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Modeling Torque Converter Characteristics in Automatic Drivelines: Lock-up Clutch and Engine Braking Simulation

Hadi Adibi Asl
Ph.D. Candidate, Mechanical and Mechatronics Engineering, University of Waterloo

Nasser Lashgarian Azad
Assistant Professor, Systems Design Engineering, University of Waterloo

John McPhee
Professor, Systems Design Engineering, University of Waterloo

ABSTRACT

A torque converter, which is a hydrodynamic clutch in automatic transmissions, transmits power from the engine shaft to the transmission shaft either by dynamically multiplying the engine torque or by rigidly coupling the engine and transmission shafts. The torque converter is a critical element in the automatic driveline, and it affects the vehicle's fuel consumption and longitudinal dynamics.

This paper presents a math-based torque converter model that is able to capture both transient and steady-state characteristics. The torque converter is connected to a mean-value engine model, transmission model, and longitudinal dynamics model in the MapleSim environment, which uses the advantages of an acausal modeling approach. A lock-up clutch is added to the torque converter model to improve the efficiency of the powertrain in higher gear ratios, and its effect on the vehicle longitudinal dynamics (forward velocity and acceleration) is studied.

We show that the proposed model can capture the transition from the forward flow to the reverse flow operations during engine braking or coasting. The simulation results also show that the engine braking phenomenon (due to the flow reversal) can effectively assist the braking system to slow down the vehicle.

INTRODUCTION

The approach of powertrain modeling with physically meaningful parameters and equations, which is called physics-based modeling, gives a detailed view of powertrain components and operations. The most important benefit of using physics-based models is to track the effects of the parameters on the system's operation. For instance, the schematic diagram in *Figure 1* shows different approaches to the modeling of a torque converter. As indicated in *Figure 1*, the torque converter model includes more physical parameters by approaching from the left to the right of the diagram. For instance, the most complex approach is using computational fluid dynamics (CFD) analysis which accurately simulates the interactions between the torque converter fluid and mechanical elements.

The level of complexity must be defined based on the application of the model, and there is a tradeoff between the model accuracy and the simulation time. In this study, the math-based torque converter model is used along with a mean-value engine model, gearbox, and vehicle longitudinal dynamics to evaluate the torque converter characteristics in the automatic driveline. Since our focus is towards design and control applications, the model must be able to capture both transient and steady-state characteristics while having fairly fast simulation response.

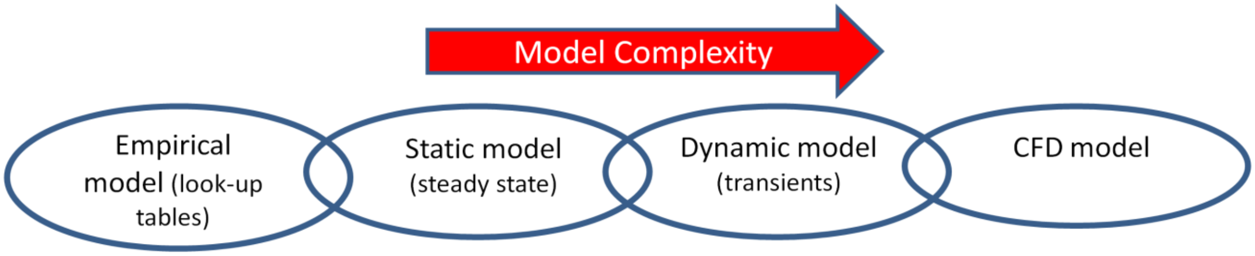

Figure 1: Level of complexity in torque converter modeling

The torque converter includes three rotating elements: the pump (impeller), the turbine, and the stator (*Figure 2*). The pump is attached to the engine shaft, which is called the prime mover, and the turbine is connected to the transmission shaft. The stator, which is placed between the pump and the turbine, redirects the returning fluid from the turbine to the pump. The one-way clutch is used along with the stator to either lock or unlock the stator depending on the fluid direction (whether it hits the front or back of the stator's vanes). In modern automatic transmissions, a lock-up clutch is implemented in the torque converter to lock the engine and the transmission shafts at higher gear ratios [1].

