High Torque CVT P930, design and test results

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SYNOPSIS

25 Years experience in the design of the pushbelt type of Continuously Variable Transmission (CVT), has recently resulted in the design of the P930 transmission. The P930 project was started to allow a new customer the chance to evaluate CVT technology using a transmission according his requirements.
State of the art development techniques and rapid prototyping were used to reduce the development lead-time and to achieve optimal results. An extensive test program was carried out. This has resulted in a high torque prototype CVT, setting new standards with respect to torque capacity, performance and fuel economy.
This paper gives an overview of the design process and the achieved technical results.

1 INTRODUCTION

Ever since Van Doorne’s Transmissie’s (VDT) foundation in the early seventies, the development of complete CVT systems has played an important role in the companies R&D strategy. Although the early objective was to develop and manufacture complete transmissions, VDT later realised that as a transmission manufacturer, VDT would be a competitor of its own pushbelt customers. VDT therefore changed its strategy from the production of complete transmission systems as the core business to the production of the CVT’s key component: the ‘pushbelt’.
The experience, know-how and patents VDT gained over this period of CVT transmission

development however, were considered valuable for VDT's customers. This consideration led to the decision to continue CVT transmission development as a market development activity with two main objectives:

1. Supporting customers in developing their CVT and thereby reducing development risks by offering the VDT experience and know-how as a reference.
2. Development of new transmission technology in order to demonstrate the benefits of CVT technology and as platform for new pushbelt development.

The strategy to concentrate on pushbelt development and production was a turning point in VDT's history. New belt types have been developed and nowadays the belt range covers a wide range of engine capacities. The reliability and endurance are proven and CVT market share is increasing. As of today the Van Doorne belt CVT is the only CVT in series production in the automotive market. By now about 1.5 million vehicles are equipped with CVT.

In 1988 the development of the P884 transmission started as an advanced development project [1]. The targets for this project were to develop a transmission featuring:

- High torque capacity (250 Nm) demonstrating the newly developed 30/9 belt. (In fact this was a doubling of the torque capacity of production transmissions at that time)
- Reduced fuel consumption obtained using full electronic control.
- Improved comfort using a torque converter as a starting device.

After prior studies, the development of the transmission resulted in first test results with the P884 transmission in a 3.3ltr. Chrysler Voyager in 1991. The many improvements in the design (high ratio coverage, optimised clamping force control, 2 stage pump, etc.) resulted in an improved fuel economy of 10 – 15% relative to the original 4AT.

The development of the P930 transmission started in 1993 and can be considered as a logical next step succeeding the P884 project towards:

- Higher torque capacity: 325 Nm featuring the 30/12 belt.
- Improved durability by incorporating P884 test experience in the design.
- Application of the latest standards in automotive control technology.
- Reduction of the development lead-time and improvement of quality standards by using state-of-the-art development methods and tools.

2 TRANSMISSION SPECIFICATION

The main target was to design one basic transmission layout capable of covering a range of engines and vehicles. In its realisation, design details and manufacturing processes had to be representative of the final production transmission.

Mechanical specification

The transmission is designed to cover a range of four engines (230 - 325 Nm, gasoline and diesel) and two vehicle types. This was be realised by adapting only some of the transmission parts.

Functional requirements

For functional requirements, the same vehicle with a standard 5 speed manual transmission (5MT) is set as a reference. The target fuel economy was set to be the higher and the target performance was to be comparable to the 5MT. The transmission has to withstand functional and durability tests according to normal automotive standards.

The control system should offer 3 fixed drive modes and some special features to improve comfort and driveability. The transmission controller includes the latest technology: integrated in the transmission, CAN, diagnosis, etc.

3 TRANSMISSION DESIGN

layout

The P930 transmission layout (figure 1) consists of the following components:

- Reverse flow type torque converter (TC) with lockup and torsional damper.
- 2 Stage roller vane pump.
- Forward and Reverse planetary gear set between TC and primary pulley.
- Primary pulley with double acting cylinder.
- 30 mm Pushbelt.
- Secondary pulley, cylinder compensated for centrifugal pressure build up.
- Final reduction gear set and differential.
- Electro-hydraulic control unit with integrated microhybrid controller and sensors build on top of the transmission.

