Torque Converter Clutch Systems

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Introduction

Modern vehicle drive-train engineering must exhaust all potential drive-train options in order to provide maximum acceleration and fuel efficiency with high overall efficiency and optimum comfort. At the same time, attention must be paid to ever stricter emission standards. These requirements often work at cross-purposes with each other, which means that improving emissions often entails increasing weight, fuel consumption and decreasing acceleration, not to mention incurring constantly increasing costs [1].

Despite this trend, LuK has developed a torque controlled clutch system - called the TorCon System - that increases driver comfort, reduces fuel consumption and emissions, improves acceleration and even results in a 4-speed automatic transmission that is superior to a conventional 5-speed automatic. This means that wherever an expensive 5-speed automatic transmission is used due to fuel consumption and acceleration requirements, the same results can be achieved with a 4-speed automatic transmission.

LuK's design philosophy is centered on holistic system design, and the automatic transmission area is no exception. This approach meets the demands that automotive industry have come to expect of it's system suppliers.

Given the parameters it is not possible to fall back on large test facilities and a fleet of test vehicles. Yet LuK is confident that it is a competent development partner and can ensure the introduction of new transmission systems into production with the shortest possible development lead times. The following demonstration of LuK's development philosophy shows why this is possible.

LuK, as a component supplier, has given special thought to the total system, not just to the parts supplied by LuK. In concrete terms, this means that when dealing with automotive transmissions, it is also necessary to look at control systems, engines, vehicles and external influences (see Figure 1).

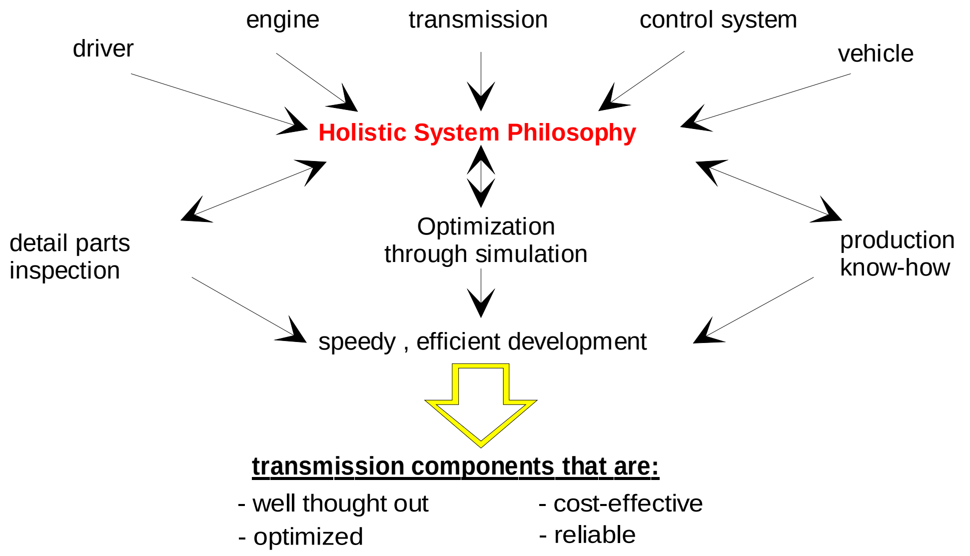


Figure 1: Holistic System Philosophy

LuK greatly appreciates the importance of simulation and detail component testing as important tools for cutting development lead-times and costs. LuK also possesses considerable production know-how (for instance, LuK produces over 2 million conventional torque converter clutches per year for the automatic transmission market).

LuK conducts extensive basic tests in order to ensure reliable product function. Based on these tests, the structure of the development model gradually becomes more complex compared to the previous model [2]. In this way, general knowledge can be integrated and extensive, time-consuming - not to mention expensive - vehicle tests (Figure 2) can be significantly reduced. Nevertheless, some information must be obtained from vehicle tests and vehicle tests serve to confirm projected data.

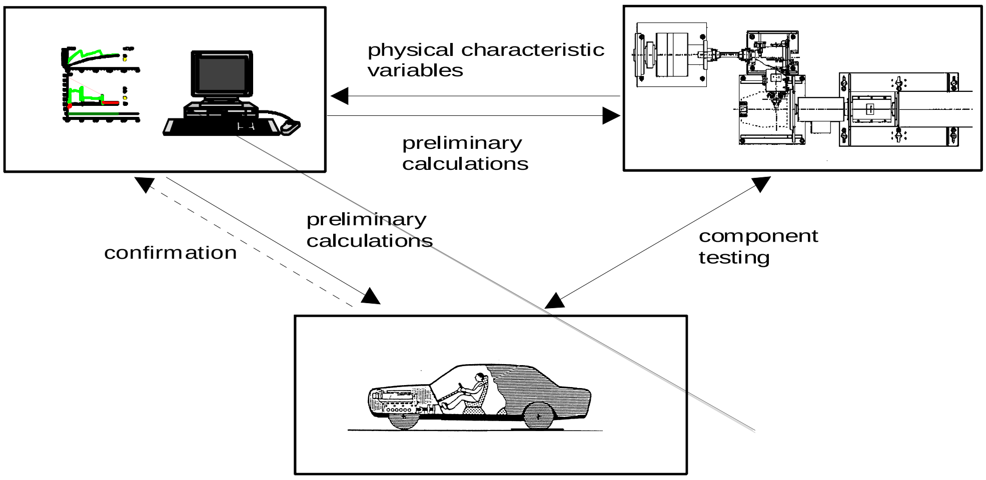


Figure 2: Integrated Development Tools

An example of this kind of development is an analysis of the relationship between friction linings and hydraulic fluid. The torque converter clutch is, of course, a wet clutch and basic knowledge of this kind of clutch is important in developing transmission systems. Typical problems, such as shudder, only occur at relatively high mileage levels. In order to reduce the time it takes to gather data on long-term performance, a small test stand has been developed that reduces the fluid volume used in the test to ¼ liter, a value that corresponds to the relation between the friction surface and the quantity of fluid present in the automatic transmission. Considerably more fluid has been used in traditional test stands, with the result that, if oil additives are damaged at the friction surface, it takes a relatively long time for any consequences to show up because of the dilution effect of the fluid. A small test stand enables fairly rapid results to be obtained concerning the interaction of hydraulic fluid and the friction lining when exposed to specific loads. One can also determine the stress that the fluid and the facings can be exposed to over time. These findings go directly into new designs, for example the slipping torque converter clutch. This results in new torque converter clutch designs that withstand extensive customer durability tests without any problems.

The Physics of the Torque Converter

The torque converter consists of a fluid coupling with an impeller, a turbine and a stator.

Without slip it cannot transmit torque.

Given a constant output speed, the higher the slip speed, the higher the torque. Figure 3 shows this relation for a stalled converter.

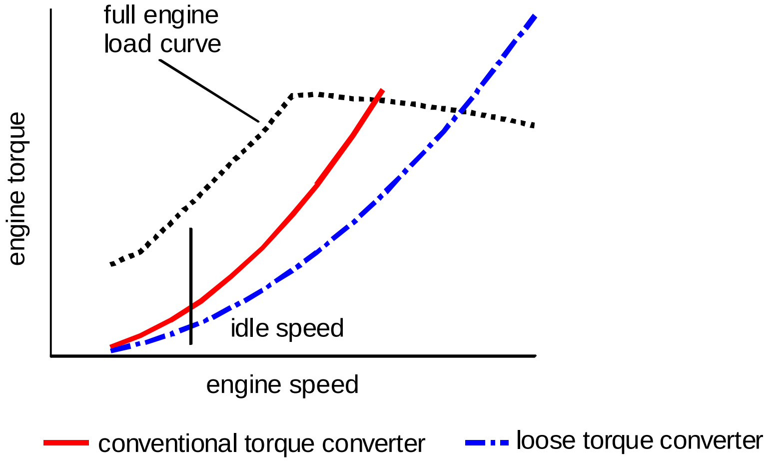


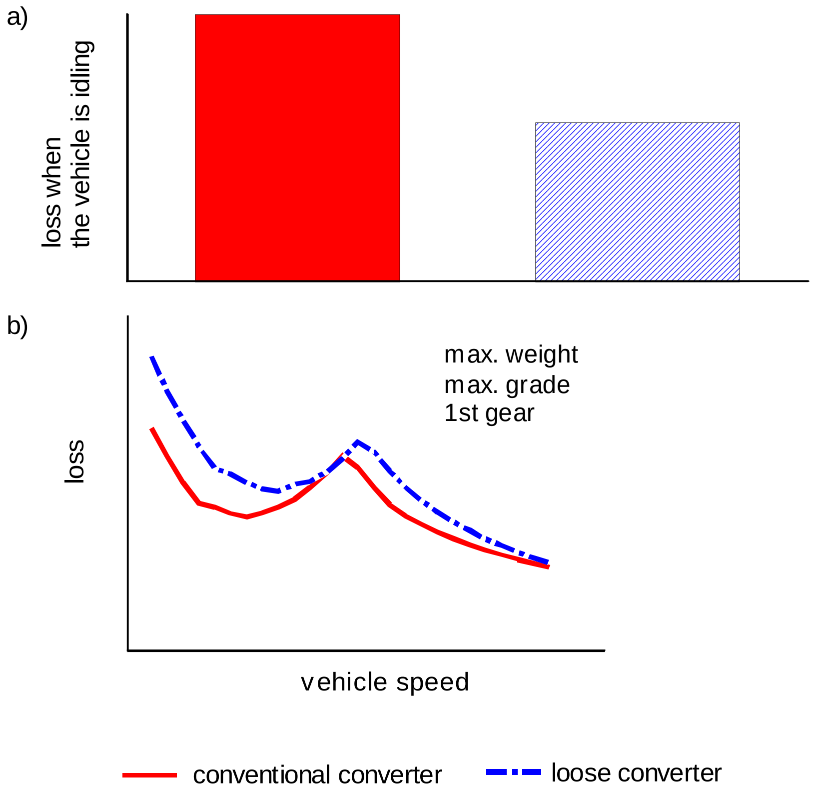
Figure 3: Converter stall torque in relation to the engine torque curve

One says a torque converter is "looser" if, compared to another torque converter, it has a higher slip at the same torque level, which also means that it transmits less torque at the same slip level. A looser torque converter exerts less resistance on the engine. If the driver demands greater torque, the looser converter builds up higher speed differentials.