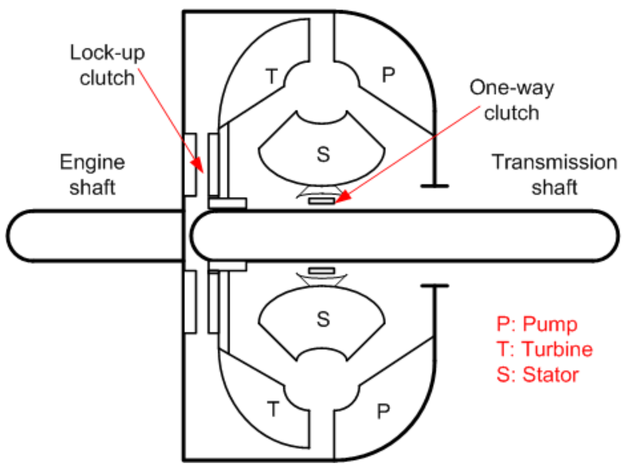

Figure 2: Cross section of a torque converter

The torque converter plays an important role in transmitting the engine's torque during the multiplication (converter) and coupling (lock-up) modes. The torque multiplication mode happens in lower gear ratios to help the vehicle to accelerate, and then by speeding up the vehicle, in higher gear ratios, the engine and transmission are mechanically connected via the lock-up clutch (appropriately called lock-up mode). Furthermore, during gear shifting, the torque converter response characteristics considerably affect the vehicle longitudinal dynamics and, consequently, the fuel consumption and drive quality [2].

BACKGROUND

Torque converters are expressed as a look-up table in some powertrain models [3, 4]. The look-up table torque converter model, which is based on experimental data, is useful to study the application of powertrain controllers. Although the simple look-up table is useful for control studies, it cannot capture the effects of the transient variables as well as design parameters. The following literature introduces the related works on dynamic torque converter modeling and simulation.

The mathematical formulation of a torque converter has been developed by Ishihara and Emori [5], Kotwicki [6], and Hrovat and Tobler [7]. The torque converter model in [5] is expressed by three first-order differential equations for pump, turbine, and energy conservation. The transient characteristics and damping effects of the torque converter are studied in that paper and the numerical results are verified with experimental results. Moreover, it concludes that in case of a slow unsteady state (transient) phase, the working fluid inertia can be neglected and the steady state equations can be used to describe the torque converter's operation. Kotwicki [6] derived the equations of torque converters to obtain a simplified quadratic algebraic form of torque converter characteristics. The simplifications have been done by approximating the volumetric flow rate as a function of the pump and turbine's angular speed. Due to the simple nature of algebraic equations in comparison with differential equations, the simplified model in Kotwicki's paper is used along with some controllers to investigate the powertrain dynamics and control.

A comprehensive study of torque converter dynamics is presented by Hrovat and Tobler [7], who used four first-order nonlinear differential equations to represent the torque converter dynamics. The stator's dynamic equation is included in this paper [7], and the coupling point, which typically happens when the turbine to pump speed ratio reaches around 90%, is defined based on the stator's torque. Bond graph theory is employed to model a torque converter and the numerical results are verified by experimental tests. The proposed model in [7] is useful for investigating the parameters' effects on the torque converter's performance. Moreover, the transient characteristics of the torque converter can be evaluated. The authors also derive the torque converter equations during the reverse flow mode. This mode, which is also called the overrun mode, happens when the turbine's speed is greater than the pump's speed and the flow direction is changed. In this case, the turbine drives the pump and the stator overruns. This mode of the torque converter could occur during engine braking or coasting.

Mercure [8] explained the torque converter operations and characteristic plots in this review paper. The author mentioned that there is a tradeoff between improving the drivability and efficiency. In automatic transmissions, the series of mechanical clutches are replaced by the torque converter which can improve the drivability, because of less engagement of the mechanical clutches, at the expense of the torque converter's efficiency. However, in modern torque converters the lock-up clutch, which is a type of mechanical wet clutch, is used to improve the efficiency. Rong et al. [9] added a lock-up clutch to Hrovat and Tobler's torque converter model to enhance the torque converter's efficiency. The lock-up clutch, in the modern transmission, mechanically connects the engine shaft to the transmission shaft, and it starts acting at the beginning of the coupling mode. The proposed model in [9] considers a converter range, where the stator is fixed, and a coupling range, where the stator can freely rotate. It concludes that the lock-up clutch can significantly improve the torque converter efficiency. Xia and Oh [10] studied the effect of torque converter dynamics on vehicle longitudinal dynamics. The proposed torque converter model in [10] is similar to Hrovat and Tobler's model [7]. The results are compared with Kotwicki's model, which includes merely the steady-state behavior of a torque converter represented by two algebraic equations. The plots show better response of Xia and Oh's torque converter model and the simulation results are closer to the experimental data. This paper [10] verifies that using a torque converter model based on the differential equations is more realistic and the vehicle longitudinal dynamics based on this model is a better match to experiments.

