Department of Mechanical Engineering
FACULTY OF ENGINEERING AND DESIGN

FINAL YEAR Meng PROJECT
PROJECT PLAN AND LITERATURE REVIEW

INVESTIGATING THE POTENTIAL PERFORMANCE ADVANTAGE OF A CONTINUOUSLY VARIABLE TRANSMISSION APPLIED TO A FORMULA STUDENT CAR.

Samuel Cohen

24/11/2020

Word Count: 2694

[1]

Supervisor: Sam Akehurst

Assessor: Fulvio Pinto

Summary

Continuously Variable Transmissions (CVTs) have been used in the automotive industry for over a century, with their development and popularity increasing since the mid 1900's when the Minicar introduced a metal belt CVT. CVTs offer improved fuel consumption and emissions performance, and better power and torque outputs than conventional transmission, by continuously varying the gear ratio and allowing the engine to operate almost entirely in it its optimal region. There are multiple variants of CVTs, including Rolling Traction Drive (RTD), belt driven and hydrostatic CVTs. The operating principles of each, along with their advantages and disadvantages in various applications, are explained in this report.

Application of CVTs in Motorsport is reasonably uncommon, despite clear potential performance advantages attainable through correct implementation and control. One racing series in which the regulations allow for a CVT is Formula Student, in which Team Bath Racing (TBR), the University of Bath's combustion Formula Student team, competes. This project aims to further the understanding of the potential performance advantages of implementing a CVT in motorsport, with particular application to a Formula Student car. Specifically, this research involves simulation of the TBR car with the original powertrain, and comparing the performance results of this (on various Formula Student Dynamic events) with those from the same car fitted with a CVT. Much of the project will focus on how the CVT can be optimised for the specific demands of Formula Student events, with the compromise between performance and fuel economy also important for the Efficiency event. A set of detailed Work Packages have been outlined, along with the resource requirements, time expectations and required results of each, which have then been scheduled into a Gantt Chart for overall planning.

Project Background

A Continuously Variable Transmission (CVT) is one in which the overall gear ratio of the vehicle can be varied constantly, as opposed to conventional manual and automatic transmissions which feature stepped-ratio gearsets. This means that there is no requirement for the driver to change the gear with a CVT, and no disturbance is felt by the occupants as a result of changing gear.

The first recorded application of a CVT in an automobile was in 1886. CVTs were developed alongside conventional manual and automatic transmissions in the early 1900's[2], but only started to become significant in their current form in the mid-1900s when Dr H. Van Doorne developed a metal belt CVT used in the 'minicar'[3]. CVTs have been developed significantly over the past few decades and can now be found in a wide range of automobiles including snowmobiles, industrial equipment, buses, and passenger cars[3].

One sector in which the application of CVTs has been relatively unexplored is in Motorsport. Generally, this is considered a result of wanting driver skill to be the main differentiating factor, which removing the requirement for gear shifting would have an appreciable effect on[4]. Williams F1 developed such a system in 1993, but it was reasonably unreliable and was outlawed by the FIA before it was able to race[4].

Being able to continuously vary the gear ratio of the vehicle allows the engine to operate in its optimum torque or power region much more of the time than with a stepped-ratio transmission. Removing the time lost to changing gear under acceleration is also beneficial[4]. CVTs allow for reduced exhaust emissions and improved fuel economy[5] in addition to these outright performance advantages, again by virtue of being able to run the engine in a more efficient window. As demonstrated, the theoretical performance advantages of using a CVT for high performance applications are significant. This project will investigate the potential performance advantage of using a CVT in the Team Bath Racing (TBR) Formula Student race car (Figure 1[6]).

Figure 1: TBR18 Formula Student car, featuring a hydraulic, semi-automatic stepped-ratio transmission system[6].

Formula Student (FS) is an international engineering competition, in which students design, build, and race a single seater race car against other universities from all over the world. The competitions are comprised of Static and Dynamic events; points are awarded for the design processes and decisions and business aspect of the teams as well as the car's on-track performance[7]. Straight line acceleration, handling, reliability, and fuel economy are all assessed, so compromising between these is crucial.

