

Co-ordinated Powertrain Control for CVT Shifts Expectations

Continued enhancements in comfort and efficiency

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Summary

The already exemplary driveability of the Continuously Variable Transmission (CVT) is further enhanced by a full integration of this component into the driveline where it forms a natural extension of the engine. The use of Co-ordinated Powertrain Control (CPC) allows the driveline to operate along the most comfortable shift trajectories, at the same time giving way to significant fuel consumption reductions. In a joined effort of several fields of expertise within the BOSCH Group, a prototype has been built that reveals that with this new feature the CVT based driveline remains to set the standard for the future.

Abstract

At this moment transmission and engine designers concentrate on the optimisation of driveline components in their field of expertise. An important step to come to a more joint effort to optimally realise power transfer from engine to road and to prevent disproportionate component sub-optimisations is formed by the Co-ordinated Powertrain Control (CPC).

Where in many applications components such as engine and transmission are hardly aware of each other's presence, this concept assures full integration of these components into a driveline strategy that leads to good responsiveness of torque and speed to the drivers expectation. The integrated approach enables an improved vehicle response making it fun to drive. The use of a continuously variable transmission in this aspect helps to raise this quality to exceptional levels.

Instead of separately controlling engine torque and CVT ratio, CPC focuses on the active control of drive torque, based on pedal position and pedal position transients initiated by the driver. The control algorithm transforms this set point into a practical and harmonious

relationship between comfort and efficiency priorities, keeping in mind the subsystem boundaries. Tests with prototype control hardware and a prototype CVT in an Alfa Romeo 156 GTA show a remarkable improvement for these characteristics.

Introduction

Continuously Variable Transmissions are on the market since 1987. After a moderate start-up, mainly on the Japanese market, the annual volumes exceeded one million CVTs per year in the year 2002. CVTs are expected to grow to a volume of up to 5 Million units per year on the Triade-market (JAP, NAFTA, EUROPE) by the year 2010. The CVTs will find typically their place in front-wheel driven cars in the Mid to Upper range of vehicles (1,5 – 4 L engines), which covers the main volume of cars. The expectation for new markets like China are being explored, but give no clear view yet. The principal market-drivers for CVTs are Fuel Economy (Emission) and driving-comfort, due to the absence of shifts.

However, these market-drivers are being perceived and accepted differently in the three markets. Where the absence of shifts specifically suits very well to the typical Japanese traffic, the CVT is very well accepted here over the high shift business of conventional 4 speed (or even more) Automatic Transmissions. In the USA, the shifting is less of a problem, but the expected increase of the CAFÉ-limits will urge the OEM's more to changeover to transmissions and engines providing better fuel-economy. Especially the SUV class will suffer from that. Here, therefore, fuel-economy and emission will become the main market-driver for CVTs. In the European market, there is now a tendency going-on to more automation in cars, mainly caused by growing traffic jams and increased demand for luxury, starting with the more expensive cars. But still, automatic transmissions suffer a "image-problem" with the European drivers of being not sporty to drive, no "Fun to drive". More over in Europe, fuel consumption is an important factor, caused by high fuel prices.

For mentioned reasons, CVTs are now being threatened, especially on the European market, by further development of conventional ATs to 6/7 speed (6 AT), and Automated gear boxes with dual clutch arrangement (6-DCT). But all of these competitors, 6AT, 6DCT and CVT, have the aim of providing better fuel-economy and fun-to-drive for the end-customer.

This paper presents a project by Bosch of developing a proto-type CVT, targeting for the following features:

High power / performance

The car with CVT offers a high-performance for demonstrating the sportive drive-character of CVTs.

Better fuel-economy

By further integration with engine-management, the Bosch daughters Bosch Engineering Group (BEG) and Van Doorne's Transmissie (VDT) have combined forces to develop the so-called Co-ordinated Powertrain Control (CPC).

This is a further step forward in combining the possibilities of controlling engine torque by active torque-management, towards engine-speed by the CVT controls in stationary and dynamic driving conditions. This is the main subject of this paper.

