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Foreword

Innovations are shaping our future. Experts predict that there will be more changes in the fields of transmission, electronics and safety of vehicles over the next 15 years than there have been throughout the past 50 years. This drive for innovation is continually providing manufacturers and suppliers with new challenges and is set to significantly alter our world of mobility.

LuK is embracing these challenges. With a wealth of vision and engineering performance, our engineers are once again proving their innovative power.

This volume comprises papers from the 7th LuK Symposium and illustrates our view of technical developments.

We look forward to some interesting discussions with you.

Bühl, in April 2002

Helmut Beier

President
of the LuK Group

Content

The XSG Family

Dry Clutches and Electric Motors as Core Elements of the Future Automated Gearbox

Robert Fischer
Georg Schneider

Introduction

Within the XSG family, LuK has brought together automated gearboxes that are based on the Manual Transmission (MT, in German ‘Handschaltgetriebe’) and use essentially similar technology. They include Electronic Clutch Management (ECM), the Auto Shift Gearbox (ASG), the Uninterrupted Shift Gearbox (USG), the Parallel Shift Gearbox (PSG) and the Electrical Shift Gearbox (ESG). The first part of this paper presents an overview of the family members and how they relate to each other. In the second section, some of the family members are presented in more detail, in particular the ASG and USG. The ECM has already been adequately covered in earlier papers [1], [2] and the PSG and ESG will be covered elsewhere in this book [3], [4]. The third part of the paper introduces the common components of the XSG family whilst the fourth part contains a system comparison.

Presentation of Family Members

As previously mentioned, the XSG family is based on the **Manual Transmission** (**MT**, figure 1). The diagram has been simplified for the purposes of this paper; parts which interact are shown in the same colour, where necessary with a different shade. A transverse gearbox has been used as the example here.

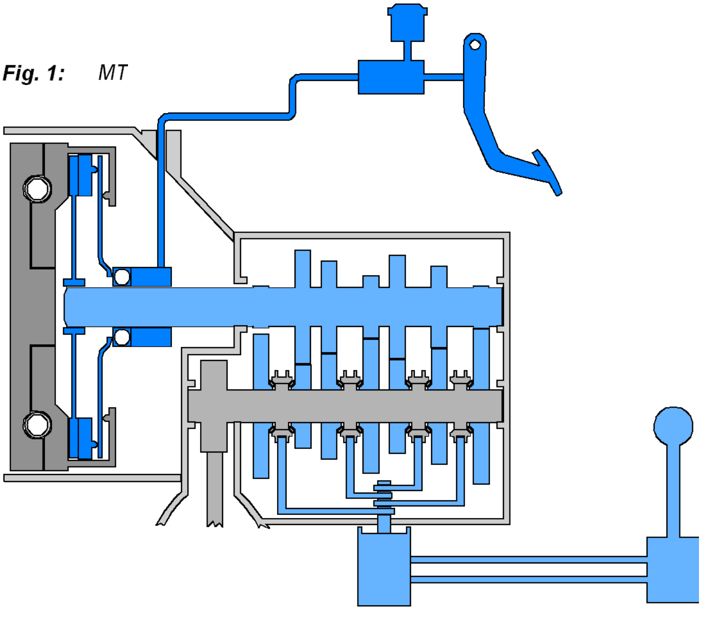
Manual transmissions have the advantage of being very efficient and relatively low in weight; they are low-cost and there are numerous manufacturing plants.

The first step in automation of the manual transmission is **Electronic Clutch Management** (**ECM**). This dispenses with the clutch pedal. The clutch is controlled by an actuator, which can be either electrical, hydraulic or pneumatic. The diagrams show the electromotoric variant preferred by LuK, see figure 2.

Automating the clutch itself brings significant benefits in comfort, which are particularly advantageous, especially in urban traffic, which is becoming increasingly heavier. ECM is also a fundamental requirement for all subsequent members of the XSG family.

With an **Auto Shift Gearbox** (**ASG**) the actual gear shifting is also automated. Two electric motors take over the task of selecting and shifting gears from the driver, see figure 3.

Fig. 1: MT



This also brings about an additional increase in comfort. Fuel consumption can be reduced through the automatical and optimally configured shift point selection - that‘s one reason why an auto shift gearbox is used on practically all energy-saving vehicles. A further advantage is the flexible interior design, since with shift-by-wire, the mechanical connection between gearbox and the driver’s control element is omitted. This can extend as far as the gear lever being completely omitted and being replaced by tip switches or a lever on the steering wheel. The interior acoustics are also improved by shift-by-wire, since the noise bridge is removed.

