AN CONTINUOUSLY-VARIABLE, MULTIPLE ENGINES SOLUTION FOR TRACTORS

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ABSTRACT

In modern heavy duty and agricultural vehicles the Continuous Variable Transmission (CVT) is highly requested. However, the implementation of the concept is not so easy. Many solutions were patented in last two centuries to solve the problem. Many are based on planetary gearings. In the recent years the introduction of hybrid light-duty vehicles with power split planetary CVT has revolutionized the market, reviving the interest in the solution. This paper is aimed to introduce a new concept of CVT dual drive with multiple speed controlled engines. The example of a dual drive CVT with four common rail engines is detailed.

Keywords: continuous variable transmission (CVT), hybrid light-duty vehicles, planetary gear, common rail engines.

INTRODUCTION

The planetary gear is a system that consists of several outer gears (planet gears) revolving around a central one (sun gear (1)). The planets are mounted on a movable carrier (P) which rotates relatively to the sun gear. There is an outer ring gear (annular gear or annulus (3)), which meshes with the planet gears. The advantages of planetary gearings are high power density, larger gear reduction in a small volume and multiple kinematic combinations. This planetary gear system is used to achieve our Continuous Variable Transmission (CVT).

If the planetary or carrier is locked the gear ratio i can be calculated with equation (1). The sun gear and the annular gear rotate in the same direction.

$$\tau = \frac{z_1}{z_3} = \frac{\omega_3}{\omega_1} \tag{1}$$

If the carrier is free to rotate, you will see the speed of the annular gear reduced by the carrier angular velocity ω_p. Formula (1) therefore becomes (2):

$$\tau = \frac{(\omega_3 - \omega_p)}{(\omega_1 - \omega_p)} \Rightarrow \omega_1 - \omega_3\tau + \omega_p(\tau - 1) = 0 \tag{2}$$

If the input is on the sun gear and the output on the annular gear, the carrier gear velocity ω_p can be controlled (3).

$$\omega_3 = \omega_1 + \tau(\omega_1 - \omega_p) \tag{3}$$

With ω_1 is kept constant, and the carrier p rotates in the same direction of the sun gear 1, the annulus gear will slow down, so it is possible down to ω_3=0. If it rotates opposite to the sun, $\boldsymbol{\omega_3}$ will be increased.

If the input is on the sun gear 1 and the output on the carrier p, the annular gear speed ω_3 is controlled (4).

$$\omega_p = \frac{\omega_3 - \omega_1\tau}{\tau - 1} \tag{4}$$

If the annulus 3 rotates in the same direction of the sun gear, the carrier speed will be slowed down to ω_p=0. It is possible also to have a reverse speed. If the annulus rotates in the opposite direction of the sun gear, speed ω_p will be increased.

The annulus control may be easily used to obtain a very simple CVT (Continuously Variable Transmission). The proposed solution implements a single stage planetary gearing for each sprocket. Two internal combustion engines power each sprocket. The first, the main one, moves the sun gear, while the second moves the annular gear. In this way the torques of the two motors are added at low speed and the highest transmission ratio is obtained. At high speed the transmission ratio is reduced and the main engine outputs most of the power. This solution makes it possible to control the four sprockets independently. Since modern engines can be controlled in speed up to the 1/10 of crankshaft rpm, it is extremely easy to keep the two sprockets of each track at the same speed. This solution halves the tension on the track and reduced significantly track wear. It is also possible to control the tension on the track and two forecast and schedule accordingly the moment of the substitution. Finally the possibility to split the torque into four units makes it possible to use smaller engines from the automotive market. Since several engines of the same power-torque class are available from different manufacturers, it is perfectly possible to use several different suppliers, so reducing manufacturing and maintenance costs. In case of engine failure it is possible to keep the vehicle efficient by using the remaining ones. The substitution of the single engine is simpler since the engine is smaller. The positioning of the engines inside the vehicle is easier since several different possibilities are possible. In general it is easier to find room for four small units than to single larger ones. The four units totalize a smaller volume than the single one, since the automotive derived engines are far more advanced than large specialized engines. Spare parts and specialized personnel and maintenance site availability is highly increased. When an APU (Auxiliary Power Unit) is needed with the vehicle stopped it is possible to disconnect one of the 8 engines and use it as an APU: Finally performance and efficiency (fuel consumption) are significantly improved by the CVT solution.

