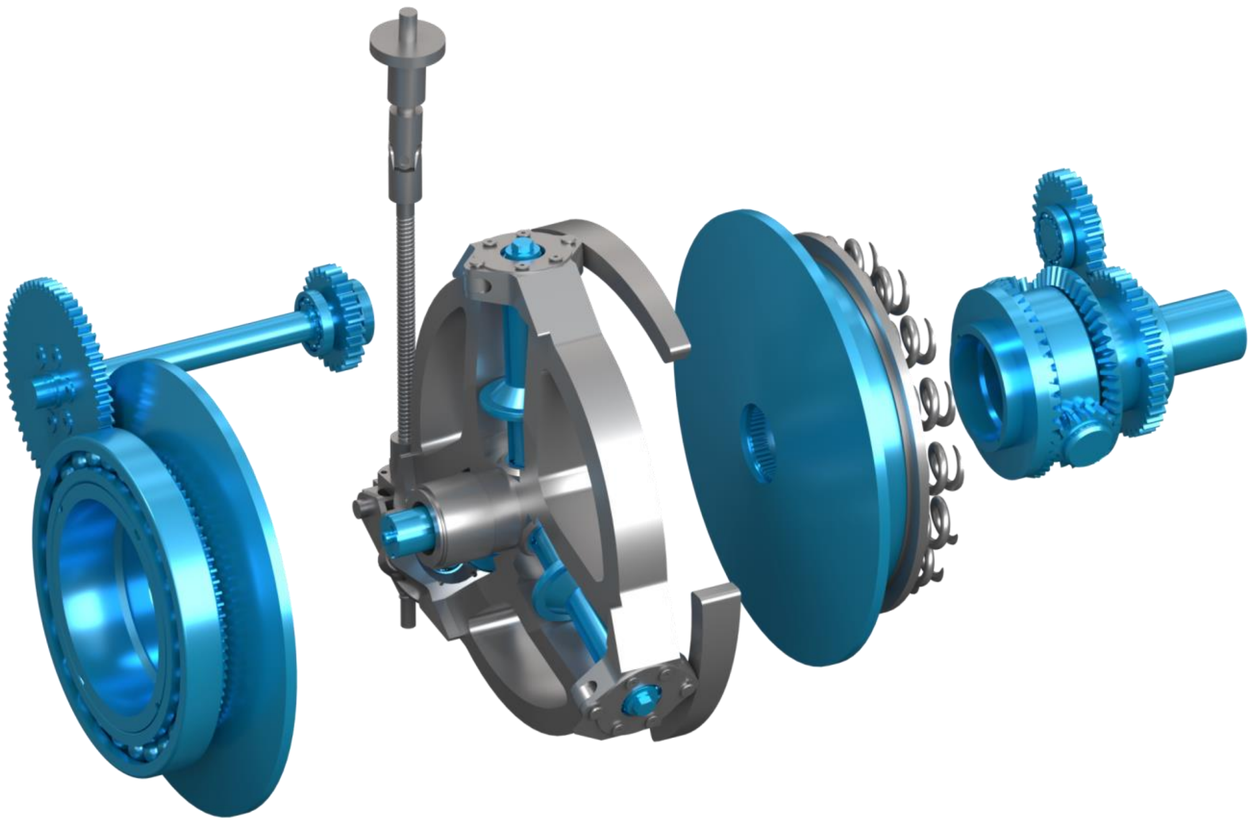
Automotive transmission explained and compared to the RADIALcvt



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1 Automotive transmissions state of the art

The automotive transmission is a device that is located between the engine and wheels and is used to alter the ratio between the engine and wheels to allow the vehicle to operate optimally at different speeds and loads. In recent years a much bigger emphasis is being placed on the automotive transmission as an optimization and coordination tool between the power source (engine and/or electric motor) and the vehicle varying load demands to produce lower fuel consumption and emissions. This is particular important in the cased of hybrid vehicles where an additional power storing component (batteries) are included to harness energy previously being wasted, for example in braking. Above exponentially increased the complexity of optimization of the vehicle powertrain as a whole.

Automotive transmissions can be categorised in the following categories

- MT Manual transmission
- AMT Automated manual transmission
- DCT Dual clutch transmission
- AT Automatic transmission (traditional automatic transmission)
- CVT Continuously variable transmission

2 MT (manual transmission)

MT is the simplest transmission, requiring the highest level of driver input, with the highest mechanical efficiency and comes in at the lowest cost.

All transmission require a launching or pull away device, the simplest and cheapest of which is a dry clutch. A MT employs a driver operated dry clutch at the input from the engine. Meshing gear sets with different ratios are selectively engaged by the driver according to the drivers driving style.

MT’s typically have up to six ratios, because more would be ineffectively used by the driver.