In a paper by Pohl [11], the parameter values for three types of automobile torque converters are given. This paper also studied the transient characteristics of the torque converter based on Hrovat and Tobler's equations and compared the results with experiments. The results show that the simple static model can be used for low frequency conditions (e.g. less than 1 Hz). In other words, the transient fluid momentum effects are insignificant for low frequency, but for higher frequencies (between 1 - 10 Hz) the transient fluid momentum must be considered to obtain acceptable results. Lee and Lee [12] designed a nonlinear model-based estimator, using a sliding mode observer, to estimate the pump and turbine torques as well as fluid flow rates. The four nonlinear dynamic equations, derived by Hrovat and Tobler are used for this purpose. The vehicle test data, pump (engine) and turbine angular speeds are implemented along with the nonlinear sliding mode observer to generate estimated torques as inputs to the nonlinear torque converter model.

Adibi-Asl et al. [14] developed a math-based torque converter model and studied the effects of the model parameters on the torque converter performance (efficiency and capacity factor). The model in [14] only includes the operation during the forward flow mode and did not simulate the torque converter characteristics in an automatic driveline.

In this current paper, we use the math-based torque converter model to investigate the torque converter characteristics in an automatic driveline during the torque converter lock-up mode as well as reverse flow operation the torque converter. We show that our model is able to correctly capture the effects of reverse flow on engine braking situations.

MATH-BASED TORQUE CONVERTER MODEL

A math-based torque converter model has been developed in MapleSim by the authors and published in [14]. In the present work the Honda CRV parameters [11] are employed for the torque converter simulation (*Table 1*). The simulation set up, *Figure 3,* includes a custom component block to implement torque converter equations [7], dynamometers to generate and control input torques, and sensors to measure torques and angular speeds. The turbine side dynamometer generates a constant load (-100 Nm), and the pump side dynamometer generates the engine torque as a ramp function (from 50 Nm to 100 Nm).

Table 1: Torque converter parameters of Honda CRV [11]

Fluid density (ρ)	840 kg/m^3
Flow area (A)	0.0097 m^2
Pump radius (R_p)	0.11 m
Turbine radius (R_t)	0.066 m
Stator radius (R_s)	0.060 m
Pump exit angle (a_p)	18.01 deg
Turbine exit angle (a_t)	-59.04 deg
Stator exit angle (a_s)	59.54 deg
Pump inertia (I_p)	0.092 $kg.m^2$
Turbine inertia (I_t)	0.026 $kg.m^2$
Stator inertia (I_s)	0.012 $kg.m^2$
Fluid inertia length (L_f)	0.28 m
Shock loss coefficient (C_{sh})	1
Frictional loss coefficient (C_f)	0.25
Pump design constant (S_p)	-0.001 m^2
Turbine design constant (S_t)	-0.00002 m^2
Stator design constant (S_s)	0.002 m^2

