COMPACT SEVEN- AND TEN-SPEED DUAL-CLUTCH TRANSMISSIONS

The ongoing trends downsizing and downspeeding require new transmission concepts with large ratio spread and number of gears in order to simultaneously improve fuel consumption and launch behaviour. Using a systematic synthesis process, FEV has developed a new generation of dual-clutch transmissions with seven and ten gears, the xDCT family. Through a combination of the features "gear generation" and "supported shift", these concepts set a new benchmark regarding number of gears per mechanical complexity.

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MORE TURBOCHARGED ENGINES WITH SMALL DISPLACEMENT

The ongoing trends downsizing and downspeeding have led to the introduction of more and more turbocharged engines with small displacement, high torque and significant disadvantages in response compared to previous generations of naturally aspirated engines. This trend will grow even stronger in the future, creating a huge demand for ratio spread, on the one hand in order to improve launch behaviour via short first gears, on the other hand to reduce fuel consumption via long last gears.

Especially dual-clutch transmissions (DCTs) without the advantage of torque amplification by a hydraulic converter are affected by this circumstance. They will require launch ratios in the area of 20 and ratio spreads larger than 10. In order to maintain acceptable ratio steps, this will lead to an increasing demand for DCT concepts with a large number of gears [1].

Small vehicles and especially cost sensitive markets will call for concepts which maintain today's number of gears with significantly reduced complexity. Current series-production DCTs feature a maximum of seven speeds, which can be realised using three main shafts and four shift sleeves. With conventional gear set concepts this complexity cannot be reduced, as each gear requires a separate switchable connection. To even increase the number of gears, more gear wheels, shift sleeves and shafts have to be added thus increasing package dimensions, weight and cost.

A NEW DCT FAMILY

The solution developed by FEV is the xDCT family, a series of DCT concepts for transverse installation, which effectively minimise mechanical complexity for any given number of gears by combining two non-conventional ideas: "gear generation" and "supported shift". In order to generate gears, at least one switchable connection between the two input shafts is installed which eliminates the strong differentiation in two separate transmission branches and allows to use all gears inside the transmission with both clutches.

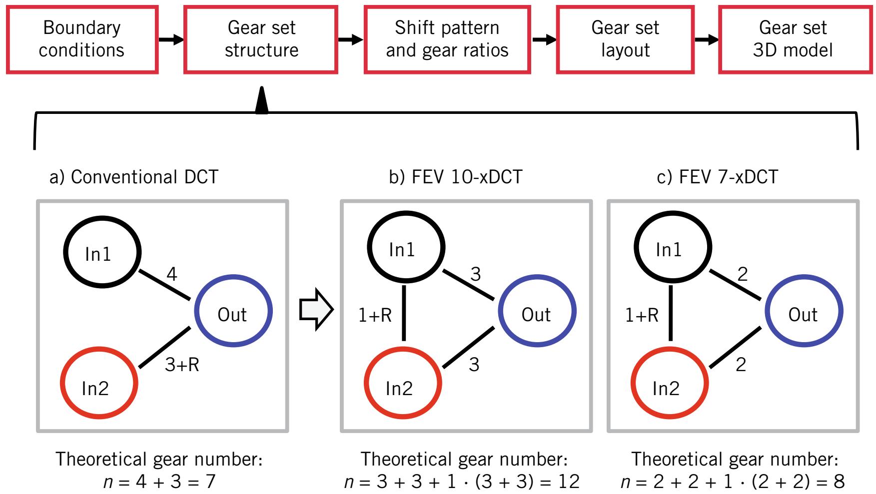
This approach has been presented in the 1990s yet and reoccurred several times since then [2, 3, 4]. Although the use of a single switchable connection theoretically doubles the number of gears, the remaining challenge is to effectively use these gears in a shift schedule without torque interruption.

The solution introduced by FEV for the xDCT family is to incorporate one or two so-called supported shifts into the shift schedule. For these shifts, two adjacent gears are assigned to the same clutch which usually requires a gear change with torque interruption. For a supported shift however, torque fill is provided with the second clutch using the next higher gear. The energy which is stored in the engine inertia and released during the upshift compensates for the smaller torque amplification of the supporting gear. Only the combination of the two ideas gear generation and supported shift allows to effectively use the theoretically available gears without torque interruption.

