Future Automatic Transmission Requirements

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Abstract (optional)

So far engine downsizing in passenger cars has been used to increase the vehicle performance and to compensate the vehicle weight increase. In the future the continuing downsizing trend on the engine side will be used to maintain today’s performance level and further reduce the fuel consumption. To maintain launch performance and at the same time exploit the engine potential a (torque) ratio spread of up to 10 and launch ratio of up to 20 will be necessary. The future automatic transmission will be the enabler to exploit the potential of these extreme downsized vehicles. Today’s planetary automatic transmissions with up to 8 gears and torque amplification during launch (converter) are already close to this target. For DCT transmissions new gear set approaches will become necessary to realize the demanded ratio spread with acceptable mechanical complexity. With the X-DCT FEV shows such a DCT transmission concept. The X-DCT has 10 forward gears and a ratio spread of about 10.3 with a mechanical complexity comparable to a conventional 6 or 7 speed DCT.

Introduction

Transmission development has seen a revolution in technology over the last decade. The market has witnessed a large diversification in technology with automatic transmissions (AT), continuously variable transmissions (CVT), automated manual transmissions (AMT), dual clutch transmissions (DCT) and last but not least hybrid transmissions. The number of gears has been steadily increasing from 4, 5 up to 8 and more gears. Where does it stop? Are these gears still useful or not? This paper will from address these questions from a technical point of view. By looking at future engine and vehicle trends, technology requirements for future transmissions can be generated. Finally some solution scenarios will be presented.

Engine Technology

Specific power and torque output of engines has been continuously increasing over time. However, naturally aspirated engines are physically restricted in torque capacity by ambient air pressure. They have come to saturation at about 100 Nm/l displacement (gasoline engines). Further power increase will either cause increase in swept volume or boosting. Boosted Diesel engines have been in common use for many years. Demands for increase in power and reduction in fuel consumption have also resulted in application of boosting technologies to gasoline engines. In the near future it is expected that this so called downsizing will continue, mainly driven by fuel economy requirements.

Gasoline engines with specific power of up to 100 kW/l and torque levels up to 200 Nm/l (PME up to 25 bar) and diesel engines with specific power of up to 80 kW/l and torque levels up to 220 Nm/l (PME up to 28 bar) are currently under development. Figure 1 shows an expected roadmap for specific power and specific torque trends of gasoline engines.
Vehicle Level Analysis

Passenger cars have seen a continuous increase in vehicle weight, mainly driven by increased safety and technology demands. At the same time the performance level also increased. Air resistance shows a slow decreasing trend, but does not play a major role for this analysis. An analysis of the vehicle fleet in Germany clearly shows this trend. From 2000 to 2009 the average vehicle weight increased by 11%. At the same time the vehicle performance increased. Both effects together caused an engine power increase of around 50%.

Although engines have been steadily increased in specific power (downsizing) they were not able to meet the power requirements without increasing swept volume. The statistics show an increase in engine swept volume of up to 30% for gasoline engines over the last decade, despite an increase in specific engine power.

In other words: engine downsizing was so far not used for actual downsizing on vehicle level, but was overcompensated by weight and performance increase. Figure 2 shows an analysis of the gasoline vehicle fleet in Germany [1].

Driven by the recent CO₂ awareness the vehicle driving resistance will remain nearly constant in the near future. For the same reasons and the very high performance levels already achieved today also they will remain nearly constant in the near future. By combining the data of the engine roadmap with the vehicle fleet data it becomes clear that in the near future the downsizing effect will no longer be overcompensated by increased vehicle demands.

In other words, “real downsizing” on vehicle level, i.e., decreasing the swept volume to vehicle weight ratio, has only just begun.
Impact on transmission system

The motivations for buying a vehicle have moved away from powertrain specifications to other features like image, comfort and accessories. This means that the driver does not specifically ask for a 6 or 8 speed transmission. This however, does not mean that the expectations on the vehicles' driveability have changed.

As an example for future transmission requirements we will study a typical C-Class vehicle with the following specifications:

| Vehicle Attribute | Unit | Remark | | Engine Attribute | Unit | Remark |
|-------------------|------|--------| |-----------------|------|--------|
| weight [kg]       | 1600 |        | | Displacement [cm³] | 1500 |        |
| load [kg]         | 150  |        | | Max Torque [Nm]   | 330  |        |
| Air drag coefficient [-] | 0.29 |        | | Max Power [kW]    | 150  |        |
| frontal area [m²] | 2.30 |        | | Boosting | single turbo | |
| tire radius [m]   | 0.320| tire 215/55R16 | | 90% Torque from [rpm] | 1750,00 |        |
|                   |      |        | | 90% Torque to [rpm] | 4600,00 |        |

Table 1: Overview of vehicle and engine data
**First gear ratio requirement**

In the first gear the vehicle must be able to launch under all circumstances, e.g., trailer towing or uphill driving without overheating or breaking down. In addition, the vehicle must be able to launch with acceptable performance and have reasonable engine speeds during low speed driving (especially manual transmissions). Today, the first gear ratio is mainly defined by launch behaviour and not by “classical” items such as clutch heat capacity.

