General background of the application of the CVT

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General background of the application of the CVT
by example of the VDT EcoDrive transmission

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1. Abstract

A further reduction of fuel consumption, while maintaining or even improving driveability and performance, is the primary aim of VDT's EcoDrive project. The general design considerations that led to the newest push-belt based CVT forms the topic of the present paper. The following items are covered: transmission layout, fuel consumption map, ratio coverage, variator clamping strategy and engine speed control. Measurements on a test vehicle are presented. This paper is intended to present the relevant results influencing the primary project targets: fuel consumption and driveability improvement. Details on the developments on subsystems can be found in [3] and [4].

2. Introduction

Continuously variable transmissions allow a reduction of fuel consumption while maintaining good driveability. The fuel consumption advantage is based on loading the engine in operating points with higher efficiency, but the EcoDrive project also aims at improving the transmission efficiency. A further goal is the further improvement of driving comfort.
Targets for this part of the project are:
- 10% fuel consumption reduction (gasoline) compared to 5AT on NEDC (NEFZ) cycle.
- Improved driveability

to be achieved by:
- Optimised CVT ratio coverage
- Improved CVT efficiency, especially in part load, which is relevant on the NEDC
- Accurate ratio and clamping force model based control

leading to
- new CVT design
- new hydraulics layout
- new control algorithms

valid for
- midclass passenger cars.

The EcoDrive development project is a joint effort of Van Doorne's Transmissie B.V., TNO Road Vehicles Research Institute and the Technical University Eindhoven, supported by the Dutch E.E.T. Programme (Economy, Ecology and Technology).

3. Measures to improve fuel consumption.

The key aspects defining fuel consumption of a vehicle with ICE and CVT are given in table 1 (see [1] and [2]).

Table 1. Key aspects defining fuel consumption

Key aspect	Defined by
Road load	Vehicle frontal area, C_w value, rolling resistance, vehicle mass
CVT ratio coverage, final drive ratio	**CVT layout; CVT design**
Fuel consumption map	Engine layout; Engine design
CVT efficiency	**CVT layout, CVT design, CVT control**

This paper focuses primarily at those items related to CVT design, CVT layout and CVT control.

Ratio coverage, final drive ratio

As is commonly known nowadays, the main advantage of a CVT regarding fuel consumption is its large ratio coverage, when compared with MT or AT. Fig. 1 shows the relationship between V1000OD and fuel consumption, as obtained by means of simulation [1]. (V1000OD, vehicle speed with transmission in OverDrive with engine running 1000 [rpm], is a direct measure for ratio coverage when the low ratio is kept fixed.)
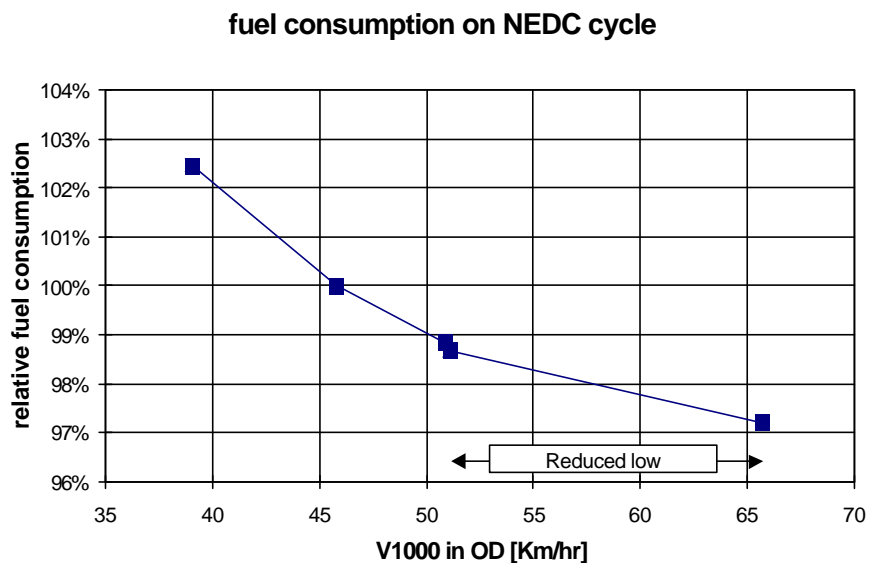
fuel consumption on NEDC cycle

Figure 1. Relative fuel consumption on NEDC versus V1000 in OD. "Reduced low" designates that the final drive ratio is modified to realise the very high V1000OD values, but correspondingly higher V1000LOW values leading to reduced launch performance. The other data points were obtained with equal low ratio.