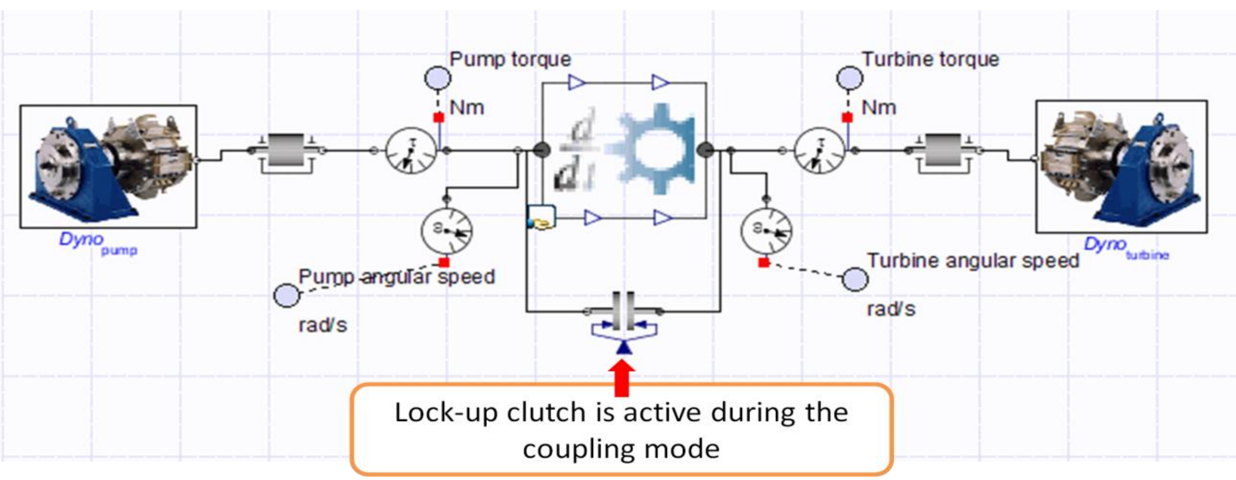

Figure 3: Torque converter test set up in MapleSim

In modern automatic transmissions, a lock-up clutch is implemented in the torque converter to lock the engine and the transmission shafts at higher gear ratios (e.g. gear ratios = 3 and 4). The main advantage of using a lock-up clutch mechanism is improving the torque converter efficiency. During the coupling mode, and without a lock-up clutch, the speed ratio and the torque ratio remain around 0.95 and 1 respectively. Therefore the torque converter efficiency, which is defined as products of the speed ratio and the torque ratio, can ultimately reach 95%. The lock-up clutch mechanism increases the efficiency value to 100% due to the rigid connection between the pump and the turbine shafts. However using the lock-up clutch, the mechanical connection generates some undesirable torque pulses during the clutch engaging, which affects the drivability [2].

The turbine to pump speed ratio plot from the MapleSim simulation, *Figure 4*, shows that the turbine and pump shafts are rigidly connected through the lock-up clutch. The efficiency curve in *Figure 5*, which is the product of speed ratio and torque ratio curves, depicts the 100% efficiency at the expense of some torque pulsation when the clutch is engaged.

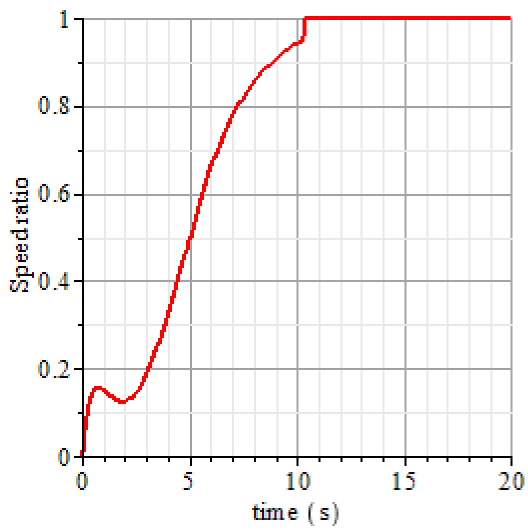

Figure 4: Speed ratio plot (including lock-up clutch effects)

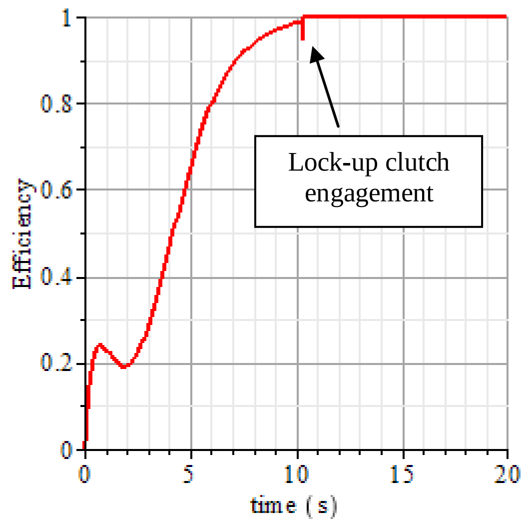

Figure 5: Efficiency plot (including lock-up clutch effects)

The proposed acausal torque converter model is integrated with a mean-value engine, transmission, and vehicle longitudinal dynamics to evaluate the torque converter characteristics in the powertrain model.

AUTOMATIC DRIVELINE MODEL

The proposed torque converter model is placed between the mean-value engine model from the left side and the transmission shaft from the right side (*Figure 6*).

