Research on Power Loss of Continuously Variable Transmission Based on Driving Cycles

Bing Fu[1], Yunshan Zhou[1,*], Chenglong Cao[2], Quan Li[1] and Feitie Zhang[1]

[1]College of Mechanical and Vehicle Engineering, Hunan University, Changsha, China
[2] Hunan Jianglu & Rundar Vehicle Transmission Co., Ltd. Changsha, China

*Corresponding author e-mail: zys8888@sina.com

Abstract. In order to further enhance the fuel economy of vehicles with continuously variable transmission (CVT), a CVT power loss model under dynamic condition is established based on the power loss model of each transmission component and the vehicle dynamic model. With driving cycles 10-15, NEDC and US06 as input, the distribution of CVT power loss and the influence of the main losses to vehicle fuel economy are analysed. The results show that the variation loss, oil pump loss and torque converter loss are the main losses of CVT power loss under driving cycles, and the metal belt and oil pump have relatively larger fuel saving potential. At low speed reducing the pump loss is more effective to fuel saving, while at high speed reducing the variation loss is more effective.

Keywords. Continuously variable transmission (CVT); power loss; driving cycle; fuel economy.

1. Introduction

With the increasingly stringent regulations for fuel consumption and emission, to further improve the efficiency of the vehicle transmission system is of great significance. The continuously variable ratio characteristics of the CVT can keep the engine working in the region of better specific fuel consumption (BSFC). However, compared to vehicles with other types of transmission, the advantage of CVT vehicles in actual fuel consumption is not obvious. It is because the lower transmission efficiency of CVT itself offsets some of the advantages obtained by its continuously variable ratio characteristics [1]. The transmission efficiency is directly related to the power loss, how to improve the vehicle fuel economy by reducing the CVT power loss is an important subject of CVT research. CVT contains many transmission components, and the power loss of each component has different effects on the transmission efficiency and fuel economy under various driving conditions. Therefore, it is necessary to study the composition and variation of CVT power loss based on driving cycles, which is an important prerequisite for the efficiency optimization of CVT.

Micklem investigated the aviator loss of CVT and proposed a semi-empirical model to describe the loss [2], Lakehurst developed a series of steady-state theoretical models to explain the variation loss [3], Narita [4] evaluated the effect of the CVT oil on the CVT loss. However, Most of these studies focus on the power variation loss in steady-state. In this paper, a CVT total power loss model under dynamic operating condition is established, and the distribution of CVT power loss and the influence rules of main losses to vehicle fuel economy in driving cycles are analysed.

2. Power loss model of CVT components

The schematic diagram of CVT structure is shown in figure 1. The engine power is inputted from the torque converter, then transmitted to the reverse mechanism, variation, reduction gears and finally outputted to the wheels. There is hydraulic loss in the torque converter which works in the unlocked state when vehicle starts or at low speed. There are also drag loss in clutch which is in a separate state in the reverse mechanism, friction loss in variation and transmission loss in gears. In addition, the oil pump is driven directly by the engine, the power consumption of the oil pump also contribute to CVT power loss. For better analysis, the CVT power loss is decomposed into variation loss, oil pump loss, torque converter loss, reduction gear loss and clutch loss. Firstly, the loss model of each component is built based on the following assumptions: (1) CVT is working in the forward drive state; (2) The losses caused by bearings and oil seals in CVT are not considered due to it is relatively small [5]; (3) CVT oil temperature is stably in 90℃±5℃.