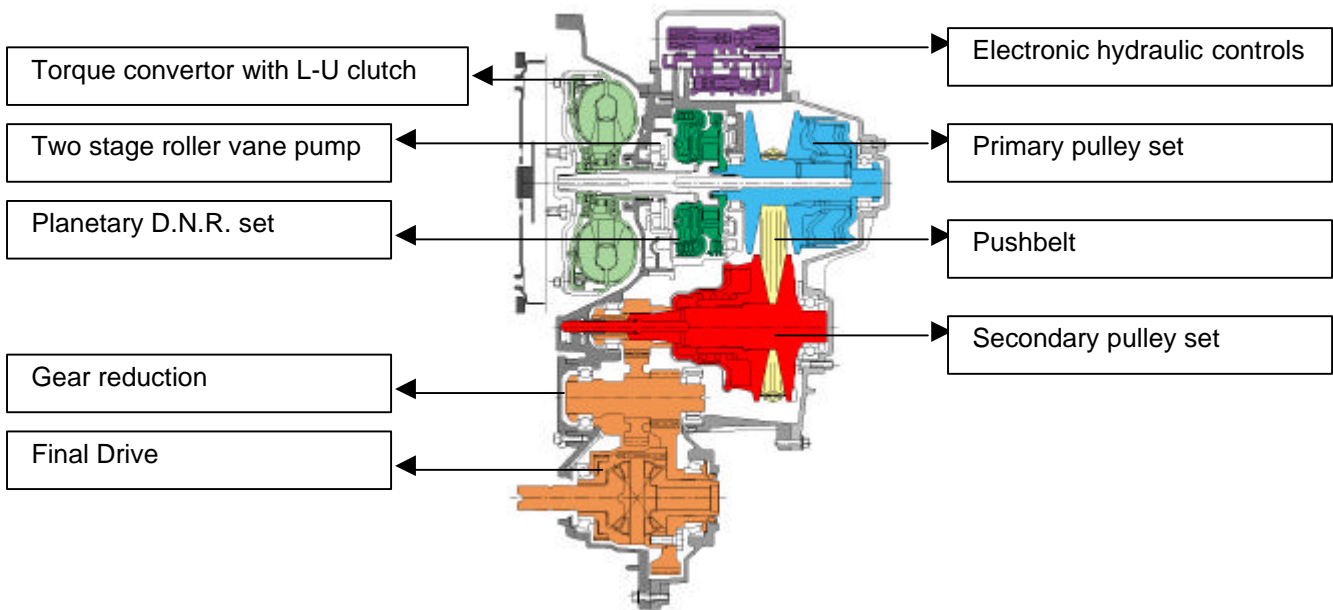
Fun to drive

CPC can also offer the driver numerous programs to balance the driver of appreciating to drive a car with CVT. The demonstration-car offers a number of programs in that respect.

Prototype hardware

Specifications

Vehicle	ALFA 156 GTA, 3.2 litre, V6 ,24V			
Tires	225/45 ZR 17			
Engine	Maximum torque at speed	300 Nm 4800 rpm		
	Maximum power at speed	184 kW 6200 rpm		
Torque converter	Torque ratio	2.46		
CVT	Center Distance	178 mm		
	Ratio Coverage	5.619		
	Low	2.433		
	Overdrive	0.433		
Belt	30 /12			
Final Drive	5.89 (=51 /28 & 55 /17)			
Speed at 1000 rpm	CVT		6 speed manual	
	Low	8.1 km /h	1 st	8.9 km /h
	Overdrive	45.3 km /h	6 th	38.1 km /h



Basic software technology

In recent years, the trend in the automotive industry towards the reduction of product development cycles has continued to gain in significance. Thus it is increasingly necessary to directly transform the results obtained in studies into series products, without additional modifications being made. The use of a high-performance software design is central to achieving this aim, along with the implementation of a rapid prototyping system and a global development process. Bosch Engineering has developed a system for this purpose in which customer functions can be realised as plug-ins, based on the CARTRONIC architecture.

Basic concept

The basic concept is illustrated in Figure 1. A standard architecture of the sort currently to be found in many vehicles contains several control units, each of which being equipped to perform a certain task. These are linked together via a bus, ensuring their co-ordination with influencing functionalities. On the left-hand side of the graphic above, an engine control, a transmission control and a brake control are shown which communicate with each other via a CAN bus. For optimum control of the ratio change process, the transmission is able to communicate, for example, with the engine and demand a torque reduction. If an adaptive cruise control (ACC) is also included in this network, changes must be made to all other systems in order to match the new requirements as regards function and communication.

