Torque Control Isolation (TCI) The Smart Clutch

Dr.-Ing. **Albert Albers**

In recent years the main emphasis in the development of clutches and clutch discs has shifted more and more in the direction of the torsion damper [1, 2], as has been indicated by the previous presentations. This work is centered on drive train dynamics, with the goal of improving driving comfort with respect to:

- transmission noises (rattle)
- body boom
- tip-in/back-out performance (surging)

Developments in modern automotive engineering have contributed to the importance of this design trend as a result of

- reduced idle speeds to improve fuel efficiency
- more rapid combustion and higher engine torque output
- transmission designs that allow driving at low engine speeds with respect to the gear selected
- reduced weight designs
- traffic situations (traffic jams, stop & go traffic).

Conventional torsion dampers (as shown at the top of Figure 1) affect drive train dynamics only with respect to spring rate and hysteresis. The dual mass flywheel shifts the distribution of inertial masses in the drive train and allows further spring rate reductions. Application of these systems alters the parameters of the torsional vibration chain, but does not allow for any on-going adjustment in overall performance.

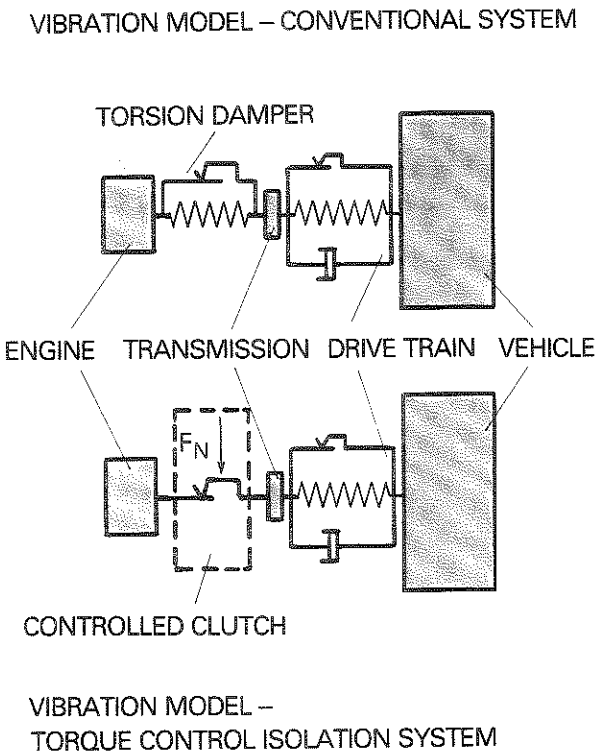
Another approach to affecting drive train dynamics returns us to the clutch itself. In a conventional system, the clutch represents a shiftable shaft connection that has no effect on performance during normal driving operation. Consequently, the clutch does not appear explicitly in either the model for the torsion damper or the model with the dual mass flywheel.

However, if we introduce the clutch with its transmitting parameters as an element in the vibration model, we completely alter the system. The clutch clamp load represents a constantly changing system variable that not only actively affects dynamic behavior, but which can actually be used to manage it [3, 4, 5, 11, 19].

In developing torque control isolation (TCI), LuK has created a total system in which an electronically controlled clutch has been designed to have an impact on overall dynamic drive train performance.

With TCI, LuK has succeeded in significantly improving two major areas:

- Original clutch actuation for start-up and shifting gears is automated, thus considerably increasing vehicle operating comfort. At the same time, the design improves driving safety because gear shifting procedures have been simplified considerably.
- Active control of dynamic drive train performance during vehicle operation, coupled with vibration isolation of torsional engine irregularities, considerably enhances driving comfort.


VIBRATION MODEL – CONVENTIONAL SYSTEM

VIBRATION MODEL –
TORQUE CONTROL ISOLATION SYSTEM

Figure 1:
Vibration models for vehicles with Torque Control Isolation

Drive Train Configuration in Vehicles with TCI
A Model of the Vibration System

The bottom section of Figure 1 shows the simplest vibration model for the vehicle drive train with TCI in comparison to the conventional model. Between the engine and the transmission inertias, we have now introduced a component that allows torque transmission via lock-up between the friction surfaces. The torque transmitted can be controlled by the clamp load. In this model, the entire drive train represents a controlled system. In order to develop an appropriate control strategy for this system – the entire drive train – it is necessary to determine and describe the controlled system mathematically, along with any possible disturbance variables. We will discuss a number of important basic relationships.

Force Transmission via Friction Surfaces
The Physical Principle

The most important component in this controlled system is the clutch with its friction surfaces. The friction phenomenon between two bodies manifests itself in two different forms:

- resistance to the maintenance of an existing relative movement between two bodies: dynamic friction
- resistance to the initiation of a relative movement of one body relative to another: static friction.

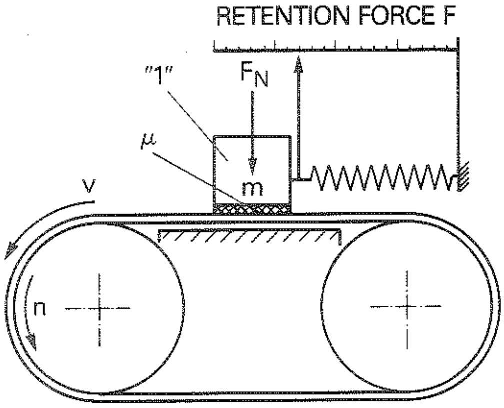


Figure 2:
Coulomb friction

$$F_R = \mu \cdot F_N$$

Figure 2 shows a simple model representing the relationships described here. Body 1 having the mass m rests with the weight F_N on a belt. The rollers can set the belt into motion. A spring holds Body 1 in place.

If the belt starts to move, Body 1 starts to move along with it, and the static friction force F_{RH} transmitted due to friction contact deflects the spring. According to Coulomb [6], the friction force is proportionate to the normal force exerted on the contact surface, that is:

$$F_{RH} \leq F_{R,o} = \mu_o \cdot F_N.$$

As soon as the retention force F reaches the maximum transferrable static friction force $F_{R,o}$, Body 1 cannot deflect the spring any further. Since the belt continues to move, a relative motion occurs between the belt and Body 1. The dynamic friction

$$F_R = \mu \cdot F_N$$

acts by the proportionate factor μ, which is the dynamic coefficient of friction.

If we assume that the static coefficient of friction μ_o and the dynamic coefficient of friction μ are equal and constant, then there is no difference between the forces F_{RH} and F_R. Given this assumption, Body 1 remains in the equilibrium position for the spring.

Increasing or decreasing the speed of the belt does not change the position of Body 1 because dynamic friction remains constant. A periodic motion, for example such as that produced by the irregularity of an internal combustion engine as described in Presentation 1, can be introduced at the belt drive without moving Body 1 from the equilibrium position it has assumed. Dynamic friction shields Body 1 from the irregular motion of the belt, that is, it constitutes a filter.

Of course, the friction coefficient μ is by no means a natural constant [6, 7, 8]. Among other factors, μ is a function of material mating characteristics, surface condition, unit pressure and also of the slip speed.

Slip speed variation assumes considerable importance for clutch control. Figure 3 shows basic possible curves for the dynamic coefficient of friction as a function of slip speed, differentiated according to:

- the constant friction characteristic, which corresponds to ideal Coulomb friction

- an increasing friction characteristic
- a decreasing friction characteristic.

As shown in Figure 3, if a periodically changing slip speed is introduced to the band drive for the model shown in Figure 2, it is apparent that Body 1 will remain in the equilibrium position only if the friction coefficient remains constant.

