4-2018

Forward-Looking, Velocity-Driven, Powertrain Modeling and Optimal Control for Continuous Variable Transmission

Paresh Deshmukh

FORWARD-LOOKING, VELOCITY-DRIVEN, POWERTRAIN MODELING AND OPTIMAL CONTROL FOR CONTINUOUS VARIABLE TRANSMISSION

by

Paresh Deshmukh

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science in Engineering
Mechanical and Aerospace Engineering
Western Michigan University
April 2018

Thesis Committee:

Jennifer Hudson, Ph. D., Chair
Richard Meyer, Ph. D.
Koorosh Naghshineh, Ph. D.

FORWARD-LOOKING, VELOCITY-DRIVEN, POWERTRAIN MODELING AND OPTIMAL CONTROL FOR CONTINUOUS VARIABLE TRANSMISSION

Paresh Deshmukh, M.S.E.

Western Michigan University, 2018

This thesis is the second part of a two-part study focused on improving Continuous Variable Transmission (CVT) ratio management and control. The objective of the overall project was to develop a methodology for a vehicle with a CVT and a downsized gasoline engine to deliver the maximum vehicle fuel economy within drivability and performance constraints. The first part of this study, as described in [1], focuses on developing a cycle driven model for optimizing the CVT ratio. The study presented in this paper focuses on developing a velocity driven model to simulate the real-time behavior of a vehicle. The results from the optimization schedule presented in backward-looking velocity driven model were utilized to develop a new powertrain optimal operating line (hereafter referred to as P-OOL) which considers powertrain (engine and CVT) efficiency. This P-OOL was created to ensure that the control strategies utilized in the forward-looking model could be used in a real-time vehicle. The proposed P-OOL has been simulated in the model using the Federal Test Procedure (FTP-75) test cycle. Simulation results show that the engine operating points deviate away from the P-OOL. The reasons for deviation of operating points from the P-OOL are vehicle dynamics and powertrain response lag. A control algorithm was simulated which considers powertrain loss and inertia torque due to CVT ratio changes to minimize powertrain response lag. Simulations show a significant improvement in the fuel economy by applying the powertrain response lag compensation algorithm.

ACKNOWLEDGEMENTS

I would like to thank Dr. Jennifer Hudson of the Mechanical and Aerospace department at Western Michigan University for granting me the opportunity to work on this project. I would also like to thank Edward Dai, Weitian Chen, Yang Xu, and Guopeng Hu of the Powertrain Research and Advanced Engineering team at Ford motor company for their vital inputs and guidance at every stage of the project. This project could not have been possible without the support of the team at Ford motor company and Dr. Jennifer Hudson. Also, I would like to thank Dr. Koorosh Naghshineh and Dr. Richard Meyer for serving on this thesis committee.

Paresh Deshmukh

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The automotive industry is going through a transformation with emerging technologies like Electric Vehicles (EV), Hybrid Electric Vehicles (HEV) and Autonomous Vehicles (AV). Research and development in traditional automotive vehicles is focused on improving the efficiency to save fuel. In the downsized vehicles segment, the Continuous Variable Transmission (CVT) has emerged as an efficient alternative to stepped ratio gearbox transmissions. The infinite range of gear ratio availability in a CVT enables the engine to always operate at the most efficient operating points within hardware limits.

Figure 1 shows a representation of engine efficiency lines and constant engine power contours [1].

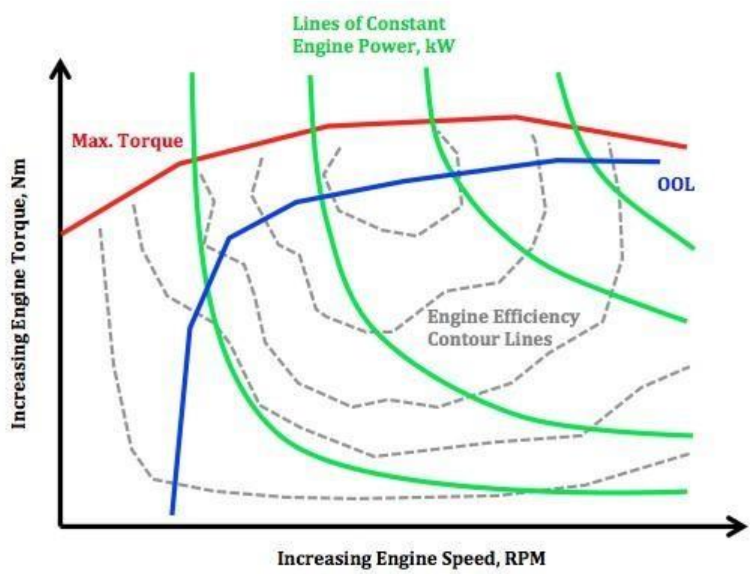


Figure 1: Sample speed vs. torque map with the derivation of an engine OOL

The OOL is generated by connecting the points where each engine power contour intersects the highest engine efficiency contour. It is the line of least specific fuel consumption across the range of engine operating speed and torque. It is known that the engine operates at the highest efficiency at these points.

But the fuel economy of a vehicle is dependent on the transmission efficiency as well as the engine efficiency. Operating the engine at the OOL neglects the effect of CVT efficiency on the fuel economy. In this paper, we generate a new OOL which considers both engine and CVT efficiency. We investigate the improvement in fuel economy by tracking the new OOL.

Also, there exists a lag in the operation of the CVT due to shift characteristics. The frictional energy of the hardware needs to be overcome, which induces a time lag in the system. We have implemented an algorithm to minimize the effect of powertrain response lag in the system by considering powertrain loss and inertia loss due to CVT ratio changes.

