FEV’s new parallel hybrid transmission with single dry clutch and electric torque support

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Acknowledgements
The following article will give an overview of FEV’s new 7H-AMT (7-speed hybrid AMT), which is being developed within the project “Europa-Hybrid: Innovativer PKW-Hybridantrieb für Europa” funded by the German Federal Ministry of Economics and Technology (BMWi). This project is going to take the 7H-AMT and other hybrid system components from concept to working prototypes inside a demonstrator vehicle based on the Ford Focus ST. The authors would like to thank the BMWi for its kind support of this ambitious research project.

Abstract
FEV is currently developing a new 7-speed hybrid transmission for transverse installation. The transmission with a design torque of 320 Nm is based on AMT (automated manual transmission) technology and uses a single electric motor. The innovative gear set layout combines the advantages of modern AMTs such as best efficiency, low costs and few components with full hybrid capabilities and electric torque support during all gear shifts. Furthermore, the gear set layout allows for very short shift-times due to the favorable distribution of inertias. Other features include an A/C compressor being electrically driven by the electric motor of the transmission during start/stop phases.

1. Introduction
In contrast to the American or Japanese car market, the European car market is still dominated by the manual transmission. Therefore, the efficiency of any new transmission has to compete against that of a manual transmission. This is especially true for transmissions in hybrid powertrains, where the customer expects a significant fuel economy benefit for the price premium. In order to achieve maximum fuel economy at a competitive price, AMT technology was chosen as the basis for the development of FEV’s 7H-AMT. AMTs are not only the most efficient automated transmissions, but also the most inexpensive ones. In order to maintain this cost advantage for the entire hybrid system, it was decided to use only one electric motor in a parallel hybrid configuration. Previous investigations have shown that parallel hybrid configurations represent the best compromise between fuel efficiency and costs [1].
The main disadvantage of AMTs compared to DCTs (dual clutch transmissions) or conventional automatic transmissions is the torque interruption during shifts. Because of this, the conventional AMT does not fulfill today’s comfort requirements and is only found in vehicles of the compact- and sub-compact classes or in sports cars, where shift comfort does not play a key role. The basic idea of the 7H-AMT is to bring back AMT technology by eliminating its torque interruption using the electric motor.

2. Concept considerations
In general, there are several different possibilities to integrate the electric motor into a parallel hybrid powertrain. Figure 1 shows concepts where the electric motor is located either in front or behind a conventional AMT.

Fig. 1: Standard layouts for parallel hybrids

Only configuration 2 allows for a torque support during shifts. However, only one fixed gear ratio is available for the electric motor. Consequently, the fixed gear ratio has to be chosen based on the top speed of the vehicle. Because of the resulting tall gear ratio, only limited e-motor power is available for torque support especially at low vehicle speeds and thus also low e-motor speeds. This is especially disadvantageous for shifts in the lower gears and at high loads. Alternatively, the system could be equipped with an additional clutch in order to disconnect the e-motor at high speeds, which would of course mean additional hardware effort. Also, the e-motor would not be available as a generator.
As a consequence, several gear ratios would also be desirable for the e-motor in order to solve the trade-off “high driveaway torque vs. high top speed”. Figure 2 shows two alternative configurations.

![Figure 2: Alternative layouts for parallel hybrids](image)

One possible solution would be to connect the e-motor to the output shaft with its own multi-speed transmission (configuration 3). However, this will increase required space, weight and cost.

FEV’s 7H-AMT concept (configuration 4) with its unique new gear layout now solves the described conflict by providing several gear ratios for the e-motor without increasing the complexity and part count of a comparable conventional AMT. To achieve this aim, the e-motor is directly geared to the transmission. The innovative layout results in a 3-shaft-transmission for transverse installation which uses a single dry clutch, only 19 gear wheels in total and four shift sleeves to provide eight gears (7+R) for the combustion engine and four gears (3+R) for the electric motor.
3. The 7H-AMT gear set layout

In figure 3, an example for a transmission which features the same basic components as FEV’s 7H-AMT is shown.