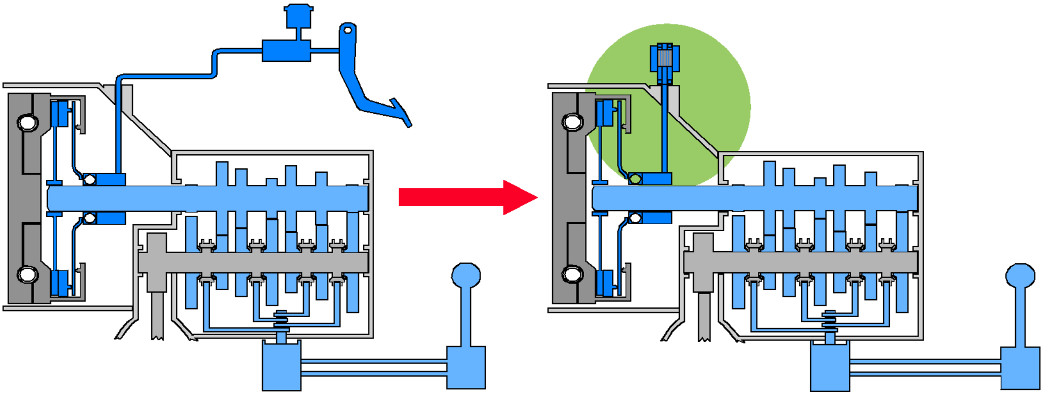


Fig. 2: From MT to ECM

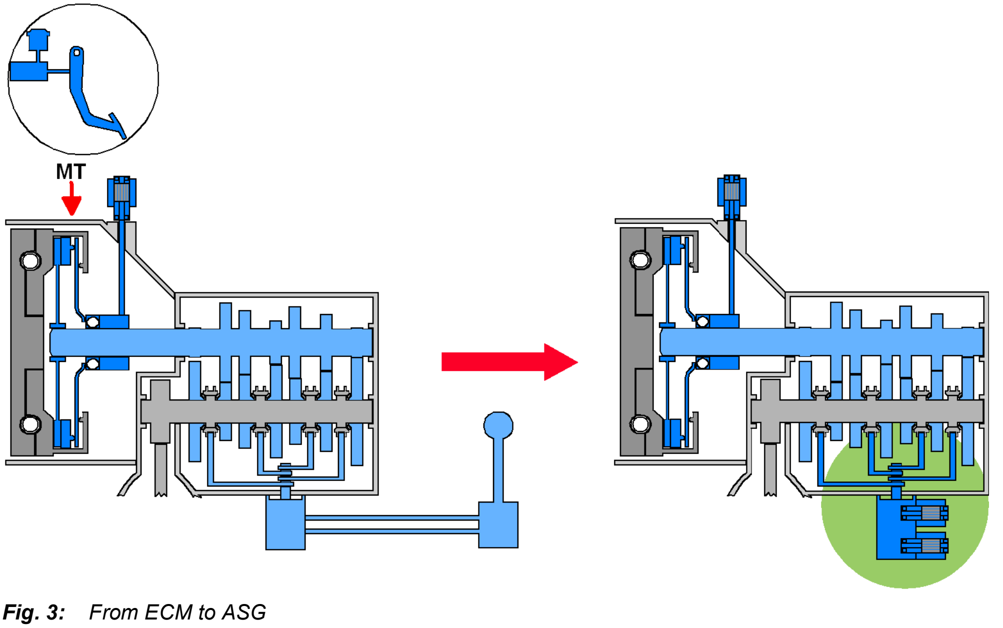


Fig. 3: From ECM to ASG

On an **Uninterrupted Shift Gearbox** (**USG**, figure 4) a partial filling of the torque interruption during a gear shift is achieved with an additional clutch.

As a result the shift comfort is further improved. The extra cost compared with an ASG is minimal; as explained in [5], only one clutch actuator is necessary for both clutches on the USG. However, this gearbox can only be used up to a certain level of engine torque.

The **Parallel Shift Gearbox** (**PSG**) belongs to the twin clutch gearbox group. LuK has given the PSG (figure 5) its own name, as it is rather a special design. Dry clutches and electromotoric actuators are used. An additional feature is that only **one** actuator similar to the ASG is used for the gear shifting of both gearbox sections.

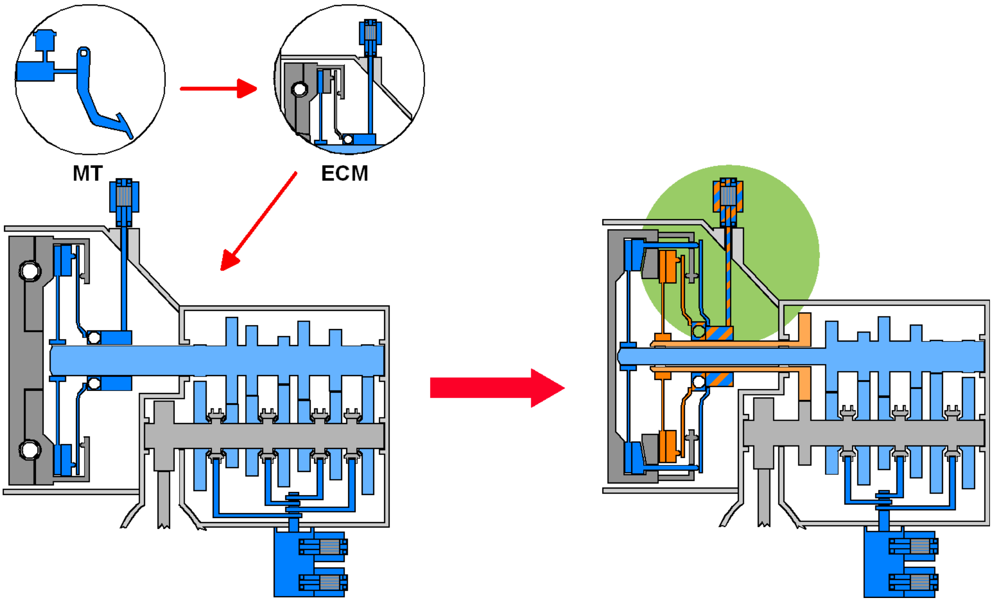


Fig. 4: *From ASG to the USG*

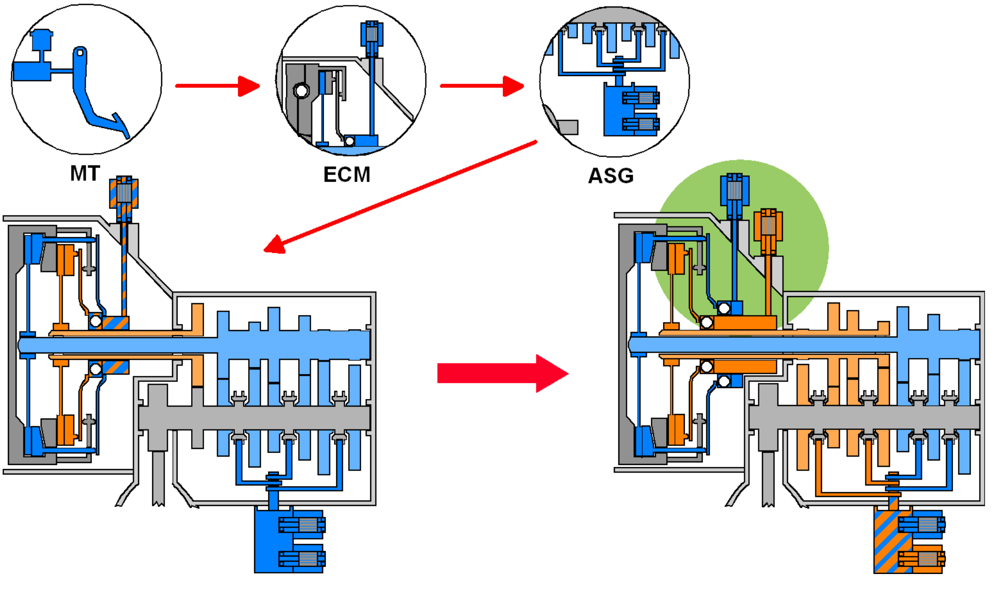


Fig. 5: *From USG to PSG*

With PSG, an additional increase in comfort over ASG and PSG is achieved, since it is possible to have a fully torque filled power shift. In contrast to the USG, LuK sees no limit to the options for high engine torque. The benefit for fuel consumption is almost as great as with the ASG.

