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Characterization of an Adjustable Centrifugal Continuously Variable Transmission for a Baja SAE Prototype.

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ABSTRACT

Motivated by the continually growing challenge of the Baja SAE competition, the primary goal of the present study is to understand the behavior of the Continuously Variable Transmission (CVT), manufactured by CVTech-IBC® for Baja SAE vehicles, and understand the way in which each element of the calibration kit (masses, drive pulley spring, and driven pulley spring) provided by the manufacturer affect this behavior. A characterization procedure for the particular engine-CVT couple employed is defined by establishing the variables to be studied and a test protocol. An ad-hoc dynamometer was designed and built, able to measure drive pulley's rpm, driven pulley's rpm, and torque on the output shaft. Then, Power vs. Output rpm charts for each configuration is generated for each possible combination of the calibration kit elements. Finally describing how each of these elements changes the CVT behavior. A lap simulator for the different events combined with the measured drivetrain curves is devised to select the best configuration for overall performance in the competition.

INTRODUCTION

The Baja SAE® competition is a challenge for students in which they must act as a team to design, build, and test an off-road vehicle. [1] Currently, all prototypes built by the Baja SAE team of the Universidad Simón Bolívar (USB) have had a Continuously Variable Transmission (CVT) system. The goal of this study is to understand how the CVT works and how its components modify its behavior.

There are many types of CVT available, Variable Geometry CVT, Electric CVT, Hydrostatic CVT, Friction CVT, etc. Inside the Friction CVT type, are the Rubber Flat Belt CVT, Metal Pushing Belt CVT, and the Rubber V-Belt CVT. [2] This one is the used by the Baja SAE USB prototype.

This type of CVT was designed by Hub Van Doorne who implemented it on a car, the Daffodil, in 1959. [2] This CVT transmits the torque by a normal force generated by two conical pulleys (drive and driven one) to a rubber V-belt who links them. The CVT used by the Baja SAE USB team is manufactured by CVTech®. On this CVT, the normal force is controlled by a set of masses that spin with the drive pulley generating a centrifugal force applied to a tilt surface resulting on a component applied to the V-belt. This system automatically adjust the transmission ratio depending on three main factors: 1) the centrifugal force generated which depends of the angular speed, weight of the masses, and radius, 2) the drive pulley spring stiffness, actuating against the centrifugal force, 3) the brake torque on the driven pulley and the stiffness of the torsional spring inside this.

The Baja SAE competitions consist on several tests, each of them with an assigned amount of points; finally the winner is the team that accumulates most points through the whole competition. One of the factors that increase the dynamical performance of the prototype, in order to win the most amounts of points, is a well tuned-up powertrain, which includes the CVT. For this reason, the primary goal of the present study is to understand the behavior of the Continuously Variable Transmission (CVT), used on the 2008 prototype of the Baja SAE USB team, and understand the way in which each element of the calibration kit (masses, drive pulley spring, and driven pulley spring) provided by the manufacturer affects this behavior.

In order to achieve this goal, a custom dynamometer for the specific couple of engine - CVT is designed and built, and a test protocol is defined. The results are then analyzed and charts created to characterize the behavior of the CVT for each combination of the calibration kit elements. Finally, a criteria to choose the best configuration is applied, then the best configurations selected are compared with the ones selected by the lap simulator program which uses acceleration curves measured on the prototype to simulate its behavior on different tracks.

V-BELT AUTO ADJUSTABLE CVT FOR BAJA SAE® COMPETITION

The CVT subject of this study is the one manufactured by the Canadian corporation CVTech®, which developed a special V-belt auto adjustable CVT for the Baja SAE® competition.

COMPONENTS OF THE CVT

This CVT has three main components, the drive pulley, the driven pulley, and the Rubber V-belt.

The drive pulley

The drive pulley consist of two conical surfaces, one fixed and one floating (axially). These two faces are linked by a helical spring that pushes the floating surface away from the fixed one. This pulley also has a set of inertial components or masses, these elements spin with the whole pulley generating a centrifugal force that pushes the masses out of the CVT. When spun, the masses press on an inclined surface, thus generating an axial component which compresses the spring, making the conical surfaces closer. Fig. 1 shows a scheme of the drive pulley.

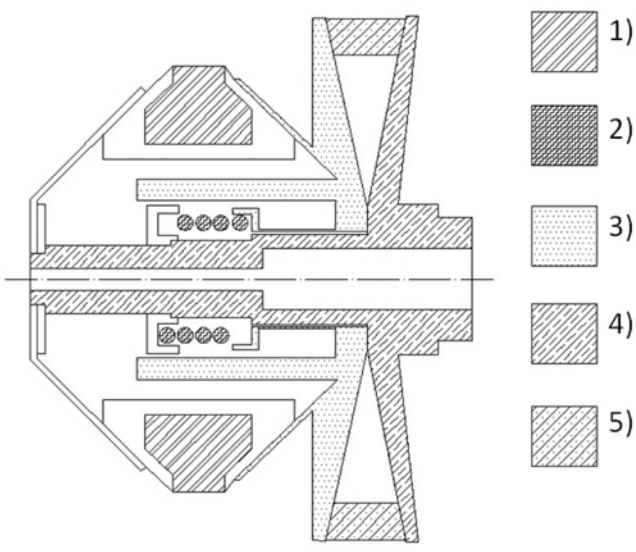

Fig. 1. Drive pulley scheme. 1) Masses, 2) Helical spring, 3) Floating surface, 4) Fixed surface, 5) Rubber V-belt.

