Transmission Systems: A Comparative View

Dipl.-Ing. **Gunter Jürgens**

Introduction

Automatic transmissions have taken over in the USA and Japan, where they account for between 75 and 85% of the market. There are several reasons why this trend toward increased automation in the power train is to be expected in Europe. The automobile is becoming more and more just a means to an end - it is used to get from Point A to Point B comfortably and little operating effort possible. The "fun of driving" frequently disappears into the traffic gridlock, and more or less perfect clutch and shift lever operation becomes just another annoyance. Stringent exhaust and noise regulations require that vehicles be run at the optimum operating point - for instance during the warm-up phase. Without automatic gear selection, driver action could very well negate pollution control features.

Modern automatic transmission designs can compete with manual transmissions in fuel consumption and driving performance. The added cost is in the price range of a good car radio. The advantages of more relaxed driving and the world-wide statistics indicating fewer accidents with automatic transmissions should not be underrated.

This presentation will focus on several options for automating the power train, starting with the manual shift transmission equipped with an automated clutch and concluding with a look at continuously variable transmissions.

For purposes of comparison, these examples are all based on a vehicle with a 3 L engine because either production or prototype models of all the various automatic systems exist for this vehicle class. This comparison will include the following features:

- cost
- weight
- space required
- comfort
- fuel consumption
- driving performance

First, the transmission to be compared will be described.

5-speed manual transmission with an automated clutch (MT)

Figure 1 shows the outline of a manual transmission together with critical installation data.

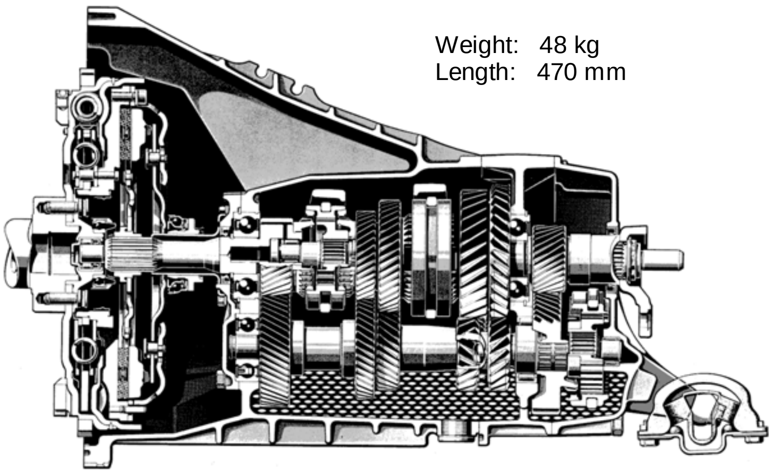

Figure 1: 5-speed manual transmission (MT)

The transmission is very compact and weighs only 48 kg, including the dual mass flywheel and the shift linkage. Figure 2 shows transmission losses in 1st and 5th gear as efficiency under street load [1].

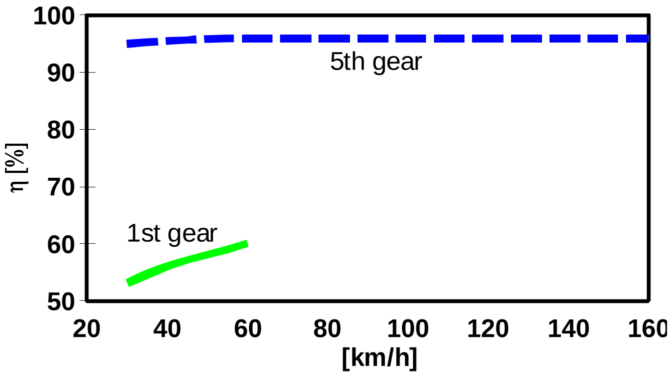

Figure 2: Efficiency under partial load

Losses for other gears range proportionately between these two values. Losses that are incurred as the result of electronic clutch management and slip strategies will be explained later when fuel consumption is compared.

These discussions will also account for the efficiency of the electrical drive and the battery.

The overall space required (including the clutch actuation system) is considerably less than for the automatic transmissions discussed later. Only the actuator - with the electonics incorporated - requires space in addition to the normally very compact manual transmission. The transmission has a total drive ratio range of 4.82.

This value is typical for the Power-to-weight ratio of the vehicle class treated in this study. It is not necessary to increase the transmission ratio for 1st gear (underdrive) because of the need to avoid exceeding the tire adhesion limit, and the ratio in 5th gear (overdrive) must not be too low because of acceptance problems with respect to acceleration capability in top gear. Consequently, there are logical limits to the drive ratio range [2, 3]. Even most 6-gear manual transmissions have drive ratio ranges of between 4 and 5.

Additional costs for automated clutch systems, including the flywheel and the gear-shift mechanism, currently lie in the range of 25 to 30% of base transmission costs.

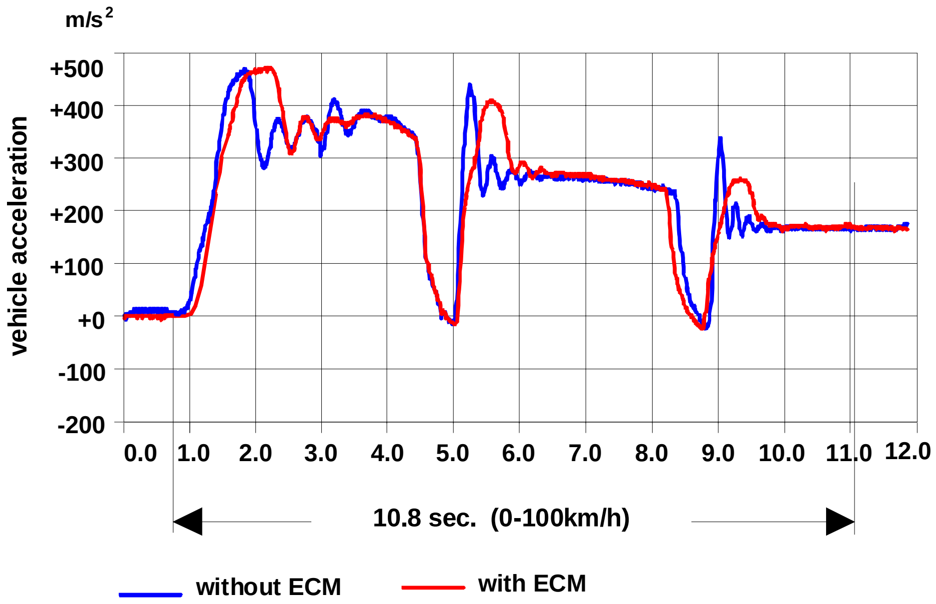

Figure 3: Comfort comparison for start-up (0 - 100 km/h)

Comfort during start-up and gear change is clearly improved for an average driver , as shown in Figure 3.

This figure compares acceleration under full load from 0 to 100 km/h for systems with and without ECM. The acceleration curve is a good indication of comfort. High acceleration peaks with resonant decay phases decrease comfort with non-automated clutches.

With automated clutch management, even inexperienced drivers shifting gears in the partial load range can achieve the same shift quality as with a modern multi-ratio automatic transmission.

Tip-in/back-out performance in engaged condition is often a critical point for power trains with manual transmissions. Figure 4 shows the potential that can be achieved with a good software strategy even without high clutch slip.