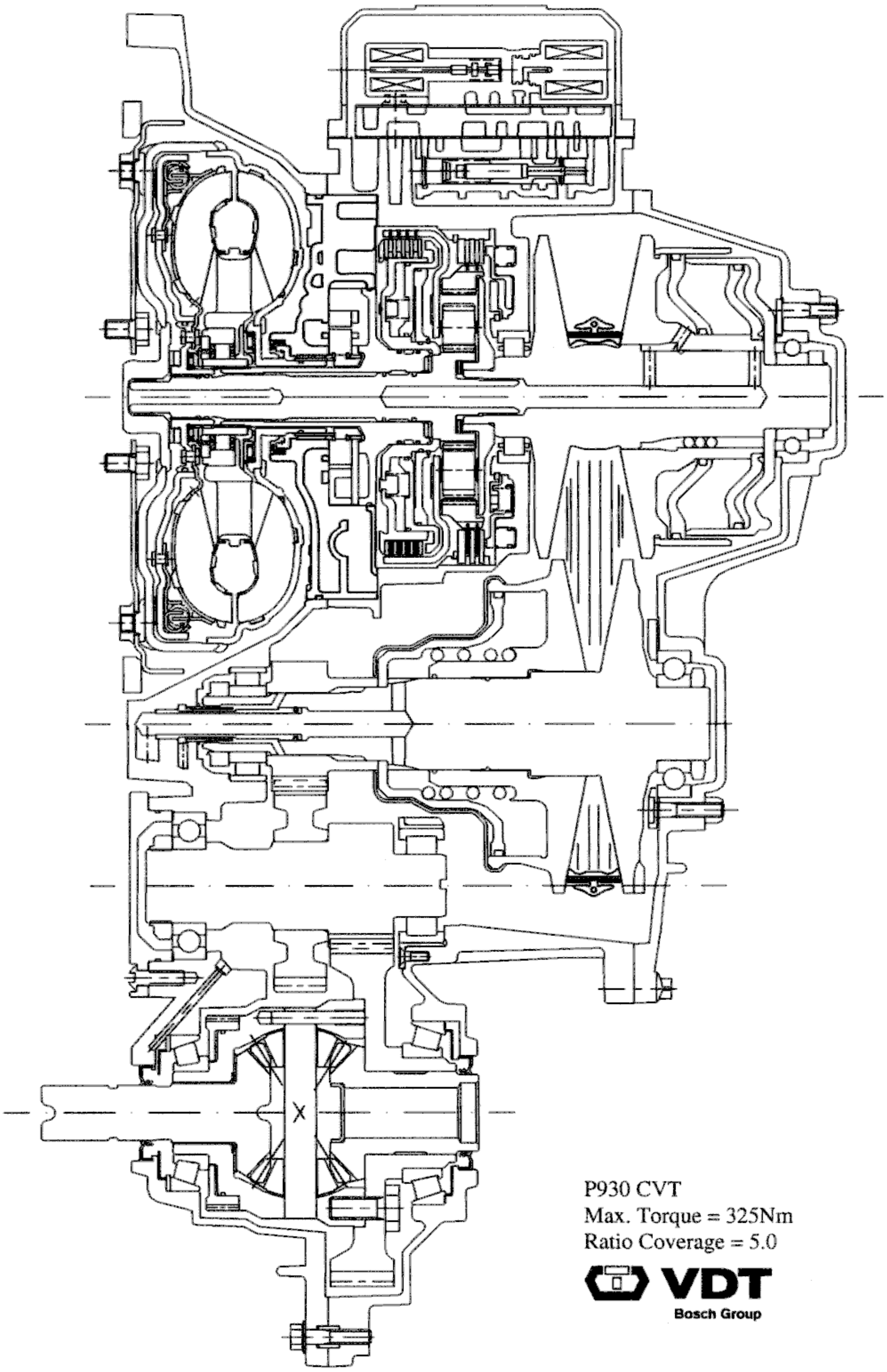

Figure A: cross section P930 transmission

3.1 Variator

The variator is designed to cover the complete torque range from 230 to 325 Nm. This is realised by adapting certain transmission parts and by the reduction of the transmission ratio coverage (RC) by increasing the primary running radius for the high torque version. The secondary pressure is limited to 50 bars for the complete range.

Survey technical specification P930 transmission

		Engine #1	Engine #2	Engine #3	Engine #4
Max. Torque	[Nm]	230	270	270	325
Max. Speed	[rpm]	4500	4500	6000	4500
Torque Converter ∅	[mm]	246	246	246	246
Stall torque ratio	[-]	2.0	2.0	1.6	1.6
Turbine shaft and DNR set		standard specification			high strength
Belt type		30/9	30/9	30/12	30/12
Ratio coverage		5.8	5.5	5.5	5.0
Centre distance	[mm]	178			
Length at crankshaft	[mm]	383.5			

3.2 Torque converter

The torque converter is a standard production type reverse flow torque converter. Since the maximal hydraulic pressure is limited to 50 bars, the input torque for the primary pulley is restricted to 410 Nm. To avoid overload situations, the primary torque is limited to this value by reducing the engine torque in brake stall conditions. In normal take-off situations, the input torque will never exceed the 410 Nm limit and the engine torque reduction will not be activated.

This system allows the application of a torque converter with a high stall torque ratio (2.0) resulting in an improved initial launch of the vehicle.

3.3 Housings

The transmission consists of 3 housings: a converter housing, transmission case and side cover.

The housings were newly designed using 3D CAD tools (figure 2). In the design, special attention was given to reducing oil spin losses. This resulted in considerable transmission efficiency improvements at high speeds. Stiffness of the housings and deflection under typical load conditions was another point of attention, resulting in improved alignment of the variator and gears.