Driven pulley

This pulley also consists on a fixed and a floating surface, linked by a torsional spring. The motion of the floating surfaces occurs when the torque applied by the V-belt over this one, is greater than the torque applied by the spring. These torques generate axial loads since the contact between the fixed and the floating surfaces are wedges.

Rubber V-belt

This belt is the element that transmits the power from the drive pulley to the driven one. On this belt the tension is not generated by adjusting the center to center distance between the spinning pulleys, but by the friction created by the normal forces that the conical surfaces of the pulleys apply to the lateral sides of the belt.

OPERATING PRINCIPLES

Idle position

On the idle position (drive pulley spinning or not, driven pulley not spinning) both conical faces of the drive pulley are separated, allowing the V-belt to be placed as closer to the rotation axis as possible (limited by the components geometry) this causes the V-belt to describe a low radius arc around this pulley, contrary to the drive pulley which has its faces as closer as geometrically possible, then describing a high radius arc. The ratio between the arcs above is the minimum transmission ratio (defined as driven pulley radius divided by the drive pulley radius).

Engagement

When the drive pulley raises its angular speed, the centrifugal force on the masses increases, as well as the axial loads on the helical spring. This results in a narrowing of the pulley's surfaces thus creating friction between those and the V-belt. At the moment that this friction generates a higher tensile load on the V-belt than the one generated by the brake loads on the driven pulley, the engagement occurs (the driven pulley begins to spin).

Continuously Variable

Once the engagement occurs and the drive pulley keeps increasing its angular speed, the friction on the V-belt will increase as well, causing the drive pulley's surfaces to get closer while the driven pulley's surfaces get away from each other. This is reflected in the belt as a continuous change on the radius described on each pulley. The radius increases on the drive pulley while decreases on the driven one, finally getting the maximum transmission ratio.

Fig. 2 shows the torque and forces (red, continuous line), and the displacements and rotations (blue, discontinuous line) on the CVT.

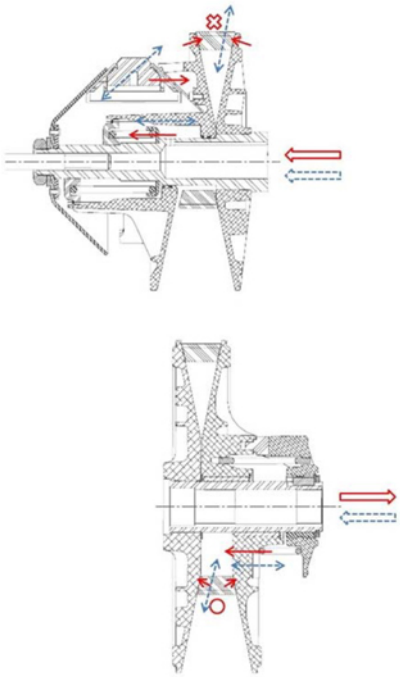

Fig. 2. Forces/Torque and Displacements/Spin on the CVT [3]

CVT SPECIFICATIONS AND CALIBRATION KIT

Specifications

The CVT subject of the current study is an Automatically Adjustable V-belt CVT for the 2008 Baja SAE competition. CVT part numbers are showed on Table 1.

Table 1. CVT specifications [3]

Description	*Value*
Drive pulley part number	0600-0012
Driven pulley part number	5100-0073
Center to Center distance [mm]	235
Belt number	B3211AA1008
Cable length [mm]	992
Minimum transmission ratio	0.241
Maximum transmission ratio	1.357

Calibration kit and nomenclature

The manufacturer of the CVT provides a Calibration Kit which includes several masses and springs for both pulleys. For the current study a name was given for each element. Then, a nomenclature created to define each configuration (specific combination of the calibration kit elements). The elements and the given name is shown on Table 2.

Table 2. Calibration Kit elements and Given Name.

Description	*Part Number*	*Name*
Masses		
Weight (135g)	0135-2019	135
Weight (160g)	0135-2024	160
Weight (190g)	0135-2030	190
Drive pulley springs		
Spring (silver/gold/white)	X-5218214	1
Spring (silver/red/blue)	X-5243212	2
Spring (silver/red/brown)	X-5243214	3
Driven pulley springs		
Spring (orange/yellow/yellow)	ACS-3-162	A
Spring (orange/blue/blue)	ACS-3-188	B

The stiffness of the drive pulley springs increases from the number 1 to the 3 (1 having the lower stiffness, 3 having the higher). For the driven pulley springs, the spring B has a higher torsional stiffness than the A.

