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Design parameters for continuously variable power-split transmissions using planetaries with 3 active shafts

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Abstract

Since 1996, when the first agricultural tractor with CVT transmission was shown, the presence of this type of transmissions has been increasing. All companies offer them in their products range. Nevertheless, there is little technical documentation that explains the basics of its operation. This report shows all types of CVT transmissions: non-power-split type and power-split ones, as well as the three types used in agricultural tractors, hydro-mechanical power-split transmissions (3 active shafts, input coupled planetary; 3 active shafts, output coupled planetary and 4 active shafts). The report also describes the design parameters of a type of CVT transmission, which use a power-split system with 3 active shafts as well as the fundamental relations among them.

Keywords: CVT; Transmission; Hydro-mechanical power-split transmission; Hydrostatic CVT; Tractor transmission

1. Introduction

Since the emergence of the power-shift transmissions in agricultural tractors, the requirement to combine the engine and transmission to increase productivity in the tractor's performance, has led to stepped transmissions with a greater number of gears. The introduction of computing in tractors allows the possibility of managing both factors automatically and simultaneously. However, with a high number of gear shifts it is necessary to place a high number of clutches or hydraulic brakes to govern the transmission. Under these circumstances, the appearance of CVT technology in agricultural tractors, paved the way to an integral management and to the development of driving strategies, which improve productivity and comfort.

CVT transmissions (with continuous variation) were installed in agricultural tractors beginning in 1996. Fendt's VARIO was surprising because of its originality; it was not related to its equivalent in an automobile. It split the power in two ways and joined it again later on. It was innovative but much easier to use than to understand. Then, Steyr-Case's S-MATIC arrived at a series production, which was also a power split, but very different. On the other hand, in Germany, Claas has a vehicle, Xerion, with a similar transmission: HM-I, which later led to HM-II [2]. Claas meanwhile replaced it with ZFECCOM CVT. Then, John Deere was incorporated into the CVT family with two transmissions AUTOPOWR which were the same on the outside, relative to management and driving strategies, but different on the inside. Later, Deutz introduced the Agrotron TTV and New Holland introduced the TM series with a continuous TVT transmission. Most recently, Massey Ferguson has developed Dyna-TV transmission and McCormick has developed VTX. Their structures are

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Nomenclature

C	ring gear (or clutches in Fig. 12)
C_a	clutch a
C_d	clutch d
CVT	continuously variable power-split transmission
CVU	continuously variable unit
divider planetary	CVT power-split transmission with the PGT in the input node
e	CVT unit input shaft
em	mechanical input shaft to the PGT
F	forward
f	shaft connected to the variable path (called floating shaft)
η	efficiency
HMT	hydro-mechanical transmission
i_1	internal transmission in CVT unit; transmission ratio between PGT and CVU
i_2	internal transmission in CVT unit; transmission ratio between PGT and coupling
i_m	internal transmission in CVT unit; transmission ratio between CVU and coupling
i_t	overall transmission ratio engine-wheels
I_t	transmission ratio in the CVT Unit
k_f	torque ratio of the floating shaft (M_f/M_{em} in divider planetary; M_f/M_{om} in summing planetary)
k_m	torque ratio of the mechanical path (M_{om}/M_{em} in divider planetary; M_{em}/M_{om} in summing planetary)
λ	teeth ratio in the PGT (Z_C/Z_P)
M_{em}	torque in mechanical input shaft to the PGT
M_f	torque in shaft connected to the variable branch, called floating shaft
Mixed transmission	transmissions with a shiftable combination of different modes of work
M_{om}	torque in mechanical output shaft to the PGT
MR	mechanical regenerative power flow
n	rotation speed
N	power
n_1	rotation rate in shaft 1 of the variator (connected to the coupling)
n_2	rotation rate in shaft 2 of the variator (connected to the floating shaft)
n_{C1}	rotation speed in ring gear number 1 (in a commercial CVT transmission)
n_e	rotation speed in CVT input shaft
N_e	input power in CVT unit
n_{em}	rotation speed in mechanical input shaft in PGT
n_f	rotation rate of the floating shaft (shaft connected to the variable path)
n_m	rotation speed in shaft between planetary gear train
N_m	power in mechanical shaft
n_o	rotation speed in CVT output shaft
n_{om}	rotation speed in output shaft in PGT
n_{out}	rotation speed in output shaft in Fig 12 (after even clutches box)
NR	non-regenerative power flow
N_v	Power in variable shaft
o	CVT unit output shaft
om	mechanical output shaft from the PGT
om	rotation speed of the mechanical output shaft(s) from the PGT
P	sun gear
PGT	planetary gear train
PS	planet carrier
R	reverse gears
R_f	transmission ratio of the floating shaft
R_t	transmission ratio in the mechanical path of the planetary system
R_{tb}	transmission ratio in the lockup point
R_v	transmission ratio in the CVU
Shaft to shaft	non-splitted CVT transmission
Summing planetary	CVT power-split transmission with the PGT in the output node
TTM	transmission teaching model (CVT power-split transmission with the PGT in the output node)
Variator	continuously variable unit
VR	variable regenerative power flow
VU	continuously variable unit
X_{mt}	power distribution in mechanical path
X_{vt}	power distribution in variable path
Z	number of teeth
Z_c	number of teeth of the ring gear
Z_p	number of teeth of the sun gear

presented in the German Yearbook Agricultural Engineering [15].

These kinds of transmissions have been well received by farmers because of their clear advantages, such as comfort, ease of handling, and response to the most diverse requirements. However, there is not a systematic theory of operation to study them, which is a disadvantage in presenting the transmission characteristics.

2. Types of CVT transmissions

The main feature of CVT transmissions is a stepless speed change. A continuous variable unit that allows infinite gear ratios, must be incorporated.

There are different types of CVT transmission systems which can be classified according to several criteria:

- Power flow.
- Type of variator.
- The nature of its components.

The first criterion of classification is power flow (Fig. 1). In the non-split type, there is only a single path for the power to flow through. These CVTs are addressed as "Shaft to Shaft" [7]. On the contrary, in the split type, the power is split in two paths and then rejoined. In addition, there are the mixed-flow CVTs, which have two power flow paths (brakes and clutches) which allow it to operate in different modes, such as split or non-split, or in several other patterns (Fig. 1).

Two types of variators exist, mechanical and hydraulic. Within the mechanic type, there are belt, chain and roller-based variators (toroidal transmission). These are used in the CVT transmission found in cars, motorcycles and tractor prototypes. As for hydraulic variators, there are another two types: Hydrostatic Transmission, and torque converters.

According to the third criterion of classification, the nature of the components included in the CVT transmission, there are several different categories. The components can be all-mechanical, all-hydraulic, or a combination of mechanical and hydraulic elements (HM). Within the all-mechanical type, both split and non-split exist. The split type, hydrostatic and hydrodynamic transmissions, however, is not present in all-hydraulic transmissions. Mixed mechanical-hydraulic transmissions can be split or in series configurations.

