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ECODRIVE: DRIVELINE SYSTEM INTEGRATION WITH A CVT

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Abstract

The EcoDrive project aims at reducing fuel consumption while maintaining good driveability and performance for mid-class passenger cars with Continuously Variable Transmission. The key element in the development is the push-belt type CVT. The approach is to match both Diesel and gasoline engine and transmission layout for optimum fuel economy, performance and driveability. Aspects like emissions, cost and weight are also considered. At this level of detail, CVT ratio coverage, transmission efficiency, engine displacement and engine breathing are considered as layout parameters. The present paper gives the results from this study.<AE>

Introduction, Project objective

The benefits of the CVT as a passenger car transmission are recognised more and more in the passenger car automotive industry [1]. The CVT is starting to penetrate into the mid-class vehicle range with the increase of torque transmitting capability of steel push belts. The CVT allows use of the engine in its most favourable operating point, for virtually all required power levels. Large ratio coverage and the ability to “shift gears” under load form the key features. The ability to continuously match vehicle and engine speed leads to fuel economy figures comparing favourably with those obtained with conventional stepped automatics.

The main objective of the EcoDrive project is to investigate the possibilities to further improve fuel economy of a CVT-driveline. This objective is based on the ever-increasing demand for lower fuel consumption and lower CO_2 emissions, without compromises with respect to driveability or performance. Design aspects like emissions, cost, weight, size, reliability and durability are to be considered as well.

The EcoDrive development project is a joint effort of Van Doorne’s Transmissie B.V., TNO Road Vehicles Research Institute and the Technical University Eindhoven, supported by the Dutch E.E.T. Programme (Economy, Ecology and Technology). Separate papers cover engine and CVT design [2] and the development of a flywheel hybrid driveline.

EcoDrive vehicle specification and targets; project phasing

The ultimate deliverables of the EcoDrive project will be two mid-class vehicles (one Diesel, one Gasoline) demonstrating the technologies developed during the project. Since the project objective is focused on the optimisation of the drivetrain, typical vehicle optimisations, like vehicle weight, aerodynamic and rolling resistances and auxiliaries, are not considered.

The tentative specs, representing an average midclass vehicle, and targets for the EcoDrive demonstrator vehicles are given in the table below.

Table 1. Tentative specs and targets for the EcoDrive demonstrator vehicles

vehicle specs and targets		SI engine	diesel engine
curb weight		1150 kg	1150 kg
frontal area	C_wA	0.65 m^2	0.65 m^2
rolling resistance	Fr	0.011	
Acceleration	0-100 km/hr	10 sec	12 sec
	80-120 km/hr	10 sec	10 sec
top speed		190 km/hr	190 km/hr
Launch		0.45g	0.45g
fuel consumption	w.r.t. same vehicle with 5 MT on MVEG cycle	- 10%	- 5%
Emissions	MVEG cycle	Euro 2000	Euro 2000
driveline cost	w.r.t. AT	equal	equal

The EcoDrive System Integration project comprises four phases:

1. **Driveline specification phase.**
   This phase, which has been finished, covers the study of the optimal driveline design. Driveline variants are evaluated by various simulation studies. For details, see the remainder of this paper.
2. **Subsystem development phase.**
   The components and technologies resulting from the specification phase are developed during this phase.
3. **Test phase.**
   The test phase comprises the testing and optimisation of the drivelines on a dynamic test rig.
4. **Vehicle phase.**
   During this phase the drivelines are built into vehicles and tested versus the initial targets.

EcoDrive System Integration specification

Transmission and engine layout can be modified such that they can make use of their respective strengths and can avoid their respective weaknesses.