Literature Review

Existing Technologies & Theory

An initial Literature Review focussed on identifying the existing CVT technologies, determining the advantages and disadvantages of each in relation to the specific application of interest in this project, and analysing the results of any similar work that has been conducted previously.

The most common types of CVTs are belt type, rolling traction drives (RTDs), and hydrostatic CVTs, as outlined in [8] by Akehurst, Brace et al.. RTDs are the main focus of their report, which are then broken down into Toroidal and Milner (MCVT) variants. As explained in [9] by Akehurst, Parker and Schaaf, RTDs operate by transmitting the drive force between a pair of discs and rollers (as illustrated for toroidal CVTs in Figure 2[4]) by producing a shear force in a thin film of lubricant fluid between the contact faces, in a small elliptical area, through subjecting this fluid to high local pressure.

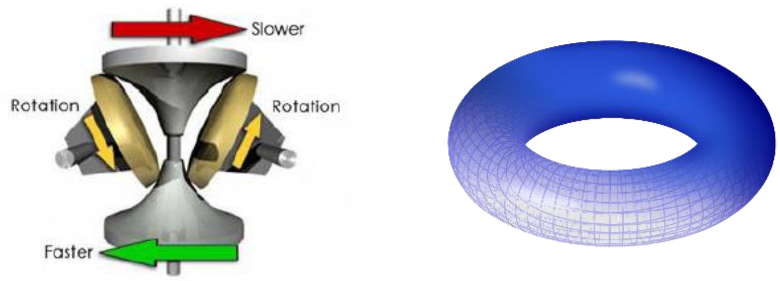

Figure 2: Typical toroidal CVT arrangement[4] and geometrical 'toroid' visualisation for clarity.

The result of this operating principle is that the torque capacity and associated losses of the CVT is directly related to this local behaviour[9]. The modelling of this fluid behaviour is incredibly complex, however Figure 3 (from[9], adapted from [10]) gives a good idea of how the traction coefficient – which should be maximised for transmission efficiency[3] – and film thickness vary with contact pressure on a typical RTD.

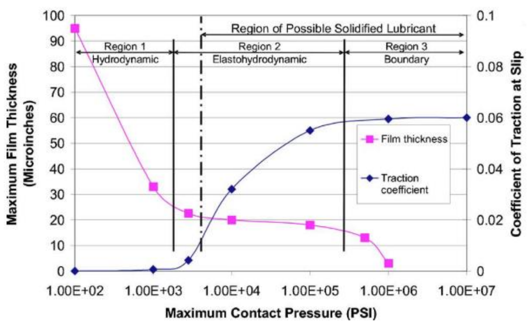

Figure 3: Typical tractive coefficient and film thickness curves with contact pressure for RTD CVTs[10].

Toroidal CVTs can be either full or half variants. Verbelen et al. [11] have conducted a detail study into the comparative performance of each in transient conditions i.e. whilst the ratio varies. The geometrical differences between the two can be seen in Figure 4[11]. The most notable findings were: the half-toroidal CVT has the higher torque carrying capacity across the entire ratio range, meaning that for a given torque capacity the design can be made lighter and more compact; the ratio variation speed performance is higher for the half-toroidal type, particularly at higher engine speeds, due to the higher slip levels associated with the full-toroidal CVT; and the half-toroidal outperforms the full-toroidal in terms of efficiency across the whole ratio range. However, an important trade-off is required between torque capacity and high efficiency.