"Reduced low" designates that the final drive ratio is modified to realise the very high V1000OD values, but correspondingly higher V1000LOW values leading to reduced launch performance. The other data points were obtained with equal low ratio. This graph shows that it is worthwhile to use the maximally attainable ratio coverage, despite the fact that the variator efficiency deteriorates somewhat at extreme ratio's. This led to the conclusion, that the EcoDrive transmission should have the highest ratio coverage that could be realised within the envelope and within the limitations of the belt variator.

CVT Efficiency

The efficiency of the CVT is, to a large extent, determined by the efficiency of the variator and the power taken up by the pump. The variator efficiency depends strongly on the amount of overclamping that is used for transfer of the torque. The amount of overclamping can be expressed as a safety factor, S_f, which is the ratio of the maximum torque that can be transmitted without gross slip divided by the actual torque. The relationship between S_f and variator efficiency is shown in Fig. 2 for a typical case. The 1.3 safety factor is needed to accommodate for uncertainties in various quantities determining the required clamping level: variator input torque and belt-sheave friction coefficient.
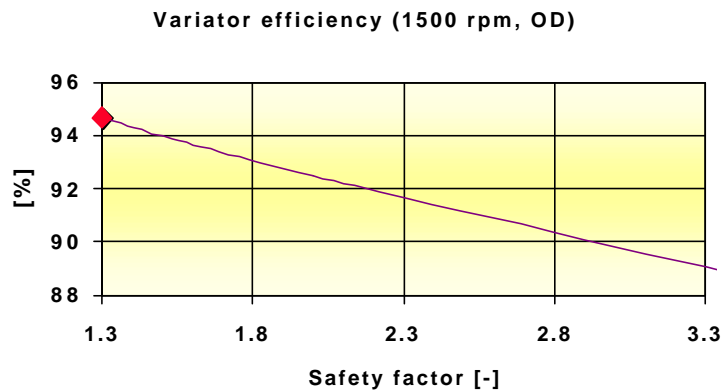
Variator efficiency (1500 rpm, OD)

Figure 2. Variator efficiency vs Safety factor for a specific operating point.

In order to prevent damage to the variator by torque shocks, overclamping is commonly used according to the line labelled "Reference" in the left graph in Fig. 3. This leads to safety levels, as depicted in the right graph in Fig. 3. which become high at low input torque levels. In order to improve this, it was decided to change the clamping force control in such a way that a safety level equal to 1.3 could be maintained over a large input torque range, instead of only at maximum torque.
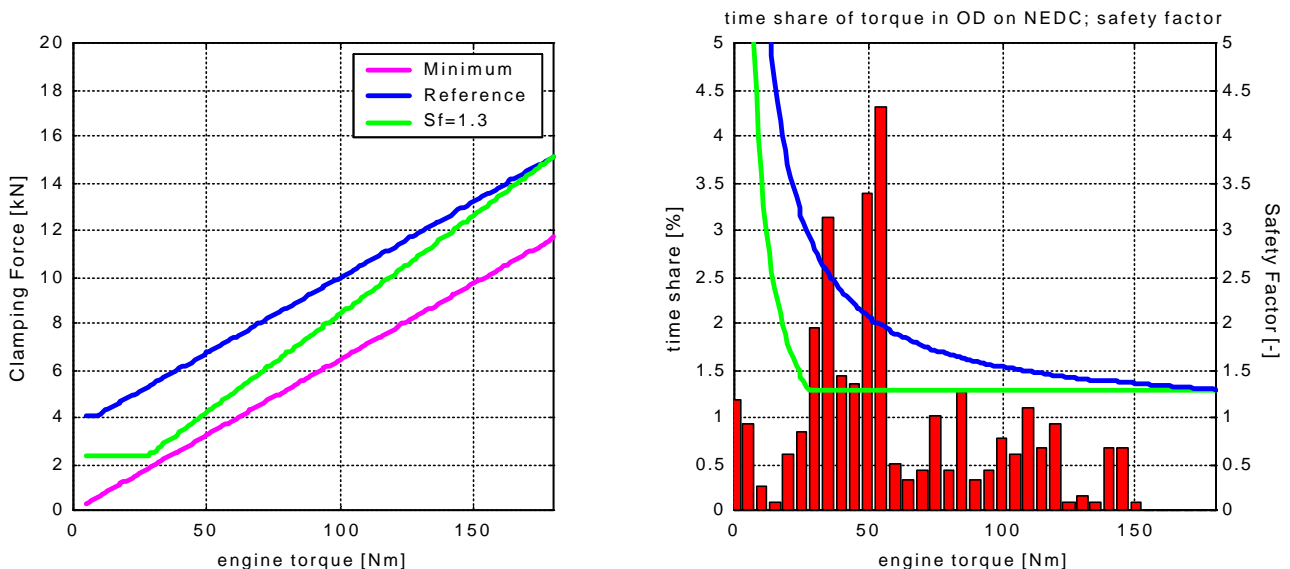
Figure 3. Left: Relationship of clamping force and Input torque for a specific ratio. `reference` denotes the usually used clamping strategy; Sf = 1.3 denotes the clamping force used with 30% safety. `Minimum` means the minimum clamping force required to transmit the corresponding torque in OverDrive.
Right: Left Y-axis (bar graph): Time share of torque in OD on NEDC. (see Fig. 7)
        Right Y-axis: Safety factor, valid in OD