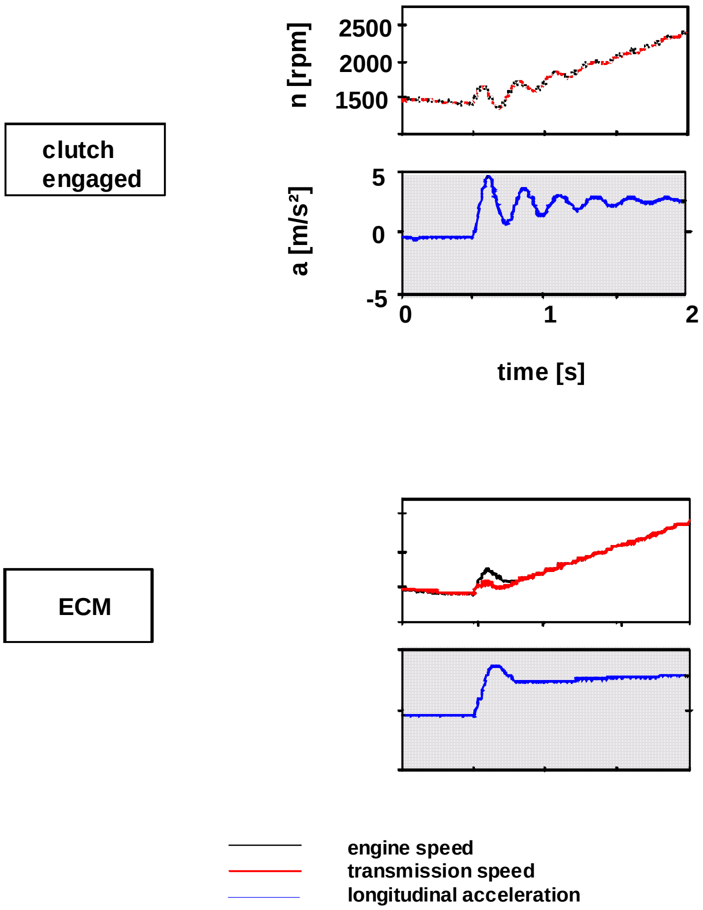

Figure 4: Tip-in/back-out performance with and without ECM

Automatic transmissions

When designers automate the clutch engagement process, it is obvious to think about automating gear shifting itself.

This solution is already in production for commercial vehicles, which often have more than 10 gears. Because conventional automatic transmissions with planetary gears would be very expensive and complex to build, designers have equipped the shift linkage in these systems with either semi- or fully automatic servo system operation. The additional expense of these systems, even for transmissions with up to 16 gears, is within an acceptable range when compared to what it would cost for a conventional fully automatic transmission. Shifting gears is, however, not fully automatic; the driver decides based on his own judgement or a shift indicator whether to up or downshift. The driver pushes a shift level in the desired direction to shift up or down; it isn't necessary to select the appropriate gear slot.

The interruption of tractive force - resulting from the clutch disengagement required to shift gears - occurs when the driver initiates the shift command and is prevented from occuring at an unwanted moment, which could occur with a fully automated system.

Although the additional expense for fully automatic as opposed to semi-automatic, demand-activated transmissions is quite minimal, the interruption of tractive force could, however, be one reason why no automated power-shift transmission has ever been introduced for production commercial vehicles.

Regardless of whether gear shifting is achieved using a servo cylinder or a stepped shifting mechanism, strategies need to be developed for engaging any gear under any circumstances. Because torque transfer in the synchromesh gearset is achieved using gear teeth, i.e. via positive contact, it is possible for the gear teeth to be touching at the moment the driver decides to engage gears. Under these conditions, it is impossible to complete the shifting operation without an additional adjustment to the system. This occurs sometimes with manual transmissions - particularly in first gear and reverse - and can, for instance, make it necessary to circumvent this problem by rotating the shafts another turn by reengaging the clutch in the neutral slot.

When only a few gears are involved, it costs almost as much to add an automatic gear selection feature as it does to introduce a fully automatic transmission, so this option has very little chance of establishing a market position. Although this design offers some slight fuel savings, in comparison to a fully automatic transmission, these savings are outweighed by the decreased shifting ease due to the interruption of tractive force.

Dual Clutch Transmission

Some of the problems cited above, such as the interruption of tractive force, can be circumvented with dual clutch transmissions. The main feature of these transmissions is that they actually consist of two intermeshed transmissions linked to a single output shaft. Each transmission has its own clutch.

The desired transmission ratio is selected by engaging the usual synchronizer in either sub-transmission 1 or subtransmission 2. It is possible to shift from one transmission to the other without interrupting the tractive force. If handled skillfully, controlled shift selection can be introduced virtually without disadvantages. For more than 5 gears, this transmission principle is equal to a planetary gear transmission. One of the two power shift clutches or perhaps an upstream torque converter with or without a bypass clutch can be used as the start-up component. Basic designs [4] demonstrating this principle already exist (Figure 5).

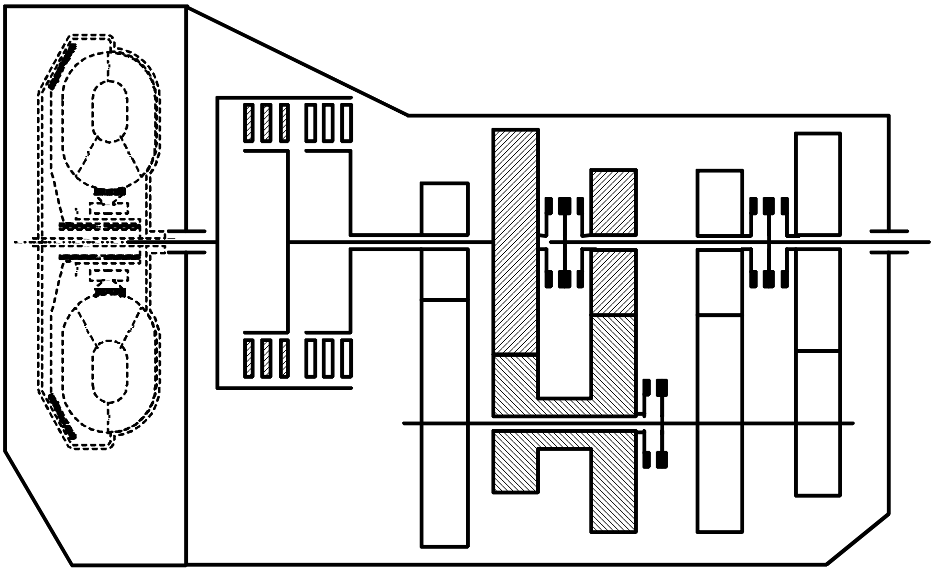

Figure 5: Dual clutch transmission

Figure 6 illustrates a shift mechanicsm that operates without interrupting tractive force. For purposes of simplicity, one sub-transmission is represented as a shaft with a single drive ratio and a second drive ratio is obtained by pairing with a spur gear. Despite the speed differentials involved, torque can be transmitted via both clutches, but the sum of the torque values from both clutches must be accounted for. For instance, if one clutch transmits the full engine torque, the 2nd partially activated clutch only generates losses as a result of its slip. If the transmittable torque from clutch 1 is reduced the torque from clutch 2 synchronously increases, the engine will be accelerated or decelerated to the speed of the other transmission train. Fine-tuning these procedures is easy with a fully electronic control system. Both theoretical and practical experience indicate that this design can be used to achieve the same shifting ease as with a planetary gear system.

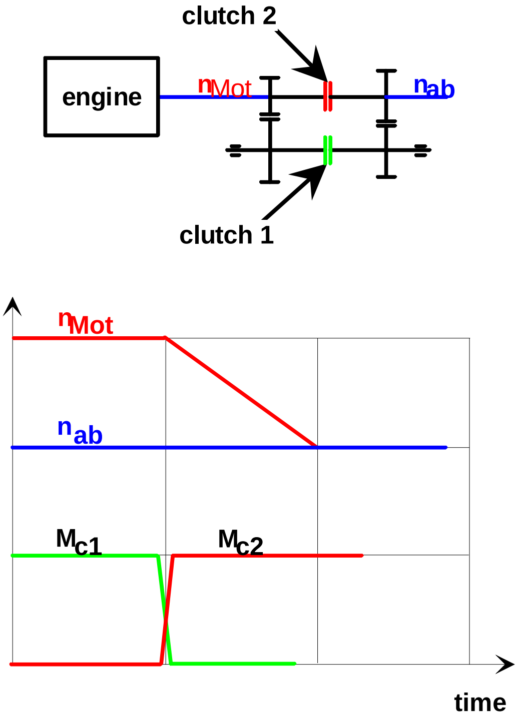

Figure 6: Shifting procedure without interrupting tractive force

In comparison to a manual transmission, additional costs include: the division of the transmission into two sub-transmissions, the additional clutch, the cost of the automatic controls for the two clutches, the operating systems for the synchromesh elements and the hydraulic oil supply in the event that a torque converter is used. Losses can be lower than for a planetary gear system.

Depending on the number of gears involved, Dual clutch transmissions - as the name would indicate - operate with two friction clutches and, depending on the number of gears, several positive clutches, which are usually combined with synchromesh elements.

4-Speed automatic with hydraulic torque converter

Automatic transmissions with a friction clutch for virtually each gear have been around for a long time. Whether this transmission is designed with a layshaft or as a planetary gear transmission, at least each of the forward gears is switched by means of a friction clutch.

