

VT2+: Further improving the fuel economy of the VT2 transmission

Gert-Jan Vogelaar, *Punch Powertrain*

Abstract— This paper reports the study performed at Punch Powertrain on the investigations on the VT2 transmission with the aim to improve the fuel economy of the transmission. The package of improvements provides the transmission with a new name: VT2+.

The approach of the project was really down to earth and split into two separate investigations. One part focuses on reducing the losses in the transmission, in the other part ways for extending the operating range to more beneficial engine operating areas was investigated. In general this means lower engine speeds for an improved overall efficiency and thus lower fuel consumption.

In the efficiency improvement part of the project, firstly the most important areas of operation of the transmission were identified in relation to fuel economy. In the NEDC cycle, these operation areas are (near) the Overdrive ratio of the transmission and at standstill. All further investigations focused on these operating areas. The analysis showed that no less than 65% of the losses in Overdrive were related to the variator and the oil pump. At standstill most of the losses (no less than 69%) was found to be caused by drag in the D clutch. Just by improving the clamping control software the overall losses in the transmission could be reduced by no less than 19%. At standstill the improvement was a staggering reduction of the losses of 67%.

Apart from looking at reducing the transmission losses, it was also reviewed where and how the transmission range could be extended. Allowing lower engine speeds with a CVT all comes down to improving the oil balance. Investigations are ongoing to increase pump capacity (which will also have an adverse effect on efficiency however) and to reduce the oil amount of oil consumption.

Even though the investigation has not yet been completed for all improvements, it is clear that the VT2 transmission can be further improved significantly. The software improvements are being implemented and the first results show that the transmission can provide as good or even better fuel economy as the same car equipped with a manual transmission. With the other planned improvements, the VT2+ transmission will provide a fuel economy which can be up to 4.4% better than an MT and by doing so, it is among the best in class DCTs and AMTs. With the standard available option of idle stop, the improvements can increase up to 9% better than an MT.

I. INTRODUCTION

The VT2 transmission was developed to be used in clean powertrains. It found its first applications in the Hyundai (Accent) and Kia Pride (Rio). These were Hyundai's and Kia's first hybrid vehicles on the (Korean) market. In both

Gert-Jan Vogelaar is project manager of the powertrain development at Punch Powertrain in Sint-Truiden, Belgium (phone: +32 11 679 294; fax: +32 11 679 230; e-mail: gert-jan.vogelaar@punchpowertrain.be).

these mild hybrids with pancake style motors, the option of idle stop was already integrated and still is a standard feature of the VT2 transmission (without any adaptations to the transmission itself). This idle stop feature also came of use in the Proton EVE full hybrid prototypes (developed by Lotus).