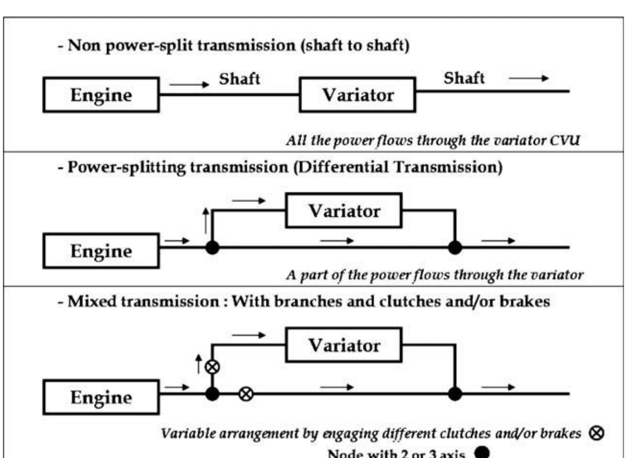


Fig. 1. Types of CVT transmissions with respect to the power flow. CVU: continuously variable unit (variator).

3. Power-split CVT transmissions

Power-split transmissions divide the power into two paths, one with fixed transmission ratio (the mechanical path) and another which includes the variator (the variable path). Both rejoin in the output shaft. The CVT effect is provided by the path with the variator.

There are three different types of commercial transmissions (Fig. 2):

- *3 active shafts:*
  - Input coupled planetary or summing planetary.
  - Output coupled planetary or divider planetary.
- *4 active shafts: bridge type planetary.*

The definition of "active shaft" refers to those connected to the planetary gear train (PGT), the true mechanical heart of the CVT system. When there are 3 active shafts, the PGT has one mechanical input shaft (em), one or several output shafts (om) and a single floating shaft connected to the variator (f). On the other hand, in the 4 active shafts type, also known as "bridge type" [18], the two variator shafts are connected with the PGT.

In the transmissions with 3 active planetary shafts there are two nodes, one at the input of the CVT unit, and the other one at the output. Two basic configurations are known [7]; the difference between them depends on the position of the PGT. In the input coupled planetary (summing planetary), the PGT is the output node and the input node is the coupling. In the output coupled planetary (divider planetary), the input node is the PGT and the output node is the coupling.

For each layout there are 3 patterns of operation according to the flow of power through the CVT, see Fig. 3 [9]. If the power flowing through one of the paths is greater than the input, the power is said to be regenerative. In contrast, when the power flow through each of the two paths is lower than the input, the power is said to be non-regenerative. In the regenerative power scheme, since there are two paths, situations can arise:

- The power through the fixed path is greater than the input power (mechanical regenerative).
- The power through the variable path is greater than the input power (variable regenerative).

Kress [7] of John Deere's Technical Center, laid out the fundamentals which explain how this type of transmission operates, but there was no series production for tractors for many years. Recently, CVT transmissions and power split have started to be used in the automobile industry, for implementation in hybrid vehicle transmissions [19] as well as in agricultural tractors. Renius [13], Renius and Resch [14], Renius et al. [15] have explained and commented on existing tractor CVT transmissions. Hsieh and Yan [5], Sheu et al. [17], Lu [9], Shellenberger [18], Mangialardi and Mantriota [10,11], Mantriota [12] and Gómez [4] have

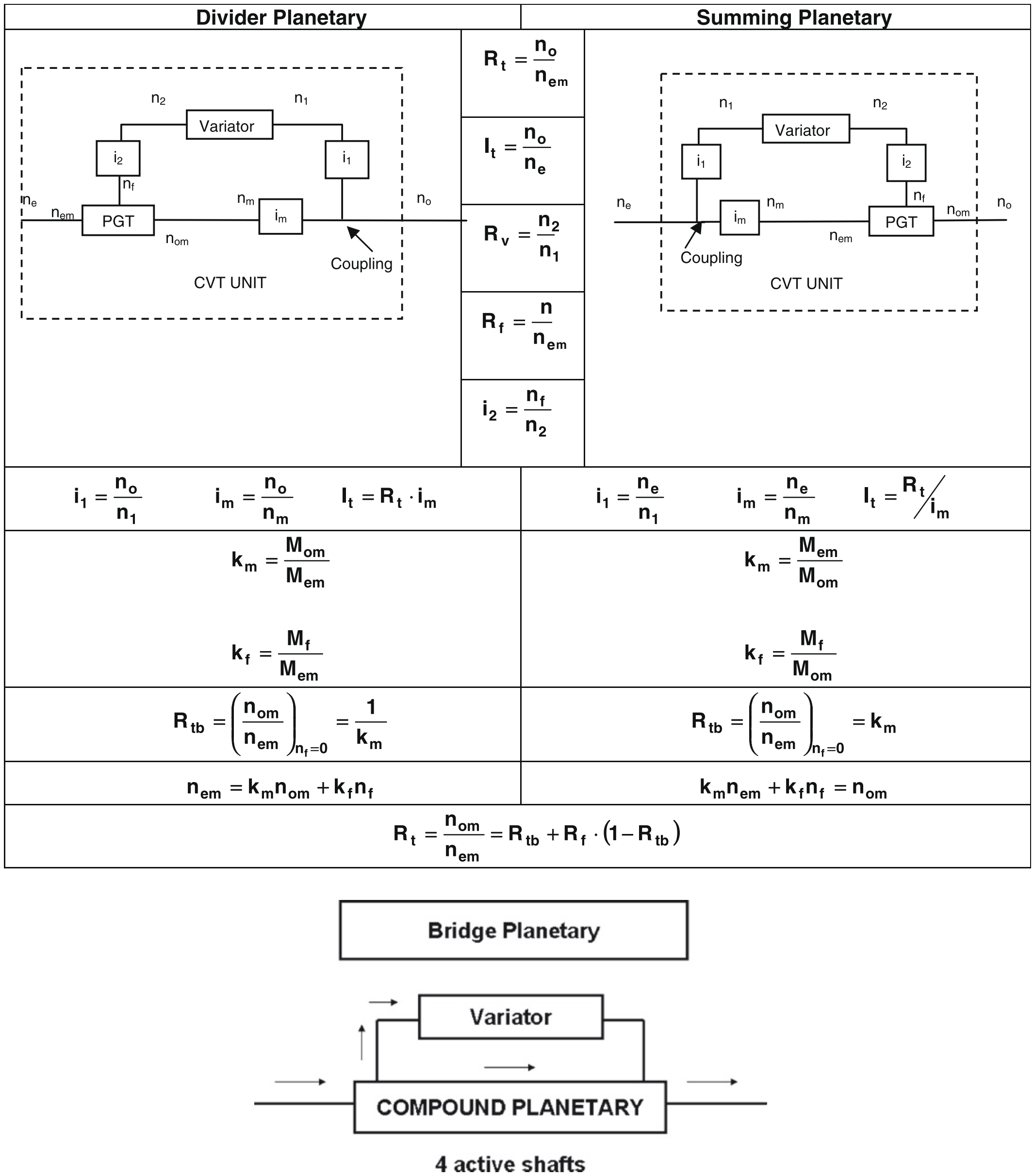


Fig. 2. Types of commercial hydro-mechanical power-splitting CVT transmissions. HMT: hydro-mechanical transmission. PGT: Planetary gear train, n_e: rotation in CVT input shaft, n_o: rotation in CVT output shaft, n_{em}: rotation in mechanical input shaft in PGT, n_{om}: rotation in output shaft in PGT, n_1: rotation rate in shaft 1 of the variator (connected to the coupling).