Literature Review

Steven Beuerle presented a study in which a novel ratio scheduling technique was proposed for a CVT transmission in a backward-looking cycle-driven model [1]. The optimization methodology in this study considered both the transmission and engine efficiency for scheduling the CVT ratio. This optimization methodology included generating multiple seed points around every point on the OOL and choosing the optimum point within power and ratio constraints. The optimized data points obtained from the optimization schedule were utilized to develop a new optimum operating line considering powertrain efficiency which includes both the engine and CVT.

This offline optimization methodology cannot be utilized in a real-time critical situation for ratio scheduling due to the computational load and processing time. This study works in a backward fashion, the model is assumed to be cycle driven. The desired value of engine RPM is assumed to be the same as actual engine RPM. In real-time operation the vehicle actual speed can deviate away from the desired speed due to inherent delays in the powertrain hardware. The vehicle would not always be able to operate at the desired operating points but deviate according to the actual values of RPM and torque.

In this paper, we propose a forward-looking methodology which is one step closer to real operating conditions. The proposed model is designed as a velocity-driven model which considers the desired vehicle speed and actual vehicle speed while calculating the desired power.

Other relevant literature for this report includes Reference [2], by Lee et al., which focuses on control algorithm development with CVT powertrain response lag consideration. The powertrain response lag-compensation algorithm utilizes the previous desired speed profiles of the vehicle to predict the future desired speed for the vehicle. Constant acceleration of the vehicle is assumed for future desired speed prediction. This prediction enables the control to reduce the lag induced in the system. This type of lag-compensation algorithm is implemented in the forward-looking model to verify the gain in fuel economy. It is further discussed in detail in Chapter 5.

Richard T. Meyer et al. presented an optimal control study for a CVT powertrain [3]. A future vehicle speed prediction technique is implemented to reduce speed trace error and fuel usage. The prediction is dependent on the current speed profile and the known speed profile from the past. This technique is similar to the one discussed in [2].

Other studies have used different techniques to address the issues of CVT optimal control, speed prediction, and system lag. The studies presented in [4,5] investigated optimal control strategies while considering CVT efficiency are similar to the work described in [1]. The CVT efficiency was modeled using analytical equations in both the studies.

The study presented in [6] describes an engine-CVT control algorithm by considering inertia torque and CVT ratio change lag in acceleration. Optimal torque compensation and optimal speed compensation algorithms are developed with OOL tracking control.

The study presented by Wang and Jiang focuses on mathematical modeling of a CVT-engine control with throttle opening consideration [7]. The vehicle model simulation setup is partially similar to the work presented in this paper. The CVT control strategies were simulated by considering throttle valve opening to improve time delays.

Lastly, a study presented by Daekyun Kim et al. focuses on designing a control strategy for a vehicle equipped with an automatic transmission [8]. The torque converter setup and equations in the simulation are similar to the one presented in this paper.

However, the existing literature does not address the formation of a different lookup curve apart from the OOL which considers combined (engine + CVT) powertrain efficiency. Also, the performance of the new lookup line is compared with the OOL in a cycle driven and velocity driven model. The unique contribution of the research presented in this thesis is the consideration of combined (engine + CVT) powertrain efficiency while addressing powertrain response lag in a modeling environment that simulates real-world control implementation.

Assumptions

Several assumptions remained consistent from [1] to this study. Steady-state operating conditions were assumed for this study; operating temperatures of the engine coolant and transmission fluids were considered as constant. The benchmarked data of the 2.5L, 4-cylinder internal combustion engine remained consistent from [1] to this study. Fuel consumption and CVT efficiency were determined using the same benchmarked data developed in [1].

CHAPTER 2

FORWARD-LOOKING VELOCITY DRIVEN SIMULINK MODEL

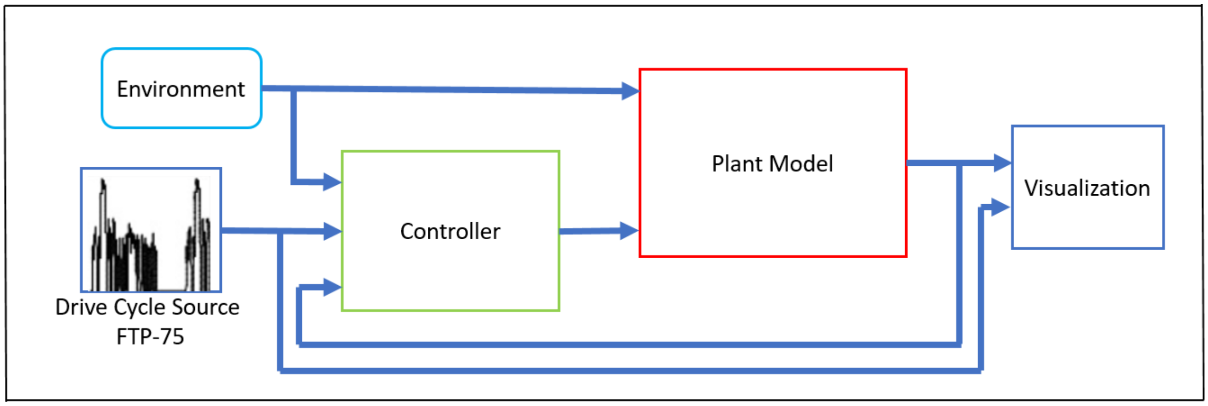


Figure 2: Simulink model overview

Figure 2 shows the general outline of the forward-looking model. Portions of the Federal Test Procedure (FTP–75) cycle are used as the desired speed input for the model. The controller block contains the required power calculation, engine RPM and engine torque lookup according to required power, CVT ratio calculation, and the shift rate constraint for the CVT ratio. The environment block contains the external resistance forces on the vehicle. These resistances are considered in the control and plant model. The plant model consists of an engine model, torque converter model, CVT model, vehicle model, and fuel consumption and CVT efficiency calculations. The visualization block is used to compare traces of the actual vehicle speed to the desired speed. The environment, controller, and plant model are described in greater detail below.

