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Analysing Impact of Different CVT Tuning Parameters on Baja Vehicle Performance Through MATLAB

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Abstract. As CVTs are bought as off-the-shelf products, a team can profit from tuning the CVT according to their car's dynamics. This is generally in the form of customising components such as the weights or the springs inside the CVT pulleys such that the shift speed and engagement RPM of the CVT can correspond to the optimal conditions for maximum acceleration/torque of the car. Many teams that wish to customise their CVTs adopt a time-consuming, expensive and inefficient trial-and-error approach whereby they manufacture different versions of each component and then test the performance of the car with each different component. Moreover, the added step of measuring the vehicle's end performance can add to the challenges as the entire car must be ready before the CVT can be tuned. The purpose of this paper will be to outline the specific CVT tuning objectives, use a MATLAB model to generate the results of CVT parameter tuning on vehicle performance and lastly analyse the results to develop meaningful conclusions regarding which parameters and components one should focus their efforts on to get the most significant change in CVT performance.

Keywords. CVT Tuning, MATLAB, Baja, Gaged GX9

1. Introduction

For a CVT, shifting occurs across different shift RPMs and varying the shift RPM can significantly impact the final vehicle performance, making shift RPM a highly important aspect of proper CVT performance. Engagement RPM is also an important parameter that controls the vehicle performance during the full slip to full engagement phase. The Shift RPM and Engagement RPM will be the focus of evaluation for the different CVT iterations. This paper thus aims to compare how different individual tuning parameters from both the primary and secondary pulley affect the shift RPM and engagement RPM individually. The speed diagram shall be used to compare the different iterations of the CVT when the different parameters are varied individually and at times in unison. Teams shall also be able to use the results from this paper to specifically identify which exact parameters to configure in order to meet their custom performance requirements, instead of varying all possible tuning parameters, reducing total tuning time with a more efficient tuning approach.

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2. Literature Review

The study by Frédérique (2012) [2] presents the overall physics behind modelling the components of the CVT while also presenting useful assumptions that can be used in this study's model such as all friction coefficients being constant and the centre distance between the two pulleys being fixed i.e., assuming no bending in the CVT supporting shafts. However, a lacking aspect of this study that this paper aims to address is presenting no information related to how the three individual models of the primary pulley, secondary pulley and belt can be interlinked on a software.

The paper by Timothy R. (2013) [3] focuses on a tuning methodology through an iterative approach. The tuning procedure starts with identifying the engine performance aspects and desired profile of the vehicle. The author incorporated these components in equations to formulate vehicle performance and engine operation for a set of possible gear ratios. This study also shows decisions and alterations made during tuning based upon the objective goals.

The paper by Singh et al. (2018) [4] discusses how variations in various CVT parameters such as the mass of the rollers, length of V-belt, spacer length etc. affects it and also experimentally derives some important results like: - The wheel force is inversely related to the mass of rollers and to the length of the CVT Belt, the Wheel Force tends to increase as wedge angle of the pulley increases, and spring stiffness is also found. This paper is thus useful as it clearly describes the parameters which affect CVT performance.

The paper by De Silva (1994) [5] explains the procedure for designing and analysing a CVT belt. It primarily utilises equations derived from basic energy balancing. This paper also describes how a software or model can be developed and used to tune a CVT belt according to the requirements of the user. The approach used in this model is one where the outputs to the user would be the ideal flyweight and the primary and secondary spring stiffness.

The paper by Aladağlı (2015) [6] titled "Advanced CVT Modelling and Control" investigates the advancements in CVT technology from the perspective of systems and control theory. The author undertakes an application-based approach in order to devise various systems for CVT modelling and control. For this paper, this work can be used to formulate the governing equations on MATLAB.

3. Methodology

The first step is to define the Tuning Objectives by considering the textbook by Olav Aaen on "CVT Clutch Tuning". Next, the paper shall proceed to explain the general structure of the MATLAB model by explaining the subdivisions of the Model. A Flow Chart shall then aim to explain how input variables get converted to results and explain the flow of information in between the subdivisions of the model. Lastly, the results will be analysed by focusing on the speed diagram as this relates most closely to overall vehicle performance.