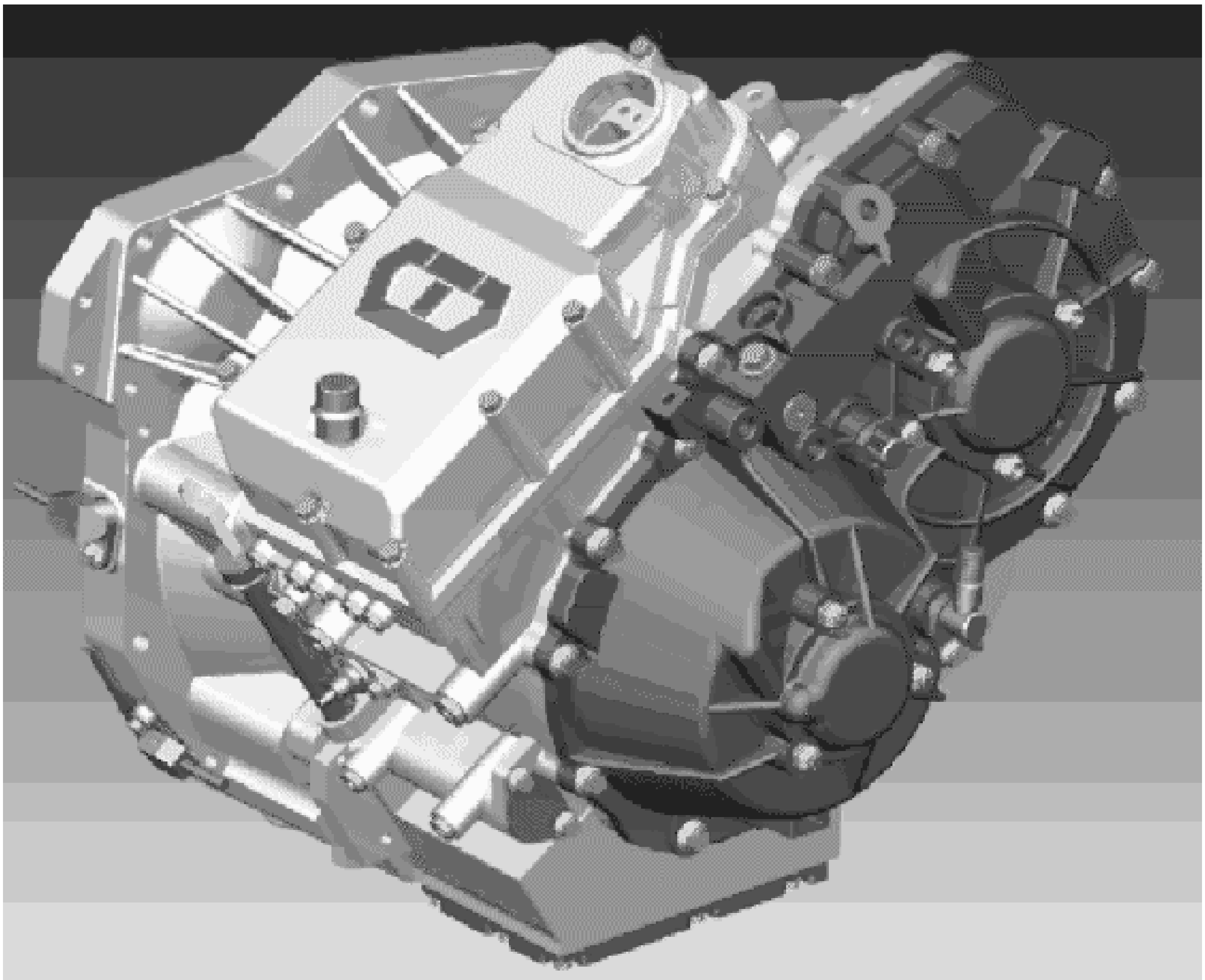

Figure B: 3D-model P930 transmission

The application of a 3D CAD tool made a fast design of the complex housings possible. The flexibility of this tool made it possible to allow design changes up to late in the design phase. This had advantages for the design process since the housings are often the last parts affected by design changes. Using the 3D-model information, a good interface was possible to:

- Vehicle body and interior design to prevent that the transmission has interference's with other components in the engine compartment.
- FEM calculation programs. During the design, stresses and deflections were calculated. The results of the FEM analysis were verified by measurements. The results of these tests will be used to improve the next series of prototypes.
- Rapid prototyping processes. In the P930 design process, Laminated Object Manufacturing (figure 3) was used to make a view model which later was used as a casting model.
- Casting process simulations. The Vacuum Foil and Precision Casting processes chosen, offered the possibility to realise wall thickness comparable with die-casting (3 to 4 mm). This is convenient for small production series resulting in considerable less costs and shorter lead-times.

