Automation of Manual Transmissions

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Introduction

Many people complain about increasing traffic, more and more regulations as well as higher gasoline prices. All of these factors point to an increase in the automation of the drive train. The automation solutions that will be accepted will depend on how economical and comfortable the new systems are. The automation of the manual transmission promises to be an economical and comfortable solution.

In which market segments do we expect manual transmission automation to gain acceptance?

With Electronic Clutch Management (EKM), the driver determines when and how the gears change. In this respect, the behavior is very similar to a conventional manual transmission. LuK mastered the clutch strategies for all vehicle and torque classes. Therefore, the EKM can be offered in every torque class for drivers who like to shift gears themselves.

The gears are changed automatically with the automated shift transmission. In contrast to the automatic step transmission, the ASG must interrupt the tractive force when shifting. This is more clearly detectable the higher the tractive force that is interrupted. For this reason, it can be surmised that ASG will be accepted mainly in small cars. The increasing use of electronic throttle simplifies the introduction of ASG.

This report can be divided into three major sections. First, the current production status of the EKM will be presented. The second section deals with the further development of this system. The third part deals with the automated manual transmission.

Electronic Clutch Management: Production Status

Basic Layout

Figure 1 illustrates the basic layout of the electric motor-driven EKM. This picture was presented already at the last colloquium [1] and illustrated the direction of development at that time. The basis of the EKM here is the self-adjusting, reduced-load clutch (SAC) [2], which allows a small electric motor as an actuator in combination with the torque tracking (see Chapter 2.3). This small electric motor has low heat build-up, so that the actuator and controller can be integrated into an “intelligent actuator”. This replaces the clutch pedal and delivers the highest clutch comfort. Changes to the release system and to the transmission are not necessary. The only additional expenses required are sensors to detect the intention to change gears and to recognize the gear. All other signals are already available in the vehicle.

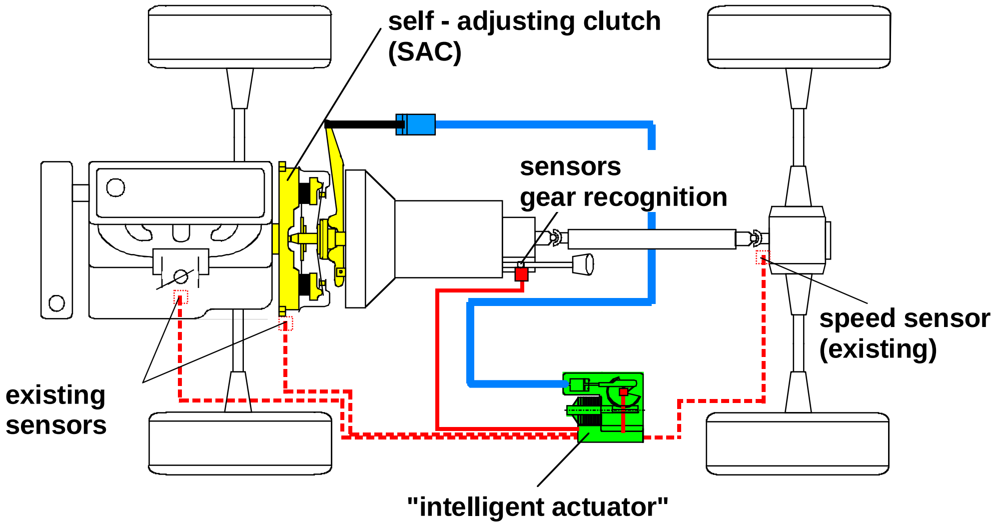


Figure 1: System overview: electric motor-driven EKM

LuK is cooperating with BOSCH in the development of EKM and LuK is responsible for the entire system.

Minimizing Costs

One very important goal in the development of the EKM was keeping costs down. The system was supposed to be purely an add-on system, i.e., changes to the transmission, gearshift mechanism and release system should be avoided. In addition, the number of sensors needed should be limited to as few as possible and the cabling expenses should be reduced (see Figure 2). It was thus determined to eliminate the clutch travel sensor and the transmission input speed sensor. The goal for the intention to change gears was to detect the driver's intention by using a travel measurement and without changing the gear-change feeling or modifying the gearshift. All this could be realized through intelligent software strategies [3].

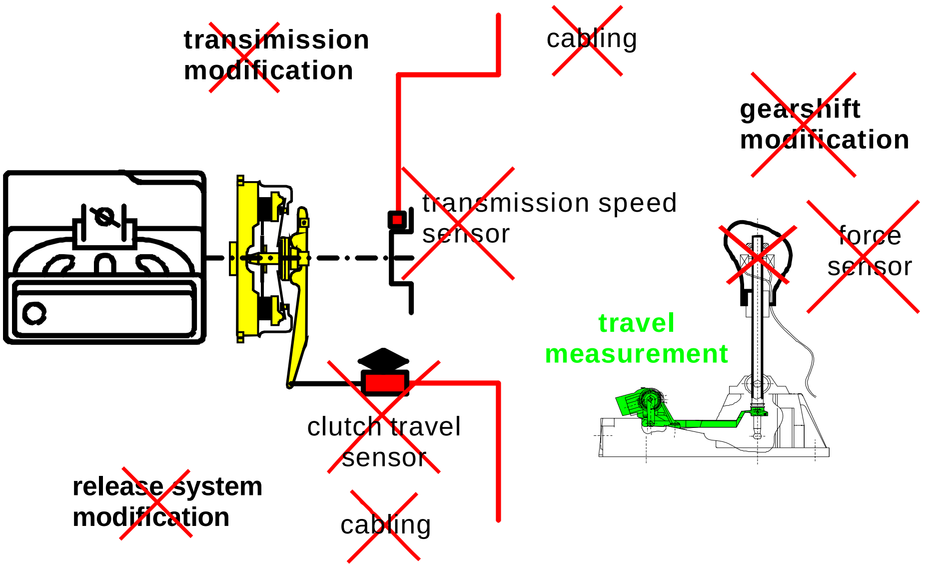


Figure 2: Add-on EKM: Minimizing costs

Another point is the integration of actuator and control that were already mentioned.

Torque Tracking

Torque tracking is the important basis for fast clutch times despite a small electric motor, and for good load cycle comfort. The function of torque tracking is explained with the help of Figure 3.