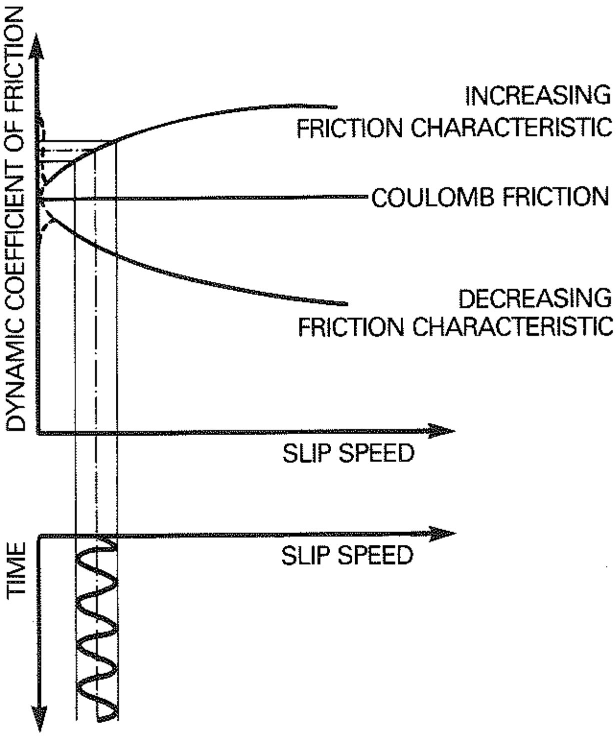


Figure 3:
Basic friction coefficient curves

Given a changing slip speed, the other two friction characteristics lead to different dynamic coefficients of friction and thus to changing transmitted friction forces. This also leads to different retention forces F. Consequently, Body 1 will move in accordance with the spring characteristic in order to achieve equilibrium positions. Hence the theoretical filter effect is not 100% effective. In fact, the decreasing friction characteristic can even lead to the excitation of natural vibrations in the vibration system consisting of "Body 1 + spring" [7, 8, 9].

The following presentation on "Chatter" will treat this topic in more detail. Frictional vibrations have a decisive impact on the development of a control system because they determine the stability limits of the control loop. Furthermore, the increasing friction characteristics combined with the response times and delay components present in every system can produce phase-excited instabilities in the controlled system. These factors must also be considered in designing the control strategy.

A simple model represents some of the most important characteristics of the controlled system for such a drive train with a friction clutch. If we represent the simplified linear system as the rotational vehicle drive train system, then the "belt" becomes the friction surfaces of the clutch and the flywheel. "Body 1" with the "retention spring" becomes the rest of the drive train, consisting of the clutch disc with its facings, the transmission and the vehicle, as well as the spring characteristics of the drive train (spring rate) (Figure 4).

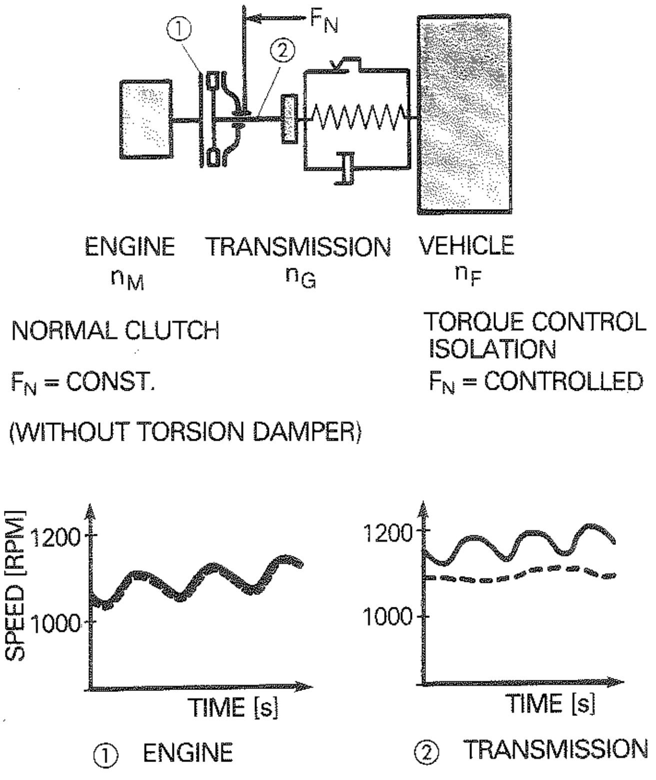


Figure 4:
The friction clutch as a vibration filter

The bottom section of Figure 4 shows two speed measurements. Measuring point 1 is located on the engine flywheel and measuring point 2 is located at the transmission input shaft. In a system with a "normal" clutch, the clamp load F_N is designed so that even the highest engine torque is transmitted due to static friction. In the measurement, it becomes clear that the periodic irregularity of the engine is completely transmitted to the transmission input and thus, for instance, excites gear rattle. When we use the LuK TCI as shown in the measurement on the right, the filter effect achieved becomes evident. The clutch is controlled so that the engine torque is transmitted with a defined relative movement, that is, sliding with a certain slip. In spite of the fact that the excitation remains identical on the engine side, virtually no irregularity occurs at the transmission input (measuring point 2) – the "slipping clutch" filter is doing its job. The difference between the average engine speed and the transmission input speed corresponds to the controlled slip.

LuK's Torque Control Isolation (TCI) In-Vehicle Realization

In order to turn the clutch into a "smart" clutch and to achieve the demonstrated filter effect in the vehicle, LuK has developed an electronic clutch control system as shown in the block diagram in Figure 5. The system consists of 4 major components:

- mechanical single-disc clutch as an actuator
- hydraulic power control of the actuator
- electronic microcomputer control
- sensor system.

The interaction of all four components must be carefully optimized in order to solve the problems associated with both

- automatic clutch operation and
- driving with torque control isolation.

A setpoint is selected in order to determine the torque to be transmitted by the responding actuator – the clutch. The 40 – 60 bar hydraulic system actuates the clutch via a servo cylinder controlled by a proportional valve. Figure 6 shows the most important components.

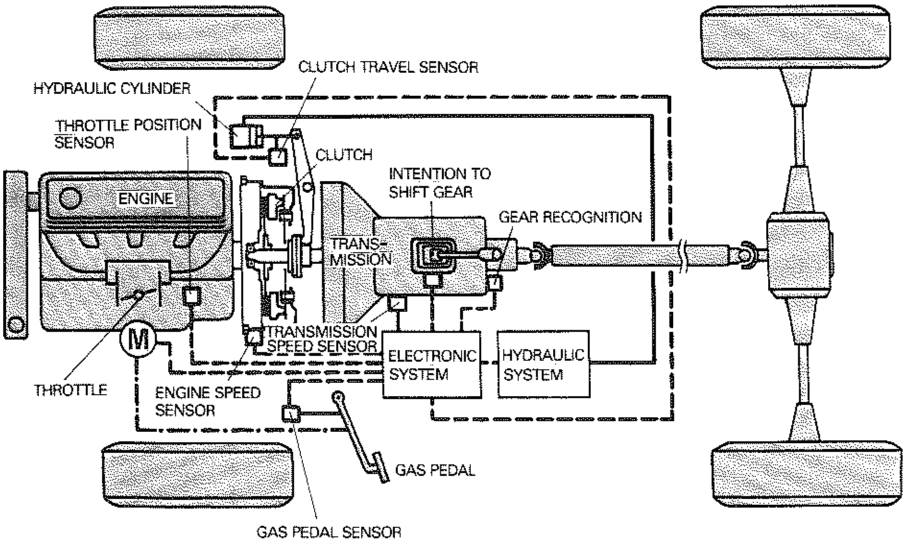


Figure 5: Electronic Torque Control Isolation TCI

A separate electric pump unit or – if available – the central vehicle hydraulic system provides the power supply (Figure 6). The electronic control system triggers the proportional valve [10]. The heart of the electronic control system is a microcomputer driven by a program containing the control algorithms and control strategy. The sensor system provides information to the microcomputer for determining system condition. The system includes sensors to register:

- clutch travel
- gear recognition
- recognition of the intention to shift gears
- engine speed
- transmission input speed
- gas pedal position
- throttle position.