Figure 3: Example for a transmission layout

This simplified layout features four gear ratios for the combustion engine (CE) and four gear ratios for the electric motor (EM). With this gear set, all four gears of the CE can be engaged independently from the EM gears. But in order to fulfill today’s requirements for a transmission such as large total ratio spreads, four ratios for the CE are not acceptable. Therefore, the layout has to be modified. In figure 4, one synchronizer unit has been moved from the second input-shaft to the output-shaft.

Figure 4: Example for a transmission layout
At first glance, this setup has the same complexity, but offers less flexibility than the one in figure 3. If one of the ratios CE1 or CE2 is engaged, the EM is forced into one of the ratios EM1 or EM2. However, this configuration has one great advantage: As long as one of the idler gears next to the synchronizer unit C on the output-shaft is not engaged, this gear can be used to transfer torque from the first input shaft to the second input shaft. Thereby, existing gear ratios are multiplied to "generate" new ratios (figure 5).

![Figure 5: Generation of gear ratios](image)

By choosing appropriate ratios for each gear pair, this basic principle will provide 7+R well-stepped ratios for the CE and 3+R ratios for the EM. Additionally, one long 1\textsuperscript{st} gear (1L) and one long reverse gear (RL) are available for the CE. Figure 6 shows how the gears are arranged in FEV’s 7H-AMT prototype.

![Figure 6: Arrangement of gear ratios in the FEV prototype](image)
The gears 2, 4, 5 and 6 are available as “direct” gear ratios using only one gear pair each. Especially for the gears 4, 5, and 6 with their large share in the transmission’s duty cycle, this guarantees optimum transmission efficiency. The gears 1, 3, 7 and R are so called “generated gears”, where three gear pairs in a row are used to create the total ratio. In order to achieve the desired progressive gear stepping, the idler gears next to the synchronizer unit C have been designed as double row gears. The actual layout and the gear stepping of the prototype transmission are shown in figure 7.

![Figure 7: Actual layout and gear stepping](image)

The progressive gear stepping and the large ratio spread of 6.77 for the CE have been optimized to provide both good fuel consumption and drivability. Because of optimized helical angles, the double row gears do not create axial forces when being used as intermediate gears for the transfer of torque between the two input shafts.

### 4. Torque support during shifts

One important feature of the described configuration is that it provides two independent torque paths to the wheels. During gear shifts, one of the two paths always remains active. During CE gear shifts, the EM can fill up the torque gap that would usually occur for AMTs. During these short periods of time, the EM can provide up to two times its nominal power to guarantee smooth shifts even at high CE loads. On the other hand, the CE can provide additional torque during all EM shifts. The next sequence of figures explains the alternating shifts of the CE and the EM.
Figure 8: 7H-AMT in gear mode 2-1

Figure 9: 7H-AMT in gear mode 2-4

Figure 10: 7H-AMT in gear mode 3-4
All other single shifts can be performed in the same manner. Multiple shifts for the CE are easily possible as long as no gear change is required on the EM side (e.g. true for CE 2 to 4 and CE 3 to 5).

5. Shift comfort
The shift comfort of the 7H-AMT concept is of course highly dependent on the ratio of available CE power to available EM power. By concept, shifts can be performed unnoticed by the driver up to the short time peak power of the EM. This ensures excellent shift quality at part load, an operating area in which conventional AMTs have often been criticized. If the CE power is increased beyond the short time peak power of the EM, a torque reduction during the CE shifts will be noticeable. One key to optimize shift behavior during these situations is a reduction of shift time. All CE shifts take place using the two synchronizer units A and B (dual cone) on the CE input shaft. As shown in figure 11, this means that the inertia which has to be synchronized during these shifts is reduced to an absolute minimum, consisting of not more than the clutch disc of the single dry clutch, the input shaft itself and two synchronizer units. The result: With moderate shift forces of 800 N, the synchronization time for all CE single shifts is 50 ms or less.