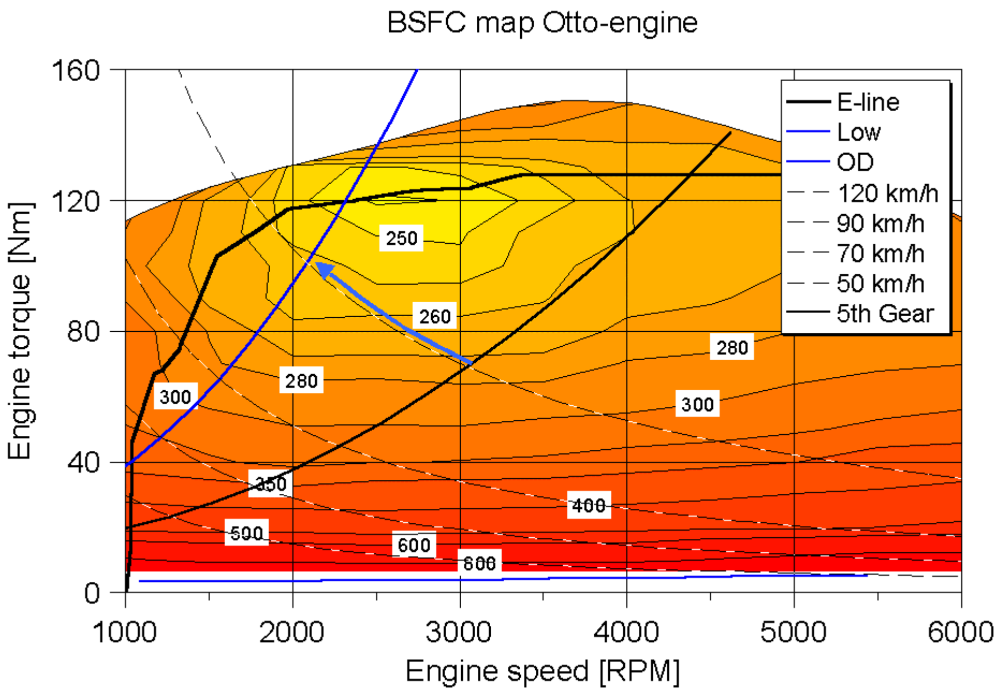

Figure 1. SI engine BSFC map [gr/kWh]. E-line denotes line connecting points with minimum fuel consumption for a given power. Parabolas represent Road Load lines in OverDrive or Low. Hyperbolas are isopower lines for a power level required to sustain a certain vehicle speed under standard conditions. The arrow indicates the transition in operating point at a constant vehicle speed of 120 [km/h] from 5MT to CVT.

One of the most interesting features of the CVT is, for example, its ability to shift under load without shift shock, combined with its very large ratio coverage. This means that the engine operating points can be moved to lower speeds, higher loads, as indicated in Fig. 1. In this operating point, specific fuel consumption is considerably lower. A further increase of ratio coverage opens the possibility to further reduce the engine speed, but also leads to more complicated CVT layouts, as described below. Feasibility of this ratio increase is to be investigated.

At constant engine power, the factors influencing fuel economy for a CVT-equipped vehicle can be described in the following way: The required wheel power is approximately given by the **road load** equation, in combination with the drive cycle dependent vehicle acceleration:

The required engine power is given by the required wheel power, divided by the **transmission efficiency**.:

$$P_{RoadLoad} = (f_r \cdot m \cdot g + 1/2 \cdot r \cdot c_w \cdot A \cdot v^2) \cdot v + m \cdot a \cdot v$$

The required engine power is generated in its operating point with lowest specific fuel consumption, according to the **bsfc map** of the engine (see Fig. 1). This fixes engine speed and torque. The required CVT ratio is then determined by the ratio of engine and vehicle speed:

$$P_{eng} = \frac{P_{RoadLoad}}{h}$$

$$i_{CVT} = \frac{w_{eng}}{v} \cdot \frac{r}{i_f}$$

(r equals dynamic wheel radius; i_f indicates the final drive ratio).
If this ratio is outside the **CVT ratio range**, this ratio cannot be realised and the engine is forced to operate in an operating point deviating from its best operating point. This simple reasoning immediately identifies the key aspects defining fuel consumption of a CVT equipped vehicle. The table below shows these aspects, how they can be influenced and the main layout alternatives considered within the specification phase of the EcoDrive project:

Key aspect	**Defined by**	**Main layout alternatives considered within EcoDrive specification phase**
Road load	Vehicle frontal area, Cw value, rolling resistance, vehicle mass	(Road-load related layout alternatives are considered beyond the scope of the project.)
Transmission efficiency	CVT layout; CVT design	Conventional layout, Two stage lay-out, i-square-layout, declutch at rest; reduced clamping force; optimised hydraulics design
Fuel consumption map	Engine layout; Engine design	Multipoint fuel injection, Miller cycle, Variable valve timing, GDI, Turbo charging, naturally aspirated DI/IDI, Boosted DI/IDI, Aftercooler, turbocharger, supercharger, comprex, variable turbocharger geometry, reduced engine speed range
CVT ratio range	CVT layout, variator design	Conventional layout; Two stage lay-out; i-square-layout, variator ratio coverage

The effect on fuel economy of most of these variants was estimated by means of computer simulations. Results of these simulations are presented in later paragraphs.

CVT layout alternatives

Description

Selection of CVT layout alternatives was based on aspects like: available experience, driveability, cost and to study non-conventional lay-out alternatives (see also [3]).

Alternative CVT layouts are compared to a reference CVT, based on state of the art CVT technology.
Following alternatives are considered:

- A CVT with a conventional single stage layout.
- A 2-Stage concept in which the variator is followed by an AT-like epicyclical gear, making available a speed reduction, a reverse and a direct drive
- An i-square, using its variator ratio coverage twice by reversing torque direction between two operating modes. A schematic representation is given in Fig. 2.

These concepts result in a wide variety in ratio coverage. Intermediate ratio coverage can be obtained easily within each layout. Keeping the LOW-ratio equal for all variants, V1000 in Overdrive (V1000OD, vehicle speed in transmission overdrive with engine running at 1000 [rpm]) can be increased, thereby allowing the engine to run at operating points with better fuel economy.
Unfortunately, an increase in ratio coverage generally means a decrease in transmission efficiency. If the transmission layout is kept unchanged, the efficiencies in LOW and in OD are reduced, when the ratio coverage is increased.
The 2-stage and i-square alternatives have reduced efficiencies due to an increased number of components, like clutches and gears. The contribution of these components to the transmission losses was carefully modelled in the overall efficiency formulas.
By means of a further optimisation of CVT internal design parameters, like belt clamping pressure or hydraulic system, improved part-load efficiency can be obtained. The effect on efficiency can be

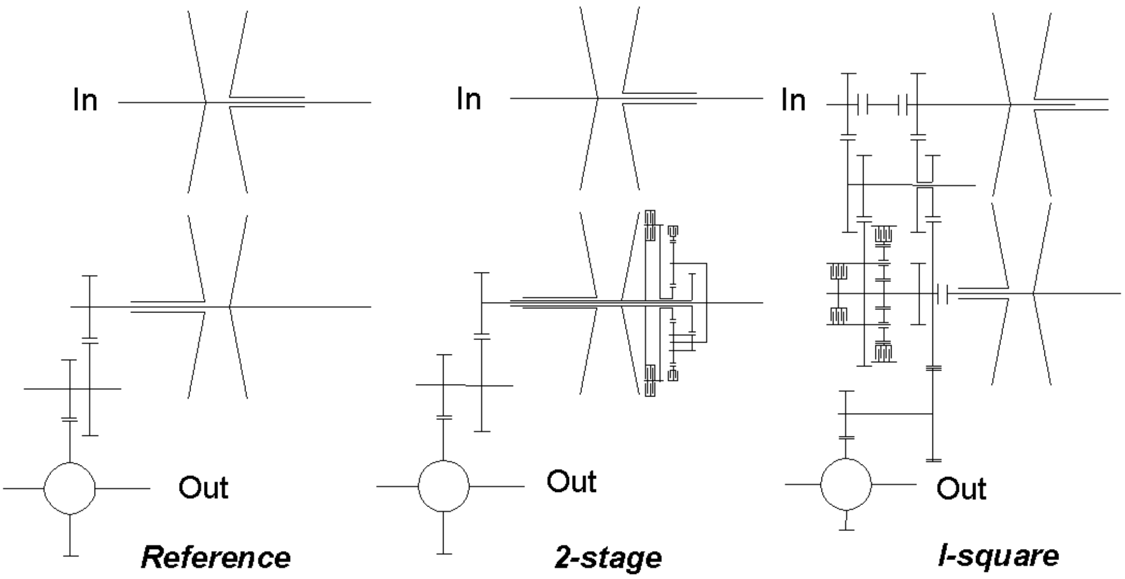

Figure 2. Transmission variants used for simulation study.

modelled quite accurately in the efficiency equations, used for the simulations.