An example is proposed to explain the CVT solution. This is the best way to introduce the concept. The data are taken from existing heavy duty vehicles. However the example suffers from many shortcomings. For example the torque converter is not included in the model. The mass of the vehicle and the many data needed for the design of a transmission and steering device are not included. The focus of this paper is on the transmission concept, not on its design. In general it is a good philosophy to keep the speeds as high as possible down to the final reduction. This is due to the fact that the mass of the transmission goes with the torque, while the power goes with the torque multiplied by the speed. It is a good policy to use the torque curve fully, from the speed where torque begins to be "reasonable" up to the maximum speed. A good design may reduce transmission mass and volume by a factor 4 from a "commercial", apparently "low cost" choice.

Transmission design requires specific knowledge about transmission components, design solutions and it should include a simulation of the dynamics. In general, it is convenient to design the vehicle around the engine and the transmission and not vice-versa. The common practical approach to design the vehicle and then to install the transmission generally outputs very slow, underpowered machines. This fact is particularly common in heavy duty tracked vehicles, with masses that often run out of designer control.

This paper introduces the CVT concept and the equations that can be used for its calculation. The numerical example demonstrates the feasibility of this CVT solution.

Tracked vehicle: electronically stabilized dual drive steering

Steering a tracked vehicle is very different from steering a wheeled vehicle. In a typical four wheeled car, the front two wheels can be pivoted to point the vehicle. The power is delivered to the traction wheels via differential gear(s). This type of transmission allows the radial velocity difference between the wheels to be accounted for, and the wheeled vehicle can theoretically turn without any slippage or skidding. With a few exceptions, like the universal carrier and tetrarch, tracked vehicles have to rely on skid steering. If one track is moving faster than the other, the forward and rearward sections of the tracks slip laterally over the ground and the vehicle turns. The ideal track steering mechanism is simple, continuous, efficient and additive; this means that, when transitioning to a turn, the mean track velocity remains the same. Tests have shown that additive steering works better when the vehicle is in deep mud or sand, since keeping both tracks moving helps prevent the tracked vehicle from getting stuck. In addition the ideal tracked vehicle steering mechanism should make driving in a straight line easy. Neutral steering should also be allowed, that is, that the tracked vehicle can turn within its own length. Additionally, the energy from the slowed track should be transferred to the sped up one in a regenerative way.

The most obvious way to drive the tracks at different speeds is to have an engine for each track. To turn the vehicle, it is sufficient to increase the speed of one engine and decrease the speed of the other. This steering method has not been successful, although some very early tracked vehicles and Ferdinand Porsche's various mechanical abortions did use this method of steering.

In a few dual drive electric hybrid vehicles (Porsche Tiger, IS-6...); the energy was recovered from the slowing track by running the electric motors in reverse to act as generators and then giving that power to the motor of the speeding up that. This made the hybrid dual drive steering regenerative (up to 65%). However larger motors were required to handle the additional power.

If the transmissions have reverse gearing, dual drive provides infinitely variable turn radii and allows neutral steer. It is very mechanically efficient, since there is no power flow from the transmission to the steering mechanism. Unfortunately, dual drive tracked vehicles are inherently unstable. This means that they are poor at manually driving in straight lines. In fact it is difficult to balance manually the speed of both engines. Also the tracked vehicle will tend to veer if it hits irregular terrain, being the two drive sprockets not cross-linked. An electronic stability system should then be used.

In cars an ECU (Electronic Control Unit) measures the car slip and, in case of necessity, cuts the throttle and the direction by breaking each wheel in a proper way. The objective is to reduce the error on desired direction inputted by the driver via the steering wheel. The control system is a digital PID (Proportional Integrative Derivative) control. The ESP is superimposed on an ABS (Antilock Braking System) that avoid wheel blockage. This system works very well in many conditions and turns off when adherence is too low or control is beyond recovery leaving to the driver a normal car. For every car model a proper tuning is to be made. Normally a car simulator calculates the optimum values to be inputted into the ECU, then standard experimental tests are performed on special test paths that were designed for the specific application of the ESP/ABS. These systems are difficult to implement on a tracked vehicle in uneven terrain. This is due to the extremely variable conditions that, in most cases, turn the ESP off, leaving the driver to steer manually the vehicle. Brake efficiency on tracked vehicle is also reduced by vehicle inertia and the track-soil friction. For the electronic stability program a dual drive is highly recommended since it can control independently the velocity of the two tracks. Single track velocity can be easily achieved by the engine ECU. The diesel braking capability reduces the necessity to use an external brake enhancing the endurance of the brake and reducing is thermal sizing. The unstable behavior of the dual-drive