With the names assigned above, each configuration, is defined by three numbers indicating the weight of the masses, a dot, one number indicating the drive pulley spring, a dot, and a letter indicating the driven pulley spring (e.g. 135.1.A).

From this calibration kit, eighteen CVT configurations are possible.

ENGINE

According to the competition rules, the only allowed engine is the Briggs & Stratton® OHV Intek Model 205432, set to a maximum speed of 3800 RPM by means of the governor. [1] This engine is a mono-piston, 4-strokes gasoline engine that delivers 7.46 kW at 4000 rpm. [4] For the current study the idle speed was set to 1500 rpm and the maximum to 3800 rpm according to the 2008 Baja SAE rules. The performance charts of the engine are shown on Fig. 3.

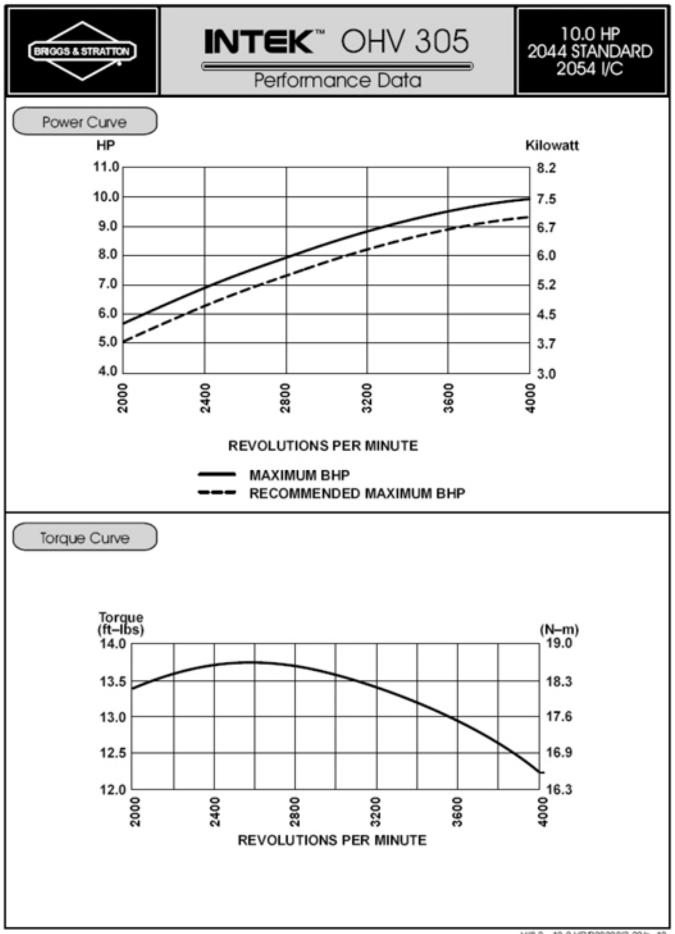

Fig. 3. Engine's performance charts by B&S [4]

CVT AND ENGINE ON BAJA SAE COMPETITION

On the SAE Baja competition the standard mounting of the CVT is as follow: the driven pulley is attached to the engine's output shaft, and the driven pulley is coupled to a reduction gearbox (with a single or multiple ratios).

CHARACTERIZING THE CVT, METHODOLOGY

In order to understand the way in which each part of the calibration kit changes the CVT behavior, a test protocol was defined as well as the variables to be measured.

VARIABLES

The selected variables to measure are: angular speed of the drive pulley [RPM1], angular speed of the driven pulley [RPM2], and torque delivered on the driven pulley shaft.

The drive pulley RPM equals the engine's RPM, this means that knowing this RPM it is possible to estimate the power and torque delivered by the engine.

The instant transmission ratio is calculated from both pulleys' RPM.

With the driven pulley RPM and the torque on the output shaft it is possible to calculate the brake power on the output shaft and compare it with the estimated power delivered by the engine in order to have an estimated of losses due to the CVT.

The fuel consumption was not taken into account for the present study.

TEST BENCH

In order to measure and log the variables described above, an Ad-hoc dynamometer is designed and built. This dynamometer has a main structure in which the engine, an output shaft for the driven pulley, and other measure devices are fixed.

On this dynamometer, the driven pulley is coupled to an output shaft, this one is mounted over two bearing units fixed to the main structure.

MEASURING AND DAQ

Angular speed [RPM]

The angular speed in both pulleys is measured with a Hall effect sensors, these generates a pulse when each of two magnets attached to each pulleys passes in front of these. Then the RPM are calculated from the time between pulses.

Torque [N*m]

The devised mechanism to measure torque on the output shaft consists of a brake rotor, a brake caliper, a master cylinder, and an S-beam load cell.