Results and Discussion

In Figs. 4 and 5, the relative fuel consumption is displayed for the various transmission alternatives, indicated by their V1000OD. The two figures represent two different drive cycles.

As expected, a higher V1000OD leads to lower fuel consumption, but the effect is regressive. Two reasons can be identified: 1.) Increasing V1000OD reduces the driving time share in overdrive; and 2) the efficiency of the transmission decreases with increasing V1000OD.

Due to the efficiency penalty, caused by adding transmission components, a considerable increase in V1000OD is needed to obtain a fuel consumption reduction comparable with the reference transmission.

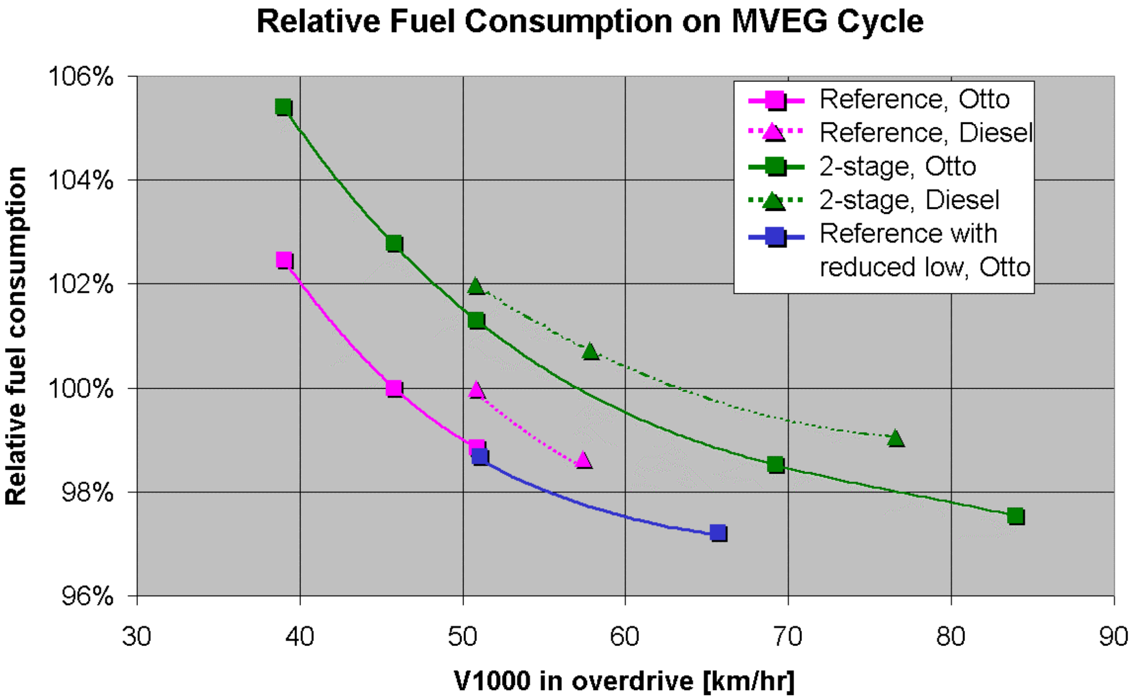

Figure 3. Relative fuel consumption on MVEG cycle

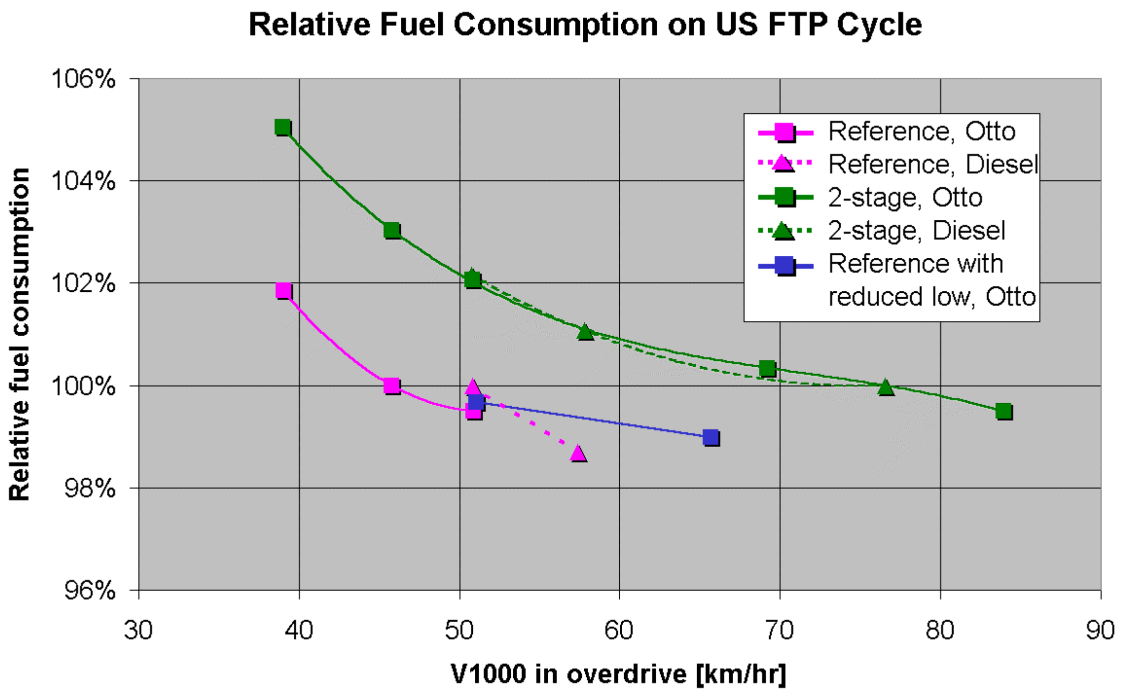

Figure 4. Relative fuel consumption on US FTP cycle

Simulations show, that the effect on fuel consumption (MVEG cycle) of improved clamping force control can add up to 7% reduction. Due to limitations in the lowest attainable clamping pressure, a reduction of 4 to 5% should be regarded as realistic.

Engine layout alternatives

SI-Engines; description

Simulations showed that an engine power of approx. 78 kW, preferably with a Torque ≥ 120 Nm from 1000 rpm onward, is necessary in order to meet the targeted performances of the EcoDrive vehicle. This power of ≥ 78 kW can be generated by a wide variety of engine types and sizes.
Some typical engine types, covering the technology and displacement range, were selected for study in more detail. Objective of this study was to identify trends and to find out whether possibly one engine type would particularly favour CVT application.
Following engine options were selected for further evaluation:

Some of the engines in this list did not physically exist in the versions as were used for this survey. Their properties were simulated in order to allow comparison of the different engine concepts:

- There are some VTEC® engines available on the market, but for this program a somewhat different VTEC engine was simulated with seriously reduced intake valve duration and lift in the low rpm, low part load area. This leads to a 1.6 L MPFI engine with improved part load efficiency, due to reduced throttle losses. For emission reasons λ=1 operation is maintained in all part load conditions.
- The 1.6 L GDI engine was simulated by downsizing an existing 1.8 L GDI engine.
- Using an existing 1.2 L engine, the performance of this engine was simulated when applying the Miller-cycle to it, using a mechanical supercharger.
- Using an existing 1.2 L engine, a turbocharged engine was simulated.