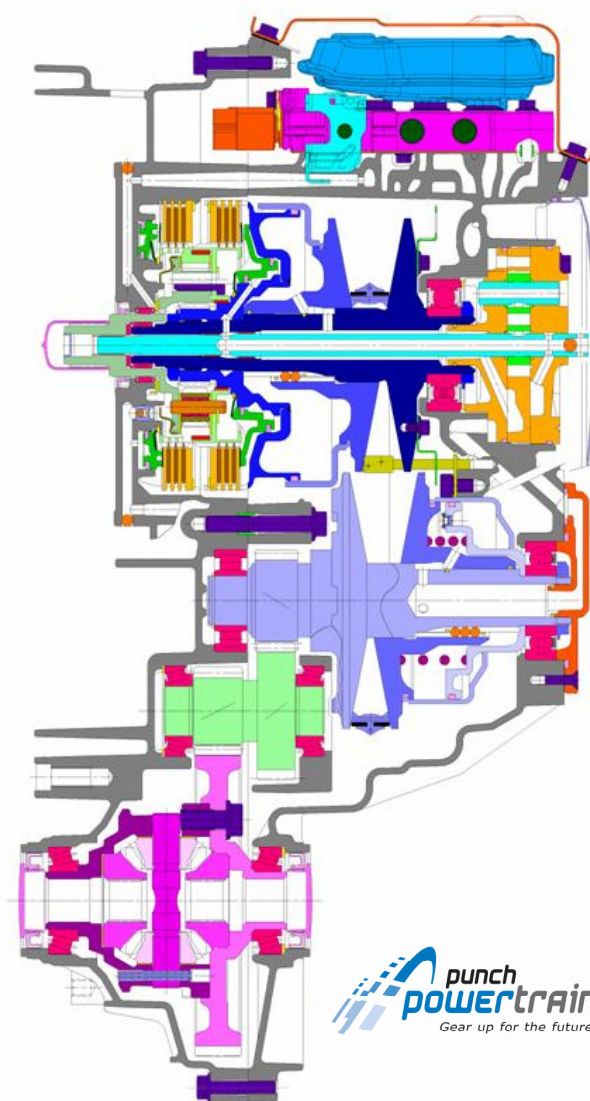


Figure 1. VT2

After these hybrid application and demonstrators, the VT2 transmission has since then been applied in a large number of vehicles. With the ever increasing requirements on emissions, an improvement project was started to further improve the fuel economy of vehicles that are and will be equipped with the VT2 transmission.

II. APPROACH

Compared to AMT or DCT transmissions, a CVT has a worse efficiency. However, because of the higher flexibility or variability of the CVT transmission, it allows the combustion engine to operate in a more fuel efficient area compared to the AMT and DCT transmission. This results in overall comparable fuel economy figures for AMT, DCT and CVTs. Figure 2 shows how AMTs, DCTs and the VT2 CVT perform in terms of fuel consumption in relation to the manual transmission in the same vehicle equipped with the same engine. The VT2 applications are shown over time with a clear improvement over time.

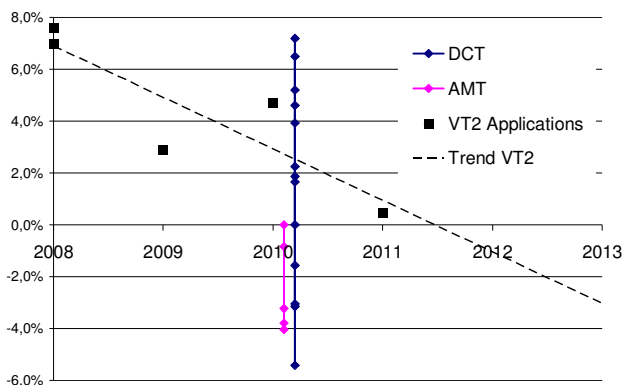


Figure 2. Relative fuel consumption vs. MT

The approach for the VT2+ transmission was to improve both the transmission's weaknesses (the internal losses) as well as on its strengths (its flexibility and capability to bring the engine to a better operating point).

A. Reducing transmission losses

To focus on the real important working points, the NEDC cycle was reviewed and the following operating conditions were identified as most important for improvement:

1. Driving in the OD range
2. Standstill

These operating conditions form the starting point of the investigations for improvement. After validation of the several improvements in these areas, the effect on the NEDC cycle will be reviewed.

B. Improving the flexibility and range

Apart from looking at reducing the transmission losses, it was also reviewed where and how the transmission range could be extended. Basically this implies, allowing the engine to operate at lower engine speeds. To do so, the oil balance of the CVT has to be improved. Again there are two ways to do so:

1. Improve the oil pump output
2. Reduce the oil consumption in the transmission

The current transmission control does not allow a further reduction without mechanical changes to the transmission.

III. TRANSMISSION LOSSES

Via a combination of measurements, the losses caused by various components could be determined for the most relevant operation conditions of the gearbox.

A. Overdrive

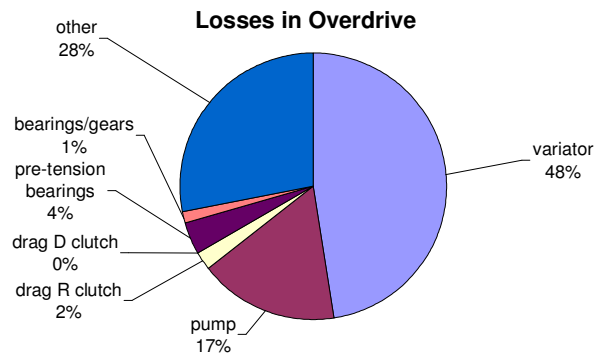


Figure 3. Overview of losses in OD

As can be seen in figure 3, the main cause for losses is in the variator. Apart from the grouped losses under "other", the pump losses are the 2nd largest group of losses. Both these losses are largely depending on the level of the pressure in the secondary pulley, which is equal to the line pressure in the VT2 transmission.