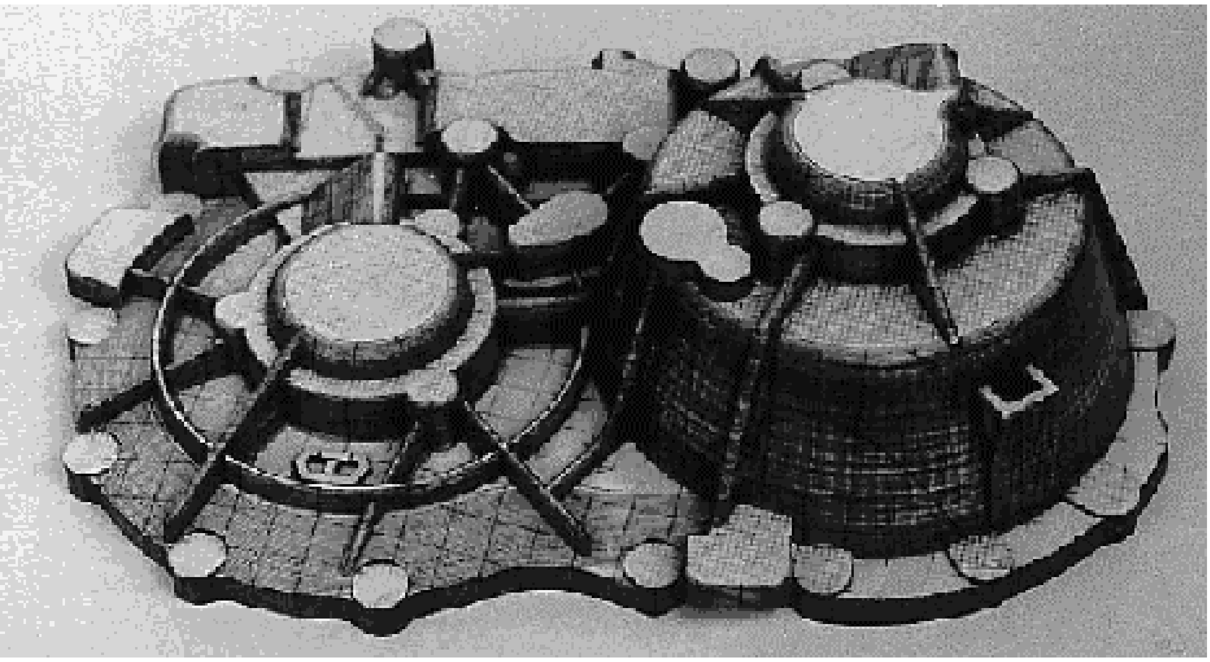

Figure C: Laminated Object Model side cover

3.4 Pump

For CVT applications, the pump has to fulfil specific requirements. To enable fast transmission shifting, high flow rates are required at low engine speeds. To realise the high torque capacity, high pressures are required. Further, sufficient supply for (belt) lubrication, clutch control, TC-operation and cooling are required.
VDT opted for the roller-vane principle as this has the following functional advantages:

1) It can be designed as an intermediate placed pump driven by the TC (like AT's).
2) It can be designed as a 2-stage pump, so pump losses at high speeds and in steady state conditions can be reduced by switching off one pump half.
3) Low cost price relative to other flow-controlled pumps.

For the P930 pump (figure 4) development, a number of improvements were made based on P884 test experience:

- A separate bearing of the rotating pump parts resulted in improved pump durability.
- The geometry of the porting into the pumping chambers was improved by optimising the channelling and cam-profile. This has resulted in reduced noise and the cavitation point is moved to a higher speed.
- The weight was reduced by using aluminium instead of steel (P884). To reduce deflections, the housings were cast in one piece (using lost foam casting).
- In the new design, less parts are necessary.

Figure D: Exploded view P930 pump

3.5 Electro-hydraulic Control Unit

The control system for the P930 transmission (hydraulic control unit, TCU and software) was developed in close co-operation with Robert Bosch GmbH.
Before starting the P930 project, Bosch developed an A-sample control module for the P884 transmission based on the VDT control system. This Bosch unit used standard automotive components and a state of the art controller. The A-sample control module was used for software development and to evaluate the CVT in combination with a low cost hydraulic module and advanced controller software.

Mechatronic approach
For the P930 a completely new unit was developed according to a so-called, mechatronic approach [3]. This means that the hydraulic valve body, solenoid valve body, sensors and the (microhybrid) controller are integrated into one unit (figure 5).
The advantages of this mechatronic approach are:

- Costs savings by a reduced number of components.
- The module can be completely pre-tested separate from the transmission prior to assembly.
- Reduced wiring and electrical connections, resulting in better reliability

The mechatronic CVT control module for the P930 consists of the following parts: Hydraulic main stage, a solenoid valve body build as a sandwich together with an intermediate channelling plate acting as a hydraulic interface to the transmission,. A pressure and oil temperature sensor are integrated in the module. A microhybrid TCU will be integrated in the solenoid valve body. A connector to the vehicle wiring harness and the transmission speed sensors is connected by a flex foil to solenoid valves, sensors and TCU.

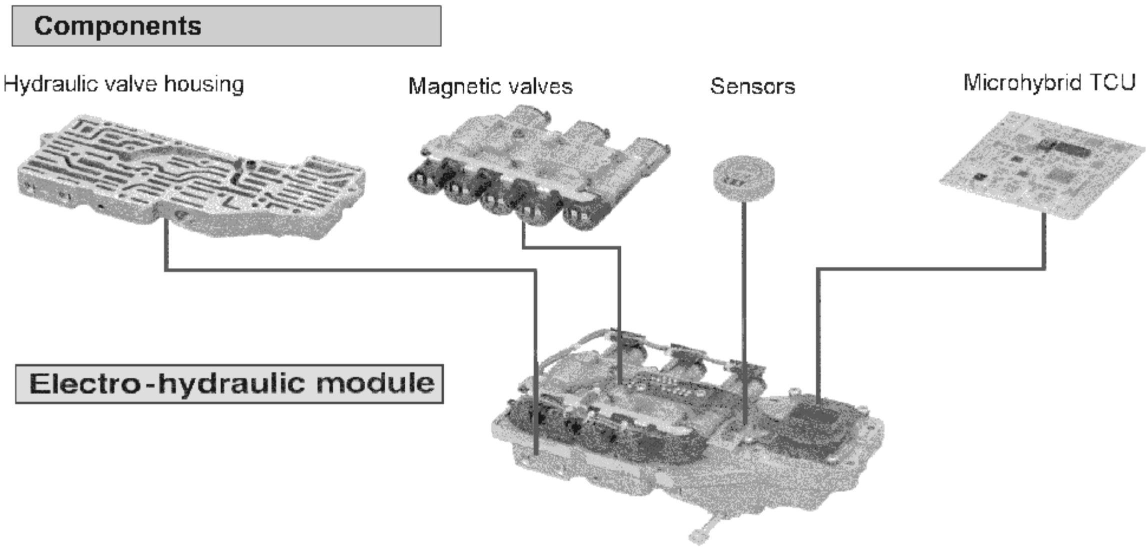

Figure E: Mechatronic control module

The unit is fully pre tested on an automated hydraulic test rig.