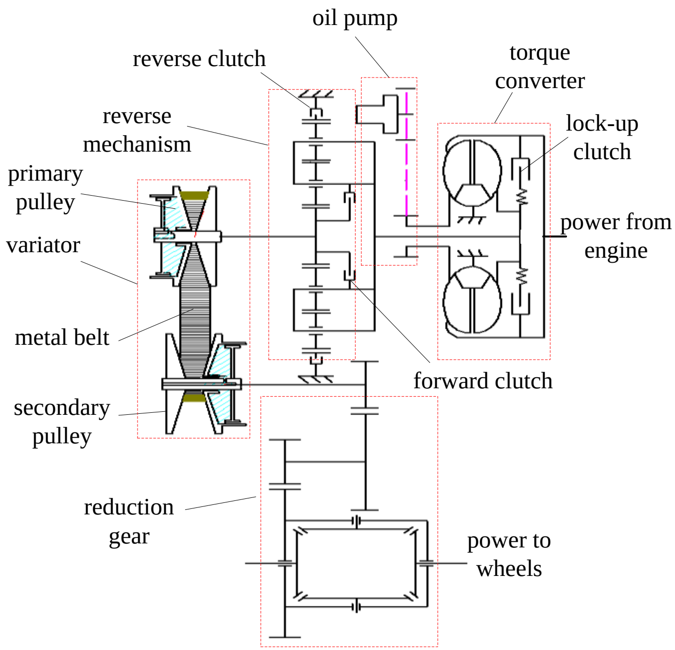

Figure 1. Schematic diagram of CVT mechanism

2.1. Variator loss model

The variator loss includes the friction losses between the metal belt and pulley, the steel rings and metal elements and the adjacent steel rings, which are related to input torque, input speed, belt ratio, clamping force safety factor, cooling oil characteristic and pulley stiffness [6]. Because there is no general analytic model to accurately calculate the variator loss, in this paper the variator loss is described by test data under different torque Tp , belt speed ratio ib and primary angular velocity ωp:

$$T_{\mathrm{lb}} = f(T_{\mathrm{p}}, i_{\mathrm{b}}, \omega_{\mathrm{p}}) \tag{1}$$

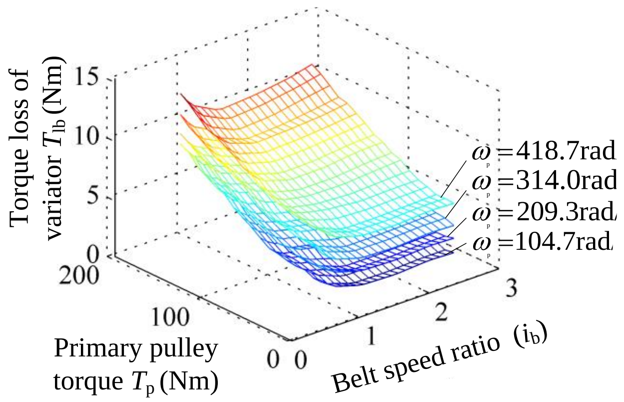

Figure 2. The variator torque loss map

2.2. Torque converter loss model

The torque converter used in CVT is a centripetal turbo-torque converter with a lock-up clutch. The transmission characteristics are described by following formulas:

$$\omega_t = i\omega_b \tag{2}$$

$$T_b = \lambda_b \rho g \omega_b{}^2 D^5 \tag{3}$$

$$T_t = KT_b \tag{4}$$

$$\eta = Ki \tag{5}$$

Where ωt is turbine speed and ωb is impeller speed respectively, i is speed ratio of torque converter, Tt is turbine torque and Tb is impeller torque, λb is torque capacity coefficient of torque converter, ρ is oil density, g is acceleration of gravity, K is torque ratio, η is the transmission efficiency. λb and K can be expressed as the dimensionless characteristic curves of speed ratio, as shown in Figure 3.

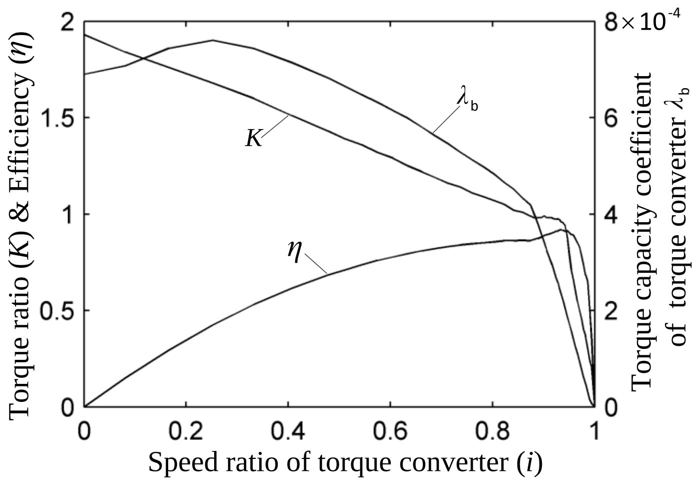

Figure 3. The dimensionless performance curves of torque converter

From formula (2) ~ (5), the torque converter loss Pt can be derived:

