Analysis and simulation of power split
Continuously Variable Transmissions

Applying for a PhD degree in the topic entitled

Supervisor:

Dr. György Kerényi, associate professor

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1. Introduction

In technical practice, the purpose of transmissions is to connect the power machine and the machine tool, synchronize their mechanical parameters and transmitting energy. Said mechanical parameters such as form of motion, movement frequency, force and torque, are usually formed based on the requirements of the machine tool. In practice during most work processes the mechanical parameters – required by the machine tool or given by the power machine – change separately or together. The optimal power machine – machine tool connection requires changing the number of sprockets and changing these during the work process. Continuously Variable Transmissions (CVT) fulfils these requirements, so they are ideal for the power machine – machine tool connection.

A CVT unit can be integrated into a drive train in two ways. One of them is mounting directly into the power flow (Figure 1.a), the other is mounting into a branch created by power split (Figures 1.b and 1.c). The continuously variable power split transmission mechanisms thus produced can be divided into two further main groups. One of the main groups consists of single (Figure 1.b), the other of multiple power split transmission mechanisms (Figure 1.c).

![Diagram of CVT unit integration methods](image)

- **a, direct integration**
- **b, single power split**
- **c, multiple power split**

*Figure 1. Options for mounting a CVT unit into the drive train (schematic diagrams)*

The rising energy prices and the increasingly stringent emission regulations require the operation of economical and environment friendly energy systems. Tractors used with agricultural, communal and forestry cases require varied usability, so during different work processes the driving engine, the transmission and the implement system must work with optimal parameters.

This dissertation covers analysis and simulation of single power split Continuously Variable Transmissions, which are widely used in high-performance universal tractors. The goal of these analyses is to observe the efficiency, operational individualities and to define rpm – gear ratio pairs, that make it possible for the vehicle – given moving with certain speed – operation of vehicle with good efficiency and low fuel consumption.
2. Literature analysis, overview

Leonardo DaVinci sketched the first CVT (Continuously Variable Transmission) in 1490 [1]. Long time has passed since the first records and continuously variable transmission technology has been applied in more and more areas (machine tool, wind power plant, vehicle and tractors). Tractors play a vital role in agricultural prime movers, because it has the most versatile usage and application possibility. Different agricultural works such as tillage, operating PTO (Power Take-Off) or hydrostatic-driven machines, shovel loading or transportation tasks require a wide spectrum, optimal power train.

The central part of the drive train is the transmission, which is able to modify the revolutions and torque of the engine to get the optimal speed and drawbar power for the current task. Apart from driving the mechanism, it must ensure offsetting the engine’s performance for driving PTO or hydraulic controls. Because of this, the transmission is the most important and expensive part of the tractor, its cost can reach 25-30% of the machine [2].

In order to analyze agricultural drive trains, I collected parameters from the internal combustion engine and special needs of interfacing engine and transmission. In the past, development of continuous variable transmissions were on mechanic chain variators and hydrostatic gears. This is why I analyze the 10 top decisive mechanical [3], [4], [5], [6], [7] and 12 hydrostatic constructions [4], [8], [9], [10], [11], [12] in detail.

Studies of prime movers’ continuous variable transmissions were carried out by developing companies, universities and agricultural laboratories. In the last two decades there is significant activity in studies of prime movers’ continuous variable transmissions. I also overviewed public national and international studies that were going on before [4], [13], [14], [15], [16], [17] [18] [19], [20] and parallel [21], [22], [23], [24] to my study.

Based on operational and experimental results it is observable, that power trains with continuous variable transmissions do not yield obvious benefits, moreover, they are sometimes performing worse than discrete geared switchable under load (PowerShift) transmissions.

3. Goals of the research

I declared the following research goals after studying the power split continuously variable transmission’s construction and public analytic results:

- Observing performance flow in industrial and prototype transmission, modelling of behaviour and decision of optimal working range.

- After careful analysing of losses in transmission – data gathered from literature – creating the simulation models of the base power train parts of the input and output coupled systems. Analysing, and interpreting data from this should be lossless, even in the case of considering losses in the system.
- Modelling the one or multiple speed-range power split continuously variable transmission, determining total efficiency change in the whole operational region. Analysis of the efficiency change in range changing process of the multi speed-range power train.

- Analysis of combustion engines and CVT’s for given value sets of lowest fuel consumption and largest efficiency of transmission, and determination operational parameters for them.

- Gathering and ordering industrial CVT’s technical specifications regarding the power train.