Higher speed differentials result in an "elastic" connection between engine and transmission, which causes a delay in the vehicle reaction to changes in throttle position. This means that the vehicle is no longer immediately responsive to the throttle.

The advantage of this feature is that most emission tests begin with a cold phase. If it is easier for the engine to reach high speeds in this phase, then it heats up faster and emission levels improve considerably.

At any given engine speed, the looser torque converter exerts less torque in resistance to the engine. If the vehicle engine is idling, it has to overcome converter torque. This means that the energy loss is lower for loose converters in a stationary vehicle than it is for standard designs (Figure 4a).



Figures 4a and 4b: Converter Losses

For any given output torque demand, for example, for a given vehicle speed on a given grade, slip increases with the loose converter, as shown in Figure 3. This means that loss increases as well (see Figure 4b).

In contrast to a clutch, a torque converter can multiply engine torque. This torque conversion can be higher for a loose torque converter than for a conventional design with the same diameter.

A higher torque ratio means that the tractive force increases along with acceleration (Figure 5).

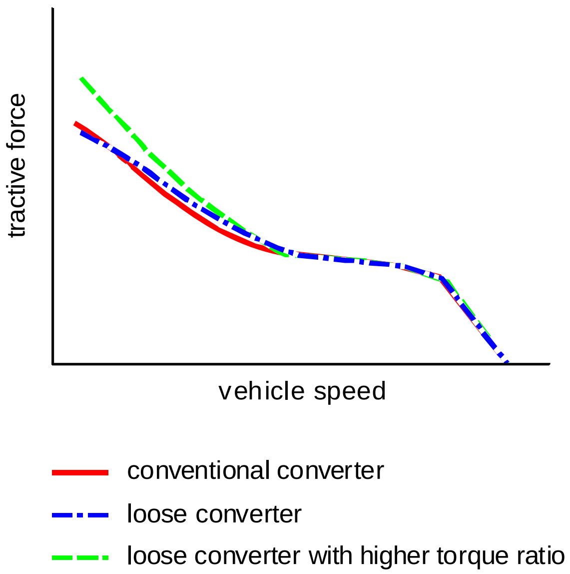


Figure 5: Effect of converter design on tractive force

Losses for a given driving condition (weight, grade) also decrease, if the torque ratio is higher in comparison to those of a loose converter without a higher torque ratio. Nevertheless, they remain higher than with a conventional converter (Figure 6).

All converters produce large amounts of slip at low speed and under extreme load. When slip values are high, load losses are no greater for a loose converter than for a conventional converter because the higher torque ratio improves the efficiency (See Area A in Figure 6).

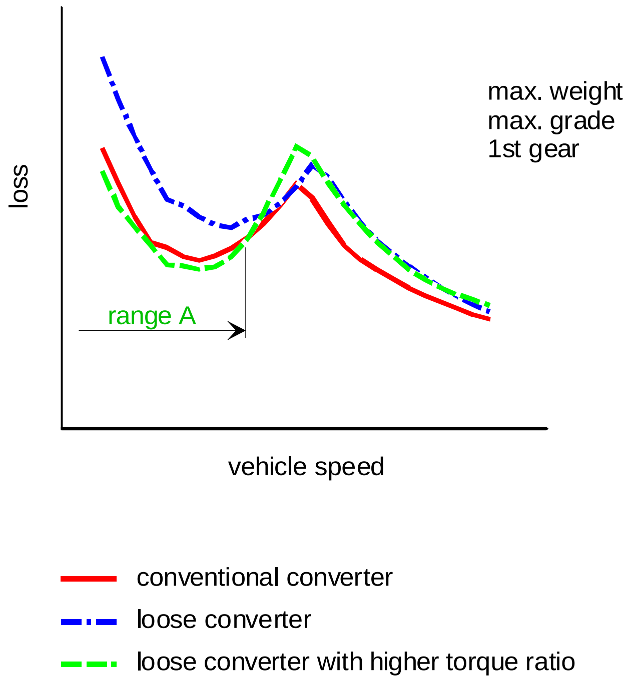


Figure 6: Effect of converter design on losses

Although reducing idle losses, lowering emissions in the cold phase and improving acceleration would seem to require a loose converter, in applications without torque converter clutches conventional converters are used in order to reduce losses during normal driving operation and to achieve an acceptable power response.

Torque Converters with Traditional Torque Converter Clutches

Losses in a traditional torque converter can be limited by using a torque converter clutch (TCC) with a conventional spring damper. Because of comfort problems - boom, rattle and tip-in/back-out reactions -, these TCCs can only be used in higher gears at average speeds, despite the use of the torsion damper. Even then, certain compromises with regard to comfort must be expected.

To clarify the problem of boom and rattle, figure 7 shows vibration amplitudes for the engine and the transmission output as a function of the engine speed. Depending on engine excitation and vehicle sensitivity to boom, a torque converter clutch can only be used at higher speeds. It is well known, however, that most of the time engines are running at relatively low speeds, which means that any reduction in fuel consumption is limited.

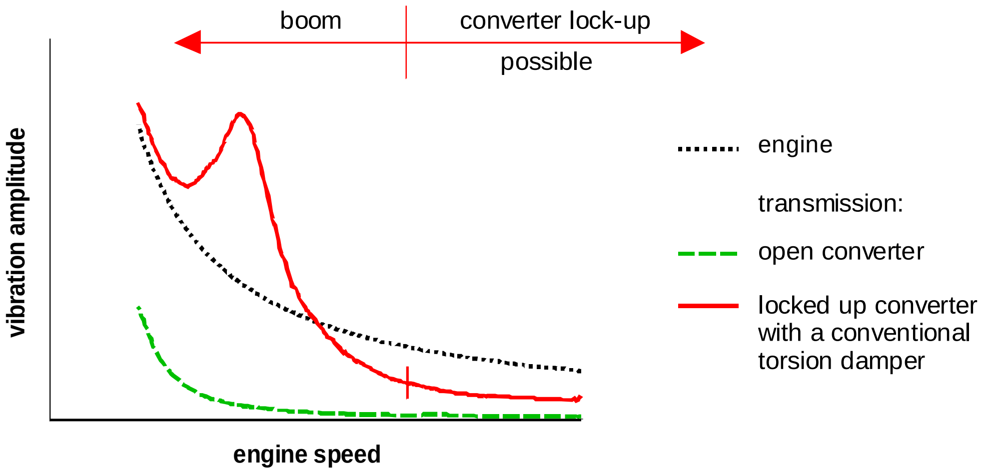


Figure 7: Torsional vibrations in the engine and the transmission

Tip-in/back-out performance is also a problem as well as changing gears and engaging and disengaging the torque converter clutch (Figure 8). If the driver steps on the gas when the torque converter clutch is engaged, he gets surge vibrations instead of the desired increase in tractive force. Then the torque converter clutch opens up, which in some situations even briefly cuts off torque transmission, before the driver finally gets the desired increase in tractive force.

Closing the torque converter clutch again can produce a drive train vibration.

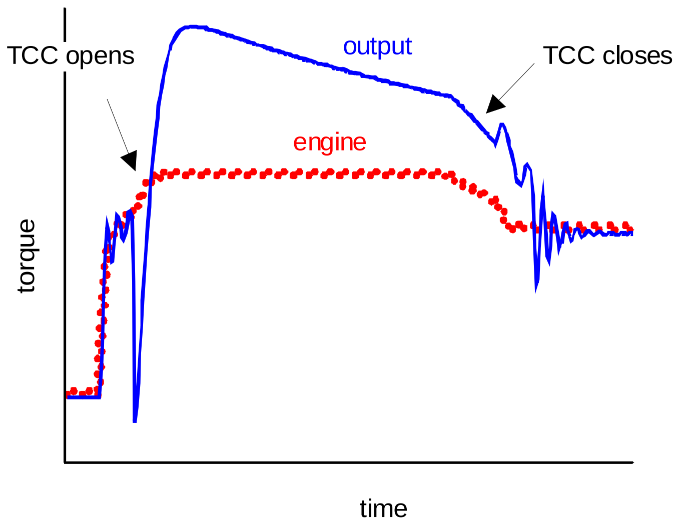


Figure 8: Tip-in/back-out cycle with a conventional spring damper

Comfort problems can also occur when changing gears, so it is customary to open the torque converter clutch when changing gears.