A minimum controllable hydraulic pressure level (about 4 [bar]) sets a limit towards very low input torque levels (lower than about 25 [Nm] in this case), as shown in Fig. 3. In order to minimise this effect, the cylinder area's were reduced, so that the force resulting from this lower limit pressure is minimised. This, in turn, required the highest level of pressure, that is needed to transfer stall torque's, had to be increased to 80 [bar]. This high pressure is not suited for the supply of various auxiliary functions, like cooling and lubrication. Therefore, a separate pump pole was used for these functions.

Another consequence of the lowering of the safety is the higher sensitivity for torque shocks. For instance, transitions from low-mu (ice) to high-mu road surface, lead to high torque shocks in the driveline, which are likely to cause slip between belt and pulley sheaves. It was therefore decided to protect the variator from this type of peak loads by positioning a so-called Torque fuse down stream of the variator. This function could be nicely integrated in the DNR set, but then this set had to be positioned between variator and wheels. By allowing a few rpm's of slip on the drive clutch, the safety on the clutch clamping is always 1, so that a torque shock will lead to gross slippage on this clutch, thereby preventing the torque peak to arrive at the variator. Details for the torque fuse function can be found in [4].

Reduced engine speed error by more accurate control algorithms
Fig. 4 shows how fuel consumption is influenced by deviations from the optimal efficiency operating points at the steady state engine speed.
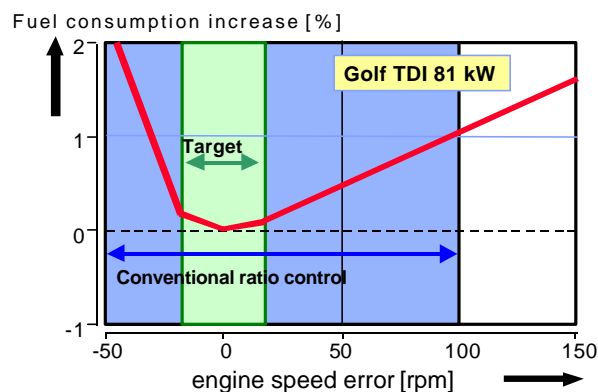

Figure 4. Fuel consumption increase vs engine speed error

This data is based on simulations with a 81 kW TDI engine. This effect is due to the fact that the BSFC is strongly engine-speed dependent. Conventional ratio control allows for a steady state error of about 150 [rpm]. It was therefore decided to develop a model based variator control, that should allow for a steady state error of ± 20 [rpm]. Details for model based variator control can be found in [3].