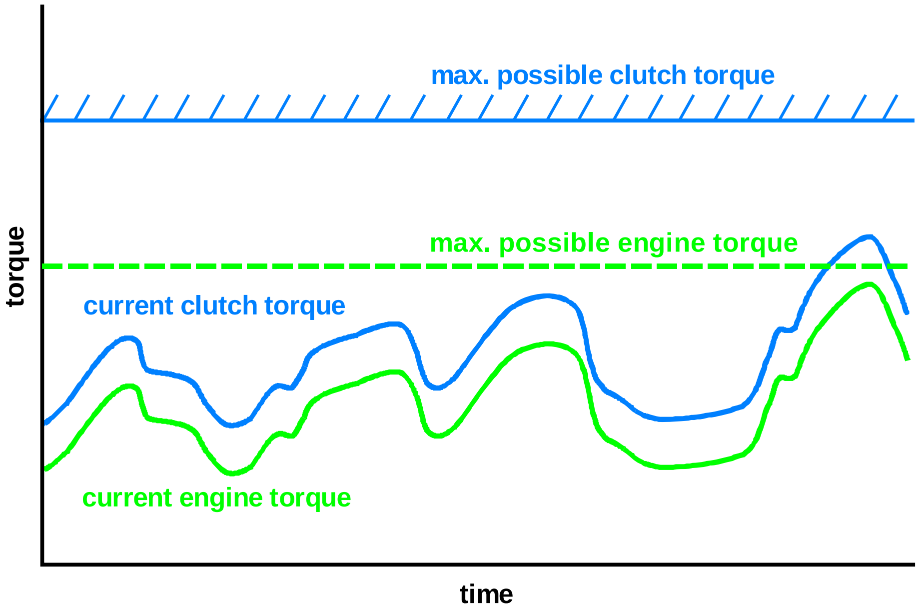


Figure 3: Time curve torque tracking

A clutch must be able to safely transfer the engine torque even in the worst case and must thus have sufficient additional reserves. In practice, a fully closed clutch can transfer 1.5 to 2.5 times the maximum possible engine torque. Torque tracking is based on the idea of adjusting the clutch torque to the current engine torque and only allowing a small safety margin.

Figure 4 illustrates the advantage during a shifting cycle. With a conventional system without torque tracking, the clutch torque remains much higher than the engine torque. If the driver wants to change gears and lets up on the gas pedal, the engine torque decreases. When he moves the shift lever, the intention to switch gears is triggered and the clutch must now go from “completely closed” to “completely open”. This defines the disengagement time. This must not be too long or else the clutch still transfers torque during the synchronization of the next gear, which can lead to transmission chatter or damage. Figure 4b illustrates the same process with torque tracking. The clutch torque is only slightly higher than the engine torque. Thus the travel to “completely open” is already significantly less than with a conventional sequence. If the driver then lets up on the gas because he wants to change gears, the engine torque and thus also the clutch torque decrease immediately. By triggering the intent to switch, the clutch is thus already almost open and the rest of the disengagement occurs very quickly. Even very sudden gear changes are thus possible without transmission noise or damage.

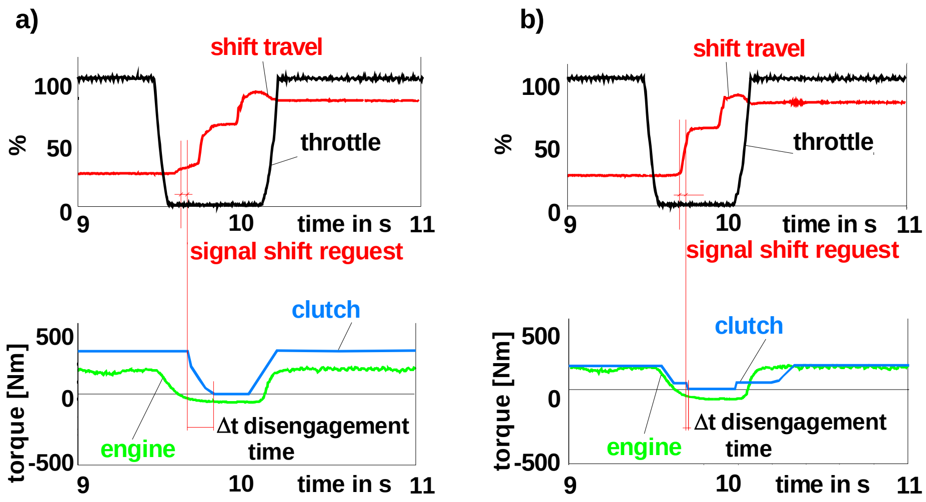


Figure 4: The shifting process a) without torque tracking and b) with torque tracking

The alternative to the electric motor-driven EKM is the hydraulic EKM. Such a system has already been produced by LuK. It is considerably more expensive than the electric motor-driven version, but in exchange it is theoretically faster. Torque tracking makes extremely short electric motor-driven clutch times possible, making it comparable to the hydraulic solution.

Load cycling is another advantage of torque tracking. A faster gas tip-in generates torque peaks and thus surge oscillations, which occur with very different intensities depending on the vehicle (Figure 5a). These are prevented by torque tracking through a very short slip phase, which is not relevant to use and wear.

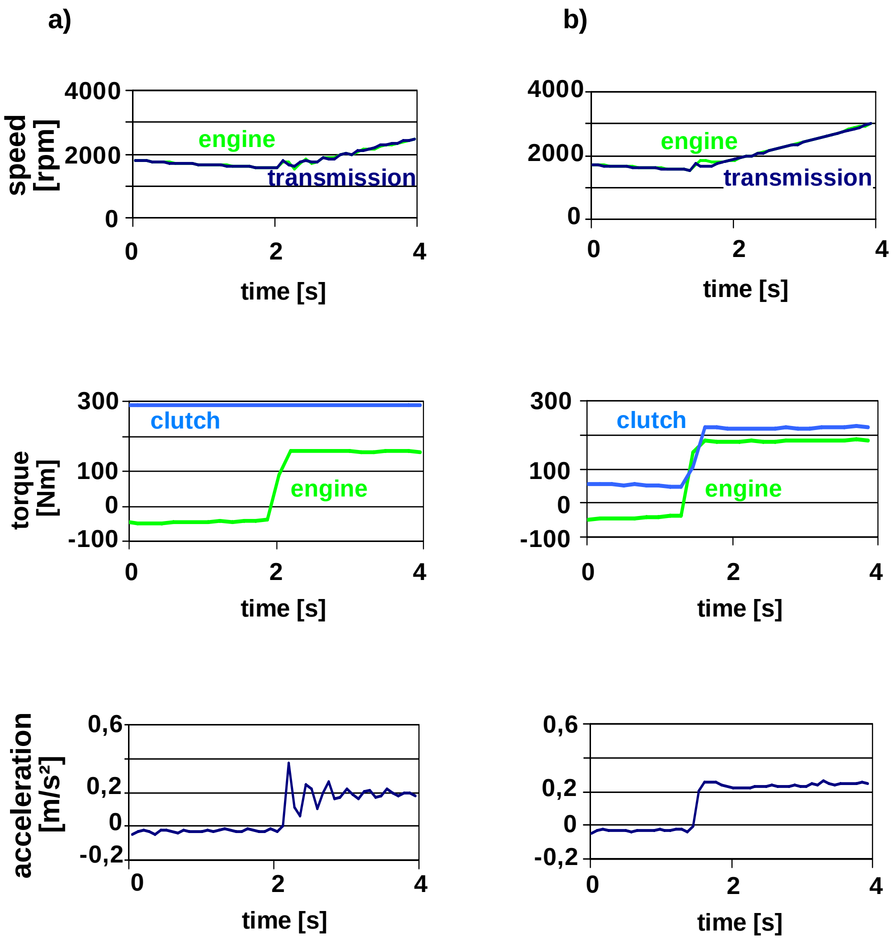


Figure 5: Load cycle a) without torque tracking and b) with torque tracking

The demands on the drive train are also limited via EKM with torque tracking:

- With jack-rabbit starts there are no jerks due to sudden snapping of the clutch (valid for all EKMs).
- The maximum torque transfer reserve of the clutch is usually not used; the clutch works as a torque limiter.
- For this reason, even with output-side impacts the peak torque value is reduced.
- The clutch wear tends to be lower than with pedal actuation because the electronic systems act optimally in every situation, in contrast to the driver (applies to all EKMs).