Boretti's investigation into using a toroidal CVT for a Super-Turbo-Charger, although not an identical usage case, also provides an insight into the general comparisons between half and full-toroidal CVTs[12]. One advantage of full-toroidal CVTs over half-toroidal, not covered by Verbelen et al., is that they offer a maximum ratio range of 8 (max ratio/min ratio), compared to just 4 for a half-toroidal. It is not yet known what range is sufficient for FS-specific application, but this will be an important consideration if a toroidal CVT is the preferred concept. Coupling multiple half-toroidal CVTs in series was also investigated by Boretti; this is unlikely to be relevant for this project as the required output rotational speed is significantly lower than it would be for a turbocharger, but does display how coupling these can further increase the ratio range significantly if required.

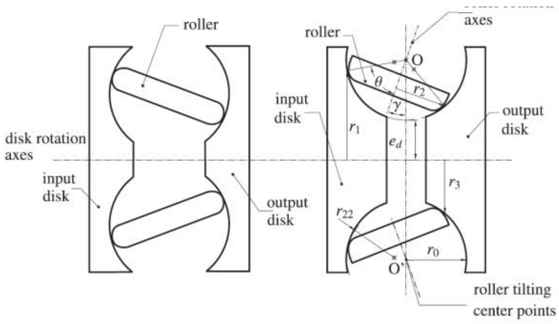

Figure 4: Full-Toroidal CVT arrangement (left) and Half-Toroidal CVT arrangement (right)[11].

The Milner CVT, analysed in [8], acts more like a planetary gearset than a toroidal CVT. This layout is described as ideal for applications where packaging space is limited where weight is an important factor. These are true of a FS car and so this concept will be considered further, however it is more novel and less widely understood than toroidal RTDs.

The other common CVT variant used in industry is the belt type, which is the most widely used in a variety of applications[3]. This system, shown basically in Figure 5[3], utilises two pairs of sheaves with a belt joining the two. One sheave in each pair can move, changing the diameter that the belt sits at and subsequently changing the gear ratio. Actuation for this type of CVT can be electrical, hydraulic, mechanical (springs) or a combination of these[3, 13].

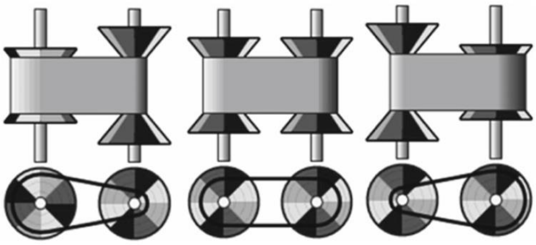

Figure 5: Basic operating principle of the belt-driven CVT[3].

The modelling of belt driven CVTs is less complex that RTD variants due to the mechanical nature of the belt system. The aforementioned paper by Verbelen et al. states that the torque capacity and efficiency of belt type CVTs are lower than for toroidal RTDs, with the toroidal CVT being 5.4% more efficient on average, whilst the belt CVT allows for easier control and implementation[11]. The main technology variation with belt CVTs, aside from the actuation type, is the belt material, which can be rubber, metal, chain, or a composite.

The other CVT variant mentioned in [8] is hydrostatic, which uses a hydraulic motor and pump for actuation. The review says this is typically more common in larger, industrial applications. This is supported by Kanphet et al. [14], who's report details their investigation into optimising the control of a hydrostatic CVT for reducing fuel consumption and emissions – although more complex and expensive than more conventional CVTs, it does offer energy recovery for hybrid vehicles. Hybrid vehicles are not permitted in FS, so this concept will not be investigated further.

Application in Formula Student

Two instances were found in which FS teams have investigated and reported their findings on implementation of a CVT. Firstly, simultaneous reports by Marquenie[15] and Kuijpers[13] looked into the integration of a Suzuki Electronically Controlled Belt type CVT (SECVT) into the 2009 car from the Eindhoven University of Technology. The former looked into the required engine and drivetrain modifications and design work for fitting the CVT, with the latter focussing on the CVT itself regarding its design, operation, and control. The 650cc engine used for the modification has similar specifications to the engine used in the TBR car, so the limitations identified and overcome throughout these projects will likely be highly informative for the further stages of this project. The limitation of this joint investigation is that no data is presented on the potential performance advantages of the CVT.