- Working out an analysis method to compare tractors equipped with PowerShift and CVT transmissions that allows precise, complete comparison of transmissions. With the help of this method, experiments, analysis and interpretation of results, application benefits and cons and deciding optimal operational parameters.

4. Description of research method and means

Based on a review of references, test results and the objectives defined, the research method was founded on theoretical (simulation) and experimental, measurement-based (laboratory and field) testing.

I performed MIL (Modell in the Loop) simulation tests broken down into each elementary drive component of the drive gear as well as on the complete assembled transmission itself. I carried out analyses on drive gears of one as well as multiple speed ranges. I also extended the analyses to the level of the coupling between the internal combustion engine and the continuously variable transmission. I used a fuzzy-based CFM (Corrected Fuzzy Mean) method to specify optimum operational parameters.

In the scope of laboratory measurements, I determined the power and fuel consumption characteristics of tractor engines. I performed tests at the laboratory of the MGI Hungarian Institute of Agricultural Engineering (Mezőgazdasági Gépesítési Intézet), using a Sigma 5 mobile and a SCHENK W-400 type dynamometer, as well as a PIERBURG PLU-116H fuel consumption meter, in compliance with OECD (Organization for Economic Co-operation and Development) CODE I requirements, by applying standard braking on the PTO shaft of the tractor.

A program for the field test was developed, which is a first step of the complete comparison. The two basic level of the examination series are the tractor drawbar test and tractor-implement test. The tractor-implement test level was also separated to transport test, high power operation - and PTO operation test. The measurements were performed in Cegléd Cifrákert district of the Dél-Pest County Agricultural Plc. between 22-25 June 2003 and 9-19 October 2007. Drawbar tests were conducted on a plane cereal stubble field of loamy soil with no upward or downward slopes, in compliance with MGI’s internal standard (MGI SZ 39-1-321) established on the basis of the OECD method. Regarding the power machinery tests, the transport tests were executed on a plane test track covered by asphalt, using an unloaded tractor as well as towing a HW 8011 type two-axle trailer of 7 tons of gross weight.
Between 22–25 June 2003, the measurements were conducted on Case IH CS 150 and Case IH CVX 150 type tractors. The CASE CS 150 has a SYNCROMESH 4 range gears electro hydraulic controlled PowerShift transmission, which has 4 range gears with 6 synchro. gears included. The Steyr hydrostatic-mechanic power split, continuously variable transmission is used in the CASE CVX 150 tractors. The investigated tractors – because of the test methods developed by us – have same engine power ($P_{\text{nom}}=108$ kW), tyre dimension and pressure, and their axial load was also the same by extra weighting. Due to these specifications the tested tractors were the same only the transmission was different.

Between 9–19 October 2007, the measurements were conducted on Case IH Puma 195 and Case IH CVX 195 type tractors. By reason of the different weight and tyre dimensions of these machines, I performed these measurements for further exploration and verification of the drive chain characteristics, rather than for the sake of comparison.

I conducted this research in cooperation with ENTAM (European Network for Testing of Agricultural Machines), more specifically with MGI, a Hungarian member of the European Network for Testing of Agricultural Machines. In the course of testing procedures, I used the laboratories and equipment of both MGI and BUTE (Budapest University of Technology and Economics). I conducted simulation tests in Pro/ENGINEER, Matlab and Matlab SIMULINK systems.

5. Test results

For the purpose of simulation tests, I first modelled basic drive gear components, including the cylindrical gear drive, the planetary gear, bearings, and the continuous variable transmission unit. In line with the objectives set, I also analyzed losses on basic components in detail. Rpm ratios and power flows were determined in case of input coupled (IC) and output coupled (OC) continuous variable transmission structures of single power branching. I supplemented the three operating modes described in the literature – PS (Power Split), +PC (+Power Circulation), and -PC (-Power Circulation) – by the analysis of further two operating modes for the sake of accurate efficiency analysis and calculation. These two operating modes included GN (Geared Neutral) related to the stationary output shaft of the gear drive; and $P_{\text{var}}=0$ PV0, when no power flows in the continuously variable branch.