The drive train would not require as high of a safety factor with 100% EKM use.

Because of the torque tracking, the release system with its seals, lines and the release bearing is constantly under load. This has proven not to be critical in more than 4 million test kilometers because:

- The low release force of the SAC leads to a comparably low maximum load.
- The additional travel will be compensated with clutch torque modulation by shortened actuation travel when opening the clutch so that the total actuation travel is not longer than with a conventional system.

Production Design

Figure 6 illustrates the current production components, the intelligent clutch actuator, which replaces the clutch pedal, the release force-reduced self-adjusting clutch (SAC) and the sensors offered as add-ons for gear-change intention and gear recognition.

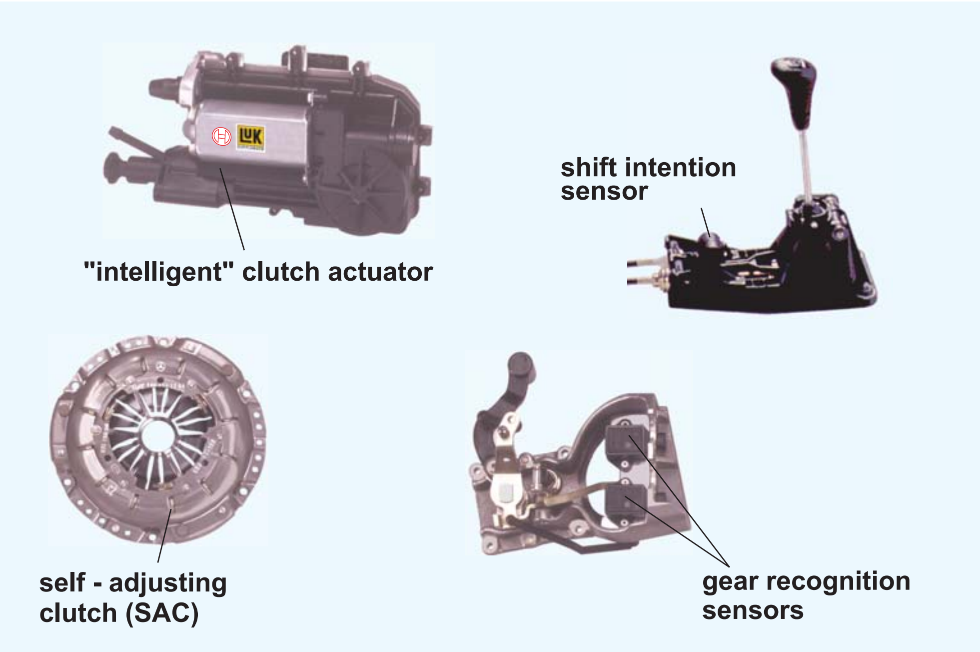


Figure 6: Add-on EKM: Components

The clutch actuator includes the master cylinder, which is otherwise integrated into the pedal block. A semi-hydraulic release system could serve instead of the hydraulic release system with a central release bearing. With very little modification, it could be adapted to purely mechanical clutch actuation.

The simplicity of the components means that high functional reliability can be expected. The components are also so simple because of major software development expenses for additional sensors, which means, for example, that a transmission input speed sensor and clutch travel sensor could be avoided. The following press statements prove that this does not mean that comfort is compromised in any way:

...during the test drives, it was equipped with a semi-automatic (only shifting, not using the clutch), which harmonizes excellently with the concept...
Autoflotte 7/1997

...Shifting made fun - especially if the automatic clutch is ordered. It functions so perfectly that we would abandon all tip and steptronics in this world for this clutch...
FAZ 10/1997

...Another advance in comfort is provided by the automatic clutch developed by the specialists LuK...
mot 17/1997

...The recently developed automatic clutch...Shifting has become a true pleasure and it can even lead to lazy shifters using the best gear with regard to comfort and fuel consumption...
Handelsblatt 26.06.97

...or semi-automatic with manual shifting without using the clutch (David Coulthard would buy this version)...
Die Welt 28.06.97

Figure 7: Press statements on the LuK EKM (translation)

Electronic Clutch Management: Further Development

Goals

A truly economical and efficient solution has already been achieved with the current production status. The market penetration will increase as the system becomes less expensive and more compact and as additional functions are realized. LuK has set the following goals for itself:

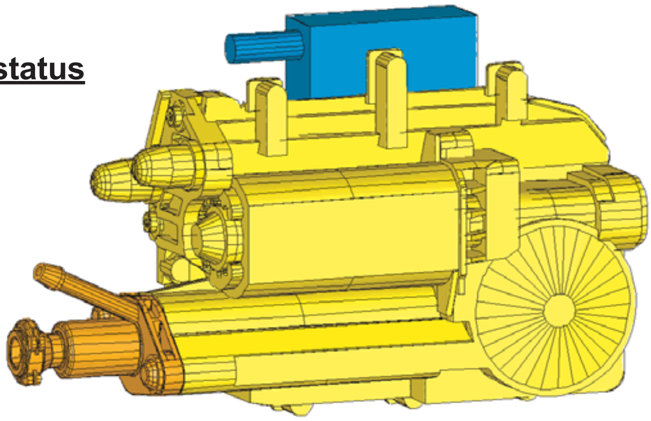
- Minimizing size and weight
- Improving applicability
- Offering higher torques
- Expanding functions
- Decreasing costs

Clutch Actuator

The current production status includes components that have been proven in other vehicle applications and thus have been used. These include a worm gear transmission and a crank mechanism among others. A screw drive offers greater flexibility and the possibility to balance out the tolerances without initial adjustment.

In addition, the control and electronic power units are smaller. Overall, therefore, the size and weight are reduced and a higher efficiency is achieved.