The brake caliper is joined with a bracket that houses a bearing joint to the output shaft. In this way the caliper just can spin around the shaft, and the distance from the center of the caliper's piston (center point of the applied force) to the center of the shaft is fixed and knows.

The S-beam load cell is joined by one side to the same bracket that holds the brake caliper, and the other side joint to the main structure.

When the brake caliper is actuated by master cylinder, it generates a pressure over the brake pads which press the brake rotor, transforming this pressure into a friction force opposed to the rotating speed of the rotor. This force is directly proportional to the tension measured by the load cell. Finally with this force and the distance between the application center of it and the spinning axis of the rotor, the brake torque is calculated.

The master cylinder is actuated manually through a lever. The test bench is also equipped with a pneumatic system to cool the brake rotor.

The test bench is shown on Fig. 4.

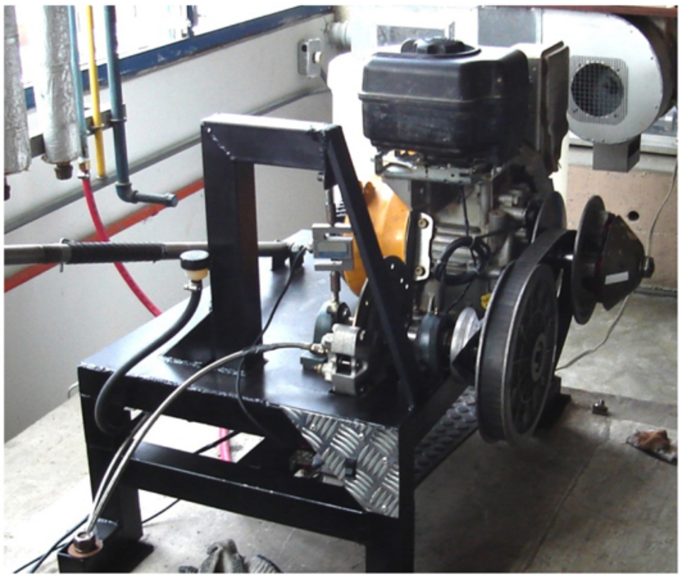

Fig. 4. Test Bench picture.

Data Acquisition Board (DAQ board)

For the data acquisition an Ad-hoc circuit was build. This circuit board has a Motorola® programmable chip, this chip takes the signals from the different available sensors, assemble a data package and send it to a computer via serial port. The circuit board is shown on Fig.5.

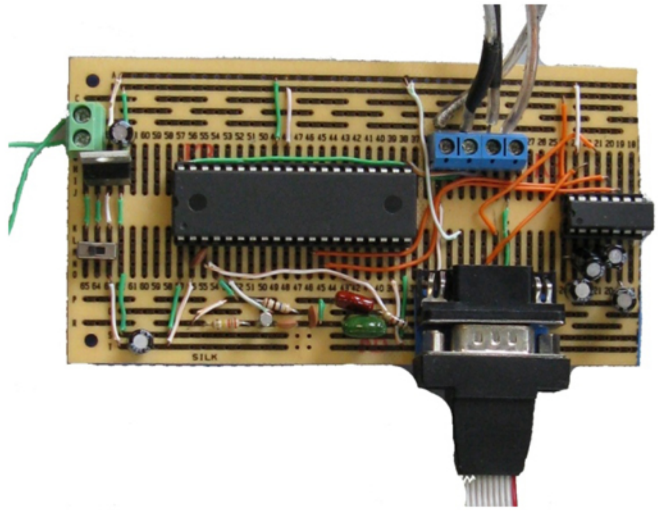

Fig. 5. DAQ circuit board.

DAQ interface

Once the data package is sent by the DAQ board, it is received by a computer interface that shows both pulleys RPM, the instant transmission ratio between them, and the tension force on the load cell in real time and log the acquired data into a file for post-processing it. Interface is shown on Fig.6.

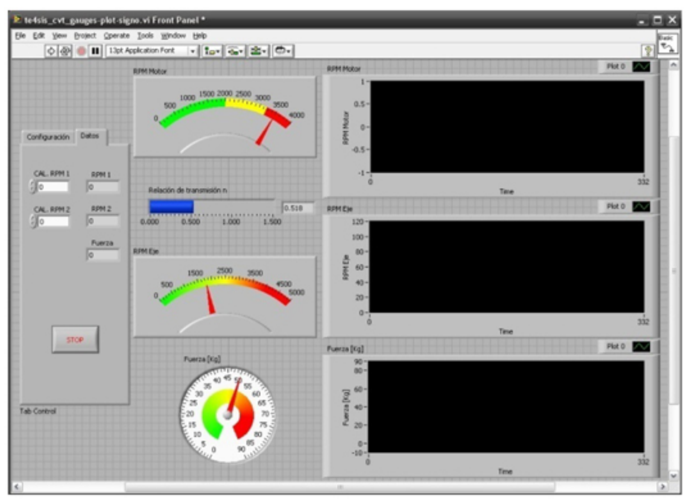

Fig. 6. Computer interface for DAQ

TEST PROTOCOL

After several tries with the Test Bench, the final protocol is defined as follows:

1. Engine started and warmed up. No loads on the output shaft.

2. Start data logging on the interface.

3. Accelerate the engine up to 3800 RPM (maximum).

4. Wait until the CVT ends to adjust the transmission ratio and reaches a steady state condition.

5. Slowly apply a growing load over the output shaft until it stops. By this moment the V-belt starts to slip on the drive pulley.

