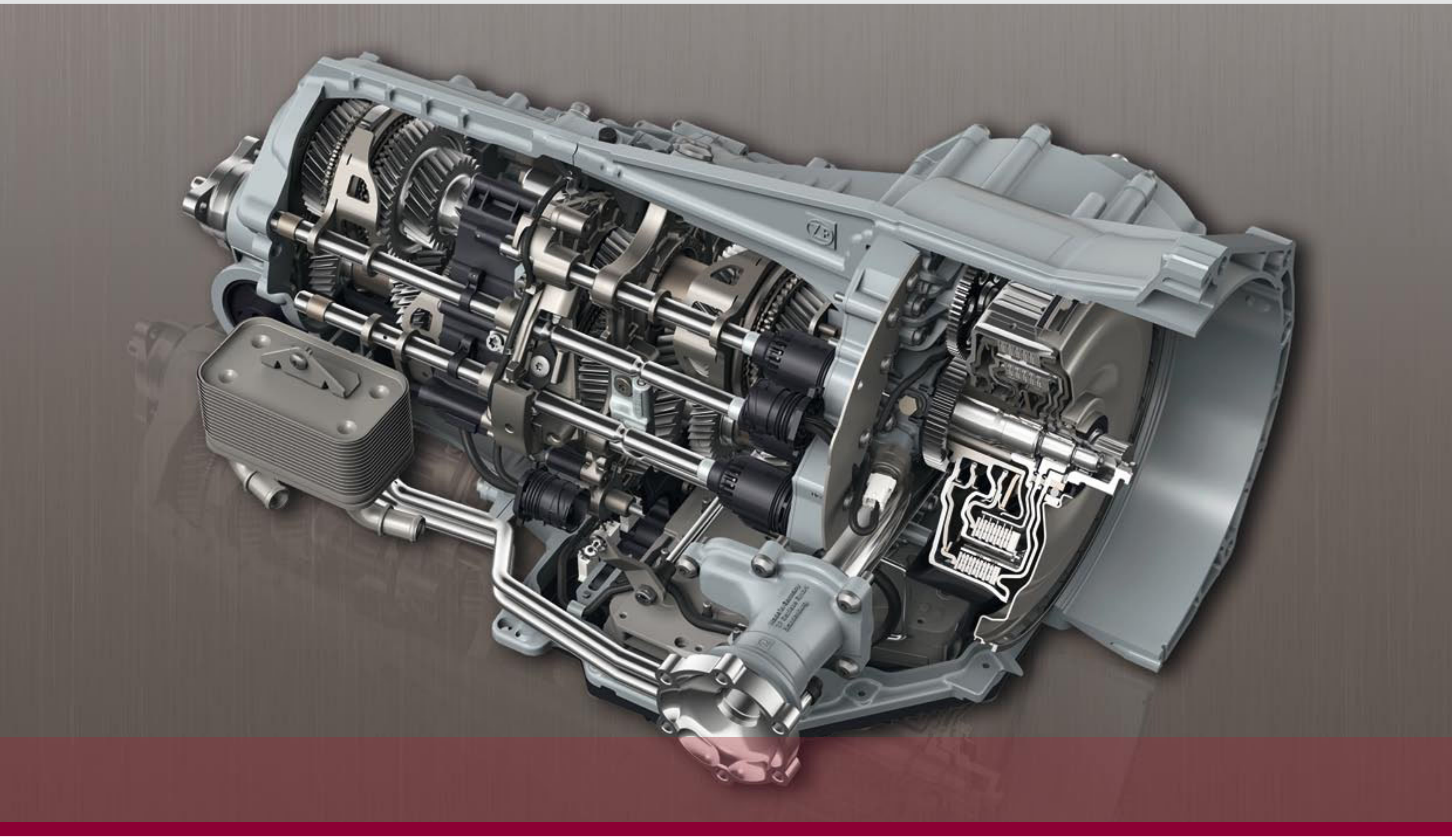

New Seven-Speed Dual-clutch Transmissions in Transaxle Design

The transaxle construction is actually the designation for a transmission model where the vehicle transmission, the differential transmission, and the axle drive are located in one housing. It is primarily used with sports cars. The well-known seven-speed dual-clutch transmission by ZF has been extended and now forms a transaxle kit for various installation positions and torque categories. The kit comprises automatic transmissions as well as the correspondingly derived manual transmissions. Gear set structure, bearing concept, as well as the structure of the transmission are illustrated. Special requirements of a transmission intended for high dynamics and the respective shift times are presented. The scope of application is presented for these transmissions vis-à-vis the converter planetary transmissions developed by ZF.

1 Introduction

Today, car buyers can choose from different transmission variants. If they want a full automatic transmission, the offer will comprise a multi-ratio automatic transmission with planetary gear sets, a CVT, or a dual-clutch transmission, depending on the vehicle manufacturer. In sporty applications, dual-clutch transmissions feature benefits that have led to corresponding demand and an individual product range at ZF. With the new modular kit for dual-clutch transmissions, together with the also newly engineered automatic planetary transmission, ZF is able to offer the suitable transmission to suit the vehicle characteristics, providing optimal performance and lowest possible fuel consumption.

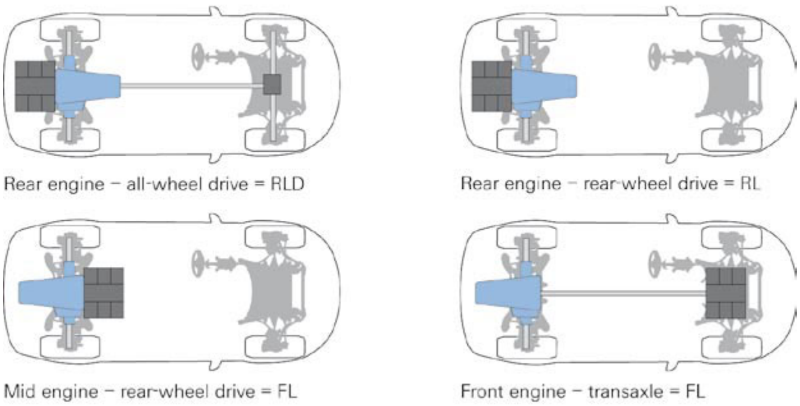

Figure 1: Schematic illustration of the modular concept for various powertrain concepts and installation positions of the dual-clutch transmission – the dual-clutch transmission of ZF can be used for all drive concepts, from middle engine / rear wheel drive to front-longitudinal engine with rear-wheel drive

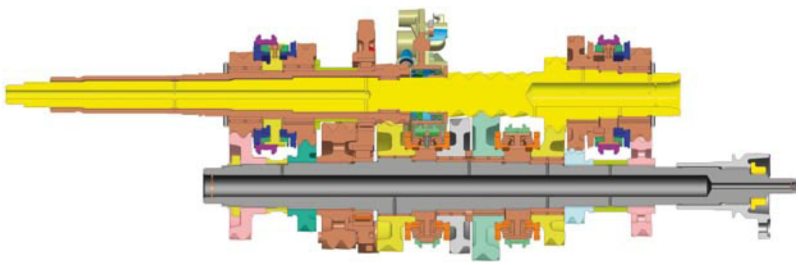

Figure 2: Section view of the gear set

2 Modular Concept

Particularly in the sports car sector, in addition to the transmission for the standard drive described under [1], there is a demand for transaxle transmissions (designation for a transmission design where the vehicle transmission, differential transmission, and axle drive are located in a housing) in longitudinal installation for both, pure rear wheel drive as well as all-wheel drive. The engine can either be located in front of or behind the transmission. In addition to these installation variants, they are also designed for various torque classes. ZF meets these complex requirements by offering a modular principle. A gear set which has been optimized for the torque limit and an axle drive are combined with a housing which is adapted to the installation and a standard control unit. Depending on the torque category, two variants of the dual-clutch transmission are available with the same structure but different diameters. If necessary, a manual transmission can be derived from the kit, using identical parts from the dual-clutch transmission for gear set and axle drive. Some of the possible combinations (modular concept) are illustrated in **Figure 1**. First series application was in 2008 with the 7DT45 HL in the torque category of up to 450 Nm.

3 Gear Set Concept

The center distances and installation lengths of the gear set, **Figure 2**, were selected for a maximum engine torque of 700 Nm and a maximum input speed of 8000 rpm. Differentiation between both torque classes is done via material selection and gear finishing. The ratings for both transmission ranges 7DT45 and 7DT70 can be found in the data sheet in the **Table**, the gear set pattern is illustrated in **Figure 3**. As it is required with dual-clutch transmissions, the even and uneven gears are distributed among one sub-transmission each [2].

The reverse gear is in the same sub-transmission as the 1st gear and the extension of the first gear is used as a fixed gear [3]. This has the advantage that reversing can also be initiated with the big clutch and, without extending the transmission, a ratio can be implemented which nearly corresponds to that of 1st gear. This leads to the same starting quality in reverse gear as in the forwards gear and the driver is not surprised by different tractive power even though the accelerator pedal may be in the same position. A disadvantage, however, is that when reversing D-R or R-D, one process is required each for deselecting, synchronizing, and selecting, which leads to slightly increased shift times with a pure comfort calibration.

Figure 3 also shows that a center support became necessary for the shafts due to the high torques and large installation length. An additional bearing plate in the level surface next to the output con-

The Authors

Dr.-Ing. Ulrich Remmlinger is head of product engineering dual-clutch transmissions at ZF Getriebe GmbH in Kressbronn (Germany).

Dipl.-Ing. (FH) Manfred Fischer is project manager dual-clutch transmissions at ZF Getriebe GmbH in Kressbronn (Germany).

Dipl.-Ing. Jens Patzner is head of product engineering manual shift transmissions and basic transmissions for dual-clutch transmissions at ZF Getriebe GmbH in the production plant Brandenburg (Germany).

stant reduces forcing back of the shaft, thus preventing gearing noise which would result from mal-positioning due to shaft deformation. The constructive design of the tubular shafts can be seen in **Figure 4**. It also becomes obvious in the section view, Figure 2, that all free spinning gears of the gear set run on needle bearings with a separate inner race. This design was chosen because the axial play of the free spinning gears then only depends on the longitudinal tolerance of the inner race and can thus be kept small. If the needles ran directly on the shaft, this would lead to axial clearance which is the sum of the tolerances across the entire shaft length. The reduction of axial clearance and thus backlash is an important contribution to the sportiness behaviour of the transmission. As shown later on, small angular clearance is a decisive factor for the subjective impression that the vehicle is very responsive.

To attain a high level of power density, the gears and shafts are produced according to special ZF supply specifications from case-hardened steels, for which the over years at ZF established SIN curves are available. The counter shaft for the rear-longitudinal (RL) transmission is cold-extruded from a tube and the material is thereby stretched both in radial and axial direction. In the all-wheel drive version with an additional output, the shaft is too long to use this new technology. Therefore, the all-wheel drive version is manufactured conventionally with deep-hole drilling.

When selecting the synchronizers, the requirement for sportiness with short shifting times was met by using linings with a high admissible synchronizer performance. For gears 1, 2, 3, and reverse (R) gear, these are triple synchronizers with powder sinter linings. For gears 4, 5, 6, and 7, simple synchronizers with carbon linings are used. Moreover, to protect the linings, the energy input due to drag torques during the synchronizing process is kept at a small level. This is ensured by a continuous, requirement-based control of the coolant flow, which flows through the open clutch. During the synchronizing procedure, the cooling oil flow is interrupted for a short time.

4 Transmission Structure

Figure 5 shows a cutaway view of the entire transmission. The two concentric drive shafts are at the top, the counter shaft with the output constant is underneath, and the pinion shaft with engagement in the ring gear is at the side. The parking lock is located at the end of the pinion shaft. The axle drive with differential and flange shafts is located transversal to transmission, through the ring gear. Optionally, the transmission can also be supplied with a mechanical differential lock. For transmissions for all-wheel drives, the additional output is implemented at the end of the main shaft. The control unit is at the bottom of the transmission.

Since the axle drive with the bevel gear set requires the use of a hypoid oil, which is not suitable for use with the starting clutch, however, two separate oil chambers had to be designed. Both oil chambers with separation are illustrated in **Figure 6**. The clutch oil was selected in combination with the friction linings of the starting clutch. This first oil chamber with 5.5 liters

Table: Data sheet of the new seven-speed dual-clutch transmission – models 7DT45 with 450 Nm and 7DT70 with 700 Nm input torque (all data is based on ZF design cycle)

Feature	Value or item		
Übertragungsfähigkeit		7DT 45	7DT 70
Torque capacity	$T_{max, engine}$ at 4200 rpm	450 Nm	700 Nm
	n_{max}	8000 rpm	7500 rpm
Starting element	Dual clutch ND 2014 to 450 Nm and ND2216 to 700 Nm		
Gears	7		
Center distance	85 mm		
Spreading	6.335		
Ratios	3.909 – 2.929 – 1.654 – 1.303 – 1.081 – 0.881 – 0.617 ; R = -3.545		
Transmission steps	1.335 – 1.771 – 1.269 – 1.205 – 1.227 – 1.428		
Axle ratio	3.444		
Selector lever positions	P, R, N, D; electric shift mechanism, cable-controlled parking lock		
Control system	Hydraulics with external ECU; controlled powershifts; various shift programs		
Weight with oil	RL 450 Nm 115 kg / RL 700 Nm 121 kg		

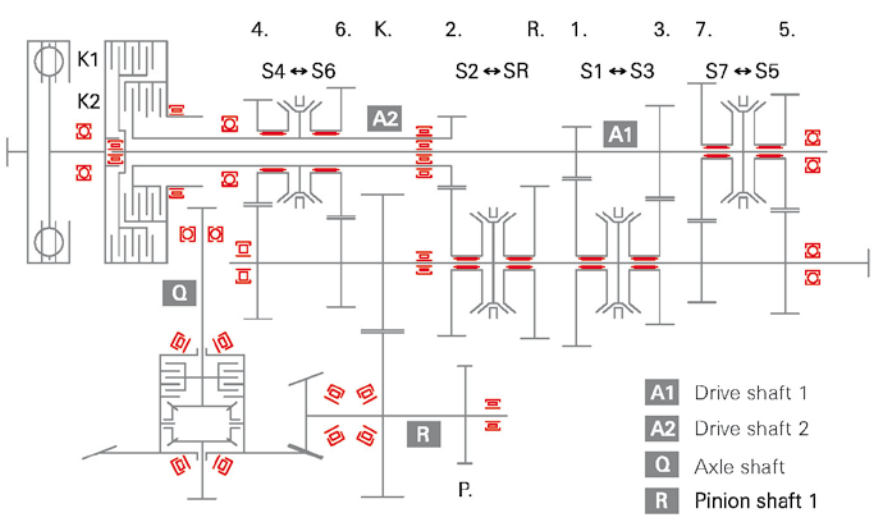

Figure 3: Gear set and bearing pattern

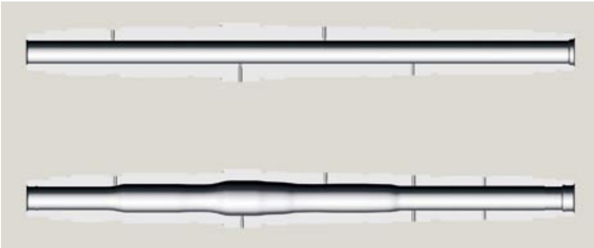

Figure 4: Tubular shafts as main shaft in all-wheel drive version as well as the main shaft, cold-extruded in the version without additional output

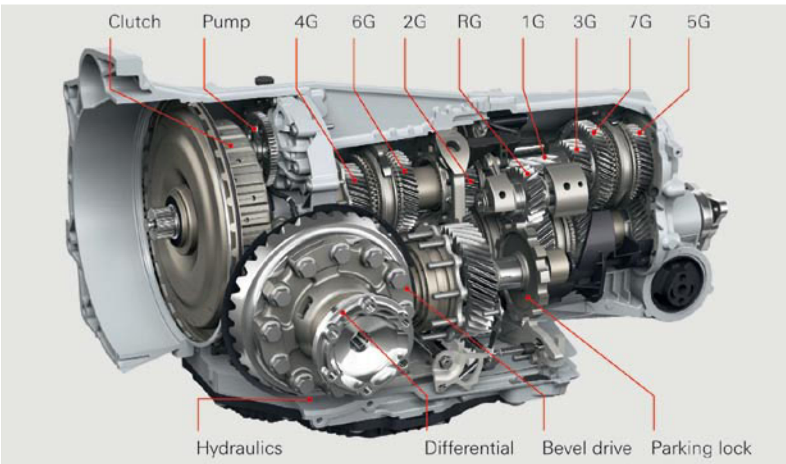

Figure 5: Dual-clutch transmission (all-wheel drive version) with seven gears 1G to 7G and reverse gear RG

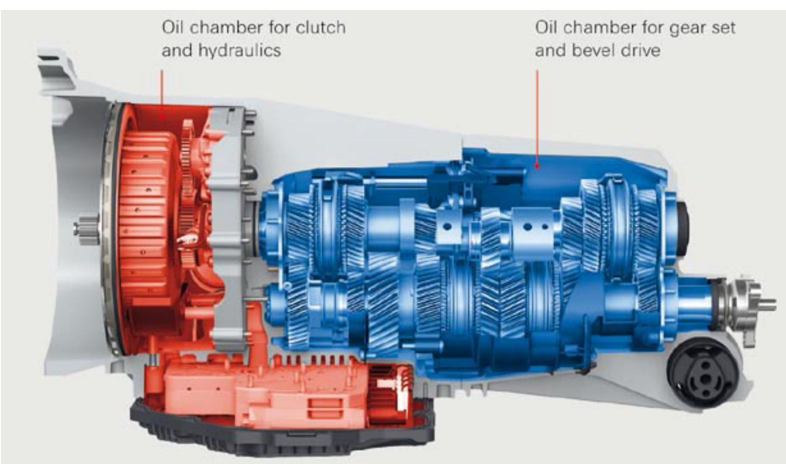

Figure 6: Oil chamber separation

comprises the clutch, pump, hydraulic control unit, gearshift rod cylinder, oil filter, and oil pan. A second oil chamber is in the housing part which contains the gear set and bevel gear. It is filled with 3.0 liters of hypoid oil. Double radial shaft seals with relief bore ensure safe separation of the oil chambers. No additional pump is planned for the second oil chamber. Therefore, the oil drip channels and oil baffles, **Figure 7**, known from the manual transmission must be used in order to ensure sufficient lubrication and cooling of the gear set.

Additional components, such as the dual clutch, the pump, and the valves of the hydraulic control unit are identical to those of other ZF dual-clutch transmissions and have already been described in [1]. Regarding the clutch, it must be mentioned that the control of the cooling oil flow in line with the requirements provides the enormous cooling power required for a racing start, but also reduces the oil flow in constant operation to such an extent that drag torques, splash losses, and splash of oil are minimized. The cooling power required is continuously calculated in the software by means of an online temperature model.

5 Design for High Level of Dynamics

In addition to a low power-to-weight ratio of the vehicle, the following features must be available among others, so that the driver rates the driveline response as being sporty:

1. Fast acceleration change with transient changes of drive power („vehicle is responsive")
2. Smallest possible backlash, meaning no lag time in the case of traction/thrust changes
3. Short shifting times
4. Sporty shift program which allows for driving in low gear with high traction reserve, if the driver wishes to do so
5. Upshift prevention before bends and with delayed overtaking maneuvers.

The quick response claimed in item 1 requires a dynamic driveline with a high natural frequency. The latter is determined by the mass moments of inertia which are shown in **Figure 8** for a sporty sedan. Even in the first gear, the masses which can be influenced by the transmission are low compared with the vehicle mass relating to the input shaft. The limitation in transmission installation length in the sports car exacts the alignment of both clutches one above the other in the transmission. This means that further reduction of rotating mass in the dual clutch is not possible. With the dual-mass flywheel (DMF), a reduction would be allowed if it was possible to reduce irregularities in terms of engine excitation. Furthermore, the natural frequency of the driveline is determined by its spring stiffness. Here, for the first natural frequency, exclusively the drive shafts have an impact on the wheels, the rest of the driveline is stiff. When selecting the stiffness of the drive shafts, however, their impact on the longitudinal and pitching natural frequency in particular is to be considered in combination with the transmission sus-

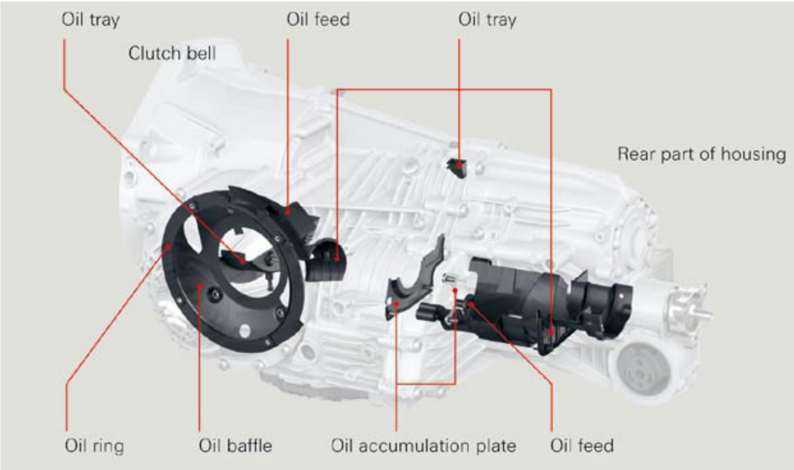

Figure 7: Oil baffles

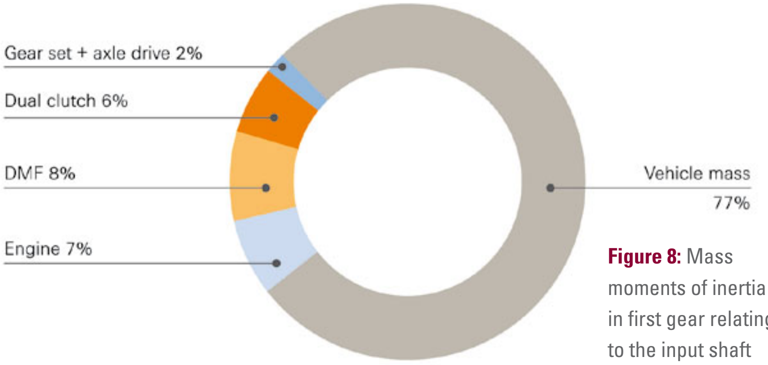

Figure 8: Mass moments of inertia in first gear relating to the input shaft

pension. If it is designed incorrectly, this can lead to unpleasant vibrations during starting with a resonance peak [4]. In terms of spring stiffness, the second natural frequency is dominated by the torsional damper. Here again, slight engine excitations allow for the design of a dynamic driveline with a stiff torsion spring.

The dynamics achieved by the dual-clutch transmission is compared in **Figure 9** with that of a converter transmission. Here, the torsion angle between transmission input and output was calculated for a specified rev-up with a vibration simulation and standardized to the value of the dual-clutch transmission. It can be seen immediately that the slip in the converter decisively worsens the dynamics, which is perceived by the driver as a „spongy" response. Thus, after starting, the lock-up clutch would have to remain permanently closed to ensure that the converter transmission achieves the dynamics of a dual-clutch transmission. This is not possible with the converter transmissions currently available on the market because the damping element in the converter clutch does not have the quality of a dual-mass fly wheel and there are driving situations in which the open converter is required to decouple vibrations. The measures to reduce clearance as mentioned in item 2 have already been described in Chapter 3 for the gear set. The backlash in the bevel gear is set with a narrow tolerance during assembly. The other backlash settings in the drive shafts are determined by the OEM irrespective of the transmission.

The short shifting times demanded in item 3 constitute the most important criterion for a sporty transmission. For the first time, a new speed control concept is used with the 7DT45 in series, to achieve even shorter shifting times. In multiratio automatic transmissions, the engine torque during shifting is usually influenced in the speed adaptation phase by a CAN signal sent to the engine control so that the desired speed gradient is realized. With the 7DT45, control in this phase is transferred to the engine control unit, which will set a prescribed target rpm for the engine. The hydraulic control unit with pre-controlled valves also contributes to the short shifting times described in [1]. Very short shifting times are realized by the interaction with the four position sensors on the gearshift rods and the cumulative effect of these measures, which are compared in **Figure 10** with measurement values from competitor transmissions. When comparing shift times, it must be considered that these depend strongly on the selected setup. The differences between a comfort shift and a sporty upshift with peak traction have already been illustrated in [1]. Sporty shifts with similar rpm gradients are taken for this comparison. It immediately becomes obvious that with the traction upshifts, the dual-clutch transmissions and modern automatic transmissions from ZF have a head start compared to the competitors' conventional converter transmissions. A system-inherent disadvantage of dual-clutch transmissions makes itself felt during downshifts across two gears with the competitors' transmission. The new gear cannot be pre-synchronized because it is located in the same sub-transmission as the driving gear, which results in longer shifting times. With the 7DT45, this drawback is largely compensated by the described rpm control measures. In the sports and supersports program, the high rpm gradients which are possible with the 7DT45 control unit are fully utilized. All gear changes run equally quickly without any difference and thus set a new reference for sportiness.

The functions and features demanded under item 4 and item 5 must be considered in the driving strategy. Here, the dual-clutch transmission benefits from the experience made with the 5HP and 6HP transmissions by ZF and can take over the software functions for the driving strategy and hill detection with only few changes. Especially the upshift prevention by the „fast off" function, which processes the gradient of the accelerator pedal change, suits the character of a sports car very well. Since the software design is modular, an individual driving strategy program of the OEM can be incorporated upon request. The racing start, another function to support the sportiness offered by the transmission, has already been described in [1].

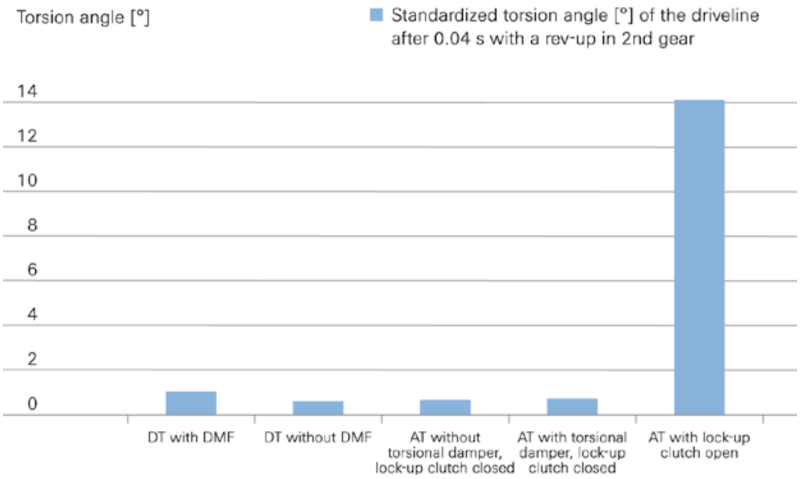

Figure 9: Standardized torsion angle of the driveline after 0.04 s with a rev-up in second gear

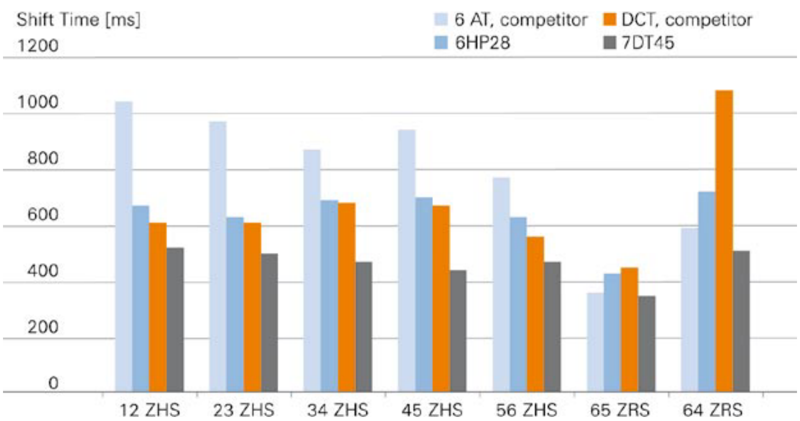

Figure 10: Comparison of different sports program shifting times (example: 12 ZHS means: traction upshift from gear 1 to 2)

6 Transmission Losses

The future legislation on CO_2 emissions will make no exceptions for sports cars, so the demand for a high transmission efficiency will gain even more importance. The dual-clutch transmission has the potential of achieving the same high level of efficiency in all gears, similar to the characteristics of a manual transmission. However, this requires careful optimization of the details of all individual components. In contrast to the manual transmission, the dual-clutch transmission requires an oil pump, which is designed as an axially parallel internal-gear pump with small diameters and the smallest possible play in order to achieve good efficiency. Moreover, compared with manual transmissions, there is an additional open clutch with the dual-clutch transmission which generates drag torque. This loss can be kept at a small level if a sufficient air gap is provided for and the coolant flow can be controlled in terms of time and quantity.

With the dual-clutch transmission, the efficiency not only depends on the selected gear, rpm, and oil temperature, but also on the gear pre-selected in the other sub-transmission. For the measurement, the next highest gear was pre-selected at 1500 rpm; for lower engine speeds and in seventh gear, the downshift was prepared. Especially in second gear it becomes clear how the pre-selection of the lower gear below 1500 rpm leads to higher speeds in the other sub-transmission due to the high gear step, thus generating higher drag torques. In general it can be said that the losses in gears 2 to 6 are very close together, similar those of a manual transmission, and they do not exceed the relevant area of 8 % for the fuel cycle.

With a planetary transmission, the gear-dependent losses vary more strongly, depending on the design versions and the gear set system used. In addition, compared with the planetary transmissions, it becomes obvious for similar performance ranges that the transmission losses above the speed only rise slightly with dual-clutch transmissions. When using the transmission with a sporty driving style in a vehicle with a high-revving engine, this behavior has a very favorable impact on consumption.

7 Summary

According to these explanations, there is a clear delimitation for the use of dual-clutch transmissions with a longitudinal design. Dual-clutch transmissions have advantages when used with high-revving engines, in terms of shift times and the stiffness of the driveline. Compared with converter transmissions, they lead to smaller losses, which allow for more favorable fuel consumption and better acceleration values in the vehicle. In terms of travel after 4 s, converter transmissions are still unbeatable due to their gain in traction in the torque converter, especially when it comes to vehicles which are weakly motorized. With the new generation of ZF's 8HP transmissions, the converter transmission will catch up in terms of performance and consumption. Therefore, it is in the market segment for sports cars and sporty sedans where the benefits of dual-clutch transmissions take effect. Since the volumes in this segment are limited, a kit with a high share of equal parts was the right response to the requirements of the different vehicle concepts.

References

[1] Kubalczyk, R.; Ebenhoch, M.; Schneider, H-J.: 7-Gang-Doppelkupplungsgetriebe für sportliche Anwendung. [7-Speed Dual-Clutch Transmission for Sporty Applications.] VDI-Berichte Nr. 1943, Düsseldorf, 2006

[2] Patentanmeldung DE 10 2005 058 946 A1

[3] Patentanmeldung DE 10 2005 005 163 A1

[4] Böger, T.; Pfingst, J.; Kurrle, F.; Krüger, A.: Entwicklungsmethodik zur Optimierung des Anfahrkomforts bezüglich Gesamtfahrzeugschwingungen. [Development Method on the Optimization of Starting Comfort in Terms of Overall Vehicle Vibrations,] VDI-Berichte Nr. 1987, Düsseldorf, 2007