CONCEPT DEFINITION

The need for a large number of well-stepped gear ratios without increasing the mechanical complexity of current transmissions requires new ways of gear set synthesis and optimisation. Therefore new gear sets at FEV are developed using a systematic, computer aided synthesis process. During this process, all theoretically possible solutions are analysed until the optimum solution considering all boundary conditions has been found, ❶.

The visualisation of gear set structures shown in the lower part of ① allows a very simple and fast analysis of the functionality possible with a certain transmission layout. It illustrates the degrees of freedom and the number of switchable connections between them for a given gear set [5]. The total number of theoretical possible gears is the sum of "direct gears" (direct connection between input and output) and "generated gears" (gears in which the switchable connection between the inputs is active). All possible arrangements of switchable connections can be evaluated for example with respect to the theoretical number of gears and the number of efficiency-optimum direct gears. The lower part of ① shows the gear set structures of 10-xDCT (b) with ten usable forward gears using a total of eight switchable connections (four synchroniser units/four shift sleeves) and the gear set structure of a smaller version, the 7-xDCT (c), which features seven forward gears using only six switchable connections (three synchroniser units/three shift sleeves).



❶ Five steps (red) of systematic gear set synthesis (upper part) but also gear set structures a, b and c of conventional DCT, FEV 10-xDCT and FEV 7-xDCT (lower part)

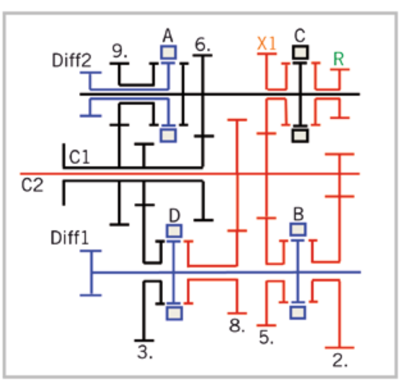
GEAR SET LAYOUTS

❷ shows two exemplary gear set layouts of FEV's xDCT family. Both the 10-xDCT gear set with four shift sleeves and 17 gear wheels and the 7-xDCT gear set with three shift sleeves and 14 gear wheels set a new benchmark for "functionality per complexity". The configuration of the shafts and shift sleeves looks similar to conventional DCTs, but two transfer connections (shift sleeve C) are placed between the inputs, one of which is used for reverse.

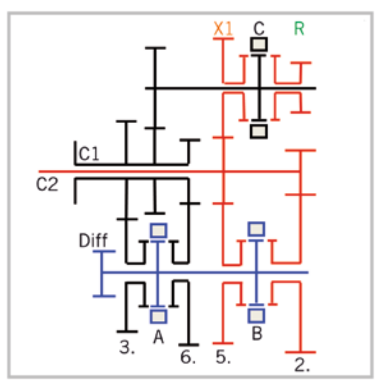
The transfer connection X1 between the two inputs has a choosable ratio step and will create shorter gear ratios if the transfer is used from clutch C1 to C2. Respectively, if the transfer is used from clutch C2 to C1, the ratio step will create longer gear ratios. In order to minimise axial length, the connection X1 and fifth gear use the same gearwheel on the input shaft. If the shift sleeve C is actuated in the direction of R, the first input (C1) uses the second gear to generate the reverse gear. A dedicated reverse idler is not required. During parking manoeuvres second gear has sufficient torque amplification so that a clutch-to-clutch powershift between reverse and launch gear is possible.

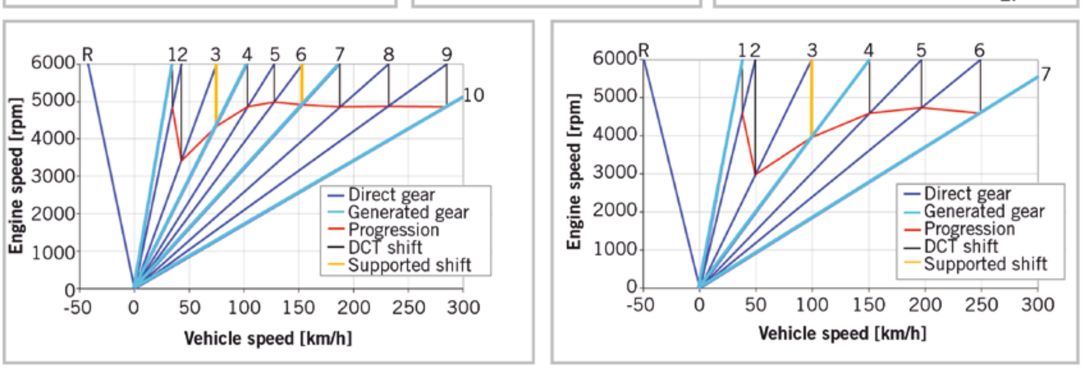
② also shows the gear stepping of 10-xDCT and 7-xDCT. Between second and sixth gear the stepping is progressive, in higher gears of the 10-xDCT approximately geometric. First gear ratio has a high value for good launch performance. With conventional gear sets, first gear ratio is often limited because of centre distances and minimum gear wheel diameters. This limitation does not exist for the xDCT family: The short first gear is made possible because the first gear is generated using the transfer connection and second gear.