4-Speed automatic transmission with layshaft

Figure 7 shows an example of a 4-speed automatic transmission like those that have been built in the USA and Japan for many years.

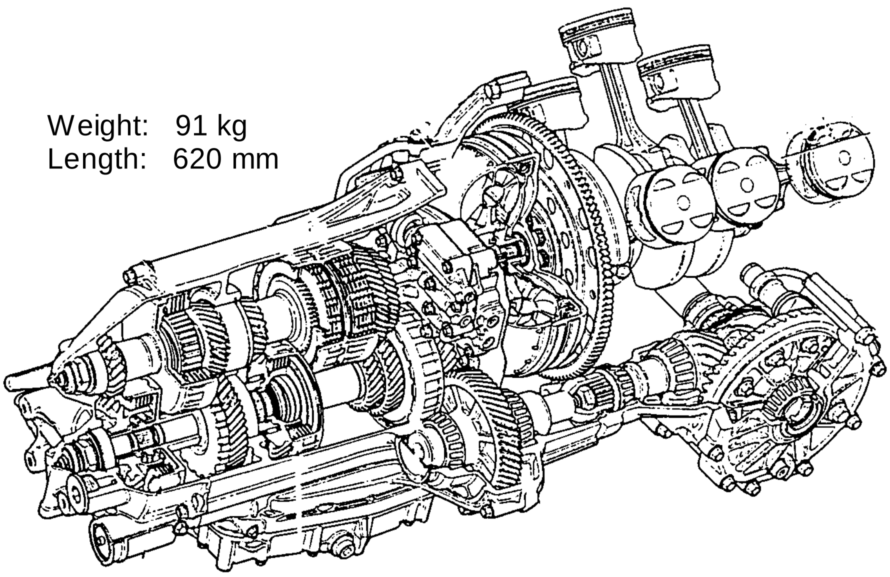

Figure 7: Automatic transmission with layshaft

The advantage of this transmission design is that it provides a relatively free ratio selection because each transmission ratio uses its own set of gears. A disadvantage is that the clutch diameter is limited by the distance between the shafts. State-of-the-art gear design and manufacturing procedures make it possible to suppress gear noise to the same level achieved by a planetary gear transmission - in other words, these transmissions are virtually noiseless. With or without one-way-clutches, they provide the same shift quality as planetary gear transmissions both in theory and in practice.

Planetary gear transmissions

The first automatic transmissions were manufactured in the United States for high-torque engines. Planetary gear transmissions were used at the time because of the power density involved and remain the standard.

As was the case with the dual clutch transmission, two power-shift clutches are used to shift gears without interrupting the flow of tractive force. If the torque converter has been retained as a start-up element, the total costs for this system are comparable to the cost for planetary gear transmissions with 5 shift elements, for layshaft transmissions with the same number of elements or for dual clutch transmissions (Figure 8).

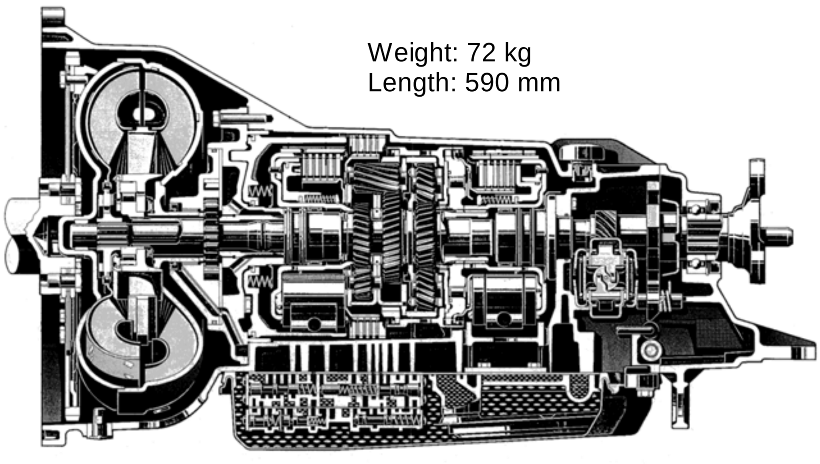

Figure 8: 4-speed automatic

All these transmissions require an oil pump for the transmission fluid supply to the torque converter and for the hydraulic control system. The hydraulic control system is basically in effect an analog, partially digital hydraulic "computer". Even when equipped with an electronic control unit, some of the control functions are still assigned to the hydraulic control system. Because oil is used as the operating medium and because wet clutches - in contrast to the clutch used in manual transmissions - cannot transmit torque without any pressure or load, the pump must run constantly. Figure 9 shows the total resulting efficiency rating for a 5-speed automatic transmission with a hard locked torque converter under street load. Efficiency ratings can vary depending on the design.

The total drive ratio for an automatic transmission in first gear can be somewhat "longer" than for a manual shift transmission if a torque converter is used to assist start-up. The drive ratio in top gear is usually somewhat "shorter" than for a manual shift transmission, which naturally leads to higher consumption at higher velocities, e.g. freeway driving.

Start-up comfort is similar to MT with ECM, but the ability to shift gears without interrupting tractive force is readily apparent. This elimination of the "shift interval" reduces the acceleration deficit that results from the lower number of transmission ratios.

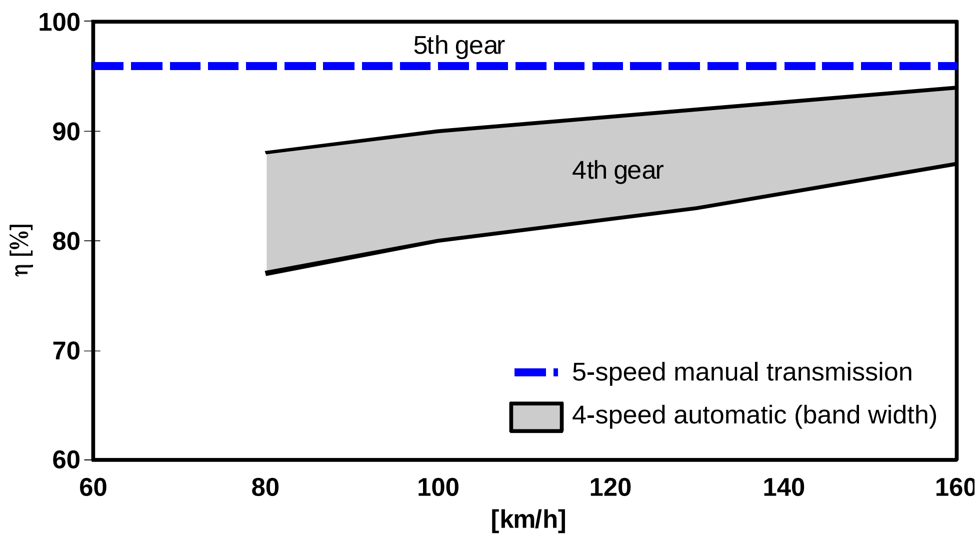

Figure 9: Partial load efficiency

The total weight of the 4-speed automatic with a torque converter is significantly higher than that for the 5-speed manual transmission. There are several reasons for this:

- The torque converter weighs about as much as a dual mass flywheel, which is most frequently used in the vehicle class in question.
- The friction elements used to transmit power flow - i.e., the full-load shift clutches - add weight to the design. These full-load shift clutches are usually oil-cooled, but a certain amount of shifting heat must be stored in an intermediate thermal mass, which of course adds weight.
- The required quantity of oil is significantly higher (6 - 8 l) than in a manual transmission.
- The hydraulic control system and the oil pump also weigh at least 5 kg. If the oil cooling system is added, then a transmission for this vehicle performance class has a total weight of between 80 and 90 kg, depending on the design used.

The design volume of the torque transmitting components (shift elements, planetary gear sets and shafts) can be about the same as for the corresponding components of a manual transmission, but the hydraulic control system and the oil sump provide additional volume. In addition to the cost, this is the main reason why, although 5-speed manual transmissions are used in all front-wheel drive vehicles, generally only 4-speed automatic transmissions are used in these vehicles.

In comparison to manual transmissions, the total costs (including the flywheel and the clutch, etc.) are considerably higher. The additional cost can vary considerably depending on the design. For instance, if one-way-clutches are used to simplify gear shift control, they have to be bypassed with additional clutches in coast.