MT is further classified as the simplest stepped ratio transmission, since it is characterised by discrete stepped ratio’s

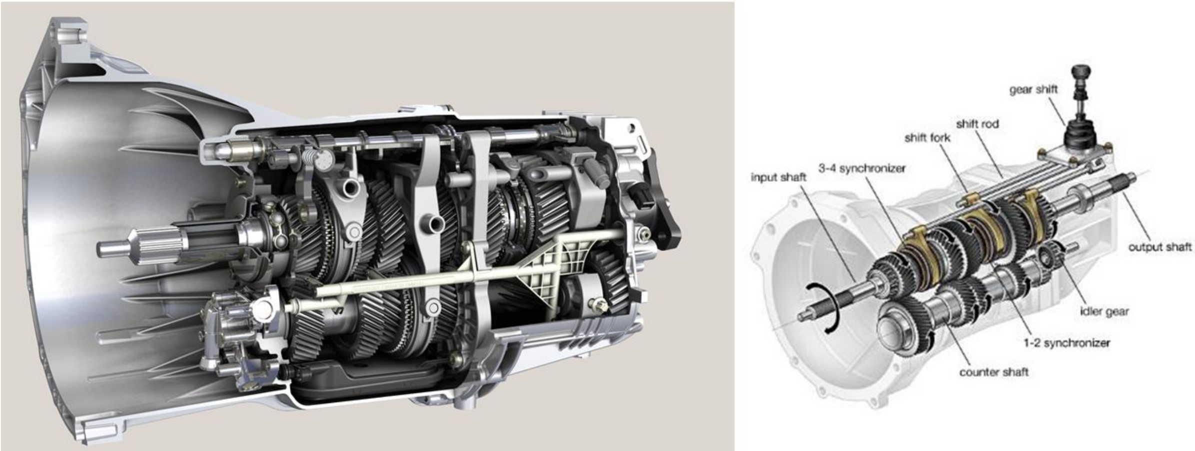


Figure 1 ZF 6 speed manual transmission together with a manual transmission schematic.

The ZF 6 speed manual transmission is presented in the left of Figure 1 and to the right a schematic of a typical MT to the right.

Mechanical efficiency: The manual transmission typically only involves power transmission through 2 meshing gear sets without any hydraulic control and therefore presents the automotive transmission with the highest mechanical efficiency, typically above 95%.

Fuel consumption and emissions: The fuel consumption and emissions of a MT transmission is directly related to the driving style of the driver.

Power interruption: During gear shifting a power interruption between the engine and wheels occur. Power interruptions are typically associated with jerks as well as fuel consumption and emission spikes.

3 AMT (Automated manual transmission)

An AMT is a manual transmission in which the clutch and gear shifting has been automated. This automation can be hydraulic or electric or a combination. Dry or wet (clutch operates in oil) clutches are used.

AMT’s presents the cheapest and simplest form of an automated/automatic transmission but has largely fall out of favour due to its shifting quality as a result of power interruptions during shifting..

Mechanical efficiency: Losses in AMT are the same as for the MT but additionally include the power consumption losses of the automated clutch and ratio shifting system.

The mechanical efficiency of an AMT is therefore a little bit lower than the MT because of the power consumed by the automated system.

Fuel consumption and emissions: As a AMT is an automated or 2 pedal transmission, the ratio selection is done automatically and therefore the AMT fuel consumption and emissions is less dependent on the driver's driving style.

Power interruption: During gear shifting a power interruption between the engine and wheels occur. Power interruptions are typically associated with jerks as well as fuel consumption and emission spikes.

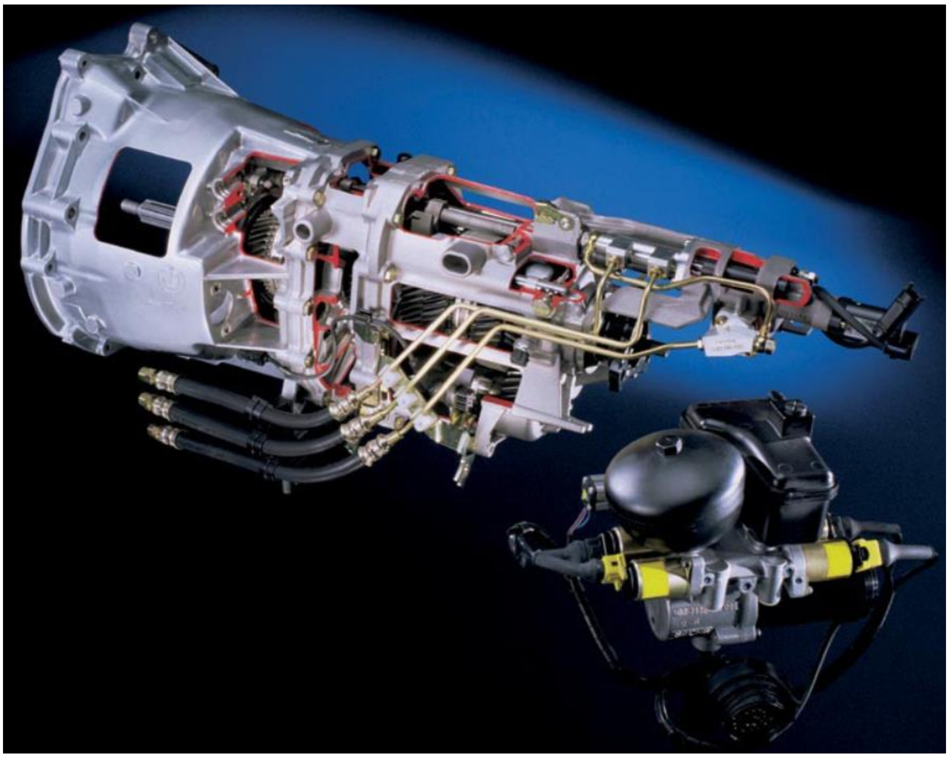


Figure 2 BMW SMG AMT

Figure 2 presents the well-known BMW SMG AMT.