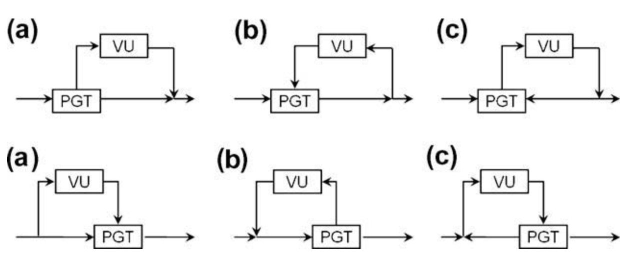


Fig. 3. Possible power flow in different operation modes. Up: divider planetary; down: summing planetary. (a) The power flow produces split function. (b and c) The power flow leads to power recirculation. PGT: planetary gear train; VU: variator. Lu [9].

studied power flow and performance under different operating conditions. Studies made in transmissions provided with belt mechanical variators prove that those with summing planetaries render a better mechanical performance. In order to compare variators which are hydrostatic transmissions, they must be equal and only the position of the PGT can be changed. This is not true in commercial transmissions, because those with divider planetary transmissions have a hydrostatic element which is much more sophisticated (variable displacements unit, type bent-axis hydraulics units and very large displacements and offset angles). On the other hand, although the PGT is more sophisticated and they have several maneuvering elements, in summing planetary transmissions there is a simpler variator, with conventional hydraulic units. As a result, comparing performances between the two types is not easy.

4. Elements of a power-split CVT with 3 active planetary shafts

The basic elements of a CVT transmission are (Fig. 2):

- CVT unit input shaft (e). Rotation rate: n_e
- CVT unit output shaft (o). Rotation rate: n_o
- *Coupling or junction: 2-shaft node:*
  - One connected to the variable path.
  - One connected to the mechanical path.
- *Planetary gear train (PGT)*: Node with, at least, 3 active shafts:
  - Mechanical input shaft to the PGT (em). Rotation rate: n_{em}.
  - Mechanical output shaft(s) from the PGT (om). Rotation rate: n_{om}.
  - Shaft connected to the variable path, called floating shaft (f). Rotation rate: n_f.
- *Variator (CVU: continuously variable unit)*: with 2 shafts:
  - Shaft 2: Connected to the floating shaft (rotation rate n_2).
  - Shaft 1: Connected to the coupling (rotation rate n_1).
- *Internal mechanical transmissions*:
  - Connection between PGT and variator (i_2).
  - Connection between variator and coupling (i_1).
  - In the mechanical path (i_m).

5. Parameters for power-split CVTs with 3-shaft planetaries

In order to understand the operation of CVT transmissions, it is useful to define a series of parameters by which they are characterized. The famous paper of Kress [7] contains (besides other systems) the complete model of power-split systems with 3-shaft standard planetaries. The authors developed their parameter study on this basis, however they did so with structures which contain an additional ratio of gear wheel(s) between the planetary and the second junction point. This enlargement of the basic structures by i_m can better accommodate commercial power-split systems with internal transmissions between planetary and junction point. Definitions of internal transmission ratios are given by Fig. 2 based on the methodology of Kress [7]:

- Transmission ratio in the mechanical path of the PGT: R_t.
- Transmission ratio in the floating element of the PGT: R_f.
- Transmission ratio in the CVT unit: I_t.

The ratios between the speeds of the PGT shafts are expressed by the basic speed equations as shown in Fig. 2, by means of parameters k_m and k_f [8], which represent the share of torque for the two paths assuming no power losses. The lockup is the point at which a power-split CVT transmission becomes purely mechanical, the floating shaft being stationary and the transmission ratio as the lockup ratio, R_{tb}. When calculating a CVT transmission, the first step is to analyze the PGT in order to achieve the lockup transmission ratio and the values for parameters k_m and k_f.

Once the ratios for the lockup point transmission and the floating element are known, we can calculate the transmission ratio for the PGT using the following formula, which is valid for all types of transmissions (divider and summing planetaries):

$$R_t = R_{tb} + R_f(1 - R_{tb})$$

6. Power distribution in a power-split CVT transmission

Once the lockup transmission ratio is known, we can determine the distribution of power and its status at any given time (Tables 1 and 2).

The diagram showing the power distribution curves allows us to determine the status of the transmission: Non-regenerative (NR); mechanical regenerative (MR) and hydraulic or variable regenerative (VR). In both types of transmission when the transmission ratio is negative, the power is regenerative through the hydraulic path (VR). However, the behavior is different in the case of positive transmission ratio. In divider planetaries, power is non-regenerative up to the lockup transmission ratio, and from that point on it is mechanical regenerative. In summing planetaries, power is mechanical regenerative up to the lockup transmission ratio, and from that point on it is non-regenerative.

The operative status of the transmission can also be shown by means of the diagram in Fig. 4, based on the studies made by Fredriksen [2]. In this model, there are as many vertical axes as shafts contained in the PGT, that is, input shaft, floating shaft and as many output shafts as it may have. Fig. 4 shows only one output shaft. The speed for each shaft is shown, taking the speed relative to the input shaft. Thus, on the floating shaft we have indicated the transmission ratio R_f and on the output shafts, we have indicated the transmission ratio for the PGT when the shaft is active. If we assume that the speed of the input shaft remains constant, at that shaft the single point is the unit.

In Fig. 4, the distance between the different vertical lines is an arbitrary distance, considering the unitary distance between the input and the floating shafts. Vertical lines representing R_t and R_f are placed at a specific distance from the floating shaft. This distance is determined by the lockup transmission ratio corresponding to the PGT when this shaft is active.