These effects are most apparent in the lower gears, so it is customary to use traditional torque converter clutch systems only in the upper gears.

This means that the torque converter cannot be locked up to reduce losses when driving up a steep grade in first gear. The losses in the torque converters are converted into heat, so the "looseness" of the converter is restricted by the capacity of the cooling system.

Furthermore, the power response demands during acceleration limits how loose the converter can be.

The Turbine Damper [3]

A Significant Step in Conventional Technology:

The problems of boom and rattle cited here for conventional torque converters can be reduced with torsion damper modifications. It would appear possible to achieve improvements by using a torsion damper with a lower spring rate. This is actually the case in some drive trains (Type A, Figure 9). Nevertheless, there are drive trains where this solution does not work (Type B, Figure 9).

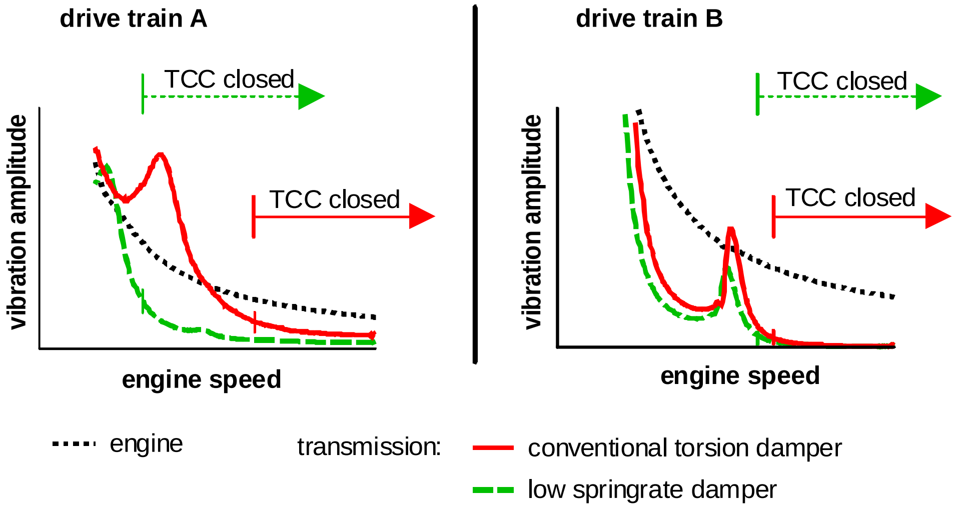


Figure 9: Effect of a low spring-rate damper

Why is this the case? The answer lies in the analysis of characteristic vibration modes and frequencies (Figure 10). In type A drive trains, boom is a function of the second characteristic mode. Relative torsion damper movement is fairly high during this mode, which means that damper modifications will have an effect. For Type B drive trains, on the other hand, the third characteristic mode is the problem. In this case, there is very little relative movement in the torsion damper, which means that changing the stiffness (spring-rate) has little effect. Based on the characteristic curve, one can assume that the stiffness of the transmission input shaft will have to be reduced.

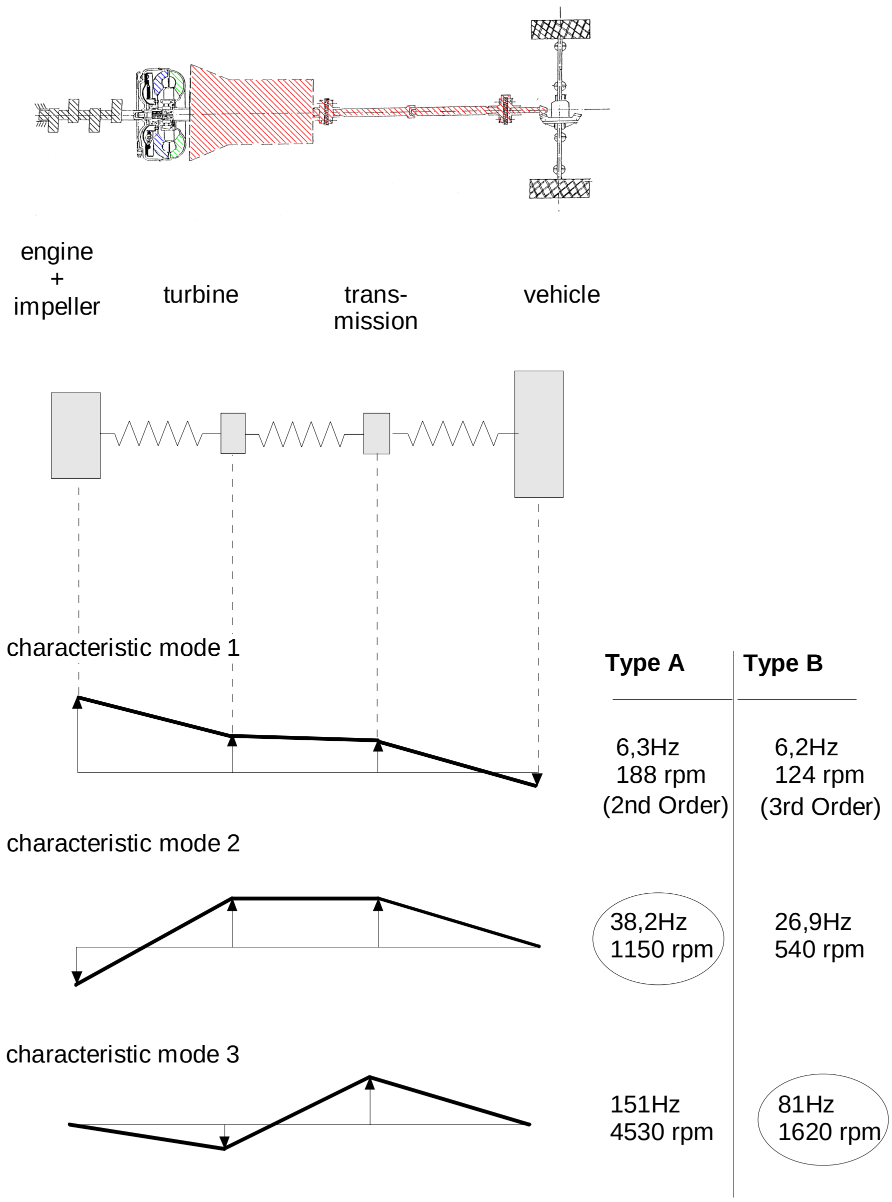


Figure 10: Natural frequencies in a vehicle with an automatic transmission

The amplitude curve in Figure 11 shows that a significantly softer transmission input shaft in a Type B drive train will achieve significant decreases in boom resonance, which cannot be achieved using a torsion damper with a lower spring-rate (Figure 9).

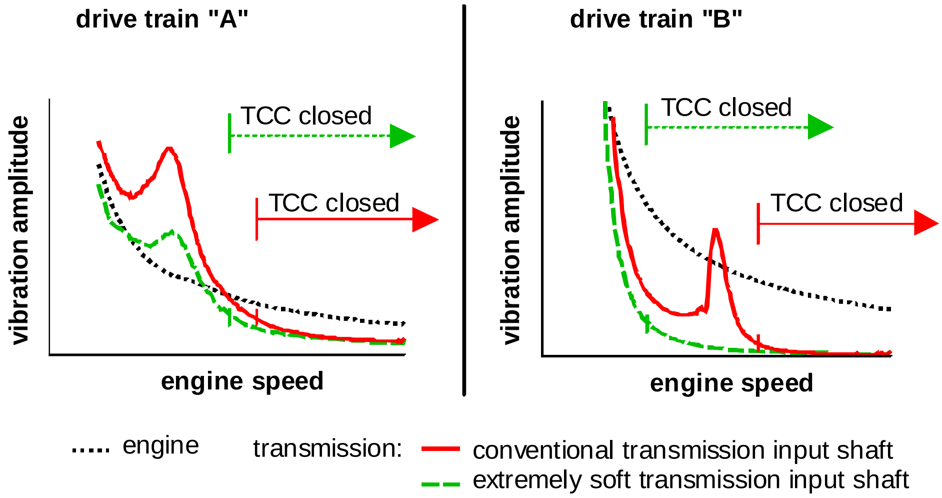


Figure 11: Effect of an extremely soft transmission input shaft

The stiffness of the transmission input shaft itself cannot be reduced to the required level, so a serial torsion damper is installed (Figure 12). The torsion damper between the engine and the turbine is removed and a damper is placed between the turbine and the transmission input shaft. LuK calls this design a turbine damper. It is important to note that with this design, power still flows through the torsion damper even when the torque converter clutch is open.