$$P_t = T_b \omega_b (1-\eta) \tag{6}$$

Figure 3 shows when torque converter speed ratio is close to 1, the transmission efficiency drops sharply, in order to avoid excessive transmission loss, the locking clutch will lock the impeller and turbine. Vehicle speed is the main parameter used as a sign of locking and unlocking of the torque converter in CVT vehicle. Because the torque converter efficiency is always less than 1 under unlocked state, for fuel economy, the lower locking vehicle speed the better, therefore the locking vehicle speed is the key factor of torque converter loss.

2.3. Oil pump loss model

CVT oil pump is directly driven by the engine, it provides hydraulic driving force to the CVT pulleys &clutch and cooling & lubrication flow for other transmission components. The driving torque of the pump can be expressed as:

$$T_{pu} = P_s V_p / 2\pi \eta_m \eta_v \tag{7}$$

Where Ps is the outlet pressure, The CVT which studied in this paper is a non-independent hydraulic system, the outlet pressure is equal to the secondary pulley pressure. Vp is the theoretical displacement of oil pump, ηm and ηv are the mechanical efficiency and volumetric efficiency of oil pump respectively. The pump driving torque is usually expressed as the data model of outlet pressure Ps and input angular velocity ωpu, so the torque loss of oil pump can be defined as:

$$T_{lp} = f(P_s, \omega_{pu}) \tag{8}$$

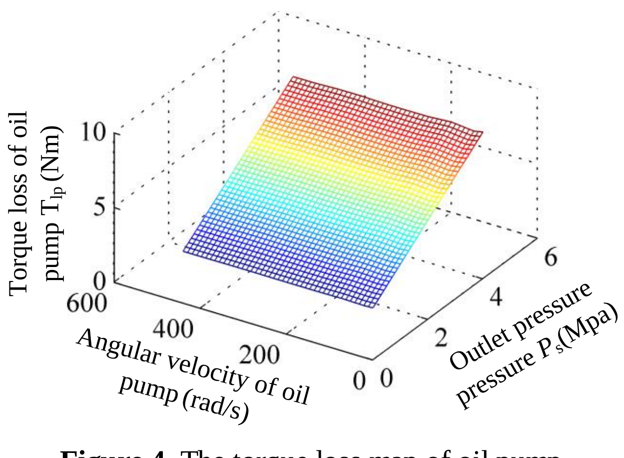

Figure 4. The torque loss map of oil pump

2.4. Reduction gear loss model

The gear loss consists of meshing loss and oil churning loss. The existing calculation models are chosen to calculate the gear loss. The meshing loss can be expressed as following formulas [7].

$$P_{lg1} = P_A \mu_{mz} H_v \tag{9}$$

Where PA is input power, μmz is mean coefficient of friction of the gear mesh, Hv is tooth loss factor, and the oil churning loss can be calculated by the following formulas [8]:

$$P_{\mathrm{lg}2} = 0.5\rho_{\mathrm{o}}\Omega^3 S_{\mathrm{m}} R_{\mathrm{p}}{}^3 \Delta C_{\mathrm{m}} \tag{10}$$

Where ρo is oil density, Ω is rotational speed of gear, Sm is immersed surface area of the gear, Rp is pitch radius of gear, and ΔCm is a dimensionless variation of churning torque. The reduction gear loss is the sum of meshing losses and oil churning losses:

$$P_{\mathrm{lg}} = \sum P_{\mathrm{lg}1} + \sum P_{\mathrm{lg}2} \tag{11}$$

2.5. Clutch loss model

When CVT working at forward drive state, the forward clutch is locked and the reverse clutch is unlocked, there is drag loss in reverse clutch duo to speed difference of friction plate and separate plate, the drag loss can be expressed as [9]:

$$P_{\mathrm{lc}} = 2\pi\omega_{\mathrm{c}} Z \int_{r_1}^{r_{\mathrm{o}}} \frac{\mu\Delta\omega r^3}{h}\left(1 + 0.0012(\frac{\rho_{\mathrm{o}}\Delta\omega r h}{\mu})^{0.94}\right) dr \tag{12}$$

Where ωc is the rotational speed of reverse mechanism, Z is the number of friction surfaces, ro and r1 are the equivalent outer and inner radius of the friction pair respectively, Δω is the relative rotational speed between friction plate and separate plate, h is the clearance in friction pairs.