Environment Model

The environment block calculates all the resistances that must be overcome by the vehicle. The formulae used for aerodynamic, rolling, and grade resistances are listed in Eq. (1) - (4).

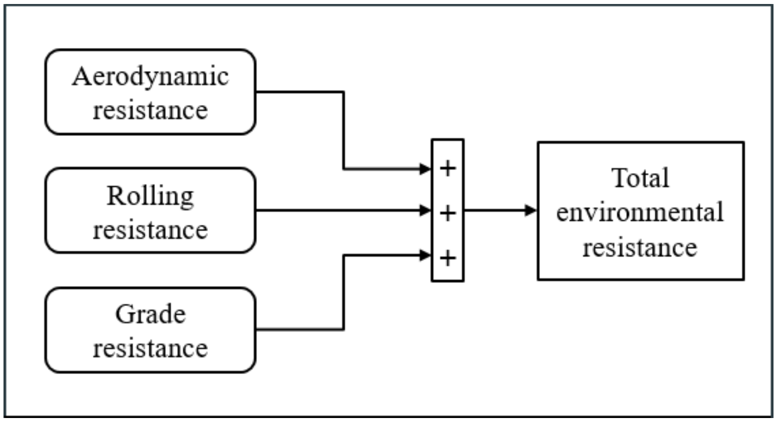


Figure 3: Environmental resistances

$$R_{rolling} = 0.02mg \cos\theta \qquad \text{[Eq.1]}$$

$$R_{air} = 0.5\rho_{air} C_d A {v_a}^2 \qquad \text{[Eq.2]}$$

$$R_{grade} = mg \sin\theta \qquad \text{[Eq.3]}$$

$$F_r = R_{rolling} + R_{air} + R_{grade} \qquad \text{[Eq. 4]}$$

where g is the acceleration due to gravity, m is the mass of vehicle, v_a is the actual speed of the vehicle, θ is the grade of the driving surface, ρ_{air} is the density of air, C_d is a drag coefficient, and A is the frontal area of the vehicle.

Control Model

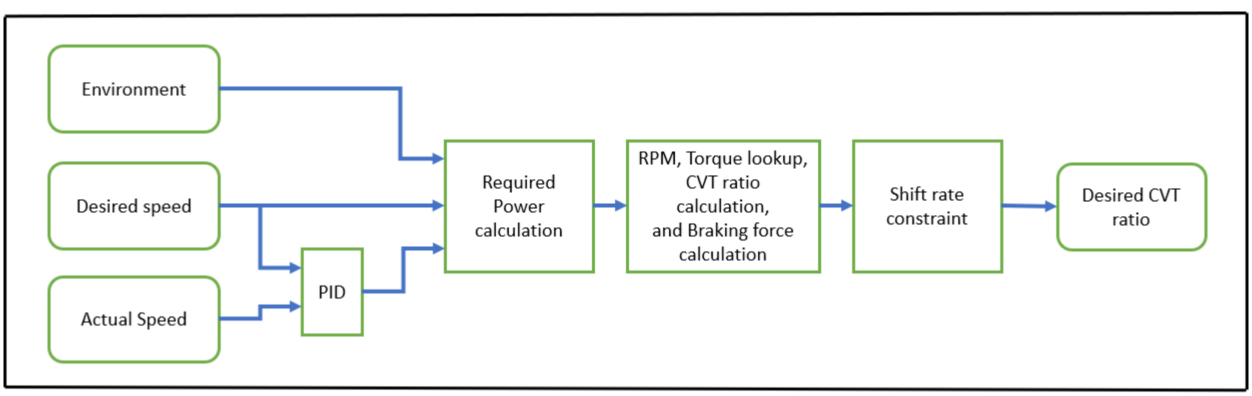


Figure 4: Control model overview

As this model is velocity driven, the required power is calculated in the controller block using the actual vehicle speed along with the desired speed and the environmental resistances (rolling resistance, aerodynamic resistance, and grade resistance). A PID controller is used to evaluate the power required to eliminate the difference between the actual and desired speed. The required power is calculated using Eq. (5):

$$P_r = \frac{(v_d m\alpha + v_d F_r + P_{PID})}{\eta CVT} \qquad \text{[Eq. 5]}$$

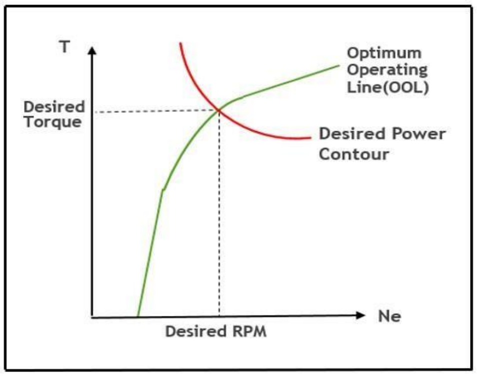


Figure 5: Desired torque and desired RPM lookup

where v_d is the desired speed and α is the desired acceleration. ηCVT is the CVT efficiency determined using the non-linear function developed using the benchmarked CVT torque-loss data in [1].

The green line in Figure 5 represents the OOL and the red line represents the contour of the desired power value. The desired engine RPM and torque values are the axis values at the intersection point of the desired power contour and the OOL. The desired CVT ratio is calculated as the ratio of the desired RPM to the output shaft speed.

Braking force is only applied when the required power (P_r) is negative. The magnitude of braking force is calculated as shown in Figure 6. The saturation block ensures that only negative values pass through it for braking force calculations.

