fig. 4, it can be seen clearly that the engine operating points for the case of DP shifting scatter at low engine speed region and close to the optimal operating line (OOL) compared to the case of applying *"normal shifting"*. It means that more fuel savings is obtained when applying DP shifting algorithm.

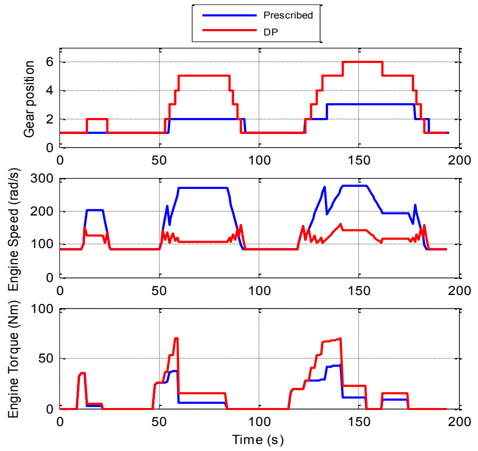

Figure 3: Simulation results with both cases of "*normal shifting*" and DP shifting.

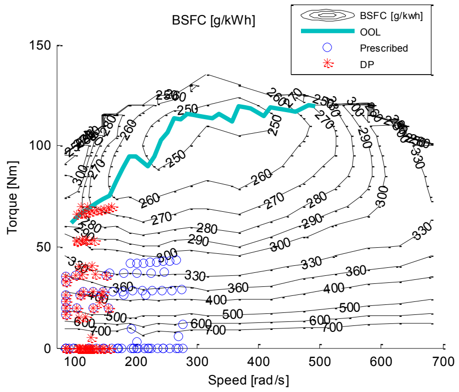

Figure 4: Engine operating points.

C. Validations

1. Prototype PS-AMT vehicle

The PS-AMT is incorporated in the prototype vehicle (Mitsubishi Colt, as in Fig. 5) to study its traits on shifting capability.

Figure 5: The prototype PS-AMT vehicle.

2. Forward facing modelling

The prototype vehicle's forward facing dynamic model is built and developed in Matlab/Simulink environment. The pre-optimized gear sequence obtain from DP is implemented in this forward facing simulation to recomputed the fuel consumption.

TABLE2

FORWARD MODEL SIMULATION RESULTS.

	Fuel consumption (gram)	Improvement (%)
PS-AMT (baseline) *normal shifting*	56.10	-
PS-AMT *DP shifting*	47.29	15.7

In table 2, it shows that fuel consumption for the baseline result of forward facing simulation is different from that of based on backward facing simulation (referred to table 1). This is apparent due to the different natures between backward and forward modelling methods and the differences of time step for simulations of DP algorithm and the forward simulation method. However, the relative improvements of fuel consumption of the forward facing model simulation nearly coincide with that of backward model simulation (model for DP algorithm).

3. Experimental validations

DP is not a practical solution for shifting strategy of real vehicle systems because it requires the prior knowledge of drive cycle and heavy computational burdens. Therefore, an online implementable shifting method based on intuitive knowledge and heuristic engineering is designed to perform tests for the prototype vehicle on roller bench. This shifting strategy will also capture the main characteristics of the "*normal shifting*" and the DP shifting to yield the nearest approximated ones, called "*near normal shifting*" and *"near DP shifting"* respectively.

The tests were performed in the lab in which the vehicle was driven to follow the ECE cycle on the roller bench. Vehicle could not follow exactly the ECE cycle due to human driving. The results for cases of shifting strategies, the "*near normal shifting*" and the *"near DP shifting"* strategy, are shown in the Fig. 6&7.

The fuel consumption results for both cases are given in table 3. Compared to the case of "*near normal shifting*", the *"near DP shifting"* strategy improves fuel economy up to 11.2%. It can be concluded that by optimally changing the shifting points for the transmission, a potential fuel saving is realized.

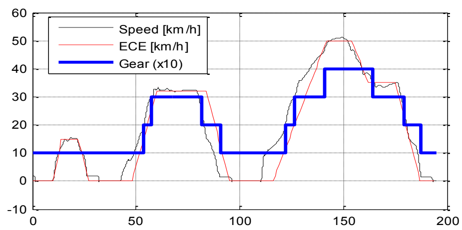

Figure 6: Test results for "*near normal shifting*".

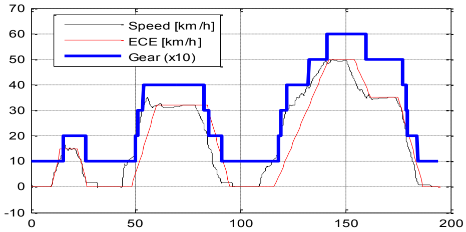

Figure 7: Test results for *"near DP shifting"*.

TABLE3

EXPERIMENTAL RESULTS.

	Fuel consumption (gram)	Improvement (%)
PS-AMT (baseline) *"near normal shifting"*	52.92	-
PS-AMT *"near DP shifting"*	47.0	11.2

IV. CONCLUSIONS

Shifting strategy for a step-change transmission vehicle plays a crucial role in improving fuel economy. The test results validate the simulation model, control algorithm and the consistency of gear shifting design method. This method is not only applicable for PS-AMT powertrain but also applicable for step-change transmission powertrain in general.

Future research will be focused on designing shifting control algorithm which is applicable for vehicle running on traffic road to improve fuel economy. Study from DP shifting strategy will a base for designing such a control algorithm.

ACKNOWLEDGMENT

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Appendix A. VEHICLE SPECIFICATIONS

Items	*Quantities or Type*
Mass	1250 (kg)
Wheel radius	0.287 (m)
Final reduction ratio	4.529
Gearbox ratio	[3.071, 1.913, 1.258, 0.943, 0.763, 0.643]
Clutch type	Dry clutch
Clutch capacity	220 (Nm)
Engine type	Spark Ignition
Engine volume	1.5 (litter)
Max. power	80 (kW) at 6100rpm
Max. Torque	145 (Nm) at 4150rpm