With respect to single speed range drive gears, I modelled a drive gear of OC-RSC structure (Figure 2.a). In order to explore differences between OC and IC structures, an IC-RSC structure (Figure 2.b) – the reverse of the drive gear – was also analyzed by using the parameters ($Z_S=50$, $Z_R=110$, $i_{C1}=-3$, $i_{C2}=-1$) of a Fendt Vario gear drive. Figure 3 shows the changes of the overall efficiency of the drive gear in the function of the output rpm, at constant input rpm ($n_{\text{IN}} = 1900$ 1/min), by taking into consideration the efficiency of the gear drive unit, the continuously variable transmission unit and the bearings. Figure 4 shows the changes of the overall efficiency of the drive gear in the function of the output rpm, at constant input rpm ($n_{\text{IN}} = 1900$ 1/min), in case of different figures of continuously variable transmission efficiency.
Figure 2. Power split CVT

Figure 3. Efficiency changes of the transmissions in function of output revolution
\(n_{IN} = 1900 \text{ 1/min, } \eta_{Var}=0.87\)

Figure 4. The efficiency changes for different constant efficiency values in the variable gear unit in function of output revolution \(n_{IN} = 1900 \text{ 1/min}\)
I performed the simulation tests of a continuously variable transmission comprising power branching and various speed ranges on a transmission of IC-SRC structure with four speed ranges. I used the specifications of a Steyr S-Matic transmission for analysis (Figure 5).

![Diagram of IC-SRC transmission](image)

Figure 5. The Steyr S-Matic transmission [13]

I performed tests on a dynamic model generated in the Matlab SIMULINK system, starting from the stationary position of the vehicle, gearing up to all four speed ranges, and then shifting to lower gears until the vehicle stopped. Changes in the rpm of drive gear components during testing are shown in Figure 6, and load changes of drive gear components in the function of time are shown in Figure 7. Figure 8 shows changes of the overall efficiency of the transmission in the four speed ranges based on analytic calculations. The efficiency figures of the component with variable gear ratio was taken into consideration at \( \eta_{\text{var}} = 0.95 \) and \( \eta_{\text{var}} = 0.75 \), respectively. The highest efficiency of the drive gear is produced in the third speed range, at vehicle speeds between 15-25 km/h depending on engine rpm.

![Graph of IC-SRC transmission components axes](image)

Figure 6. Rotation per minute diagram of the IC-SRC transmission components axes \((n_{\text{rev}} = 2580 \text{ 1/min})\)
I specified the optimal drive chain parameters on a drive train obtained by connecting a 667TA/EBC (Cummins) type diesel engine built in a Case IH 195 Puma tractor with a Steyr S-Matic transmission. Among the drive train parameters, I intended to specify those engine rpm and drive gear ratio pairs, which ensure that all target values are simultaneously fulfilled, i.e. high-efficiency drive gear operation and low fuel consumption of the internal combustion engine at a given vehicle speed. I set vehicle speed at 8 km/h, mostly used for agricultural soil cultivation works. The evaluation by a fuzzy-based CFM procedure yielded a parameter range of rpm and drive gear ratio (indicated by purple in Figure 9), where the target values are best reached.
Tables 1 and 2 show the traction test results of Case IH CS 150 and Case IH CVX 150 type tractors. For a better comparison, I also specified the traction characteristics corresponding to the maximal drawbar power of the CASE IH CVX 150 type tractor at the travel speeds and drawbar forces which correspond to the maximal drawbar powers measured in each individual gear of the CASE IH CS 150 tractor. Based on the results – and also taking drive train, rolling and sliding losses into consideration – the maximal achievable power of the engine at a given rpm can be better exploited by a tractor with continuously variable transmission.

Table 1. Drawbar test results of the CASE IH CS 150 tractor at the maximal drawbar power in each gears

<table>
<thead>
<tr>
<th>No.</th>
<th>Gear</th>
<th>Travel Speed [km/h]</th>
<th>Drawbar Force [kN]</th>
<th>Drawbar power [kW]</th>
<th>Slip [%]</th>
<th>Engine rev. [1/min]</th>
<th>Local. max. PTO power [kW]</th>
<th>Local power ratio [kW/kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>II/1</td>
<td>4,0</td>
<td>32,9</td>
<td>37,0</td>
<td>24,9</td>
<td>2323</td>
<td>88,8</td>
<td>0,416</td>
</tr>
<tr>
<td>2</td>
<td>II/2</td>
<td>4,8</td>
<td>31,9</td>
<td>42,1</td>
<td>24,9</td>
<td>2318</td>
<td>90,1</td>
<td>0,467</td>
</tr>
<tr>
<td>3</td>
<td>II/3</td>
<td>5,7</td>
<td>32,0</td>
<td>50,8</td>
<td>23,2</td>
<td>2251</td>
<td>92,8</td>
<td>0,547</td>
</tr>
<tr>
<td>4</td>
<td>II/4</td>
<td>7,4</td>
<td>27,1</td>
<td>55,9</td>
<td>15,5</td>
<td>2216</td>
<td>94,5</td>
<td>0,591</td>
</tr>
<tr>
<td>5</td>
<td>III/2</td>
<td>8,7</td>
<td>23,7</td>
<td>57,4</td>
<td>12,2</td>
<td>2239</td>
<td>93,5</td>
<td>0,614</td>
</tr>
</tbody>
</table>