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tracked-vehicles greatly improves the response of the system. However, the tracked vehicle system is highly not linear. In this case an Improved Electronic Stability Program (IESP) based on a fuzzy logic algorithm may be the best choice [1]. The IESP may use the same hardware (sensors/actuators) of a standard ESP (Mercedes-Benz™); only the control system is completely different. It is sufficient a software upgrade to convert a car from ESP to IESP. The IESP reads the driver steering angle and the dynamic condition of the vehicle and selectively acts on throttle and track-engine speed in order to put the vehicle on the required direction even during a sudden and complete loss of adherence. The fuzzy logic advantage is the capability of self-tuning. Once the inertia data of the vehicle are introduced into the software, the fuzzy control system does not need any further tuning. On the contrary the standard ESP, which is based on a traditional PID control system, needs to be adapted to every car model and the tuning differs from sedan, cabriolet and 2 volumes of the same car. The traditional ESP tuning process is long and expensive and experimental tests are required. Traditional ESP cannot recover direction from a spin and cannot control the car direction after a tyre burst. The only known limit of the IESP proposed in [1] is small oscillations in very limit condition. This oscillation affects not only the yaw axis, which is normal, but also the pitch and the roll giving the impression to the driver of an unstable and unsafe handling. However, this “unsafe felt” l behaviour takes place in a condition very close to the physical limit of the vehicle dynamic. In this case these oscillations may be a good warning to the driver to behave more properly. “Physic cannot be fooled” as Richard Feynman said about the famous Shuttle accident. As for the aircrafts, artificial stability improves handling, giving to the driver the possibility to reach the ultimate dynamic and static limits of the unstable vehicle. The overall performance of the vehicle is then enhanced. The extremely simplified solution of the dual drive transmission with its extremely high efficiency reduces also the fuel consumption.

Automotive derived power units’ application and durability (TBO)

Starting from a good car engine is always a good idea, since they are mass produced in millions of items. Up-to-date automotive Common Rail Direct Injection Diesel (CRDID) has a thermal efficiency that exceeds 50%. "The vast majority of Europe’s new cars are powered by gasoline or diesel motors. Diesel cars account for 55% .... hybrids, electrics, gas and ethanol-fueled vehicles - combine to make up the remaining 3%."[2]. in 2010, the European Union stock of light-vehicles reached the 239 millions. In the same year, the EU heavy vehicle stock was of only 35 millions [2]. Modern CRDIDs have High Pressure fuel Pumps (HPP) which supplies fuel constantly at high pressure with a common rail to each injector. Each injector has a solenoid/piezoelectric actuator operated by an Electronic Control Unit (ECU), resulting in an extremely accurate control of injector opening times that can be varied on many control conditions, such as engine speed and loading, altitude, temperature and humidity. This provides engine extremely accurate engine control. It is perfectly possible to control the engine speed with the accuracy of 1/10 rpm with excellent performance and fuel economy. This fact opens new perspectives in the possibility of powering these extremely heavy duty vehicles with more than one engine. The multiengine option was already adopted with success in "sport cars" like the Mercedes A190 Twin (1999). The maintenance level of these modern CRDIDs is extremely reduced with limited scheduled maintenance and build-in, predictive On Board Diagnosis (OBD) systems. OBD controls the emissions and the efficiency of the engine, providing a tool to avoid unnecessary maintenance and improving the engine availability and reliability.

Automotive CRDID durability and volumes

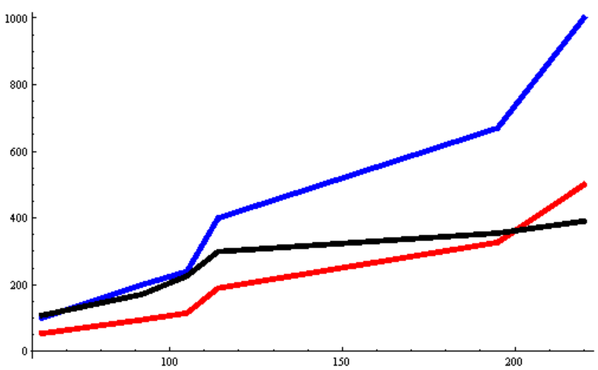

Figure-1. Mass [kg] (x axis) → Power [HP] (red line), Size [cc] (black line), Torque [Nm] (blue line) (y axis).