4 DCT (Dual clutch transmission)

A DCT is a transmission which basically integrates two AMT's and therefore also has two automated clutches that can be wet or dry. For example the first AMT will include gears 1, 3, 5 and 7 and the second 2, 4 and 6 in a 7 speed DCT. The rationale behind the DCT is that if the first AMT is in a certain engaged gear with its clutch engaged, the ratio control algorithm will determine to which most likely gear of the second AMT (with its clutch not engaged) the next gear shift will be, and that gear will be selected by the control system.

When gearshift from the first AMT to second AMT is required the process is simply the disengagement of the first AMT clutch and the engagement of the second AMT clutch, which can be done very fast.

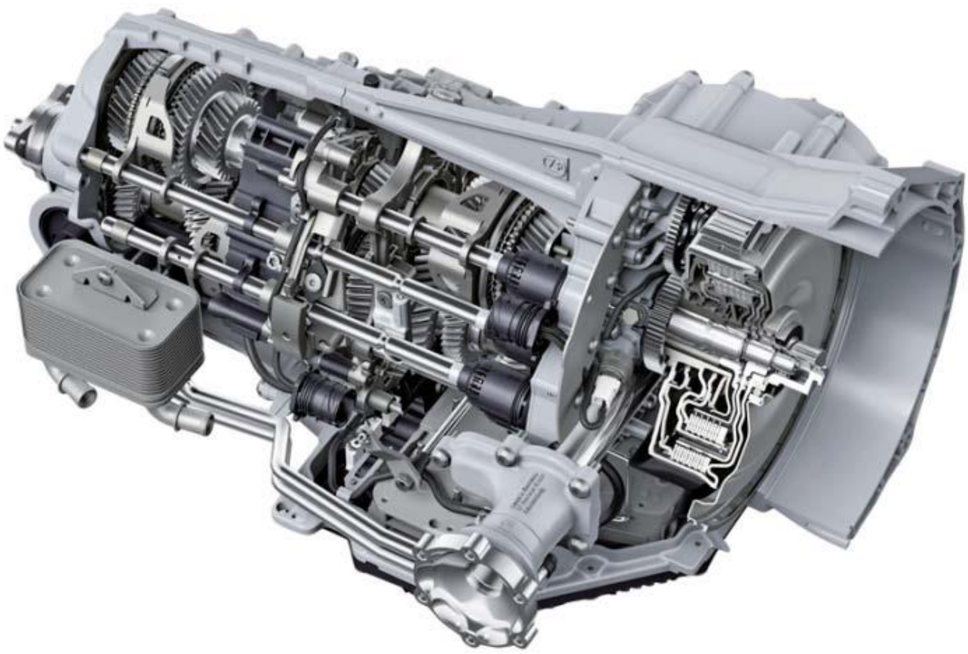


Figure 3 ZF's 7 speed DCT

DCT's therefore have very fast ratio shifting, but are more costly and heavy that AMT's because of the additional components. The disengaging and engaging clutch can also overlap to produce an uninterrupted power transmission between the engine and wheels. Figure 3 presents ZF's 7 speed DCT.

Mechanical efficiency: Losses in DCT's are similar as for the AMT and therefore has a similar mechanical efficiency.

Fuel consumption and emissions: As a DCT is an automated or 2 pedal transmission, the ratio selection is done automatically and therefore the DCT fuel consumption and emissions is less dependent on the driver's driving style.

Power interruption: During gear shifting no power interruption between the engine and wheels occur.

5 AT (Automatic transmission)

Automatic transmission function very differently from MT's, AMT's and DCT's and utilize planetary gear sets in combination with wet clutch packs to realise the gear ratios. For a launching device automatic transmission use a torque convertor. A torque convertor is a hydraulic device that under idle engine speeds transmit a very low amount of torque (allow the vehicle to creep) while the torque being transmitted increases at the engine speed increase. Torque convertors are not very efficient devices and are only used for pull away and some gear shifts while the rest of the time they employ a lockup device. Figure 4 presents the Mercedes 9 speed automatic where the nine speeds are generated by engaging combinations of the 6 clutch packs (shifting elements) engaging 4 planetary gear sets. To operate AT's required a hydraulic control system for actuating the various clutch packs. AT's are therefore also classified as stepped transmissions the same as MT's, AMT's and DCT's. Note that any transmission in which ratio selection is automated are often referred to as "automatic transmissions" or "two pedal transmissions" and is often mistaken for AT's. AT's as per above, specifically refer to an automated transmission in which gear ratios are realised via planetary gear systems.