Mean-value engine models (MVEMs) represent an intermediate level of internal combustion (IC) engine models that include more physical details than simplistic linear transfer function models, but are significantly simpler than large complex cylinder by cylinder models [15]. In the mean-value modeling approach, the operating time scale is assumed longer than the engine cycle. The detailed combustion dynamics cannot be captured by the MVEM, but the major engine component dynamics can be mathematically formulated in this approach. The mean-value engine model has been developed in MapleSim by M. Saeedi [16]. The input to the mean-value engine is a throttle angle controlled by depressing the accelerator pedal, and the outputs are fuel consumption and the mechanical power delivered to the torque converter shaft.

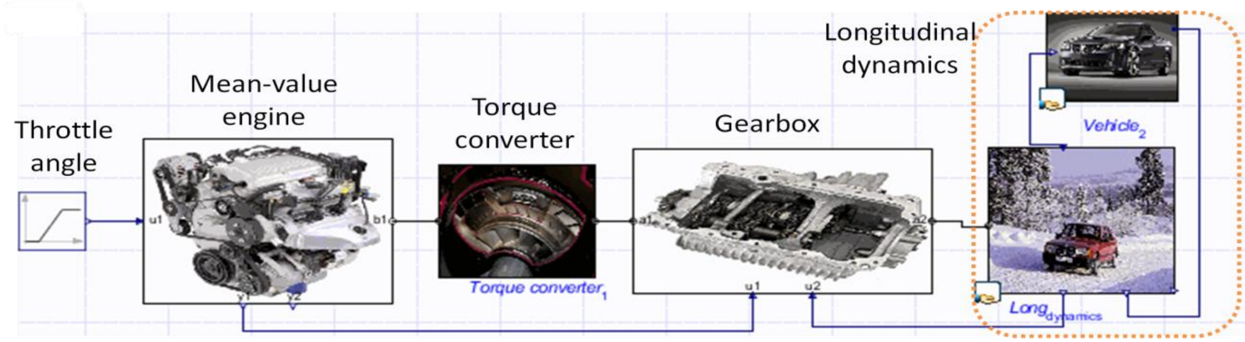

Figure 6: Powertrain model in MapleSim

The transmission gearbox is modeled as a simple input-output torque with variable gear ratios (GR_i) along with the efficiency of each gear (Eff_i) [17]. The input torque to the gearbox is the torque converter turbine torque ($T_{in}(t)$), and the output torque ($T_{out}(t)$) is multiplied by the final drive ratio to obtain the driving torque. The gear ratios are changed based on vehicle longitudinal velocity and engine rotational speeds (*Table 2*). Equations 1 and 2 represent the gearbox model that is implemented in a custom component block in MapleSim. The variables $w_{in}(t)$ and $w_{out}(t)$ represent the input and output angular speed, respectively.

$$T_{out}(t) = T_{in}(t)\, GR_i Eff_i \qquad (1)$$

$$w_{in}(t) = w_{out}(t)\, GR_i \qquad (2)$$

Table 2: Gear ratios and efficiencies

Gear number	**Engine speed (rpm)**	**Longitudinal velocity (km/h)**	**Gear ratio (GR_i)**	**Gear efficiency (Eff_i)**
Gear 1	n(t) < 1000	V(t) < 15	2.8	0.94
Gear 2	1000 < n(t)	15 < V(t) < 30	1.6	0.94
Gear 3	1000 < n(t)	30 < V(t) < 50	1.1	1
Gear 4	1000 < n(t)	50 < V(t)	0.8	0.98

The simulation results, *Figure 7*, show the variation of the engine rotational speed and gear ratios. The input throttle angle is a ramp function which is started at fully closed throttle angle to the half-opened throttle angle. The longitudinal dynamics sub-model includes vehicle mass, inertia, final drive ratio, and resistance forces such as aerodynamic drag and rolling resistance forces. The vehicle parameters are listed in *Table 3*.