3. Dynamic power loss model of CVT

3.1. CVT Dynamic model based on component loss

Based on the component loss models above, the CVT dynamic model is established based on following assumptions: (1) ignoring the influence of the drive system stiffness and viscous damping; (2) the lock-up clutch can be locked or unlocked without slipping. The simplified dynamic model can be described by the following equations:

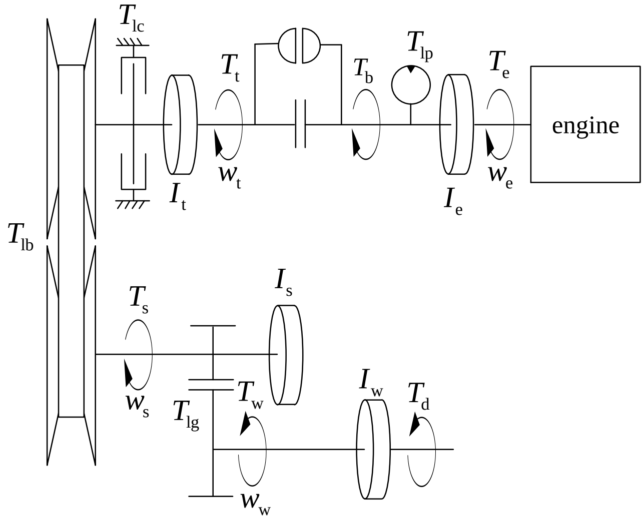

Figure 5. Schematic of CVT dynamic model

$$I_{\mathrm{t}}\dot{\omega}_{\mathrm{t}} = T_{\mathrm{t}} - T_{\mathrm{lc}} - T_{\mathrm{lb}} - T_{\mathrm{s}} / i_{\mathrm{b}} \tag{13}$$

$$I_s \dot{\omega}_s = T_s - T_{lg} - T_w / i_g \tag{14}$$

$$I_w \dot{\omega}_w = T_w - T_d \tag{15}$$

$$i_b = \omega_t / \omega_s \tag{16}$$

$$i_g = \omega_s / \omega_g \tag{17}$$

$$I_e \dot{\omega}_e = T_e - T_{lp} - T_b \tag{18}$$

Where Ie,is the inertia of engine flywheel and torque converter turbine, It is the inertia of torque converter impeller and primary pulley, Is is the inertia of secondary pulley and reduction gears, Iw is the inertia of vehicle and wheels. ωe , ωt , ωs and ωw are the rotational speed of engine, impeller, secondary pulley and wheels respectively. Te is engine torque, Ts is secondary pulley torque, Tw and Td are the driving torque and the resistance torque on wheels respectively. Tlc and Tlg are the torque loss of reverse mechanism and reduction gears respectively, ig is the total ratio of reduction gears.

3.2. Vehicle simulation model

The engine model is fitted by the test data, and the engine torque and fuel consumption rate are expressed as the function of throttle opening and engine speed. The CVT target speed ratio is expressed as a function of vehicle speed and throttle opening. The locking law of torque converter is defined as vt=[vt1, vt2], if vt ⩾vt2 , torque converter is locking, if vt ⩽vt1 , torque converter is unlocking. The vehicle simulation model is established in Matlab/Simulink, the flow chart for simulation is shown in figure 10. The model is driven by target vehicle speed vo, and the driver model automatically adjusts the throttle opening θ and the brake pedal opening Xd by PID control to track the target vehicle speed. CVT speed ratio ib, secondary pulley pressure Ps and other control parameters are determined by looking up the table according to the target parameter model. Based on input of belt speed ratio, secondary pulley pressure, engine torque and wheel angular velocity, the component loss models calculate the transmission loss of each component and feed back to the vehicle model.