Table 2. Drawbar test results of the CASE IH CVX 150 tractor at the maximal drawbar power in each cruise control steps

<table>
<thead>
<tr>
<th>No.</th>
<th>Cruise Control</th>
<th>Travel Speed [km/h]</th>
<th>Drawbar Force [kN]</th>
<th>Drawbar power [kW]</th>
<th>Slip [%]</th>
<th>Engine rev. [1/min]</th>
<th>Local. max. PTO power [kW]</th>
<th>Local power ratio [kW/kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T1</td>
<td>4,0</td>
<td>39,5</td>
<td>43,5</td>
<td>28,4</td>
<td>2192</td>
<td>96,9</td>
<td>0,448</td>
</tr>
<tr>
<td>2</td>
<td>T2</td>
<td>4,6</td>
<td>38,2</td>
<td>49,1</td>
<td>28,6</td>
<td>2151</td>
<td>95,7</td>
<td>0,513</td>
</tr>
<tr>
<td>3</td>
<td>T3</td>
<td>6,0</td>
<td>35,5</td>
<td>59,5</td>
<td>25,7</td>
<td>2055</td>
<td>99,8</td>
<td>0,596</td>
</tr>
<tr>
<td>4</td>
<td>T4</td>
<td>8,9</td>
<td>28,0</td>
<td>68,9</td>
<td>12,1</td>
<td>2047</td>
<td>100</td>
<td>0,689</td>
</tr>
</tbody>
</table>
In order to explore and analyze the differences between PowerShift and continuously variable transmission, I developed a simulation software in Visual Basic (Figure 10) environment, which is suitable, in addition to processing and displaying transport test measurement data, for calculating other parameters including the distance covered and the drive gear ratio as well.

![Figure 10. The CVT-PowerShift Simulator (v 1.6)](image)

Based on the results yielded by the CVT-PowerShift Simulator, Table 3 shows transport test figures in case of unloaded and loaded test.

**Table 3. Transport test results**

<table>
<thead>
<tr>
<th>No</th>
<th>Type of Tractors</th>
<th>Pos. of full load pot. meter</th>
<th>Unloaded</th>
<th>Loaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CASE IH CS 150</td>
<td>42,1</td>
<td>17</td>
<td>0,130</td>
</tr>
<tr>
<td>2</td>
<td>CASE IH CVX 150</td>
<td>50,0</td>
<td>18,1</td>
<td>0,134</td>
</tr>
<tr>
<td>3</td>
<td>CASE IH CVX 150</td>
<td>42,1</td>
<td>13,2</td>
<td>0,095</td>
</tr>
<tr>
<td>4</td>
<td>CASE IH CVX 150</td>
<td>52,0</td>
<td>17,5</td>
<td>0,131</td>
</tr>
<tr>
<td>5</td>
<td>CASE IH CVX 150</td>
<td>42,1</td>
<td>10,4</td>
<td>0,088</td>
</tr>
</tbody>
</table>

As indicated by the results, the main reason of the lower fuel consumption by the CASE IH CVX 150 tractor is the continuously variable transmission gear ratio changes at a continuous engine rpm, and engine rpm reductions at the appropriate moments. In addition to transport operations, power machinery equipped with continuously variable transmission can also be used most advantageously for loading operations involving intensive accelerations of short duration.
6. New scientific results

Thesis 1. [F1], [F2], [F3], [F7], [F8], [F11], [F12], [F14], [F15], [F16], [F17], [F18]

I developed a new testing method suitable for the simulation of the operating mode of continuously variable transmission gears of single power branching and of one as well as several speed ranges, as well as for their operating parameter analysis, simultaneously using the results of laboratory and field test measurements consisting of engine braking, drawbar and tractor – implement tests and of simulations based on kinematic, dynamic and CAD models.

I verified the applicability of this method by testing single speed range OC-RSC and IC-RSC, and IC-SRC structured transmission of four speed ranges.