production status



new development

size / weight	**- 30%**
applicability	⇑
performance	**+ 50%**
costs	**- 10%**

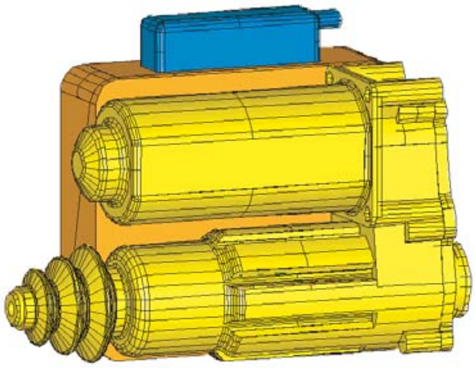


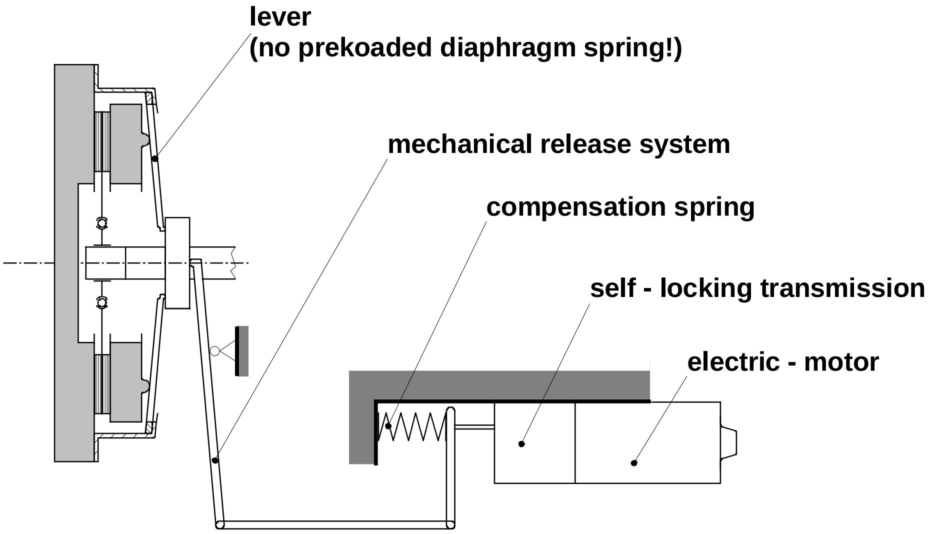
Figure 8: New development - clutch actuator

By following a modular concept, the applicability of the clutch actuator has also been improved, particularly by building it directly on the transmission.

Clutch

The SAC used with the EKM already reduces the load needed and thus the work the actuator must perform in comparison to the conventional system. The development goal is better tuning of the entire “clutch, actuator and software” system in order to achieve simpler and less expensive components. approach is that a clutch can be closed by an outside force, which LuK calls an “active clutch” (AC), see Figure 9.

In the form presented here, the AC is simpler than the SAC or a conventional clutch. A simple lever is used to close it. This results in a direct relationship between actuation travel, actuation force and clutch torque, which improves the controllability and the ability to modulate the clutch.



size / weight	⇓
applicability	⇑
costs (clutch)	**-20%**

Figure 9: Active clutch (AC): Basic diagram

Why can the clutch be simplified in this way?

Because of the torque tracking, there is a characteristic frequency distribution of the clutch torque and thus also of the actuation travel. It is known that the idle stage and low-load portions are relatively high not only in the specified driving cycles but also in practical operation. Correspondingly, the maximum in the frequency distribution is at a relatively low clutch torque (partial load and coasting operation) see Figure 10a.

If the actuation force of the SAC is then considered, one sees that the greatest force occurs mostly at the maximum frequency (Figure 10b). The idea was to set the actuation force to “zero” at the maximum frequency with a new clutch design. The AC fulfills this condition, see Figure 10c.

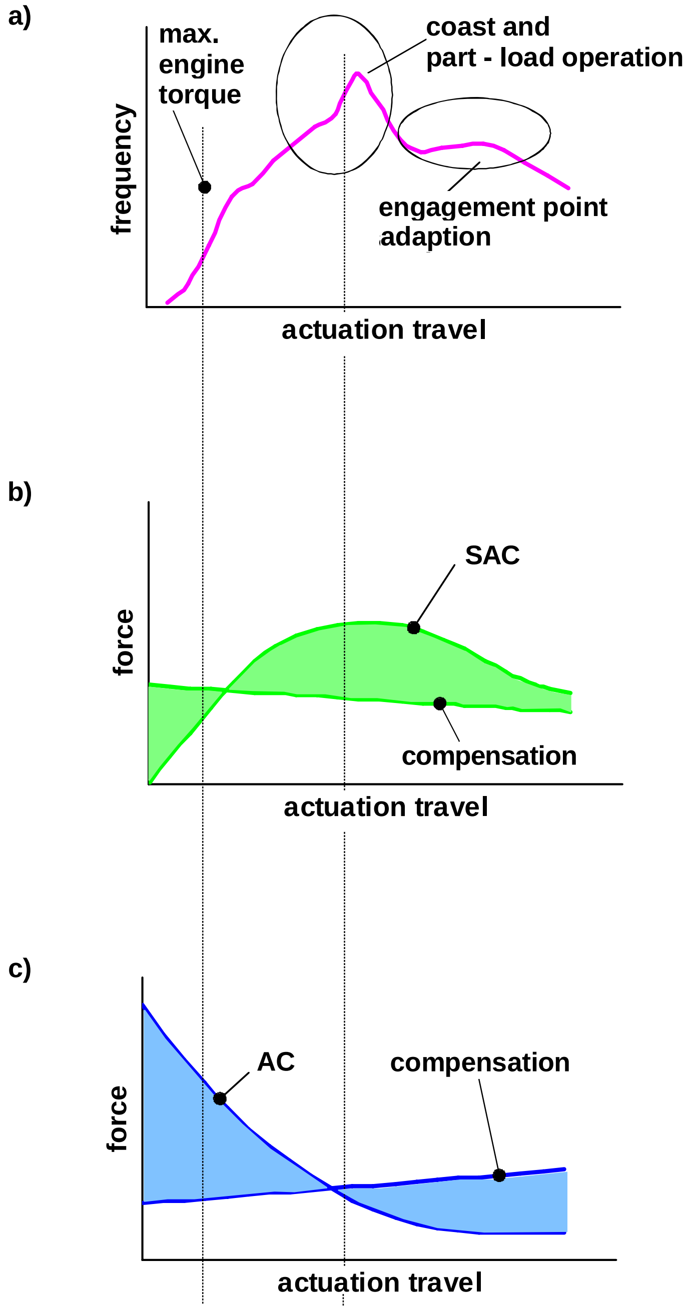


Figure 10: Active Clutch (AC), load population with torque tracking

The total energy load (actuator work) limited by the performance capacity of the actuator is the same for the AC and SAC, but clearly better than with a conventional clutch. Figure 11 illustrates this. Through suitable wear compensation, it is again possible to achieve a clear decrease of the required force with the AC and thus the actuator work (hatch-marks in Figure 11). The result is that it is possible to transmit higher torques or use a smaller electric motor.

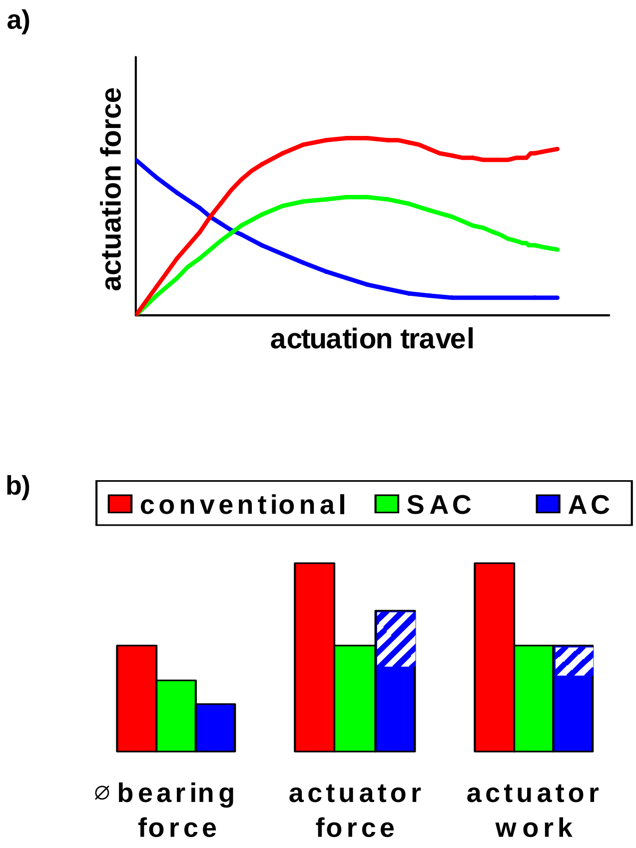


Figure 11: Active Clutch (AC) - system comparison

Recognition of Gear and Intention to Shift

Today, one sensor is used for the intention to shift and two sensors for gear recognition.