Hydraulic control functions

The hydraulic control unit provides the following functionality:

- Variator control according to the 'standard VDT' Master-Slave principal. Electronic closed loop control of line pressure (feed back of electronic pressure sensor signal) and ratio (feedback of measured speeds). This system ensures that the required pump pressure is minimal for a given torque capacity and that all pump flow is available for transmission shift back to LOW (in emergency stop situations, for example).
- Direct drive clutch pressure control using a variable force solenoid (VFS) valve. This ensures flexibility to calibrate optimal drive clutch engagement. The electronic pressure control also has the ability to operate the drive clutch as a torque fuse. A torque fuse is an advanced software function letting the drive clutch slip in case a high torque peak exceeds the controlled clamping force (for example if the max. line pressure is reached).
- Reverse clutch control using accumulator and switchable orifice.
- Electronic control of the torque converter. The lock up clutch is PWM operated to ensure smooth engagements.
- Electronic control of the 2-stage roller vane pump and the reverse inhibit valve.
- Limp-home valve activating full hydraulic control should a malfunction of the TCU or electrical disconnection occur. The limp home system is providing full transmission

performance but with restricted comfort and driveability.

3.6 Electronic Controls

Hardware

A stand-alone (PCB) controller was designed as a prototype for the microhybrid TCU that was developed later (figure 6). Both TCU's have identical circuitry based on the Siemens 80C167 microprocessor with CAN interface. The controller is designed as a universal CVT controller. The microhybrid TCU has to withstand the severe transmission conditions with respect to temperature and vibrations. In order to protect the electronics in this environment, the microhybrid is encapsulated in a welded steel housing. In the transmission, the TCU housing will be cooled with the oil cooler return flow. Extensive tests were done to prove this concept both on component test benches and in the vehicle.

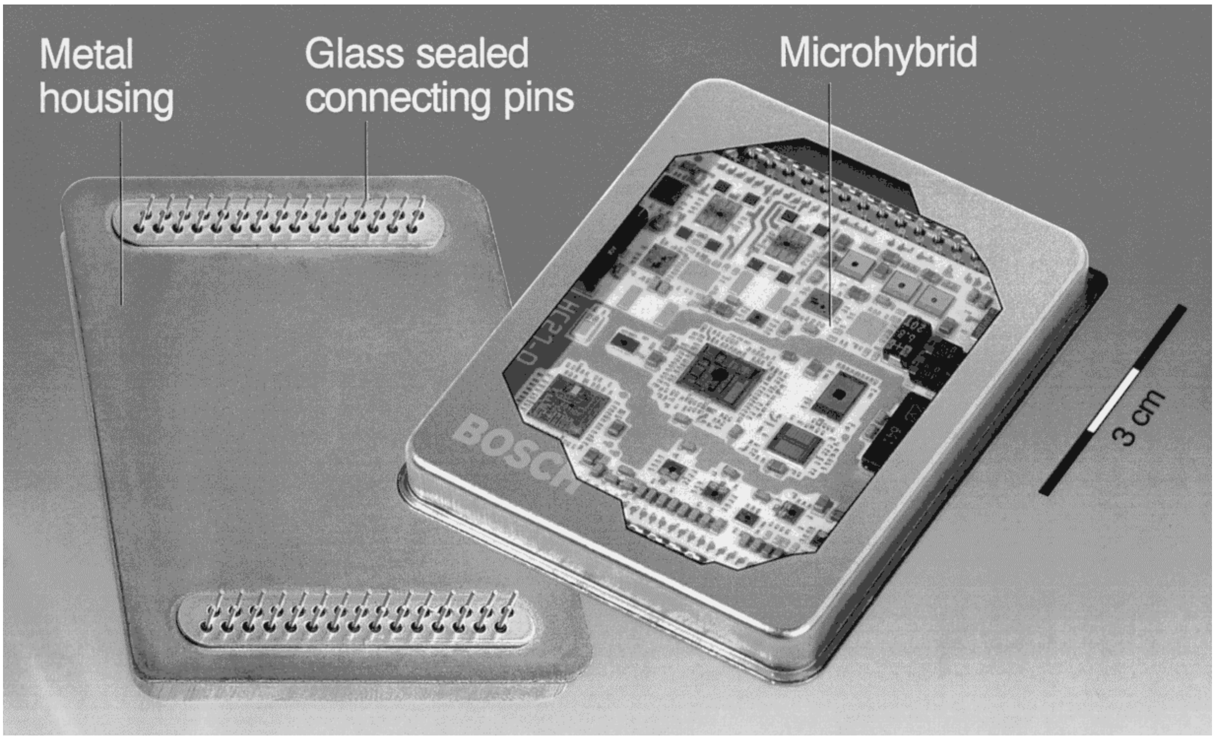

Figure F: Microhybrid TCU in welded metal housing

Software

The P884 controller software is rewritten for the new TCU. The basic transmission functions are extended with new functionality to improve driveability and reliability especially in extreme driving manoeuvres.
The software development was performed using the 'Advanced Simulation and Control

Engineering Tool' (ASCET) [1]. The prototype controller software was first developed using ASCET and tested on a vehicle model. In the next step, the prototype software was tested with the P930 transmission hardware-in-the-loop. Subsequently the prototype ASCET software was converted to TCU-code. This development method enables fast and flexible development. Special attention was given to the reliability of the software and to calibration parameters. Where possible, easy to understand physical parameters were used. In some conditions, adaptive algorithms are used to prevent the implementation of high production tolerances in certain areas of the transmission or individual calibrations. Diagnosis functions using plausibility checks are in development.