6. Turn off the engine.

7. Stop data logging and save the file.

8. Wait about a minute for the brake rotor to cool down before running again.

With this test protocol, the torque transmitted to the output shaft is obtained for the whole range of speeds, meaning, the whole range of transmission ratios possible with the CVT.

However, this test assumes that for all the measured points the system engine-CVT is on steady state condition.

ENGINE-CVT STABILIZATION TIME TEST

The CVT generates a torque due to its rotational inertia, this is a positive value when the speed ratio decreases (e.g. from a ratio of 1.3 to 0.241, defined as driven/drive pulleys speeds). In this case, the torque above reduces the acceleration torque and vice-versa [5]. The engine's inertia has a similar effect.

These effects of the rotational inertias appear when the system is disturbed and gets into a transient state until it stabilizes and reaches a steady state condition. For the proposed test protocol, the only source of perturbation is the force applied on the output shaft.

To prove that the simulation of quasi-static conditions for the protocol defined above was viable, a test to measure the stabilization time of the engine-CVT system was performed as follows: engine at maximum speed, with a constant load on the output shaft (constant pressure on the brake caliper created by weights over the master cylinder lever), then the load was suddenly removed. The drive pulley speed was plot vs. time.

Fig. 7. shows the engine at minimum speed, the engine at maximum speed with the constant load, then a peak when the load is removed and the engine on steady state condition at maximum speed. Given the stabilization time (0.97s) the simulation of a quasi-static condition is assumed.

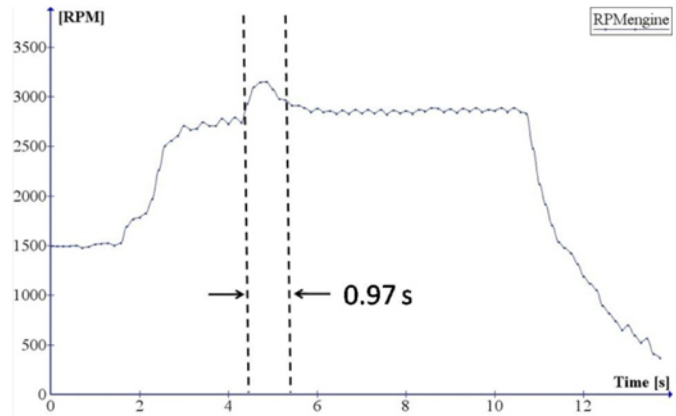

Fig. 7. System (engine-CVT) stabilization time.

Later tests on the dynamometer showed that if the applied load is applied slowly enough, the plot of torque does not show torque peaks (meaning transient condition). But if this load is applied in a faster way, erratic torque peaks actually appear on the plots.

PROTOCOL RUNS

For each configuration of the CVT, the test protocol is run five times; the data from each run is saved into a file for further analysis.

DATA TREATMENT

Once logged the five runs for each CVT configuration, these logs are cleaned, only preserving the data inside the range of interest. That is, from the maximum engine speed reached at the beginning of the test to the 0 RPM on the output shaft.

With the acquired data, the construction of several charts is possible, however, in order to achieve the main goal of this study (understanding how each elements of the calibration kit changes the CVT behavior), the Output Power vs. Output Speed chart, is considered as the most representative of the CVT behavior.

Overlapping two curves from different configurations on this chart, one can easily infer that the configuration delivering a higher power for a fixed speed, is the one delivering more torque to the drivetrain, hence, a higher acceleration on the vehicle. Meanwhile, the Output Speed has a direct relation with the vehicle speed.

All the data collected from the five runs are overlapped in order to get a higher density of points than a single run, then a polynomial trendline is added, as shows the Fig.8.

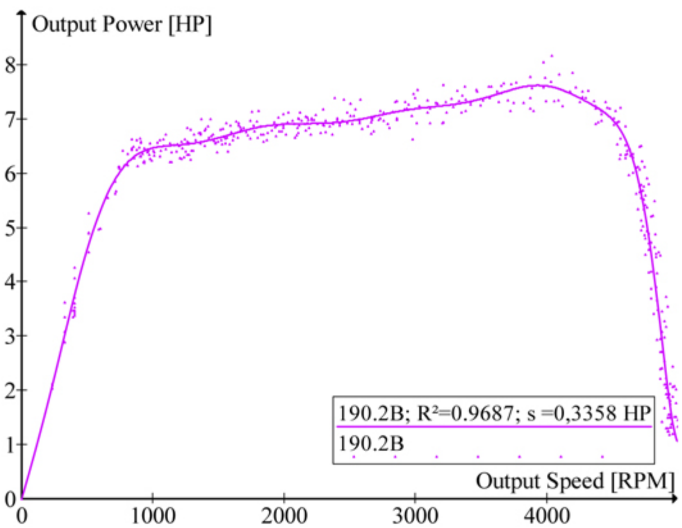

Fig. 8. Point series and trendline.