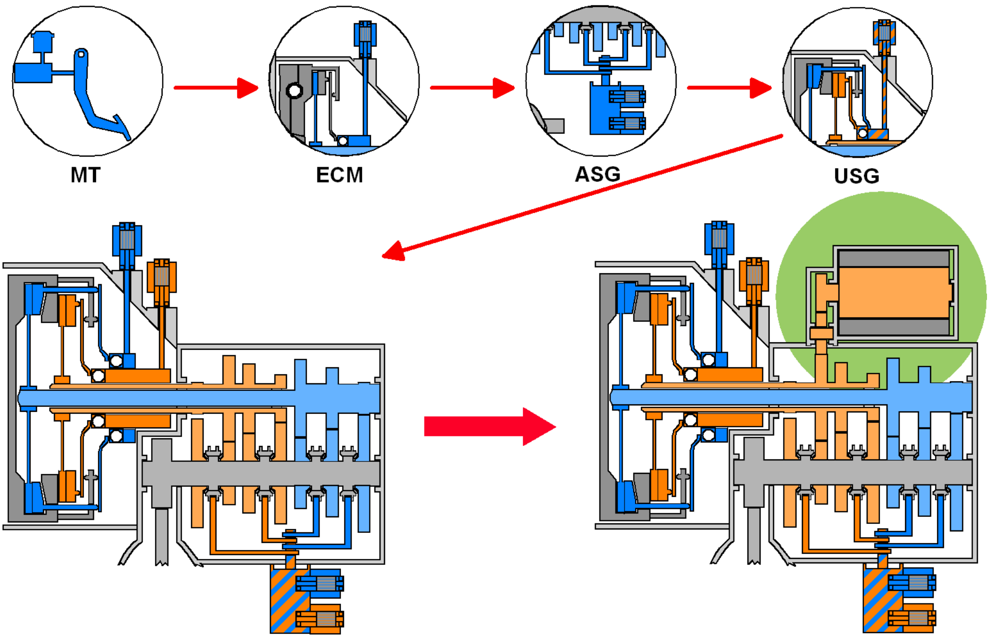


Fig. 6: *From PSG to ESG*

The next step is to combine the starter generator with the gearbox. A PSG can be easily extended into an **Electrical Shift Gearbox** (**ESG**, figure 6), in which a starter generator is coupled in parallel to one of the two input shafts.

If this option is considered when designing the PSG, only minor modifications to convert to an ESG are necessary. The advantages of the ESG are a further reduction in fuel consumption and an additional increase in comfort.

That completes the XSG family - at least for the time being, who knows what the future holds.

Common features of the XSG family are therefore:

- similar manufacturing technology (such as spur gears)
- the use of dry clutches [6]
- the use of similar actuators
- the use of electric motors
- common software strategies [7]

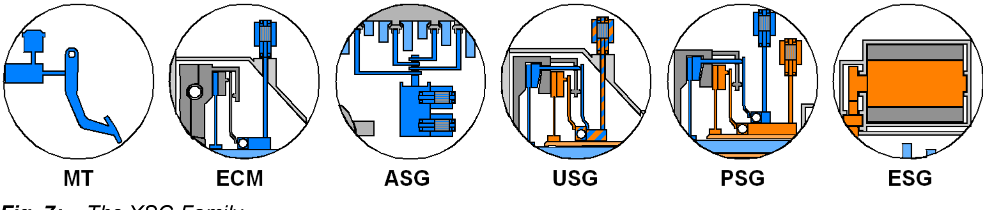


Fig. 7: *The XSG Family*

Two XSG Family Members in Detail (ASG and USG)

The Auto Shift Gearbox

The ASG was presented in detail in [2]. This system has already been in production for a year in the form of the Opel Easytronic® (figure 8).

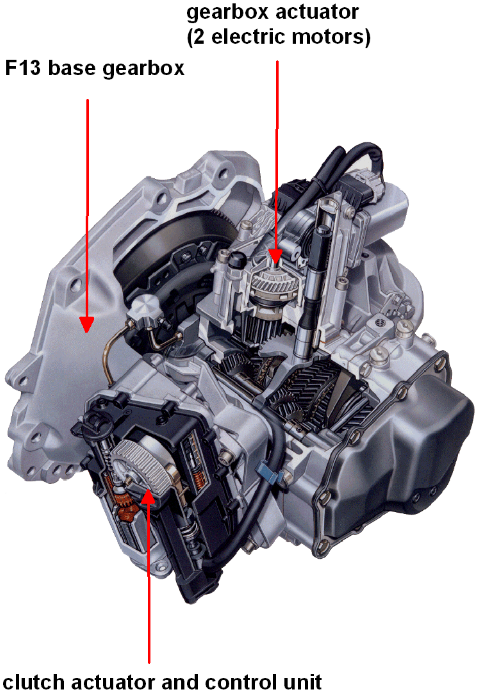


Fig. 8: Easytronic®(Source: Opel), [9]

The LuK-ASG is the first and, until now, the only electromotoric auto shift gearbox

- that offers free gear selection,
- that is designed as an add-on concept,
- that makes it possible to have engine torque of over 200 Nm.

Each of these properties is a unique feature in its own right.

Not for much longer though – the launch of LuK ASG components into production by another car manufacturer isn't far away.

LuK also has production experience with hydraulically operated ASGs (figure 9), which, although technologically sound, are more expensive and heavier. After the successful launch of the Corsa Easytronic®, LuK decided to focus on pursuing the electromotoric route. This path also supports the trend for substituting hydraulically driven functions with electromotoric ones.

The LuK ASG is in this version an add-on system (figure 10). The manual shift mechanism with shift cables or shift rods and shift lever is replaced with the gearbox actuator (two motors). The clutch actuator, which is fixed to the gearbox, replaces the clutch pedal and houses the control and power electronics, including software, for the entire system. In the Corsa it actuates the same hydraulic concentric slave cylinder which is used on the manually operated gearbox. A self-adjusting clutch (SAC) is used, ensuring low release forces. As on the ECM in the A-Class, system operation is achieved without a clutch travel sensor on the release system and without a speed sensor on the gearbox input shaft. This not only saves on the cost of the sensors themselves, but also on associated gearbox modifications and wiring.

With the LuK ASG, the Corsa Easytronic® has an extra weight of less than 4 kg when compared with the manual version. The extra costs for the end customer are only approximately 50% of that of the automatic transmission. Responsiveness and driving pleasure are distinctly greater than with an automatic transmission, whilst fuel consumption is considerably lower than on an automatic. It is even lower than on a manual transmission. On the 1.2 l engine, a reduction in fuel consumption of 2% was achieved without any special tuning being optimised for fuel consumption. On the Corsa Eco 1.0 l a substantial proportion of the more than 10% of fuel consumption reduction has been achieved through economic shift point selection.