LuK uses sensors that operate according to proven physical principles and that have been adapted to meet rugged vehicle performance requirements.

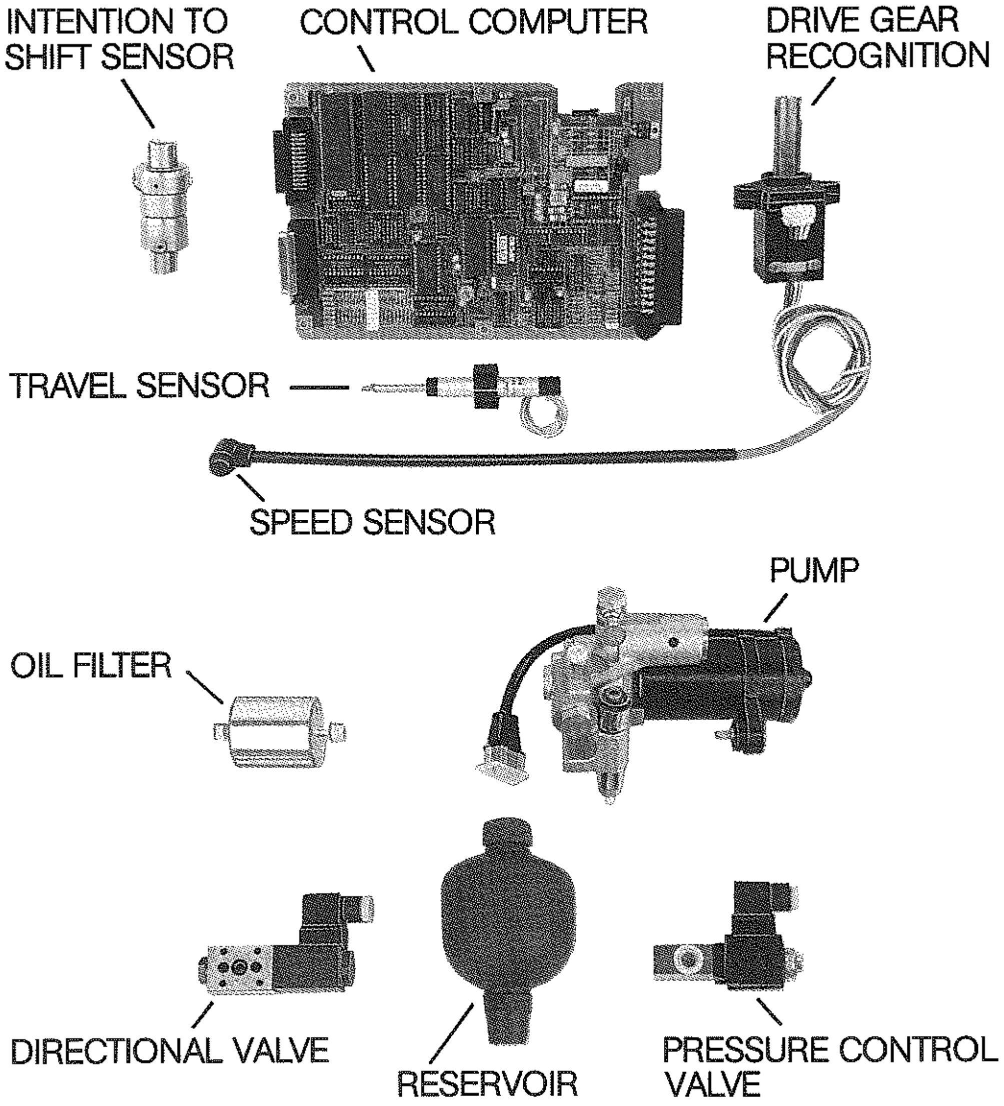


Figure 6: TCI-components

Figure 7 shows the design structure and the signal flow in the TCI system. The driver's senses constantly provide him with information on vehicle operating status. He bases his reactions on this information and responds to the vehicle via actuators – such as the steering wheel, shift lever, light switches, gas pedal and clutch pedal.

The vehicle then reacts to the driver's setpoint instructions. This internal control loop in the conventional vehicle is affected by various external conditions, which constitute disturbance variables – weather, road conditions, traffic situations, etc. The TCI system is superimposed on this conventional control loop.

Part of the information on the status of the actuators (clutch travel, gas pedal, throttle, shift lever) as well as on the current operating condition of the entire vehicle (engine rpm and transmission speed) is collected by the sensors and converted to be fed to a microcomputer.

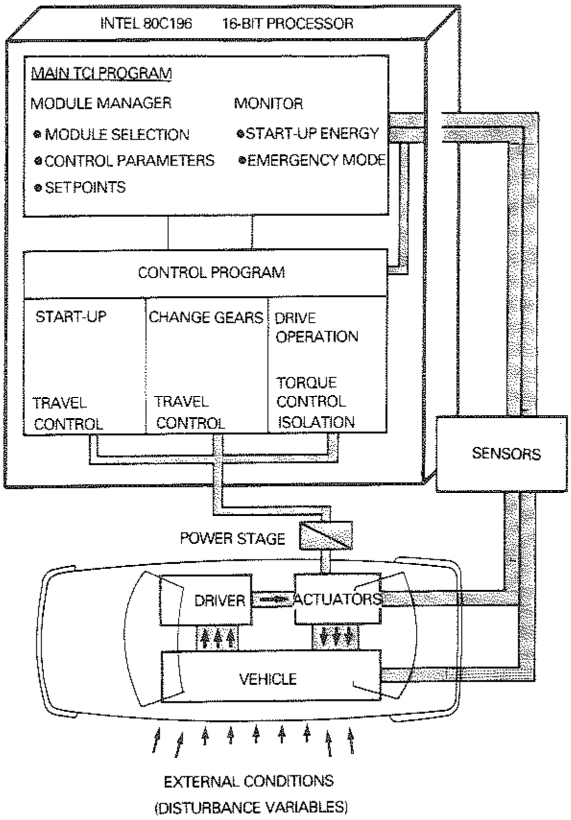


Figure 7:

Signal flow and software structure in TCI vehicle

This microcomputer is based on the INTEL 80C196 16-bit processor and uses a special software program to process the information collected from the sensors.

The software has been designed and developed according to strict modular criteria for structural programming in order to ensure maximum flexibility, universality, functional capability, reliability, and efficient data maintenance. Figure 7 illustrates the basic software structure. The TCI software is made up of the main program and the controller program. The module manager for the control program resides in the main program. Depending on the driving status recognized by the sensor system, the module manager activates the currently appropriate controller module. At the same time, the module manager transmits control setpoints and control parameters in order to actively adapt the controller to prevailing external conditions. Based on the actual sensor values, control parameters and setpoints are either calculated or read directly out of multi-dimensional fields. Parallel to this procedure, monitoring, diagnosis and emergency operation functions are also implemented in the appropriate software modules included in the main program.