4. Results of measures to improve fuel economy

Fig. 5 shows the result of the measures to improve CVT efficiency, measured on an actual transmission. As expected, especially part load efficiency is improved by the reduction of overclamping. Equal safeties at high loads lead to equal efficiencies there. Extra losses in the secondary positioned DNR set (running at higher speed in OD when compared to the situation with a primary positioned DNR set), are more than offset by the reduction of losses in the variator.
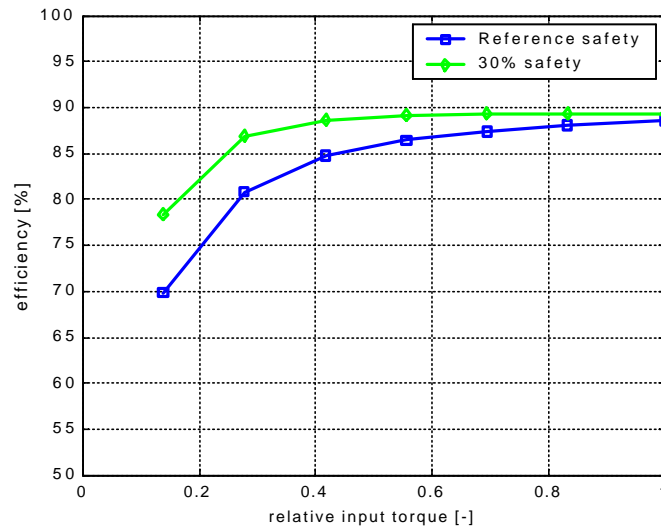
Figure 5. Transmission efficiency vs relative input torque. `Reference safety` denotes the usually used clamping strategy. See also fig. 3

Fig. 6 represents the results of model based engine speed (indicated by "primary" in the
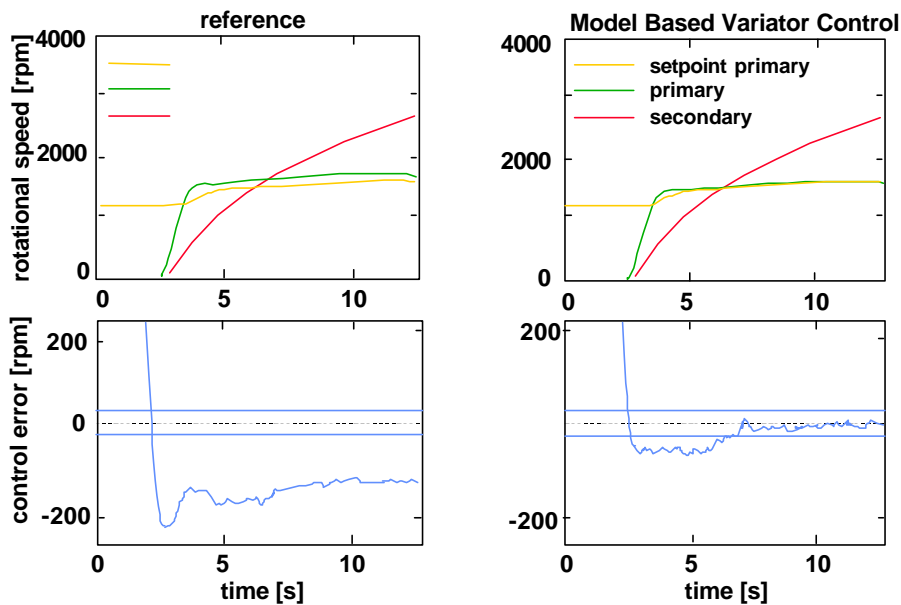

Figure 6. Engine speed error for reference variator control algorithm (left) and Model Based Variator Control (right).

graph) control. Clearly, the much smaller steady state error can be seen.

All measures together lead to fuel consumption which is close to 10% better on the NEDC than that of the same vehicle with gasoline engine and state of the art AT and comparable to that of a vehicle equipped with an MT. In order to achieve this, the control of the CVT is such that the variator is shifted towards overdrive at or near 1000 [rpm] engine speed. The engine is kept at this speed, also when an acceleration is required. When the required power cannot be delivered at 1000 [rpm], the variator is shifted back. This behaviour is seen in Fig. 7, showing that the CVT is primarily used in Overdrive. The main timeshare in Low is at standstill. This figure also illustrates once more the importance of improving part load (<60 [Nm]) OD efficiency, but the higher load efficiency cannot be neglected (10% timeshare over entire cycle). In the table below, the various time shares on the NEDC are shown (typical for economy mode CVT control scheme).

Breakdown of time share on NEDC.(Depends on engine speed control scheme of the CVT.)