Mechanical efficiency: Losses in AT's are generally more than in DCT's as a result of the drag losses in unengaged clutches as well as the hydraulic control system that needs to maintain pressure even when no gear change is taking place, which results in a lower mechanical efficiency

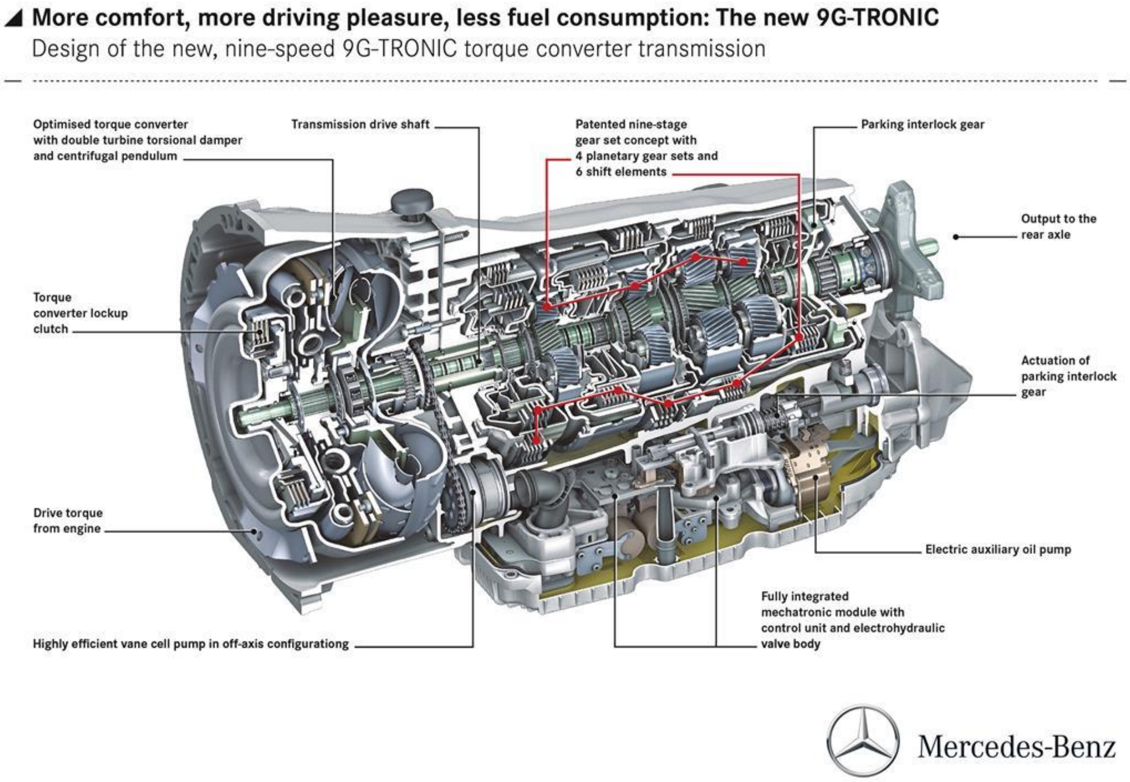


Figure 4 Merceded 9 speed 9G-Tronic AT.

Fuel consumption and emissions: As a AT is an automated or 2 pedal transmission, the ratio selection is done automatically and therefore the AT fuel consumption and emissions is less dependent on the driver's driving style.

Power interruption: During gear shifting no power interruption between the engine and wheels occur as the disengaging and engaging clutches overlap.

6 CVT (Continuously variable transmission)

CVT presents the only non-stepped transmission in that its ratio can be continuously varied in infinite small steps throughout its ratio range. CVT's also require a launching or pull away device which can be a wet clutch or torque convertor. All current CVT in production or development employs a friction drive. This friction drive involves steel on steel contact, lubricated in a traction fluid. The traction fluid has a special property in that it momentarily solidifies under high contact pressure (1 to 4 GPa) in the steel on steel contact and thus provides the friction drive as well as provide a solid boundary layer separating the steel on steel contact. Currently only the Belt and Chain types of CVT's are currently in production while the Toroidal, Cone ring, Planet ball and Radial driver CVT's are in development.

6.1 Belt and Chain CVT

The belt/chain and pulley CVT employs two sets of split pulleys and a metal belt or chain. The pulleys are hydraulically clamped together to tension the belt/chain resulting in a friction drive in traction fluid (special oil) between the belt/chain sides and the pulleys.