The controller program consists of three main modules for:

- Stand-still and start-up
  (Idle mode, start engine, turn off engine, start-up vehicle, stop, start up on a grade ...)
- Changing gears
  (Disengage, engage, maximum speed monitoring)
- Drive operation
  (Drive, coast, maneuvering)

The first two main modules implement a travel control feature for the clutch travel and the third main module implements the slip control between the engine speed and the transmission speed [12]. The digital controller determines a setpoint and activates the hydraulic power stage, which consists of the proportional valve with the servo cylinder and responds by adjusting the clutch clamp load. So it is at the clutch that we are able to intervene in the controlled system represented by the vehicle, thus influencing the system.

The Torque Control Loop Design and Strategy

The three controller modules work together with the main program module manager to solve all the problems that occur in any given operating situation. The system simplifies start-up on a steep grade just as readily as maneuvering or shifting gears. The following discussion provides a brief description of the electronic control system for torque control operation during normal driving (Figure 8).

The block diagram for the control loop shows the controlled system – that is, the vehicle represented as a 3-mass model; the actuator; the slave cylinder and clutch; and the controller, represented by the box surrounded by a broken line. The system features cascade control with proportional, integral and differential components. [12, 13].

System sensors collect data for engine speed n_M and transmission speed n_G. Then the slip control loop (bottom of graph) first determines the actual slip n_S and compares it with the slip setpoint. Then the PI-controller corrects the slip variation Δn_S. In order to prevent the engine rpm from revving too high during tip-ins, the cascade control provides a feedback control for engine speed. In the case of a hard tip-in, this feedback of the engine peak causes the clutch to close more tightly. Additional features designed to improve controller characteristics include a differential element to provide feedback of the actual clutch travel value and a high order form filter.

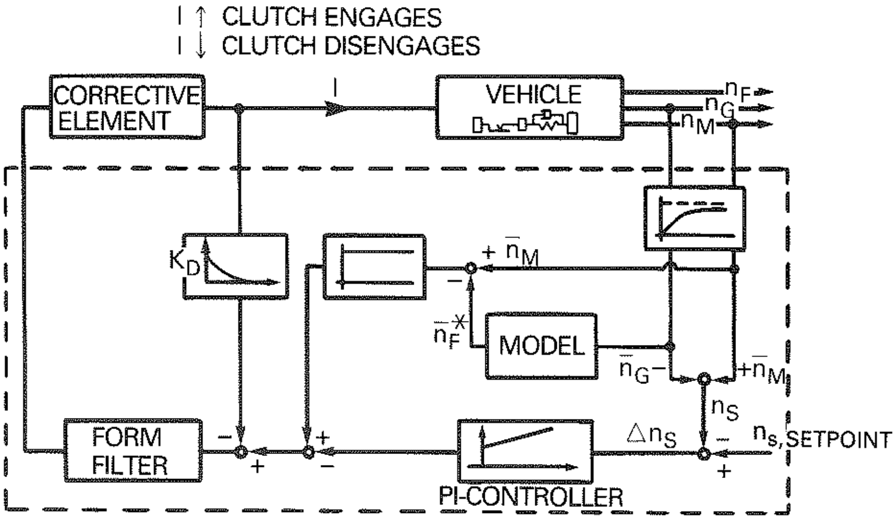


Figure 8: Electronic control loop during TCI operation (simplified)

Figure 9 shows the reaction of a vehicle equipped with TCI to a tip-in.

The top graph shows the engine and transmission speed curves, while the bottom section shows several system signals. The throttle valve is fully opened at Point (1). At first, the engine hesitates (2), but then builds up increasing torque and accelerates (3). From (1) to (3), the actual slip decreases significantly, so the controller opens the clutch. As the engine accelerates, the system recognizes the great increase in the engine speed and the engine speed feedback control quickly closes the clutch (3 – 4). The stronger coupling with the vehicle mass causes the engine to brake again (4 – 6). The clutch opens. At this point, the PI controller corrects the slip deviation (6 – 7).

This example illustrates the way the control system operates. The overall TCI system is highly flexible and features numerous parameters that can be used to adjust the system to prevailing vehicle conditions. Individual tuning is always required. No universal "off-the-shelf" solution can completely realize the full potential of the TCI system.

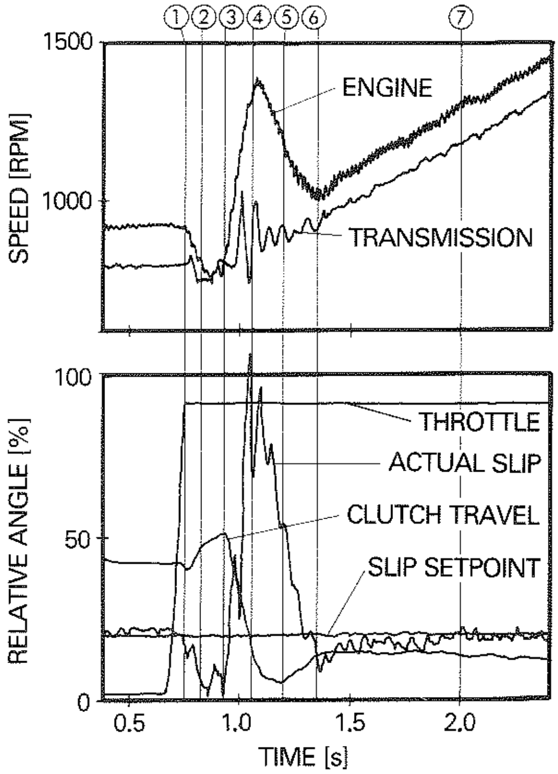


Figure 9:

Control performance during acceleration

TCI on the Road
Torque Control for Improved Comfort

The following illustrations show measurements taken in a TCI vehicle and are designed to demonstrate the practical advantages offered by the "smart" clutch system. Figure 10 shows a measurement taken in drive mode. The left side of each graph represents a rigid clutch disc, and the right side shows the measurement taken with an active TCI system. The upper section of both graphs shows engine and transmission speed, while noise measurements and subjective ratings are entered in the bottom sections.

During drive mode measurement, speed increases continuously as a function of time. Magnified sections demonstrate rigid performance without TCI (transmission and engine speed are identical). With TCI, the difference between the engine and the transmission speeds reflect the actual slip. Without TCI, a clear maximum noise with a rating of 3 – 4 occurs until about 15 sec., that is 2,000 rpm. With active TCI, the rating is 9 throughout the entire speed range covered. The increase in the noise signal with increasing engine speed can be explained by vehicle rollover noises at higher speeds and therefore cannot be influenced.