All shifts performed by the remaining synchronizer units C and D (single cone) are actively synchronized by the EM. Because the CE remains connected to the wheels during these shifts, they are by far less critical with regard to shift comfort. For all synchronizer units, the smallest available size is used (installation space 36 mm, shift sleeve diameter 89 mm).
6. Multiple downshifts

For automated transmissions, the capability to perform multiple downshifts is often considered to be an important criterion. For the 7H-AMT, the so-called “direct downshifts” are of particular interest. During these CE shifts, the EM remains connected to the wheels and can start boosting as soon as the driver requests acceleration. Therefore, the response of the vehicle for these direct downshifts is much faster than for any conventional non-hybrid transmission.

<table>
<thead>
<tr>
<th>direct downshifts with immediate e-motor boost</th>
<th>CE</th>
<th>Gear</th>
<th>Ratio</th>
<th>EM</th>
<th>Gear</th>
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<tr>
<td></td>
<td>1</td>
<td>1L</td>
<td>3,369</td>
<td>2</td>
<td>2.333</td>
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<td></td>
<td>2</td>
<td>1.815</td>
<td>1.608</td>
<td>2</td>
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<td>3</td>
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<td>4</td>
<td>0.978</td>
<td>0.543</td>
<td>5</td>
<td>-0.695</td>
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<td>5</td>
<td>0.784</td>
<td>0.543</td>
<td>6</td>
<td>-0.441</td>
</tr>
<tr>
<td></td>
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<td>0.441</td>
<td>7</td>
<td>-1.739</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>0.497</td>
<td>-2.511</td>
<td>RL</td>
<td>-1.983</td>
</tr>
</tbody>
</table>

Figure 12: Direct downshift capability

As can be seen in figure 12, a direct downshift to 2\textsuperscript{nd} CE gear is possible from all CE gears 3 to 7. This is possible due to the conventional “idler gear/fixed gear” arrangement of CE gears 2 and 5 on the first input-shaft. These two gears can therefore be engaged independently from the active EM gear. The important CE downshifts 7 to 5 and 5 to 3 are also possible as direct downshifts.

7. Hybrid operating modes

The 7H-AMT features all standard operating modes of a full hybrid transmission, including start/stop and boosting/regeneration in all gears. All-electric driving is performed in first EM gear, which can be used up to a speed of around 70 km/h. This ensures that all inner city driving situations can be covered by the all-electric driving mode if desired. As soon as the driver requests more torque than can be delivered by the EM alone, the combustion engine is started by controlled slip of the clutch and precise modulation of EM torque. For this restart, several different gear ratios are available, including CE 1\textsuperscript{st}, 2\textsuperscript{nd} and 5\textsuperscript{th} (figure 13).
This is especially important when the driver approaches the limits of the all-electric-driving mode (e.g. vehicle speed or state-of-charge limits). In that case, the driver should not be disturbed or even surprised by a sudden restart of the CE which has not been explicitly requested by him. By using 5th gear, the CE can be restarted at moderate rpm and thus low noise levels. For situations where maximum acceleration is requested, restart can be performed in 2nd or even 1st CE gear.

As an additional feature, the EM can be used to drive an A/C compressor, e.g. during start/stop phases. The compressor is mounted in front of the transmission and connected to the second input shaft and thus to the EM using a conventional magnetic clutch and belt drive. In order to package the compressor without increasing the installation length of the transmission, this belt drive has been integrated into the clutch housing. As the available standard materials for poly-V-belts cannot withstand the temperature inside the clutch housing, a toothed belt has been chosen for the prototype transmission. Because the automation prevents clutch abuse and with it very high temperatures inside the clutch housing, this solution is not expected to have any lifetime issues. If ease of maintenance becomes the focus, the belt drive can also be located at the back of the transmission, then of course occupying additional axial space. During standard driving, the compressor is mechanically driven by the second input shaft. Thereby, efficiency is increased compared to electric compressors. Also, weight and costs are reduced because no additional electric motor is required for the A/C compressor.