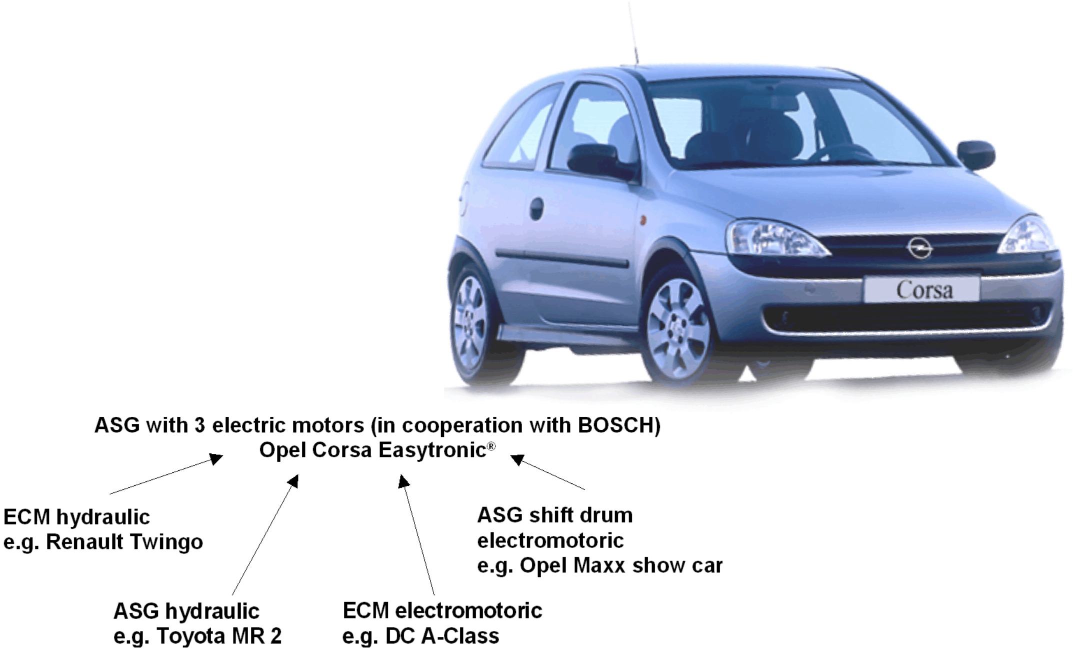


Fig. 9: *LuK´s Route to the Corsa Easytronic®*

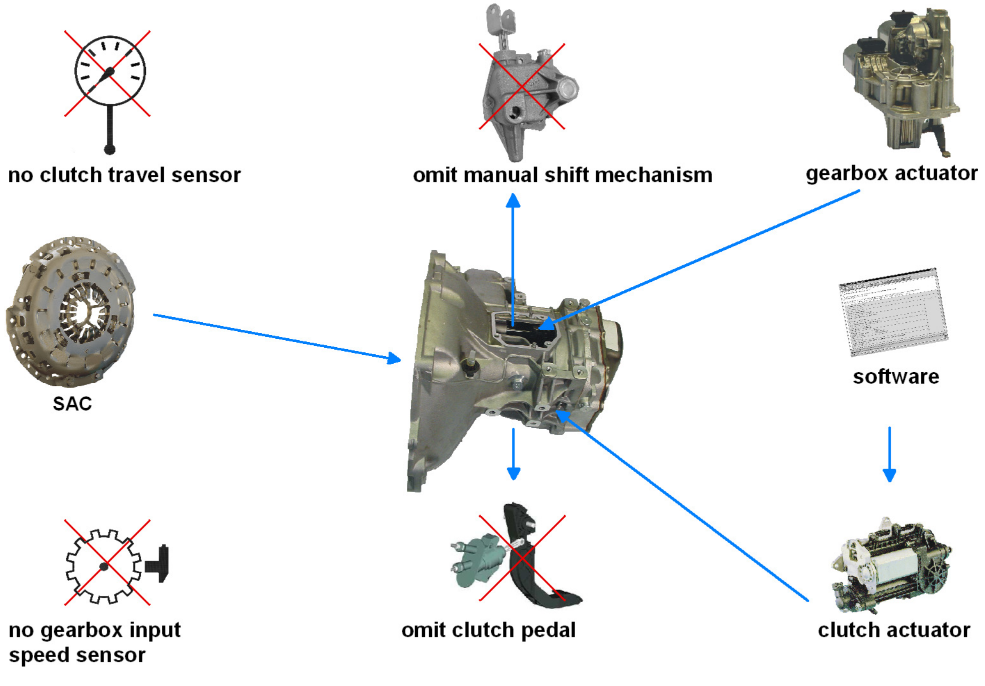


Fig. 10: *ASG as Add-On System*

The Uninterrupted Shift Gearbox USG

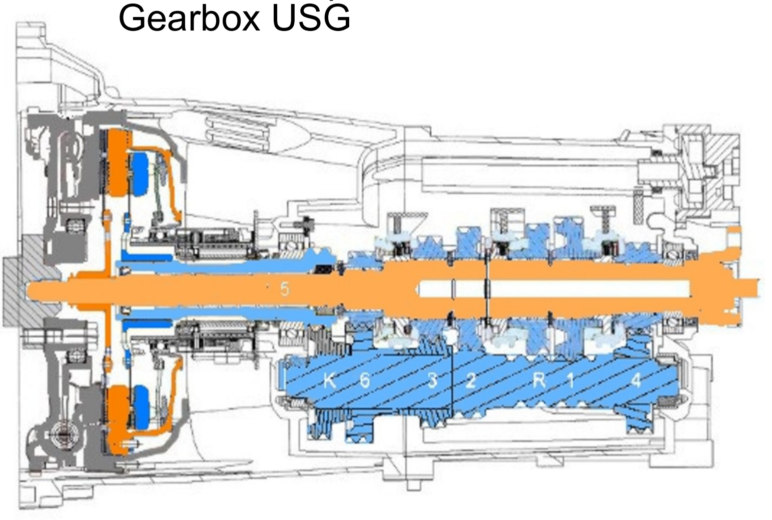


Fig. 11: The Uninterrupted SG - USG

The USG was presented in [5]. In the meantime, an initial prototype for a vehicle with front-wheel drive transverse gearbox and a more well-proven prototype for a vehicle with rear-wheel drive were built. The section of an USG, built in co-operation with BMW and Getrag (figure 11), shows that the USG is well suited for rear-wheel drive. Synchronisation units could also be dispensed with to a large extent.

The measurement in figure 12 shows an example of the effect of the torque filling. Depending on gear and accelerator position, this filling amounts to between 40% and 100%. Interestingly, even with partial filling, it is subjectively hardly possible to detect any torque interruption. The important point here seems to be that the vehicle acceleration doesn't become negative, as occurs during gear shifting on the ASG.

The power shift is achieved by the fact that the power shift clutch linked with the highest or second highest gear not only allows synchronisation, but also transfers the necessary torque for this to the output. The clutch is loaded the entire time with a relatively high differential speed, especially during gear shifts into lower gears. The power shift torque depends on the desired level of fill. This high load during every gear shift means that this clutch is significantly more heavily loaded than the start-up clutch. That's why in figure 11 the larger clutch is the power shift clutch. A connection can be made between the engine torque and the necessary external diameter of the clutch disc (figure 13). The packaging conditions mean that the USG is restricted to engine torques of max. 200 to 250 Nm. For a gearbox generation which does not exceed this torque level, the USG is a solution which provides a high degree of comfort at sensible costs. The development of new high-performance friction linings could still increase the upper torque limit of USG.