Table 3: Parameters for a compact sedan [17]

Vehicle mass	1417 kg
Coefficient of rolling resistance	0.012
Coefficient of air drag	0.35
Frontal area	2.58 m^2
Rolling radius of tire	0.3 m
Final drive ratio	3.64
Inertia of engine	0.42 $kg.m^2$
Inertia of wheel and axle	1.5 $kg.m^2$

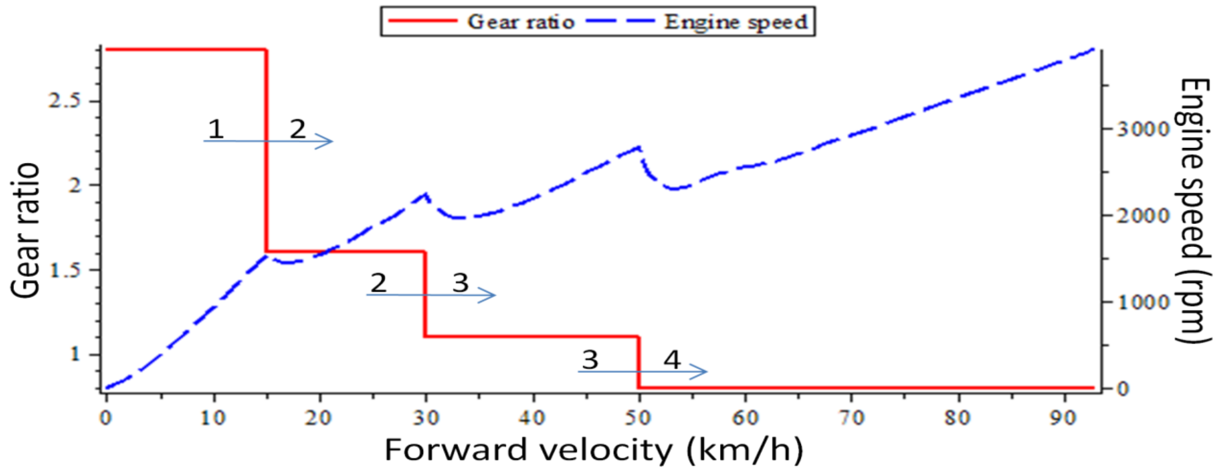

Figure 7: Engine speed and gear ratio variations

The proposed powertrain model can be used for different modeling and control purposes. In this section, we evaluate the effects of the torque converter lock-up clutch on the vehicle longitudinal dynamics. *Figure 8* represents the torque converter speed ratio simulation with and without a lock-up clutch mechanism. The lock-up clutch is engaged at gears 3 and 4.

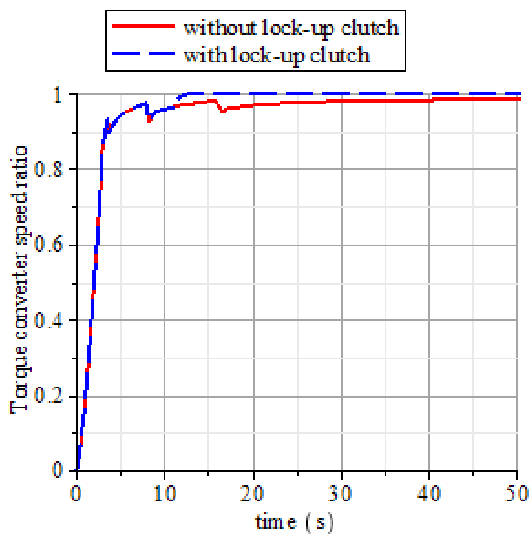

Figure 8: Lock-up clutch effect on speed ratio

The simulation results in *Figure 8* show that the pump and turbine shafts are rigidly connected through the lock-up clutch and rotate as a rigid body. As discussed earlier, the power loss due to the torque converter fluid coupling is eliminated in the lock-up clutch model and consequently the powertrain efficiency has been improved in comparison with the torque converter model without the lock-up clutch. The simulation results of the forward velocity (*Figure 9*) show that the lock-up clutch improves the vehicle forward velocity in comparison with the clutch-less torque converter for the same throttle angle profile. However, there is a sharp acceleration peak due to the lock-up clutch engagement as shown in *Figure 10*.