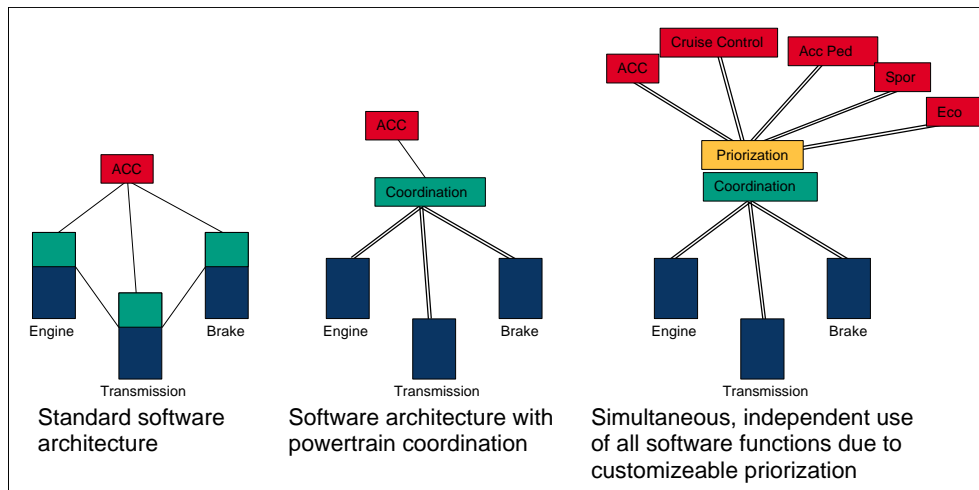


Figure 1

The centre of Figure 1 shows the same situation with the implementation of co-ordinated power train control. In addition, functions are combined into one co-ordination if they do not require connection to a component or to the corresponding control unit. This includes for instance the accelerator pedal interpretation in the engine control (determination of the desired engine torque from the accelerator pedal angle) or the accelerator pedal interpretation and ratio selection in the transmission control (determination of the optimum ratio from the vehicle speed and accelerator pedal position). The functions remaining in the control units are those which are directly linked to the corresponding components, i.e. the air control, injection control and ignition control in the engine, or the ratio change process in the transmission. The co-ordination, which communicates with the components via the physically based standard interfaces, now determines the required engine torque or the optimum ratio. This is highly advantageous, as the specific component type (e.g. Diesel or gasoline engine, converter transmission or automated manual transmission) exerts no influence on the interfaces. In this case, the adaptive cruise control must only communicate with the co-ordination. An adaptation of all three components is no longer necessary.

Plug In concept

If other functions are included in the system parallel to the ACC, as the right-hand side of Figure 1 shows, it becomes necessary to prioritise all of the functions in order to avoid illogical or impossible combinations. For example, the driver can usually use the accelerator pedal to override the cruise control (CC) and to cause the vehicle to accelerate, despite the fact that the CC continues to “drive” the vehicle as long as the driver lessens acceleration or ceases to accelerate. A fixed prioritisation of the various functions could be programmed in the co-ordinator with the disadvantage that this first requires knowledge of the functions and the priority of the functions amongst themselves, as well as the number of functions to be

considered. To avoid this difficulty, an anonymous prioritisation scheme is used which has no knowledge of the number and the types of the functions. A standardised procedure is then implemented for all functions, which is able to consider dynamically varying function priority and the function demand, from which it determines the most beneficial overall demand. The process of establishing an anonymous and standardised prioritisation procedure results in a standard interface which offers considerable openness and flexibility. In this way, functions can be included, removed or exchanged independently from one another, giving rise to the term 'plug-in', which is used to refer to the functions in the text to follow.

By issuing corresponding demands, the plug-ins are able to influence the operating point selection of the co-ordinated power train control in a number of ways:

- Demands for required transmission output torque, required engine torque, brake torque or required transmission ratio, directly influence the driving behaviour of the power train.
- Demands for a certain optimisation criterion (e.g. consumption, sporty driving feel or wear) enable the plug-ins to indirectly influence the driving behaviour, with the plug-in priorities being adapted to each other.