To assure the trendline accuracy the Standard Deviation is calculated, obtaining values between σ=0.24HP and σ=0.42HP (lower and higher deviation) as well as the Determination Coefficient (R^2, with a mean value of 98%), which is reported for each trendline too.

Finally, the curves obtained for each configuration are plotted together to be qualitatively compared and analyzed.

ANALYSIS

MASSES INFLUENCE

The weight of the inertial elements located on the Drive Pulley changes the moment in which the engagement and sleep occurs.

Using heavier masses, the drive pulley engages when the engine is spinning at a lower speed because of the higher centrifugal forces generated (relatively to the effect caused by lighter masses). It means a lower engagement torque (and consequent vehicle acceleration) since the engine is delivering lower power at that lower engagement speed. However when the Output shaft (or the vehicle) reaches a higher speed, the friction force generated on the V-belt is higher, preventing the slip of it, allowing higher power to be delivered at the output shaft at high speed.

The slip occurs when the friction force generated over the V-belt by the centrifugal forces is not able to create a higher tension than the one generated by the loads on the driven pulley. On slip condition, the V-belt has a relative movement over the drive pulley producing heating of both elements and power loss on the output shaft.

On the other hand, when using low weight masses, the pulley engages at higher engine speed (and thus higher engine power), hence, reaching higher acceleration rates at low output speed. Yet, the normal force generated at high engine speed is lower than the one produced when heavy weighs are used, causing an earlier slip.

On Fig. 9, the curves from two configurations are plotted with the same springs on both pulleys, but different weight of masses. It is appreciable how the lighter masses deliver more power than the heavier ones at lower speed (0 ~ 2500 RPM), but lower at high speed (3500 ~ 4500 RPM), this is due to slip.

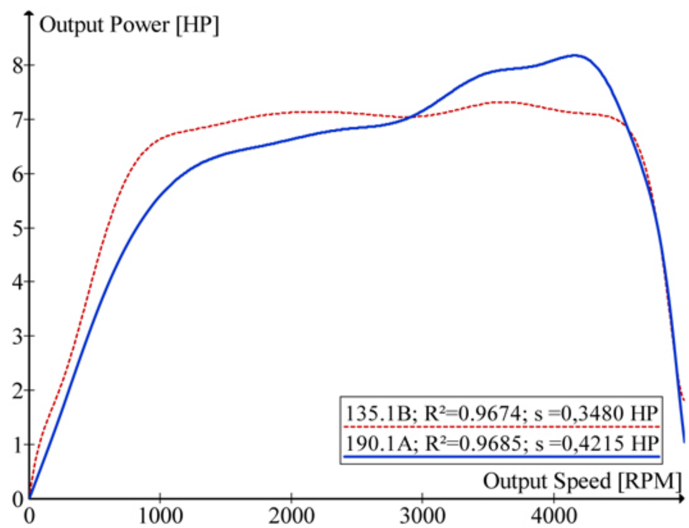

Fig. 9. Masses Influence on CVT behavior

DRIVE PULLEY SPRING INFLUENCE

The effect of this spring's stiffness is opposite to the weight of the masses. When using a low stiffness spring, force from the masses is required a smaller to generate the same tension on the pulley than using a spring with a higher stiffness, put another way, using a lower stiffness spring has a similar effect than using heavier masses and vice-versa.

On Fig. 10, the dashed curve (green), shows the CVT behavior with a higher stiffness spring on the drive pulley, than the one used to obtain the continuous curve (blue, lower spring stiffness). The behavior with the lower stiffness is similar to the one described by the higher weights (continuous, blue line) on Fig. 9.

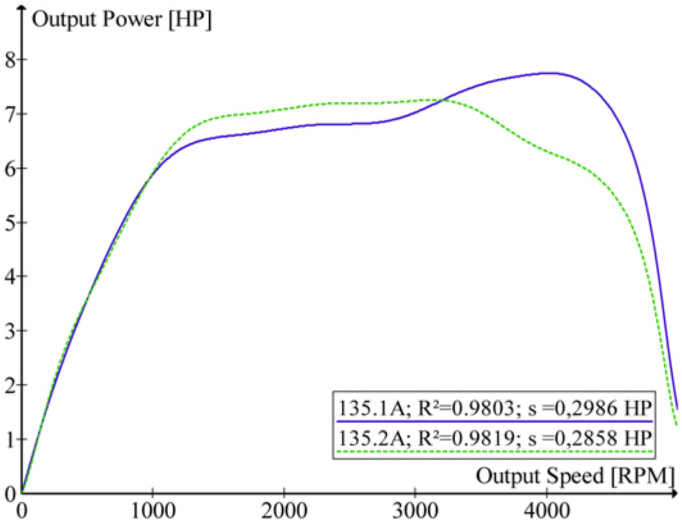

Fig. 10. Drive pulley spring's stiffness effect on CVT.