Because of the effect of the line pressure level on the losses, following options were reviewed for improvement.

- New oil with increased friction between belt and pulleys
- A pressure sensor with improved accuracy
- An improved secondary pressure control with reduced safety margins were possible
- Adaptations to the valve body allowing lower pressure levels
- New friction plates requiring a lower oil flow for cooling and thus allowing downsizing the oil pump

The impact of the higher accuracy in the pressure sensor is rather small and the same applies for the friction plates. These improvements were not continued. New oils are still being investigated. The improvement that could be realized so far, comes from the improved software and hydraulics. As can be seen in figure 4, via the improved clamping control, a reduction of the transmission losses in OD could be realized of 19%.

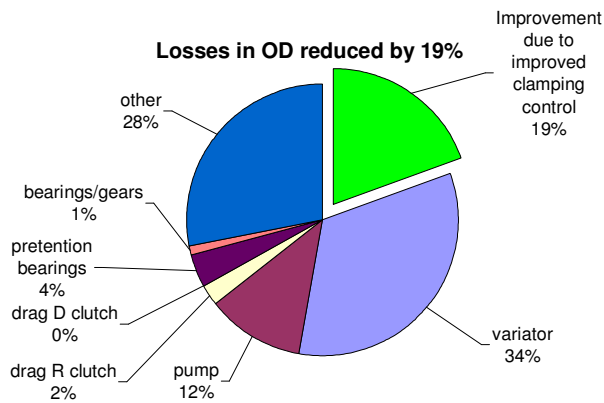


Figure 4. Reduced losses in OD

The losses in other components are fairly small. Therefore it makes no sense to reduce these losses at a large cost. It is unlikely that their improvement can even be measured on a fuel economy driving cycle. The effect of the reduction in clamping pressure level was measured at constant speeds (2-4% improvement). Simulations indicate a possible improvement in the NEDC cycle of approximately 1.5%.

B. Standstill

The same approach as for the losses in Overdrive was also applied for the losses at standstill. The result of the measurements is summarized in figure 5.

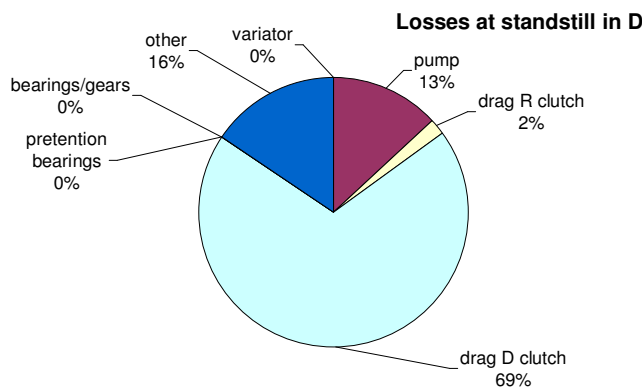


Figure 5. Losses at standstill

It is quite clear that the biggest potential can be found in reducing the drag losses in the D clutch. A clear relationship between the losses and the clutch pressure was found. When reducing the clutch pressure, the (total) losses can be reduced by no less than 67%, as can be seen in figure 6.

After the improvement, the oil pump becomes the cause of the largest amount of remaining losses. Again a pressure sensor with higher accuracy and the friction plates that would require less cooling flow could bring an improvement. As the impact is rather small, these options were not yet investigated in further detail.

The reduction of the D clutch losses can of course only be realized via an improved clutch control functionality to maintain the comfort level of a well engaged clutch during

take off actions. This software has been developed and its effect on the transmission hardware has been tested successfully. As a result, the improved software is being introduced for the VT2 applications. The reduction of clutch pressure could bring an improvement of 1 to 1.5% in fuel consumption. Evidence will follow in this document.

