IC-Engines and CVTs in Passenger Cars:
A System Integration Approach

Wolfgang Kriegler
Albert Zrim
Gert-Jan van Spijk

AVL List GmbH, Austria
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Synopsis

Continuously variable transmissions (CVT) based on steel push belts have reached a high stage of development and offer high comfort and good driveability to the customer. Besides that, the possible decoupling of the ic-engine and vehicle speed enables ic-engine operating conditions with lower specific fuel consumption resulting in an attractive vehicle fuel economy.

In the study – using a block oriented graphical simulation tool – three different CVT concepts, which primarily differ in the design complexity and their ratio coverage, are investigated and compared to a five speed manual transmission.

Together with the mentioned CVT concepts three spark ignited engines using latest combustion technologies and one advanced direct injection diesel engine are used to simulate various drive train variants and to show their possible system integration benefit.
Fuel and engine-out emission predictions are gained by a closed loop simulation of urban driving cycles using stationary engine maps.

Possible fuel improvements, measures and target conflicts of the ic-engine adaptation to CVTs are highlighted from the view of the engine developer by means of the obtained simulation results.

1 INTRODUCTION

With continuously variable transmissions (CVTs) in passenger car powertrains high comfort, good driveability and acceptable acceleration can be accomplished. In addition with further improvements regarding efficiency vehicles equipped with CVTs might achieve comparable or better fuel economy than vehicles equipped with conventional automatic or even manual transmissions. So finally, CVTs might become a highly comfortable and cost effective solution for the end user as well as for the car manufacturer.

There are numerous possibilities to realise continuously variable transmissions. The various systems may base on different physical principles (hydrostatic, hydrodynamic, electric, mechanic) and not all of them are equally suitable for passenger car application (1), (2).

So throughout a joint research project the integration of ic-engines and improved CVTs has been investigated by a series of driveline simulations to prove and quantify the fuel consumption and emission benefits. The investigated three transmission structures are based on the van Doorne's (VDT) steel belt system (3) and differ from their possible ratio coverage.

In general compared to manual transmissions higher fuel consumption is to be expected with CVTs due to the lower part load efficiency. However, it is worth to investigate to which extent this drawback can be compensated by shifting the ic-engine's operating area to lower speeds and higher torques with better specific fuel consumption - an operating range, which hardly can be reached with stepped multi-ratio transmissions with limited input/output ratios.

By superimposing the specific fuel consumption map of the ic-engines and the CVT efficiency maps operating trajectories may be found in the engine map offering best possible fuel consumption for every desired power. These operating lines can be optimised not only with regard to fuel consumption but also regarding emission and performance. Furthermore due to the large CVT ratio coverage high overdrive ratios may be realised which also help to improve fuel consumption in driving practice.

To quantify the benefit of advanced CVTs in combination with newest combustion engine technologies, three different spark ignited (SI) engines including one gasoline direct injection (GDI) and one advanced direct injection diesel engine were used in the driveline simulation programme. The choice of these engines was not only influenced by technical aspects but also by terms like availability, costs and the demand of using non-prototype state of the art combustion engines.

2 SPECIFICATION OF VEHICLE AND POWERTRAIN

2.1 Vehicle

For the vehicle simulations a mid-class passenger car with the following specification was chosen, see Tab. 1.

Tab. 1: Vehicle Specification

vehicle curb weight	1150 [kg]
Cd *A value	0.65 [m^2]
top speed	190 [km/h]
dynamic rolling radius	0.29 [m]
rolling resistance coefficient	0.011 [-]

2.2 CVT-Concepts

To keep the number of simulations restricted a choice was made out of an almost infinite number of possible configurations. The final choice was made regarding aspects concerning the chance that the solution is acceptable in terms of available experience, driveability, costs, etc. on the one hand and trying to make a "big step" in development on the other.