4 TRANSMISSION EVALUATION AND TEST RESULTS

Test program

An extensive test program was planned:

- Full functional test program in the vehicle in all normal operating conditions
- Transmission efficiency test on test rig.
- Durability tests of complete transmission on test rig.
- Endurance tests in the vehicle.
- Component durability tests for pump, filter, variator, hydraulic control unit, microhybrid TCU, torque converter, DNR-set, etc.

Within the design validation program, a number of transmissions were used for evaluation and testing purposes: 2 units for durability tests on a dyno test rig, one unit is used for efficiency measurements on a dynamometer test rig, further a number of transmissions were built for various purposes.

VDT equipped a number of vehicles for various purposes:

Vehicles equipped with P930 transmission

Engine	**Vehicle**	**Features / purpose**
2.2 ltr TD	customer vehicle	Functional tests and calibration
2.2 ltr TD	customer vehicle	Endurance test
2.2 ltr TD	customer vehicle	Driveline management
1.9 ltr TDI (81 kW)	VW Golf TDI	Optimised engine - transmission calibration
2.8 ltr VR6	VW Golf VR6	Development vehicle

[1] Advanced Simulation and Control Engineering Tool developed by ETAS GmbH, Schwieberdingen, Germany

2.8 ltr VR6 (ME 7)	VW Golf VR6	Driveline management
2.8 ltr VR6	Ford Galaxy VR6	Demonstration vehicle

4.1 Transmission calibration and application

The control unit in combination with the newly developed software allows VDT extensive calibration facilities. For calibration, the TCU will be equipped with an EPROM-emulator making direct access to internal controller signals possible and allowing direct parameter calibration. Using integrated application and calibration tools it is possible to evaluate internal controller signals and external transmission measurement signals using the same environment where parameters can be changed and optimised.
First the transmission was calibrated on a spin-loss calibration test rig. Here all mechanical transmissions function were checked and most control loops have been calibrated. Special attention is given to the response of the closed loop controlled functions (ratio, clamping force and drive clutch) which main valves are actuated by pilot valves. The clamping force control loop was considered as specially critical since a very fast and accurate response is required. All responses were according to VDT standards and comparable to the P884 control response (where the main stages were actuated directly by solenoids).
In a second phase, the transmission control was calibrated in the vehicle. Since the dynamics of the ratio control is determined by the driveline, it is only possible to calibrate the ratio control loop for the first in the vehicle. All other functions depending on transmission load (drive-, reverse- and lock up clutch engagement) were then calibrated.
When the transmission is fully technically calibrated, the calibration of customer specific requirements with respect to driveability, fuel economy, etc. can be performed very effectively thanks to the flexible tools (figure 7).

4.2 Functional tests

Transmission functional test in a vehicle
A road test was performed to verify durability and general functionality. About 70.000 km were driven with a pre-prototype version of the P930 transmission in a 3.0 ltr. V6 gasoline vehicle loaded up to 1900 kg. Except for a broken turbine shaft, the design of which has been changed in the final P930 transmission, no unexpected problems appeared.

Transmission functional tests on a dyno test rig
The P930 transmission was tested on a dyno test rig. The total test comprises 50.000 km (550 hrs.). It was done with a 230 Nm / 4500 rpm engine. The test includes all driving conditions: full load, partial load and zero load conditions in all ratios, dynamic driving manoeuvres, reverse driving, up hill driving and driving in limp home mode. The test rig is not able to simulate down hill driving.