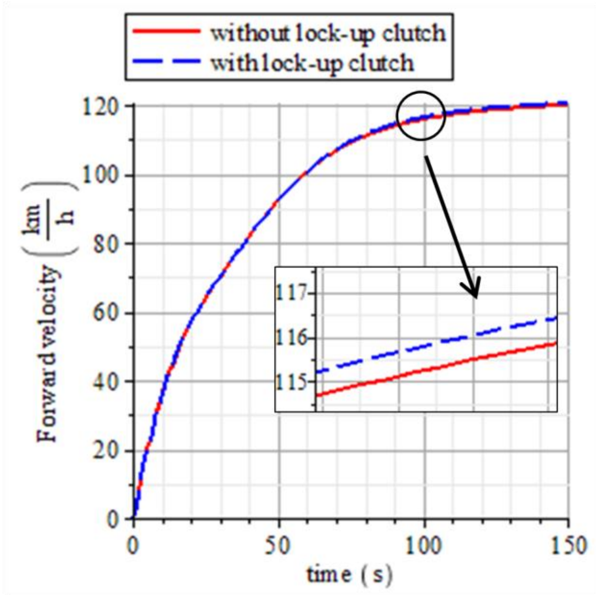

Figure 9: Lock-up clutch effect on forward velocity

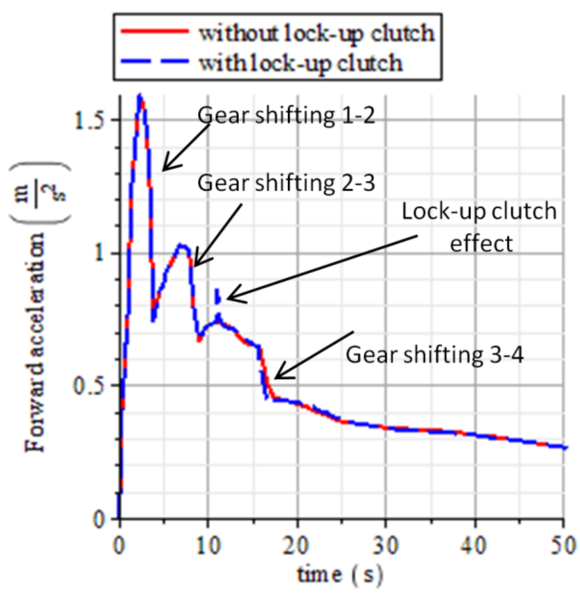

Figure 10: Lock-up clutch effect on forward acceleration

ENGINE BRAKING

During vehicle deceleration, kinetic energy is lost due to the road load, aerodynamic forces, mechanical braking, and engine braking [18]. Using the torque converter in the reverse flow mode during engine braking can help to slow down the vehicle without using an external braking mechanism. This is the most significant advantage of the reversal flow mode during the engine braking, which saves the brakes from unnecessary wear and tear.

In this section, the input to the powertrain model is a throttle angle that feeds in to the mean value engine sub-model to generate indicated power and torque to accelerate the vehicle. The proposed math-based torque converter sub-model contains both forward and reverse flow mode operations. The input throttle angle is a ramp function which is started at fully closed throttle angle to the half-opened throttle angle. Then, the driver pulls off his/her foot from accelerator pedal and the throttle angle sharply declines to the fully closed throttle position. Thus, the vehicle is first accelerated and then decelerated.

The torque converter volumetric flow rate and speed ratio plots (*Figure 11*) depict the transition from the forward flow operation to the reverse flow operation. Consistent with expectations [7], the flow rate becomes negative and the speed ratio exceeds one during the flow reversal.

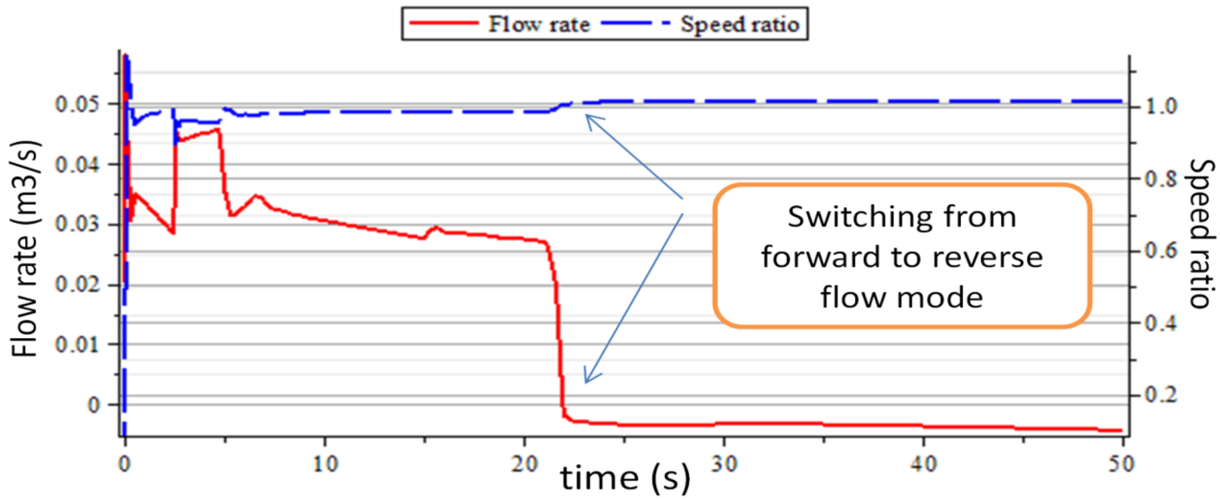

Figure 11: Torque converter flow rate and speed ratio during forward and reverse modes