The result of this is a comparison with the inevitable Reference, that is a lay-out based on the existing developments. A 2-Stage concept in which the variator is followed by an AT-like epicyclic gear, making available a speed reduction, a reverse and a direct drive. And third an i^2, which is using its variator ratio coverage twice by reversing torque direction between two operating modes. These concepts result in a wide variation in ratio coverage. This variation was then concentrated on applying ratio-coverage for higher V1000 in Overdrive, thus keeping performance comparable and striving for maximum fuel economy. Fig. 1- Fig. 3 show the schemes of these systems where variator ratio is the speed of primary pulley shaft divided by secondary pulley shaft. Transmission ratio is the engine speed divided by the speed before final reduction.

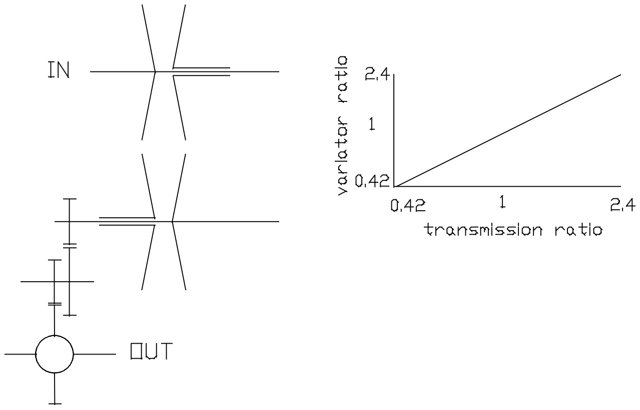

Fig. 1: CVT-concepts EcoDrive: Reference

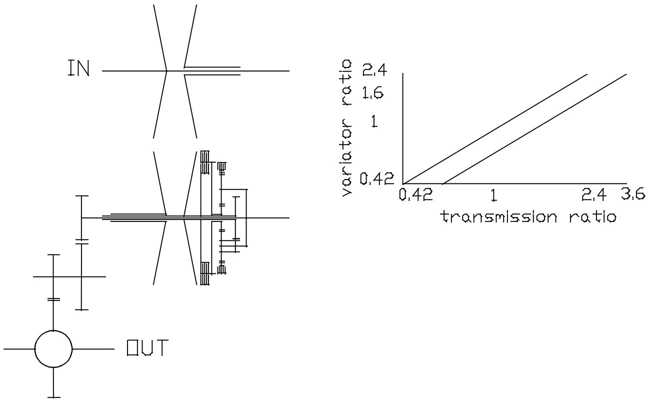

Fig. 2: CVT-concepts EcoDrive: 2-Stage

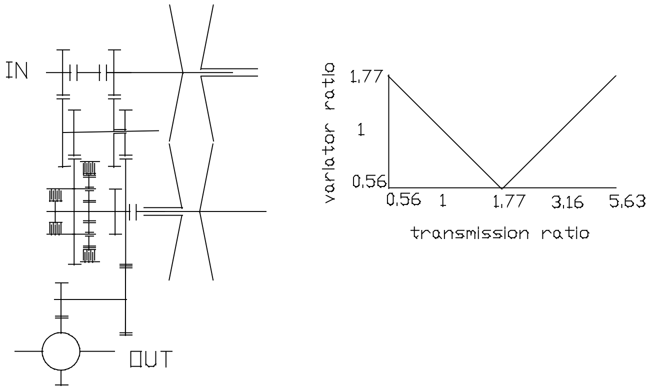

Fig. 3: CVT-concepts EcoDrive: i^2

2.3 IC-Engines

To study the effect of different ic-engines in the drive train three SI-engines and one advanced diesel engine are implemented in the simulation model using stationary fuel consumption and emission maps.

SI-engines:

- MPFI (Multi Point Fuel Injection), 16V, VIS (Variable Intake System), 1.4 ltr., N.A., 50 kW/ltr.
- AVL-CBR (Controlled Burn Rate), MPFI, 16V, VIS 1.4 ltr., N.A., 50 kW/ltr.
- GDI (Gasoline Direct Injection), 16V, 1.4 ltr., N.A., 50 kW/ltr.