Simulating AT and AMT with a CVT

It is therefore possible to implement and repeatedly use functions, which exert a significant influence on driving behaviour in vehicles with very different configurations, in the form of plug-ins. In this study, test drivers were presented with a total of 6 different strategies for determining the operating point of the power train, all of which were implemented as plug-ins. In this context, an Automated Manual Transmission with traction force interruption and a 6 gear AT are also simulated as plug-ins, in order to demonstrate the freedom with which driving feel can be shaped using co-ordinated power train control and CVT.

Determination of operating point

The purpose of operating point determination is to define the most "optimum" power train operating point at any moment. The complete power train co-ordination ensures a high degree of freedom:

- Interpretation of the driver input (pedals, control buttons, driving behaviour) and setting the requested wheel torque
- Setting of engine torque
- Setting of transmission ratio

In general, the question of when an “optimum” operating point has been selected can only be answered with some difficulty. However in this study it was distinguished by a clear requirement: the determination of driving pleasure in a sporty vehicle with CVT transmission, with exploitation of the potential for fuel economy. The typical characteristics of a pleasure-orientated driving style such as a high torque reserve, spontaneous vehicle response and direct link between vehicle speed and engine speed usually involve high levels of fuel consumption. Thus, the purpose of operating point determination was to dissolve this contradiction. Therefore three different approaches have been combined and will be discussed further on.

First approach: Driver command interpretation as transmission output torque

The popularity of modern Diesel engines - even amongst sporty drivers - can be attributed to some extent, to the power characteristic of such engines. A large torque reserve is available even at low engine speeds, enabling a spontaneous vehicle response to adjustments in accelerator pedal position, without a ratio change being required. This effect is usually not available in vehicles with automatic transmission, as from a certain point, an increase in accelerator pedal position leads to a downshift, without dethrottled engine operation being possible and therefore, without the maximum possible torque being attained. This represents a starting point for co-ordinated power train control and for overcoming contradictory requirements, as the interpretation of the driver command from the accelerator pedal position can be carried out without influencing the complete dethrottling of the engine. Figure 2 and Figure 3 illustrate this connection once again: the starting point is identical in both graphics, the driver drives with relatively little use of the accelerator pedal, before increasing this in order to accelerate.

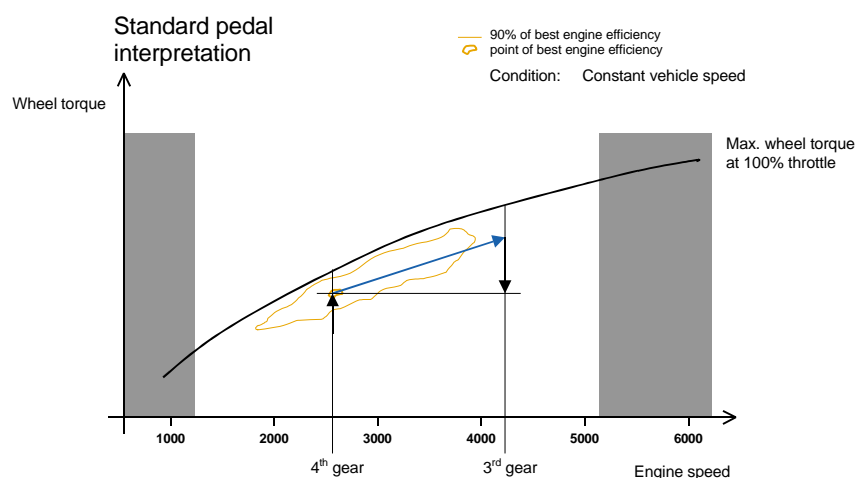


Figure 2

In conventional system configurations (Figure 2) however, the transmission control performs a downshift in order to accommodate the increase. Although the accelerator pedal position initially remains unchanged by the driver, the transmission output torque is increased significantly more than was intended by the driver. He must therefore release the accelerator pedal slightly in order to maintain the desired rate of acceleration.