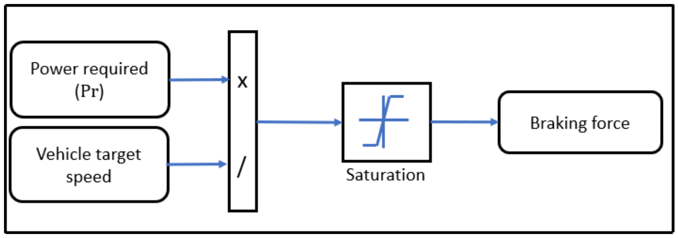


Figure 6: Braking force calculation

Plant Model

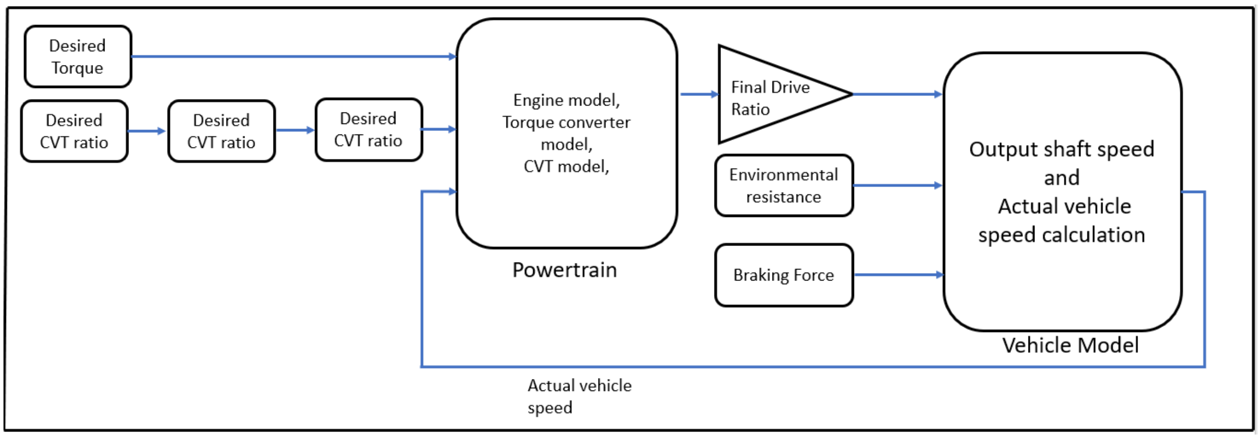


Figure 7: Plant model overview

The plant model, shown in Figure 7 consists of the powertrain and vehicle models. The inputs to the powertrain model are desired torque, actual CVT ratio and vehicle speed. The final drive ratio is the last gear reduction between the transmission (CVT) and the wheels. The desired CVT ratio value cannot be achieved in every scenario due to the hardware actuation constraints. Hence actual CVT ratio is calculated using the shift rate constraint equations.

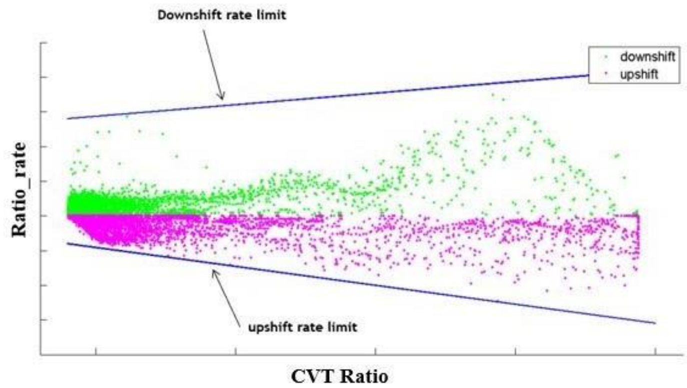


Figure 8: Upshift and downshift rate limits

The equations of the shift rate constraint applied in the model are derived from calibrated data of a representative vehicle equipped with CVT. The shift rate limits for upshift and downshift are a function of CVT ratio. In Figure 8, the upshift/downshift rate limits for the benchmarked CVT are modeled as a function of the CVT ratio. The CVT ratio obtained after applying the shift rate constraint is the actual CVT ratio.

The powertrain model consists of an internal combustion engine and CVT coupled with a torque converter. The torque converter model calculates the impeller torque, T_i, as a function of turbine speed and impeller speed,

$$T_i = N_e^{2} / K \qquad \text{[Eq. 6]}$$

where the capacity factor K is a function of the ratio between the torque converter's input and output speed, calculated from tabulated data [8]. The driving torque to the vehicle is evaluated using turbine torque, lock up clutch torque and CVT ratio. The engine model calculates the actual engine RPM by integrating the difference between desired torque and impeller torque, divided by engine equivalent rotational inertia (Je), as shown in Figure 9.

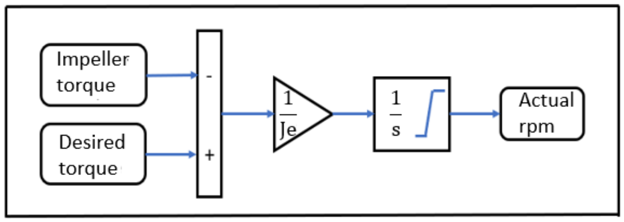


Figure 9: Engine model overview

Fuel consumption is determined from the benchmarked fuel consumption map with the actual engine RPM and engine torque inputs. CVT efficiency is determined with inputs of primary pulley torque, primary pulley speed, and CVT ratio.