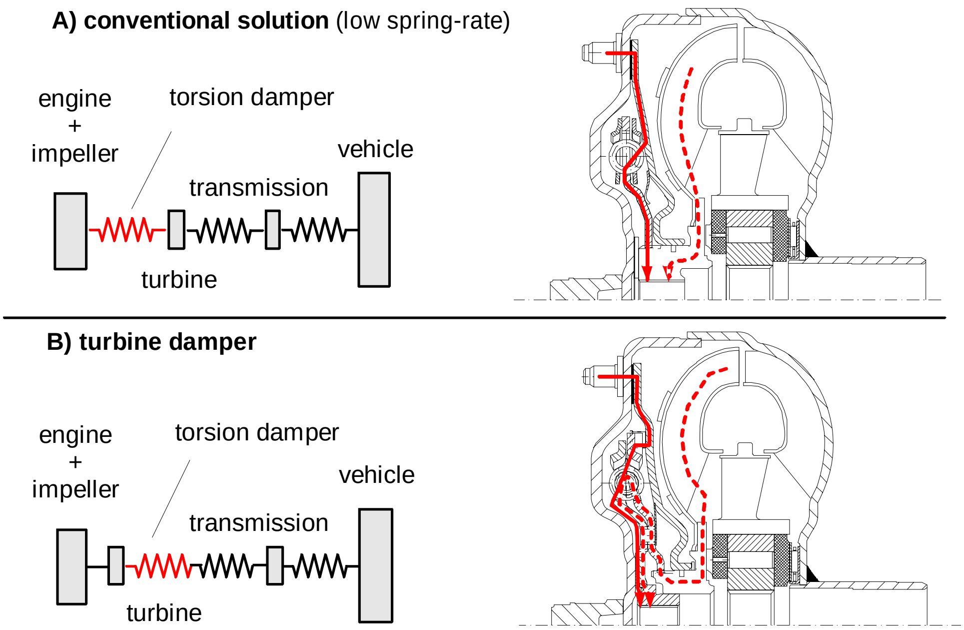


Figure 12: Turbine damper design

The choice of whether to use a LuK low spring rate conventional damper or a turbine damper depends on the drive train design. In comparison to other systems, both designs allow the clutch to be closed at a significantly lower engine speed. Depending on the customer control strategy - the tip-in/back-out peformance must be considered - a significant fuel saving can be achieved.

A Holistic Concept: The LuK TorCon System

What does the LuK TorCon System entail?

The LuK torque control clutch system (TorCon) consists of the following components: a conical slipping torque converter clutch, a mini-torsion damper, an adaptive control strategy and a loose converter.

Slipping torque converter clutches have been the subject of considerable debate for many years, have been introduced into production, and have been abandoned. One major problem is shudder due to hydraulic fluid damage. In some cases, control strategies result in comfort problems or in increased slip.

LuK has been aware all along that the slipping torque converter clutch has a very high potential, but also that full realization of this potential involves a three-step process:

- careful analysis of the interaction of mechanical, hydraulic and electronic systems (hy-mech-tronics)
- assignment of each function to the system that can best perform it
- ensuring that the three systems interact as effectively as possible.

Slipping Torque Converter Clutches

Theoretically, a slipping clutch offers the advantage that in addition to preventing high frequency vibrations such as boom, it is also capable of isolating low-frequency vibrations like those caused during tip-in/back-out cycles.

By reducing boom excitation, the slipping torque converter clutch, like the turbine damper, can be engaged at a lower engine speed than with traditional systems (Figure 13).

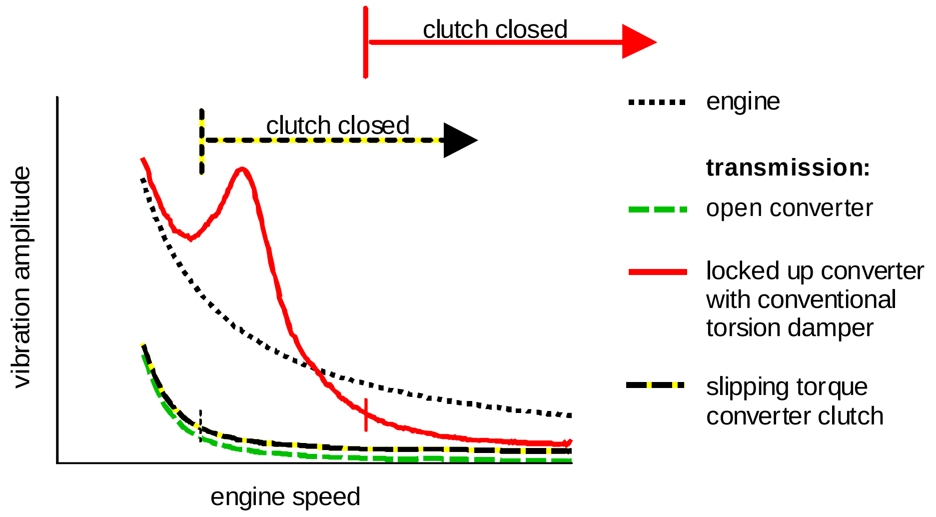


Figure 13: Effect of slip on vibration behavior

In comparison to traditional systems, a slipping torque converter clutch significantly improves tip-in/back-out performance and the supply of tractive force (Figure 14). No surging occurs when the driver steps on the gas because the torque converter clutch slips. The additional slip causes the converter torque to increase and prevents any break in torque transmission. As a result of increased torque conversion, torque increases continuously beyond the engine torque. The torque converter clutch can be engaged sooner, even in lower gears and at lower speeds.

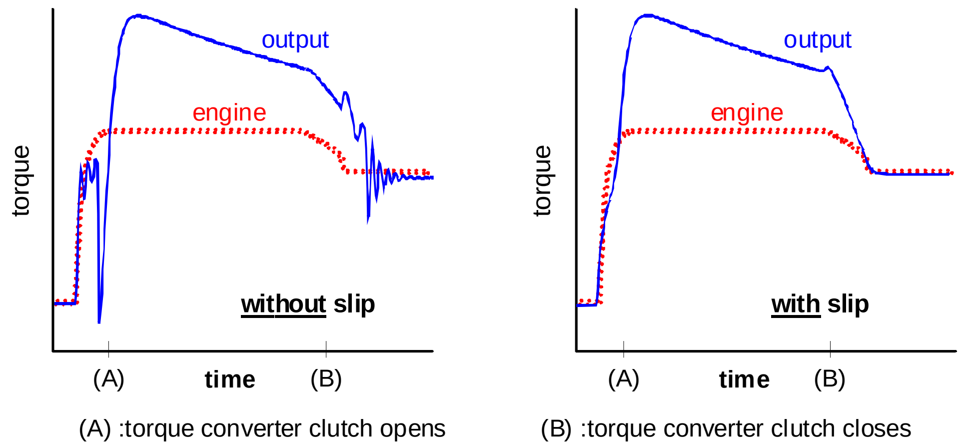


Figure 14: Tip-in/back-out performance with and without slip

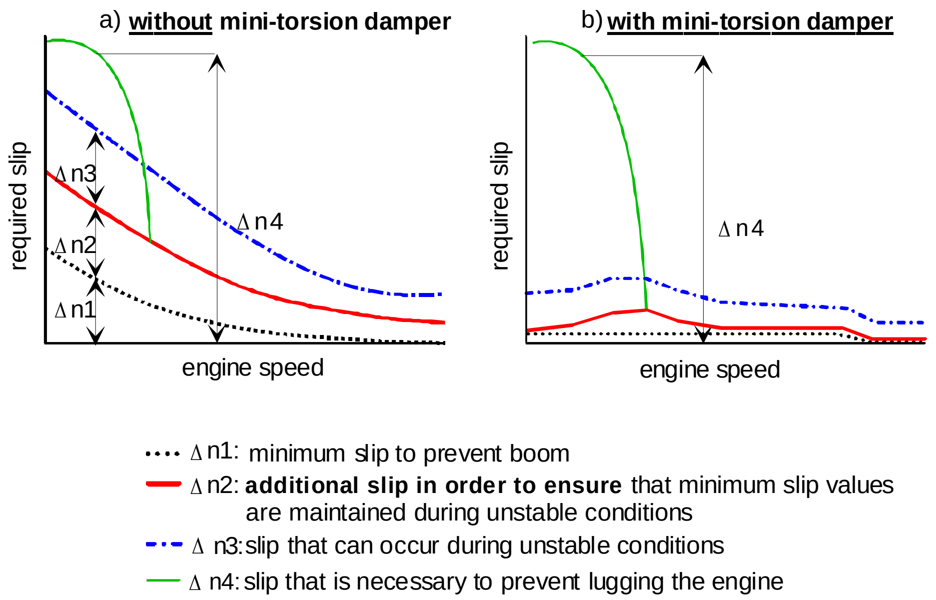
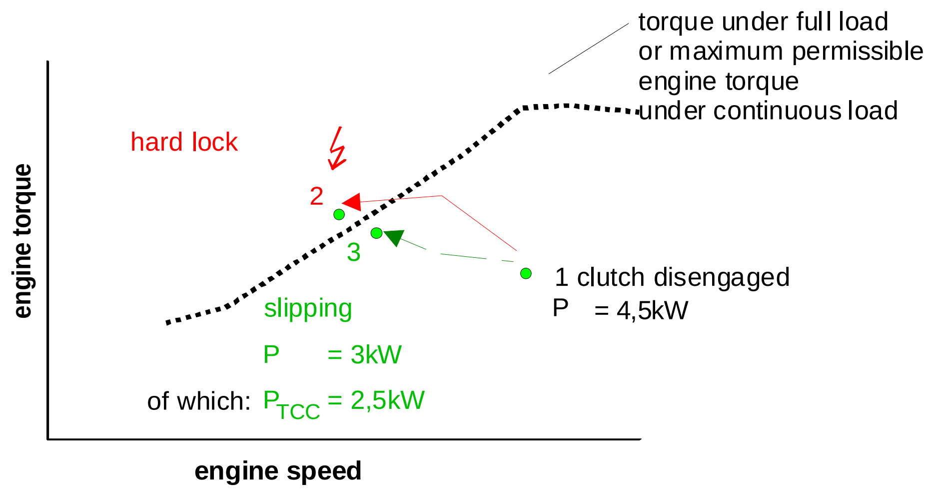


Figure 15: Slip requirements for designs with and without mini-torsion dampers



1) Converter clutch disengaged, **Total Losses = 4,5kW**

2) Converter clutch hard locked, required torque exceeds permissible values.