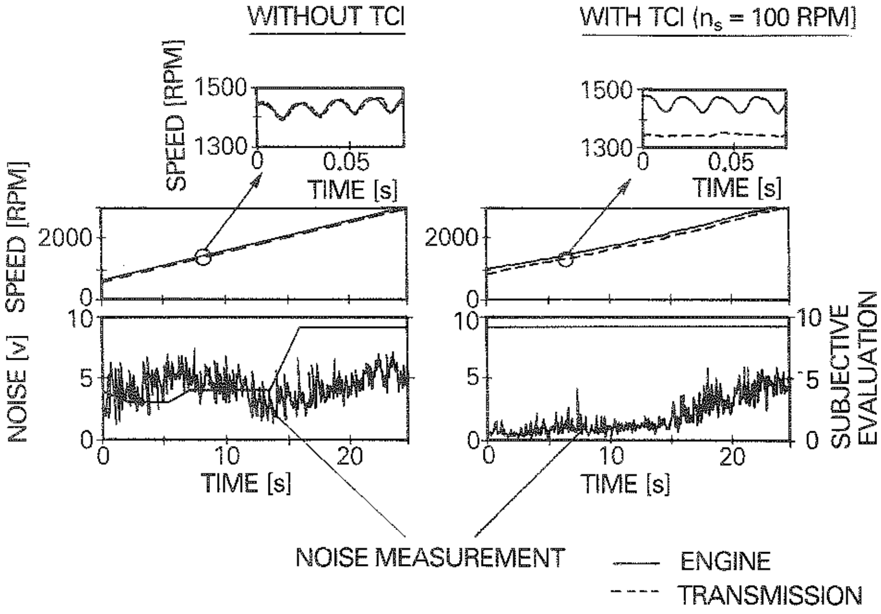


Figure 10: Effect of Torque Control Isolation on noise-related comfort factors in drive mode, 4th gear

The measurements shown in Figure 11 for coast mode without TCI show a typical noise peak in the higher speed range (in this case after 15 sec. at about 3,000 rpm). This maximum value is associated with rollover noise, which is reduced proportionate to the decreasing engine speed. It is reflected in the subjective rating, which falls to 4. With the active TCI system, this gear rattle does not occur, which yields a subjective noise rating of 9 over the entire vehicle speed range.

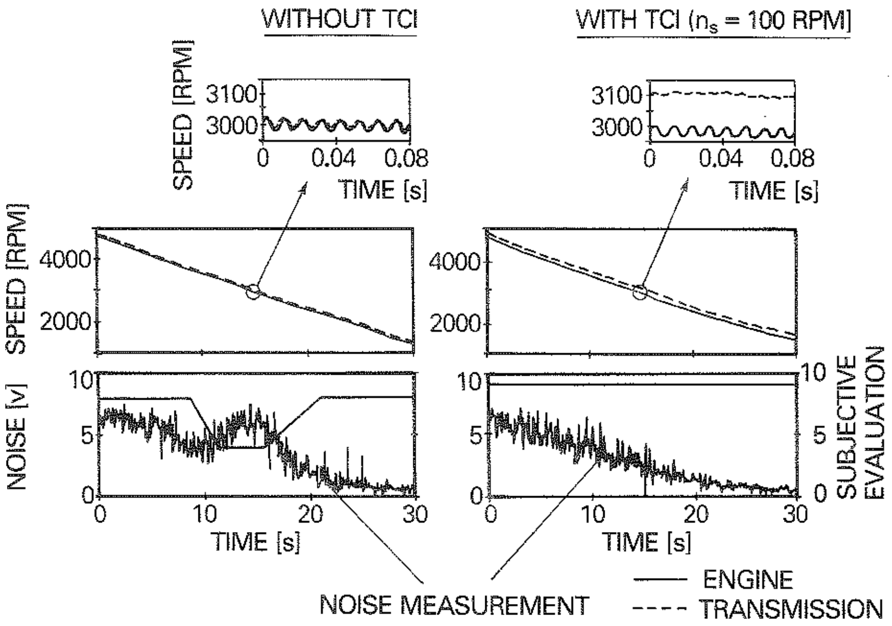


Figure 11: Effect of Torque Control Isolation on noise-related comfort factors in coast mode, 3rd gear

The last two figures show the filter effect of the TCI system on high frequency vibrations that can lead to gear rattle and body boom. However, the TCI system provides vibration isolation down to very low frequencies, which enables us to counteract low-frequency phenomena such as surging and tip-in/back-out jerk.

Figure 12 shows an example of measurements taken for tip-in/back out behavior in second gear.

The lower graph shows the fore-aft acceleration measured in the vehicle at driver head height.

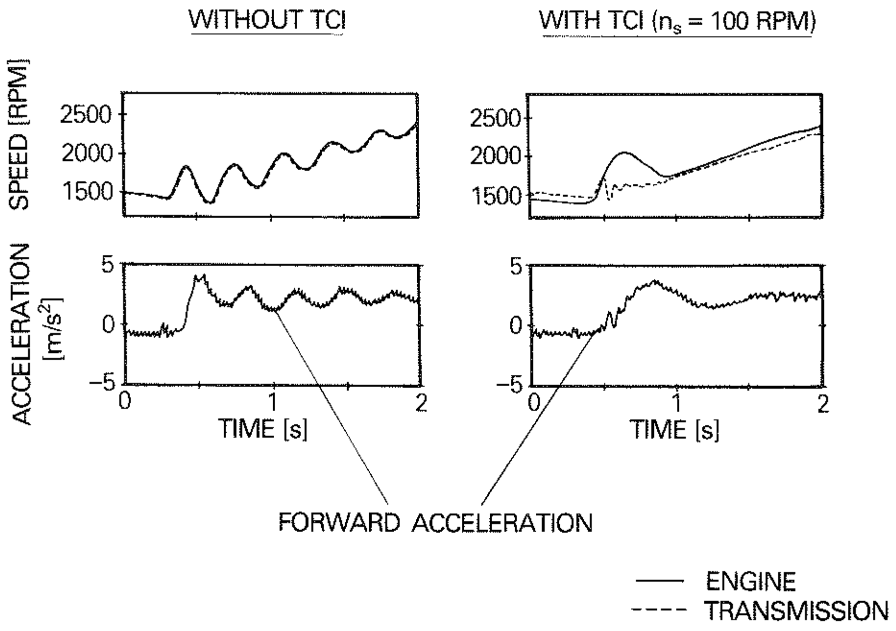


Figure 12: Improvement in tip-in/back-out performance in 2nd gear using TCI

Without TCI, the broad-band excitation occurring after rapid acceleration excites the vehicle to natural vibrations in the first natural mode of the system. The driver perceives these vibrations as "surging" in the vehicle. When the TCI system is activated, this surging no longer occurs.

The fore-aft acceleration peak occurs only as a result of the increased available engine torque in the higher speed range and the utilization of kinetic energy during the braking of the engine inertia. Neither the engine speed peak nor the initial low frequency acceleration peak are perceived as negative in an optimally tuned vehicle.

The following measurements illustrate another important positive effect of the TCI system (Figure 13). After short tip-ins in the rolling vehicle (for instance, stop-and-go traffic, creeping), the vehicle exhibited self-induced, escalating surge vibrations in the first natural mode . This leads to extremely unpleasant vehicle reactions (jerky ride). This phenomenon disappears entirely when TCI is activated.

These few examples have demonstrated TCI's ability to increase driving comfort.