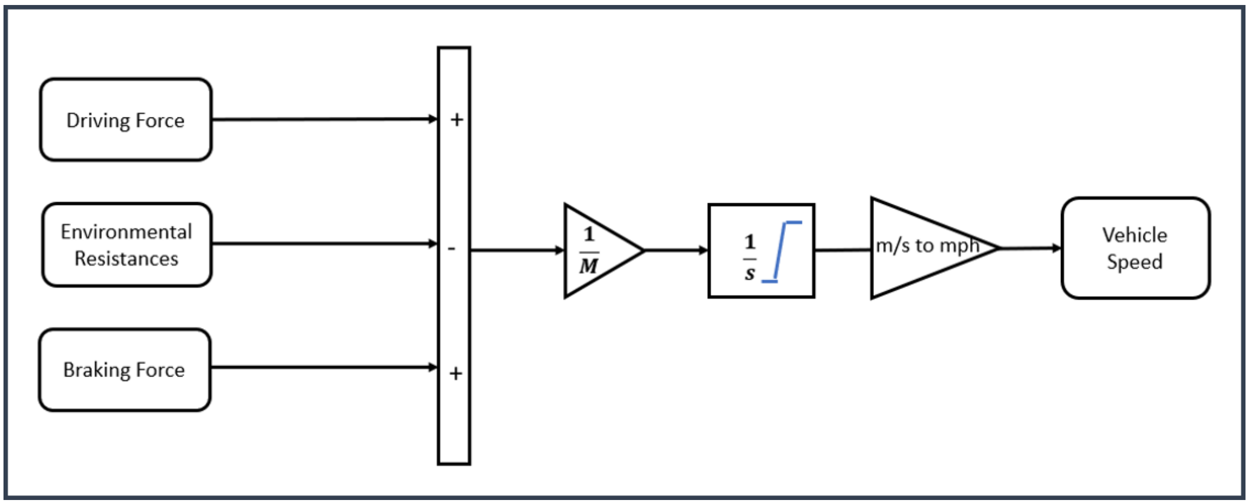


Figure 10: Vehicle model overview

The inputs to the vehicle model are driving force, braking force and the force due to environmental resistance. The vehicle model considers all the forces acting on the vehicle to obtain the vehicle speed using the process shown in Figure 10.

CHAPTER 3

P-OOL FORMATION METHODOLOGY

Curve Fitting for Optimized Data Points

As described in the Introduction, the OOL is the line of least specific fuel consumption across the range of engine operating speed and torque. It only considers engine efficiency; the effect of transmission efficiency is neglected. The results of the optimization schedule presented in [1] are multiple optimum operating points as shown in Figure 11. These optimized data points were obtained as a result of an offline optimization process which consider both engine and CVT efficiency while scheduling CVT ratio.

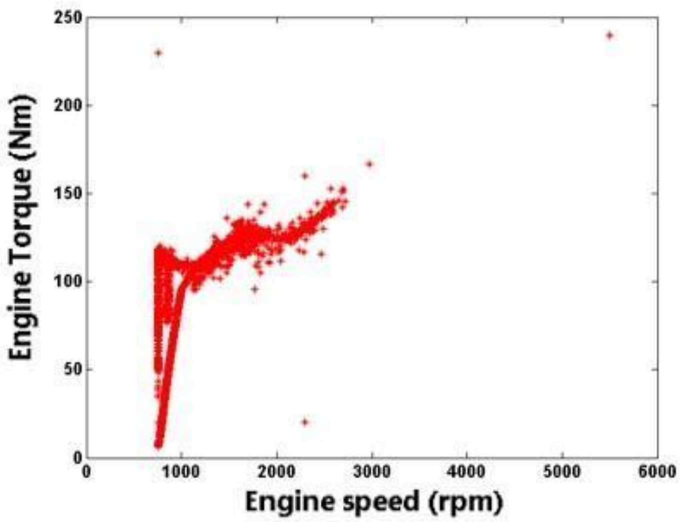


Figure 11: Optimized data points

This optimization process requires a couple of hours to complete because of high computational load and processing time. It cannot be applied in a real-time vehicle as a part of online optimization.

To overcome the high processing time and also consider CVT efficiency, a new OOL was generated using the optimized data points for consideration of engine and CVT efficiency. A curve fit was generated for the optimized data points. The outlying points and unlocked torque converter operating points (engine speed less than 1150 RPM) were ignored while performing the curve fit calculations.

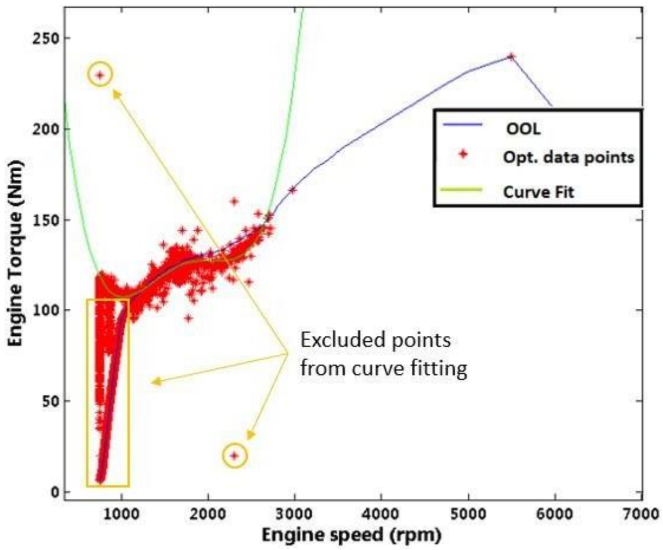


Figure 12: Curve fitting

The curve fit was found using the curve fitting toolbox in MATLAB. The toolbox-generated curve is a 4th order polynomial fit. The polynomial equation is shown in Eq [7].

$$f(x) = p1 * x^4 + p2 * x^3 + p3 * x^2 + p4 * x + p5 \qquad \text{Eq. [7]}$$

where the coefficients with 95% confidence bounds are:

p1 = 5.322e-011;

p2 = -3.637e-007;

p3 = 8.0e-004;

p4 = -0.9101;

p5 = 435;

Using the curve fit and OOL, a new Powertrain-OOL (P-OOL) was generated which considers both engine and CVT efficiency and could be applied in a real-time vehicle.