3) Converter with slipping clutch, **Total losses = 3 kW**,
Losses at the converter clutch = 2,5 kW,
Engine operating point for maximum fuel efficiency

Figure 16: Using torque control isolation to reduce overall losses

If a slipping torque converter clutch has so many advantages, why are so few units in operation today? The answer is that slip control also has its problems (See Figure 15 a for further explanation).

1. Preventing boom at low speeds usually requires a relatively high amount of slip. This means that total loss is also high. Decreasing slip often results in short-term sticking, which causes boom in many cases (n_1).
2. Low slip is difficult to control. Problems often occur if the control parameters are very stringent, but easing up on the parameters can result in significant deviations in slip values. In many cases, a open loop control system has distinct advantages, but even in such cases, slip fluctuations are hardly avoidable. Sticking can occur (with a possibility of boom) or slip can be too great (high loss).
3. The control system is imprecise. The lower the control torque, the more difficult it is to achieve exact control.
4. The system has a response time. Under unstable conditions, the control system requires a certain response time. During these conditions, slip values vary. The system must maintain a certain slip level in order to prevent boom, which again results in higher slip values (n_2, n_3).
5. With many engines, it is important not to lug the engine at low speed under heavy load or if the tractive force is insufficient, when the torque converter clutch is engaged (Figure 16). Driving at low speeds with high load can also cause problems with the cooling system. There are two options if it is important not to lug the engine at high loads. One can increase the engine speed by completely opening the torque converter clutch or one can let the torque converter clutch slip more. In fully open condition, loss will be unnecessarily high. If more slip is allowed, total losses decrease, but losses will increase in the torque converter clutch (n_4), which will increase clutch cooling requirements.
6. Heat build-up in the torque converter clutch must be dispersed. The essential problem with slip clutches is durability. Usually they will tolerate the heat built up during operation for a while, but after a few thousand kilometers, they begin to exhibit shudder problems. These problems are usually attributable to oil breakdown rather than to any problem with the friction lining. Petroleum additives are damaged by local overheating and over time affect all fluid in the system. Even when heat build up is relatively low, the facing should be well cooled. The design should provide maximum protection from local overheating! In addition to the heat caused by slip during vibration isolation, as well as the type of losses described in Points 1, 2 and 5, losses occur when the torque converter clutch engages and disengages. The lower the

speed and the higher the load at which the torque converter clutch engages, the larger the loss and greater the heat produced - especially if the system is designed for a comfortable converter clutch engagement.

One can counteract these problems by using a **simple torsion damper** (designed for partial load), a **conical design** and an **adaptive control strategy**. Figure 17 features a bubble chart that illustrates the interaction of these system components. The thick-lined bubbles represent customer requirements, and the shaded bubbles represent the components in the TorCon System.

The Mini-Torsion Damper

Advantages of a simple torsion damper (see also Figure 15b):

- Problem 1 (boom): the torsion damper will filter out the impulses caused by brief sticking, so no boom occurs.
- Problem 2 (control parameter problem): provides a partial solution. The torsion damper prevents brief sticking from causing boom.
- Problem 3 (control precision at low torque levels): The torsion damper assumes the vibration isolation function if the clutch briefly sticks, therefore the torque converter clutch can transmit a higher torque at low torque levels without control imprecision causing problems.

Slip can be maintained at a lower level. Slip prevents excitation in the damper resonance range, which means that friction elements are unnecessary in the damper. The mini-torsion damper is lighter and cheaper than conventional torsion dampers.

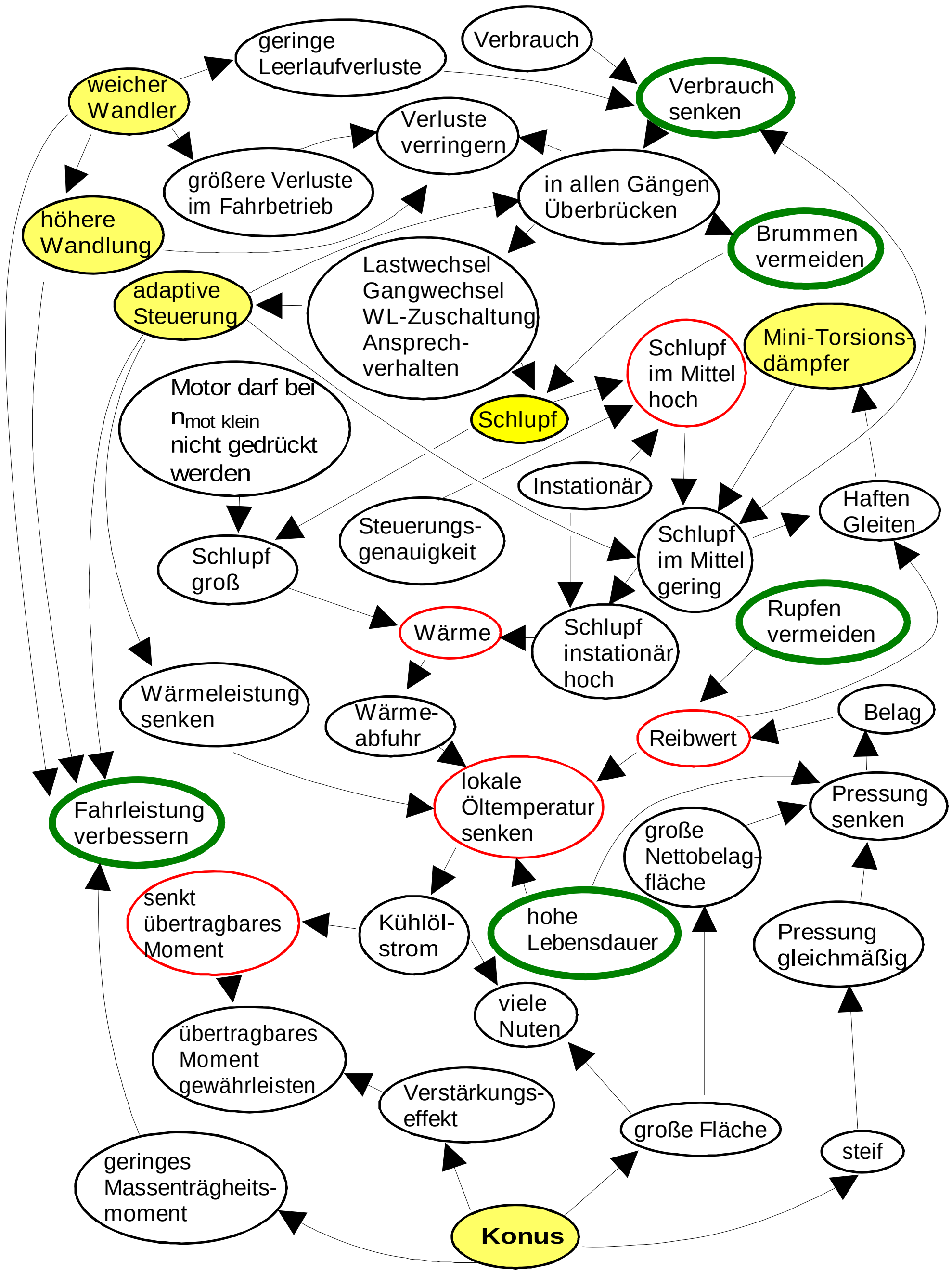


Figure 17: Bubble chart showing the interaction of slip, the mini-torsion damper, the conical design, and the adaptive control strategy

The Conical Design

The advantages of the conical design are primarily attributable to the stiffer design and the increased friction area:

- It is easier to dissipate heat build-up, which means that the maximum oil temperature will be lower for the same amount of heat. This factor helps solve problem 6 (dissipating the heat) and with that problem 4 (control response), problem 5 (lugging the engine) and the rest of problem 2 (the control parameter problem).
- More uniform unit pressure decreases lining load.
- Transmittable torque increases. Many of today's existing single-disc bypass clutches are operating at their capacity limits. The effect of coolant flow further decreases transmittable torque. The conical clutch compensates for this.
- The weight and the mass moment of inertia are decreased because the stiffer design allows use of thinner material.
- The converter ballooning decreases, which improves control capability.

The maximum local temperature has a significant effect on the service life of the oil. Lining cooling reduces the temperature in this area (Figure 18).