Diesel engine:

- HS TDI, 2V, 2.0 ltr., EURO III Emission concept, EGR

The MPFI engine is used as a state of the art base engine. Part load fuel economy improvement and knock optimisation is achieved with the AVL CBR combustion system where a different design of two intake ports

- one straight intake port – "tangential port" – which creates an intake flow induced in-cylinder swirl with the swirl axis parallel to the cylinder axis

- one "neutral port" that induces an intake flow directed downwards the cylinder

increases the charge motion both with and without port throttling (4), (5).

The GDI engine is used in the first mass produced vehicle with GDI technology. It utilises four distinct modes of operation.

The engine is operated stratified in the low speed - low load area. The combustion concept changes to homogenous lean, homogeneous stochiometric in medium part load and homogenous (Lambda < 1) at full load. The engine is tuned for the Japanese market and does not yet comply with the EURO II regulation.

3 ESTABLISHMENT OF CVT EFFICIENCY FORMULAS

One of the crucial parts of implementing the CVTs simulation model is the establishment of appropriate efficiency formulas. A study was made concerning the losses of the different transmission configurations. The reference in the investigation is a CVT set up which has been tested and whose efficiency data are available.

Aspects that are taken into account are losses in gears, losses in bearings as a function of load and speed, losses in dragging clutches, losses in the variator and losses because of clamping force.

The losses generated by the gear meshes are almost constant, the main influence is observed in the 2-Stage and i^2 where the number of load transferring gears is higher in low ratio mode, and therefore a stepwise change in efficiency occurs (Fig. 4).

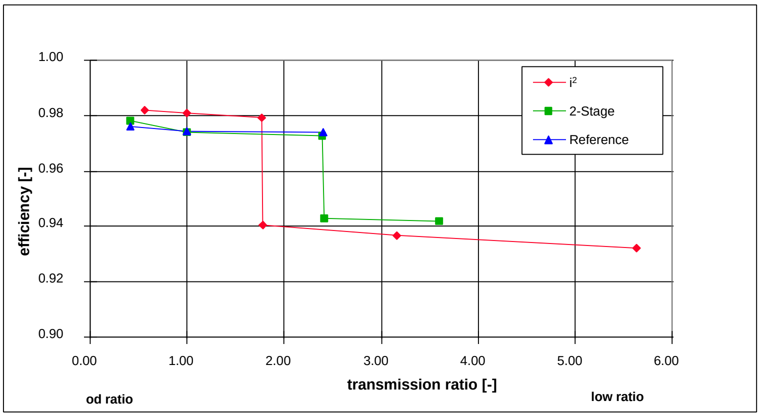

Fig. 4: Gear efficiency

The load dependent bearing losses are linear with bearing load and ratio. Especially for the i^2-concept the losses raise stepwise when low ratio-mode is entered. The chosen lay-out has a direct torque path in high ratio mode and follows a long gear path for low ratio mode.

Speed dependent bearing losses are related to engine speed to the power 2/3, and ratio: For higher variator ratios the losses raise strongly, because of the increasing speeds at the secondary side of the variator.

Under the assumption of a constant friction coefficient the losses in open clutches are constant for the conventional reference lay-out; decreasing with lower ratios for a 2-Stage and minimal in the synchronisation point of an i^2 and raising towards low and high ratios.

From the calculated results the difference of losses compared to the known reference transmission are determined. For this difference a fit as a function of speed, torque and ratio was established and added to the efficiency formula.

Together with known relations for variator efficiency, this leads to overall efficiency formulas. Fig. 5 shows the relation for full load conditions at an ic-engine speed at 2000 rpm.