P-OOL Tracking Strategy

As specified earlier, the P-OOL is developed by combining the OOL and curve fit. It is clear that the OOL will be tracked for unlocked torque converter case (up to 1150 RPM). The end points of the curve fit utilized in P-OOL were tested within the 1150 to 3500 RPM range. The backward-looking model was used to evaluate vehicle performance using the curve-fit P-OOL. As shown in Figure 11, the optimal data points relevant to the P-OOL strategy are located between 1150 and 3500 RPM. Over the range of engine speeds in the simulation, the OOL and curve fit were tracked for different portions of the RPM range, with bounds as shown in Figure 13.

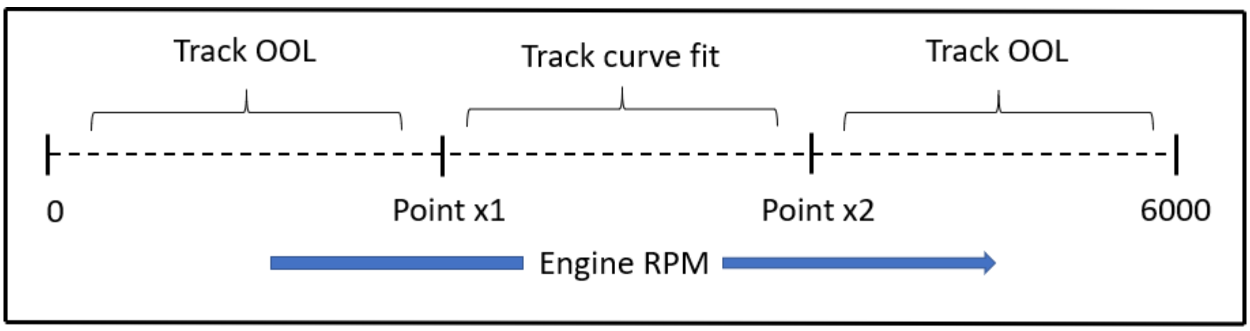


Figure 13: P-OOL formation

The backward looking cycle driven model developed in [1] was used to test the fuel economy of the various combinations of points x1 and x2. For finalizing the optimum values for point x1 and point x2, one variable at a time optimization (monothetic analysis) was utilized. Initially point x2 was considered as constant (around 3500 RPM) and the fuel economy was evaluated using the backward-looking model by varying the value of point x1 (1150 RPM and beyond) to test all candidate points. The candidate value corresponding to the highest fuel economy obtained was assigned as Point x1. The same procedure was repeated for point x2 by keeping point x1 value obtained earlier. The following values were obtained as the optimum candidate points for x1 and x2.

Point x1 : 1366 RPM

Point x2 : 1867 RPM

Figure 14 displays the comparison of the OOL and the P-OOL. The P-OOL deviates slightly below the OOL between points x1 and x2.

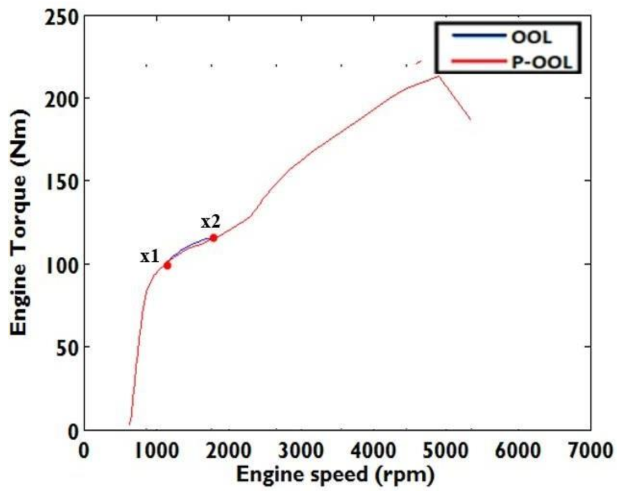


Figure 14: OOL and P-OOL comparison

The increase in the fuel economy in the backward looking model for the P-OOL and the optimized data points compared to the OOL are displayed in Table 1.

Table 1: Fuel economy results for Bag-3 portions of the FTP75 cycle by tracking P-OOL

FTP cycle portion	% change for P-OOL	% change for opt. points
Bag-3	+ 0.56 %	+ 1.7 %

As expected the optimized data points display the best fuel economy as the offline optimization also considers vehicle speed along with engine speed and engine torque while scheduling CVT ratio. P-OOL tracking displays better results compared to OOL tracking due to consideration of both CVT and engine efficiency. The advantage of developing the P-OOL is that it can also be utilized as a part of online ratio scheduling in a real-time vehicle.

Implementing P-OOL in Forward-looking Model and Results

It is evident from the previous chapter that the P-OOL yields better fuel economy in a cycle driven model compared to the OOL. Implementing the P-OOL in the forward-looking velocity driven model could re-verify the gains in a more realistic scenario. The OOL is replaced with P-OOL for calculating desired torque and desired rpm values as shown in figure 5. The working of the forward-looking simulink model is explained in Chapter 3.

When the forward-looking model was used with P-OOL tracking, it was found that there was no significant improvement in fuel economy compared to OOL tracking. The primary reasons for these results are the model shift characteristics and plant delays in the model. In a realistic vehicle simulation, the operating points deviate away from the P-OOL significantly as shown in Figure 15.