4. Operating Stages

To tune a CVT it is necessary to take a closer look at how it reacts during use. There are many important phases through which the vehicle goes through as it accelerates to high speeds. These phases are shown in the Figure 1 [7]. (A) represents the region where the engine speed is lower than the idle speed, so it should be made sure that the engine doesn't run at such low speeds. (B) represents the point when the vehicle is not in motion, and the engine is said to be running at an idle speed. (C) represents the region where the speed of the engine starts to increase and the vehicle is just about to move, this is called

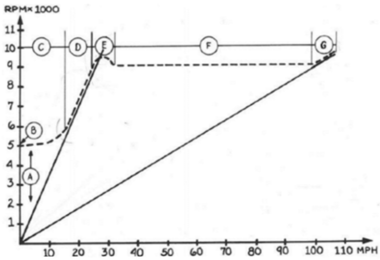

Figure 1. CVT Operating Stages.

the clutching phase. (D) In this phase the CVT belt is completely engaged and it begins to transmit power between the primary and the secondary. (E) represents the point where the sheaves begin to move; this is known as shift out. (F) is known as the shifting phase since here, the shift ratio changes. Finally, (G) represents the phase of high ratio acceleration since here, the shift ratio has completely transitioned to high ratio.

5. MATLAB Model Explanation

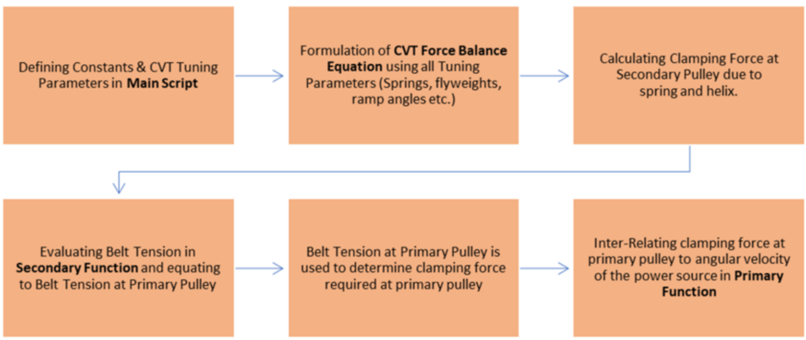

Figure 2. MATLAB Model Solution Flowchart.

To meet tuning objectives, a MATLAB model was used to establish the best combination of CVT variables. The code incorporates numerous functions depending on the operating conditions. Shifting and engagement situations were the two tuning objectives that were tested. The model goes through all potential setup combinations and truncates any that do not adhere to the design goals. The algorithm is set up to evaluate CVT performance as long as the connection between subsystems remains constant.
The structure of the MATLAB Model is as follows:

1. Main Script: This is where the CVT system's constants and variables are defined. This portion determines equations that are irrespective of operating stages and later delivers the solutions of these equations to functions. Some of the essential variables, determined during compiling this section of code are belt wrap angle, vehicle torque load and shift ratio.
2. Secondary Function: This function handles all secondary clutch computations. The goal is to determine belt tension due to the clamping force at the secondary pulley.

Clamping force is evaluated by solving the force balance equation for combinations of secondary spring and helix ramp angle.

3. Primary Function: This function handles all primary clutch computations. The goal is to identify the engine's optimum RPM in a certain operating state. Outputs of the secondary function are fed as inputs, and processed according to the operating stages. This section uses belt tension from secondary function and calculates clamping force required by primary pulley. Further this clamping force is combined with rotational angular velocity of the engine.

6. Results and Discussions

The values of the parameters to be varied were found using the values used in [8]. The range of every variable in this paper's model was kept within the range maintained in the former's paper. The MATLAB model initially computed the results from all the setup combinations possible in the given range, leading to a total number of 51840 possible setups which are evaluated. The disparity between the number of possible setups and actual number of line plots is due to some setup combinations not meeting the following design criteria:

1. Shift speed must be between 3400 and 3800
2. Maximum transferable torque must be above 80% of the minimum requirement
3. Engagement speed must be above 2100

6.1. Speed Diagram

In a speed diagram, the vehicle speed is compared to the engine speed for a given CVT system. The comparison of the different setup combinations of the CVT can be done using a speed diagram whereby each line represents a single setup combination. Table 1 contains results from the Speed Diagram for different scenarios.

Table 1. Speed Diagram Results

Varying Parameters	**Comments**	**Effect on Shift RPM (S-RPM)**	**Effect on Engagement RPM (E-RPM)**
Primary's Spring Linear Rate	Plot Lines: 3. Significantly varying results (wide-spaced bands).	Positive relationship i.e., increase in linear rate increases S-RPM	Increases the E-RPM (positive)
Secondary's Spring Linear Rate	Plot Lines: 3. Close bands.	Very small change	No effect on E-RPM
Secondary's Spring Torsional Rate	Plot Lines: 2. Close bands.	Very small change	No effect on E-RPM
Secondary's Spring Pretension	Plot Lines: 6. Close bands.	Very small change	No effect on E-RPM
Combination of Helix Start & End Ramp Angles	Plot Lines: 2. Hugely varied values of Shift RPM.	Negative relationship i.e., decreasing ramp angles significantly increases S-RPM	No significant change in E-RPM
Flyweights Mass	Plot Lines: 6. Minute difference on shift RPM but change in E-RPM.	Very small change	Negative relationship i.e., increasing flyweight mass reduces E-RPM