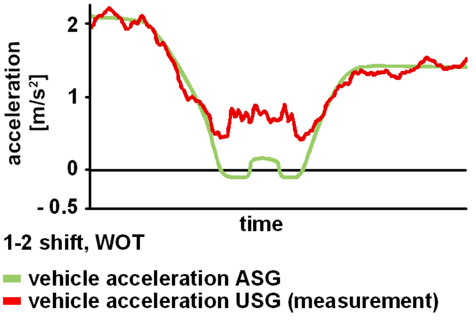


Fig. 12: USG – Increase in Comfort

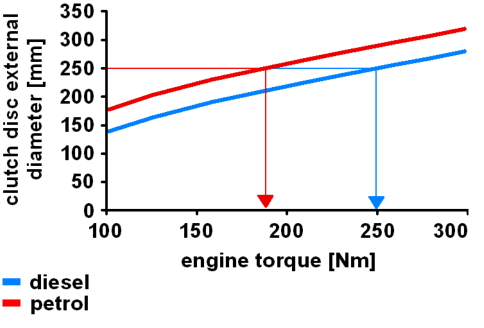


Fig. 13: USG – Torque Limit

The Common Components of the XSG Family

New Electric Motors

LuK uses electric motors for automating manual transmissions. The reasons for this have already been partly explained: the system does not use hydraulic fluid - which also follows to the trend - it is low cost, low in weight and robust etc.

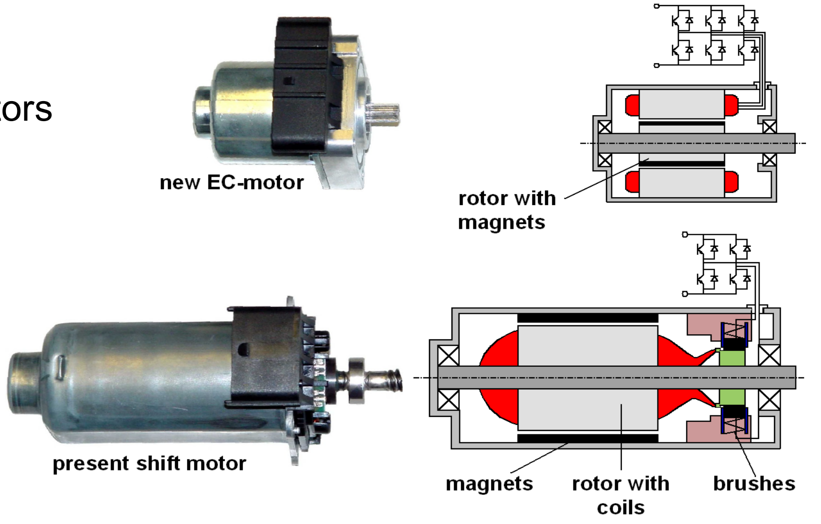


Fig. 14: Comparison of Electric Motors

The motors used on the Easytronic® are based on window lifter motors (**DC-motors**). However, the load on the ASG is far higher than on the window lifter. The motors are exposed to relatively high temperatures, heavy vibrations and salt water etc. Brush motors capable of high performance were developed with Bosch for this application (figure 14 photo bottom).

Just how these motors have become complex as a result of the environmental conditions can be seen, for example, by the incorporation of the large bearing that is necessary due to vibrations.

LuK has sought ways to further reduce the packaging space and costs, whilst increasing even the performance. Brushless motors have therefore been adopted (figure 14 top).

These electronically commutated motors (**EC-motors**) use rare earth magnets to help make the motor very compact with a high power density.

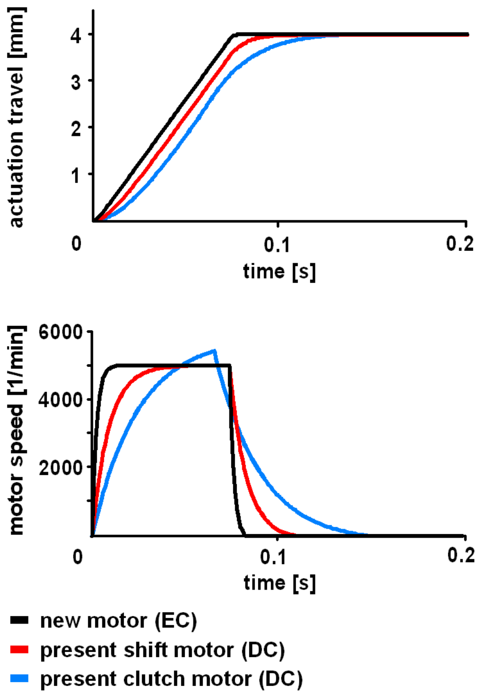


Fig. 15: Dynamics of New Electric Motors (Example: Clutch Actuation)

	present clutch motor (DC)	present shift motor (DC)	new motor (EC)
power density	**101 W/kg** **100%**	**163 W/kg** **162%**	**267 W/kg** **266%**
inertia	**$30.4 \cdot 10^{-6}$ kgm^2** **100%**	**$25.0 \cdot 10^{-6}$ kgm^2** **82%**	**$6.5 \cdot 10^{-6}$ kgm^2** **21%**
mechanical time constant	**27.75 ms** **100%**	**7.46 ms** **27%**	**1.88 ms** **6.8%**
weight	**693 g** **100%**	**813 g** **117%**	**438 g** **63%**
volume	**166 cm^2** **100%**	**162 cm^2** **98%**	**62 cm^2** **37%**

Fig. 16: *Characteristic Parameters of New Motors*

Admittedly, the rare earth motors are expensive and additional electronic components in the control unit have to be considered for electric commutation. These additional costs are more than compensated by the simple design of the motor, however. As no brushes are used, no costly measures are necessary to make the brush-holders vibration and temperature resistant. Since the rotor mass is very low, no costly bearing support is required. As shown in the next section, savings can also be made in the actuator design, since the load on the actuator is less due to the lower mass of the motors.

This factor also improves the dynamic response as the nominal operating speed is achieved substantially faster due to the lower rotor inertia. This results in an even shorter actuation time during a step response. The speed characteristics are compared in figure 15 at the bottom, the resulting actuation travels are shown in figure 15 at the top. This diagram also illustrates the characteristics of existing motors (DC), the clutch motor and the already optimised shift motor.

The advantages of the new electric motors are summarised again in the table (figure 16).