This fallback is mostly covered by a more simulation-based study by Costa et al.[4] on the CEFAST 2014 car. MATLAB Simulink was used to model a half-toroidal CVT and the original transmission in turn in the same vehicle model in order to provide a direct performance comparison for the Acceleration event. The elimination of shifting time is clearly displayed in Figure 6 below, showing the effect of the CVT on engine speed consistency and hence drivability[4], and also the subsequent increased time accelerating.

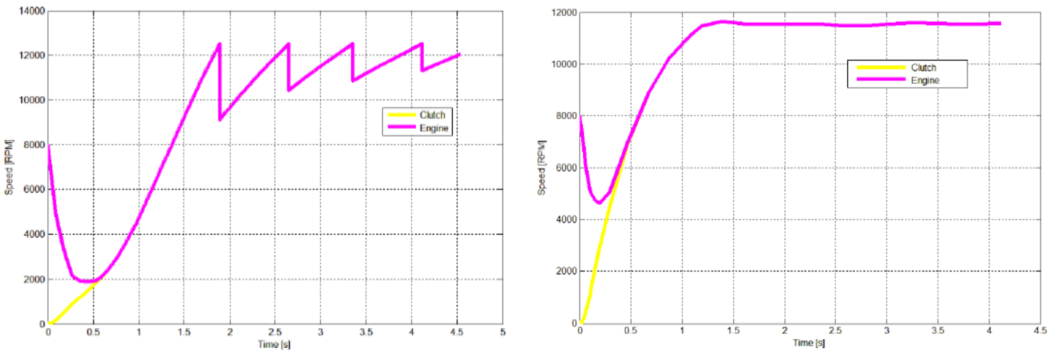

Figure 6: Engine speed traces for the original, stepped ratio transmission (left) and new toroidal CVT (right).

A performance improvement of 0.4s was found in the acceleration event which is a significant gain at just below 10% of the total event duration. Similarly, Borsboom et al. found a Laptime improvement of almost 5s by using a CVT over a conventional gearbox around a lap of Le Mans in a high-performance electric race car[16]. The simulations by Costa et al. were only conducted for Acceleration however, which contributes only a small proportion of the available dynamic event points. A further understanding of the potential improvements offered by a CVT will be obtained from this project by simulating a variety of events, and understanding how the rate of ratio change can be controlled to optimise for both maximum performance and also improved efficiency.

Aims and Objectives

The overall aim of this project is to identify the potential performance advantage of implementing a Continuously Variable Transmission (CVT) to the TBR Formula Student car, and to provide a design base for future teams to develop in order to implement the system.

The following set of more specific objectives have been outlined, the completion of which will ensure that the overall aim is achieved:

1) **Identify** the most appropriate CVT technology for application to a Formula Student Car.

2) **Model** the existing vehicle and powertrain accurately and validate this model with real data.

3) **Model** the selected CVT type integrate this into the existing vehicle model from Objective 2.

4) **Optimise** the design parameters of the CVT for typical Formula Student dynamic events and layouts.

5) **Evaluate** the comparative performance of the two designs by conducting back-to-back simulations between the vehicle models from Objectives 2 and 4.

6) **Provide** an initial design/packaging basis for integrating the CVT into the car for future teams to develop from.

Workplan

A set of 7 Work Packages (WPs) have been defined below, based on the objectives outlined previously, to help meet the overall project aim. Time and resource requirements for each have been highlighted to aid work scheduling as well as identifying and planning to mitigate any risks.

WP1 – Research and Setup

Using the researched collected as part of this Project Plan and Literature Review as a starting point, further research will be carried out to enable selection of the most appropriate CVT technologies for the Formula Student car (Objective 1). Data will be collected from the TBR Formula Student team in order to allow an accurate model of the car to be generated, including the original powertrain which will be used for baseline modelling (WP2), and 3D CAD models of the car – allowing packaging constraints to be identified for Objective 6. As a member of the team, this information should be able to be collected quickly. As such, most of the time for WP1 will be designated to selecting the most appropriate CVT.