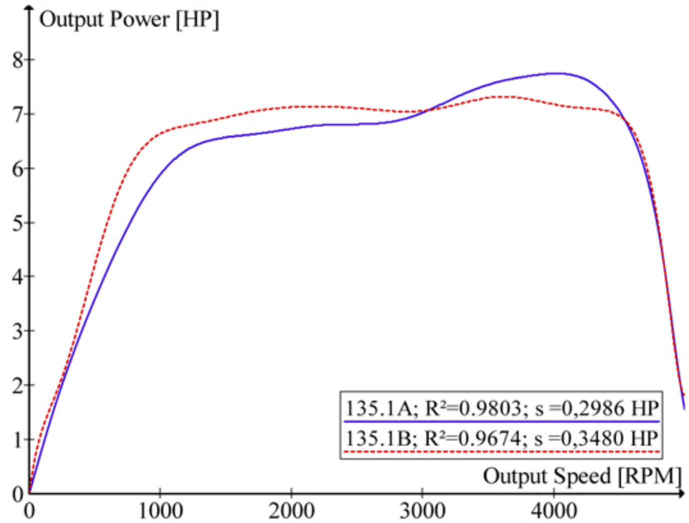

Fig. 11. Driven pulley spring's stiffness effect.

DRIVEN PULLEY SPRING INFLUENCE

This spring stiffness holds the CVT faces closed, meaning a low transmission ratio 0.241. When this stiffness is high and the CVT engages, this transmission ratio is held for a longer time than using a lower stiffness, this means that lower loads are transmitted to the engine allowing it to speed up faster and reach the maximum power level in a shorter time.

However, this higher stiffness also produces an earlier slip because when the CVT is on the maximum transmission ratio (1.357) this stiffness is trying to pull back the CVT to the minimum ratio, generating an adverse tension on the V-belt that promotes the slip on the drive pulley. However, this last effect is lower than caused by the slip promoted by higher stiffness of the drive pulley spring or the low weight masses. The effect of a lower stiffness spring is the opposite to the described above.

Fig. 11, shows a curve with the higher stiffness spring (red, dashed line) and the lower one (blue, continuous).

GENERAL EFFECTS OF THE CALIBRATION KIT ELEMENTS ON THE CVT BEHAVIOR.

The CVT behavior can be studied on three stages, defined as intervals of the output (driven pulley) speeds, being of particular interest, the first and the last of these.

The first stage comes from 0 to 1000 RPM. On this stage, the CVT behavior is mainly defined by the power delivered from the engine at the engagement moment. The faster the engine is spinning when the engagement occurs, the higher power will be available, meaning higher acceleration for the vehicle. On the mid range the CVT work close to nominal conditions and the different have little effect. On the last stage, from 3500 to 5000 RPM, the slip causes power losses.

However, obtaining a higher power on the first stage and preventing the slip from the last was not possible for a single configuration (with the available calibration kit). Elements that lead to a high power on the first stage also lead to slip on the last.

Table 3 shows general effects of the drive and driven pulley springs combination for the stages described above. Notation according with nomenclature defined on Table 2.

Table 3. General effect of the springs combinations.

Output Speed	*Power on the output shaft*		
[RPM]	Low	Medium	High
0 - 1000	1A, 2A, 3A		1B, 2B, 3B
1000 - 3000	1A	1B	2A, 3A 2B, 3B
3500 - 5000	2B, 3B	1B, 2A, 3A	1A

Complementary to the table above: the masses of 135g improve the power from 0 to 3500 RPM and decrease it from 3500 onwards. The masses of 190g cause the opposite effect.

LAP SIMULATOR COMPARISON

The 2008 Baja SAE USB prototype is equipped with a telemetry system which is capable to measure, record and display the actual engine's rpm and the car speed on real time. Based on the use of this tool, a test protocol to obtain the car's performance in acceleration conditions is designed.

The acceleration test consists in running 30 meters (100 feet) as fast as possible, starting from 0 Km/h. These runs are repeated at least four times for each configuration of the CVT (twelve available at that moment) assuring more accurate results. This data is processed by an Ad-Hoc code, developed to obtain the Acceleration Vs. Speed chart, with which the equation of motion of the vehicle for each CVT configuration is built.

Using these equations, it is possible to estimate the time the vehicle employs running a particular lap, establishing the distances, slope, and initial and final speeds of each straight line to be simulated (corner speeds were consider steady). Finally, the whole time values (for each straight line) are added to obtain the lap time. This procedure is repeated for each CVT configuration and for each type of lap devised, simulating real competition laps.