The small step between first and second gear results from the multiple use of the transfer connection. In the case of the xDCT it is used to "emulate" the torque



10-xDCT		7-xDCT
i	Gear	*i*
20.20	1st	18.44
16.35	2nd	14.11
1.98	Last	2.14
-16.38	R	-14.06
10.20	Spread	8.62





❷ Gear set layouts and exemplary ratio steppings of 10-xDCT (left) and 7-xDCT (right) amplification of a torque converter during the launch procedure. The benefit of this ratio stepping is an excellent launch feel because of the short first gear followed by smooth acceleration in second gear.

SIMULATION RESULTS

The shift schedule of 7-xDCT contains one supported shift (3 → 4), the one of 10-xDCT contains two (3 → 4, 6 → 7). The main challenge is to carry out the supported shifts with a shift quality comparable to conventional DCT shifts.

In order to analyse the feasibility of supported shifts, the shift sequence of the most critical 3 → 4 supported shift of 10-xDCT was simulated and compared to a conventional DCT shift, ❸. For the supported shift, the dual torque handover between the clutches and the reduced torque intervention during the inertia phase is visible. Due to the smaller torque amplification of the supporting gear more energy, which is stored in the inertia of the combustion engine, is used to minimise the decrease of acceleration. Therefore a smaller torque intervention is required.

The minimum acceleration during the supported shift (1.3 m/s²) is slightly smaller than during the conventional DCT shift (1.6 m/s²). In order to assess the influence of this reduction on shift quality and to create the feel of a supported shift, measurements have been carried out on a vehicle with conventional DCT and modified transmission control strategy. Even at full load, shift quality was well within FEV's scatterband of series-production DCTs. At part load, full torque support can be realised by positive torque intervention.