Thesis 2. [F12], [F15], [F18]

In an OC-RSC structured transmission, equipped with a hydrostatic unit of continuously variable transmission of primary and secondary control (fitted with an engine not operated as a pump), operating modes of power split and positive power circulation may occur during functional operation (based on parameters $Z_S=50$, $Z_R=110$, $i_{C1}=-3$, $i_{C2}=-1$).

At the commencement of output shaft rotation, the overall efficiency of the drive gear is determined by the efficiency of the hydrostatic unit.

By tilting the hydraulic pump from zero angular position ($i_{var} = - \infty$) into increasingly negative angular positions ($- \infty < i_{var}$), the overall efficiency of the drive gear will degrade at an increasing rate due to higher losses caused by the increasing rpm and the increasing positive power circulation generated. Therefore, this drive gear cannot be operated economically in this transmission range.

Thesis 3. [F9], [F13], [F14], [F15], [F16], [F17], [F18]

In an IC-SRC structured transmission, equipped with a hydrostatic unit of primary control, the transmission range of the hydrostatic unit should be restricted in order to ensure the preferred efficiency, therefore a drive gear of several speed ranges is required (four in the case examined).

I have established that operating modes of power split and negative power circulation can occur during the functional operation of this transmission. The reason of the difference in the overall efficiency of the hydraulic pump in the angular positions of the same extent but in the opposite direction is caused by the difference of the negative power circulation produced in the drive gear and the loss caused by the power split operating mode.

At the borderlines of range shifts, there is a discontinuity and value change in the trend of the overall efficiency, caused by the change between the power split and negative power circulation modes, as well as by the power flow occurring in the drive gear components of different rates of efficiency after the shift of the operating range.
Thesis 4. [F16], [F20]

I used the measurement results of a Cummins 667TA/ECB type diesel engine and a Steyr S-Matic transmission and applied a fuzzy-based CFM method to determine the range of parameter combinations of internal combustion engine rpm and drive gear transmission ratio to simultaneously fulfil the target values of the given vehicle speed, high transmission efficiency and low specific fuel consumption. Based on the test results, the control mechanism should operate the drive gear as close to the purely mechanical power transmission as possible in the power split transmission ratio range, besides the reduction of the motor rpm.

Thesis 5. [F7], [F8], [F9], [F11]

I verified and stated the following on the basis of the results of the comparative research conducted by the testing method developed by me, using CASE IH CVX 150 and CASE IH CS 150 tractors, and by ensuring identical parameters:

The tractor with a drive gear of continuously variable transmission has produced a higher drawbar power. Compared to the drive gear of the power machine with a drive gear of discrete transmission, the drive train of the power machine equipped with a drive gear of continuously variable transmission can exploit its maximal achievable power at a given rpm by 3-7% more in respect of values of identical running speed associated with the maximum drawbar power values in each gear of the power machine with a drive gear of discrete transmission, and by 4-22% more in case of identical drawbar power figures.

Based on the measurement results of transport tests and the results yielded by the CVT-PowerShift Simulator of own development, it can be established that a power machine fitted with a drive train of continuously variable transmission is characterized by better acceleration and lower fuel consumption features. It follows from this that tractors equipped with a drive train of continuously variable transmission can also be preferably applied in case of loading operations requiring phases of short-term but considerable acceleration.

7. Utilization of results

The created analysis method, and the connecting data processing, data analysis, modelling and operational experiences and results are applicable to analyse other agricultural power machines as well.

The results can be used to give improvement suggestions to decide optimal and economic operational parameter sets for both developers and users.

Further improvents of the simulation model would allow the observation of the change of efficiency in power split CVT.

Experience gathered from modelling of power split CVT can be adapted to the newly designed hybrid and electrical power trains.

The method to decide optimal operational parameters can be extended to the transmissions of PTO and hydraulic systems. The newly designed parts of electrical power trains can be implemented to simulation models to analyse them.
8. References


9. Scientific publications of the author

[F1] Farkas Zs., Kerényi Gy.: *Szimuláció a hajtástechnikában*, Gép, LIII. évf. No.6-7, 18-22p, 2002


[F8] Farkas Zs. and Kerényi Gy.: *Simulation of Powertrain of Case IH Tractors with CVT or PowerShift Transmission*, Traktori I Pogonske Masine 4, Tractors and power machines 2004/12. 38-42p, ISSN 0354-9496, 2004