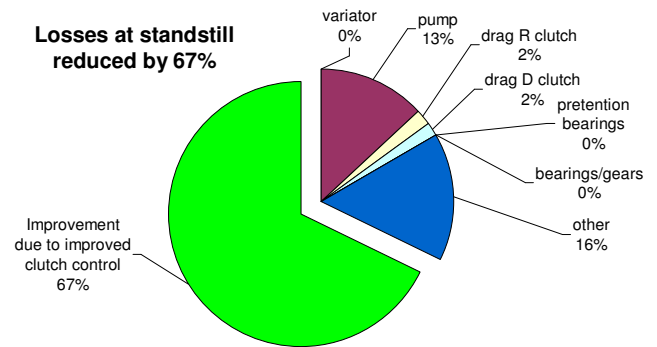


Figure 6. Reduced losses at standstill

IV. FLEXIBILITY AND RANGE

As mentioned, improving the fuel economy by extending the transmission's flexibility or range, basically involves reducing the engine speed whenever possible. Over the years the reductions have reached their limits. The effect of these reductions is shown in figure 7. The reduction indicated between 2011 and 2012 (from 4.7% worse than a manual transmission (MT) to 0.4% worse than the same MT) is caused by a combination of variogram improvements, the improved clutch control described above and an improved warm up cycle (relevance will be shown below).

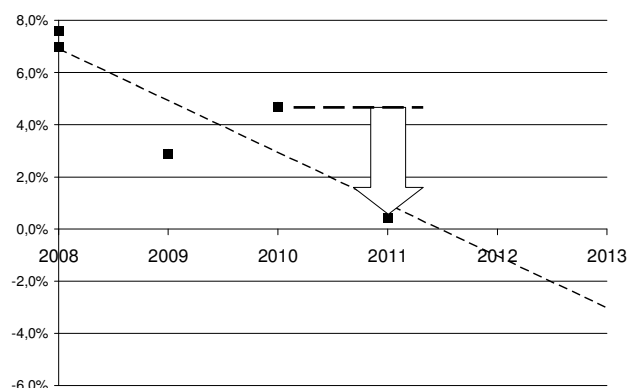


Figure 7. Improved clutch control and variogram

The improved variogram required development of new software functionalities allowing lowering the engine speeds to the absolute minimum. Developed functionalities include an oil balance model and support functions to support the down shifting at decelerations. Further reductions in engine speed can only be realized in case the oil balance is improved. Any reduction in the minimum engine speed for ratios out of Low requires an additional amount of oil for shifting. As can be seen in figure 8, the required oil flow

increases as the engine speed gets lower. Unfortunately the pump flow decreases with engine speed.

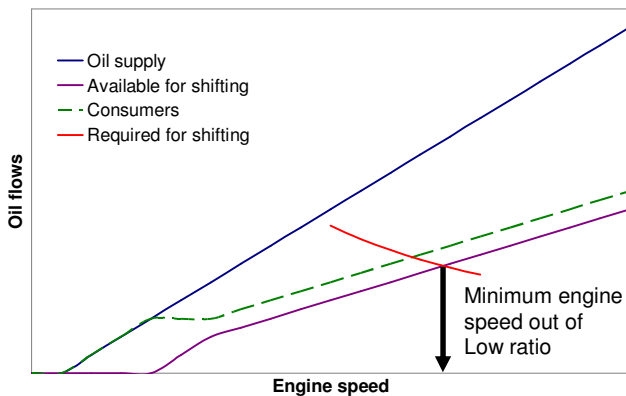


Figure 8. Available and required oil flow

There are basically two ways to achieve the improvement. The first is to install a bigger pump, as is shown in figure 9. Together with the improvement in range, comes however an increase of losses. The other option is to reduce the oil consumption. The most obvious improvement involves better pressure regulators. Direct acting valves require a complete control system re-design, but are certainly an option for the future. In the VT2+ project an investigation was started via Mini Direct Acting valves. These combine the characteristics of a pressure regulator with largely reduced oil consumption. The required changes to the hydraulics are much smaller.