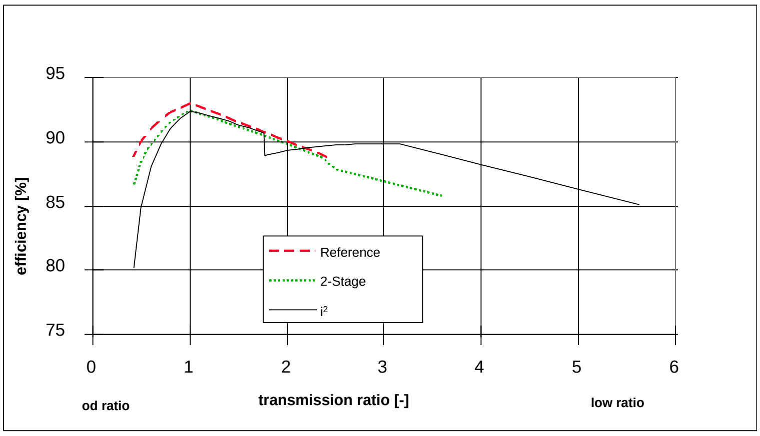

Fig. 5: Full load CVT efficiency at 2000 rpm engine speed

4 SIMULATION RESULTS

The simulation results show that with the investigated CVT concepts the fuel consumption is in the range respectively below a manual 5-speed transmission. Compared to a conventional automatic transmission there is a significant reduction of fuel consumption.

In the considered driving cycles FTP72 and MVEG (warm) the improvement in terms of fuel consumption compared to manual transmission is up to 10 % for the SI-engines and up to 19 % for the diesel engine. This improvement is achieved by operating the engine to a far extent at an operating trajectory with minimal specific fuel consumption.

Fig. 6 shows the fuel consumption values for the driving cycle MVEG. The fuel consumption of all CVT concepts is below the values of the manual transmission, the maximum improvement in fuel consumption can be observed within the i^2 CVT concept.

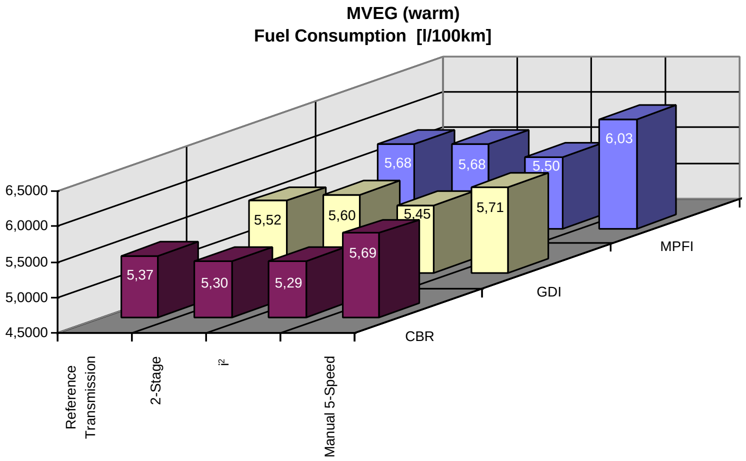

Fig. 6: Calculated fuel consumption for different SI-engines and CVT concepts

Besides other goals modern SI-engines attempt to reduce fuel consumption in the engines part load area under the constraint of existing and upcoming exhaust emission standards. Shifting loads to higher engine BMEP levels with the aid of CVTs imply that the part load improvements are less effective. This means that there is a fuel consumption reduction with CVTs in absolute values but the percent advantages of the engine part load improvements are decreased. Fig. 7 shows the calculated advantages in per cent achieved with modern combustion concepts for a manual 5-speed transmission and the i^2 CVT.

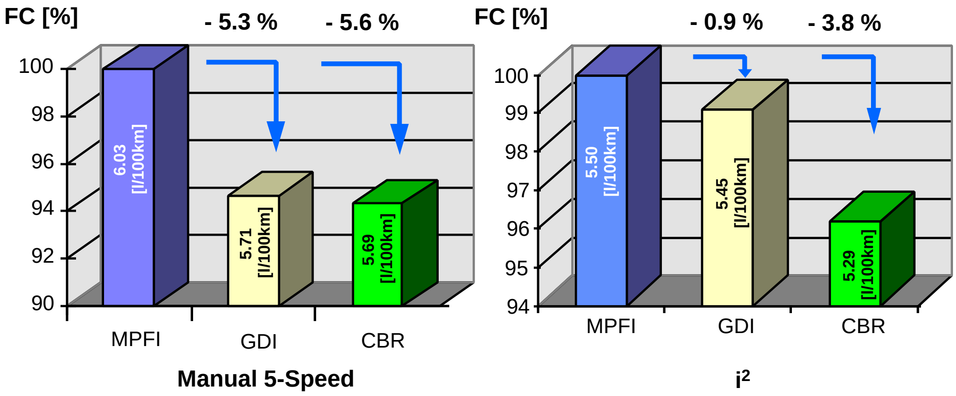

Fig. 7: Per cent difference of fuel consumption for Manual Transmission and i^2-CVT (Cycle: MVEG)