Diesel Engines; description

For diesel engines the number of basic alternatives is less than for SI engines.
Basically there are 2 types of diesel engines:

- Indirect Injected engines (IDI)
- Direct Injected engines (DI)

Either of these can be naturally aspirated (N/A) or boosted (usually turbocharged)
Furthermore the engines can be equipped with one or more of the following features:

- Charge air cooling (aftercooling)
- Exhaust gas recirculation (EGR)
- Variable turbocharger geometry (VTG)
- Catalytic converters

For this study following diesel engine options were selected for further evaluation:

The 1.7 L DI engine from table 2 is obtained by downsizing the 1.9 L DI diesel.

Considering the targeted performances of the EcoDrive diesel vehicle, the diesel engine should have ≥ 70 kW of power. Although the selected IDI engine does not quite meet the targeted power, it's performances were still used for comparison reasons.

Table 2. Selected Diesel Engine Options

Engine Type	IDI	DI	DI
Displacement [L]	1.8	1.7	1.9
Nr. of Cylinders	4	4	4
Valves/Cylinder	2	2	2
Turbocharged	yes	yes	yes
After-Cooled	yes	yes	yes
Power [kW]	68	74	81
@ RPM	4500	4150	4150
Torque [Nm]	180	212	235
@ RPM	2250	1900	1900

Simulation results

In order to allow predictions of vehicle performances with different engines and in different MT and CVT configurations, TNO's driveline simulation model ADVANCE [4] was used. For all simulations a warm engine and gearbox were assumed.
Simulations were run to predict fuel consumption in the MVEG test for an EcoDrive vehicle, equipped with the different engine options, in MT and in CVT version. In some cases also simulations with respect to the US-FTP cycle were made. Next to fuel economy, other vehicle performances were also simulated with ADVANCE.

Fuel consumption SI-Engines

For the CVT simulation of the SI-engine two different control strategies were considered :
The so-called E-mode (CVT-E), where the CVT/engine layout is strictly optimised for best fuel economy. The so-called comfort mode (CVT-C), where the CVT/engine layout is chosen such that the engine always has sufficient torque reserve to spin up within 1 second to an RPM where at least 78 kW is available, thus allowing good acceleration from any steady state condition (improved driveability).

The fuel consumption of the candidate engines in the MVEG test was primarily simulated on the basis of a limited number of carefully selected load conditions (keypoints). For the CVT vehicle these keypoints are defined as load settings (kW), to be chosen freely in the engine map. For the MT versions some typical gear ratios were selected, matching to the respective torque curves of the different engine options.
In a later stage the results of the simplified, keypoint based, simulations were confirmed by full

scale ADVANCE simulations. For the 1.6 L, the 2.0 L and the 2.8 L MPFI engine options also the fuel consumption over the US-FTP was predicted. Following Figure 1 and Tables 2 and 3 show the forecasted fuel consumptions for the different options.