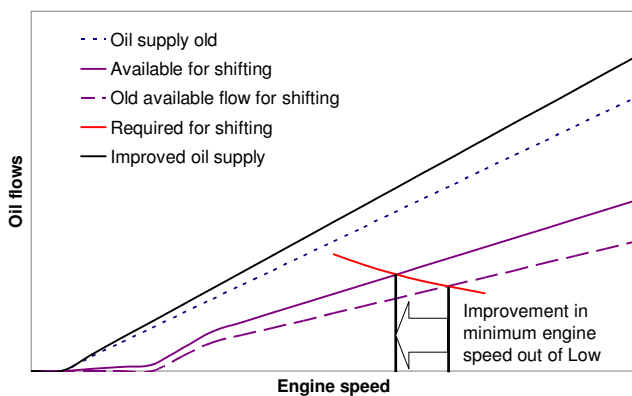


Figure 9. Reducing the minimum engine speed

As can be seen in figure 9, increasing the pump size reduces the allowable minimum engine speed where shifting out of the Low ratio is allowed. A similar picture can be shown for reducing the oil consumption (see figure 10). The reasoning applied to the minimum engine speed to shift out of Low also applies for the minimum allowable idle speed. As this speed is lower than the engine speed to shift out of low and as the pump flow is increasing with engine speed, the improvement at idle is in this case smaller than for the engine speed to shift up. For the reduction in the oil consumers via the pressure regulators, the reduction in idle speed is in the same range as for the minimum speed to shift out of Low.

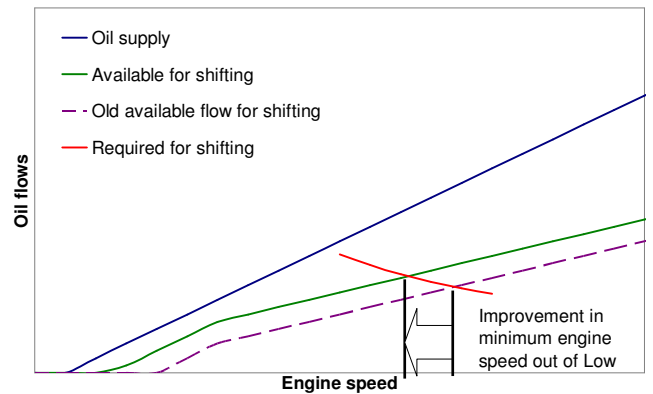


Figure 10. Effect of reducing oil consumers

The effect of reducing the minimum engine speed was measured on fuel economy in a vehicle. An improvement was found of 1.9% on the NEDC cycle for a feasible speed reduction of 200 rpm.

V. IDLE STOP AND IDLE SPEED

As mentioned under Flexibility and Range, the improved oil balance would also allow an improvement in fuel economy. How much of an improvement, is largely depending on the engine and its calibration. The contribution of the idling situations to the fuel consumption in the NEDC cycle ranged from 8 to 14%. Of course not all of this amount can be achieved. First of all, the restarting of the engine, requires fuel and there is also the effect of the warming up of the engine, which is affecting the fuel consumption much more than the efficiency of the transmission.

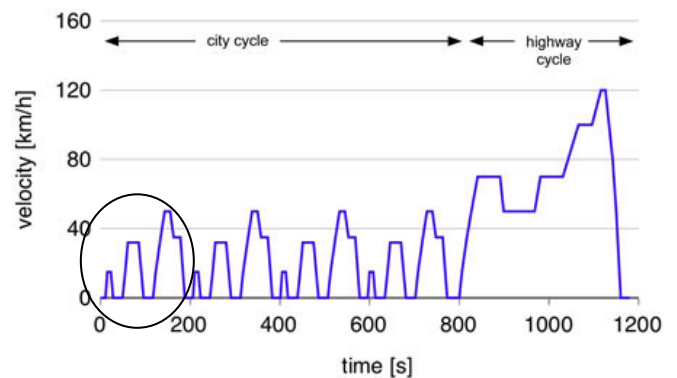


Figure 11. NEDC cycle

The NEDC cycle has a repeating profile in the city cycle as can be seen in figure 11. The fuel consumption per sub-cycle was measured. The results are shown in figure 12. It shows the fuel consumption for each cycle as a percentage of the first cycle. The results are given for the driving part, the overall total and the standstill situations per sub cycle. Both for driving as well as for standstill (and therefore also overall), it is clear that there is a big difference between the 1st and 2nd cycle and only small differences after the 2nd cycle. So the first warming up of the engine is indeed very

important. This proves the relevance of a quick warming up of the engine and the impact of the CVT software on this.