A license for a vehicle modelling software package, such as IPG Car Maker, will need to be obtained in addition to installing the necessary additional toolboxes for MATLAB Simulink (the likely/assumed selection at this stage) for modelling the CVT. It could take a few weeks to organise and install any software licences and so this process will be started in Semester 1 – omitted from Gantt Chart to allow rest of project to be shown more clearly.

WP2 – Baseline Vehicle Modelling

The purpose of this WP is to meet Objective 2, of having a complete, accurate model of the FS car with the current powertrain, and having simulated the car in various dynamic events (Acceleration, Sprint, Endurance & Efficiency) in order to characterise its performance. Data from previous cars will be used to help validate the model. The main limitation in this section will be how quickly the software can be learnt and how easily custom events layouts can be generated in the simulation environment – this is crucial to obtain representative results for the original vehicle performance, allowing for comparison with the CVT in later stages of the project. Two weeks will be assigned to WP2 to allow time for learning the software packages and processing the data from previous cars.

WP3 – CVT Modelling & Integration

With a full vehicle model developed and representative simulations of various dynamic events produced, a model for the CVT can be implemented into the drivetrain model in Simulink. In order to start with a representative CVT model, various initial hand calculations will need to be conducted; the complexity of the initial parameter calculations is not yet fully known. The findings from WP1 regarding packaging space will be important to WP3, in order to ensure that the design parameters can be achieved with components that will fit in the available volume.

WP4 – CVT Optimisation

WP4 is expected to be the most time-consuming work package. The results obtained from WP3, along with some of the more detailed research from WP1, will be combined to optimise all of the CVT's parameters for the operating conditions – the various dynamic events. This in itself is expected to require a reasonable amount of time, and there is also potential for a different CVT control strategy to be defined for each event, which could yield even further additional performance but would result in the overall workload for WP4 being very significant in relation to the overall project timeline.

WP5 – Performance Evaluation

This WP has the sole objective of providing a complete set of simulation results for both the original and optimised CVT transmissions fitted to the car (Objective 5). No additional resource is required as the track layouts and models will be used from WP2 and WP4 directly. The purpose of WP5 is to provide a distinct set of requirements and results from the models.

WP6 – Vehicle Integration *(Optional)*

By this point in the project, an initial packaging envelope has been identified, and a CVT will have been designed and optimised for the selected events. This meets the overall aim and provides the minimum information needed for this to be carried into a further design project as per Objective 6. If time permits, further design-related investigations will be conducted to build upon this objective. This work is beneficial, but not essential to achieving the overall project aim. As such, whilst time will be planned in for work in this section, WP6 can be removed as part of a contingency plan in the case that the preceding work packages require more time than anticipated.

WP7 – Report

Allowing enough time for writing the project report is vital, as this is the only piece of work submitted to represent all of the work done throughout the project. A specific work package for this will ensure that enough time is assigned for writing and checking the report, with 2 weeks assigned at the end of the project purely for report writing as well as this WP being spread across the duration of the project so that a first draft of the report can be written up as the work is being conducted. With this project being conducted entirely remotely, all data, information and simulation models will be stored together so that the report can be written as efficiently as possible.

Gantt Chart

Having identified the work required in each work package to meet the objectives and overall aim, a Gantt chart (shown in Figure 7) has been produced to approximate and allocate the time for each task and work package, including the optional WP6 which is coloured orange to represent the contingency plan. Key milestones, marked in green, have been included which directly relate to the overall objectives – repeated in Table 1 for clarity.

Table 1: Summary of project milestones and target completion dates.