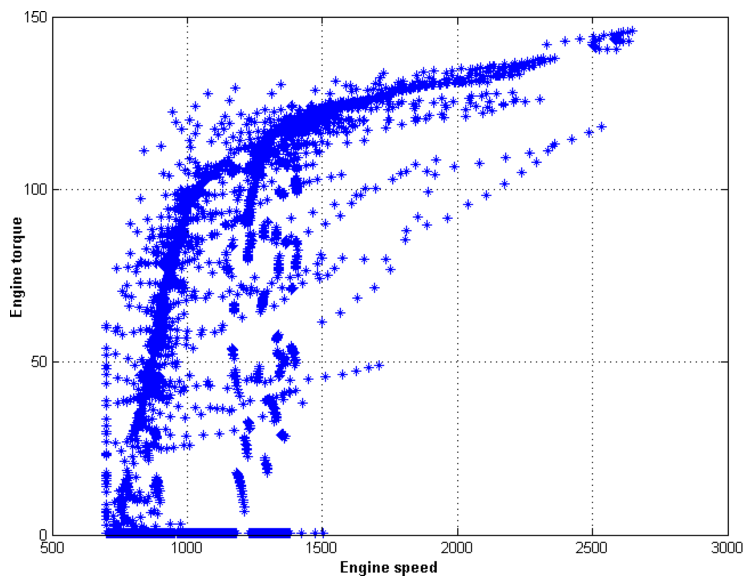


Figure 15: Model shift characteristics

The magnitude of the shift of engine operating point is significantly higher than the deviation of P-OOL from the OOL, which is the primary cause for no significant improvement in the fuel economy by tracking P-OOL

CHAPTER 4

POWERTRAIN RESPONSE LAG COMPENSATION ALGORITHM

Real driving situations differ from ideal driving situations due to multiple parameters. One of the most important parameters is the response lag induced in the powertrain. CVT hardware constraints in the powertrain induce powertrain response lag. All the errors generated due to the response lag are accumulated in the result, i.e. the actual vehicle speed. As stated earlier, the CVT ratio is dependent on the primary pulley RPM and the vehicle actual speed. It is evident that the CVT ratio calculations are affected by the response lag error.

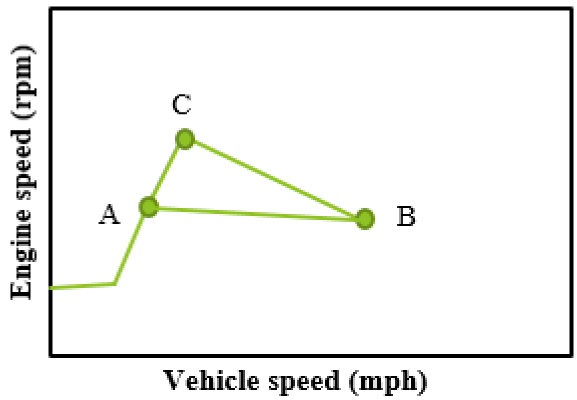


Figure 16: Engine operating point

Figure 16 displays the locations of the engine operating point for an increase in vehicle speed from point A to point B. With powertrain response lag (PRL) in the system, the system follows path A-C-B. As the error is induced in the vehicle actual speed, it results in a higher CVT ratio, causing the operating point to shift to point C before reaching point B. Without any powertrain response lag in the system, the vehicle will accelerate to point B directly from point A, with constant engine speed. Doing this would ensure improvement in the fuel economy by tracking OOL efficiently.

To reduce deviation from the P-OOL due to powertrain response lag, a predictive algorithm was implemented. This algorithm, based on the method proposed in Ref. [2], focuses on predicting the desired vehicle speed after a time delay (τ) equivalent to the powertrain response lag. The formula used for evaluating predicted speed is listed in Eq. [8]

$$\omega^{*} = \omega + \propto \tau \qquad \text{Eq. [8]}$$

where ω^{*} is the predicted output shaft speed, ω is the actual output shaft speed, $\propto$ is the output shaft acceleration, and τ is the assumed powertrain response lag time step. This predicted output shaft speed is utilized in calculating the predicted CVT ratio. The formula for CVT ratio(R) and predicted CVT ratio(R^{*}) are listed in Eq. [9] and Eq. [10]. The CVT ratio is then utilized in the plant model to calculate the torque delivered to the output shaft.

$$\mathrm{R} = \frac{\text{Desired engine RPM}}{\omega} \qquad \text{Eq. [9]}$$

$$\mathrm{R}^{*} = \frac{\text{Desired engine RPM}}{\omega *} \qquad \text{Eq. [10]}$$

Results

Simulations were performed on the Bag-3 portion of the FTP-75 cycle with the powertrain response lag control algorithm. The PID controller was tuned to maintain the vehicle actual speed within 1 mph of the desired vehicle speed throughout the simulation. Figure 16 shows the powertrain response lag control opting for a lower CVT ratio from 8.5s to 10s compared to the control without it. This enables the vehicle to save fuel by choosing a lower CVT ratio as seen in Figure 17. Table 2 displays the percent gain in the fuel economy for the powertrain response lag control algorithm with P-OOL tracking. Simulation results represent an improvement in overall fuel economy.