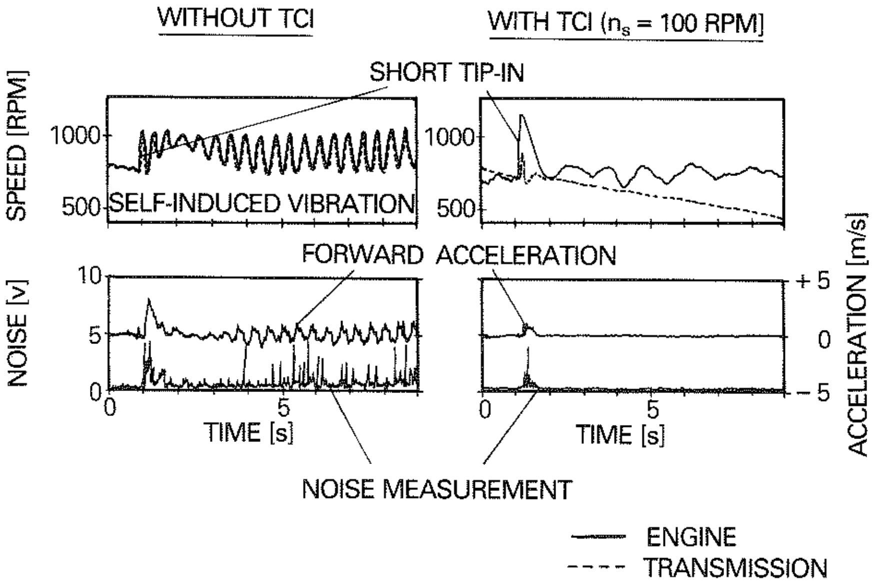
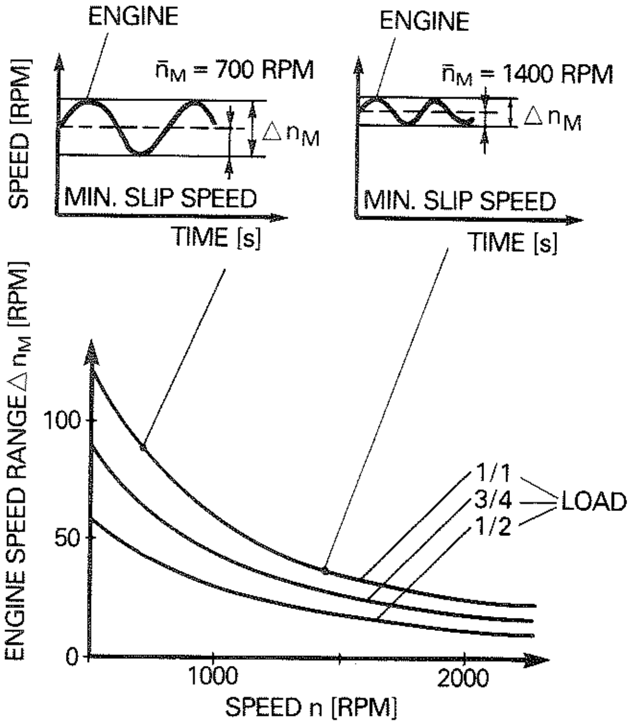


Figure 13: Eliminating self-induced drive train vibrations (tip-in, 2nd gear) using TCI

Combining TCI with Conventional Torsion Dampers Minimizing Required Slip

As with torque converters, the positive effects achieved using torque control isolation have a downside – there is some power loss due to the inherent slip in the system. The design objective must be to keep this slip as low as possible.

In general, the amount of slip must always be greater than the amplitude of the engine irregularity Δn_{mot} (Figure 14). In internal combustion engines, torsional irregularity is strongly dependent on speed and load (Figure 14, top). Consequently, a torque control isolation system must provide a flexible method for specifying the slip setpoint. LuK's TCI concept stores slip setpoint values in multi-dimensional fields as a function of speed, load and the selected gear (other parameters can be accounted for).



FOR OPTIMUM VIBRATION ISOLATION
SLIP SPEED > 0.5 × ENGINE SPEED RANGE Δn_M

Figure 14:
Required slip setpoint

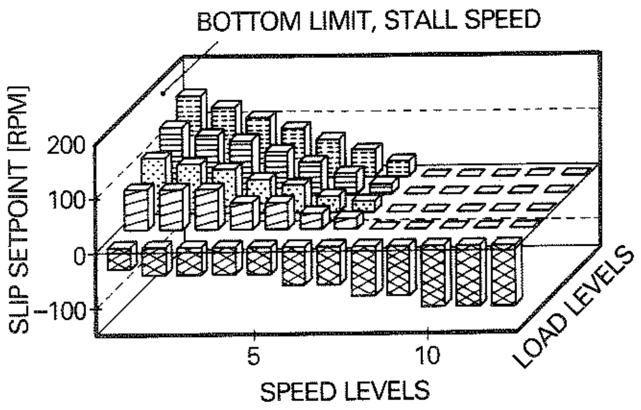
Figure 15 shows one possible slip setpoint field for one gear.

For this purpose, the engine speed range is divided into 12 speed levels and 4 load levels (throttle settings). These ranges can be defined as freely as desired. During vehicle tuning, the slip setpoint is determined using the following criteria:

- vibration isolation
- minimization of energy dissipation.

The effect of different slip setpoints can be studied in Figure 16.

The center column shows the noise measurements recorded as a function of speed. The right column for each row indicates engine and transmission speed curves in the 1,100 rpm range. For the engine speed range under 2,200 rpm, noise performance first increases with increasing slip, but then remains stable above 50 rpm. For engine speeds over 2,200 rpm, a rigid clutch disc without the TCI system rated a "9". Obviously, as shown in Figure 15, we can reduce the slip setpoint to "0".



LOAD LEVELS (E. G. THROTTLE VALVE ANGLE)
▨ COAST ▭ 0 ▦ 1 ▤ 2 ▦ 3

TUNING FOR EACH GEAR

Figure 15:

Specification of slip setpoint for TCI

CRITERIA FOR OPTIMIZATION
- ● VIBRATION ISOLATION
- ● MINIMIZATION OF DISSIPATED ENERGY

If necessary, the TCI system can also be combined with a conventional torsion damper. Figure 17 shows the main relationships for gear rattle.

The graph shows the ratio of the amplitude of the irregularity between the engine output and the transmission input as a function of engine speed. The spring rate defined in the torsion damper and the torsional inertias of the drive train determine the resonance speed.

At this speed, low damping (that is, Coulomb friction in the torsion damper), causes high peak vibration amplitudes at the transmission input. However, a good isolation effect is achieved in the driving range above natural frequency. It is possible to reduce resonance peaks by increasing torsion damper damping, but this is achieved at the cost of isolation above natural frequency. The TCI system provides satisfactory isolation

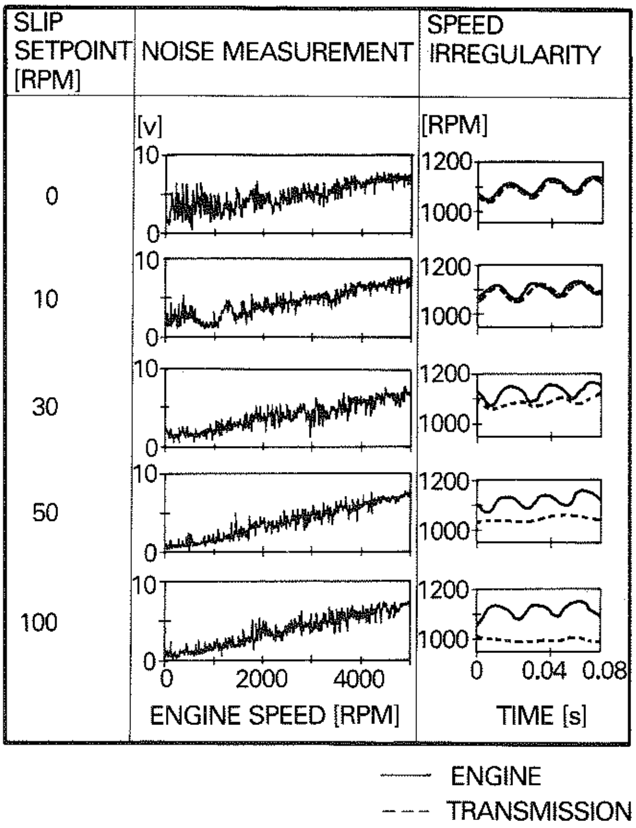
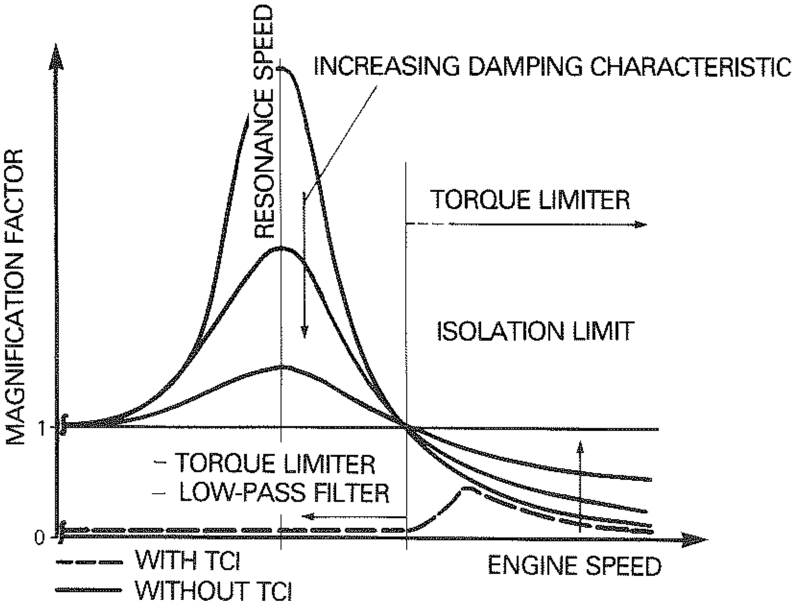