As an estimation, it is assumed that during the first two sub cycles, the idle stop is not yet applied. What remains is then a potential of about 6% if idle stop is applied. Earlier measurements on the FTP cycle with the Hyundai applications revealed an improvement of 9% with the introduction of idle stop, so the estimation seems realistic.

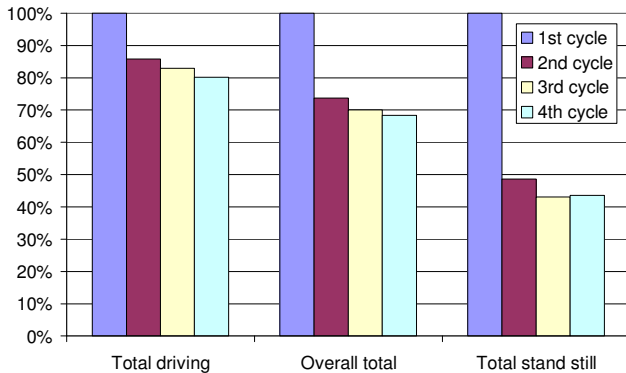


Figure 12. Effect of warm up on fuel consumption

The effect of a reduced idle speed estimated as a percentage of the improvement for idle stop. Reducing the idle speed to about 650 rpm is estimated to bring an improvement of about 1.2% on fuel economy. Of course much is depending on the engine that is used.

VI. SUMMARY OF IMPROVEMENTS

The planned improvements on VT2 are indicated in figure 13. It is clear that VT2+ can meet itself with the best in class DCTs and AMTs.

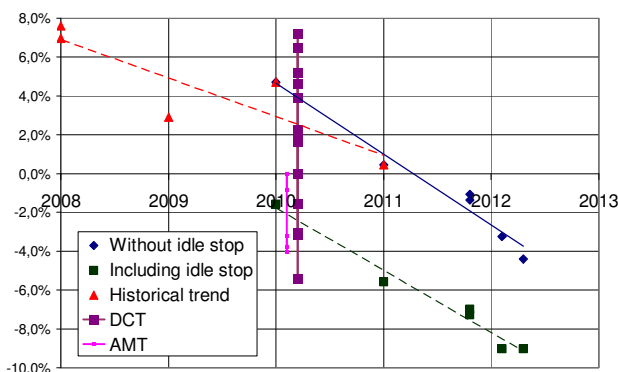


Figure 13. Future trends for VT2+ improvements.

The status of the improvements is listed in table 1.

Improvement	FE vs. VT2	FE vs. MT (cumulative)	By	Status
Baseline	-	+4.7%	2010	Production
Clutch control, variogram, warm up cycle	4.1%	+0.4%	2011	Improvement measured, SW validated
Clamping control	1.5%	-1.1%	2011	Simulation result, SW under development
New oil	0.3%	-1.4%	2011	Estimation based upon comparison of μ , testing on-going
Oil consumption	1.9%	-3.2%	2012	Improvement measured. Hardware testing started.
Idle speed	1.2%	-4.4%	2012	Improvement estimated, hardware testing started.
Idle stop	6% ^{*)}	-9.0%	Now	Option available

^{*)} value is less in case idle speed is already reduced

Table 1. Overview of improvements

VII. CONCLUSION

The VT2+ program, introduces improvements in fuel economy for powertrains with VT2 transmissions. As of 2011, a powertrain with VT2 can provide as good or even better results as the same powertrain with a Manual Transmission. Further improvements bring the transmission to the level of the best performing AMTs and DCTs in the field. Even bigger improvements can be obtained (even from now on, by applying idle stop functionality). On the short term VT2 has the potential to achieve a fuel economy that is 9% better than a manual transmission.