New Development of Clutch Actuation [8]

The small size of the new motors opens up new design possibilities. For example, the motor can be fitted directly to the clutch bell housing - actuation can then be performed via a lead screw on a MCR (mechanical concentric release system), figure 17 left.

A further benefit is the potential for higher torque. The motors currently used cannot be further extended (due to shaft deflection) and neither can they be thicker (due to packaging space, dynamics). With EC motors, extending the motors presents no problem.

In addition, LuK can offer one further innovation - to be precise, the electric concentric clutch actuator (ECA), which fits in the packaging space of the traditional hydraulic concentric slave cylinder [6].

These new clutch actuators can be used for automating the clutch of all XSG family members.

New Development of Gearbox actuation [8]

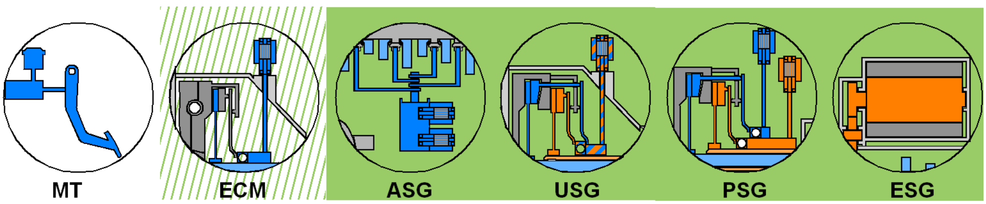
With the new EC motors it is possible to considerably reduce the volume of the gearbox actuator compared with the current - already compact - design. In most cases it is even possible that the complete gearbox actuator will fit into the space otherwise filled by the manual transmission shift module. The vibrational load of the actuator housing is reduced due to the low mass of the motors - as a result of which, weight and volume are significantly reduced.

This actuator is used throughout the entire XSG family for automating the gear shift mechanism.

On twin clutch gearboxes, two gearbox sections have to be automated. Two ASG actuators would therefore normally have to be used, but as a result of an innovative LuK development called Active Interlock, the gear shifting of both gearbox sections is possible with one actuator, as on the ASG. This is one of the fundamental features of the PSG (figure 18).

A design example of an Active Interlock gearbox actuator for an Inline-PSG is shown on the right in figure 17.

The Active Interlock technology also accelerates gear shifting on the ASG, due to the elimination of the select times. The Active Interlock can thus be used for gearbox shifting on all XSG family members and is highly modular in design (figure 19).



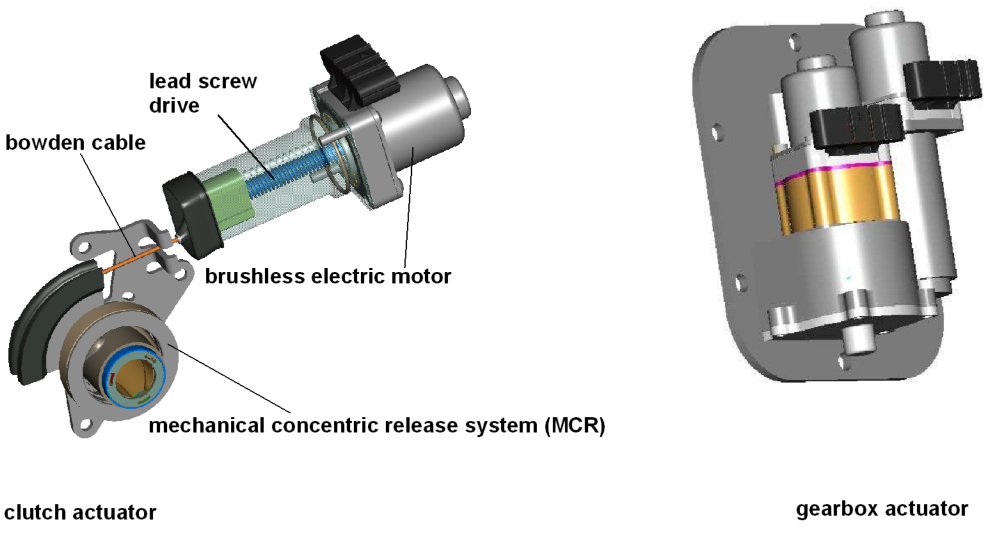


Fig. 17: New Development XSG Actuators

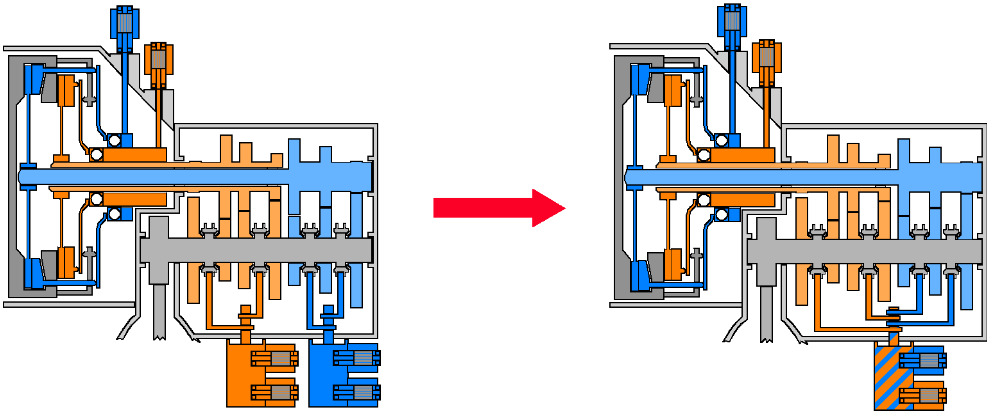
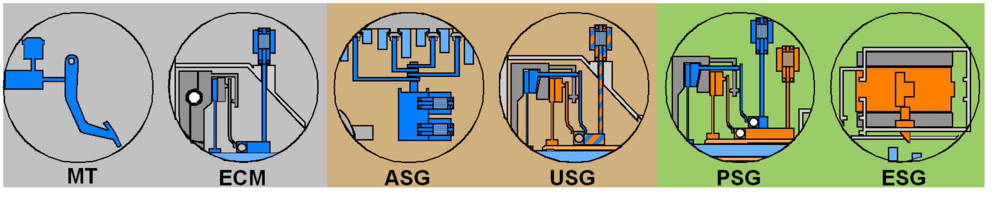