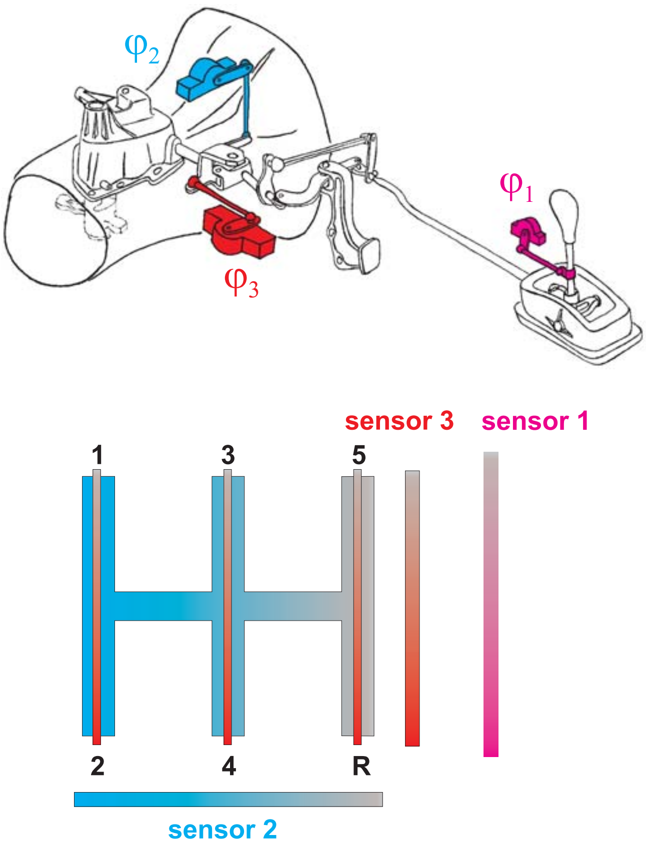
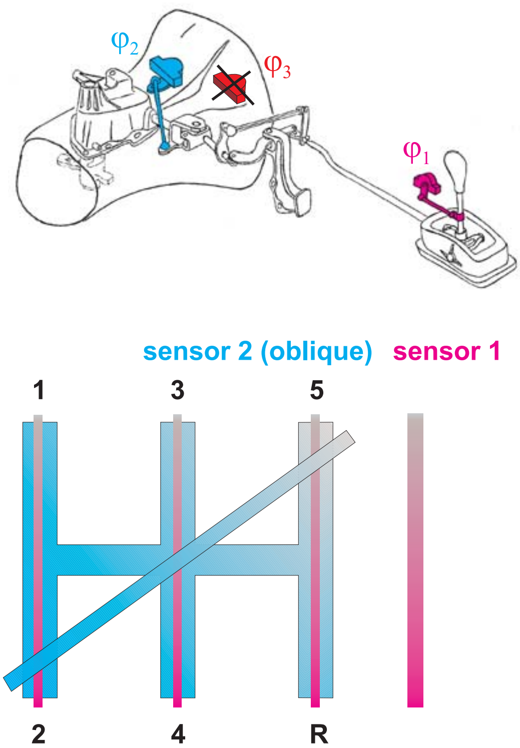


Figure 12: Recognition of gear and intention to shift with three sensors

Sensor 3 for gear recognition in the shift direction and the shifting intention sensor (1) actually operate in the same movement direction. Whether two sensors are needed here depends significantly on the external shifting. Because there is both play and elasticity there, the distinction between shifting intention recognition and gear sensing is unclear.

In order to get by with only two sensors for external gearshifts with play and elasticity, the selection sensor is disposed at an angle. In this way, it covers both the selection and the shift direction. The less precise signal of the shift intention sensor related to the transmission is sufficient in this combination to clearly identify the gear position.



size / weight	⇓
applicability	⇑
costs	-30%

Figure 13: Recognition of gear and intention to shift with only two sensors

In the best case, two sensors will be sufficient in the future for recognition of gear and intention to shift functions.

Slip

Previous EKM development focused mainly on the goal of vibration damping through slip [4]. This goal was abandoned because the overall wear was very high with continuous slip systems. This was not only because of the high dissipated energy but also the specific wear from continuous slip was clearly higher than during launching and shifting.

The SAC has an increased wear reserve and thus offers a favorable perspective. Nevertheless an effort has been made to minimize the wear that occurs in slip regulation.

Another problem area with constant slip systems is the increased fuel consumption. The fact is that with a quieter drive train, drivers drive in higher gears, resulting in better fuel consumption, as has been confirmed with the DMFW.

For this reason, LuK has optimized the entire system.

In Figure 14, the relationships are first shown without slip. Then it is possible to hold the amplitude variation at the transmission input in drive below the engine excitation (14/1) using conventionally optimized torsion dampers (14/2). If slip is then used, it can be assumed that the torsion damper can be omitted. However, the variation amplitude when using a rigid clutch disc (14/3) is, however, significantly higher than with an optimized torsion damper. Thus, in this example, the variation amplitude with the rigid clutch disc at 1600 rpm is approximately four times higher than with the normal torsion damper.

In order to achieve an improvement with slip, one can assume as a rough reference value that slip must be generated in sizes of the otherwise available variation amplitude. Hence, a rigid clutch disc requires a very high slip in all driving ranges.

For the optimal system with a slip clutch, a simplified torsion damper is used without a friction control device and with a relatively low spring rate. It is apparent in the picture that non-slipping (14/4), the isolation from a speed of 1300 rpm is better than with the optimized torsion damper.