The simulation results during the engine braking are compared with the case when the driver disconnects the engine from the transmission during the vehicle deceleration (e.g. neutral gear). The engine rotational speed, *Figure 12*, sharply drops when the engine shaft is disconnected from the rest of the powertrain. During engine braking, the transmission shaft rotates the engine shaft, and the engine rotational speed is not decreasing as quickly as the situation without engine braking. *Figure 13* shows how the engine braking phenomenon can slow down the vehicle during deceleration. This happens because part of the vehicle kinetic energy is used to rotate the powertrain inertias, e.g. engine inertia, during the torque converter reverse flow operation.

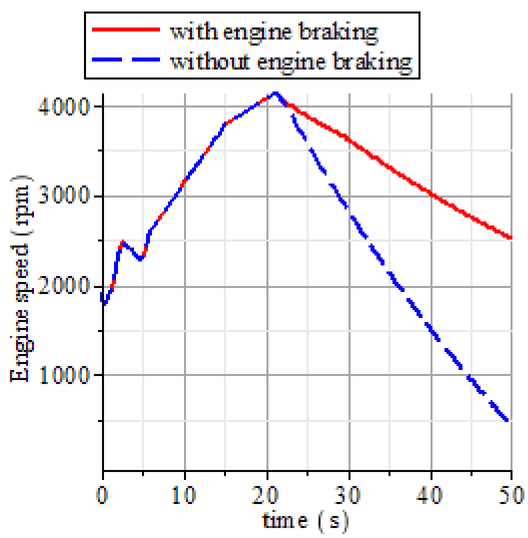

Figure 12: Engine braking effect on rpm

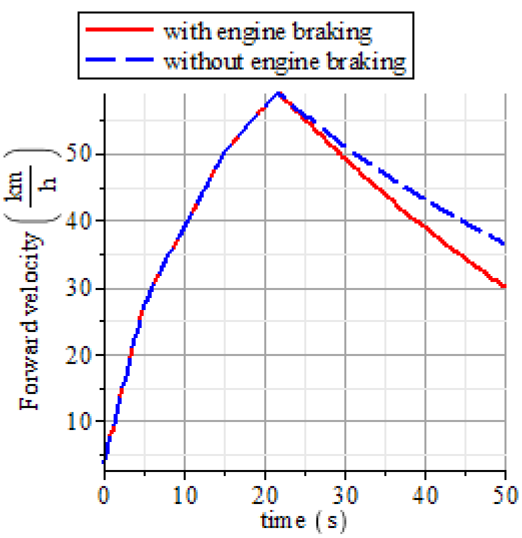

Figure 13: Engine braking effect on forward velocity

CONCLUSIONS

In this paper, a math-based torque converter model in the automatic driveline is presented. The proposed torque converter model is able to represent both transient and steady-state characteristics during forward and reverse flow operations.

A lock-up clutch mechanism is added to the math-based torque converter, which was developed in MapleSim [14]. The model is integrated with a mean-value engine, gearbox, and vehicle longitudinal dynamics to evaluate the lock-up clutch effects on the vehicle motion. The simulation results illustrate that the lock-up clutch engagement in higher gear ratios affects the vehicle forward velocity and acceleration. The powertrain efficiency is improved by eliminating torque converter power loss, and the vehicle speed is more responsive. However, the ride comfort is affected due to the lock-up clutch engagement (*Figure 10*).

Moreover, the math-based torque converter model can capture the transition from the forward flow mode to the reverse flow mode. The transition happens when the torque converter turbine's shaft starts rotating faster than the pump's shaft. This phenomenon in the powertrain, which is called engine braking, can assist the vehicle braking system to slow the vehicle. The simulation results confirm the ability of the model to represent the engine braking phenomenon in the automatic driveline, which slows the forward speed during vehicle coasting.

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