Milestone	Description	Target Date
M1	CVT Concept Selected	08/02/2021
M2	Finalised Baseline FS Car model	19/02/2021
M3	Initial CVT Model Integrated into Vehicle model	04/03/2021
M4	Optimised CVT Integrated into Vehicle model	02/04/2021
M5	Final results of CVT vs Baseline Performance	06/04/2021
M6	*Initial Assembly CAD Scheme (Optional WP)*	*14/04/2021*
M7	Final Report Completed	22/04/2021

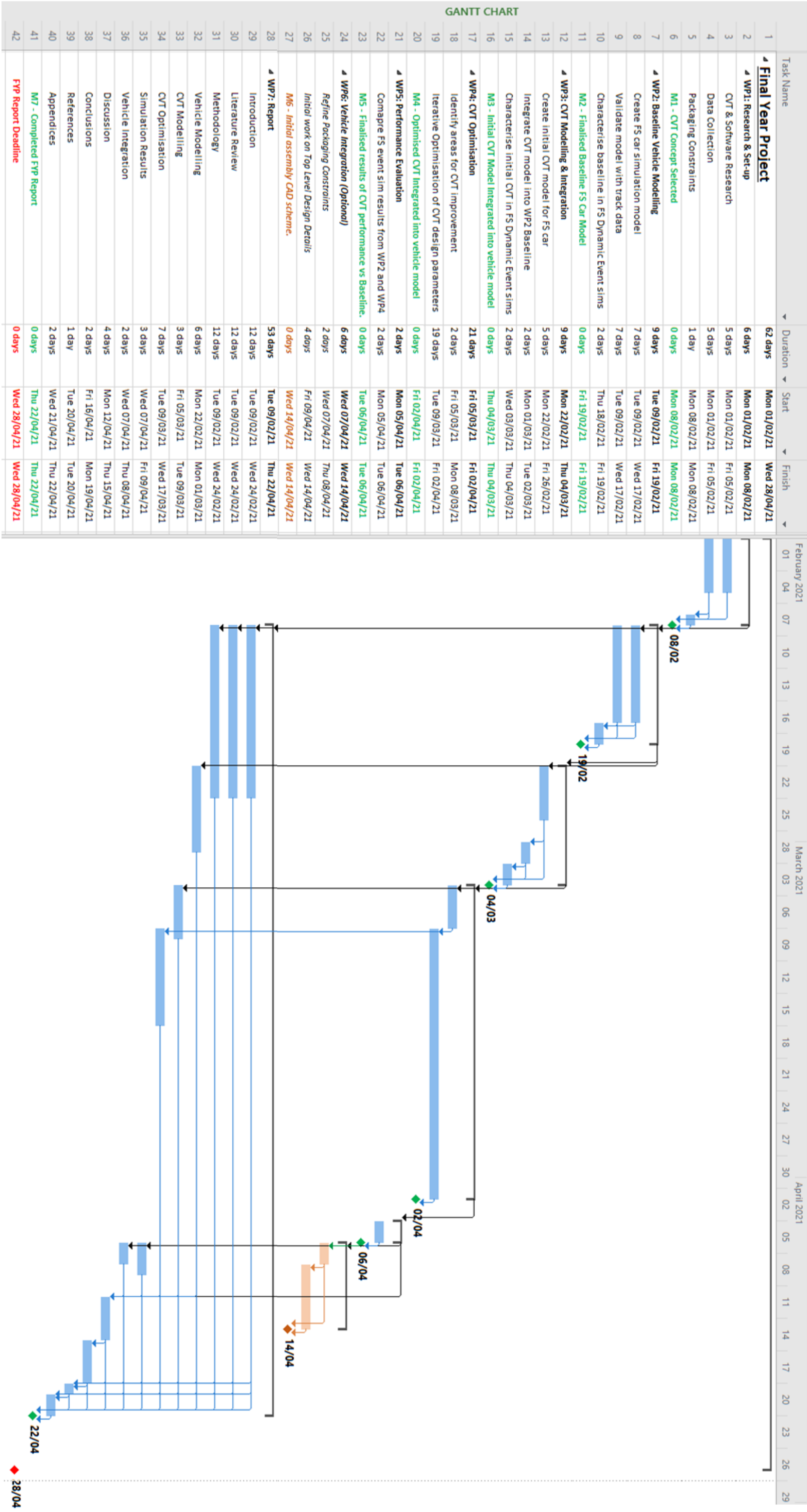

Figure 7: Gantt Chart for CVT Final Year Project, including Work Packages, task breakdowns, and milestones set to ensure compliance with project deadlines and objective completion.