Fig. 18: PSG with Only One Gearbox Actuator



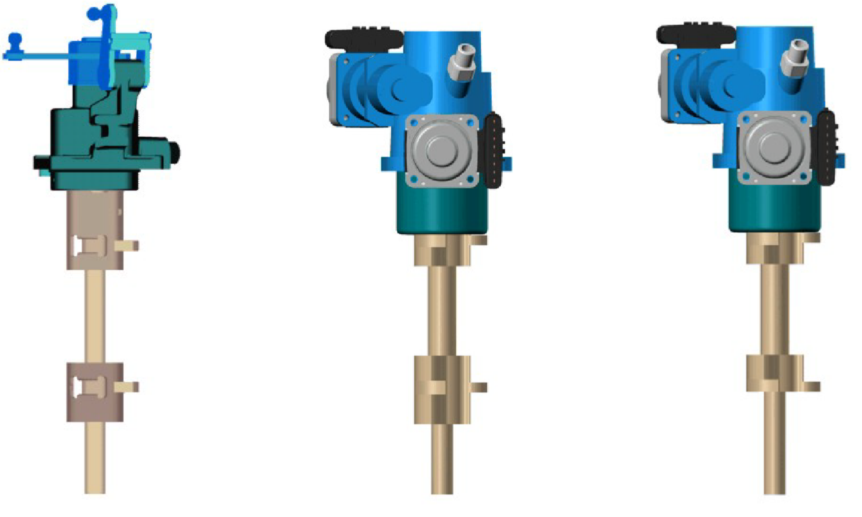


Fig. 19: Active Interlock

System Comparison

An important part of the argument in favour of automation of manual transmissions, and hence for the XSG family, is the good fuel consumption. If the manual transmission is taken as a basis, automatic transmissions suffer from greater fuel consumption at the same shift point selection due to hydraulic power loss – see figure 20 top, red arrow, marked ‘H’. This increased fuel consumption amounts to several percent. Automatic transmissions (and automated gearboxes) can use the choice of more favourable operating points in the engine map for shift point selection to their advantage. This can result in a reduced fuel consumption in legally defined cycles – see figure 20 top, green arrow, marked ‘S’. Moreover, this reduction in fuel consumption through automatic shift point selection is also realized in practice, since the average driver using a manual transmission generally avoids driving at economic low engine speeds.

The first member of the XSG family, the ECM, has the same fuel consumption as the manual transmission. The power consumption of the actuator is under 10 W, which is not detectable in fuel consumption. The automated gearboxes ASG, USG and PSG can achieve the same fuel consumption benefits with the same spread of ratios as the automatic transmission, due to automatic shift points. The difference between these automated manual gearboxes and the conventional automatic transmission is the increased fuel consumption associated with the latter caused by hydraulic power losses. This applies, even if the fuel consumption of the AT is below that of the MT in the legal fuel consumption cycle. In that case, the reduction achieved throuh the automatic selection of the shift points outweighs the hydraulic power losses. The automated manual transmissions will still remain ahead by the amount of these hydraulic losses.

A significant additional fuel consumption reduction can again be achieved through regeneration - see figure 20 bottom, marked ‘R’. The ESG therefore has the lowest fuel consumption.

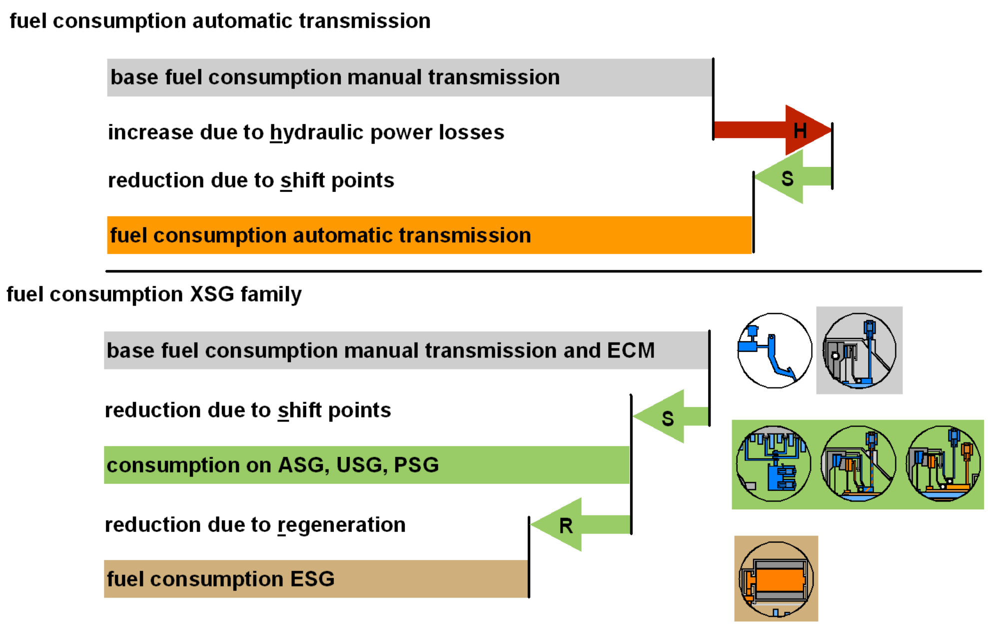


Fig. 20: Fuel Consumption

Does an increase in comfort and a reduction in fuel consumption have to be incompatible? Figure 21 shows that this doesn't have to be the case.

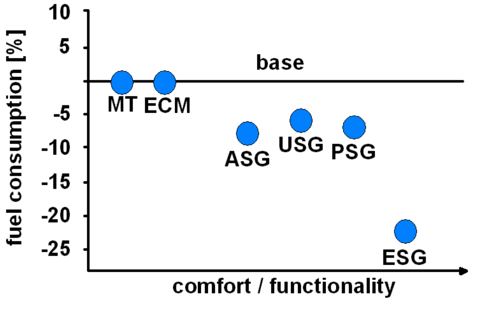


Fig. 21: Comparison of Fuel Consumption and Comfort

Despite increased comfort and functionality, fuel consumption is reduced. Implementation of power shifting on USG and PSG slightly reduces fuel consumption improvements when compared with ASG, power shift losses being smaller in case of the PSG (these losses are not taken into account in the simplified illustration in figure 20, neither for the automatic transmission; compare also [3]). The ESG is by far and away the best.

These fuel consumption values are rough guide values; they depend on many variables, in particular engine torque. There are two fundamental effects here. The first effect is that a non-torque-dependent base value exists in the absolute amount of power loss. The other effect is that the potential for reduction in fuel consumption through shift point selection is less with a small engine than with a large one.

The qualities of the first effect are illustrated in figure 22.

The power losses associated with oil pump and oil cooler, drag losses from the multi-disc clutches, splashing and torque converter losses are substantially constant and do not reduce in proportion to with decreasing engine size - to be precise, with decreasing engine torque. The relative increased fuel consumption with the automatic transmission therefore increases significantly with a decreasing engine torque.

An electrically driven oil pump scarcely reduces these losses. And the reason: as an estimate, for 100% mechanical power of the oil pump, the electric motor needs 200% electrical power. In order to supply this, the generator needs 400% mechanical power. This means that only if the mechanical energy consumption of the oil pump is reduced to a quarter by controlling its duty cycle, will its use not degrade fuel consumption.