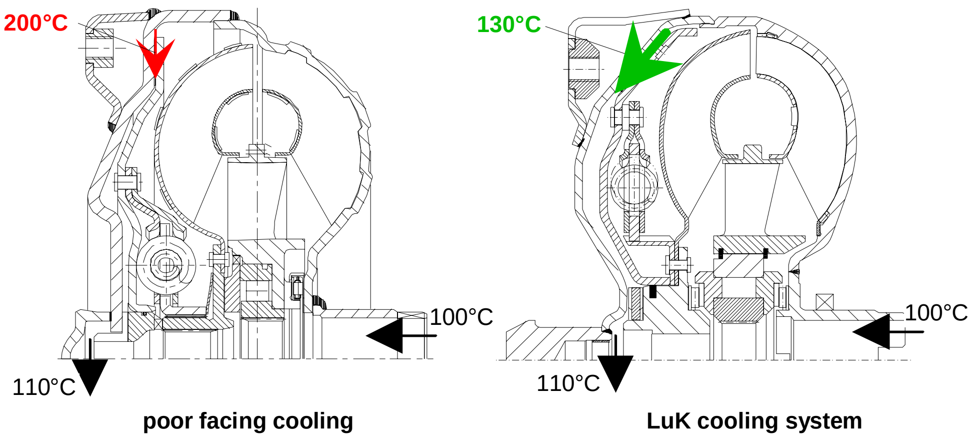


Figure 18: Facing cooling and maximum friction lining temperature

Cooling the lining decreases the bearing surface, but this is no problem with the conical design because lining unit pressure is more uniform (Figure 19). Furthermore, although the flow of oil decreases the transmittable torque, it is compensated by the amplification effect of the conical design.

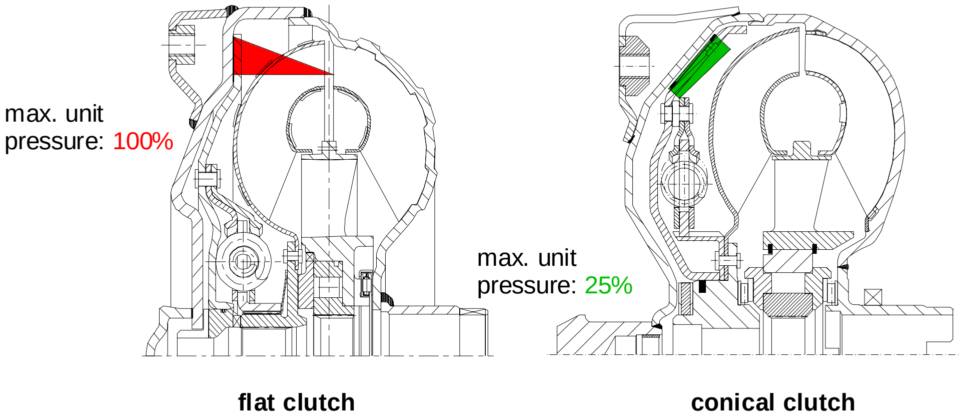


Figure 19: Unit pressure exerted on the facing

Control System Development

LuK has designed the *dyfasim* simulation program to support control system development. Figure 20 shows the basic program structure. In a typical simulation run, desired speed curves are specified and the automatic "driver" tries to follow the specifications.

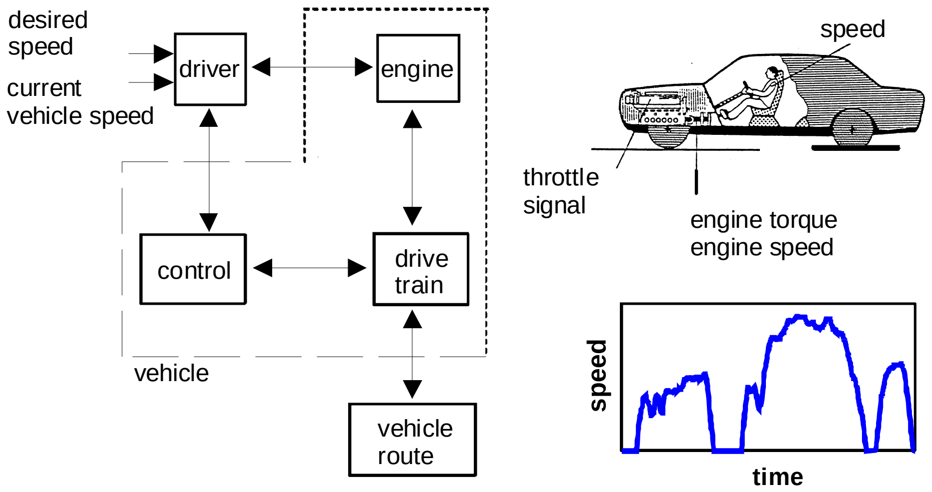


Figure 20: Total system study

Based on these calculations, it is possible to predict element load, shift quality, fuel consumption, etc. (Figure 21).

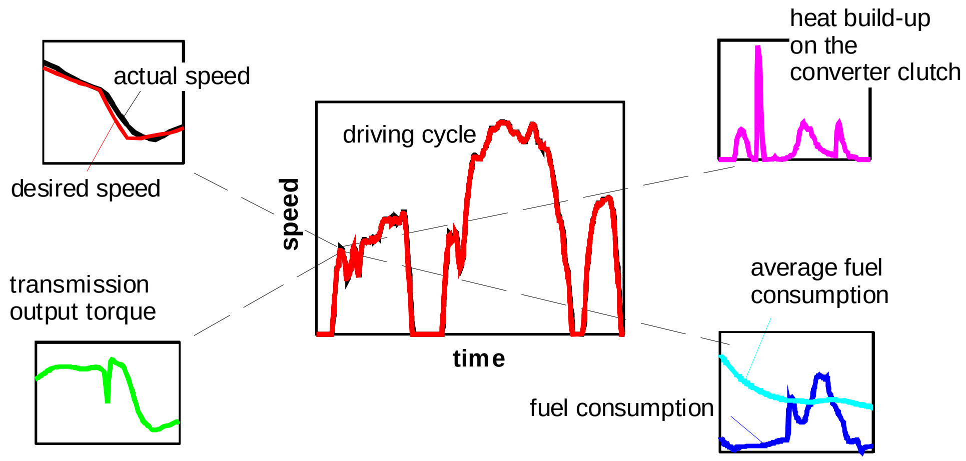


Figure 21: Simulation analysis of transmission system performance

Inclusion of the original control code in the simulation program significantly cuts down on development time (Figure 22).

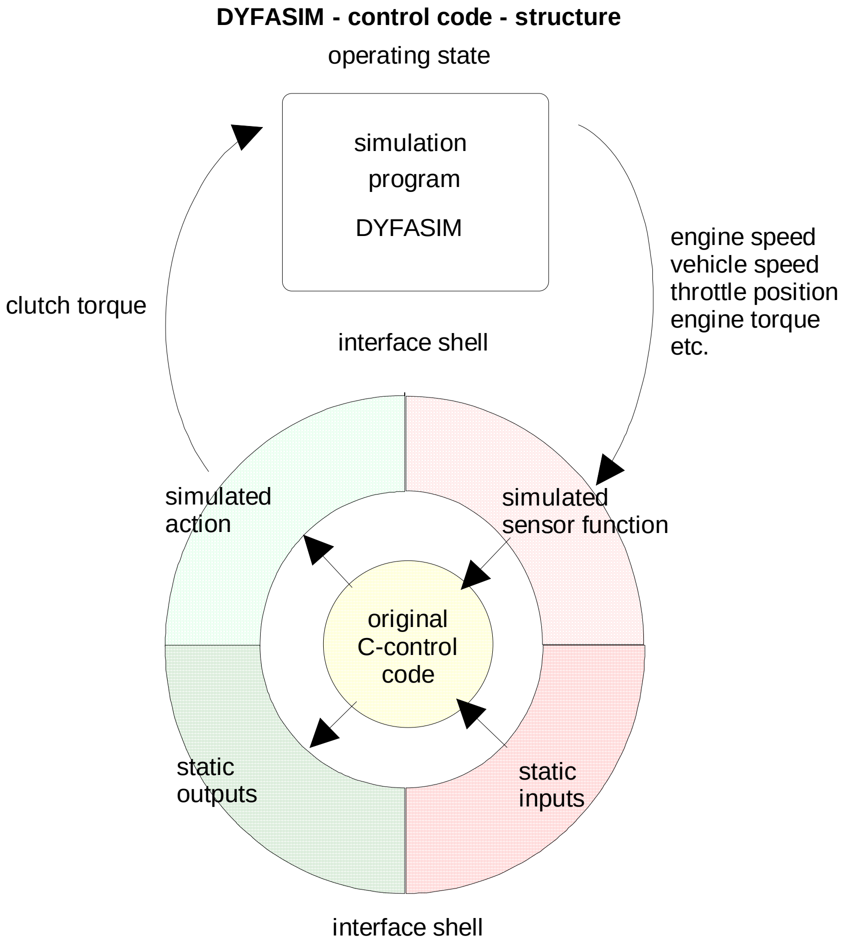


Figure 22: Integrating the control code into the simulation program

This procedure allows the development and testing of the control code long before the hardware is completed. The measured signals are not distorted by noise, so it is possible to conduct much more precise analyses. It is also possible to test performance in various situations and driving cycles, and the same program can be used to test control philosophy, to calculate fuel consumption, to test the control code, etc. Of course, it is not possible to precalculate all phenomena using the simulation program.