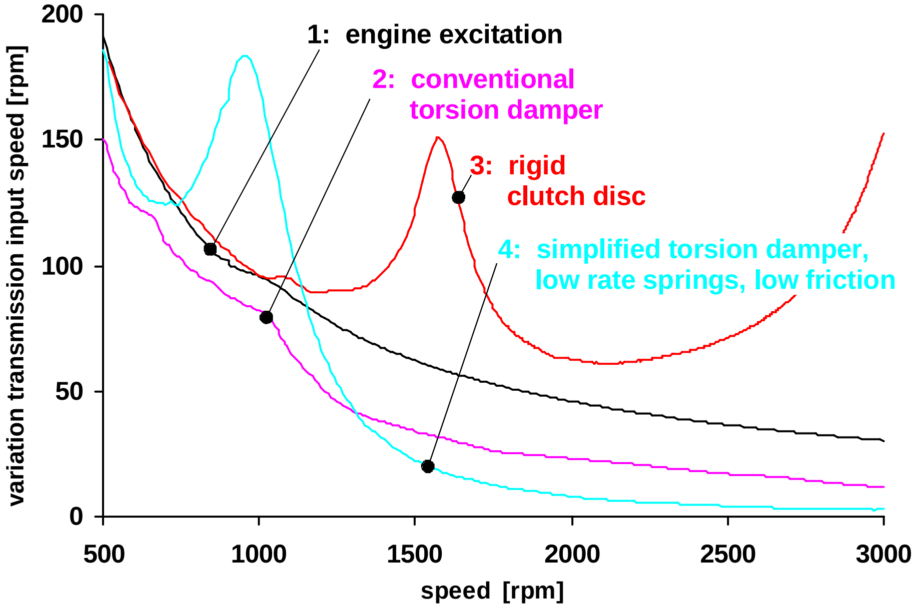


Figure 14: Drive train vibrations with non-slip systems

How is optimization achieved? If slip is used with a simplified torsion damper, the resonance can be eliminated in the lower speed range. Interestingly, a new resonance peak occurs (shown as a thin line in Figure 15), which is higher than the resonance without slip. This can be explained by the change in the distribution of the rotating masses. The drive train in the vibration system without slip is balanced between the heavy engine rotating mass and the total vehicle mass. In a slip system, the engine rotating mass is replaced by the significantly smaller rotating mass of the clutch disc. It would thus make no sense in the example shown to slip in the range from approximately 1600 rpm. Here the variation amplitude without slip is clearly smaller (see Figure 15). It remains to be mentioned why this resonance is excited at all in a slip system. The reason for this is that a slip system can never ideally isolate. Excitations come into the drive train via the slipping clutch through the friction coefficient curve, through varying slip speed, but also through flat geometric deviations like runout and similar factors.

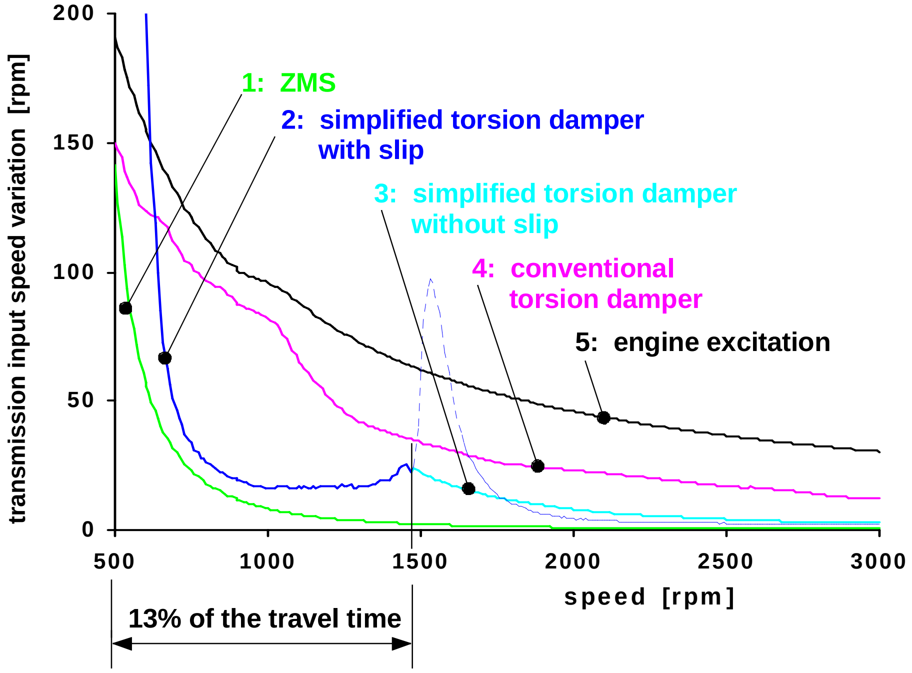


Figure 15: Optimizing the entire system with a slip clutch

It can be seen in Figure 15 that a clearly better vibration isolation can be achieved with the optimized slip system and simplified, low rate torsion damper (15/2 and 15/3) than with a conventional torsion damper (15/4) alone. In any case, the isolation quality of the DMFW (15/1) is not achieved at representative slip values.

A vehicle with such a slip system was sent for customer testing, which yielded the following interesting results: Only 13% of the driving time was within the ranges in which slip was necessary. With this collective, there was a wear increase of 13% and a fuel consumption increase of only 0.4%. The SAC slows this increase in wear slightly .

There is still one catch. This example is valid for a rear-wheel drive vehicle, whose resonance speeds are normally relatively low. The resonance of front-wheel drive vehicles is usually significantly higher and cannot be moved out of the main driving range with a low rate torsion damper. However, this optimized system still shows improvements when compared to the conventional system, but the wear and fuel consumption are still relatively high. Test on a compact class vehicle showed an increase in wear of 40 % and in fuel consumption of 0.8 %.

Automated Shift Transmission (ASG)

Set-up

The EKM and the production experience gained with it are used advantageously as a part for the manual transmission automation.

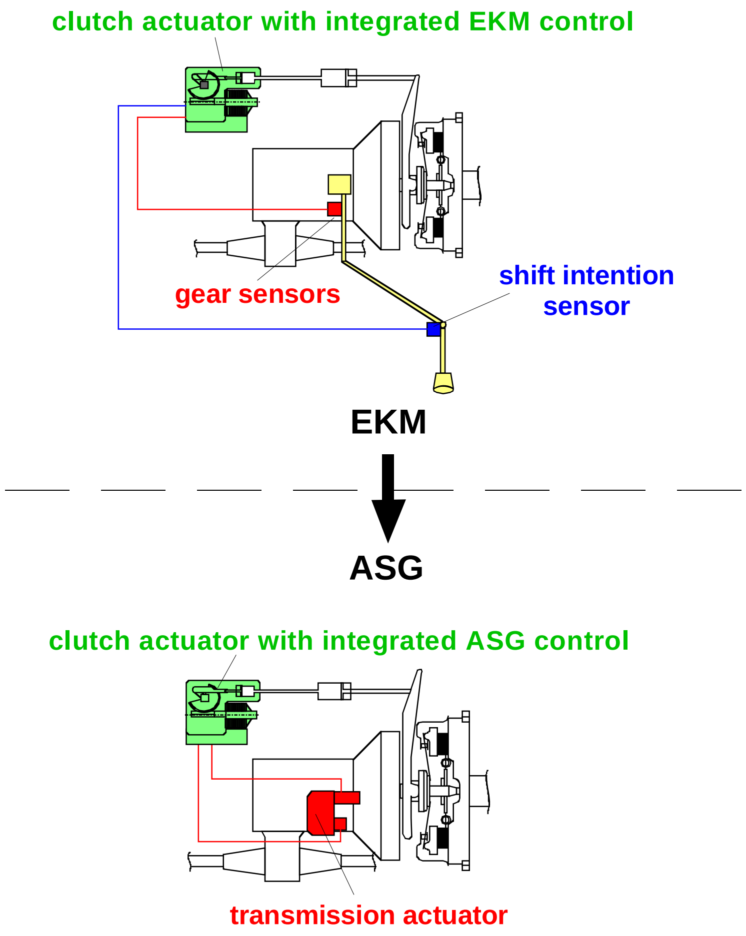


Figure 16: Add-on ASG based on EKM

The external gearshift still needed with EKM including shift intention recognition and gear recognition is no longer included. It is replaced by an electric motor-driven transmission actuator (Figure 16).