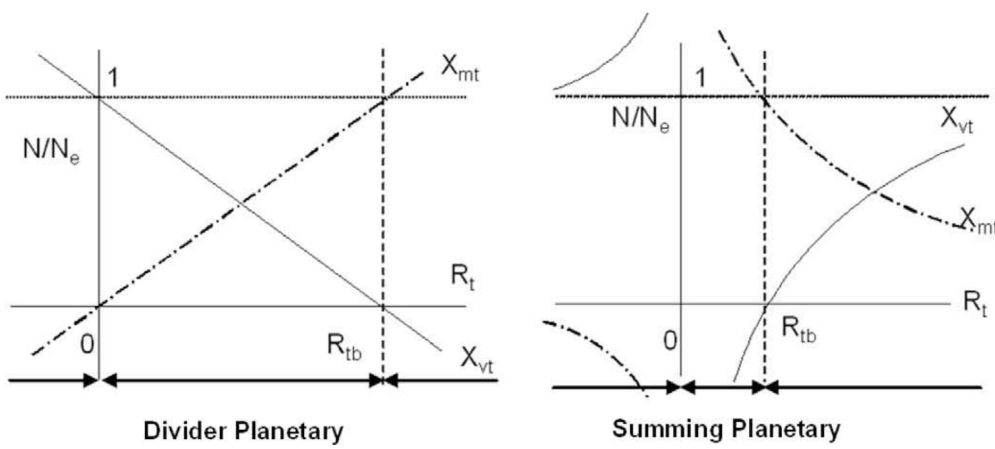
Once the organization of the PGT and the variation of the transmission ratio on the floating shaft are known, the point of the input shaft is joined to the ends of the line defined by the transmission ratio on the floating shaft. The lines thus obtained correspond to the maximum and minimum shaft speeds. The intersection of the two lines with

Table 1
Power distribution (X) in CVT transmissions.

Power distribution	
Output coupled planetary (divider)	Input coupled planetary (summing)
$X_{mt} = (\frac{N_m}{N_e})_{\eta=1} = \frac{R_t}{R_{tb}}$ $X_{vt} = (\frac{N_v}{N_e})_{\eta=1} = 1 - \frac{R_t}{R_{tb}}$	$X_{mt} = (\frac{N_m}{N_e})_{\eta=1} = \frac{R_{tb}}{R_t}$ $X_{vt} = (\frac{N_v}{N_e})_{\eta=1} = 1 - \frac{R_{tb}}{R_t}$

N_e: input power in CVT unit. N_m: power in mechanical shaft. N_v: power in variable shaft.
X_{mt}: power distribution in mechanical path. X_{vt}: power distribution in variable path. η: efficiency.
R_t: transmission ratio in the mechanical path of the planetary system.
R_{tb}: transmission ratio in the lockup point.

Table 2
Power distribution based on transmission ratio R_t.



$R_t < 0$	VR	$X_{vt} > 1$	VR	$R_t < 0$
$R_t > R_{tb}$	MR	$X_{vt} < 0$	MR	$0 < R_t < R_{tb}$
$0 < R_t < R_{tb}$	NR	$0 < X_{vt} < 1$	NR	$R_t > R_{tb}$

Power distribution in CVT transmissions with 3 active 4 planetary shafts. M_{em}: torque in mechanical input shaft to the PGT. M_{om}: torque in mechanical output shaft to the PGT. M_f: torque in shaft connected to the variable branch, called floating shaft.
VR: variable regenerative power flow.
MR: mechanical regenerative power flow.
NR: non-regenerative power flow.
N: power.
N_e: input power in CVT unit.
PGT: Planetary gear train.

the output shafts provides the transmission ratios. The lockup line is also represented; it is obtained by joining the input shaft point to the corresponding stationary floating shaft. We can easily identify the operation status of the transmission on this diagram. Assuming that Fig. 4 corresponds to summing planetary transmission; the different fields of operation have been represented. For the range of variation of the transmission ratio drawn on the floating shaft, the transmission would operate one half of the range in the mechanical regenerative zone and the other half in the non-regenerative zone.

As an example, Fig. 5 shows the CVT unit of the ZF-Eccom 1.5 box, which is included with the tractor Deutz Agrotron TTV. It is evident that it is summing planetary power-split transmission, with a compound PGT made up of three interconnected single PGT's. The variator is the hydrostatic transmission, formed by one variable displacement unit (unit 1) and another fixed displacement unit (unit 2). The PGT has 5 shafts, one for the mechanical path input (the ring-gear of the first PGT), the floating shaft (the sun of the first PGT) and 3 possible output shafts, of which at any given variator ratio, only one is active, thus making the box a "3 active shaft"-type. In series with this CVT unit is a range box equipped with 4 clutches which, in accordance to the desired speed, selects one of the possible output shafts (of the CVT unit's three output shafts, one is used in the two even-numbered ranges). The result is 4 ranges in series, in which the maximum speed for each one matches the minimum speed of the next. Fig. 5 shows the CVT parameters corresponding to each of the 3 possi-

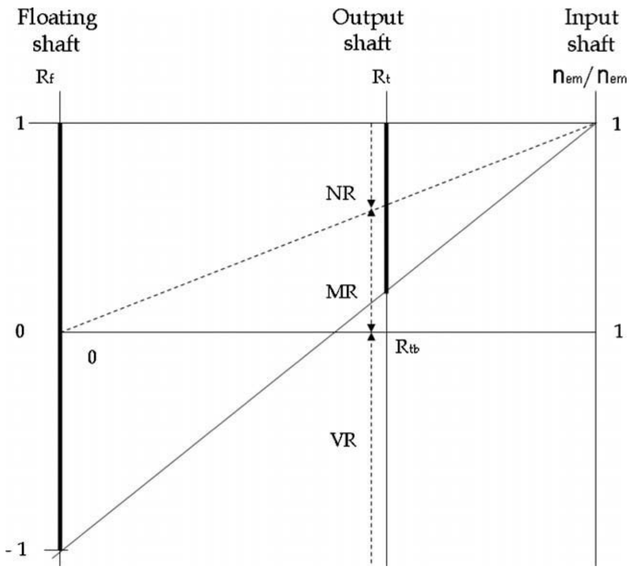


Fig. 4. Transmission ratio diagram in CVT unit. NR: non-regenerative power flow. MR: mechanical regenerative power flow. VR: variable regenerative power flow.

ble configurations of the PGT and Fig. 6 shows the speeds for the three output shafts.

7. Design of 3 active shafts power-split CVT transmissions

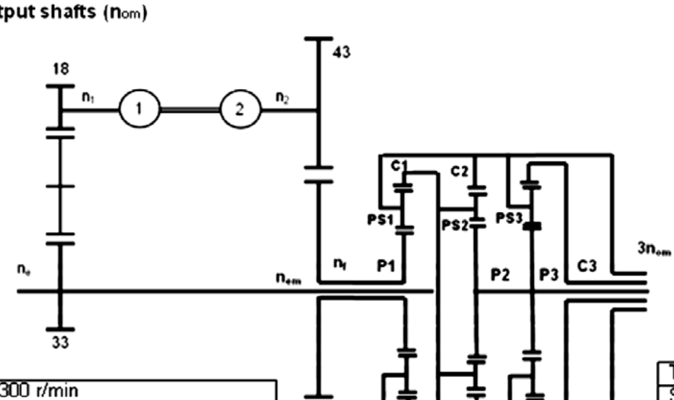
In order to achieve the desired objective (a certain range of transmission ratios), once the type of transmission has been established, there are two remaining design parameters: The ratio for lockup transmission R_{tb} and for the floating shaft R_f, which depends on that of the variator, R_v (n_2/n_1) and on the CVT unit's internal transmissions [3] (Table 3).