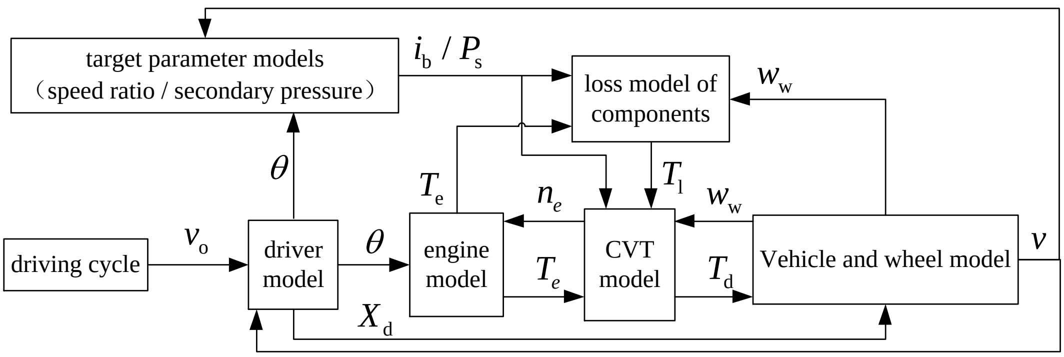

Figure 6. Flow chart for simulation

3.3. Driving cycles for simulation

A mass-produced CVT vehicle is taken for simulation, the basic parameters of the vehicle and CVT are as shown in table 1. The following three kinds of driving cycles are used to analyze the CVT power loss: Japanese 10-15, European NEDC (New European Driving Cycle) and United States US06. The above driving cycles are typical low speed, medium and high speed cycle, and their average velocity is 22.7km/h, 33.6km/h and 77.9km/h respectively, which can comprehensively reflect the driving conditions of vehicle [10]:

Table 1. Vehicle and CVT parameters

Vehicle and CVT specifications	Parameters
Vehicle model	Lifan 620
Engine displacement/peak power/peak torque	1.5L/78kW/150Nm
Vehicle speed of torque converter locking and unlocking	v_{t1}=15km/h, v_{t2}=20km/h
Range of belt speed ratio/ reduction gear ratio of CVT	0.44~2.43/5.525
CVT oil pump displacement	10ml/r
CVT oil density	865kg/m^3

4. Result analysis and discussion

The power loss of each component is analyzed under NEDC cycle. Figure 14 shows that the variator loss is related to the vehicle speed, it is about 0.5kW in ECE driving cycle, while at maximum speed it reaches 2.5kW. The oil pump loss exists in the whole driving cycle, and it remains 0.3kW even at idling speed. The torque converter loss exists at vehicle start and low speed, it reaches 3kW at the start point due to the torque ratio is large and the transmission efficiency is very low. Reduction gear loss is greatly affected by vehicle speed; it is less than 0.3kW in ECE driving cycle, while at maximum speed it is more than 1kW due to the oil churning loss increase rapidly at high speed. The reverse mechanism loss is relatively small and the maximum loss is less than 0.4kW.