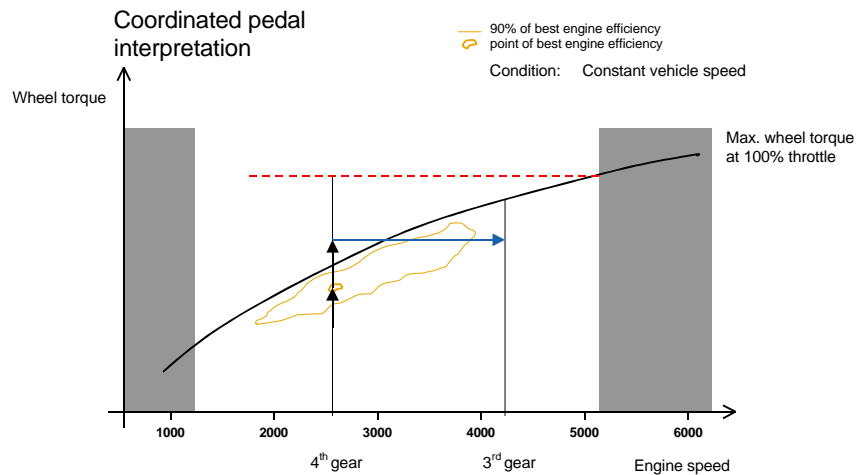


Figure 3

In the case of co-ordinated power train control (Figure 3) with accelerator pedal interpretation as a transmission output torque, the slight acceleration demanded by the driver does not necessitate a transmission ratio adjustment as the torque demanded can be represented by the engine torque increase alone. An adjustment only becomes necessary if in a second step, the driver demands a torque, which is higher than that which can be output in the current transmission ratio. A downshift then occurs without a subsequent release of the accelerator pedal being necessary, as the accelerator pedal interpretation is not changed by the change in transmission ratio.

The interpretation of the accelerator pedal as transmission output torque presents a number of advantages and exerts a positive effect on the driving feel in different ways:

- Unlike the “classic accelerator pedal” which spans the minimum and maximum possible engine torque, the maximum engine torque is demanded at accelerator pedal angles, which are significantly lower. This means that the reaction of the vehicle to small accelerator pedal changes is clearly recognisable, thus contributing to a sportier driving feel.
- A downshift must only be triggered if the demanded torque exceeds the torque adjustable in the current transmission ratio. This avoids unnecessary ratio changes and enables fully dethrottled engine operation.

Second approach: Vehicle speed to engine speed connection

A second important factor influencing the sporty driving feel of a power train lies in the link between vehicle speed and engine speed. This is created through the interaction of two effects:

- The driver experience of vehicle acceleration is based largely on acoustics (external noise and engine noise). The longer the acceleration phase continues, the more intense this effect becomes, as after a period of “familiarisation”, people no longer register constant acceleration as acceleration. Engine speed is the predominant factor in achieving this effect, as the increasing vehicle speed means changes in engine speed are more clearly audible than changes in external noise levels. This is very “noticeable” if the maximum engine speed is reached during full-load acceleration with a CVT and further acceleration at a constant engine speed is achieved by transmission adjustment. The impression of acceleration decreases persistently.
- In vehicles with manual transmission, the additional torque provided by the engine always effects the wheels directly. This enables the driver to control the vehicle precisely, for example on a straight roadway, or in a curve borderline situation. Furthermore, the behaviour can also be reproduced in future situations. In the case of automatic transmission with torque converter or CVTs, vehicle behaviour can change drastically in this respect. The torque produced by the engine in the same situation is initially converted to an increase in engine speed. The energy required is not available for acceleration. There is no direct link between the accelerator pedal and the torque influencing the wheels. Instead, a “rubber band effect” results, with slight changes in vehicle speed occurring as engine speed increases (the rubber band is stretched), with a large torque then being provided (the rubber band accelerates the vehicle). Brief, delicate accelerator pedal changes for controlling driving dynamics do not, however, result in the desired effect and are only converted into changes in engine speed.

The link between engine speed and vehicle speed is a second starting point for the coordinated power train control, which enables the implementation of strategies to positive effect. A detailed explanation is given below of the strategy selected for this study.

Third approach: Accelerator pedal response

The gradient of the requested demand from the accelerator pedal interpretation in relation to the change in accelerator pedal position was identified as the third factor influencing a sporty driving feel.