The lockup transmission ratio depends on the CVT parameters, and these depend on two characteristics:

- The configuration of the PGT, which determines the input (im), output (om) and floating shafts.
- The dimensions of the PGT, which determine λ which is the ratio of ring gear teeth and sun gear teeth.

TRANSMISSION ZF Eccom 1.5 in Agroton TTV

Type CVT : SUMMING PLANETARY PGT: Compound; Reverse speeds: Independient of CVT Unit
PGT: 3 output shafts (n_{om})



Terminology	
Sun	P
Ring	C
Carrier	PS
Number of teeth	Z

n_e = 2300 r/min		
$Z_{C1} = 99$	$Z_{P1} = 33$	$Z_{S1} = 32$
$Z_{C2} = 96$	$Z_{P2} = 48$	$Z_{S2} = 23$
$Z_{C3} = 99$	$Z_{P3} = 33$	$Z_{S3} = 32$
$\lambda_1 = Z_{C1}/Z_{P1} = 3$	$\lambda_2 = Z_{C2}/Z_{P2} = 2$	$\lambda_3 = Z_{C3}/Z_{P3} = 3$
$i_1 = 18/33$	$i_2 = 43/67$	$i_m = 1$

PGT	Mechanical entry	em : C_1
	Floating shaft	f : P_1
	Output shaft (om)	C_3 (1F/1R)
		P_3 (EVENS F/R)
		PS_3 (3F/3R)
Range of Variation of n_f	n_f = -2300 r/min	
	$n_f = 0$	
	n_f = 2300 r/min	

$n_{em} \times k_m + n_f \times k_f = n_{om}$	
1F/1R	$n_{ps2}\left(\dfrac{\lambda_1(1+\lambda_3)-(1+\lambda_1)(1+\lambda_2)+\lambda_1*\lambda_2}{(1+\lambda_1)*\lambda_3}\right)+n_{p1}\dfrac{(1+\lambda_3)+\lambda_2}{(1+\lambda_1)*\lambda_3}=n_{c3}$
EVENS F/R	$n_{ps2}\dfrac{\lambda_2+(1+\lambda_1)}{1+\lambda_1}-n_{p1}\dfrac{\lambda_2}{1+\lambda_1}=n_{p2}$
3F/3R	$n_{ps2}\dfrac{\lambda_1}{1+\lambda_1}+n_{p1}\dfrac{1}{1+\lambda_1}=n_{ps1}$

1F/1R	$k_m=\dfrac{\lambda_1(1+\lambda_3)-(1+\lambda_1)(1+\lambda_2)+\lambda_1*\lambda_2}{(1+\lambda_1)*\lambda_3}=0.5$	$k_f=\dfrac{(1+\lambda_3)+\lambda_2}{(1+\lambda_1)*\lambda_3}=0.5$	$R_{tb}=0.5$
EVENS F/R (2/4)	$k_m=\dfrac{\lambda_2+(1+\lambda_1)}{1+\lambda_1}=1.5$	$k_f=-\dfrac{\lambda_2}{1+\lambda_1}=-0.5$	$R_{tb}=1.5$
3F/3R	$k_m=\dfrac{\lambda_1}{1+\lambda_1}=0.75$	$k_f=\dfrac{1}{1+\lambda_1}=0.25$	$R_{tb}=0.75$

Fig. 5. k_m and k_f parameters in CVT ZF-Eccom 1.5 transmission (Deutz Agrotron TTV).

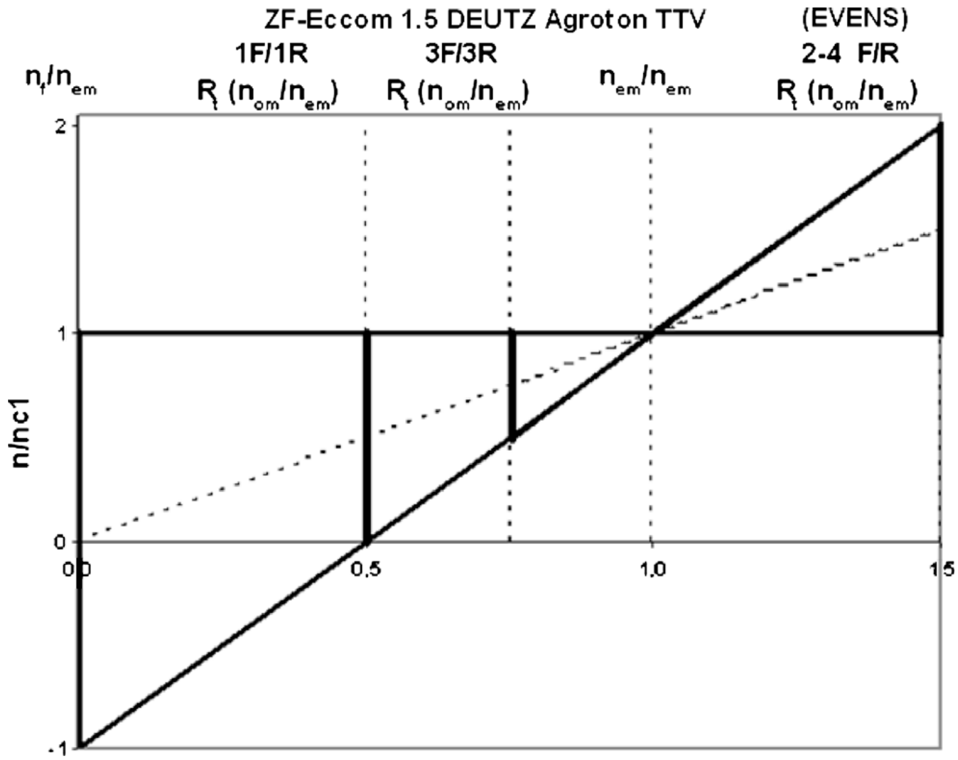
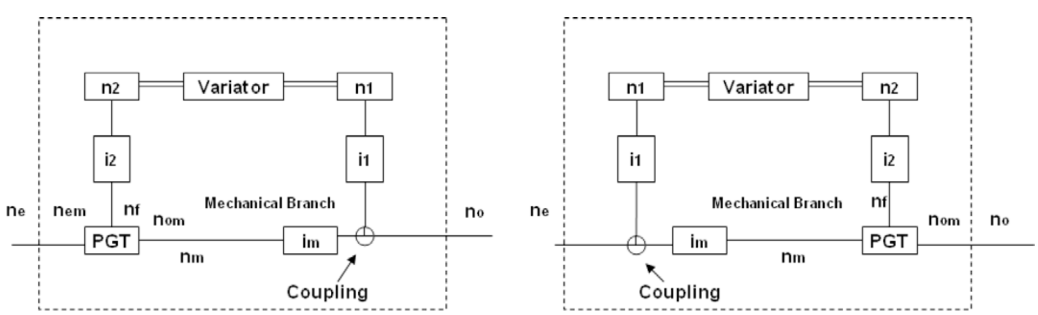


Fig. 6. Speed diagram in the Planetary Unit in ZF-Eccom 1.5 transmission. n: Rotaion speed; n_c: rotation speed in CVT input shaft.