However, the engines are tuned for conventional transmissions and modifications of the tuning strategies with consideration of the CVT peculiarities would minimise the differences. The CVT strategy to use higher loads with lower specific fuel consumption requires that the optimisation task to be solved is positioned in higher load areas.

The optimisation measures for a given engine primarily concern

- ignition timing
- injection timing
- EGR (Exhaust gas recirculation) rates

For GDI engines the optimisation also includes calibration concepts in the distinct operating areas. For part load operation homogenous GDI combustion systems offer an improved performance potential for emission reduction whereas stratified GDI combustion systems offer improvement in fuel consumption. The focus on current development efforts is primarily on extremely lean stratified operation. However, there is a wide variety of base concepts under discussion for GDI engines (6), (7).

For diesel engines a consequently striving for best fuel consumption with CVTs, leads to a bad fuel consumption - NOx tradeoff, although considerably improvement in fuel consumption is calculated (Fig. 8).

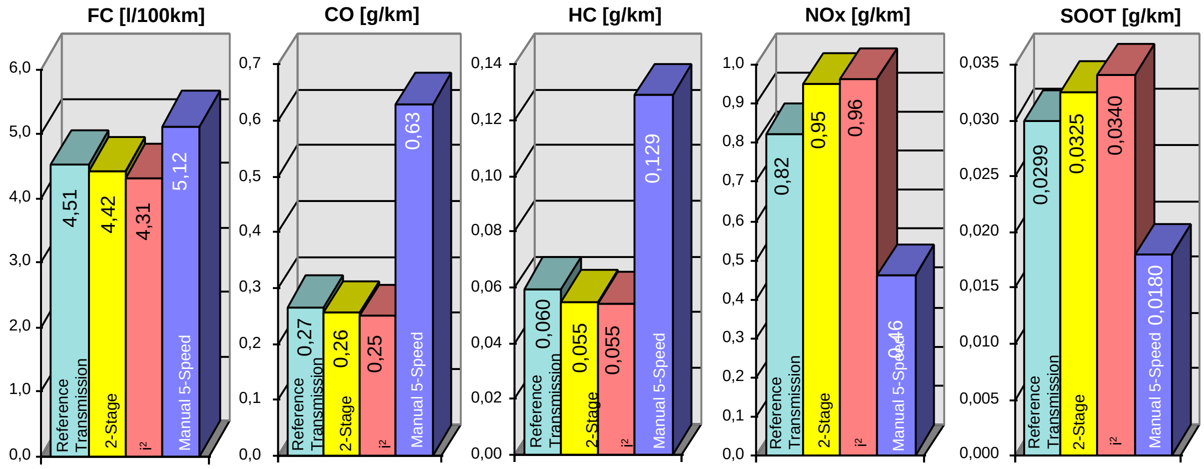

Fig. 8 Calculated fuel consumption and engine out emissions for diesel engine (Cycle: MVEG, warm)

Besides fuel consumption and emission results the simulations have shown that the contradictory power requirements of a vehicle in urban and highway driving lead to a target conflict. On one hand the average power in urban driving is pretty low, about 4-8 kW, and on the other hand for maximum speed - desired was 190 km/h - the vehicle absorbs 65 kW which determines the displacement and size of the ic-engine.

So roughly, the powertrain has to cover a power range of 1 : 12 (14). In other words if we concentrate on daily urban driving the ic-engine and the transmissions are operated in part load conditions with low efficiency. Strategies to achieve better part load efficiency of engine and transmission are raising combustion efficiency i.e. lean burn as described etc., raising load factor by downsizing engine displacement or application of CVT transmission.