Realisation of the approaches

The realisation of the approaches depend on the current driving situation. In stationary and low dynamic drive conditions the so-called "modest mode" becomes active. In situations which could be roughly described as more dynamic the "backlash mode" is used. The differentiation between the modes is based on the driver input through the accelerator pedal.

The accelerator pedal is interpreted as the transmission output torque (proportional to wheel torque) of the minimum transmission output torque possible in the current transmission ratio, up to the maximum transmission output torque which can be adjusted by the smallest possible transmission ratio at the current vehicle speed (see the red dotted line in Figure 3).

The modest mode is selected providing the torque demanded by the driver input via the accelerator pedal is not greater than the torque adjustable in the current transmission ratio. If the driver input exceeds this limit, a switchover is performed to the backlash mode, and the transmission starts changing the ratio.

Different procedures are used to determine the transmission ratio in the two modes. However, two constraints reduce the determination of the operating point to the determination of the transmission ratio:

- The accelerator pedal interpretation has already occurred (transmission output torque demand)
- The demanded transmission output torque should actually be adjusted if possible.

Since the transmission output torque results directly from engine torque and transmission ratio, it is sufficient to order the transmission ratio with the engine torque resulting automatically.

Modest mode

A transmission ratio appropriate to the current vehicle speed is set in modest mode, causing the engine to run at an operating point, which is optimal in terms of consumption. However, for reasons of driveability, it must be noted that a certain minimum torque reserve is available in order to prevent a switchover to the backlash mode in the case of small accelerator pedal changes, for example, to compensate for slight slopes or for moderate acceleration. The driving feel remains highly satisfactory, despite the fuel-efficient engine speed, as small changes in the accelerator pedal are swiftly converted by changes in the engine torque (a change in the transmission ratio of a transmission is usually significantly slower).

Backlash mode

When a switch to the backlash mode occurs, a new transmission ratio is set with a higher engine speed, enabling the conversion of the torque demand, which could not be represented in the previous transmission ratio. When calculating the engine speed jump of the adjustment, it must be ensured that it is neither too short nor too long. Although a small jump can be realised quickly and comfortably, a further increase in torque demand on the part of the driver could necessitate a further jump within a short period of time. Although this problem does not occur if the jump is too long, the more drastic increase in engine speed may be loud and uncomfortable for the driver, if the threshold between modest mode and backlash mode was exceeded only slightly. To avoid this problem it appeared useful to “inform” the driver of the threshold being reached, enabling him to make a conscious decision as to whether or not a downshift should be triggered for the purpose of increased acceleration. A hysteresis range was therefore implemented in the torque default, at which the state of the drive train was not changed despite further accelerator pedal movement, thus preventing the increased acceleration of the vehicle. However, this form of feedback was rejected by most of the drivers as being unacceptable. A Force-Feedback accelerator pedal appears to be a suitable solution for this problem.

The backlash mode remains active as long as the desired torque does not clearly sink back into a range, which can be represented by the transmission ratio of the modest mode, appropriate to the vehicle speed, including a torque reserve.

Sufficient torque reserve is available in the backlash mode at all times (restricted only by the maximum engine power, engine speed and transmission ratio coverage). Therefore, the achievement of a sporty driving feel in line with previous considerations depends largely on the link between engine speed and vehicle speed being as direct as possible. First, a constant transmission ratio can be considered which corresponds to the engagement of a gear for manual transmission. However, this is disadvantageous in that the engine speed range remaining for acceleration may be very small up to maximum engine speed. This does not present a problem for manual transmissions as the driver then engages the next gear; however, an uncomfortable procedure such as this would be unthinkable for a continuously variable transmission. The transmission ratio is usually adjusted in accordance with vehicle speed, enabling the engine speed to constantly remain at its maximum.

Semi constant transmission ratio

The concept of a “semi-constant transmission ratio” was developed as an alternative to the constant transmission ratio.