Table 3
Transmission ratio of the floating shaft R_f in the two types of three shaft power-split CVT transmission.

Transmission ratio of the floating shaft		
Divider planetary		Summing planetary
$R_f = \frac{i_2 \cdot i_m \cdot R_{tb} \cdot R_v}{i_1 - i_2 \cdot i_m (1 - R_{tb}) \cdot R_v}$	$R_v = \frac{n_2}{n_1}$	$R_f = \frac{i_2 \cdot i_m}{i_1} \cdot R_v$



Different shafts placed in the CVT unit in divider planetary transmissions (left) and summing planetary transmissions (right). n_1: rotation rate in shaft 1 of the variator (connected to the coupling). n_2: rotation rate in shaft 2 of the variator (connected to the floating shaft). n_m: rotation rate in shaft between planetary gear train and coupling. PGT: Planetary gear train.

Summing up, the design parameters, once the type of transmission has been established, are:

- Organization of the CVT unit: internal ratios i_1, i_2, i_m
- PGT of the CVT unit: type of PGT (single or compound) and its configuration (em, om, f, λ, k_m, k_f, R_{tb})
- The variator (R_v and, consequently, R_f)

Fig. 7 shows the flow diagram for the design of power-split CVT transmissions with 3 active shafts.

8. Design application of a CVT transmission model for training purposes

With the aim of preparing teaching material which represent and demonstrate concepts of power-split CVT trans-

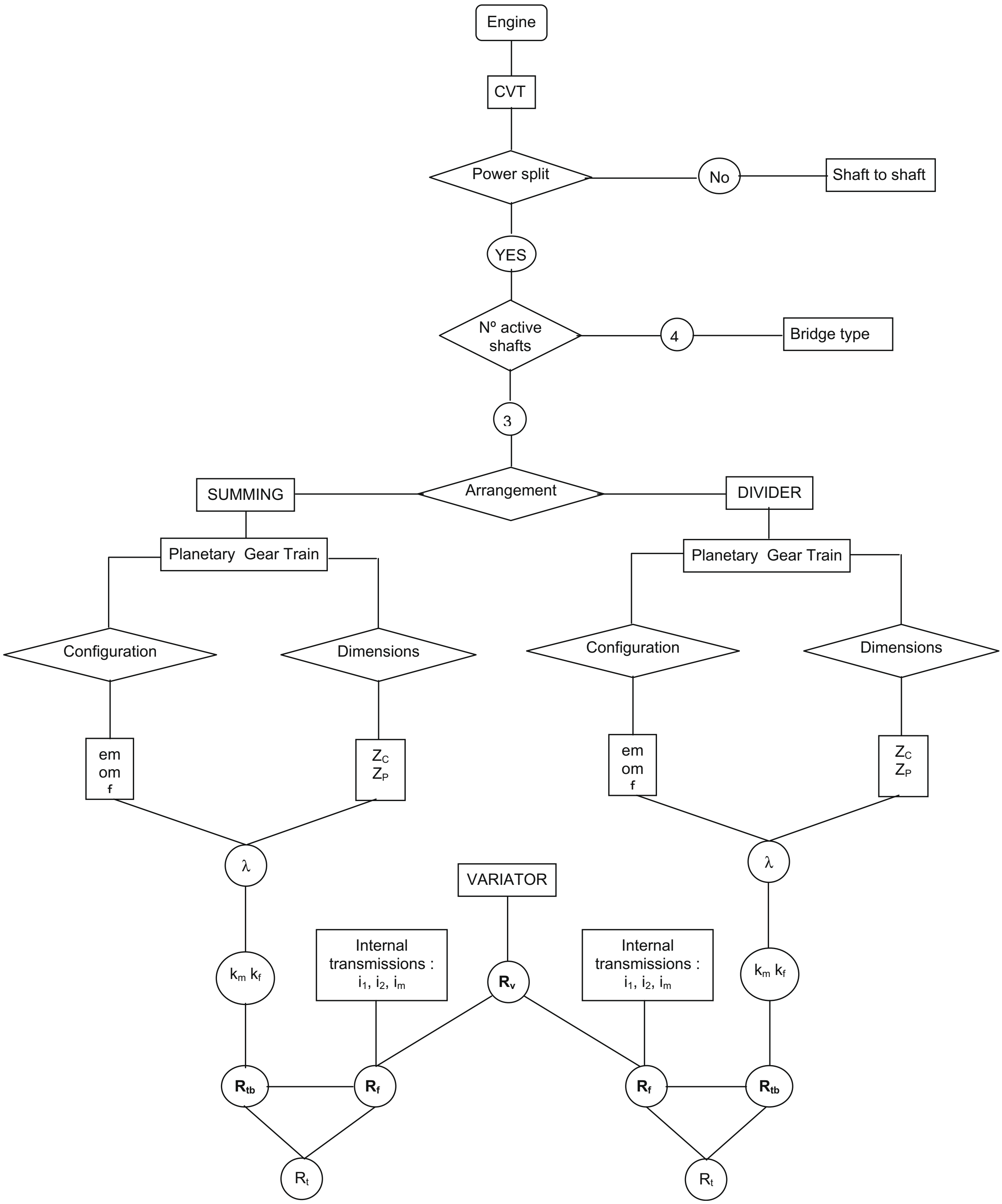


Fig. 7. Design diagram of three active shafts power-split CVT Transmissions.

missions, a model has been designed by the “Tractors and Tillage” Research Groups at the Polytechnic University of Madrid (Figs. 8–10). This model works with a 3 active shaft PGT and has the following features:

- Choice between the two possible arrangements (input and output coupled).
- Mechanical belt variator.
- Single PGT ($Z_c = 58$; $Z_p = 20$; $\lambda = 2.9$) (Fendt Vario Transmission series 400).
- Mechanical inverter.