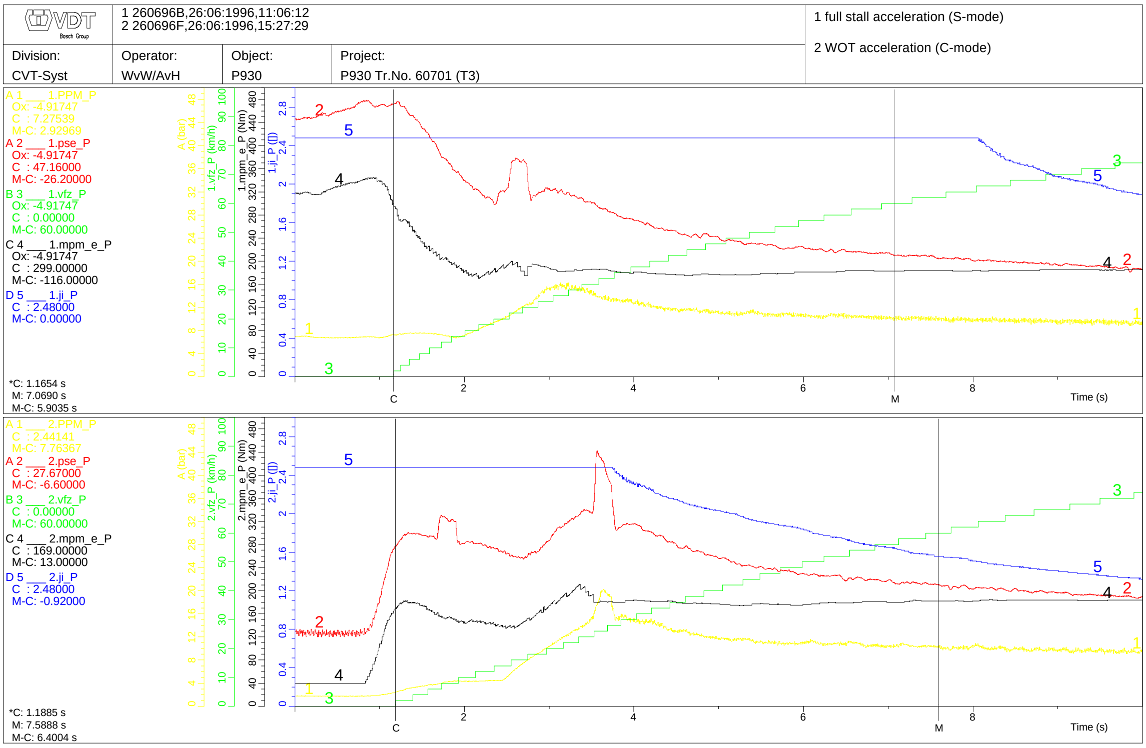

Figure 7: typical calibration measurement

The test results showed no mechanical, hydraulic or electronic failures. Apart from the normal (expected) wear on gears, bearings, seals, etc. some minor wear spots were found. These wear spots were eliminated by small design changes.
Durability tests with increased engine capacity are planned.

4.3 Efficiency measurements

Efficiency measurements were done both by an institute under the supervision of our customer and by VDT as a reference. The measurements were done on an electric driven dynamometer test rig.
Measurements were done in all possible and relevant combinations of a wide span of ratios, speeds and torque's (within the restrictions of the applied test rig).
The measurements done were stationary measurements. The measurements were started at a low transmission temperature and were continued until the transmission temperature stabilised. In- and output torque and speed were measured. The pressures for creating the clamping force during the measurements were controlled identically as in a vehicle during steady state driving conditions.
It was found that the transmission efficiency is mainly depending on clamping force, input speed and ratio, input torque and transmission oil temperature.

The effect of clamping force, ratio and torque can be lumped in the so-called safety factor (i.e. the actual clamping force relative to the critical claming force for severe belt slip). There is an optimal safety factor of about 1.3 where variator losses are minimal and durability is guaranteed.

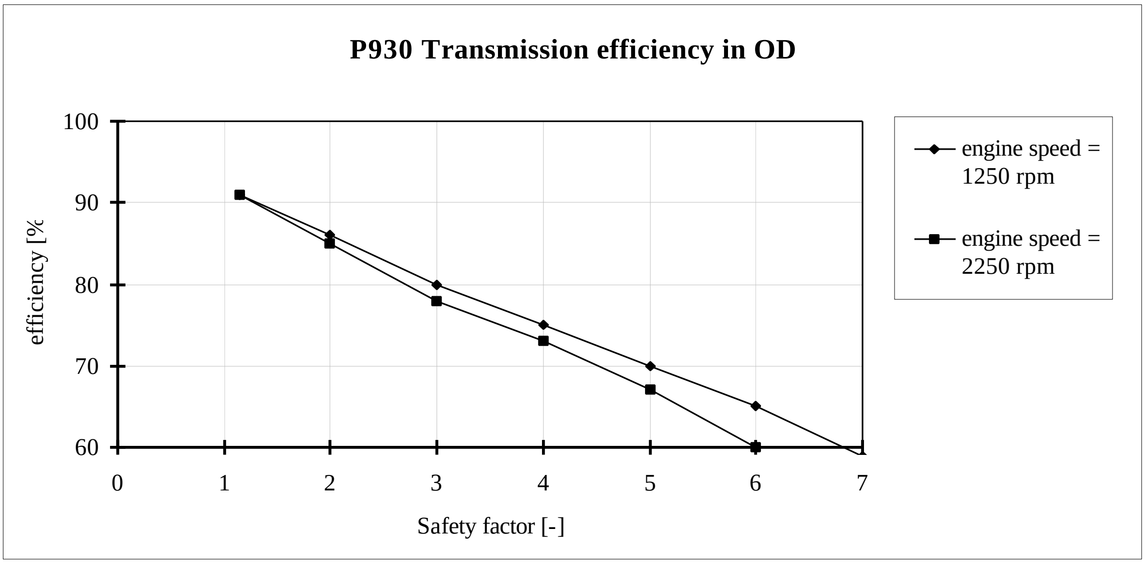

Figure 8: P930 efficiency as function of safety factor

With the standard control strategy in some conditions the clamping force is exceeding the optimal SF = 1.3 value. This is for reasons of robustness or because of physical limitations (for example the minimal pressure is 5 bar). For further transmission efficiency improvements it is necessary to control the clamping force as close to the SF = 1.3 limit as possible, specially in stationary conditions. This will be achieved by an advanced control strategy and by optimal transmission design (figure 9).