Figure-1 shows that the volume occupied by an automotive is not proportional to torque, power and mass. The larger the torque the more convenient is the Torque to Occupied-Volume (Size) and the Power to Size. The maintenance schedule is influenced by the “weariness” parameter. Historically TBO (Time between Overhauls) has been expressed in “hours”. The term “hours” has always been different from case to case. In some cases it meant the total number of revolutions of the crankshaft measured by a device installed on the crankshaft. Another parameter is the lubricant consumption rate. When this rate overcomes the limit given by the manufacturer, the engine should be overhauled. In F1 racing cars the engine durability is also affected by the number of times a certain engine speed has been overcome. This is not the case of CRDID where overspeed is controlled by the FADEC (Full Authority Digital Electronic Control). The availability of the FADEC with OBD (On Board Diagnosis) makes it possible to improve the TBO criteria with a more sophisticated algorithm. The result is an on-line indication of the residual engine life for proper TBO scheduling.

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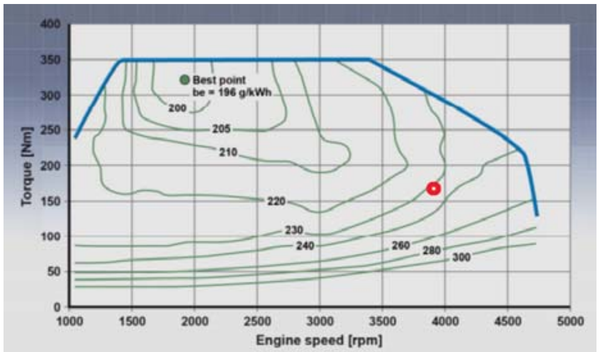

Figure-2. SFC [gr/kWh] of OM 651 DE22 [6]; 196 g/kW=42.6% efficiency.

Just for explanatory reasons, since fuel consumption is not significantly affected by the engine size, kW CRDID was chosen. Just as an example, from Figures-2 it is possible to obtain Table-1.

Table-1. Typical fuel consumption at average power settings.

Fuel consumption	
Max (100%-100 kW)	20.91 lxh
Max continuous (92%-92 kW)	18.47 lxh
Off road (73% 73 kW)	14.05 lxh
Road (60% 60 kW)	11.55 lxh

The values calculated in Table-1 are just for explanatory reasons; the true data of the engine should be supplied by the Manufacturer.

Table-2. Typical 1 hour long "heavy duty cycle".

Power setting	**Time** (min)	**Duration** (%)	**Fuel burned** (l)	**Fuel burned** (kg)
100	0.6	1	0.2	0.18
92	6	10	1.85	1.55
73	41.4	69	10	8.37
60	12	20	2.3	1.92
Total	60	100	14.35	12.02

Table-2 summarizes a typical 1 hour long "heavy duty cycle". From Table-1, it is possible to calculate an approximated fuel consumption of 14.35 l (12.02 kg). In a very simplified durability model, an engine has a lifetime that can be measured in weight of fuel burned. You can run that mass of fuel through the engine in a short time period if you are extracting large amounts of power, or you can take much more time to burn the same amount if you only extract small amounts of power. The Load Factor (LF) represents the relationship between fuel burned and the number of hours you are taking to burn it. At max continuous power, the fuel burned would have been 20.91 l. Hence the LF can be calculated (5).

$$LF = \frac{Fuel_{Burnt}}{Fuel_{\max ratedpower}} = \frac{14.35}{20.91} = 0.68 \quad (5)$$

The typical small car load factor is 0.44. It is then possible to calculate the load factor ratio LF_{ratio} (6).

$$LF_{ratio} = \frac{0.68}{0.44} = 1.54 \quad (6)$$

A small car used for typical automotive light duty will go for 250, 000 km without rebuild when properly maintained. At the average speed (city car) of 28 km/h, this means a TBO=8, 930 h. Starting from these considerations the heavy duty engine will last 3, 800 h (7).

$$TBO_{heavy\_vehicle} = \frac{TBO_{automotive}}{LF_{ratio}^2} = \frac{8930}{(1.54)^2} \approx 3800\,[h] \quad (7)$$

CVT concept and numerical example

The CVT makes it possible to work most of the time in the best efficiency area. Performances and fuel consumption are improved accordingly.

In the system proposed in this paper the reduction ratio is achieved by powering the shaft (1) and connecting the carrier (P) to the rear wheels through reduction gears. As the speed of the motor shaft increases the transmission ratio is reduced up to maximum value.

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Table-3. Data used for the numerical example.