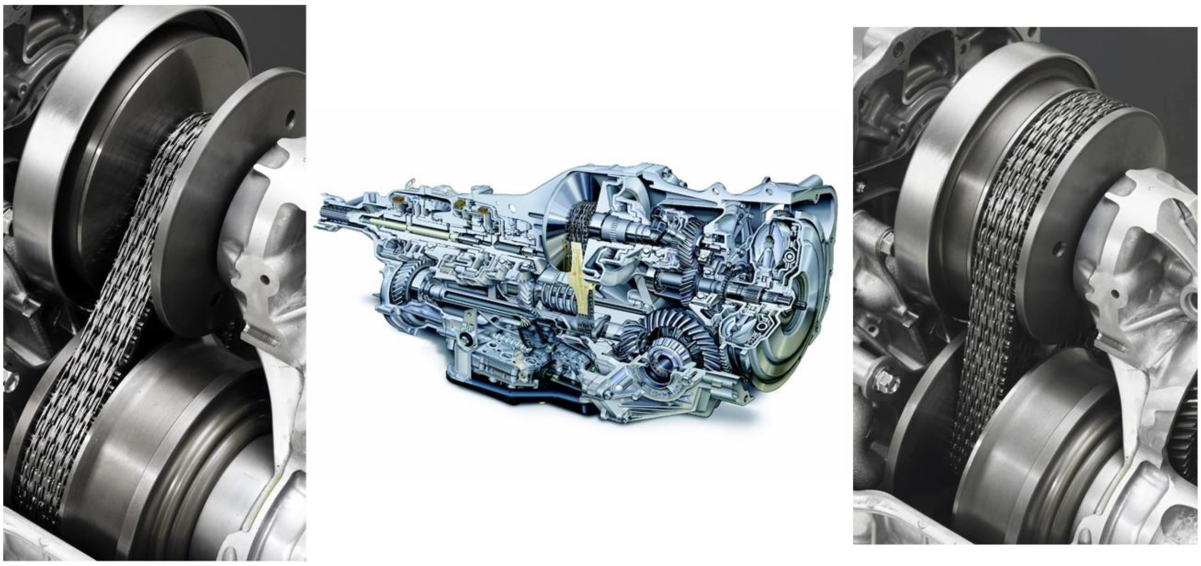


Figure 5 Subaru Linear Tronic CVT

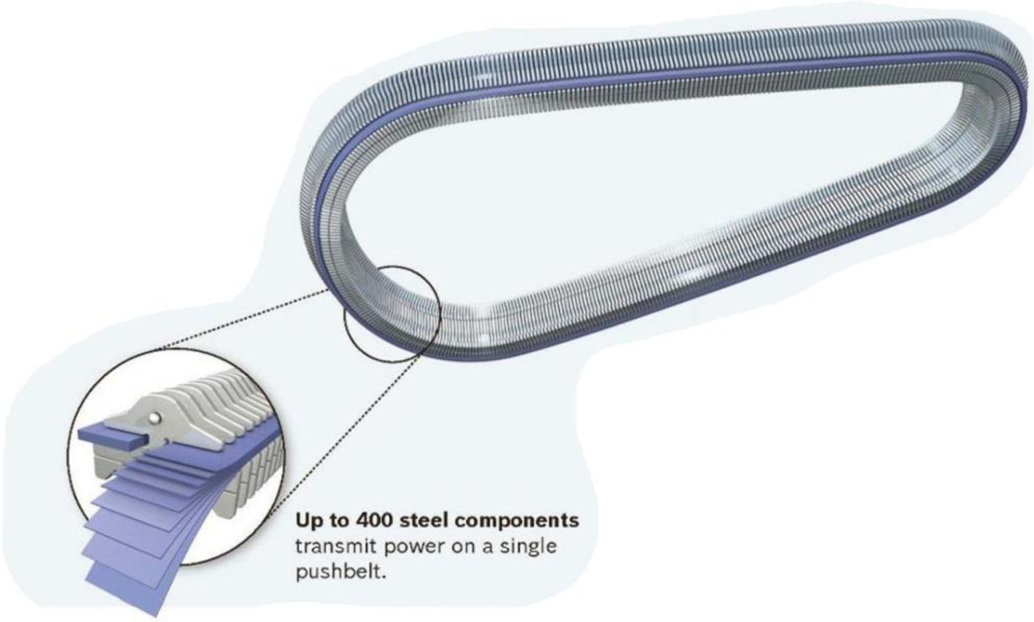
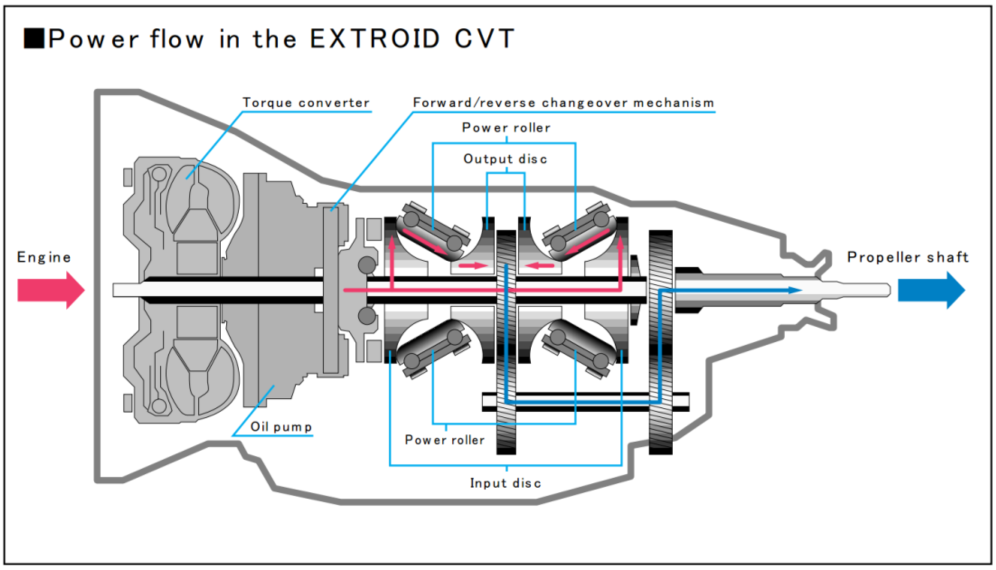


Figure 6 Bosch steel belt CVT.

The ratio is established by the varying radius on the input and output pulley. Figure 5 presents the Subaru Linear Tronic CVT with the image on the left in low ratio and on the right in high ratio.

Above Subaru Linear Tronic uses the chain manufactured by LUK while Figure 6 presents the steel belt manufactured by Bosch.