The other effect is illustrated in figure 23.

The driver requires a certain driving performance which can be achieved by different engine torque - engine speed combinations and appropriate gear ratio. This means that the operating point in the engine map is moved along the line of the same power through the gear ratio. The reduction in fuel consumption is based on the fact that normally the specific fuel consumption is lower with high load and low speed. There is substantially more potential with a high-performance engine, than with a small engine.

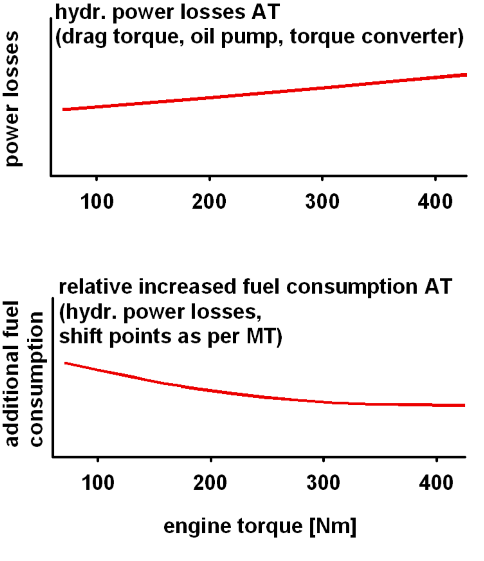


Fig. 22: AT- Increased Fuel Consumption as a Result of Hydraulic Losses

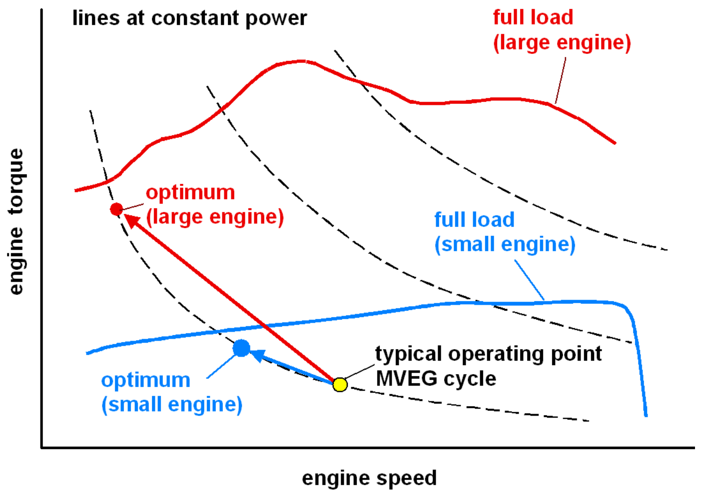


Fig. 23: Reduction of Fuel Consumption with Optimum Engine Operating Point

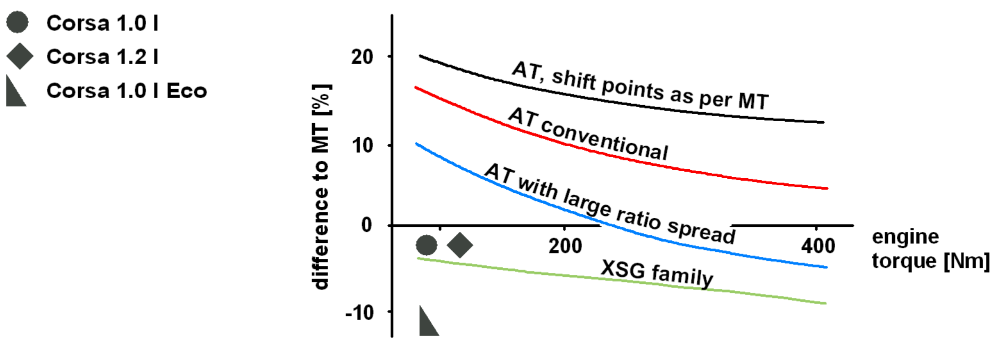


Fig. 24: Consumption of Automated Transmissions compared to MT

Furthermore, as can be seen in figure 23, a greater gearbox ratio spread makes sense, particularly with high-performance engines.

However, modern designed engines have a larger range of lower specific fuel consumption as a result of dethrottling; that means that the potential for reducing fuel consumption through overdrive and gear selection is less and the efficiency of the gearbox is, as such, increasingly more important.

This information is summarised in figure 24. It is recognised that modern automatic transmissions can even drop below the fuel consumption of manual transmissions. However, the family members ASG, USG and PSG are clearly superior, since they do not have the hydraulic losses of the automatic transmission (compare again figures 20 and 22). In figure 24, three auto shift gearboxes already in operation, using LuK components, are also shown.

Summary

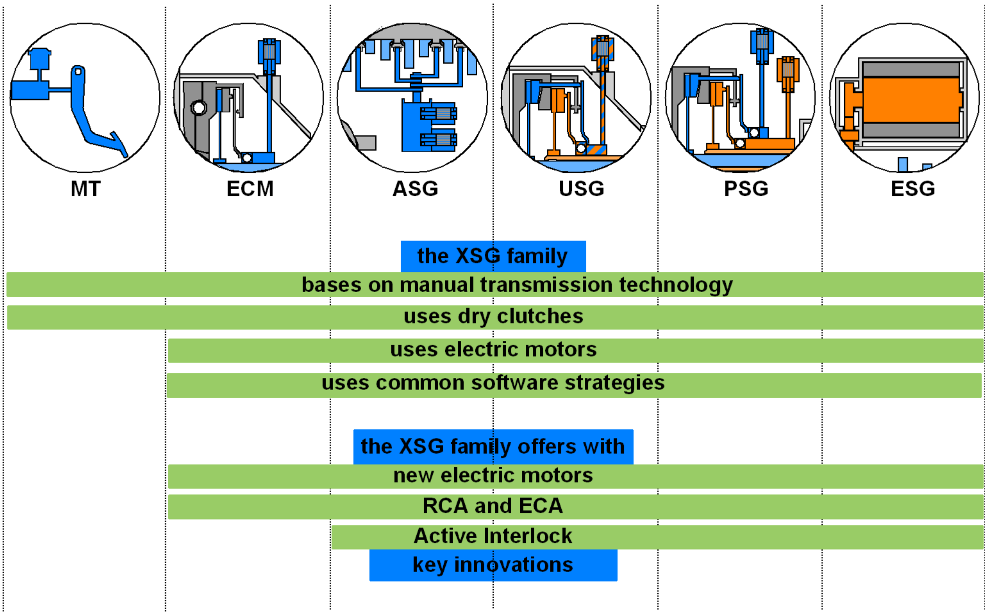


Fig. 25: *Summary - XSG Family*

The XSG family is:

- low in cost and weight
- unsurpassed in terms of its efficiency
- and thus has the best fuel consumption

LuK therefore predicts a great future for this family.

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