Subjecting every vehicle to an automatic long-term study reveals problems that might be overlooked, but long-term studies usually conjure up an image of paper printouts by the pound. In order to avoid the paper overload, measurements are taken at 100 Hz, but values are averaged and transmitted at a per second rate (Figure 23). If any unusual situation occurs, an automatic trigger function causes the system to store measured values at the 100 Hz rate for a specific time interval. Examples of special situations include exceeding a temperature threshold or an uncomfortable output torque or driver activation of the measuring button in the vehicle. This plotting technique drastically reduces the volume of measured data recorded without significantly decreasing the value of the results. To the contrary: the amount of real knowledge gained is increased because the evaluator doesn't have to plow through stacks of paper output or to settle for classified results.

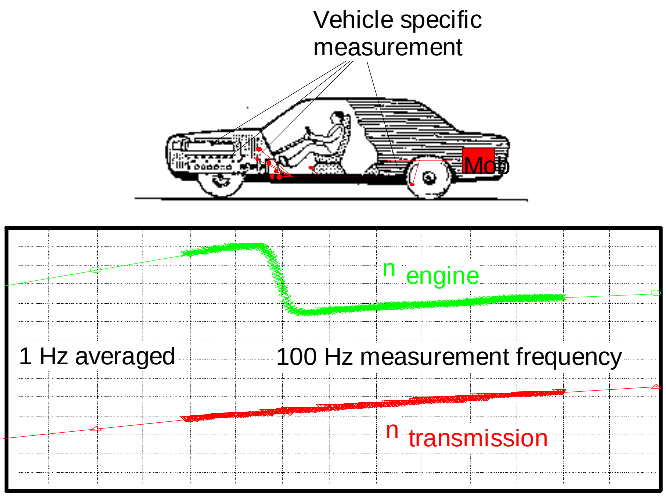


Figure 23: Long-term measurement

This development tool enables LuK to develop new transmission system products to a production-ready stage in a relatively short time and to ensure their reliability.

The Control Strategy

What control strategy was selected for the TorCon System? The problems that occur during slip control were mentioned above. The basic problem with any feedback control system is that a control deviation must occur before the controller can respond. Furthermore, there are ranges in which the default value is unachievable, for instance it is impossible to impose any higher slip than would occur with an open converter.

During shifting cycles, there is a negative effect if the controller works against the gear shift sequence. If the slip is set too low during upshifting for example, the converter clutch can stick at the end of the shift cycle, which compromises comfort. It is possible to come up with solutions to all these control problems, but they are not always optimal solutions. The LuK control concept utilizes torque control and an adaptive system to compensate for system deviations. Converter clutch torque is determined based on the engine torque.

$$M_{TCC} = M_{Engine} * \text{converter clutch factor}$$

This means that there is no slip setpoint, which allows the controller problems described above to be avoided.

This control philosophy allows a definite reduction in slip to be achieved, as shown in the cumulative frequency graph (Figure 24).

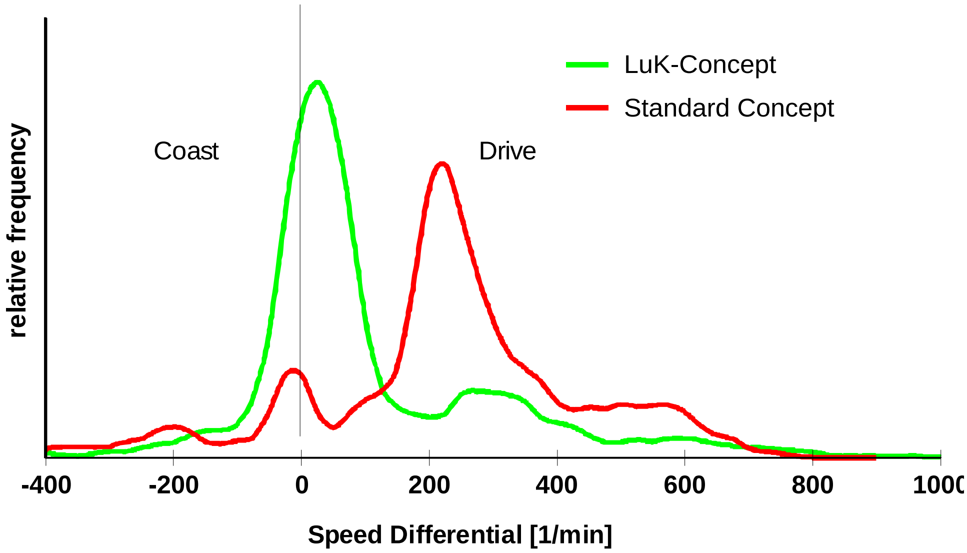


Figure 24: Slip distribution (EU without stationary phases)

Energy values determine whether the TCC is fully opened or whether it is allowed to slip. For instance:

When driving on a steep grade with a heavy load (3600 kg, 12%), the converter clutch cannot be fully closed at low speeds because of insufficient tractive force reserves or because the engine would lug. In such a case, the system constantly checks whether the total power loss is lower if the converter clutch slips or if it is fully open (Figure 25).

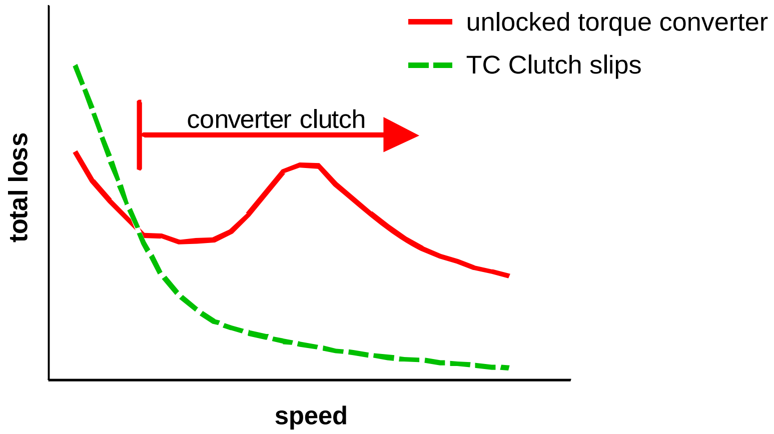


Figure 25: Driving on a steep grade

If the driver wants to increase tractive force, he increases the throttle position. Initially the engine torque increases. If this torque is insufficient, the driver again increases the throttle position to signal his demand for additional acceleration. Traditional systems usually involve downshifting to decrease the transmission ratio and increase tractive force. With TorCon, the system first checks to determine whether opening the converter clutch will increase tractive force. This would be the case if the converter would be in the conversion range after doing so. If this is the case, the converter clutch opens; otherwise, the system downshifts. The control system constantly monitors this function. In order to improve this interaction, it makes sense to adapt the transmission shifting curves to this concept. It is particularly effective to combine this tuning procedure with a loose converter (see next section). The following shifting curve graph approximates this philosophy (Figure 26).

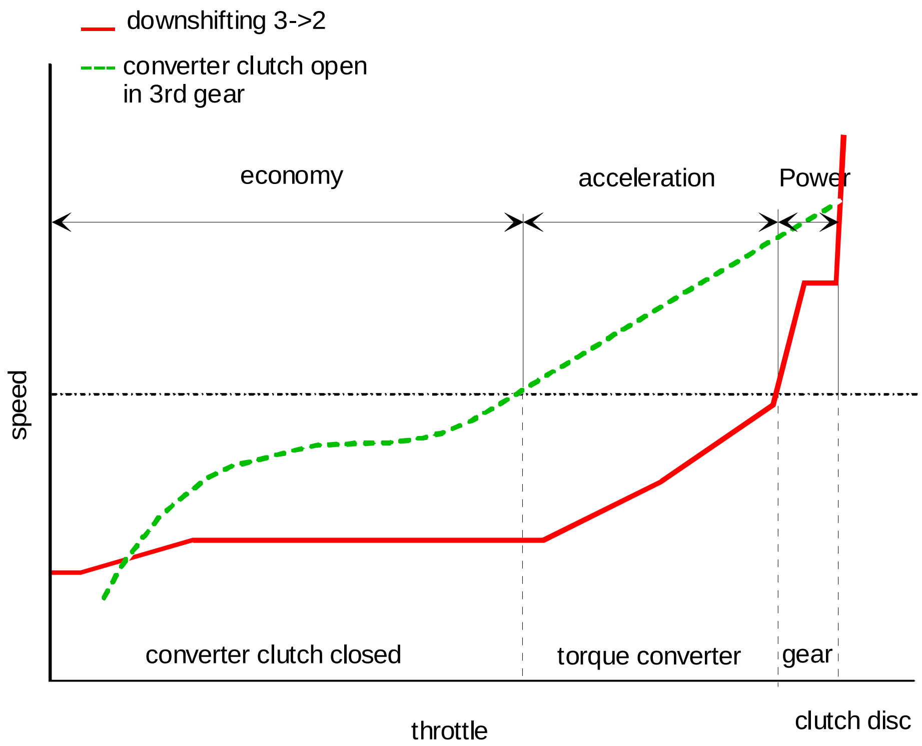


Figure 26: Control philosophy for the LuK TorCon System

Introducing slip, a conical design, the mini-damper and adaptive control strategy achieves considerable improvement in fuel consumption, but adding a loose converter results in even further improvement.