DESIGN STUDY

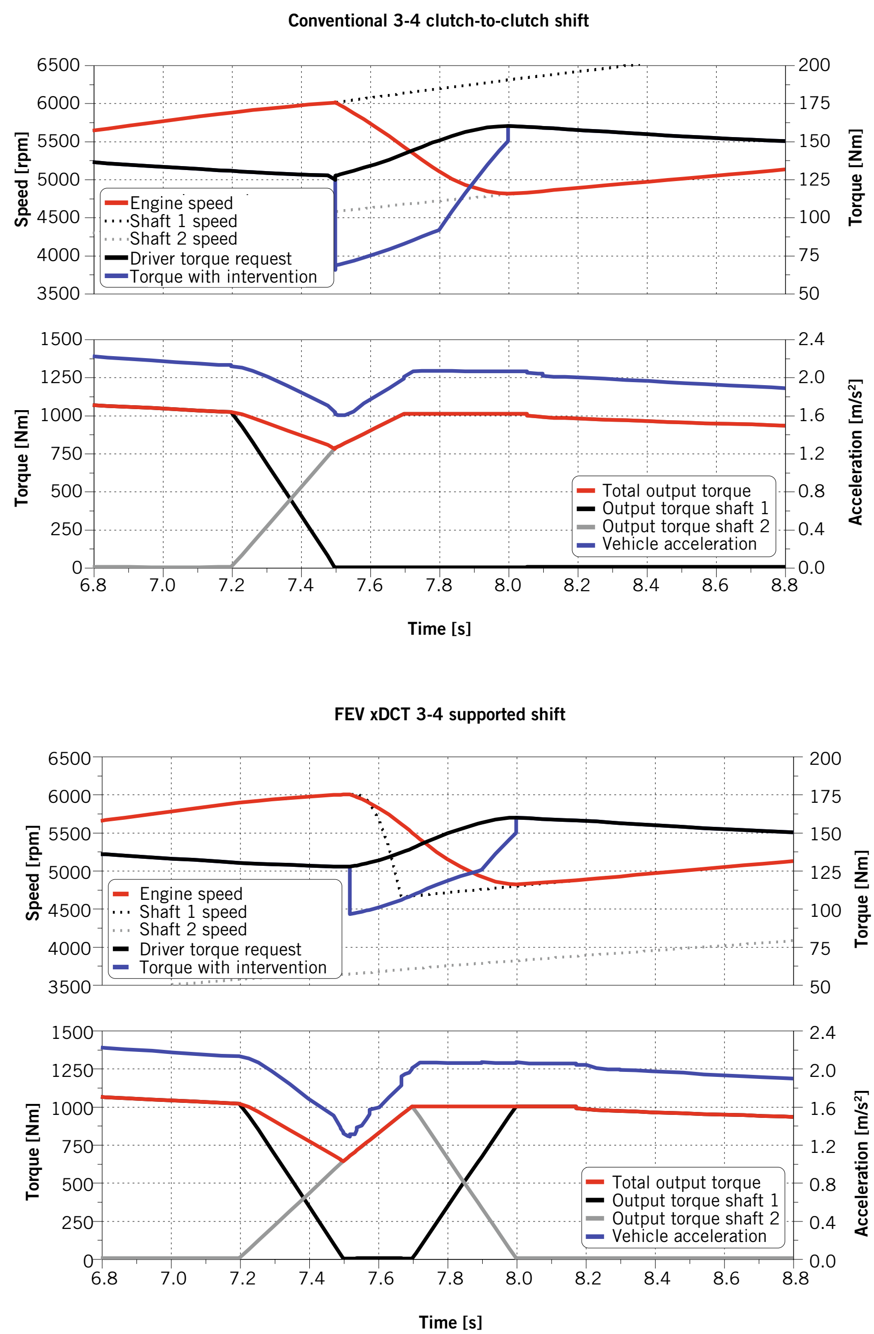
In detailed 3-D concept studies, both a 400-Nm variant of 10-xDCT and a 280-Nm variant of 7-xDCT have been laid out and designed. For both variants, a wet dual-clutch system with actuation via engagement bearings is used which significantly reduces the usual hydraulic losses. Depending on customer requirements, other dual-clutch systems (dry or conventional wet) can be integrated alternatively. As a special feature on 7-xDCT, all three shift forks and the park lock are actuated with a single shift drum. This drastically simplifies the actuation system including the sensors.

❹ shows the gear set of 7-xDCT and the actuation via the single shift drum. Another highlight is the extraordinarily short installation length of only 330 mm, which is made possible by the compact gear set with its four main gear planes and by the nested dual wet clutch. The 10-xDCT with on-demand electro-hydraulic actuation and optional hybridisation has an installation length of 370 mm and is shown on the title image.

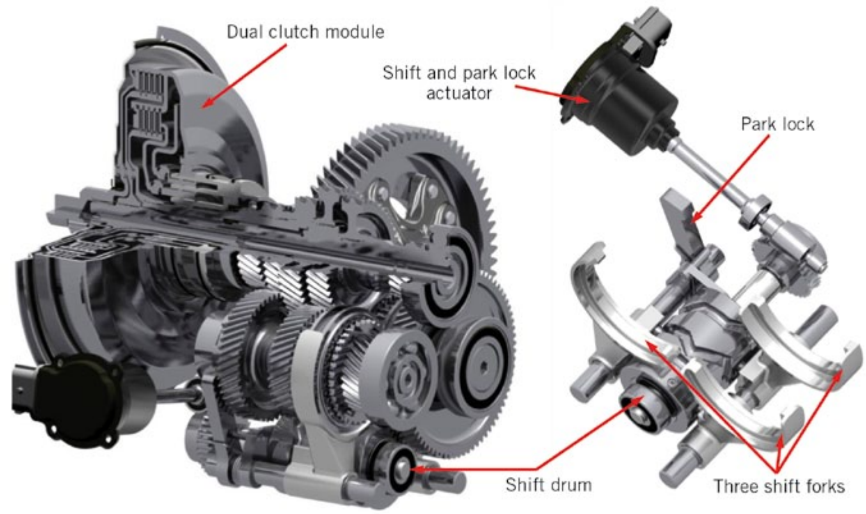
EFFICIENCY

For all generated gears (see also ②), two connections in a system of three degrees of freedom are closed which means the system is fully determined and the transmission runs with active gear pre-selection.

Also, compared to conventional gear sets, two more tooth contacts lie within the powerflow for the generated gears. However, an advantage of the xDCT fam-



❸ Comparison of the conventional DCT shift to the supported shift of the FEV 7-xDCT (3rd gear → 4th gear)



❹ 3-D model of the 7-xDCT gear set

ily is the reduced number of gear wheels, bearings and synchronisers which significantly reduces the drag losses.

❺ shows a comparison of delta speeds at non-engaged idler gears and synchronisers for 7-xDCT versus a series-production seven-speed DCT. While showing similar maximum values, the summed delta speeds of 7-xDCT are below the ones of the series-production DCT for all gears 2 to 7. In sixth and seventh gear, the difference is as significant as 40 %.

For a more precise efficiency estimation, the drag losses, efficiencies and the influence of gear pre-selection have been measured for the production DCT on a test bench. Especially in the NEDC-relevant part load range, the influence of drag losses on efficiency is actually much larger than the influence of load-dependent gear losses. Also the gear pre-selection has no significant influence on the efficiency. Therefore the drawback of more gear contacts in the power-flow will be at least compensated by the significantly lower drag losses of the xDCT family. This estimation is supported by efficiency measurements on hardware of FEV's 7H-AMT transmission, which also uses generated gears [6].

SUMMARY

With new ways of gear set synthesis FEV has developed the xDCT family, a series of dual-clutch transmissions setting a new benchmark regarding number of gears per mechanical complexity. The 10-xDCT offers ten powershiftable, well-stepped forward gears using only four shift sleeves and three main shafts thus maintaining the mechanical complexity of conventional seven-speed DCTs.

The 7-xDCT features seven speeds using only three shift sleeves and 14 gear wheels in total. In comparison to conventional concepts weight, cost and installation space can be significantly decreased. As an example, the 7-xDCT with dual wet clutch offers an installation length of only 330 mm.

Simulations and comparative measurements show that the xDCT concept is fully competitive with current series-production solutions regarding shift quality and efficiency. Due to very short first gear ratios and the small gear step 1→2, launch quality and performance are even increased.

The xDCT family offers innovative, tailor-made transmission concepts supporting both applications with high requirements regarding ratio spread and number of gears as well as applications with tight package und high cost pressure.

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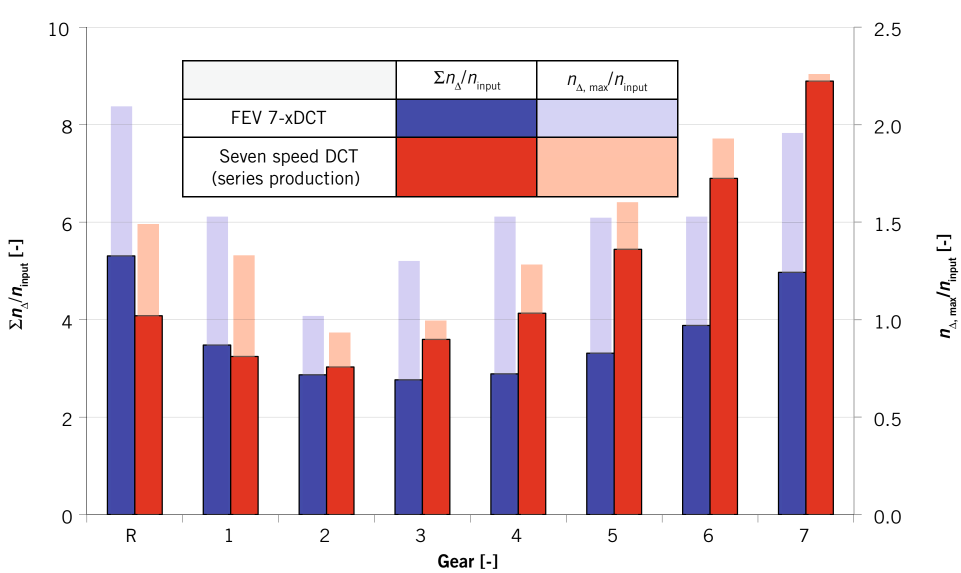

❺ Delta speeds at non-engaged idler gears for the FEV 7-xDCT and a series-production seven-speed DCT