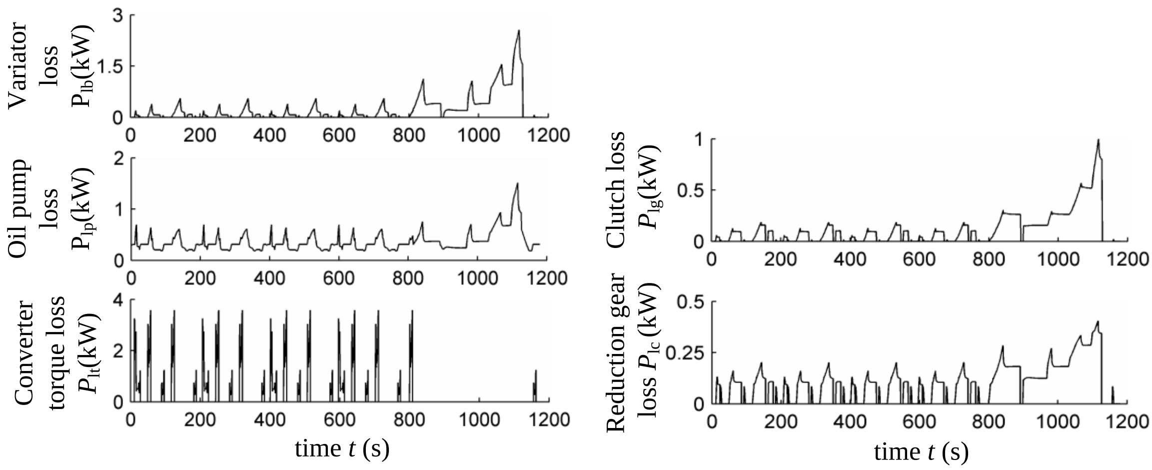

Figure 7. Power loss of each component in NEDC cycle

Table 2 is the power loss proportion of each component under different driving cycles. It shows that the variation loss, oil pump loss and torque converter loss are the main losses, the sum proportions of them is more than 80% in each driving cycle. In 10-15 driving cycle oil pump loss has the biggest proportion 47.2%, followed by the torque converter 26.1% and variation loss 18.7%. While in US06 driving cycle variation loss has the biggest proportion 48.8%, followed by oil pump 24.7% and torque converter loss 10.9%. So the contribution of the three main losses to total power loss is obviously different in different driving cycles.

Table 2. Loss distribution in driving cycles

component	10-15	NEDC	US06
variation	18.7%	33.0%	48.8%
oil pump	47.2%	39.5%	24.7%
torque converter	26.1%	16.4%	10.9%
reduction gear	4.6%	6.3%	10.5%
reverse mechanism	3.4%	4.8%	5.1%

As shown in figure 8 and Figure 9, the fuel consumption per hundred kilometers decreases linearly with the decreasing of variation loss and oil pump loss, the slops of the fitted curves indicate that the variation loss of 20% per reduction, the fuel consumption in 10-15, NEDC and US06 cycles can be improved by 0.7%, 0.9%, 2.2% respectively. Oil pump loss of 20% per reduction, the fuel consumption can be improved by 1.6%, 1.4% and 1% respectively. Similar rules can be get from figure 10: The torque converter locking speed of 2km/h per reduction, fuel consumption in 10-15, NEDC and US06 can be improved by 0.6%, 0.4% and 0.1% respectively. From the above analysis, it is seen that the fuel economy is more sensitive to variation loss and oil pump loss, which means the improve potential of metal belt and oil pump is relatively greater than that of torque converter. The sensitivity of fuel economy to the same component loss is related to the average vehicle speed. To variation loss, it increases with the increasing of average vehicle speed, while to oil pump loss and torque converter loss it decreases with the increasing of average vehicle speed. Therefore at low speed decreasing oil pump loss is more effective in improving CVT vehicle fuel economy, while at high speed it is more effective to decreasing the variation loss.