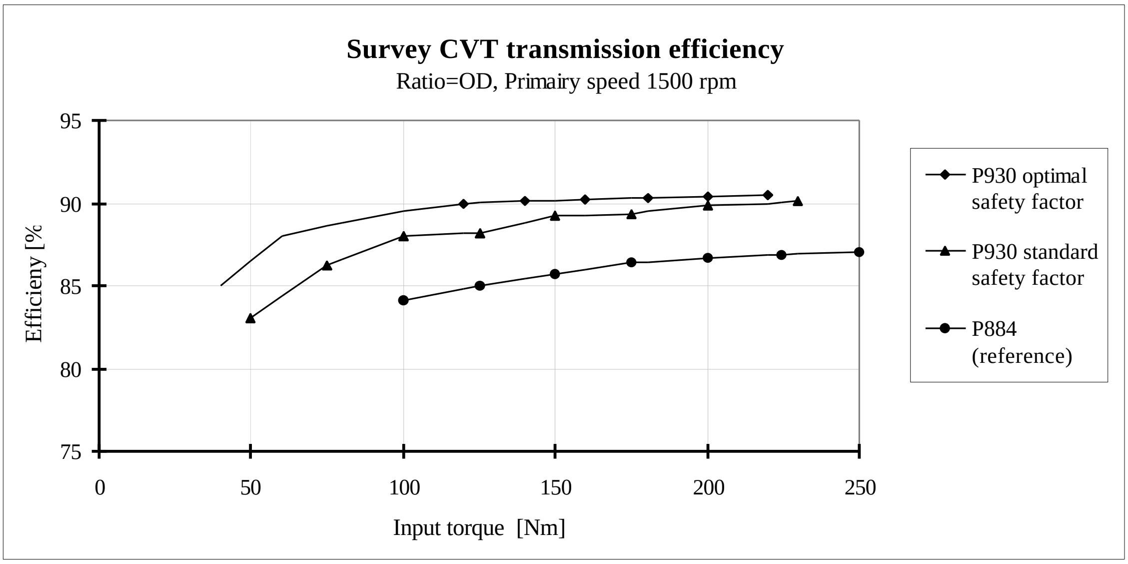

Figure 9: CVT transmission efficiency depending on control strategy

Also found was that in partial load conditions, the transmission efficiency is strongly dependent on the transmission oil temperature at low and moderate temperatures. Obviously it is useful to rapidly warm-up the transmission to normal operation temperatures. A special warm-up program was implemented for this reason.

4.4 Fuel consumption measurements

Fuel consumption measurements were performed with two vehicles. VDT equipped a Renault Safrane 3.0ltr V6 with a pre-prototype P930 for a first survey of the expected improvements. In a later stage, measurements were done by IAV[2] within a joint project to optimise the combination of a CVT and a 1.9 ltr TDI (81kW) engine.

Survey P930 fuel consumption measurements

	Renault Safrane 3.0 ltr V6			**VW Golf TDI 1.9 ltr (81kW)**		
	4AT	CVT	D	4AT	CVT*)	D
Test cycle	[l/100 km]	[l/100 km]	**[%]**	[l/100 km]	[l/100 km]	**[%]**
New ECE-cycle (cold)	12.9	11.9	**-8**	6.2	5.7	**-8**
New ECE cycle (hot)	11.7	10.4	**-12.5**			
FTP / 75 (hot)	11.4	9.9	**-15**			
Steady state [km/hr]						
70	6.9	6.5	**-6**			
90	7.4	7.1	**-4**			
120	9	8.4	**-7**			

*) CVT calibrated for optimal emissions

5 PRESENT AND FUTURE DEVELOPMENTS

5.1 Transmission system development

The development of the P930 transmission demonstrates the benefits of 3D CAD design in combination with rapid prototype manufacturing processes. Since this design method resulted in a better design quality in less time, this method will be utilised in future development projects.
New projects have been started to optimise transmission design/layout in order to improve the performance in combination with further possible reductions in fuel consumption and

2 Ingenieursgesellschaft Auto und Verkehr, Berlin

emissions. Also, the interest for very high torque applications (500 Nm and more) is growing in combination with rear wheel drivelines.
New hydraulic control system layouts are in development. They have to result in more robust systems allowing the reduction of the clamping force in part-load conditions. This will result in further efficiency improvements.

5.2 Control strategy development

The co-operation with Robert Bosch has resulted in increased activity in the field of software development allowing

- Fuel economy reduction by improved clamping force control in part-load conditions.
- Improved transmission robustness and reliability using advanced adaptive control algorithms.
- Diagnosis functions using plausibility checks.
- Better driveability by adaptive drive modes using driver and road recognition. Features like step mode, down hill cruise control, etc.
- Driveline management as a next step. An additional software strategy at a higher hierarchical level is co-ordinating the complete powertrain (engine and transmission). With the combination of electronic throttle control, the optimal compromise between fuel consumption, exhaust gas emissions and driveability can be realised.
  At this moment, driveline management is being tested in a vehicle..

5.3 System integration

The high ratio coverage and the stepless ratio change characteristics of the CVT offers new possibilities in optimising a driveline. With a CVT, the engine operating conditions differ to that where in combination with a stepped (automatic) transmission. At this moment a project is running to investigate the advantages of optimising an engine and transmission as a combined unit. Simulations are being performed where various transmission and engine design parameters are varied in order to find an optimal combination. The target is to realise a driveline with further fuel consumption reduction, according to future emission standards, with excellent driveability and a cost effective design.

6 CONCLUSIONS

In a relative short period, a new transmission was designed. The transmission comprises increased torque capacity (up to 325 Nm) and robustness, extensive functionality, and a cost-effective design for series productions.
For VDT, the project demonstrated the benefits of using new, state of the art, development

tools and rapid prototyping. With this experience, VDT is able to support their customers with up to date know-how and technology.
From the test results one can conclude that, again, the benefits of the pushbelt CVT were proven with respect to the reduction of fuel consumption and improved driveability.
With the P930 a new standard is set for VDT's prototype transmissions.

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