5-speed automatic transmission with hydraulic torque converter

If one wants to retain start-up gradeability with an automatic transmission and at the same time achieve an overdrive ratio similar to that of a 5-speed manual transmission, it is usually necessary to add a gear. Until now it has been impossible for the torque converter to completely make up for the required gear ratio spread because power losses, for instance on a steep grade with a trailer, have been too great. In order to continue to take advantage of current investments in 4-speed transmissions, a supplemental planetary set gear with its shifting elements is frequently added in order to end up with a 5-speed transmission with a wider total drive ratio range. In terms of total range, these transmissions are comparable to 5-speed manual transmissions. In fact, with the start-up assist provided by the torque converter, they even operate with a more pronounced overdrive effect. The lower tractive force in the overdrive range can be made acceptable by shifting into the second highest gear. Unfortunately it has been very difficult to come up with a successful schedule. Several test reports criticize high shifting frequency in the top two gears.

Adding the extra planetary gear ratio with two shift elements increases costs by about 25% compared to the basic design.

The weight situation is significantly worsened as well - this type of 5-speed transmission can weigh up to 100 kg. In terms of design volume, this concept is only feasible for standard drive trains because the additional length required for the additional set of gears makes the system too long to install in a front-wheel drive vehicle. The additional fifth gear also leads to higher losses, as indicated in Figure 10 [5]. One should be aware that the input speed which is mainly responsible for the losses is lower than with a 4-speed transmission.

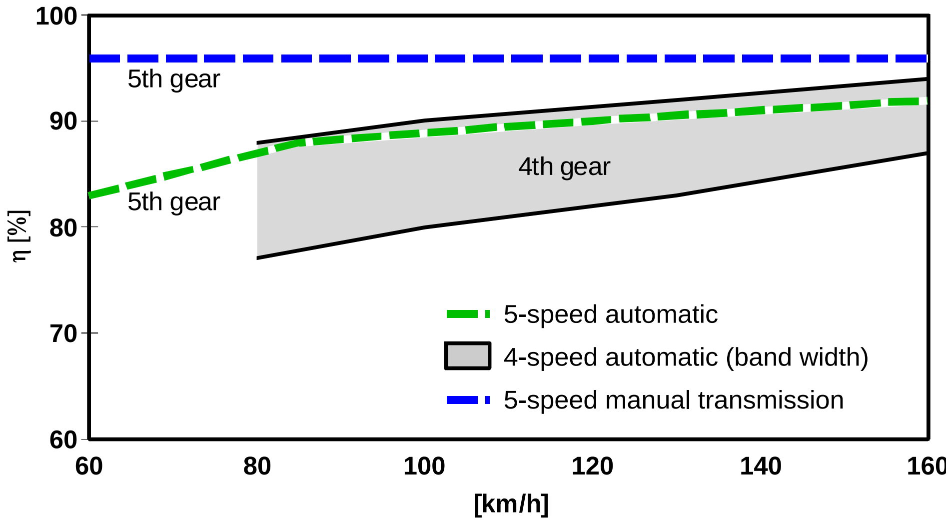

Figure 10: Performance losses for a 5-speed automatic transmission

Despite the increased weight and the higher losses, the significantly higher overdrive ratio of the fifth gear results in lower fuel consumption and improved driving performance over the 4-speed automatic. Figure 11 shows such a transmission.

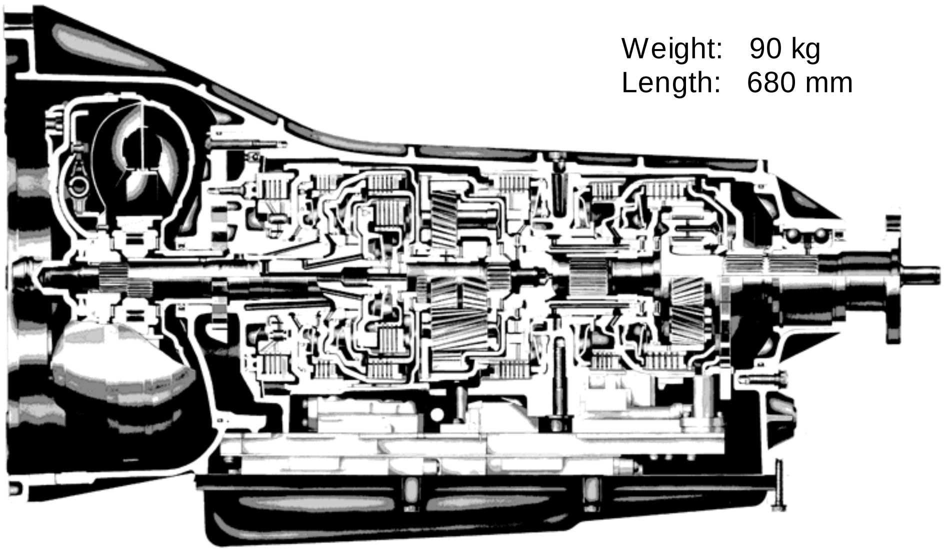

Figure 11: 5-speed automatic

Modified 4-Speed Automatic with the LuK TorCon System

The first automatic transmissions had only two, at most three, mechanical gears. They also featured hydraulic torque converters with large torque ratio and high stall speeds. These design features produce comfortable driving conditions, but they had large losses as well. Over the years losses were reduced by introducing stiffer converters. The large torque ratio was no longer possible and must be compensated for by increasing the drive ratio range with more gears.

At the beginning of the 70s, torque converter clutches were introduced to eliminate converter slip losses, at least in top gear, resulting in a transmission with improved fuel consumption, but offered less comfort. In an SAE paper from this period, one developer noted with regret, "when we locked the converter, we discovered the advantages that we had lost".

Efforts have been made to optimize the shifting strategies of the automatic transmission and the torque converter with the bypass clutch: For instance, with adaptive shifting programs or program selectors. It has proven difficult to find the ideal compromise between reduced shifting frequency and either fuel savings or performance related gear selection. Even if shifting is almost unnoticeable, drivers are still aware of acoustic changes associated with changes in engine speed. A multi-ratio transmission always provides an appropriate match between engine speed and driving speed. Only in high-slip ranges, such as can occur with loose converters, will the engine speed remain almost constant for acceleration and shifts. Even the introduction of an additional number of gear ratios - supposedly the route to an continuously variable transmission produces its own problems because of increased shifting frequency. Would more gear ratios - more then five - improve this?

LuK has found another solution to the problem.

One should take another look at the properties of the hydraulic torque converter as a comfortable, continuously variable transmission combined with a bypass clutch. Building on this model, other power train designs with transmissions having fewer speeds can be visualized. The total transmission ratio in first gear should still be very high in order to provide high tractive force for trailer operation and similar tasks, but with low power losses of the torque converter in partially or fully bypassed condition. This design features a mechanical overdrive and relatively few intermediate gears, each of which covers a wider speed range and is comfortably bridged by the continuously variable transmission "torque converter". If the torque converter only comes into play briefly during acceleration phases, short-term loss in efficiency is relatively unimportant. In many cases, the often critisized shift frequency, specially out of overdrive, can be eliminated by using a torque converter with wide conversion range; made continuously variable by partially or fully opening the bypass clutch. Figure 12 shows that the fourth gear of a 4-speed automatic equipped with the increased conversion range of the LuK TorCon System successfully covers the same range as the fourth and fifth gears in a 5-speed automatic for the speed range between 60 and 140 km/h.

Costs, power loss, and weight for this kind of 4-speed transmission are comparable to the advantages of a 5-speed automatic. Whether we can design the wider drive ratio range depends on the type of planetary gear sets used and the available free space for bearings and other elements. The additional development is less; maybe it is only required for a redesign of the hydraulic control system or something similar.

Especially in the case of automatic transmissions with layshaft design, the cost of making the changes in the ratio of the transmission is very low. The additional investment for the design change is usually no higher than would be the case with an upgrade to a 5-speed transmission. It is not necessary to incur the cost of a total reinvestment to supply an optimum 5-speed transmission design.

Figure 12 shows drive performance figures for a 4-speed vehicle with LuK TorCon System compared to a 5-speed automatic transmission. The two vehicles feature the same transmission ratios for first gear and for overdrive. Acceleration in the 4-speed was even improved because of the higher torque ratio, as was fuel economy because of the overdrive ratio and the lower losses compared to the 5-speed transmission.