Symbol	Description	Value	Unit
D	Sprocket diameter	0.67	m
V_{max}	Maximum speed	68.5	km/h
V_{min}	Minimum speed	10	km/h
rpm_{max}, $n_{1,max}$	Maximum power engine speed	4,000	rpm
rpm_{torque}=rpm_{min}	Maximum torque engine speed	1,750	rpm
rpm_{min}	Min engine speed	1,000	rpm

The data for the numerical example are summarized in Table-1. It is then possible to calculate the sprockets average rotational speed at V_{min} (8).

$$n_{\min} = \frac{60 \times V_{\min}}{\pi D} = 78[rpm] \tag{8}$$

This speed will be obtained at 3,000 rpm, so the maximum transmission ratio is i_{max}=38.33. The maximum speed will be obtained with the maximum engine speed (4,000 rpm), so

i_{min}=7.46 and n_{max}=536.

If the final reductions have a reduction ratio i_{final}=2, the CVT should achieve i_{maxCVT}=i_{max}=19.1 and i_{minCVT}= i_{min}=3.76. From equation (3) it is possible to write the system of equations (9).

$$\left\{ \begin{aligned} \tau &= \frac{\omega_{1\max} - \omega_{p\max}}{\omega_{3\min} - \omega_{p\max}} \\ \tau &= \frac{\omega_{1\min} - \omega_{p\min}}{\omega_{3\max} - \omega_{p\min}} \end{aligned} \right\} \tag{9}$$

In order to solve (9) it is necessary to define τ. The first step is to calculate i_{12} and i_{23} (10) (11).

$$\left\{ \begin{aligned} i_{\min} &= \frac{z_1 + z_3}{z_1} \\ i_{12} &= \frac{z_2}{z_1} \\ i_{23} &= \frac{z_3}{z_2} \end{aligned} \right\} \Rightarrow i_{\min} = 1 + i_{12} i_{23} \tag{10}$$

$$\left\{ \begin{aligned} m_{n1} = m_{n2} &= m_{n3} \\ r_1 + 2 \times r_2 &= r_3 \end{aligned} \right\} \Rightarrow z_1 + 2 \times z_2 = z_3 \Rightarrow i_{12} = \frac{1}{i_{23} - 2} \tag{11}$$

The final values are then z_1=29, z_2=25 and z_3=79. It is then possible to calculate ω_{3min}=128 [rad/s] and w_{3max}=44 [rad/s]. The ratio between the two speeds is compatible with the one of a CRDID that is about 3. So the solution is feasible.

The new steering mechanism

The new steering mechanism is depicted in Figure-3. In this solution we have 2 internal combustion engines: engines 1 power directly the sprockets, while engine 2 generates the electric power for the two motors M1 and M2. By varying the speeds of M1 and M2 it is possible to vary continuously the speed ratio of each sprocket. It is also possible to reverse the speed always by varying the relative speed of engine 1 and motors 1 and 2.

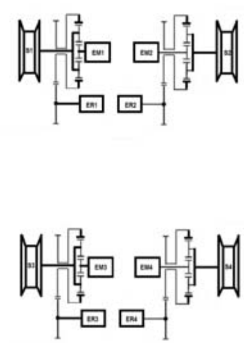

Figure-3. Possible solution for the transmission.

In this case the steering system is obtained by different speed ratio of the left (S1) (S3) and right (S2) (S4) sprockets. These speed ratios are obtained with different rotation speeds of the CRDID (ER1) (ER2) and (ER3) (ER4). The four sprockets are powered by the main CRDIDs EM1, EM2, EM3 and EM4.

This track steering mechanism is simple, continuous and efficient. Driving in a straight can be achieved only with and electronic stability software. Neutral steering can be achieved by adding a reverse gear on each sprocket.

CONCLUSIONS

The implementation of an electrically controlled dual drive inherently stable heavy duty tracked vehicle is introduced in this paper. This vehicle has to use a computerized control system to achieve the directional stability. This solution makes it possible to obtain a CVT by using single stage planetary gearings for each sprocket.

An additional internal combustion engine is added to the annular gear. By controlling this engine speed it is possible to vary the transmission ratio continuously and to obtain also continuous reverse speed. The torqueses of the two engines are added at low speeds. It is then possible to obtain extremely high torque at very low speed. This track steering mechanism is simple, continuous, efficient and additive; this means that, when transitioning to a turn, the mean track velocity remains the same. Driving in a straight line can be obtained only with electronic stability software. Neutral steering can be achieved by adding a reverse gearing to each sprocket. The possibility to use 8 engines instead of a single one makes it possible to use automotive derived engines. Their durability (TBO) has been proved to be suitable in this paper. Reliability, costs, maintenance are enormously improved by this solution. Also room occupied inside the hull is smaller and better used. On Board Diagnostic is available on these engines. Efficiency is improved. When electric energy is necessary with the vehicle stopped a single engine can be used as an APU.

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