The Loose Converter

This presentation started with a reference to converter design. Because it is impossible to engage a TCC in all operating ranges of current transmission systems, the converter has to be stiff enough to ensure driving comfort. The TorCon concept makes it possible to utilize the advantages of the loose converter without having to accept its disadvantages. The advantages include improved tractive force and less power loss in the stationary vehicle. Introducing a continuous-operation torque converter clutch eliminates the disadvantages, which include higher losses under load over a wide driving range, as well as the poor power response.

This design also achieves other significant advantages (Figure 27).

Driving performance is significantly improved, as is fuel economy. Emissions are improved disproportionately: testing cycles begin with a cold phase, but with an open converter clutch and a loose converter, the engine reaches operating temperature more rapidly, which has a positive effect on emissions. **Despite these definite advantages, TorCon does not increase the system cost, weight or overall mass moment of inertia compared to the current production standard.**

Consumption : (EU Test) — **1,1 L/100km less**

Acceleration : (0 - 100 km/h) — **0,8 seconds better**

Exhaust emissions : — **11 ... 36% reduction**

Figure 27: Statistics for the TorCon System

A cost-effective solution with many advantages:

Combining the TorCon System with a 4-speed transmission

Combining the TorCon System with a 4-speed transmission achieves similar advantages with respect to driving performance and fuel consumption as can be achieved with a 5-speed transmission and a traditional torque converter clutch, but overall weight and costs are lower than with a 5-speed transmission (quite aside from development cost savings and investment for production capacity).

A tractive force curve shows that combining a loose converter with the wider gear ranges of the 4-speed transmission results in higher tractive force than with a 5-speed transmission and a traditional converter (Figure 28).

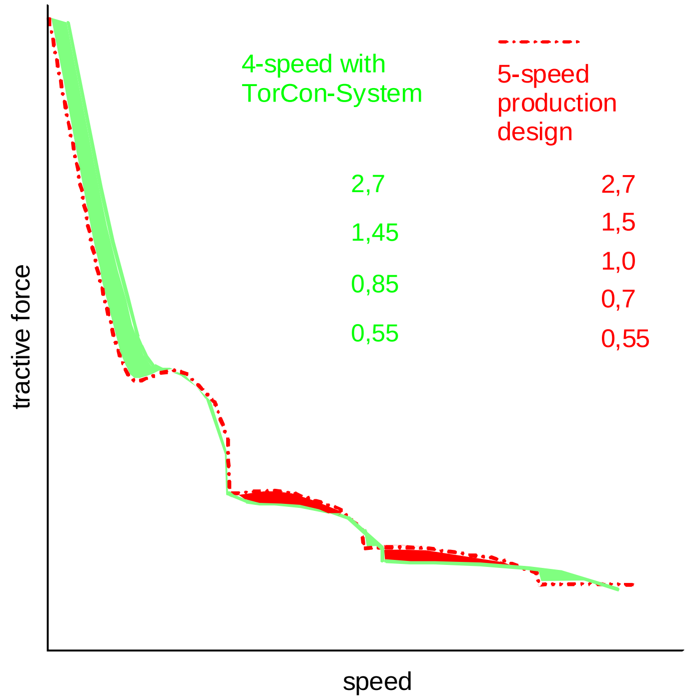


Figure 28: Full load tractive force curve for a 5-speed transmission with a conventional torque converter clutch and for a 4-speed transmission with the LuK TorCon System

The loose converter provides continuous compensation for the longer transmission gear ranges. The illustration also shows that the 5-speed transmission has to shift across two gear stages in the low-load range, whereas the 4-speed transmission with the TorCon System does not; this means that the system also reduces transmission shift frequency (Figure 29).

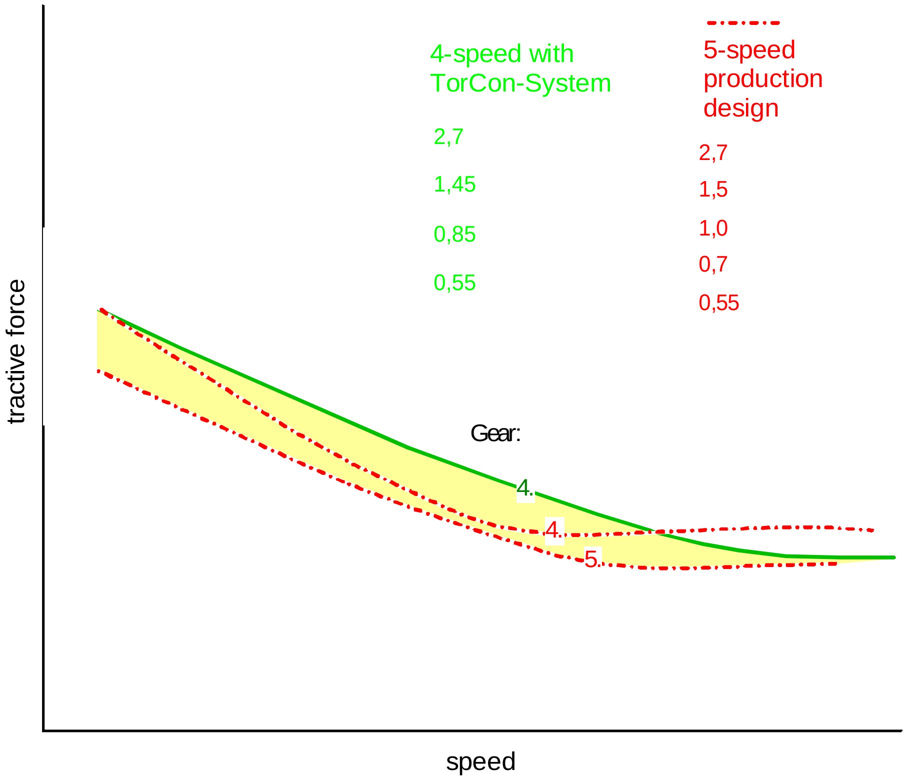
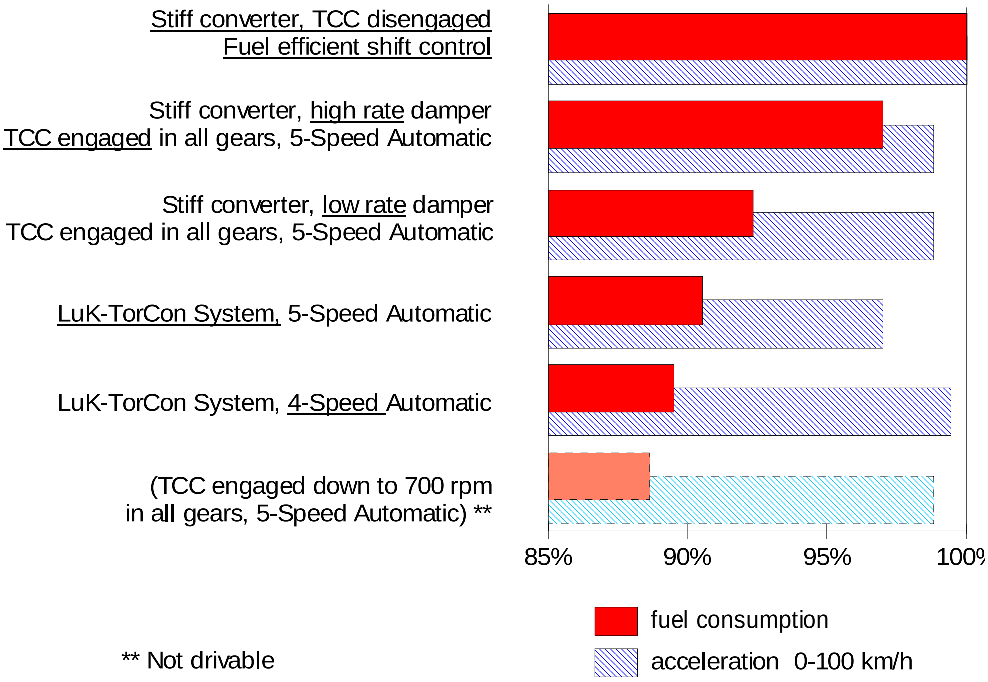


Figure 29: Partial load tractive force curve for a 5-speed transmission with a traditional torque converter clutch and for a 4-speed transmission with the LuK TorCon System

There is no great difference in acceleration from 0 to 100 km/h between conventional 4-speed and 5-speed transmissions because the transmission ratio in the lower gears is almost identical. Because of the loose converter design, the 4-speed transmission with the LuK TorCon System provide acceleration advantages in comparison to the conventional 5-speed transmission. A significant improvement in emissions is expected as well.

Summary:

As a system supplier, LuK provides a wide range of torque converter clutch solutions depending on the degree of integration the customer wants to achieve, whether these needs dictate a traditional torque converter clutch or a turbine damper, the TorCon System, or a TorCon with a 4-speed transmission. Figure 30 shows a final comparison of fuel consumption and acceleration criteria.



The high rate damper can be used down to 1600 rpm.

The low rate damper can be engaged starting with 1100 rpm. Option of turbine damper or conventional damper, depending on the drive train design.

The torque converter clutch is open during acceleration.

Figure 30: Comparison of various converter clutch systems

References

[1] VDI [Association of German Engineers] Report No. 1099 from the VDI-VW Joint Conference VDI-VW

[2] LuK Colloquium 1986, p. 5

[3] LuK internal report 047/94, H. Seebacher