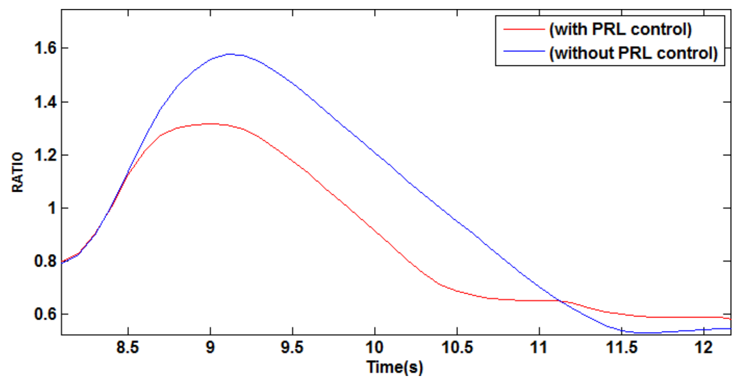


Figure 17: CVT ratio comparison

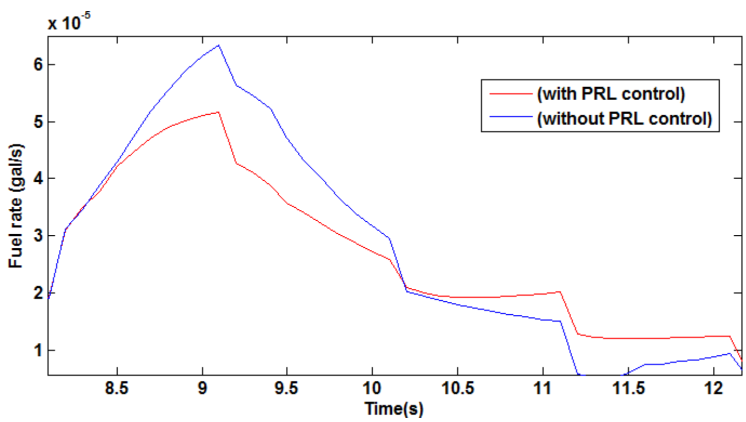
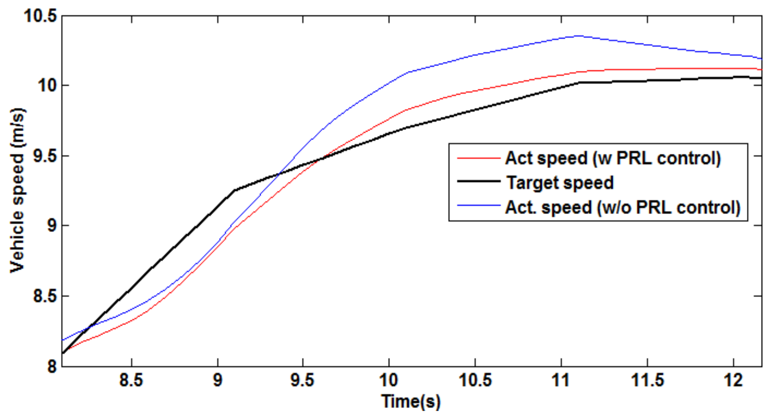


Figure 18: Fuel rate comparison



It can be observed in Figure 17 and 18, that more fuel is consumed by the PRL control from 10 seconds and beyond while choosing a higher CVT ratio. The lower actual speed for PRL control is one of the reasons for the higher CVT ratio. Inaccurate speed predictions lead to increased fuel consumption at some instances. However, it was found that over a representative portion of the FTP cycle (Bag-3), the powertrain response lag compensation algorithm saves more fuel while the predicted speed profile matches the future desired speed than the amount that is over-consumed when the predicted speed profile does not match the actual speed profile. Fuel saved by the powertrain response lag compensation algorithm is 30% higher than the fuel consumed in excess because of the algorithm. By implementing the powertrain response lag compensation algorithm, the speed trace root mean square values decreased from 0.03 to 0.01 m/s.

Table 2: Fuel economy results for Bag-3 portion by powertrain response lag control

FTP cycle protion	Change for Powertrain response lag control
Bag-3	+ 0.41%

CHAPTER 5

CONCLUSION

The velocity driven methodology presented in this paper resembles real-time vehicle operation more closely than the backward-looking strategy. The Simulink model with powertrain response lag control concepts requires around 15 minutes of computational time to complete bag 3 simulation. It could be implemented in a real-time control strategy. A CVT shift rate constraint was applied in the model using limit equations developed from empirical test data. The forward-looking model was simulated using SIMULINK and MATLAB for various portions of the FTP75 cycle.

Simulation results show improvement in the fuel economy by implementing a powertrain response lag compensation algorithm. These results underscore the importance of including vehicle shift dynamics in any strategy to track the powertrain optimal operating line. Finally, these results reinforce the importance of future work in developing a control strategy which could further shorten the gap between the desired control parameters and the actual parameter values.

REFERENCES

[1] Beuerle, Steven, "Optimization Methodology for CVT Ratio Scheduling with Consideration of Both Engine and CVT Efficiency" (2016). *Master's Theses*. 772.

[2] Lee, H., Kim, C., Kim, T., Kim, H., 2004, "CVT Ratio Control Algorithm by Considering Powertrain Response Lag," *Transmission and Driveline Symposium*.

[3] Meyer, R. T., Decarlo, R. A., Jali, N. M., & Ariyur, K. B. (2015). "Behavioral modeling and optimal control of a vehicle mechanical drive system". In *Proceedings of the American Control Conference* (Vol. 2015-July, pp. 2266-2271). [7171070] Institute of Electrical and Electronics Engineers Inc. DOI: 10.1109/ACC.2015.7171070

[4] Ryu, W., and Kim, H., 2008, "CVT Ratio Control with Consideration of CVT System Loss," *International Journal of Automotive Technology,* **9**(4), pp. 459-465.

[5] Luo, Y., Sun, D., Qin, D., Chen, R., and Hu, F., 2010, "Fuel optimal control of CVT equipped vehicles with consideration of CVT efficiency," *Journal of Mechanical Engineering,* **46**(4), pp. 80-86.

[6] Kim, Talchol, & Kim, Hyunsoo. (2000). Integrated engine-CVT control considering powertrain response lag in acceleration. *KSME International Journal, 14*(7), 764-772.

[7] Wang, C., & Jiang, C. (2011). Computer modeling of CVT ratio control system based on matlab. *Computer Research and Development (ICCRD), 2011 3rd International Conference on, 3*, 146-150

[8] Kim, Daekyun, Huei Peng, Shushan Bai, and Joel M. Maguire. "Control of integrated powertrain with electronic throttle and automatic transmission." IEEE Transactions on Control Systems Technology 15, no. 3 (2007): 474-482.