References

[1] K. Ernst. "Bad News for Enthusiasts: More CVTs On The Way." Automotive Addicts. https://www.automotiveaddicts.com/31080/bad-news-for-enthusiasts-more-cvts-on-the-way (accessed 23/11/2020, 2020).

[2] B. Anderson and J. Maten, *Continuously Variable Transmission (CVT)* (Progress In Technology). United States: SAE International, 2006.

[3] Y. Chen, "Continuously Variable Transmission," in *Automotive Transmissions*, (Springer Tracts in Mechanical Engineering, 2021, ch. Chapter 4, pp. 109-153.

[4] C. Costa, P. Maciel, D. Da Cruz, and S. Bruno, "Application Study of a Continuously Variable Transmission (CVT) on a prototyp Formula SAE," *SAE Technical Paper Series*, 2015, Art no. 2015-36-0436.

[5] E. DeVincent *et al.*, *Design Practices - Passenger Car Automatic Transmissions*, 4 ed. United States: SAE International, 2012.

[6] E. Brakes. "Team Bath Racing reflect on an eventful season using EBC Brakes." https://ebcbrakes.com/ebc-brakes-car-racing-news/team-bath-racing-reflect-eventful-season/ (accessed 19/11/2020).

[7] iMechE, "Formula Student Rules 2020," ed. United Kingdom: iMechE, 2020, p. 133.

[8] S. Akehurst, C. Brace, D. Vaughan, P. Milner, and Y. Hosoi, "Performance Investigations of a Novel Rolling Traction CVT," *SAE Technical Paper Series*, no. 2001-01-0874, 2001.

[9] S. Akehurst, D. A. Parker, and S. Schaaf, "CVT Rolling Traction Drives—A Review of Research Into Their Design, Functionality, and Modeling," *Journal of Mechanical Design*, vol. 128, no. 5, pp. 1165-1176, 2006, doi: 10.1115/1.2214737.

[10] L. O. Hewko, "Automotive Traction Drive CVTs - An Overview," ed, 1986.

[11] F. Verbelen, S. Derammelaere, P. Sergeant, and K. Stockman, "A comparison of the full and half toroidal continuously variable transmissions in terms of dynamics of ratio variation and efficiency," *Mechanism and Machine Theory*, vol. 121, pp. 299-316, 2018, doi: 10.1016/j.mechmachtheory.2017.10.026.

[12] B. Albert, "Half/Full Toroidal, Single/Double Roller, CVT Based Transmission for a Super-Turbo-Charger," *Proceedings of Engineering and Technology Innovation*, vol. 11, p. 1, 2019.

[13] B. Kuijpers, "Implementation of a Suzuki Electronicallycontrolled Continuously Variable Transmission in a Formula Student Racecar," Eindhoven University of Technology, Eindhoven, 2009. Accessed: 12/11/2020.

[14] P. Kanphet, P. Jirawattana, and B. Direcksataporn, "Optimal Operation and Control of a Hydrostatic CVT Powertrain," *SAE Technical Paper Series*, 2005, Art no. 2005-01-1467.

[15] L. Marquenie, "Modification of a Formula Student race car engine, for addition of a Continuously Variable Transmission," Technical University of Eindhoven, Eindhoven, Summer 2008 2008. Accessed: 25/09/2020.

[16] O. Borsboom, C. Fahdzyana, M. Salazar, and T. Hofman, "Time-optimal Control Strategies for Electric Race Cars with Different Transmission Technologies," Eindhoven University of Technology, Eindhoven, 2020. [Online]. Available: https://www.youtube.com/watch?v=LxN3X1Ik7Kk