Figure 16:

Effects of the slip setpoint on noise behavior in drive mode (2nd gear)

Figure 17:

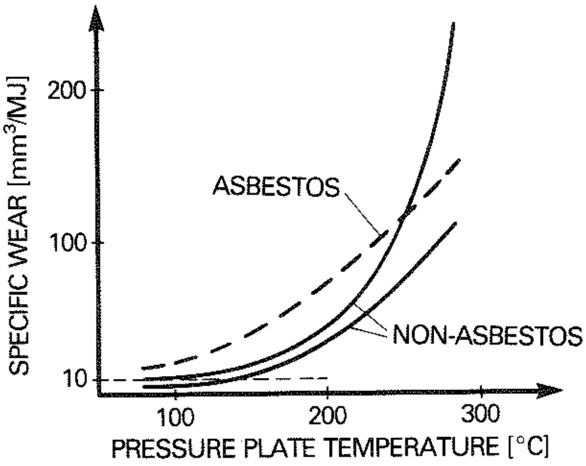
Performance of a vehicle with torsion damper with or without TCI



throughout those speed ranges where it is possible to drive with adequate slip. If we combine both systems, then it is possible to drive with slip in the lower speed range only, while a conventional torsion damper with low damping affords the necessary degree of isolation without introducing slip. In this way, we are able to reduce the overall amount of slip. Of course, it is necessary to carefully tune both systems to each other.

Friction Facings
Wear Performance and Requirements

The slip actually achieved, that is, the energy converted into heat, is not only important for the efficiency, but also for the wear of the friction facings.



EXAMPLE:

AVERAGE SLIP PERFORMANCE (SLIP UP TO 2000 RPM) : 0.50 KW

AVERAGE CLUTCH LOAD FOR START-UP AND SHIFTING GEARS : 0.25 KW

SPECIFIC WEAR : $10 \frac{mm^3}{MJ}$

OPERATING TIME IN SPEED RANGE WITH SLIP (UP TO 2000 RPM) : 1850 h

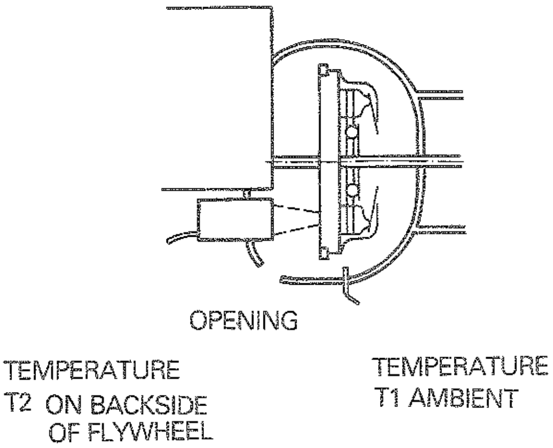
Figure 18:

Estimating facing service life

Figure 18 shows specific wear as a function of the operating temperature for several facings. The advantage of non-asbestos friction facings with respect to wear in the low and average temperature ranges is clear to see. It becomes evident that continued high temperature operation must be avoided.

Vehicle measurements provide information on the overall thermal situation. Figure 19 shows an example of measured results for Autobahn driving in 5th gear at a speed of 70 mph (corresponds to about 3,000 rpm). Operating temperature increases with increasing slip and can be lowered considerably by ventilating the clutch housing (for instance with openings).

The necessary slip speed decreases with increasing engine speed, as shown in Figure 14. However, at the same time, the engine torque increases. If we also take into consideration the fact that the slip speed setpoint cannot be fully adjusted to engine irregularity because of possible control variations, the required dissipation of slip speed often remains nearly constant, varying only with respect to the load level (throttle valve position).



SLIP	CLOSED BELL-HOUSING		OPEN BELL-HOUSING	
[U/min]	T1 [°C]	T2 [°C]	T1 [°C]	T2 [°C]
0	70	90	68	75
50	85	110	72	88
100	110	145	90	120

AUTOBAHN, 5TH GEAR 110 – 120 km/h (∼ 2800 U/min)

Figure 19:

Temperature measurement in the vehicle

For the compact cars discussed here,

P_{Slip}, 1/1 $\approx$ 0.8 kW   1/1 load
P_{Slip}, 3/4 $\approx$ 0.4 kW   3/4 load
P_{Slip}, 1/2 $\approx$ 0.3 kW   1/2 load

If we can assume more or less equal incidence of the three load levels during normal driving operation, then we arrive at an average slip performance of:

$$P_{Slip} = 0.5 \text{ kW}$$

In order to account for average clutch stress due to shifting and start-up procedures, we can assume that total driving time is made up of three more or less equivalent components, city traffic, country roads, and Autobahn driving:

$$P_{Slip+start\text{-}up} \approx 0.25 \text{ kW}$$

Given specific facing wear of 10 mm^3/MJ, a wear reserve of 1 mm and a facing surface of 25,000 mm^2, this assumption yields a total operating hour value of

$$Th = 1{,}850 \text{ h}$$

in the speed range up to 2,000 rpm.

Given an average total number of vehicle operating hours of 3,000, about 60% could be driven in the speed range under 2,000 rpm [16, 17, 18].

Even if the increased comfort afforded by the TCI system increases the proportionate amount of time spent driving at lower rpms by 10% in comparison to current figures, we would still not reach the service life limits for the friction facings.