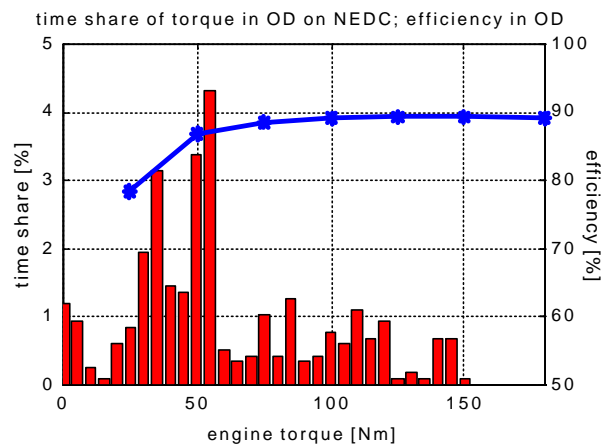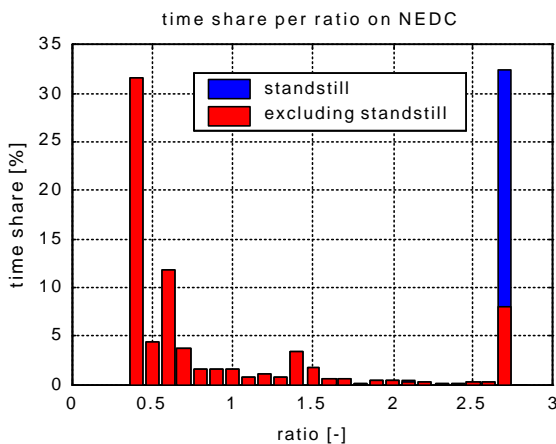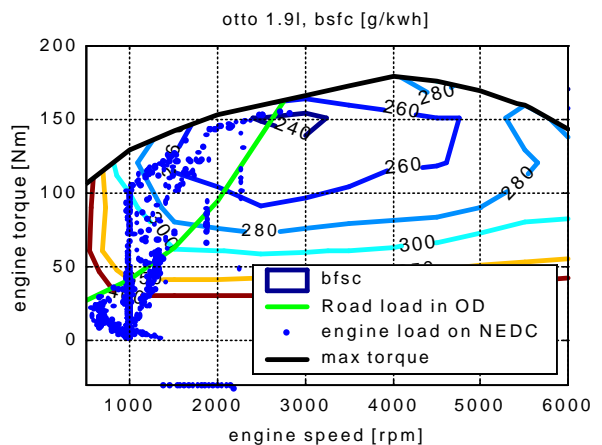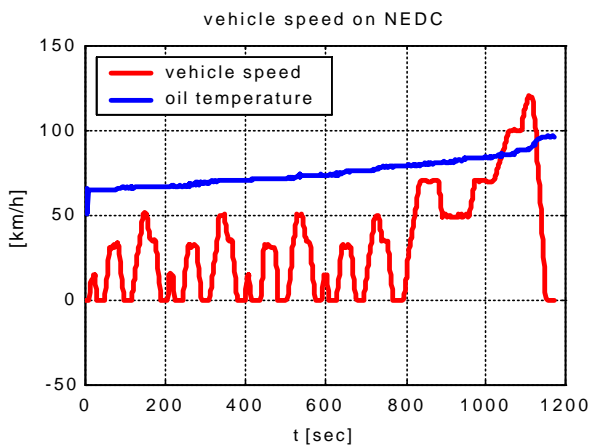| CVT ratio	time share
OD (0.4 < ratio < 0.5)	31 %
TOP (0.6 < ratio < 0.7)	12 %
LOW (driving v > 0)	8 %
LOW (standstill v = 0)	24 %
other ratios	25 %
total	100%
ratio > 1 excluding stand-still	21%
ratio < 1	54%

Figure 7. Data obtained on NEDC with EcoDrive transmission.