Also with this development, the attempt is made to avoid changes to the transmission, i.e., to design the system as an add-on. This requires a high degree of flexibility. In order to use as many standard components as possible, the ASG is laid out as a modular system. The adaptation of the transmission actuator to the transmission occurs via an intermediate transmission. Electric motors and controls are conceived as standard components for all users, in order to realize high production quantities. Even with the ASG, the cooperation with Bosch proves useful because they provide these standard components.

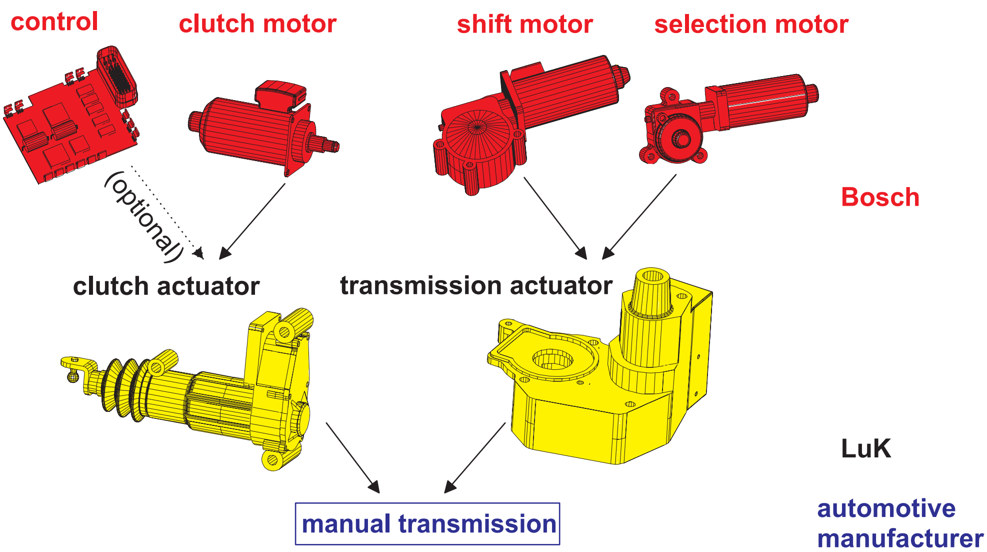


Figure 17: Modular design ASG

As mentioned in the previous chapter, the control electronics have been designed significantly smaller. For this reason, control and end stages for the ASG engines are now integrated in the clutch actuator.

The software development tasks are also being shared with Bosch. Control-operating systems, including electric motor-specific basic control and the shift-time calculation including driver model come from this worthy partner. The control of the clutch, the gear motors, the characteristic for the combustion engine and the overall coordination of the shifting process is made by LuK.

Each customer naturally has a specific philosophy when and how its transmission should change gears. The LuK concept offers wide-ranging application possibilities with which the gearshift time and process can be influenced.

Basics of the Gear-changing Process

The basic problem with an automated manual transmission is the tractive force interruption. In Figure 18 this is the valley between the two shifted gears. The torque must first be reduced on the engine and on the clutch. Then the gear is disengaged, it is synchronized, the new gear actuated and finally the torque is built up.

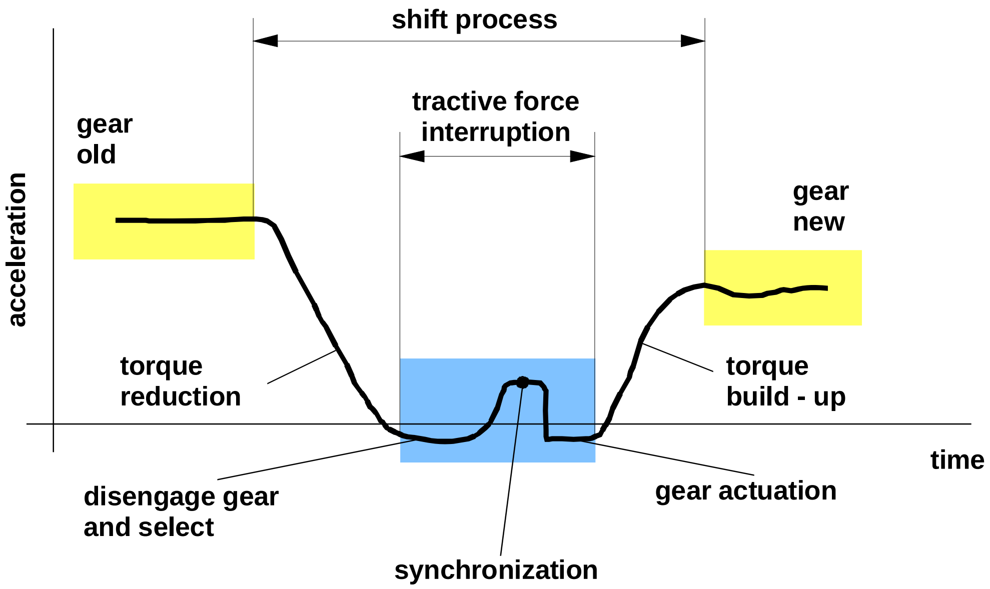


Figure 18: ASG shifting process: Phases

These phases of the shifting process can be divided into two stages with respect to the requirements of the shifting element:

- Processes that effect the vehicle acceleration
- Processes that represent pure dead times

With the processes that affect vehicle acceleration, it is apparent that the actuator element “electric motor” must be throttled, because changing the vehicle acceleration too quickly is unpleasant. Only an optimization leads to well-tuned interaction of engine, clutch and transmission engagement. The load can be greatly reduced during synchronization, for example, by intermediate gas.

In the dead times, the maximum speed of the actuators is required. With this, one must be careful that in disengaging the gear and the subsequent fast phase, the impact on the synchronization is too hard.

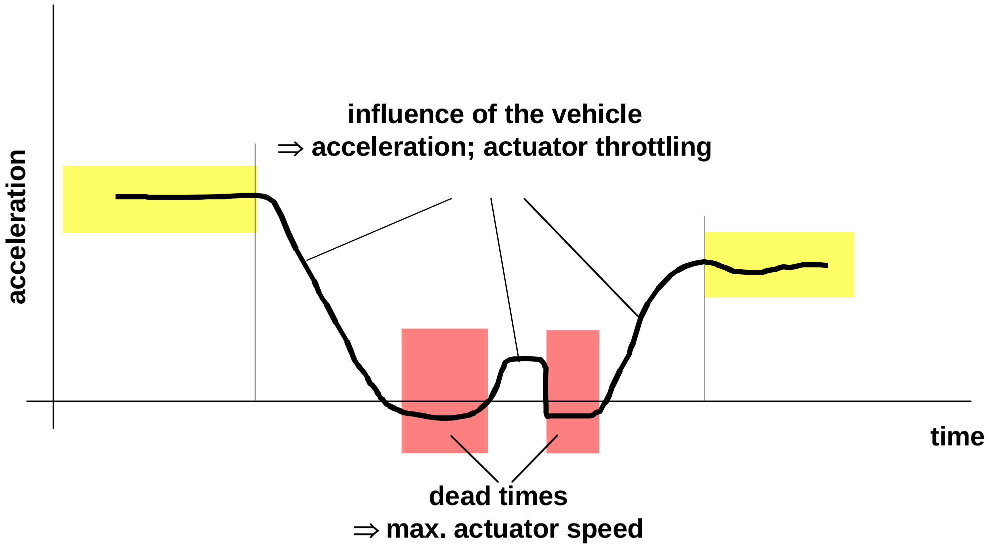


Figure 19: Optimizing tractive force interruption

In response to this contradiction, LuK has developed an integrated shifting elasticity, which responds when the shifting force threshold is exceeded and then exhibits only a low force increase (see Figure20).