To define and objectify launch behavior the following attributes can be used:

- Response time until vehicle noticeably starts moving (initial response)
- Time from pedal start until 1 m/s² vehicle acceleration has been achieved
- Steep yet comfortable acceleration increase
- Minimum acceleration gradient to be achieved from initial response to 80% of max acceleration, but limited to 4 m/s²
- Maximum Jerkiness, e.g., VDV < 0.20 measured with FEVs
- High maximum acceleration
- Achieve peak 75% of maximum acceleration or wheel slip limit within first second

An analysis of the two main parameter defining launch behavior of automatic powertrain vehicles is shown in Figure 3.

![Vehicle response scatterband](image)

**Figure 3:** Vehicle response scatterband

In summary, it can be stated that conventional automatic transmissions with torque converters achieve a torque response of 8 to 15 m/s³ and achieve their maximum acceleration within the first second. Turbocharged automatic transmission vehicles have a somewhat lower response and a later maximum acceleration, but are still in a range that does not lead to customer complaints. Turbocharged vehicles without torque converters on the market today (mostly DCT) already show significant lower performance in first second. In Europe this behavior is generally still accepted in the context of the whole picture, where DCT is generally being perceived quite positively and most buyers come from MT vehicles. Focusing in the area of launch behavior one can already observe a strong increase in complaints with respect to initial launch, especially with customers that are not coming from MT vehicles.

With respect to the statements mentioned above the vehicle response target (for this study) will be set to 7.0 m/s³, and the initial launch to 0.3 s, which is a realistic typical value. To achieve these launch targets with the given target vehicle the following wheel torque demand needs to be fulfilled:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Acceleration [m/s²]</th>
<th>Wheel Torque [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time [s]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>0.30</td>
<td>1.0</td>
<td>560</td>
</tr>
<tr>
<td>0.65</td>
<td>3.8</td>
<td>2128</td>
</tr>
</tbody>
</table>

Table 2: Wheel torque requirement

Comparing this wheel torque demand with the available engine torque will show how much torque amplification is needed from the transmission.

**Engine torque during launch**

During a wide open throttle (WOT) acceleration the engine will start at idle speed and rev up quickly to a level as desired by the clutch control, typically around 2000 rpm for a normal gasoline passenger car. The vehicle will accelerate proportionally to the clutch torque and the clutch slip will decrease to zero.

Gas dynamics simulation models can be used to compute the dynamic torque response of the engine. Specifically, FEV uses a mean value model simulation approach using GT-Power. With such a model the dynamic/transient torque response can be calculated. Figure 4 shows the simulated intake manifold pressure and torque of a 1.4l turbocharged engine during a WOT takeoff condition.
The calculations show that within the first second there is no measurable boost pressure. This means that the engine behaves like a naturally aspirated engine. This typical trace was confirmed by various vehicle measurements under real life conditions. The wheel torque demand (based on the launch performance requirements) can be calculated. The ratio of the wheel torque to the transient engine torque available is the torque ratio demand (to be provided by the transmission), as shown in Table 3.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Ratio and torque Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time [s]</td>
<td>Acceleration [m/s²]</td>
</tr>
<tr>
<td>0.000</td>
<td>0.0</td>
</tr>
<tr>
<td>0.300</td>
<td>1.0</td>
</tr>
<tr>
<td>0.650</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 3: Torque ratio Demand

To maintain the launch performance in the defined area an initial gear ratio of up to 21 is required.
Last gear ratio

From a fuel economy point of view the engine speed should always be as low as possible. Hence, the WOT power available from the engine is fully utilized to propel the vehicle at the desired speed.

From a driveability point of view a certain reserve torque in gear is needed to ensure driveability. From the customers’ point of view it would not be logical to have a last gear that can only be used above the daily and/or allowed speed limit.