Upper left: Vehicle speed and transmission temperature vs time.
Upper right: Fuel consumption diagram with Road load curve in OverDrive, engine load on NEDC and max torque line .
Lower left: time share of ratio's used on the NEDC. Note the large time share in low standing still, as well as in OverDrive.
Lower right: left Y-scale (bar graph): time share of engine torque in OD over NEDC.
*   right Y-scale (drawn curve): efficiency of CVT in OD.*

5. Driveability improvements, measures and results

Modern CVT transmissions incorporate the feature of simulating a manual transmission by selecting predefined fixed ratio's. Fast transitions between these ratio's are of importance, in

order to achieve good driveability. An example of a full shift through all ratio steps in shown in Fig. 8, where setpoint as well as realised ratio's are shown.
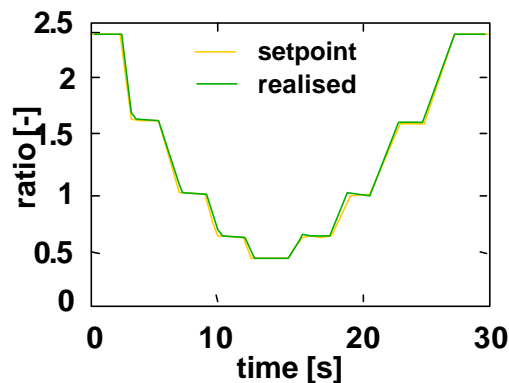

Figure 8. Step mode ratio transitions, as realised with model based variator control.

This result was obtained by applying model based variator control. Hydraulic pressures are increased during shifts, to levels higher than necessary for clamping. By this pressure increase, shift dynamics is improved, thereby allowing for a very responsive driveline.

6. Transmission lay-out and design

The overall transmission layout is shown in Fig. 9.
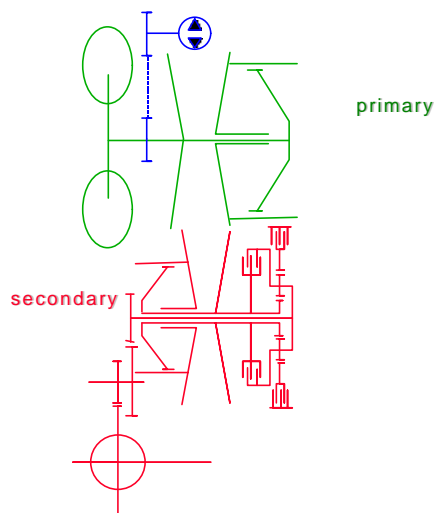

Figure 9. Left: Schematic layout of EcoDrive transmission.

specification: 180 Nm. (Ratio coverage 6.55 V1000OD = 54 [km/h] for gasoline engine) and
            250 Nm. (Ratio coverage 6.0);

The transmission comprises the following components

- A torque converter with lock-up and torsion damper is used to achieve good launch performance. It also allows a higher V1000OD, when compared to a solution with a take-off clutch. Gradeability is improved and take-off smoothness is unparalleled. Ease of control and inherent fail-safe properties add to these advantages. A prerequisite of this solution is, that it fits inside the envelope of the transmission.
- A lock-up is applied for fuel economy reasons. This lock-up is closed at low vehicle speeds, so that the penalty of using a TC instead of a wet plate clutch is minimal.
- The pump (two pole roller vane pump) is driven by means of a chain. The high pressure pump pole (80 [bar] max.) supplies oil for the variator and clutches, the low pressure pole feeds torque converter, and supplies oil for cooling and lubrication.

- The push belt is of the 30 mm; 2 times 12 rings type.
- On the secondary shaft, the DNR set is positioned. The torque fuse function is integrated in the drive clutch and therefore does not require any additional hardware components.

7. Conclusions

Fuel economy improvements (<~10% (gasoline engine) w.r.t. 5AT) as well as driveability improvements were obtained for a CVT driveline by means of the following measures:
1. Maximisation of ratio coverage (>=6.0), thereby allowing for a very high V1000OD.
2. Lowering of excess clamping force requiring a larger range of applicable clamping force
3. Application of torque fuse, safeguarding the variator during torque shocks.
4. Development of Model Based Variator Control, leading to more accurate and more responsive control
5. Optimisation of hydraulic system by separating high pressure functions (variator, clutches) from low pressure functions (cooling, lubrication)

8. Outlook

Further work will be carried out on the driveability of the vehicle and on the application of the torque fuse and model based variator control in a series application.

9. References

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[3] van der Laan, M.; Luh, J.: Model-Based Variator Control Applied to a Belt Type CVT, International Congress on Continuous Variable Power Transmission, 1999

[4] Luh, J. "Modellbasierte Regelungsstrategie eines Umschlingungs-CVT, Conference CVT-Getriebe, 15-16 November 2000, Haus der Technik, Essen