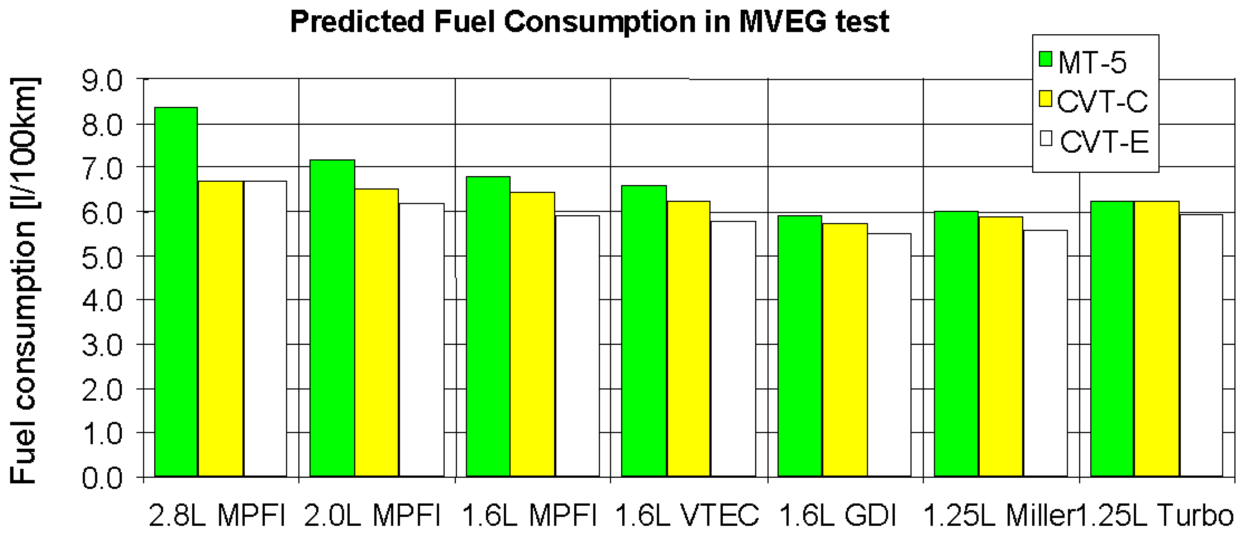

Figure 5. Predicted MVEG Fuel Consumptions for Various SI-Engine Options

Table 3. Predicted MVEG Fuel Consumption for various SI-Engine Options

MT-5	**2.8L MPFI**	**2.0L MPFI**	**1.6L MPFI**	**1.6L VTEC**	**1.6L GDI**	**1.25L Miller**	**1.25L Turbo**
[l/100 km]	8.34	7.16	6.79	6.59	5.90	5.99	6.22
CVT-C							
[l/100 km]	6.68	6.53	6.43	6.24	5.73	5.88	6.24
% of MT	80.2	91.2	94.8	94.8	97.2	98.1	100.3
CVT-E							
[l/100 km]	6.68	6.18	5.91	5.78	5.53	5.57	5.92
% of MT	80.2	86.4	87.1	87.7	93.7	92.9	95.3

Discussion

As a result of the large torque reserve, the 2.8 L MPFI engine, when operated on the E-line, can spin up within 1 second to an engine speed where at least 78 kW is available. Therefore, also in C-mode the E-line can be followed, which explains the results in E-, and C-mode being equal.

The 2.8 L MPFI engine shows an approx. 19 % fuel saving potential over the MT, in both the MVEG and the US-FTP test. This relatively big saving can be explained by the fact that this engine in MT version is often forced into very low part load operation.

In more general terms it can be concluded that vehicles with big and powerful engines benefit more from a CVT, as the CVT allows them to avoid the MT-typical inefficient low load/high rpm operation.

Conventional MPFI engines between 1.6 L and 2.0 L show a fuel saving potential of 10 to 13 % over the MT, in combination with an absolute MVEG/FTP fuel economy of approx. 6 [l/100 km].

Advanced engine concepts such as GDI, VTEC and Miller cycle particularly result in a more efficient low part load operation. A CVT vehicle typically avoids these inefficient low part load conditions. Consequently a CVT vehicle benefits only relatively little from the advantages of these advanced engine concepts, or in other words: a CVT allows conventional MPFI engines to approach the efficiency of more advanced engine concepts.

Table 4. Predicted FTP Fuel Consumption for various SI-Engine Options

MT-5	**2.8L MPFI**	**2.0L MPFI**	**1.6L MPFI**
[l/100 km]	8.64	7.41	6.90
CVT-E			
[l/100 km]	7.02	6.09	5.88
% of MT	81.2	82.3	85.2

For the SI-engines it is noticed that with a CVT the exhaust temperatures will be typically lower in an emission test cycle, due to reduced engine speeds. It is assumed that the subsequent emission increase can be covered by a recalibration and, if necessary, modified catalyst specification.