Flyweights Ramp Angle	Plot Lines: 3. Huge changes in Shift RPM & E-RPM.	Decreasing flyweight ramp angles greatly increases the S-RPM	E-RPM also increases with decrease in ramp angle
Complete Flyweights System i.e., Ramp Angle & Mass	Plot Lines: 18. 3 bands with difference in Shift RPM.	Affects S-RPM	Affects E-RPM
All Primary Parameters	Plot Lines: 50+. 5 main bands.	Change in S-RPM due to ramp angle and linear rate	Variation in E-RPM within a band is due to flyweight
All Secondary Spring Parameters	Plot Lines: 19. 5/6 bands within a range of 100 RPM.	Very small change	No effect on E-RPM
All Secondary Parameters	Plot Lines: 50+. 2 main bands.	Major changes due to helix angles; smaller changes due to secondary spring	No effect on E-RPM
Primary: Ramp Angle & Linear Rate	Plot Lines: 9. 4 main bands with sub-bands.	Bands are due to ramp angle and linear rate	Affects E-RPM

By analysing the speed diagrams produced the following conclusions can be drawn:

(i) Distinct bands form in the spectrum of lines due to the variation of parameters. How significantly each parameter affects the CVT performance is related to how greatly spaced the bands are for each parameter.

(ii) The extreme ends of the spectrum are not ideal as these combinations represent extremely high torque or high top-speed states, whereas one wants a more balanced car with both good low-end torque and high-end speed.

(iii) Increasing the Primary spring's Linear rate increases the S-RPM.

(iv) Changing the Secondary spring's three variables individually in the specified range causes a very slight change in the overall CVT performance

(v) Changing the helix ramp angle significantly affects the value of S-RPM

(vi) Flyweight mass very slightly affects S-RPM but significantly affects E-RPM.

(vii) Flyweights ramp angle influences both S-RPM and E-RPM.

(viii) Varying all three parameters as the entire primary pulley system can produce significant variation in both S-RPM and E-RPM and should be focused on for CVT tuning.

(ix) Varying complete secondary system produces changes in S-RPM but these are mainly influenced by changes to the secondary spring's helix angles.

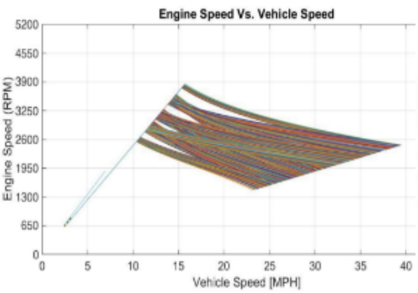

Figure 3. Varying All Tuning Parameters.

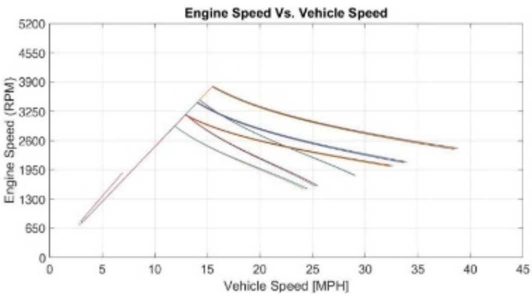

Figure 4. Varying All Primary

7. Conclusion

This paper shows that there are many parameters which do not significantly affect CVT performance along with others which can be varied individually to achieve a very significant change in CVT performance. Thus, teams should move away from the ineffective approach of manual trial-and-error and instead shift towards faster and more effective numerical approaches such as the MATLAB model used in this paper. The conclusions below are based on individual tuning objectives that were identified at the start of the study i.e., changing engagement speed and changing shift RPM

1. For a change in shift RPM, the focus on tuning should be majorly oriented on secondary's Helix ramp angles, primary pulley spring's linear rate and on the overall flyweight system
2. For a change in Engagement RPM, the focus on tuning should be majorly oriented on the Primary Pulley because only flyweight masses, flyweight ramp angles and the primary spring's linear rate influence engagement speed.
3. If drastic changes are required: for instance, if the CVT is severely underperforming or not able to shift out to the high ratio fully, the focus should be on changing flyweight ramp angles and flyweight masses.
4. If relatively minor adjustments are required: tuning should be focused on secondary springs as these provide smaller changes in CVT performance.

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