In this case, the type of transmission is already set (split power), as well as the dimensions and type (single) of the

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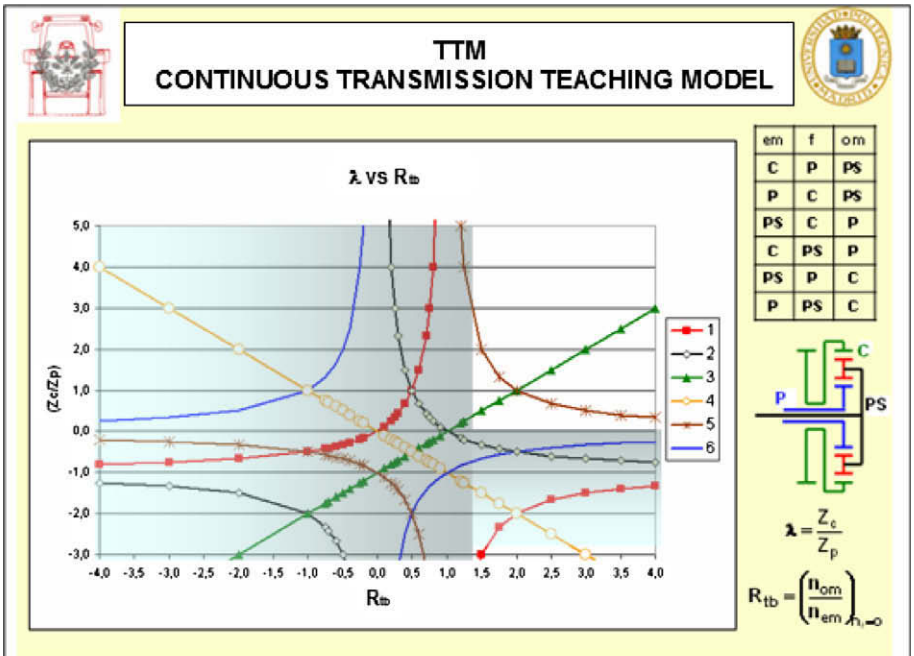


TTM

CONTINUOUS TRANSMISSION TEACHING MODEL

Planetary gear train configurations

Conf.	em	f	om	Divider	Summing	$R_{tb}=f(\lambda)$	$\lambda = f(R_{tb})$
1	C	P	PS	$k_m = \frac{1+\lambda}{\lambda}$	$k_m = \frac{\lambda}{1+\lambda}$	$R_{tb} = \frac{\lambda}{1+\lambda}$	$\lambda = \frac{Rtb}{1-Rtb}$
2	P	C	PS	$k_m = 1+\lambda$	$k_m = \frac{1}{1+\lambda}$	$R_{tb} = \frac{1}{1+\lambda}$	$\lambda = \frac{1-Rtb}{Rtb}$
3	PS	C	P	$k_m = \frac{1}{1+\lambda}$	$k_m = 1+\lambda$	$R_{tb} = 1+\lambda$	$\lambda = Rtb-1$
4	C	PS	P	$k_m = -\frac{1}{\lambda}$	$k_m = -\lambda$	$R_{tb} = -\lambda$	$\lambda = -Rtb$
5	PS	P	C	$k_m = \frac{\lambda}{1+\lambda}$	$k_m = \frac{1+\lambda}{\lambda}$	$R_{tb} = \frac{1+\lambda}{\lambda}$	$\lambda = \frac{1}{Rtb-1}$
6	P	PS	C	$k_m = -\lambda$	$k_m = -\frac{1}{\lambda}$	$R_{tb} = -\frac{1}{\lambda}$	$\lambda = -\frac{1}{Rtb}$

Fig. 8. Relationship between λ and R_{tb} in the six possible connection arrangements in a simple planetary. $R_{tb} > 0$ and $\lambda > 1.5$.

PGT. To choose the type of configuration, Fig. 8 shows the relationship between the dimensions of the PGT (represented by λ) and the lockup transmission ratio in the six possible configurations of the single PGT.

Divider or summing configurations are achieved by a sliding gears wheel selector as shown in Fig. 9, the equivalent configurations (Table 4) between both arrangements must be considered. Configuration III is chosen, in which the lockup transmission ratio is positive. It corresponds to an arrangement used in commercial transmissions, such as Vario, present in Fendt tractors, and Dyna-VT, in Massey Ferguson, which has an input coupled planetary configuration, and was presented by Sheu et al. [17], the latter featuring a mechanical variator.

For the dimensions of the PGT available (λ = 2.9), the lockup transmission ratios were 3.9 and 0.256 for divider summing planetary arrangements respectively. The variator is mechanical, belt-type, and with a variation range (R_v) between 0.7 and 2.5. All the internal transmissions in the model have a value of 1, including the mechanical inverter. With these values, the possible transmission ratio for the input coupled planetary goes from −0.92 to −3.3 when operating with variable regenerative power status and from 0.63 to 1.23 when operating in the non-regenera-

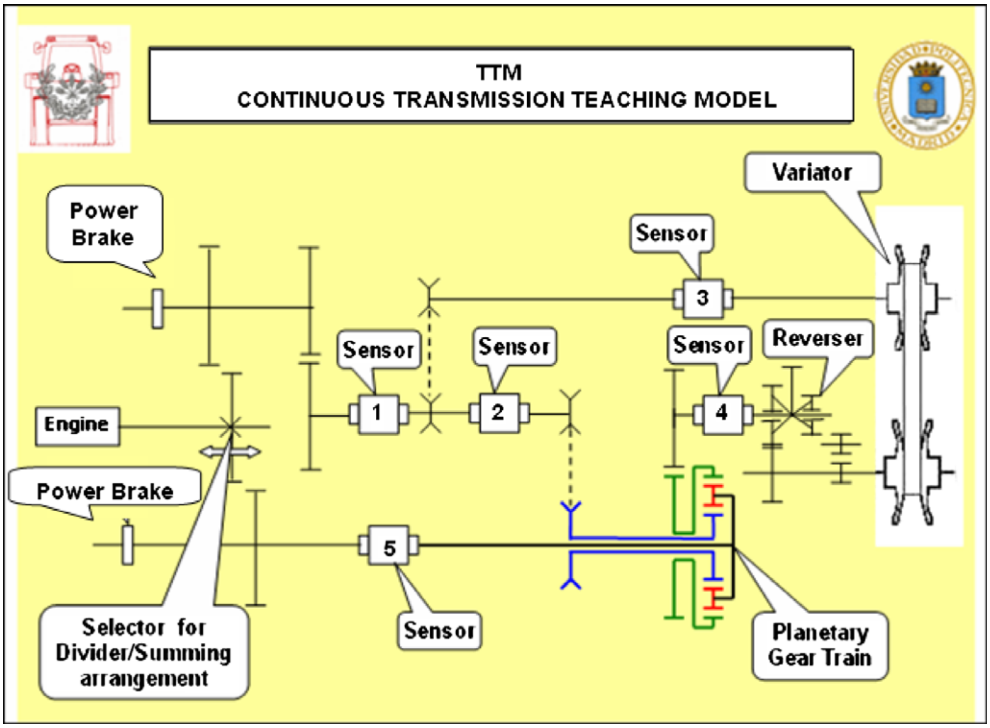


Fig. 9. First design of the transmission model [3]. 1–4 are places for positionning torsiometers.