Naturally, setting aside weight, cost and space a 5-speed automatic with the same drive ratio range would be better in a few operating ranges. Theoretically, every point in the engine operating curve has an ideal transmission ratio that results in the optimum fuel economy. However, one must keep in mind the higher losses and the very difficult shift philosophy optimization. It appears that, in any case for front wheel drive vehicles, the new "old" concept with few gears and an optimized torque converter remains the best. If one uses this concept with a 5-speed transmission with a wider total drive ratio, one can achieve the advantages of a 6-speed transmission of the current type.

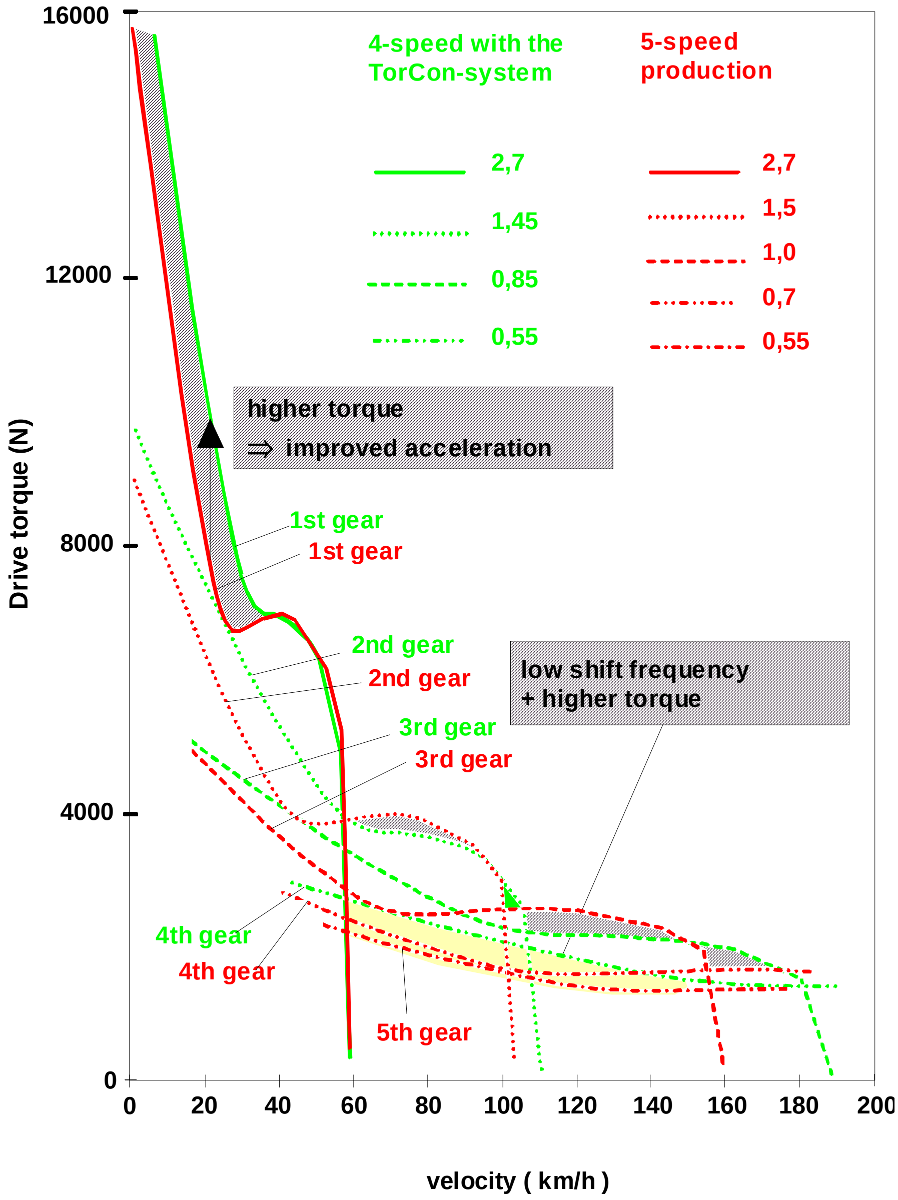

Figure 12: Comparison of tractive force for the LuK TorCon-4-speed System and a 5-speed transmission

CVT

The demand for an continuously variable transmission has been around for a long time. The hydraulic torque converter represents a compromise in this direction. However, its efficiency is not particularly satisfactory, and the selection of transmission ratios is not free - it depends on the limitations of the characteristic curves. The only way to modify the ratio is with a parallel bypass clutch like the LuK TorCon design that can modify the system within certain limits.

In mechanical continuously variable transmissions, the drive ratio is varied by modifying the friction radii of the load transmitting elements. There are several approaches to this solution; one of them will be demonstrated here.

LuK has been working together with other partners to develop a prototype continuously variable transmission designed for a torque of approximately 250 Nm (Figure 13).

The core of the design is the variator - a variable speed mechanism consisting a belt drive between tapered pulleys. In the first continuously variable transmissions introduced at DAF in 1959 this belt drive was made of rubber. Over a million transmissions were built based on this principle. Since then the belt drives have been made of metal in order to achieve higher output and to meet demands for higher product life. The most widely used design is the Van Doorne belt. Many prototypes and even production applications also operate with chains.

Because these transmissions utilize the friction between the tapered pulleys and the belt element to transmit power, high clamp loads are necessary because of the low coefficient of friction associated with steel-to-steel pairing. The transmission elements that are subjected to these loads (e.g., the pulley sets, shafts, etc.) must be extremely sturdy in design.

Currently familiar designs for continuously variable transmissions provides drive ratio ranges between five and six. This means that continuously variable transmissions make it possible to achieve transmission spreads that otherwise are only possible with five or size mechanical gears in an automatic transmission.

This wide range of transmission ratios can be used to take some of the load off the start-up element; the load exerted in this range is proportional to the square of the total transmission ratio in underdrive. It is also possible to use some of this wide range to develop an overdrive characteristic.

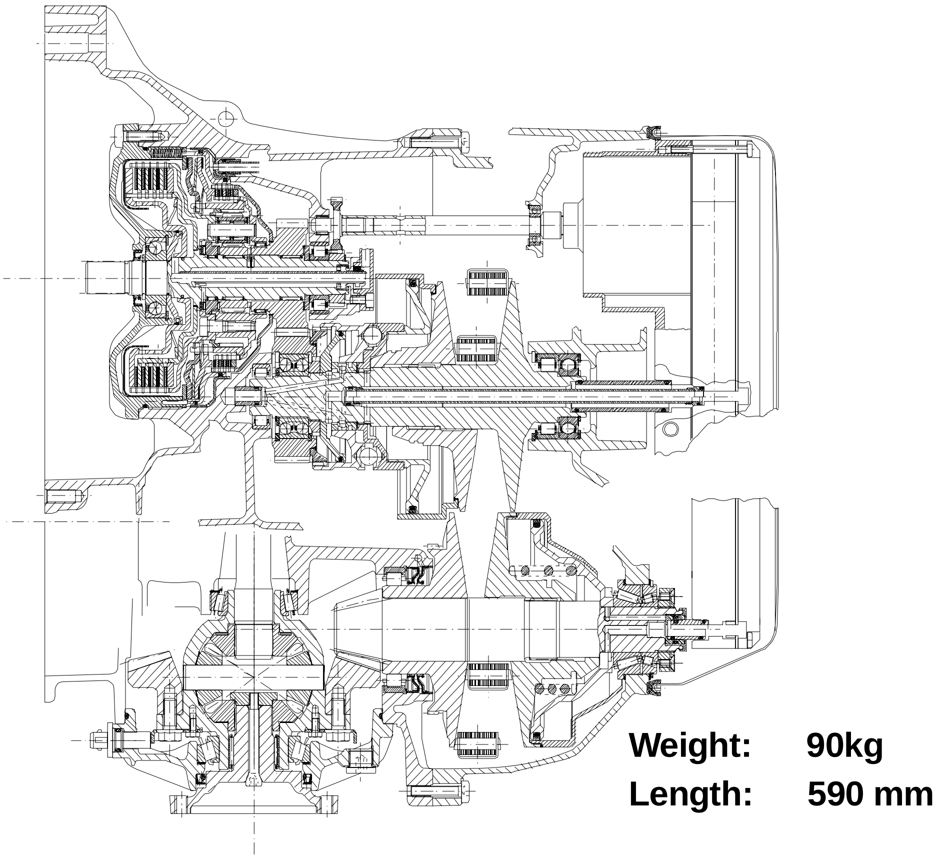

Figure 13: CVT-prototype (AUDI-LuK)

CVTs introduced in the past had relatively high losses. The high clamp loads exerted in the pulley sets required high oil pressures and large quantities of oil to facilitate the rapid adjustment of the tapered pulleys. This means that oil pump output must be considerably higher than for a multi-step automatic. The selection of the appropriate pump design is consequently very important.