6.2 Toroidal CVT



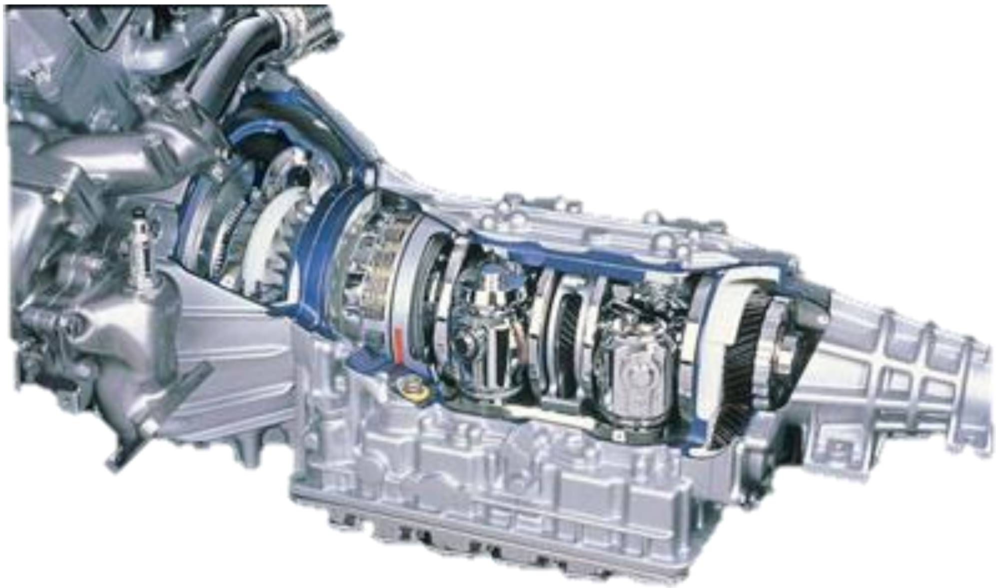


Figure 7 Nissan Extroid toroidal CVT

A second type of CVT is the toroidal CVT which utilises rollers running on different radiuses between two toroidal shaped input and output. Nissan had such a transmission in production called the Xtroid up to 2010 and is presented in Figure 7.

Mechanical efficiency: The losses in current CVT are the highest of all automated transmissions because of the losses in the friction drive interface and the hydraulic control system. Current commercial CVT’s have a mechanical average efficiency of about 85%.

Fuel consumption and emissions: As a CVT is an automated or 2 pedal transmission, the ratio selection is done automatically and therefore the CVT fuel consumption and emissions is less dependent on the driver’s driving style.

Power interruption: CVT’s shift seamlessly without any power interruption or the actuation of any clutches and therefore provides the highest level of ratio shifting.

7 Stepped vs infinitely variable transmissions

As the automotive transmission is the coupling device between the engine and wheels of the vehicle, it purpose is to match the capabilities of the engine (engine torque and speed) to the wheel requirements (speed and torque) while operating the engine at its most efficient point in terms of fuel consumption. Stepped transmission can perform this optimization in a “stepped” manner while CVT’s can perform this optimization to the highest level. However CVT’s have the lowest mechanical efficiency of all automotive transmissions, but provides the highest level of non-stepped ratio shifting producing the highest level of engine optimization as far as fuel consumption and emissions are concerned.

Above results in a race between CVT manufacturers to continually increase the mechanical efficiency of the CVT vs automated stepped ratio transmission manufacturers to continually add stepped ratios to increase the engine optimization levels. This is being done within the limits of cost, packaging.

Figure 8 presents a presentation by Bosch showing the advances (mainly by improving the mechanical efficiency and ratio range) of the CVT in terms of fuel consumption since 2007. The fuel consumption of the manual transmission is taken as a reference and between 2007 and 2017 great advances have especially been made by CVT's, DCT's and high ratio AT's to improve fuel consumption improvements up to almost 10% above manual transmissions.