This integrated shifting elasticity offers the following advantages:

- The free flight phases, which are pure dead times, are shortened if the integrated shifting elasticity was prestressed (when disengaging from the previous gear, respectively the stop position of the synchronization).
- Defined shifting force ensures constant shifting comfort.
- Transmission and actuators are protected by the elastic force limitation.

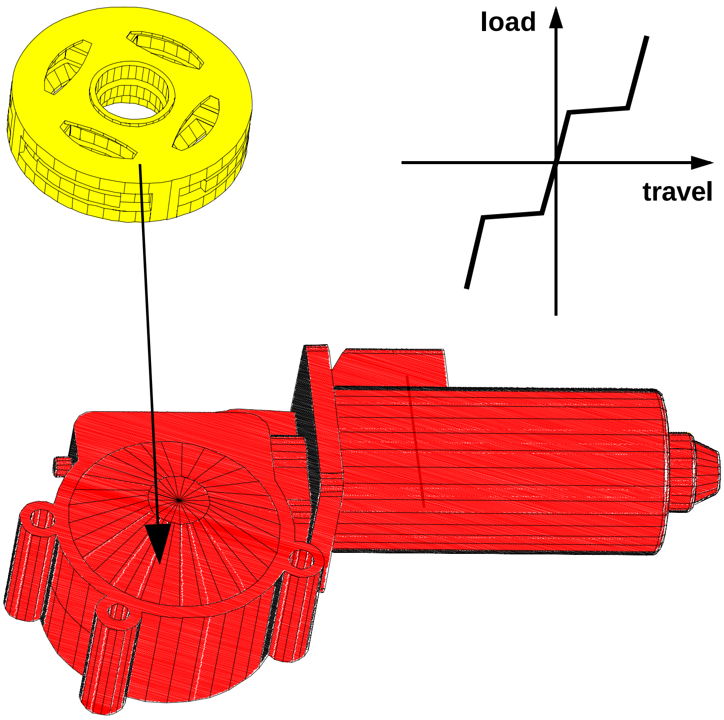
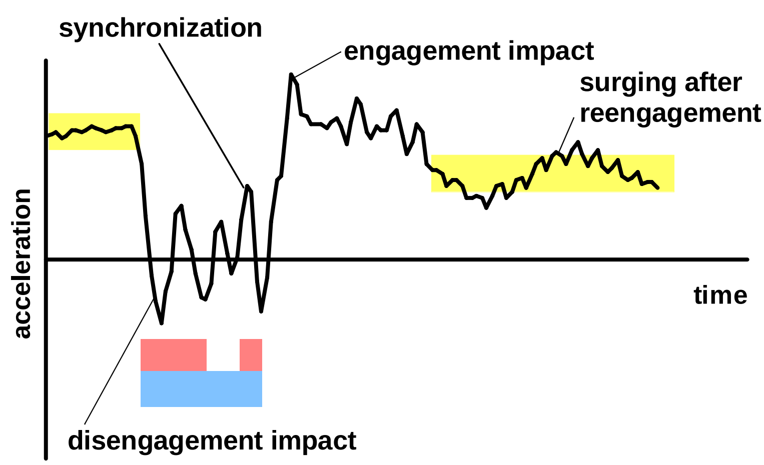


Figure 20: Shifting elasticity for transmission shifting

Measurement

The effects of different shifting process designs are illustrated with the help of measurements. Figure 21a shows the vehicle acceleration at a fast shift with full actuation speed. The rapid torque decrease causes a disengagement impact. The decay of ist oszilluations overlaps with the synchronization impact. The rapid reengagement causes an acceleration peak, followed by slip with maximum clutch torque and a resulting high vehicle acceleration. Finally, surging accurs after the end of the slippage. In comparison the vehicle acceleration during a comfortable shift is shown in Figure 21b. Torque decrease and increase as well as the synchronization period take longer in this case, while the dead times are kept at a minimum as in the shift depicted in Figure 21a.

a) uncomfortable shifting



b) comfortable shifting

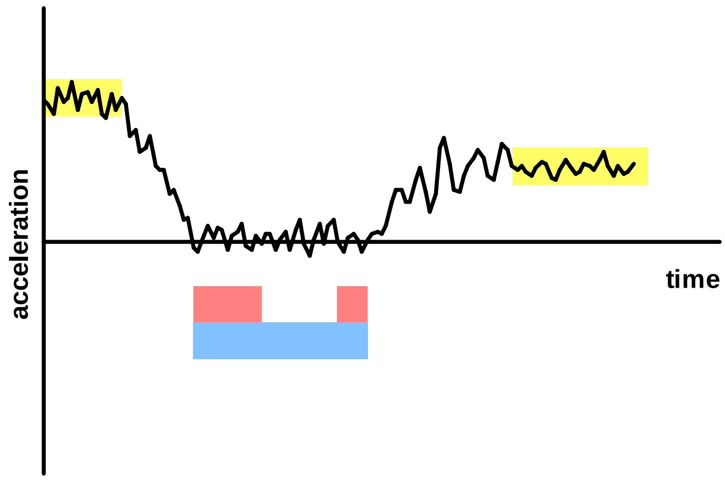


Figure 21: Shifting process measurement

The phases of the shifting process as defined in Figures 18 and 19 are marked in Figure 21 as well.

Future Outlook

LuK is developing the electric motor-driven ASG add-on as part of several customer projects. It is expected to be introduced on the market at the turn of the millennium. It has been installed in several dozen vehicles, which are currently undergoing customer testing.

At the same time, the next generation ASG is already in development. Here concepts are being investigated that differ significantly from manual transmission. The attributes of the ASG add-on are included in this new transmission at sharply reduced costs per unit

Summary

The Electronic Clutch Management (EKM), which was introduced four years ago, is now in production. This offers the customer an economical, efficient and functionally reliable solution.

Size and weight reduction, the operation of more powerful engines, functional expansion and cost reduction are in the foreground as important goals for the further development of the EKM systems. One approach to a solution involves new, more compact clutch actuators, a simplified clutch (active clutch), the elimination of a sensor and operation with constant slip in the lower speed range.

The automated shift transmission is based on the automated clutch actuation of the EKM-System. The external shifting, including gear recognition and recognition of intent to shift is replaced by another electric motor-driven transmission actuator. An important goal here as well is to produce an add-on system and to avoid changes to the transmission and release system. Theoretical investigation of the shifting process, characterized by tractive force interruption, as well as measurements confirm the assumption that fast and comfortable shifting can be achieved as well with the motor-driven ASG as with the hydraulic system.

With today’s customer expectations and the increasing number of technical options, we are convinced that EKM and ASG will have a broad market success. This especially applies to small cars and for developing countries where automatic transmission are not readily available.

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