A further source of loss is the so-called spiral circulation. The chain or belt is drawn increasingly toward the inside on the clamping points as it moves from the engagement to the output point, which results in additional losses. This can be prevented by designing stiffer pulleys and shafts [6].

The losses resulting from seal friction are actually greater than by conventional automatic transmissions because of the high pressures involved. However, there are fewer elements to service, and the seals can be reduced to very small diameters and positioned at the ends of the shafts, which reduces these losses.

Furthermore, the continuously variable transmission has fewer elements than the multi-ratio automatic, which means that drag losses due to open shifting elements and similar components are lower.

It is extremely important to maintain the tension of the pulley sets against the chain or belt. It is easy to visualize how excessive clamping can lead to friction losses between the pulley and the belt element, and to understand that pump output must increase because of higher pressure. An optimum design for a continuously variable transmission could achieve loss performance in the most important partial load range similar to values for a good 4-speed automatic (Figure 14).

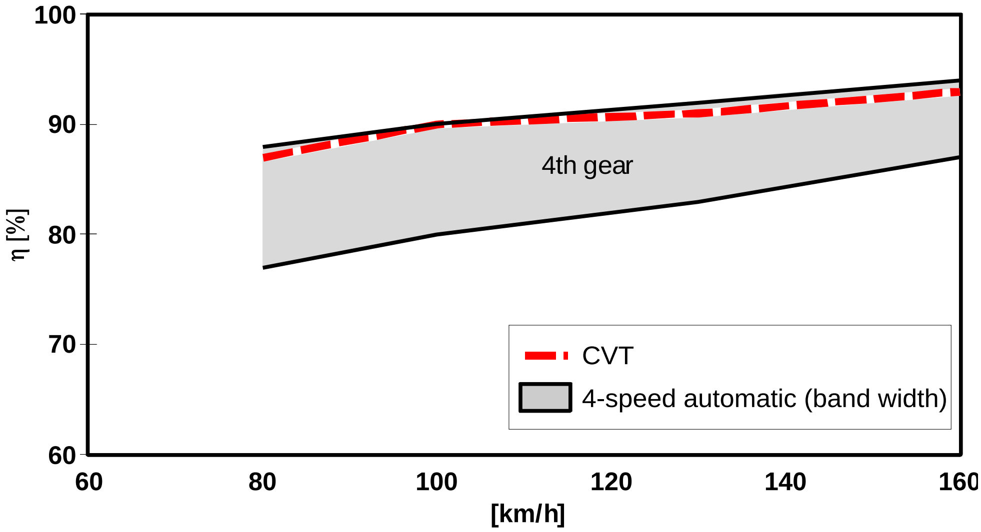

Figure 14: Comparison of partial load efficiency

Continuously variable transmissions have in the past exhibited relatively poor partial load efficiencies. In comparison to multi-ratio automatics, however, the larger total drive ratio range can be exploited to achived greater overdrive effect, which produces a more favorable engine operating point so that overall engine and transmission losses are reduced.

There have, however, been many complaints about operation in extreme overdrive because the vehicle makes a flaccid impression.

If the CVT has a very good partial load efficiency rating, designers can introduce the overdrive ratio wherever it is likely to be accepted. Because this CVT design achieves optimized drive ratio selection, it is possible to improve fuel consumption compared to manual transmissions that do not feature such precise fuel consumption control. Nevertheless, there is a tendency to overestimate CVT's advantages with respect to operation at optimum engine fuel economy. The actual fuel economy advantage lies in CVT's wide range of drive ratios and thus in its overdrive characteristic.

There are contradictions with respect to desirable objectives so far as the adjustment performance of the transmission is concerned. Uncompromising adherence to engine operation in the most advantageous range has often been criticized because of the unfamiliar acoustics of the engine speed curve in comparison to multi-ratio transmissions. On the other hand, there are complaints about changes in engine speed when the ratio changes in multi-ratio transmissions, even if the actual shifting process is imperceptible and in no way impairs driver comfort. Either a process of getting used to this shifting behaviour on a clever design compromise is required here. In the USA CVT-type shifting behavior in vehicles with multi-step automatic transmissions or "soft" torque converters has been completely accepted.

Because of the stiff pulley sets and shafts, total weight may be higher for CVTs than for comparable 4-speed automatic transmissions. There are, however, several options for optimizing the design. For instance, a start-up clutch instead of a torque converter ca be used if the CVT has been optimized for transmission losses and has a wide ratio range that can be exploited to increase the start-up ratio. This has significant weight advantages.

If one compares continuously variable transmissions with 5-speed automatic transmissions in the same performance class, it is conceivable that the weight advantage lies with the continuously variable transmission.

One also needs to compare design volume for multi-ratio automatics in the same performance range. In cases where the vehicle design dictates an axial displacement between the input and the output shaft, continuously variable belt or chain drive transmissions have design advantages.

When comparing manufacturing costs, it makes sense to limit the examination to parts that do not represent similar expenditures. If for instance, the design has an electronic control system, then the total cost for the oil pump and control system for the multi-ratio automatic and for the CVT will be similar. The transmission housing and oil pan can also be viewed as cost-neutral. In comparison to a 4-speed automatic, the forward/reverse shift element (1 planetary gearset and 2 clutches) for the CVT will amount to about 1/3 the costs of the counterpart unit for a 4 or 5-ratio automatic, assuming that the latter will use 5 clutches and 2 planetary gearsets. If the actual variator with its tapered pulleys and belt element will cost about as much to build as 3 clutches and 1 planetary gear set the total cost will be similar to a 4-speed automatic.

Whether a CVT requires more or fewer intermediate shafts between the transmission input and output shafts depends primarily on available space, specifically on the axle base. For instance, two shafts would cost less, while four would cost more.

As mentioned previously, it may be possible to elimimate a torque converter as the start-up element because of the wider ratio range.

Even if these calculations are relatively rough, nevertheless, it looks as if depending on the specifications the continuously variable transmission would be cheaper or would cost about the same to build as a 4-speed automatic, while it is highly probable that it would be less expensive than a 5-speed automatic.

At this point, the comfort of "gear changes" or changing transmission ratios probably don't need to be discussed. Especially with electronic controls, everything is possible within the physical parameters. Of course, when the engine speed increases, only part of the engine torque can be used for vehicle acceleration because part of the increase is lost for acceleration of the engine itself. As long as this limitation is accounted for, everything else is optional.

An across-the-board comparison

The total overdrive ratio is the primary determining factor for fuel consumption. On the other hand, a certain minimum first gear ratio or underdrive is necessary for good acceleration performance and trailer pulling capability. This minimum transmission ratio also contributes to a reduction of losses in the start-up element under difficult start-up conditions regardless of whether a clutch or a hydraulic torque converter is used.

	Manual trans.	4-speed AT	5-speed AT	4-speed LuK AT	CVT
Underdrive ratio	14.17	12.62	11.88	11.88	13.25
Overdrive ratio	2.94	3.27	2.30	2.30	2.21
Ratio spread	4.82	3.86	5.16	5.16	6.00

Table 1: Comparison of various drive concepts

In making this comparison neither the production design for the start-up ratio nor for the overdrive in particular has been changed, although in some cases a more highly developed overdrive design would be possible. In the case of manual transmissions, any ratio that would be readily identifiable as an overdrive gear would not be accepted by test drivers, and probably not by the market either.

In order to avoid compromises in tractive force in 1st gear of the 4-speed automatic with the ratio range shown here, the top gear had to be designed so that the maximum speed occurs approximately at maximum power. Shifting the overall design to lower total transmission ratios would result in decreased maximum speed.

For 5-speed automatic transmissions, the maximum vehicle speed is reached in 4th gear. 5th gear is used as overdrive, and first gear has an adequate tractive force.

In the 4-speed design with the LuK TorCon System, 1st gear and the top gear are the same as for the 5-speed transmission design, and the maximum vehicle speed is reached in 3rd gear.

For the CVT, part of the larger total drive ratio range is used for an even longer overdrive, and part of the ratio range is also used for a shorter underdrive ratio in order to be able to use a wet clutch as the start-up element, which has cost and weight advantages.