Fig. 12 shows an example of a simulated straight line. The solid line corresponds to the vehicle accelerating from the previous curve. The dashed line is built backwards for the vehicle braking down to the entering speed for the following corner.

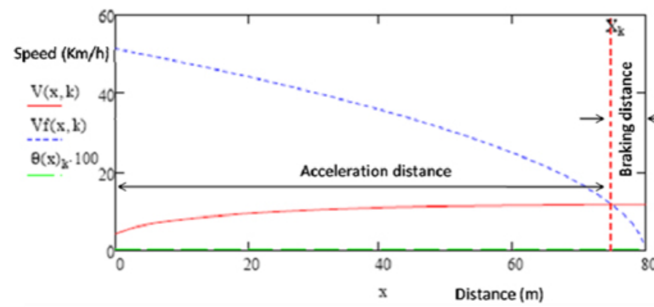

Fig. 12. Simulated Straight Performance

Different tracks representing the typical tests at the competition are simulated to estimate the performance of the different configurations at each event. Then, points are assigned to each configuration at each event according to the competition criteria, so that it is now possible to evaluate the overall performance of each configuration on the competition (i.e. which one will give the team a higher score by the end of the competition).

Table 4 shows the lap simulator results for the 2008 Baja SAE USB prototype. The best configuration on each event is highlighted on each column. It is clear that the best performance overall is not necessarily given by the best performance on the individual events but rather for the best average performance. Highlighted on the last column are the three configurations for the best overall performance.

Table 4. Lap Simulator Results, first place in green (no pattern), second in orange (dots pattern), third in blue (slashes pattern).

N°	Setting	Accel Time(s)	Accel Points /75	Lap Endur Time (s)	Endurance Points /400	Maneuv Time (s)	Maneuv Points /75	Susp & Trac Time (s)	Susp & Trac Points /75	TOTAL /625
1	135_1A	4.19	60.10	179.79	247.15	43.32	62.45	94.53	39.81	409.51
2	135_1B	4.17	62.50	173.46	357.15	45.54	46.53	93.11	47.60	513.79
3	160_1A	4.22	53.77	174.06	337.47	42.22	70.34	94.65	39.15	500.72
4	160_1B	4.10	75.00	174.46	324.07	41.89	72.71	88.12	75.00	546.78
5	190_1A	4.28	44.35	177.02	239.54	43.08	64.17	96.54	28.77	376.83
6	190_1B	4.31	39.38	178.66	185.28	43.24	63.03	95.67	35.55	321.23
7	135_2A	4.19	60.45	172.17	400.00	41.66	74.35	89.33	68.36	603.16
8	135_2B	4.54	0.00	184.26	0.00	52.03	0.00	101.78	0.00	0.00
9	160_2A	4.23	53.08	172.83	378.16	41.57	75.00	94.38	40.63	546.88
10	160_2B	4.20	58.56	175.29	296.77	47.76	30.62	94.19	41.67	427.63
11	190_2A	4.27	46.75	175.18	300.25	44.67	52.77	93.77	43.98	443.75
12	190_2B	4.17	63.70	174.17	333.66	44.01	57.50	94.55	39.70	494.56

According to the findings of the previous section, 135.2A and 160.2A configurations should engage at high engine's speed and have a good behavior at medium vehicle speed (15 to 40 Km/h) because of the effect of spring "2", which makes them suitable for the endurance event and maneuverability. On the other hand 160.1B and 135.1B show better acceleration performance between 0 and 10 Km/h, then the power remains almost constant throughout the operating range of the CVT;

these settings are recommended almost in all events, mainly in the acceleration one.

Finally, 160.1A shows a peak of power at high vehicle speed, increasing the performance mainly in the endurance event if there are long straight lines in the lap.

It is clear that the selection of the best configuration for overall performance will be highly affected by the particular tracks at the competition. The methodology hereby proposed allows for good estimation and selection of the CVT configuration, yet extreme care should be put to the track definition on the simulator.

SUMMARY/CONCLUSIONS

• An instrumented test bench capable of accommodating the engine, and CVT used by the Baja SAE® USB Team on 2008, was designed and built.

• A DAQ system capable of showing in real time the acquired data (drive and driven pulleys speed, and torque on the output shaft) as well as log it on a file was designed and built.

• It was possible to measure torque on the output shaft with a automotive brake system and an S-beam load cell connected to it.

• The data collected for the same CVT configuration on different runs, show good repetitiveness, making this data highly reliable.

• Power vs. Output speed plots were obtained for each configuration, allowing its analysis.

• With the obtained plots from each configuration, the effect of each element of the calibration kit on the overall performance of the CVT was described.

• The moment in which the CVT engages, and when it begins to slip, are critical factors to describe the CVT behavior.

• The methodology presented allows for identification of the best CVT configuration for overall performance at the competition.

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DEFINITIONS/ABBREVIATIONS

CVT
Continuously Variable Transmission.

SAE
Society of Automotive Engineers.

USB
Universidad Simón Bolívar.

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