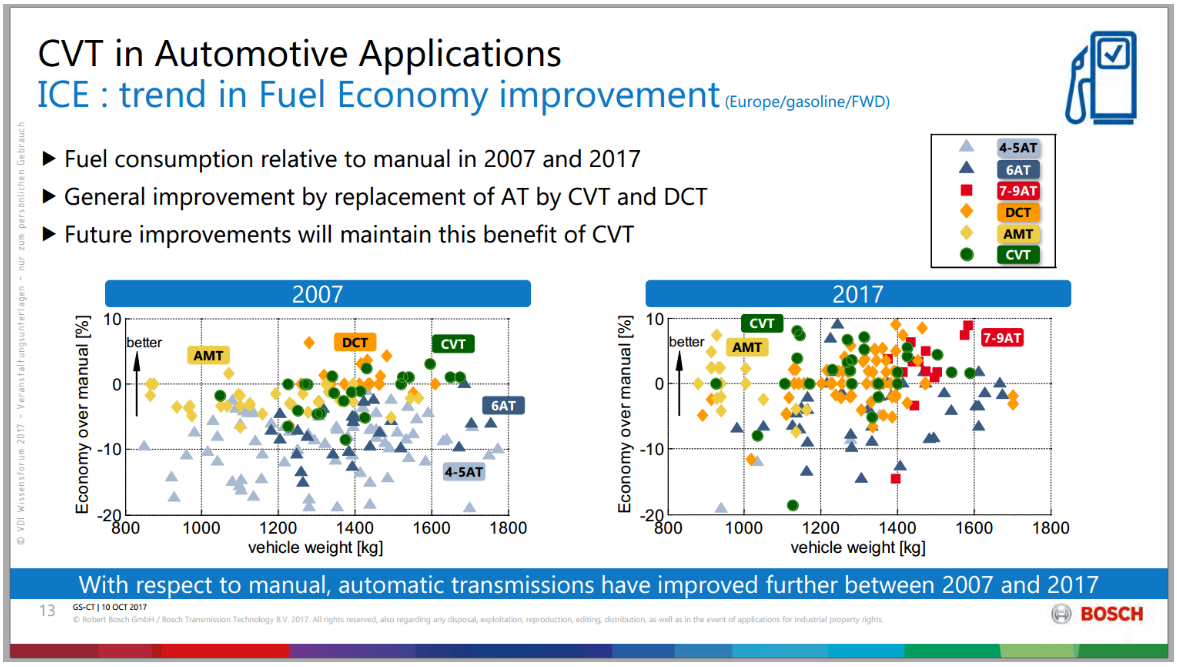


Figure 8 Transmission fuel economy advances since 2007.

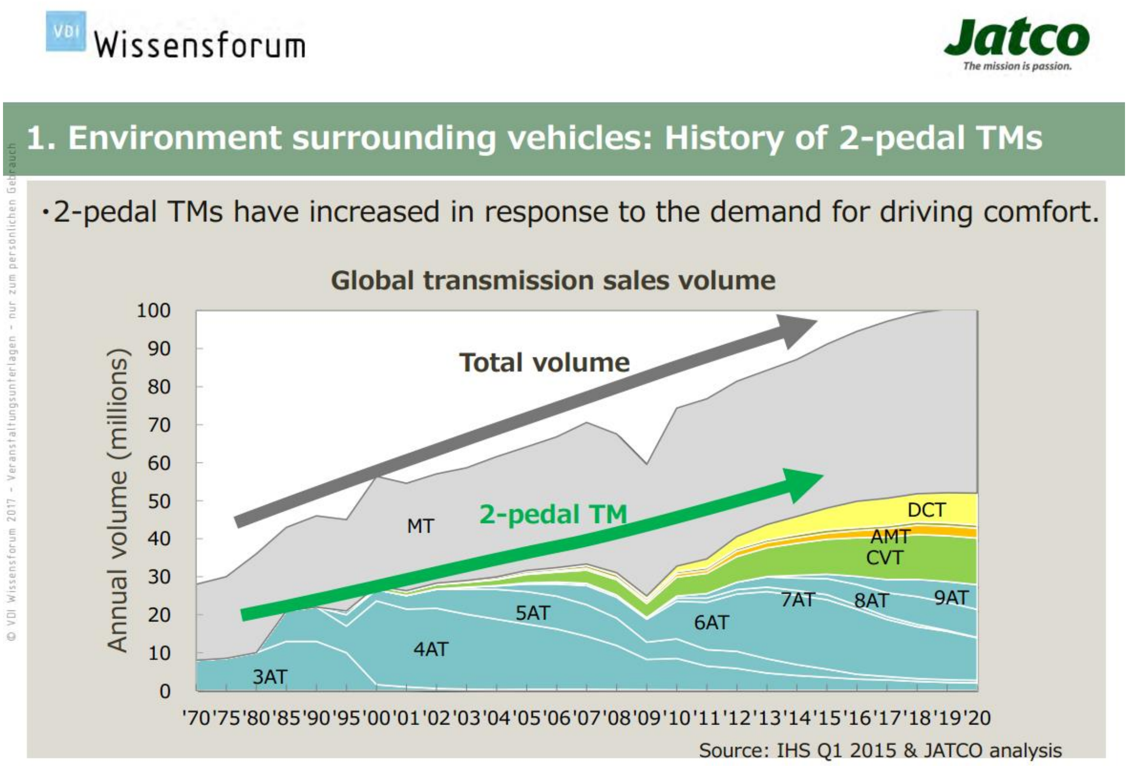


Figure 9 Automotive transmission volumes presented by Jatco.

Figure 9 presents the historic automotive transmission production volumes since 1970 up to 2017 and forecasted up to 2020, which shown the market share gain by CVT and DCT at the expense of AT's and MT's.

8 In summary

The advantage that sets the CVT apart from all other transmission is its ability to change its ratio continuously in infinite small increments and is called CVT capability. This feature is used to optimise the engine for all load conditions to always run the engine at its most efficient point in terms of fuel consumption and/or emissions. In cases where the driver demands maximum acceleration the engine is operated at maximum power point while the ratio adjusts as the vehicle accelerates.

However the disadvantage that sets the CVT apart from all other transmission is the fact that it is a friction drive where the friction drive has a much lower mechanical efficiency than a gear set in the case of MT, AMT, DCT or a planetary gear set in the case of AT.

In the race for the best fuel efficiency and emissions the following are the mayor trade-offs:

- CVT have full CVT capability but a lower mechanical efficiency, thus its full CVT capability is used to compensate for the lower mechanical efficiency and therefore all development efforts are aimed at increasing the transmission mechanical efficiency and ratio range.