Figure 14 shows two 3D CAD views of the prototype transmission. On the left, the integration of the A/C compressor’s belt drive into the clutch housing is shown. On the right, the two actuation
units of the on-demand electro-hydraulic actuation system are visible. Each of these units drives two of the four shift-forks. In an attempt to reduce the number of part variants, two identical actuation units are being used. Also, two of the four shift-forks are identical.

Figure 14: 3D CAD views of the 7H-AMT prototype transmission

8. Summary and outlook
Within the “Europa-Hybrid” project, FEV is currently developing a new 7-speed hybrid transmission for transverse installation. The transmission with a design torque of 320 Nm is based on AMT technology and uses a single electric motor. The innovative gear set layout combines the advantages of modern AMTs such as best efficiency, low costs and few components with full hybrid capabilities and electric torque support during all CE shifts. Furthermore, the gear set layout allows for very short shift-times due to the favorable distribution of inertias. Other features include an A/C compressor being electrically driven by the electric motor of the transmission during start/stop phases.

By simply replacing the electric motor with a smaller 12 V or 42 V one, the 7H-AMT can be converted into one of the most advanced AMTs for transverse installation including additional micro- or mild hybrid functionality, e.g. start/stop and intelligent battery charging strategies. In table 1, some characteristic values of the FEV prototype are compared to a hybrid transmission based on a 7-speed DCT with dry clutches [2]. The comparison shows the simple construction of the FEV prototype and its high torque-to-weight-ratio. With 356 mm, the installation length of the
7H-AMT prototype is already comparable to that of state-of-the-art 6-speed manual transmissions in the same torque range.

Table 1: Comparison of FEV’s 7H-AMT to an example of a 7-speed dry DCT hybrid

<table>
<thead>
<tr>
<th>Concept</th>
<th>7-speed dry DCT hybrid</th>
<th>FEV 7H-AMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of gear ratios / CE</td>
<td>7+R</td>
<td>7+R</td>
</tr>
<tr>
<td>Number of gear ratios / EM</td>
<td>4 or 3+R (depending on EM connection)</td>
<td>3+R</td>
</tr>
<tr>
<td>Power capacity</td>
<td>125 kW</td>
<td>160 kW + 35 kW (EM)</td>
</tr>
<tr>
<td>Torque capacity</td>
<td>250 Nm</td>
<td>320 Nm + 70 Nm (EM)</td>
</tr>
<tr>
<td>Number of shafts</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Number of gear wheels</td>
<td>20 without connection of EM</td>
<td>19 including connection of EM</td>
</tr>
<tr>
<td>Number of shift-forks / shift-sleeves</td>
<td>4/5</td>
<td>4/4</td>
</tr>
<tr>
<td>Number of actuators</td>
<td>4 + 2 (dual dry clutches)</td>
<td>4 + 1 (single dry clutch)</td>
</tr>
<tr>
<td>Mass 1)</td>
<td>77 kg (transmission only: 59 kg)</td>
<td>85 kg</td>
</tr>
<tr>
<td>Parking lock</td>
<td>yes (clutches normally open)</td>
<td>no (clutch normally closed)</td>
</tr>
<tr>
<td>Center distance</td>
<td>179 mm</td>
<td>197 mm</td>
</tr>
<tr>
<td>Installation length</td>
<td>369 mm</td>
<td>356 mm</td>
</tr>
</tbody>
</table>

1) including actuation system and dual mass flywheel, without EM and A/C compressor

As of June 2009, the assembly of the first prototype transmissions has been completed. After successful bench testing, the transmission will be installed into the demonstrator vehicle. It is FEV’s strong belief that the 7H-AMT will represent a competitive alternative to other hybrid concepts currently in the market and under development.