Fuel consumption Diesel engines

For the diesel engines fuel consumption was calculated by full scale ADVANCE simulations. Following tables 5 and 6 show the predicted MVEG and FTP fuel economies:

Table 5. Predicted MVEG Fuel Consumption for various Diesel Engine Options

MT-5	**68 kW IDI**	**74 kW DI**	**81 kW DI**
[l/100 km]	5.15	4.69	4.74
CVT			
[l/100 km]	4.94	4.65	4.79
% of MT	95.9	99.1	101.0

Table 6. Predicted FTP Fuel Consumption for various Diesel Engine Options

MT-5	**68 kW IDI**	**81 kW DI**
[l/100 km]	5.32	4.63
CVT		
[l/100 km]	4.86	4.57
% of MT	91.4	98.7

Discussion

These turbo-charged diesel engines have, similar to the 2.8 L MPFI engine, so much torque reserve that there is no effective difference between CVT-C and E-mode.

The downsized 1.7 L DI engine does not seem to offer any significant advantage over its full sized relative.

Absolute fuel economies of the 2 DI-engines are virtually identical. The net result by applying a CVT is approximately zero. In contrast, the IDI engine with CVT offers a fuel saving potential over the MT of some 4 to 8%. It can therefore be concluded that a CVT offers the possibility to reduce the efficiency difference between IDI and DI diesel engines, in a similar way as for advanced SI-engines.

For the EcoDrive project still a common rail DI diesel engine was selected, as it represents state of the art in diesel technology and still offers better absolute fuel economy than the IDI.

For the diesel engines not only fuel consumption calculations were made with ADVANCE but also emission calculations. Simulations show that an MT-optimised DI diesel will produce some 50 % more NOx over an emission cycle, when used with a CVT. This clearly indicates that the existing NOx-control is not matched to CVT operation. The preferred method to reduce NOx would be by re-optimising the EGR strategy, possibly in combination with variable turbine geometry (VTG).

Other Vehicle Performances

The other vehicle performances, apart from fuel economy, depend strongly on the engine's torque curve and on choices made with respect to torque converter, ratio of coverage (RC) of the CVT and final drive ratio. Still some trends can be identified for CVT vehicles versus 5-speed MT vehicles:

- Launch (initial acceleration) typically improves by 1 [m/s^2], by applying a torque converter.
- Acceleration 0 → 100 [km/h] in comparison to MT depends strongly on the MT gearing and the CVT stall speed. If 100 km/hr can be reached in second gear, the CVT vehicle is usually somewhat slower than the MT vehicle. At higher stall speed the CVT vehicle can be faster than the MT vehicle.
- Acceleration 80 → 120 [km/h] is typically 2 seconds faster than 4th gear acceleration.
- Top speed is typically reduced by 4 to 6 [km/h] for the CVT vehicle, due to the somewhat reduced overall transmission efficiency.

Simulations indicate that the acceleration capabilities of a CVT vehicle strongly improve with increased low speed torque. Particularly the engine speed range from 1000 to 3000 [rpm] appears to be important, due the CVT-typical low rpm operation.

Conclusions

Note: All conclusions stated below are valid only for the vehicle class considered (middle class).

1. A state of the art CVT combined with a 1.6 to 2.0 L MPFI gasoline engine offers a fuel saving potential of 10 to 13 % over an MT, in both the MVEG cycle and the US-FTP cycle (CVT strictly in E-mode).

2. Improving the part load efficiency of the CVT, primarily by reducing clamping force, proves to be a very effective route for reducing fuel consumption.

3. Combining a CVT with advanced gasoline engine technologies such as GDI, VTEC or Miller cycle result in a fuel saving potential of 5 to 7 % over an MT (CVT in E-mode).

4. It is expected that by improvement of CVT design and control, an additional 5% fuel consumption reduction can be achieved, for both gasoline and diesel engines.

5. Increase of ratio coverage leads to better fuel economy on the MVEG and US FTP cycles, but the step towards more complicated transmissions is not justified

6. Measures to improve low speed torque are recommended for SI-engines to improve the trade-off Fuel Consumption ↔ Driveability.

7. A 1.9 L turbocharged aftercooled DI diesel engine in combination with a state of the art CVT will result in similar fuel economy as an MT, in the MVEG and US-FTP cycles..

8. A diesel engine to be used with CVT will need recalibration, possibly in combination with cooled EGR and VTG, in order to comply with emission regulations.

9. Relatively high powered vehicles benefit more from CVT application of fuel economy.

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