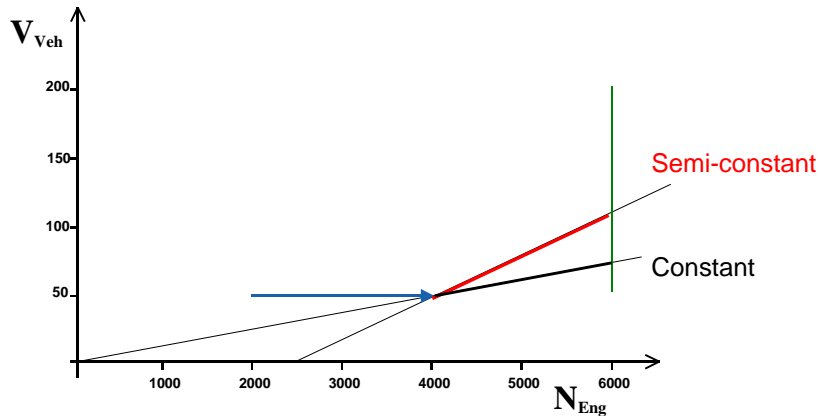


Figure 4

In the diagram showing vehicle speed over engine speed (Figure 4) a straight line selection by origin (constant transmission ratio) has not occurred. Instead, a displaced line has been selected. This enables a much longer operation time in the link range between engine speed and vehicle speed. The gradient of the straight line must be selected according to various criteria:

- If it is too flat, the resulting acceleration will be rapid, but operation in the link range will run through quickly.
- If it is too steep, the resulting vehicle acceleration will be insufficient.

If the settings are correct, the driver notices no change in transmission ratio and will be able to find a balance between the vehicle speed range and a very sporty driving feel.

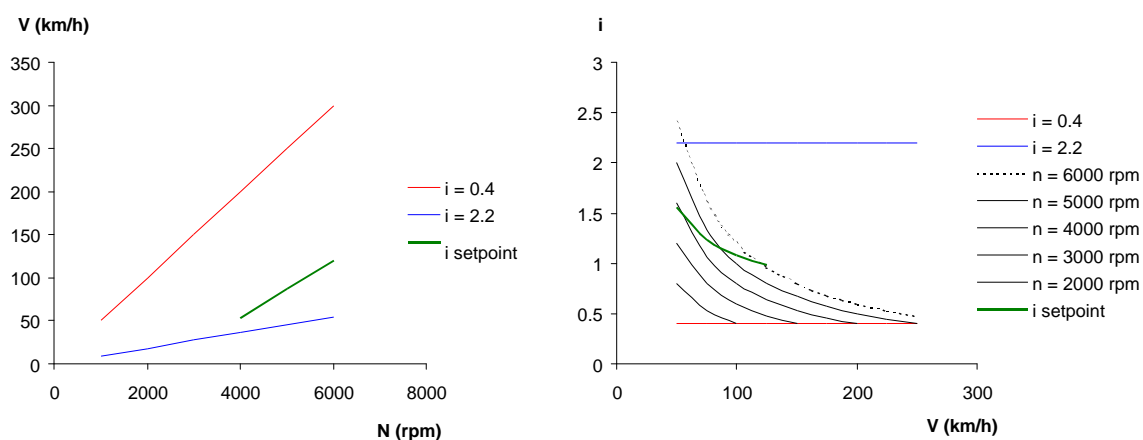


Figure 5

Figure 5 once again illustrates the connection between vehicle speed, engine speed, and transmission ratio during acceleration with a semi-constant transmission ratio. The diagram

on the right clearly illustrates the difference between this and a constant transmission ratio (horizontal straight line), with the entire acceleration phase being adjusted continuously.

Fuel consumption

The study also involved a further procedure for operating point determination, which was based on the consumption curve of a combustion engine (see Figure 6).