The achievable compromises may be seen by a simple calculation. Engine power P_{eng} is proportional to the engine's displacement V_h, brake mean effective pressure BMEP and speed n and can by expressed by the equation

$$P_{eng} = c\ V_h\ \mathrm{BMEP}\ n$$

where c is a constant depending on the number of strokes.

Effect of smaller displacement

Reducing the engine's displacement would significantly increase the load factor in urban driving and so bring the desired effect. But when maintaining the maximum power the speed range and/or the BMEP needs to be increased by the same ratio. This measure is not easy to achieve neither on spark ignited nor on the DI-diesel engines as described below.

Effect of engine speed reduction

Theoretically an engine could be redesigned for the smaller speed range and so increasing the required ratio coverage of a CVT. Furthermore some other benefits on the engine side can be achieved like the optimisation of gas exchange including charging systems and fuel injection systems etc. would be easier.

An example: To get the top speed of 190 km/h for the vehicle specified in Tab. 1 engine power of approximately 72 kW is necessary which is provided at about 5000 rpm. Assumed that maximum engine power is given at a realistic BMEP level of 11 bar (spark ignited) a reduction of engine speed to e.g. 3000 rpm would require a BMEP value of about 18 bar for identical displacement. To realise such high BMEP levels SI-engines have to be charged.

Turbocharging SI-engines requires lower compression ratios that are reducing efficiency especially at part load, and retarded ignition timing at higher loads to improve knock behaviour. Special measures are necessary to handle the expected thermal problems. So summing up, the turbo charged SI-engine would accomplish no significant benefits in urban driving and would be also a cost intensive solution.

From the above considerations it can be concluded that the desired performance of the vehicle determining the power requirements, the displacement, speed range of the ic-engine, the question of turbocharging need to be discussed very carefully. As ever, decisions on these items are not only driven by technical aspects but also by acceptance and marketing considerations.

5 CONCLUSIONS

The demand for improved economy and reduced emissions while maintaining good vehicle performance implies that vehicle optimisation becomes an integrated process of ic-engine and transmission optimisation. One promising approach to get a maximum system integration benefit is to incorporate advanced continuously variable transmissions with sophisticated driveline control.

In MVEG-cycle driving with conventional drive trains (manual or automatic transmissions) the ic-engine is mostly operated in extreme part load. CVTs enable to run the ic-engine at higher BMEP levels and lower speeds which is advantageous for fuel consumption. Due to the size of engine required by the desired performance this effect must not be overestimated. Nevertheless, with good transmission efficiencies the simulations show that with CVTs very attractive fuel economy is achievable, even better than with manual transmissions.

The implementations of CVTs in the powertrain as well as modern combustion technologies aim at the same target - to improve the part load efficiency of the powertrain. That implies that the CVT benefit together with such technologies gets relatively smaller, but of course in combination a further fuel consumption benefit is possible.

As far as emissions - without taking dynamic effects into account- are concerned the introduction of CVTs has different effects on diesel and gasoline engines. Emission reduction measures need to be shifted to the new dominant engine operating areas.

Comparing the Reference CVT and the 2-Stage CVT the latter seems to offer only small fuel reduction potential for its added complexity and cost.

For a best possible system integration of ic-engine and CVT the specification and dimensioning of the power source need to be done very carefully. However, the idea of generally narrowing the ic-engine speed range by using CVTs seems only partially feasible due to power considerations. Such a small speed bandwidth would ease the engine development and is promising cost advantages.

6 OUTLOOK

Emphasis of the current work was put on the establishment of appropriate simulation models and first fuel consumption and emission predictions. Further work will include simulations with modifications to the stationary engine maps (e.g. shifting of EGR operating area) and the variation of operating trajectories to get a deeper insight of ic-engine – CVT optimisation.

To verify the theoretical predictions and to investigate the reciprocal interaction of different CVT controller strategies and ic-engine combustion systems including exhaust gas aftertreatment systems etc., test bed measurements employing the in-house AVL test bed facilities are in the possible scope of work.

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