Test cycles

If a dual mass flywheel or DFC is used, the power train can be operated without booming or rattle noise all the way down to idle speed. This factor alone can reduce fuel consumption. Of course the driver will disengage the clutch at a certain point above idle speed in order to avoid killing the engine. This can be eliminated by installing an automatic clutch. If all the engagement and disengagement operations are automated, additional changes in the overall drive performance can be expected.

Changing driving performance will affect fuel consumption. Because official test cycles specify the shifting points, it is impossible to determine the affect of the automated clutch management system. For this reason, as noted in the previous presentation, a test route including city, overland and autobahn driving was established. This test route was driven by several persons in vehicles with and without automatic clutch management systems.

The cumulative frequency for the power used was similar to that for official cycles (Figure 15). The drivers with the highest and the lowest total output are shown as the extreme values. Because the actual power consumption figures are very low, the partial load efficiency ratings - for instance for street load (on a level road) are very important.

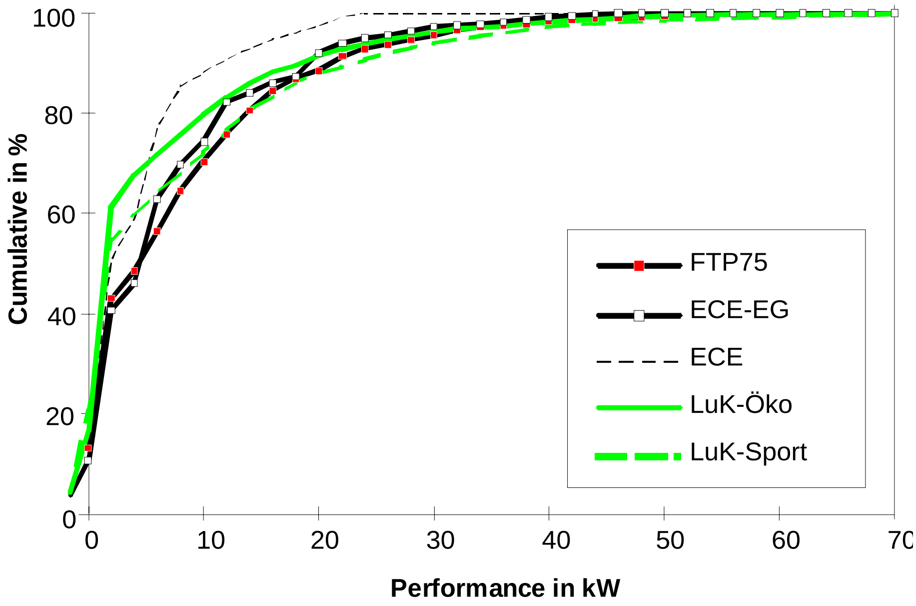

Figure 15: Cumulative frequency distribution for power

Evaluation of these figures produces some surprises. Almost all drivers achieved a higher average speed with the automatic clutch management system. On the one hand, this may be attributable to improved concentration on traffic; on the other hand, however, it may be attributable to frequent downshifting for acceleration. The inconvenience of downshifting with the accompanying loss in driver comfort, especially if the engagement of the clutch is not precisely carried out, frequently encourages many drivers to avoid using the higher engine performance in a lower gear. This may mean that with the automatic clutch management system it would be possible to take greater advantage of the overdrive characteristic in the top gear because the resistance to downshifting would be lower. This would produce greater fuel savings.

The differences in fuel consumption of the three test conditions are shown in figure 16. Because of the high average speed of the autobahn cycle, only transmissions with overdrive and low losses (e. g. 4-speed automatic with LuK TorCon System) have significant advantages compared to 5-speed manual. The reason for the similar fuel consumption of the CVT and the 5-speed manual lies in the strategy of the ratio control of the CVT. In country and city cycles all automated drive train versions are at least equal and sometimes considerably superior to the manual transmission.

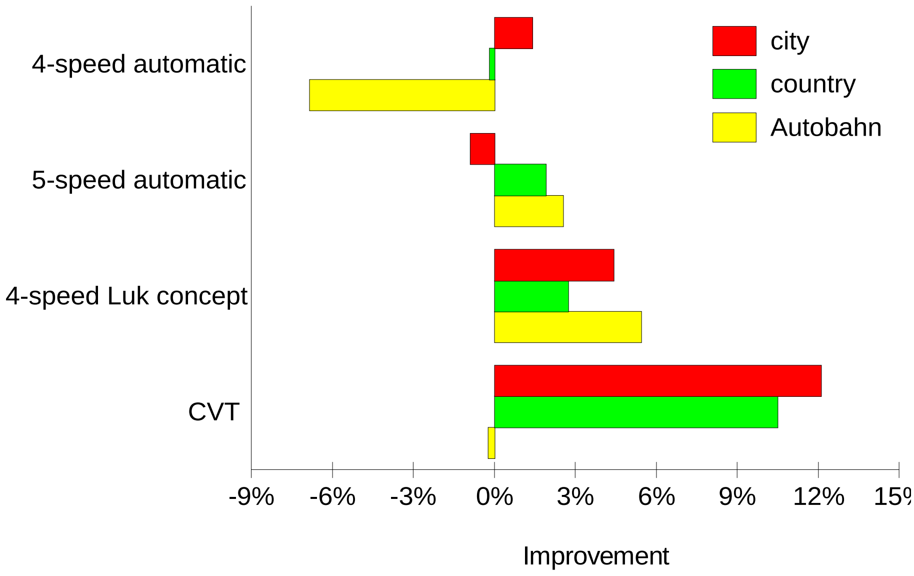

Figure 16: Comparison of fuel efficiency (estimate)

Driving performance

Acceleration from 0 to 100 km/h was used as a comparative bench mark for performance (figure 17). For acceleration under full load using foot-operated clutches, a typical start-up procedure (see figure 3) was chosen and the common "jack-rabbit start" avoided.

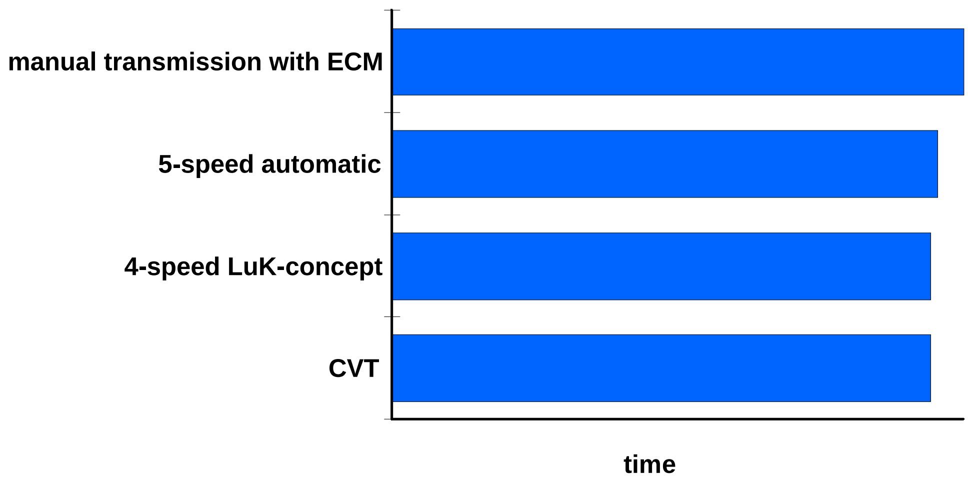

Figure 17: Comparision of acceleration

A so-called elasticity evaluation was not conducted because, in the case of automatics, this test is strongly dependent on the down-shift philosophy or, in the case of the continuously variable transmissions, on the variation philosophy.

All Consumption and performance data were determined using simulations. It was possible to compare most of the simulation calculations with measured vehicle data, so the values shown in the chart are reliable.

System size and weight

The various designs were compared based on the data cited in the previous chapters. Weight values were very carefully compared in an effort to select the most favorable designs currently on the market.

The 5-speed manual transmissions cannot be beat so far as size requirements and weight are concerned. The 4-speed automatic and the CVT come out about the same, but the 5-speed automatic takes its toll.