To define and objectify this behavior in numbers the last gear ratio should be able to fulfill:

- **Top gear must be useable in daily life:**
  - At moderate highway speeds, the vehicle must be able to climb slight grades that can not be detected by the driver.
  - **Requirement:** Being able to drive 140 km/h at 4% grade in top gear
  - Provide a sufficient acceleration reserve at normal cruising speeds
  - **Requirement:** Being able to drive 90 km/h in top gear with a minimum acceleration reserve of 0.5 m/s² (or 6.5% uphill)

- **Top gear must be useable in test cycle**
  - Being able to drive top gear from 100 km/h
  - Being able to accelerate from 100 to 120 km/h in NEDC cycle in top gear
  - **Requirement:** Being able to accelerate from 100 to 120 km/h with a minimum gradient of 1 km/h/s (equals 0.28 m/s² or 3.6% uphill)

![Figure 6: Definition of maximum ratio for highway cruising](image)

In last gear the dynamic behavior of engine and vehicle is much lower than in the launch gears. Therefore the stationary full load curve of the engine may be used for these investigations. Now the requirement boundaries can easily be calculated. Figure 6 shows an example of such a calculation. The lowest parabolic line is the vehicle’s driving resistance on a flat road. The second line is the driving resistance on a given grade. The multiple “hills” represent the wheel power in a given gear at stationary full load of the engine. Now the maximum ratio can easily be determined by matching roadload demand at a given gradient with the wheel torque curve. The dotted line shows the in gear power reserve for the top gear (7th gear in this example).
Ratio demand for future transmission
The results for the new powertrain can now be summarized as follows:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Torque ratio</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Response</td>
<td>7.40</td>
<td></td>
</tr>
<tr>
<td>Vehicle Response</td>
<td>20.9</td>
<td>for 7 m/s³ acc gradient</td>
</tr>
<tr>
<td>a at 1s</td>
<td>21.2</td>
<td>4 m/s² at 1s</td>
</tr>
<tr>
<td>Highway driveability</td>
<td>2.12</td>
<td>140 km/h 4% grade</td>
</tr>
<tr>
<td>NEDC test cycle</td>
<td>1.90</td>
<td>0.28 m/s² @ 100-120 km/h</td>
</tr>
<tr>
<td>Top gear practical usage</td>
<td>2.15</td>
<td>90 km/h elasticity</td>
</tr>
<tr>
<td>Ratio spread demand</td>
<td>9.8</td>
<td>Overall requirement</td>
</tr>
</tbody>
</table>

Table 4: Torque ratio Demand

For transmissions with torque converters the torque ratio can be met with a mechanical ratio spread which is smaller, because in the initial launch phase the torque converter provides additional torque amplification. Accounting for this amplification, a ratio spread demand of approximately 8 will be necessary for automatic transmissions with torque converters.

For non converter type transmissions the ratio spread is equal to the torque ratio. This means for DCT transmissions a mechanical ratio spread around 10 will be needed. In addition, the transmission will be required to meet this ratio spread demand without violating cost, efficiency, and package space requirements.

**Future DCT transmission: FEV xDCT**

Current DCT architectures use a gear set with one pair of gears per ratio. For a typical 7-speed DCT this results in about 19 gears and 4 full shift forks to realize in total 8 gears (7+R). Adding more gears, synchronizers and shift forks could be one solution to reach the desired ratio spread demand. However, the added mechanical complexity will be a disadvantage in all other areas.

The solution is a multiple usage of gears, similar to FEV’s 7H-AMT-[2]. In this transmission the additional required gear ratios for the electric motor are generated by using unused gears in the combustion engine path.

According to this principle, FEV developed the X-DCT concept. X-DCT is a 10-speed DCT with the mechanical complexity of a conventional 6- or 7-speed DCT. The key details of this transmission concept are provided in Table 5.
Summary and Conclusion

Until now engine downsizing was mainly used to increase vehicle performance and to compensate vehicle weight increase. “Real” downsizing in terms of actually reducing engine displacement per vehicle weight has only just begun.

These modern boosted engines show high power and torque levels, also at relatively low engine speeds. To really exploit the benefits of the downsized powertrain very long last gear ratios are required.

The high low end torque is generated by boost pressure. Studies have shown that no significant boost pressure can be achieved in the first second after vehicle launch, even with sophisticated charge systems.

To achieve good perceived performance the responsiveness within this first second is extremely important. To achieve or maintain acceptable levels of vehicle response the total first gear ratio must be significantly increased to values >20.

The resulting torque ratio demand of around 10 will be relatively easy to achieve with torque converter transmissions. Here the gap to today’s technology is relatively small.

For non-converter transmissions this will require 9 to 10 forward gears. To achieve this without increasing package space, mechanical complexity and costs the current gear set structure of DCTs will no longer work.

A possible solution is shown by FEV’s X-DCT concept. With an intelligent gear set structure this 10-speed DCT achieves a ratio spread of around 10.3 with a mechanical complexity equal to today’s 6- or 7-speed DCTs.

Literature: