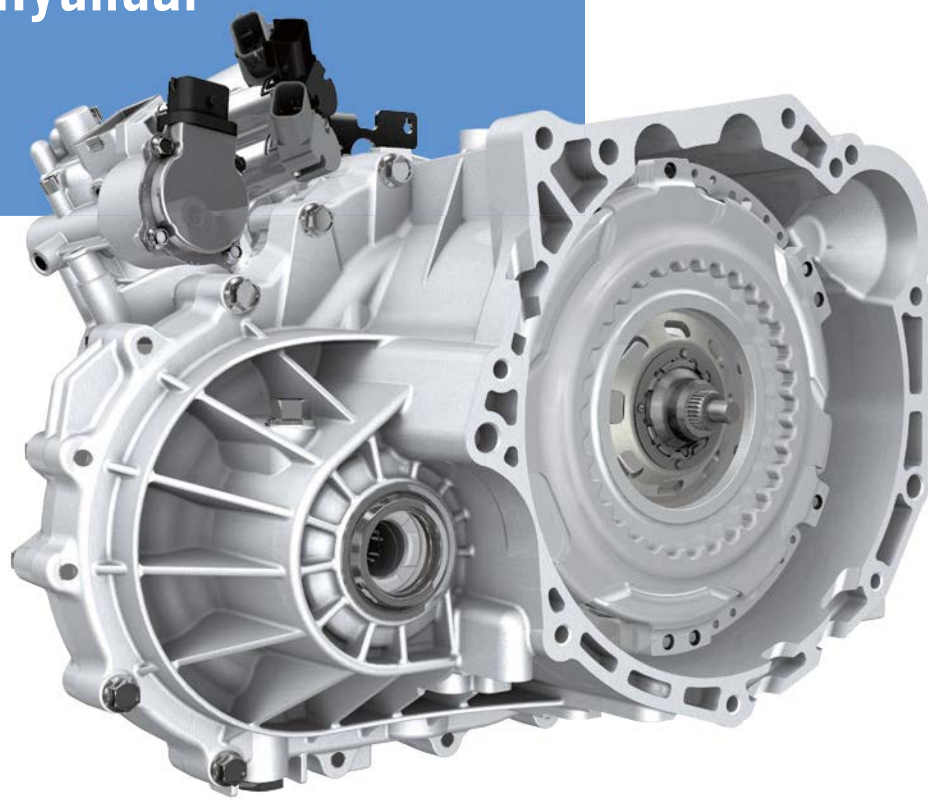
More Efficiency with the Dry Seven-speed Dual-clutch Transmission by Hyundai



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Especially as a front-wheel drive, dual-clutch transmissions have to be very compact and efficient to generate driving pleasure. Therefore, Hyundai-Kia developed a seven-speed dual-clutch transmission with dry clutch and electro-mechanical actuation, which is available in two models with 220 and 340 Nm maximum input torque. A transmission length of only 385 mm is very competitive considering this high torque capacity.

LOWERING CO_2 EMISSIONS IN THE FIRST PLACE

Even though Hyundai-Kia has already developed a full line-up of automatic transmission from small passenger car to large sedan and SUV in house, there has been a strong demand on new transmission development with better efficiency, performance and convenience in combination with downsized combustion engines (gasoline/diesel). The priority of these demands was different among vehicle model and sales region, but efficiency had a priority in common to realise lower CO_2 emission. For best fuel economy, the completely new developed seven-speed dual-clutch transmission (DCT) of Hyundai-Kia adopted dry dual clutch and electro-mechanical actuators for gear as well as clutch operation, **FIGURE 1**. On the basis of this prerequisite a modular design has been developed for two new highly efficient DCT models with the following key features:

- two transmission models with different main shaft centre distance, maximum torque and clutch size, but sharing gear/clutch actuators
- seven-speed gear train layout to provide maximised gear ratio spread in a strongly limited axial length of the front-wheel layout to fit in a variety of

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vehicles from compact passenger car up to mid-size sedan and SUV
– shift comfort to be on the same standard that current Hyundai-Kia automatic transmissions already offer and sporty feel at the same time
– fuel efficiency increased by 5 % or more compared to current six-speed automatic transmissions.

MASS PRODUCTION AND PATENTS

The design phase was started in early 2011, and the mass production started finally in September 2014 at the Hyundai-Dymos plant located in South Korea. The initial vehicle to install the new transmission was a Hyundai Sonata sedan powered by a Gamma 1.6-l turbocharged gasoline engine as well as in Europe a Kia Ceed with 1.6-l diesel engine.

Until now, 16 vehicle models with four different engines have been launched with the new seven-speed DCT – and much more vehicles are yet to come. As a result of this DCT development including actuation system and control logic, approximately 400 patents are pending. During the development process all activities and methods were reflected according to ISO 26262 (Road Vehicles – Functional Safety) [1].

TRANSMISSION MODELS AND GEAR RATIOS

Two DCT models with different torque capacity have been developed in parallel for gasoline and diesel applications: a smaller one (D7GF1) with 220 Nm and a bigger one (D7UF1) with 340 Nm. According to the modularity these two transmissions have the same structure and share the gear actuator as well as the clutch actuator. Differences can be found in the size of the gear wheels, the shaft centre distance and in the dual clutches themselves. This gives a weight benefit of 7 kg to the smaller transmission.

As these transmissions are applied to various engines and vehicle segments, there are many combinations of gear ratio, **TABLE 1**. The D7GF1 has an entire gear ratio span between 6.73 and 6.94, and the D7UF1 has a wider span from 6.53 to 7.83. A wider gear ratio span helps to achieve better acceleration performance in low gears and fuel economy when cruising in high gears. To prevent clutch overheat at steep grade, the ratio of the 1^{st} gear has been chosen with care considering engine torque at launch revolution speed, vehicle weight and tyre size.

GEAR TRAIN LAYOUT

The biggest challenge during designing the gear train layout was the limit in transmission length, because the seven-speed transmission is transversally mounted in the engine compartment between side members whereas dual clutch size and number of gears need increased space compared to conventional six-speed manual transmissions. Especially for the compact passenger car application this was a difficult mission to realise. Single pairing of input and output gear for every gear-speed, which is quite conventional in manual transmission design, was not possible to fit in that very small engine compartment.

To solve this issue multi-use gear pairing was essential. In the final layout, as depicted in **FIGURE 2**, 1^{st}, 2^{nd}, 4^{th} and 5^{th} gear are located on the lower output shaft #1, whereas 3^{rd}, 6^{th}, 7^{th} and reverse gear are located on the upper shaft #2. To shorten transmission length, 4^{th} and 6^{th} gear share one common driving gear, and 2^{nd} and reverse gear share another common gear on the input shaft. This led to a total transmission length of 385 mm from engine block face to the end of case, which is competitive considering the high torque capacity of 340 Nm.

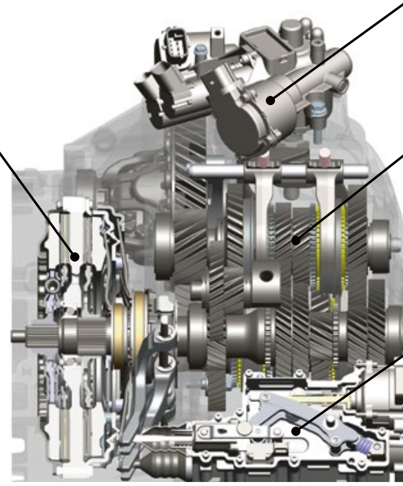

FIGURE 1 Overall structure of the completely new developed seven-speed dual-clutch transmission (© Hyundai-Kia)

GEAR ACTUATOR AND SYNCHRONISER

New DCTs have an independent gear shift structure for even and odd gears: In case even or odd gear shift system has a problem, this DCT can drive with the remaining gears in the other part of the transmission and do AMT like shifting.

Analysing the mechanism in detail showed that the select operation requires less force than the shift operation. This led to introducing solenoids for selecting the right shift lane, **FIGURE 3**. As a result, this made the overall shift time even shorter (15 % faster than previous six-speed DCT). Additionally, to ensure the quickest and reliable shift, triple-cone synchronisers are applied in 1st, 2nd, 3rd gear, and carbon linings are applied to the friction surfaces.

Gear ratio	D7GF1 (220 Nm)	D7UF1 (340 Nm)
1st gear	3.813	3.929/3.786/3.643
2nd gear	2.261	2.318/2.261/2.174
3rd gear	1.957	2.043/1.957/1.826
4th gear	1.073	1.023/1.070/1.024
5th gear	0.837	0.822/0.809/0.778
6th gear	0.902/0.878	0.884/0.854/0.837
7th gear	0.756/0.721	0.721/0.717/0.681
Reverse gear	5.101	5.304/5.074/4.696
Shaft #1 (1st/2nd/4th/5th gear)	4.867/4.375/4.125	4.857/4.643/4.643/4.429 4.294/4.286/4.176/3.941
Shaft #2 (3rd/6th/7th/R gear)	3.650/3.333/3.143	3.579/3.611/3.421/3.263 3.174/3.158/3.087/2.913
Entire gear ratio span	6.73–6.94	6.53–7.83

TABLE 1 Many combinations of gear ratio for the smaller (D7GF1) and the bigger (D7UF1) transmission model (© Hyundai-Kia)

DUAL CLUTCH AND CLUTCH ACTUATOR

The new dry-type dual clutch system, **FIGURE 4**, has also been developed to meet the very high torque capacity of 340 Nm for D7UF1: The outer diameter is 235 mm for the “odd” clutch, and 229 mm for the “even” clutch. The friction characteristic of the clutch lining directly influences the shift quality during driving because it changes dramatically. For this reason the Transmission Control Unit (TCU) needs to be aware of the friction characteristic to control the vehicle behaviour smoothly without jerk and revolution speed flare. Any change of this characteristic is estimated through monitoring the transferred torque versus clutch actuator stroke by the TCU during driving, and utilised for adaptive clutch control in every driving situation.

In case of a fixed clutch actuator lever ratio, the electric current draw of the clutch actuator motor increases proportionally to the clutch actuator stroke. This leads to higher fuel consumption. To counteract this tendency, a nonlinear clutch actuator has been designed, and its peak electric power consumption has been reduced by 40 % compared to the initial design with fixed lever ratio.

CONTROL SOFTWARE AND SHIFT QUALITY

Clutch and gear shift control logic has been developed in-house in parallel with the hardware development. One of the most important issues was to know the temperature of the clutch lining to prevent system failure at high temperature. But, it was difficult to attach a wired temperature sensor and measure it as the clutch rotates at high revolution speed. Wireless telemetric sensors could be a solution, but withstanding the very high friction heat and having a battery that lasts for the lifetime of the vehicle is also impossible.

Therefore, a precise clutch temperature model was developed, and validated through rig and vehicle tests simulating a large number of different driving conditions. Public road validation has been performed in different road conditions all over the world: high speed at German Autobahn, heavy traffic jam in Seoul, long distance cruise in the USA, high temperature in Middle East, cold conditions in Eastern Europe as well as high humidity and rough road in China. In the end a shift quality was developed to meet the customer’s taste in different regions: smooth and convenient, similar to a torque-converter automatic transmission (South Korea / USA), but also dynamic and direct, similar to a manual transmission (Europe).

NVH OF GEAR TRAIN AND ACTUATOR

Considering customer’s growing expectation as time goes by, dry DCT with electro-mechanical gear actuation has a structural disadvantage in NVH compared to an automatic transmission with torque converter and hydraulic actuator despite of high efficiency and good fuel economy. Noise from the DCT elec-

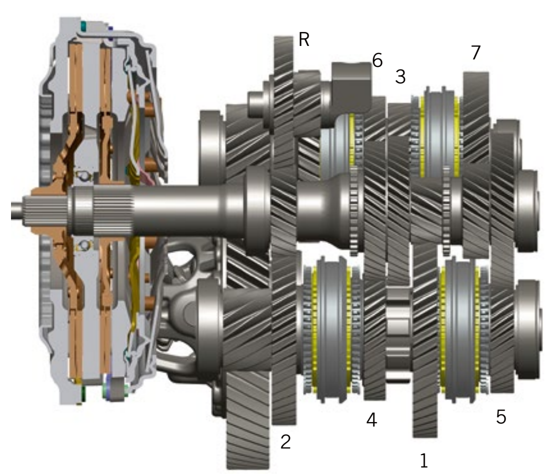

FIGURE 2 Gear train layout with shaft #1 and #2 (© Hyundai-Kia)

tro-mechanical gear actuator is higher than the one from the clutch actuator, because the reaction force on the gear actuator changes drastically without damping compared to the consistent and smooth reaction force on the clutch actuating. In addition it is perceived sensitively by the driver as he does not shift by himself. This noise could have been reduced with the help of optimised control logic and sensitive calibration to a level, which is similar to that of a hydraulic actuator.

Another sensitive NVH issue is clutch judder while launching, which can be analysed to come from friction and geometric factors. The problem has been solved by developing a new reliable clutch lining material and introducing latest production processes to reach the target geometric tolerance safely. In addition, to achieve extremely low gear noise, gear grinding process was mandatory for all forward gears. Also the stiffness of shafts and case is carefully reflected in the gear profile development.

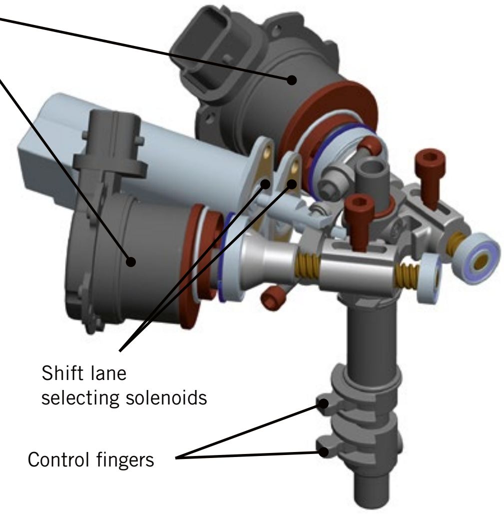

FIGURE 3 Gear actuator (© Hyundai-Kia)

EFFICIENCY, ECONOMY AND PERFORMANCE

Finally the most important issue of this transmission is the efficiency, which is directly related to the fuel consumption. To minimise the inner mechanical friction, needle roller bearings are used at all the idling gears. A roller bearing is located between the two input shafts where high thrust forces exist. The preloads were carefully optimised where tapered roller bearing are supporting the shafts and differential.

Because the churning loss in driving condition contributes a lot, a new low viscosity transmission oil has been developed to reduce the drag losses. Compared to the previous manual transmission oil, this new oil showed 49 % lower viscosity at 40 °C. As a result, this transmission showed very high torque transfer efficiency, which is the same level as the manual transmission and one of the highest in this class. Thanks to the high transmission efficiency, the fuel economy of Hyundai-Kia vehicles has been dramatically improved. Depending on the vehicle and engine characteristics, the fuel consumption has been reduced by 6 to 10 % compared to six-speed torque-converter automatic transmission applications.

Another impressive advantage is the acceleration performance. Even though initial launch of the DCT is slightly slower than the torque-converter automatic transmission, the high efficiency and short shift time enables the new seven-speed DCT to “overtake” this transmission: the 0-100 km/h acceleration time of the new DCT is 4 to 6 % shorter than the six-speed automatic transmission.

OUTLOOK

Hyundai-Kia will expand seven-speed DCT application in passenger cars and SUVs in the future. These DCTs will usually be combined with newly developed turbo-charged diesel and gasoline engines providing high torque at launch revolution speed. Additionally, DCT will be applied to new hybrid vehicles chasing two hares of fuel economy and driving pleasure at once.

The core task for Hyundai-Kia transmission development is continuous efficiency improvement to achieve lower CO_2 emission and better fuel economy. As a result, customers can benefit from higher economy of the products and people from a cleaner environment.

REFERENCE

[1] DIN 26262: Road Vehicles – Functional Safety. Berlin: Beuth, 2012

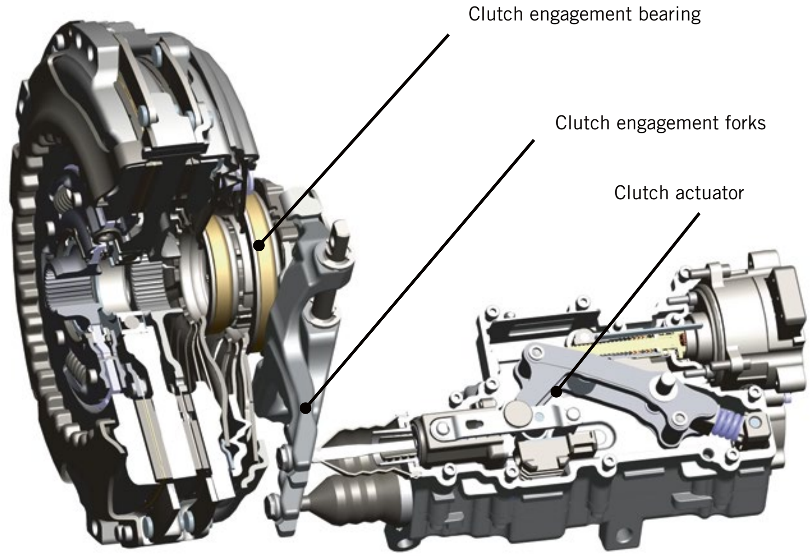

FIGURE 4 Clutch system – with the nonlinear clutch actuator, the peak electric power consumption can be reduced by 40 % (© Hyundai-Kia)