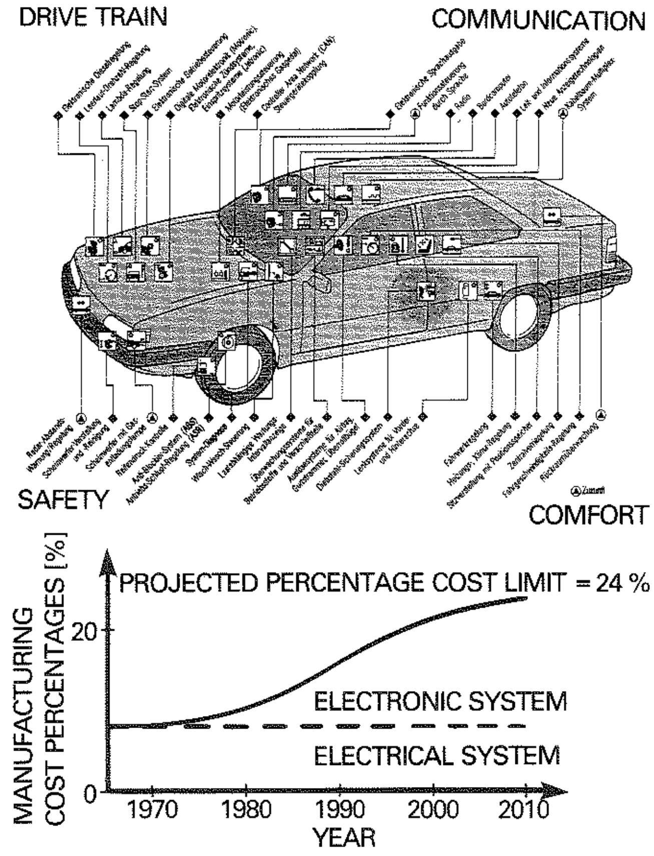
Extensive testing of facing characteristics is required to guarantee safe, properly dimensioned friction facing selection for use with a TCI system. The most important factors involved in this testing procedure include:
- the influence of slip speed on the friction coefficient
- wear performance
- long-term stability of the friction coefficient.

LuK performs these tests on specially designed test stands. The following presentation will discuss these tests in more detail.

Summary

The development of future automobile generations will be increasingly characterized by the introduction of new electronic systems (Figure 20) [20, 21].

By this point in time, there aren't any components left in the modern motor vehicle whose properties will not be optimized using electronics. This trend is by no means limited to clutches.



SOURCE: VDI REPORT G12

Figure 20:
Electronical and electrical systems in automotive engineering

The preceding presentation has introduced you to the LuK torque control isolation system (TCI). Optimized conventional mechanical clutch technology combined with flexible modern electronics and sensor systems have produced a new kind of solution to drive train problems. The most important improvements achieved here include:

- start-up without using the clutch pedal
- problem-free start-up on a grade
- no stalling
- shifting gears without manual clutch operation
- shifting without letting up on the gas
- increased driving safety thanks to simplified shifting cycles
- no idle mode rattle
- reduced idle speed
- no drive and coast rattle
- strongly reduced body boom
- torque limiter function
- no bucking bronco effect
- meaningful enhancement of ABS and ASR
- energy savings by virtue of free-wheeling function.

LuK's TCI system promises considerable improvement in both driving comfort and driving safety in order to ensure your share of the motor vehicle market of the future.

Bibliography

[1] Schöpf, H.-J., Jürgens, G. and Fischer, R.
Optimierung der Komforteigenschaften des Triebstranges von Mercedes-Benz-Fahrzeugen mit Schaltgetriebe [Optimization of Comfort Characteristics in the Drive Train of Mercedes-Benz Vehicles with Manual Transmissions], Automobiltechnische Zeitschrift 91 (1989), p. 568 – 575

[2] Jürgens, G. and Fischer, R.
Vergleich verschiedener Systeme zur Verringerung von Triebstrangschwingungen [Comparison of Various Systems for Reducing Drive Train Vibrations], VDI-Berichte Nr. 697 (1988), p. 233

[3] Lutz, O.
Kupplungsmanagement – ein Baustein zur Drehschwingungsdämpfung [Clutch Management for Damping Torsional Vibrations], VDI-Berichte 697, 1988, p. 219

[4] Winkelmann, S. and Harmuth, H.
Schaltbare Reibkupplungen [Shiftable Friction Clutches], Springer, Berlin 1985

[5] Nagler, F. and Westerdorf, H.
Regelstrategien für Trockenkupplungen [Control Strategies for Dry Friction Clutches], 2nd Aachener Symposium, Vehicle and Engine Engineering '89, p. 588 – 607

[6] Coulomb, C. A.
Théorie des machines simples, en ayant égard au frottement de leurs parties et à la raideur des cordages [The Theory of Simple Machines with Regard to Friction between Their Parts and the Stiffness of Ropes], Bachellier, Paris, 1821

[7] Krause, H. and Poll, G.
Mechanik der Festkörperreibung [The Mechanics of Friction between Solid Bodies], VDI-Verlag, Düsseldorf, 1980

[8] Kayaba, T. and Kato, K.
Theoretical Representation of the Coefficient of Friction for Multiple Contact Points, Wear, 52 (1979), P. 117 – 132

[9] Niemann, G. and Ehrlenspiel, K.
Anlaufreibung und Stick-slip bei Gleitpaarungen [Start-up Friction and Stick-slip due to Sliding], VDI-Zeitschrift, Vol. 105, No. 8, p. 221 – 284, 1963

[10] Runge, W.
Simulation des dynamischen Verhaltens elektrohydraulischer Schaltungen [Simulation of the Dynamic Performance of Electro-hydraulic Circuits], Springer, Berlin, Heidelberg, New York (1984)

[11] Zimmermann, F.; Oetting, H., Heidemeyer, P. and Haack, R.
An Automatic Dry Friction Clutch for Passenger Cars and Light Duty Trucks, SAE-Paper 860383

[12] Böcher, J., Hartmann, I. and Zwanzig, Ch.
Nichtlineare und adaptive Regelsysteme [Non-linear and Adaptive Control Systems], Springer, Berlin, Heidelberg, New York

[13] Braess, H.-H.
Steuerung und Regelung im Kraftfahrzeug – Eine systematische Betrachtung [Open and Closed Loop Control in Motor Vehicles – A Systematic Approach], VDI-Berichte 612 (1986), p. 539

[14] Seyboldt, H.
Ein Verfahren zur Ermittlung der Auslegung einer Kraftfahrzeug-Schaltkupplung [A Procedure for Designing a Vehicle Clutch], Automobiltechnische Zeitschrift 83 (1981) 7/8, p. 355 – 358

[15] Krause, H. and Christ, E.
Kontaktflächentemperatur bei technisch trockener Reibung und deren Messung [Contact Surface Temperature for Technically Dry Friction and Its Measurement], VDI-Zeitschrift 118 (1976), no. 11, p. 517 – 524

[16] Kraftfahrtechnisches Taschenbuch [Automotive Handbook], Bosch, 20th Edition

[17] Reicher, H.
Dimensionierung von Reibkupplungen nach der zulässigen Wärmebelastung [Designing Friction Clutches Based on Permissible Thermal Stress], Antriebstechnik 13 (1974), No. 12, p. 673 – 678

[18] Bausch, E.
Grenzen der Schaltbarkeit an Reibelementen von Kupplungen und Bremsen [Shiftability Limitations in Friction Elements of Clutches and Brakes], Antriebstechnik 18 (1978), No. 7 – 8, p. 367 – 370

[19] Soong, T-T. and Natke, H.G.
Von der aktiven Schwingungsbeeinflussung zur aktiven Struktur [From Active Vibration Control to Active Structures], VDI-Berichte 697 (1988), p. 1 – 38

[20] Hofmann, R.
Unterm Blech regiert der Chip [The Microchip Calls the Shots under the Hood], VDI-Nachrichten, No. 40, 6 Oct 1989, p. 42

[21] Ehlers, E.
Automobilelektronik – Start gelungen, wie geht es weiter?
[Automotive Electronics – We're Off to a Good Start, Where Do We Go from Here?],
VDI-Berichte 612 (1986), p. 547