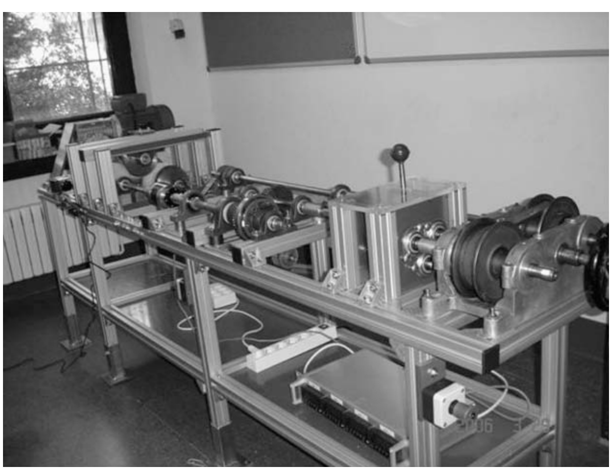


Fig. 10. CVT Transmission model designed at designed by the “Tractors and Tillage” Research Group at the Polytechnic University of Madrid.

tive zone. In the case of the output coupled planetary arrangement, the values are −1.8 to −0.3 in variable regenerative and 0.8–1.6 in non-regenerative. Operation in the mechanical regenerative zone is not carried out in either of the two arrangements.

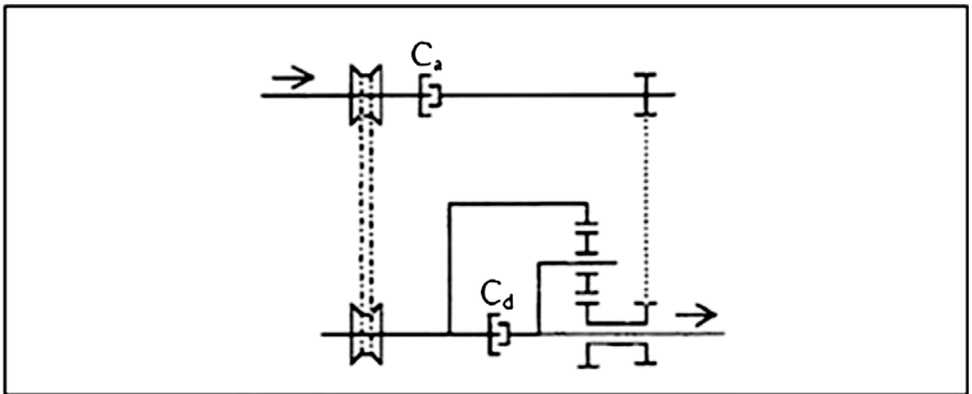
9. Mixed CVT transmissions

The authors propose to use the term “mixed CVT transmissions” for transmissions with a shiftable combination of different modes such as shaft-to-shaft (direct) variator mode and a power split mode. The mentioned “Responder” [20] worked with a hydrostatic variator in a first direct shaft-to-shaft mode for driving off and reversing and a second mode with input coupled power split for cruising. Kress [6] and Browning [1] analyzed mixed CVT transmissions with a mechanical variator.

Table 4
Equivalent configurations between divider and summing planetary arrangements [3].

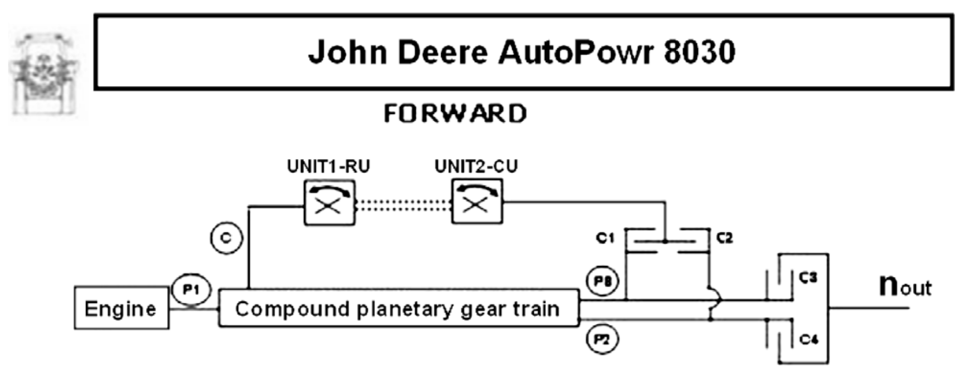
Divider planetary				Equivalent configuration	Summing planetary			
em	f	om	Basic configuration of the single PGT		Basic configuration of the single PGT	em	f	om
C	P	PS	1	I	5	PS	P	C
P	C	PS	2	II	3	PS	C	P
PS	C	P	3	III	2	P	C	PS
C	PS	P	4	IV	6	P	PS	C
PS	P	C	5	V	1	C	P	PS
P	PS	C	6	VI	4	C	PS	P

P: sun gear; C: ring gear; PS: carrier; em, om and f see Fig. 2.
I, II, III, IV, V and VI: different arrangements of em, f and om in a PGT.



Clutch enaged	Configuration
Ca	CVT power-splitted transmission Summing Planetary
Cd	CVT non splitted transmission Planetary Unit gear ratio = 1

Fig. 11. Mixed CVT transmission [17].



Mode	C1	C2	C3	C4	CVT Type
1	X		X		Divider
2		X	X		Bridge
3		X		X	Divider
4	X			X	Bridge

C1, C2, C3, C4 : Clutches

P1 : Sun gear of the 1° Planetary gear train
C : Ring gear
P2 : Sun gear of the 2° Planetary gear train

Fig. 12. Mixed CVT transmission in AutoPowr John Deere 8030 agricultural tractors simplified structure "forward".

This type of transmissions has also been discussed by Sheu et al. [17] for use in motorcycles, Fig. 11. It allows two possible modes. When the clutch Ca goes into action, it is a power split mechanical–mechanical CVT, with belt variator and summing PGT. When Cd (and not Ca) is engaged, the path to the sun gear of the PGT is interrupted and the transmission becomes a non-split CVT with a mechanical belt drive variator. It should be mentioned, that this power-split system does not always have the main objective of increasing efficiency rather its objective is to expand the band width of speeds versus zero or even crossing zero to reverse [6,1,16].

The transmission provided in the John Deere 30 series tractors can also be called a mixed transmission (Fig. 12). It has clutches in its paths and it operates in a sequential manner as an input coupled-bridge type planetary (the sequence being repeated twice in the forward speed range).

10. Conclusions

This research has been written with the aim of laying out a set of concepts which would aid in classifying and understanding CVT transmissions, as well as to present a general scheme for their depiction in terms of representative parameters, k_m and $k_{f.}$. These parameters represent the distribution of torques on the mechanical and variable paths and the lockup transmission ratio, which can be calculated as a function of those parameters.

The general diagram for the design of the transmission is outlined. The design parameters are the characteristics of the PGT (dimensions and configuration) that determine the lockup transmission ratio, as well as the variator ratio, which serves to calculate the transmission ratio of the floating shaft (the one connecting the PGT to the variator).

The formulae that link the mentioned parameters together have been established and implemented in the design of a model for training purposes, which is being constructed in the laboratory of the "Tractors and Tillage" research group of the Polytechnic University of Madrid.

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