- All other stepped transmissions have partial CVT capability but higher mechanical efficiency, where in this case development is focused on increasing the ratios (currently up to 10) to increase partial CVT capability while reducing the shifting losses between ratio shifts.

Above is then further dependent on the specific vehicle class which also introduce cost limitations.

The current state of affairs in above race is that AT and DCT are now at 10 ratios with a ratio spread of 10. Ratio spread is simply the highest ratio divided by the lowers ratio.

Current CVT cannot generate a ratio spread of 10 in one belt/chain and pulley or toroidal system and therefore need to be integrated in a at least two mode gear system to increase the ratio spread to 10. Such a two mode system is typically synchronous, thus the overall ratio remains constant during the mode change.

To complicate matters even further is the fact that different transmission mechanical efficiencies do not react the same under different load and speeds and therefore introduce a further control requirement as follows:

- For CVT the clamping for is controlled very precisely, because over clamping causes lower mechanical efficiency while under clamping will cause damage to the transmission. With lower overall clamping a smaller hydraulic control pump can be used which brings down the hydraulic losses.

- For stepped transmissions the ratio selection and control is critical as well as the shifting between gears without a torque interruption. This typically involves the controlled disengagement of the clutch associated with the current gear to overlap with the engagement of the clutch associated with the next gear.

In all of above whenever complexity is increased the cost also increases and thus a balance between performance and cost is also critical.

Above is even further complicated by the addition of a hybrid component (typically an electric motor/generator and batteries) and it is currently argued by the current CVT manufacturers that CVT can better deal with these additional complexities than stepped transmissions could.

The ideal bench mark for all transmissions will typically be using the same engine and vehicle being evaluated with different transmissions over the variety of formal drive cycles to measure fuel consumption and emissions. However in the real world another complication is added namely the engine. Thus manufacturers match the transmission with the engine to optimise fuel consumption and emission and the complete vehicle is then evaluated over the formal drive cycles. Thus the end result of these tests cannot be used alone to point to a better transmission or engine, but rather the optimised drivetrain.

9 What is different in the RADIALcvt

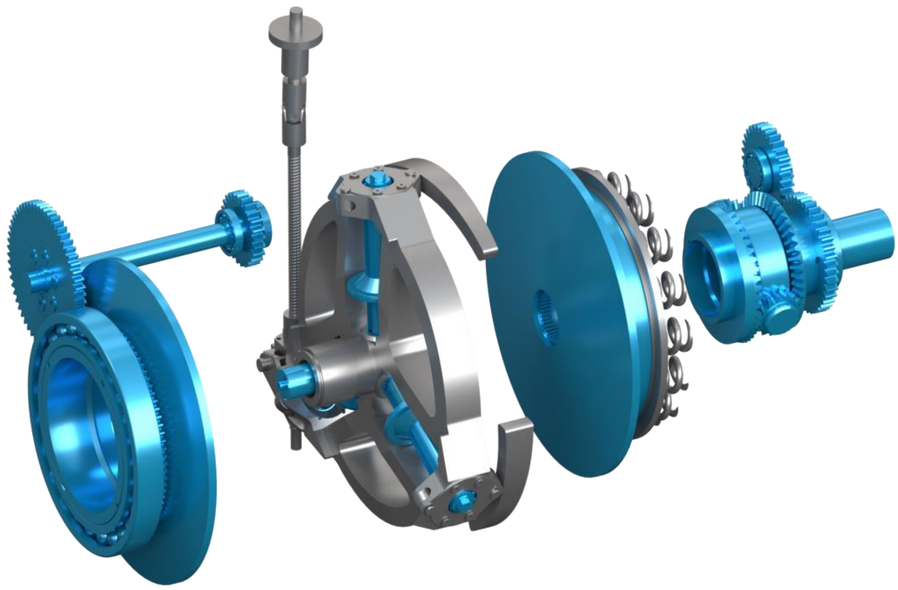


Figure 10 Varibox RADIALcvt

The RADIALcvt as a traction/friction drive with CVT capability, was designed by Varibox for the specific purpose of addressing the low mechanical efficiency and complexity associated with current CVT's. The issues listed below addresses the root cause of the respective shortcomings in current CVT and address these at a fundamental level.

- The first fundamental difference is that the RADIALcvt has only one friction drive in series in its power path where all other CVT has two. Thus the RADIALcvt concept starts off with the potential to have 50% of the friction/traction drive losses in comparison to current CVT's

- The current RADIALcvt includes a constant clamping force via mechanical springs and this allows the elimination of the hydraulic control and associated losses in current CVT's. All current CVT cannot function without a hydraulic control system.

- In the RADIALcvt the clamping force related bearing losses is only related to the output speed of the transmission. In all other CVT's these losses are related to both the transmission and output speed. This gives the RADIALcvt an advantage in low ratios associated with partial load city driving where current CVT's have their worst mechanical efficiency.

- To add onto above is the fact that each unit of clamp force in the RADIALcvt supports two parallel power friction/traction drive paths where in all other CVT's it supports two power friction/traction drive paths in series. Therefore the RADIALcvt will typically only require 50% of the clamping force if compared to current CVT's.

- All of above advantages in the RADIALcvt is realised by its unique patented mechanical component configuration while using the well matured traction drive technology which is used by all other CVT's and which has been in existence since the 1980's.