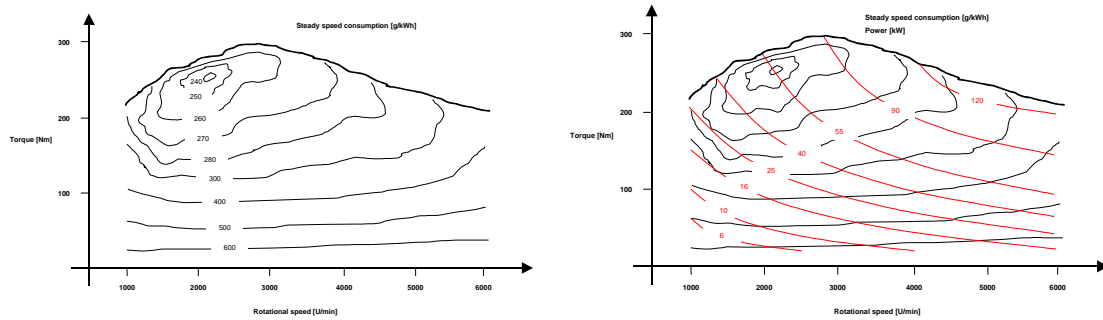


Figure 6

This involved the conversion of the driver input via the accelerator pedal into the output power of the transmission, according to the transmission output torque with the current wheel speed and axle ratio. The point of intersection of the consumption curve and the power hyperbola of the power demanded was then established in the engine map. The engine torque, engine speed and the transmission ratio to be set were then determined (power train losses were taken into account in the calculations). The advantage of this procedure is that an optimum operating point in terms of consumption is set for every demand. However, unfortunately the driving feel was very poor. Across a broad range, even small changes to the accelerator pedal resulted in distinct changes in engine speed and transmission ratio, leading to a rubber band effect which could be clearly felt, despite the fact that the reaction to a spontaneous increase in demand, depending on the maximum adjustment speed of the transmission, was actually very good.

More far reaching procedures for further reductions in consumption (such as pulse operation, acceleration with optimum efficiency followed by freewheeling with the engine switched off) were not examined, as they cannot be reconciled with the requirements of a sporty and comfortable driving feel.

Summary / conclusions

Today's situation on CVT

The majority of the current CVTs have a stand-alone TCU, acting independent from the engine ECU, or in some cases communicating with the ECU. The general comment on current CVTs is that the driveability, fun to drive, is still offering the well known rubber belt effect and high consistent engine speeds at full throttle driving. This is caused by the fact that in dynamic drive conditions, the vehicle performance is calibrated to maximum acceleration. The driver's perception, however, is used to a audible relation between increasing engine speed combined with vehicle speed, as being used to stepped transmissions through many years, either manual or automatic.

In most of the current CVT cars on the market this is the case because present CVT controls do not offer the possibility to interfere with the engine controls at those conditions. Moreover, in quasi stationary driving conditions the requirement to the CVT –controls demand different compromises for reaching optimum vehicle fuel-economy, which is a compromise hardly to achieve.

Co-ordinated Powertrain Control (CPC)

The co-operation of BEG and VDT within the Bosch Group has developed the CPC in the Alfa 156 GTA-project to improve this situation. The challenge of this development was to realise the discrepancy between stationary and low –dynamic driving conditions (modest mode) where optimum fuel-economy and driving -comfort is required, and high dynamic drive conditions (backlash mode), where optimum performance of the vehicle is required.

Where the traditional CVT controls (i.e. set point engine speeds) are being realised by pre-programmed engine-speed mappings in the several CVT-programs, with CPC the engine – CVT – controls are managed completely different. Dependent on the way the driver operates the throttle and brake pedal, the controls will understand the driver's wish how to change one situation to the new situation. From this, the controls understand the difference between a desired quasi-stationary driving condition and a dynamic one and react accordingly. This implies that the amount of engine torque (throttle opening) is completely dis-coupled from gas pedal position.

Through special algorithms in this case, the engine torque increase can be up to 100% in par – load pedal movements, and the engine speed change (ratio control) will be acting similarly

to existing transmissions by a quick initial engine speed increase of 1000 rpm and a slow increase along with vehicle speed, after that. This reflects more the driver's expectation as being used to existing transmissions.

Results

The incorporation of the CPC -engine –transmission-controls resulted in the following:

- In stationary and low dynamic drive conditions (modest mode), optimum fuel economy can be obtained while maintaining good driveability.
- In dynamic drive conditions (backlash mode), a good compromise between driveability (fun to drive) and fuel economy can be reached.

Final

By these accomplishments, Robert Bosch is able to offer the customers more than only ECUs and TCUs hardware equipment with customer defined functions, but a dedicated control strategy of the combination of engine and transmission controls, to achieve the optimum combination between fuel economy and fun to drive. The customer hereby is offered full access to perform its own vehicle calibration

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