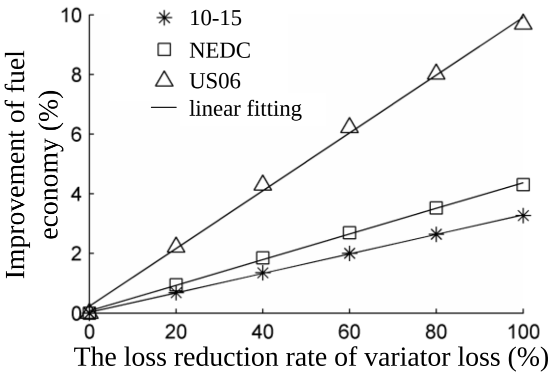

Figure 8. Improvement of fuel economy by decreasing variator loss

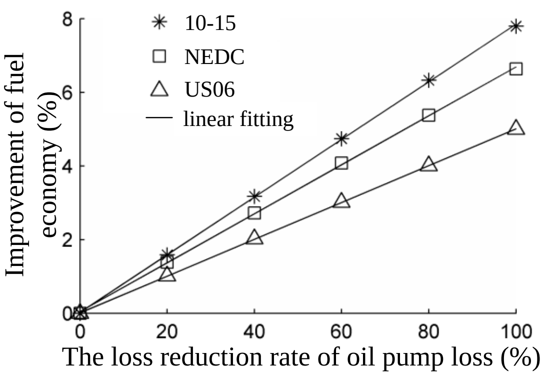

Figure 9. Improvement of fuel economy by decreasing of oil pump loss

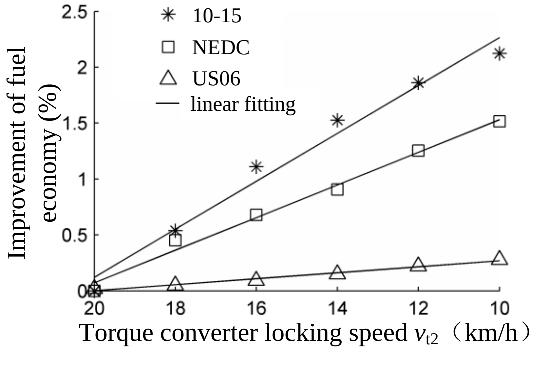

Figure 10. Improvement of fuel economy by lowering the torque converter locking speed

5. Conclusion

A CVT power loss model is established based on the component power loss models and vehicle dynamic model. The sum of variator loss, oil pump loss and torque converter loss is more than 80% of total loss, which are the main losses of CVT power loss. The fuel economy improving potential in the metal belt and oil pump is relatively greater than torque converter. The sensitivity of fuel economy to variator loss and oil pump loss are related to the average vehicle speed. At low speed, decreasing oil pump loss is more effective, while at high speed, decreasing variator loss is more effective.

Acknowledgments

This work was financially supported by The National Natural Science Fund (51475151 & 51475402) and National International Scientific and Technological Cooperation Fund (2014DFA70170)

References

[1] Srivastava N, Haque I.A Review on Belt and Chain Continuously Variable Transmission (CVT): Dynamics and Control [J]. Mechanism and Machine Theory, 2009, 44: 19-41.
[2] Micklem J D, Longmore D K, Burrows C R. Belt torque loss in a steel V-belt continuously variable transmission [J]. Proc. Instn Mech. Engrs, Part D: Automobile Engineering, l994, 208: 91-97.
[3] Akehurst S. Potential for Fuel Economy Improvements by Reducing Frictional Losses in a Pushing Metal V-Belt CVT[C]. 2004 SAE World Congress, Detroit, Mar. 2004, 2004-01-0481.
[4] Narita K, Priest M. Metal-metal friction characteristics and the transmission efficiency of a metal V-belt-type continuously variable transmission [J]. Proc. IMechE, Part J: Engineering Tribology, 2007, 221: 11-26.
[5] Lauren L, Thompson, Craig Jensen. A Design for Six Sigma Approach to Optimize a Front-Wheel-Drive Transmission for Improved Efficiency and Robustness [J]. SAE Technical Paper, 2011-01-0720.
[6] Fu Bing, Zhou Yunshan, Gao Shuai. Research on Pulley Deflection Losses of Metal Belt CVT [J]. China Mechanical Engineering, 2017, 28(12): 1420-1426.
[7] British Standards Institution. ISO/TR 14179-2-2001.Gears-thermal capacity - Part 2: Thermal load carrying capacity[S]. London: BSI, 2001.
[8] Changenet C, Velex P. A Model for the Prediction of Churning Losses in Geared Transmissions-Preliminary Results[J].Journal of Mechanical Design, 2007,129:128-133.
[9] Yiqing Yuan, Eysion A.Liu, ames Hill, et al. An Improved Hydrodynamic Model for Open Wet Transmission Clutches [J]. ASME J. of Fluid Engineering, 2007, 129 (3): 333-337.
[10] Benjamin M. Geller, Thomas H. Bradley. Analyzing Drive Cycles for Hybrid Electric Vehicle Simulation and Optimization[J]. Journal of Mechanical Design, 2015, 137: 1-14.