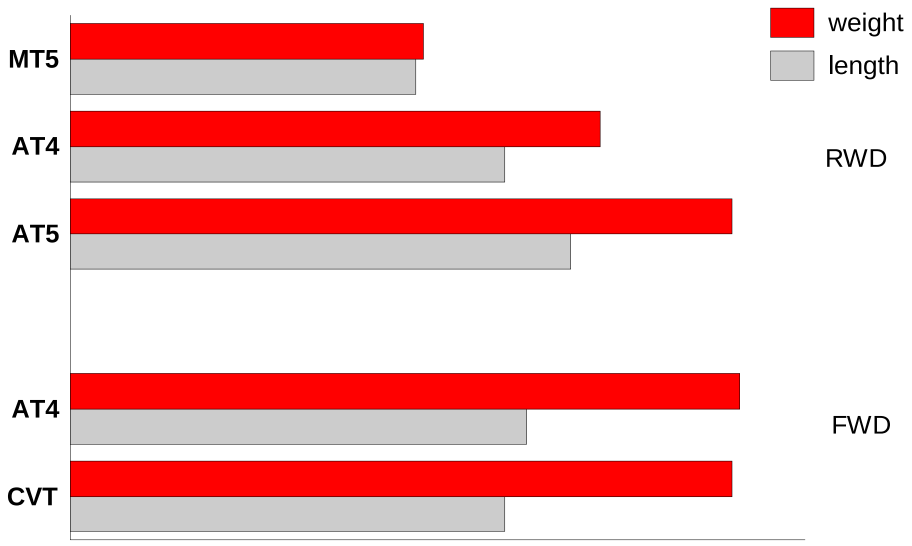

Figure 18: Comparison of length and weight

Of course, transmissions with similar features were compared, for instance, if the overrunning features were replaced with an electronic control system, space and weight were able to be saved, regardless of whether it was at a 4 or a 5-speed transmission. Nor was the so-called swapshift principle considered whereby a shiftpattern is used with the automatic to transform a 4-speed automatic to a 5 or 6-speed automatic with the same ratio range, but with a modified control system. A quantitative comparison between all transmissions must take into account that the CVT and the 4-speed layshaft automatic are designed for front-wheel drive and the integrated differential requires additional installation space and weight (figure 18).

Costs

Production quantity also plays a significant roll in manufacturing costs. It can even distort the picture. For instance, manual shift transmissions only make up 10% of the market in the US, so they can cost up to 100% more to manufacture than in Europe. Exactly the opposite is the case for automatic transmissions manufactured in Europe. Large American automotive plants produce as many units per day as some European automatic transmission plants do in a month!

Consequently, an automatic transmission manufactured in the USA can easily cost less than a manual transmission produced in small numbers. The continuously variable transmission in particular could be affected by manufacturing costs because current producion quantities are so low. An attempt to take these factors into consideration was made by postulating comparable piece numbers and development stages for all the transmission concepts. The use of electronic controls was assumed for all the designs. Figure 19 shows this comparison of manufacturing costs.

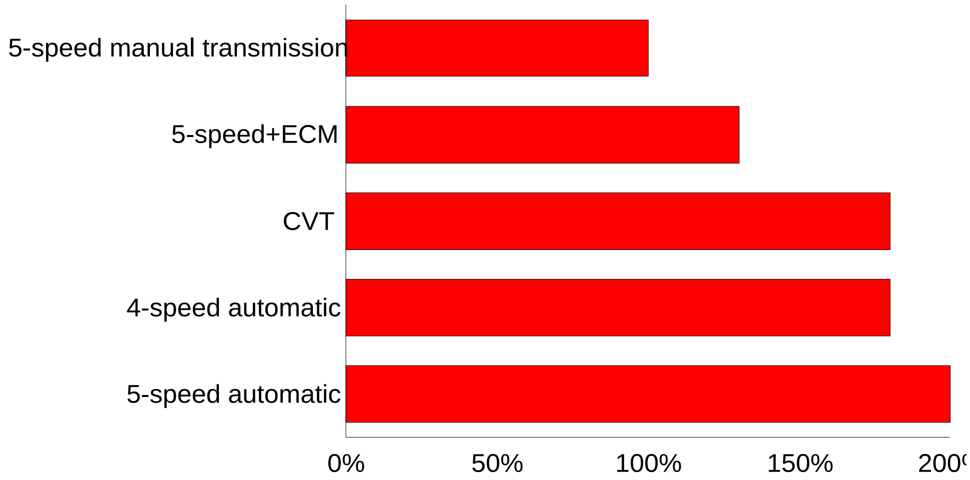

Figure 19: Manufacturing cost comparison (estimate)

Summary

Table 2 shows an attempt at a comparative evaluation. The 4-speed automatic transmission was viewed as a bench mark solution for an automatic power train.

	MT5	ECM	AT4	AT5	LuK AT4	CVT
Comfort	- -	-	0	-	+	+ +
Consumption	+	+	0	+	+ +	+ +
Emissions	-	-	0	0	+ +	+ +
Acceleration	+	+	0	+	+	+
Size	+ +	+ +	0	-	0	0
Weight	+ +	+ +	0	-	0	0
Cost	+ + +	+ +	0	-	0	0

Table 2: Comparison of various drive concepts

Comfort:

In the case of manual transmissions with foot-operated clutches, driving comfort during gear change and tip-in/back-out is almost entirely dependent on the driver. The electronic clutch management system can produce comfort improvements here if introduced with the appropriate strategies, but it cannot compete with the fully automatic transmission because of the interruption of tractive force during upshift operations.

The 5-speed automatic transmission was rated slightly less favorably for comfort in comparison to the 4-speed transmission because the higher shifting frequency very often leads to complaints. The 4-speed automatic design with the LuK TorCon System provides excellent comfort comparable to earlier automatic transmissions because of less frequent shift operations and the significantly looser torque converter. Of course, the continuously variable transmission provides the highest degree of comfort - anyone who drives for longer periods of time in a vehicle equipped with one of these transmissions will consider going back to a traditional transmission to be a step backwards.

Fuel Consumption:

Manual transmissions and automated clutches have an advantage in comparison to 4-speed automatics, especially if country roads and freeway driving make up a high percentage of overall driving. Because of the more advantageous gear selection, the 4-speed automatic may come out better in city traffic. Generally speaking, the 5-speed automatic has the advantage of an authentic overdrive. With the 4-speed automatic with the LuK TorCon System, losses can be reduced in comparison to the 5-speed automatic, which again results in improved consumption. A continuously variable transmission can achieve comparable consumption results.

Emissions:

Manual transmissions with automated clutches and all fully automatics provide the option of turning off the engine using a so-called start/stop function when the vehicle is stopped, which decreases emissions and noise. Many of today's four-speed automatics already utilize the option of engine/transmission management systems, particularly during the warm-up phase in order to force the catalytic converter to respond sooner and thus improve emission performance. The LuK TorCon System and the continuously variable transmission provide even better, more controlled operation, which makes it possible to achieve emission improvements of up to 30%.

Acceleration:

The electronic clutch management system allows even less experienced drivers to achieve good acceleration values. As shown in comparative testes more frequent downshifting, when necessary, utilizes existing engine performance. Based on the higher losses and lower ratio range, 4-speed automatics usually fair less well in this regard. 5-speed automatics, 4-speed automatics with LuK TorCon System, and the CVT can exhibit advantages even in comparison to manual transmissions. The higher losses involved are made up for by eliminating the interruption of tractive force during shifting or, in the case of the CVT, by the possibility of always utilizing maximum engine performance.

Size, weight, costs:

In this case, manual transmissions with electronic clutch management have the clear advantage. The 5-speed automatic has more design disadvantages than do the 4-speed automatic and the continuously variable transmission.

Based on the conditions analyzed above, in our opinion the primary trends in automated drive trains will include:

- 5-speed manual transmissions with automatic clutches
- 4-speed automatics with optimized torque converters
- Continuously variable transmissions

While the engineering principles for the first two options are well known and most of the existing investment can be applied to future designs without any problem, introduction of the continuously variable transmission will require investment changes in some areas. Nonetheless, the change will not be as great as is sometimes assumed because only the variator and the belt element differ significantly from conventional automatic transmissions. Electronic control systems in particular, have a great deal in common with automatics. It can be assumed that as demand grows to decrease vehicle fuel consumption and emission, a great future can be predicted for the continuously variable transmission.

References

[1] VDI-report No. 977, page 175 Dr. Wagner

[2] VDI-report No. 878, page 57 Jürgens

[3] VDI-report No. 977, page 527 Jürgens, Dr. Fischer

[4] ATZ 89 (1987) 9, page 439

[5] ATZ 91 (1989) 9, page 439

[6] Dissertation, Technische Hochschule Karlsruhe, 1953, O. Dittrich
Theorie des Umschlingungsgetriebe mit keilförmigen Reibscheibenflanken