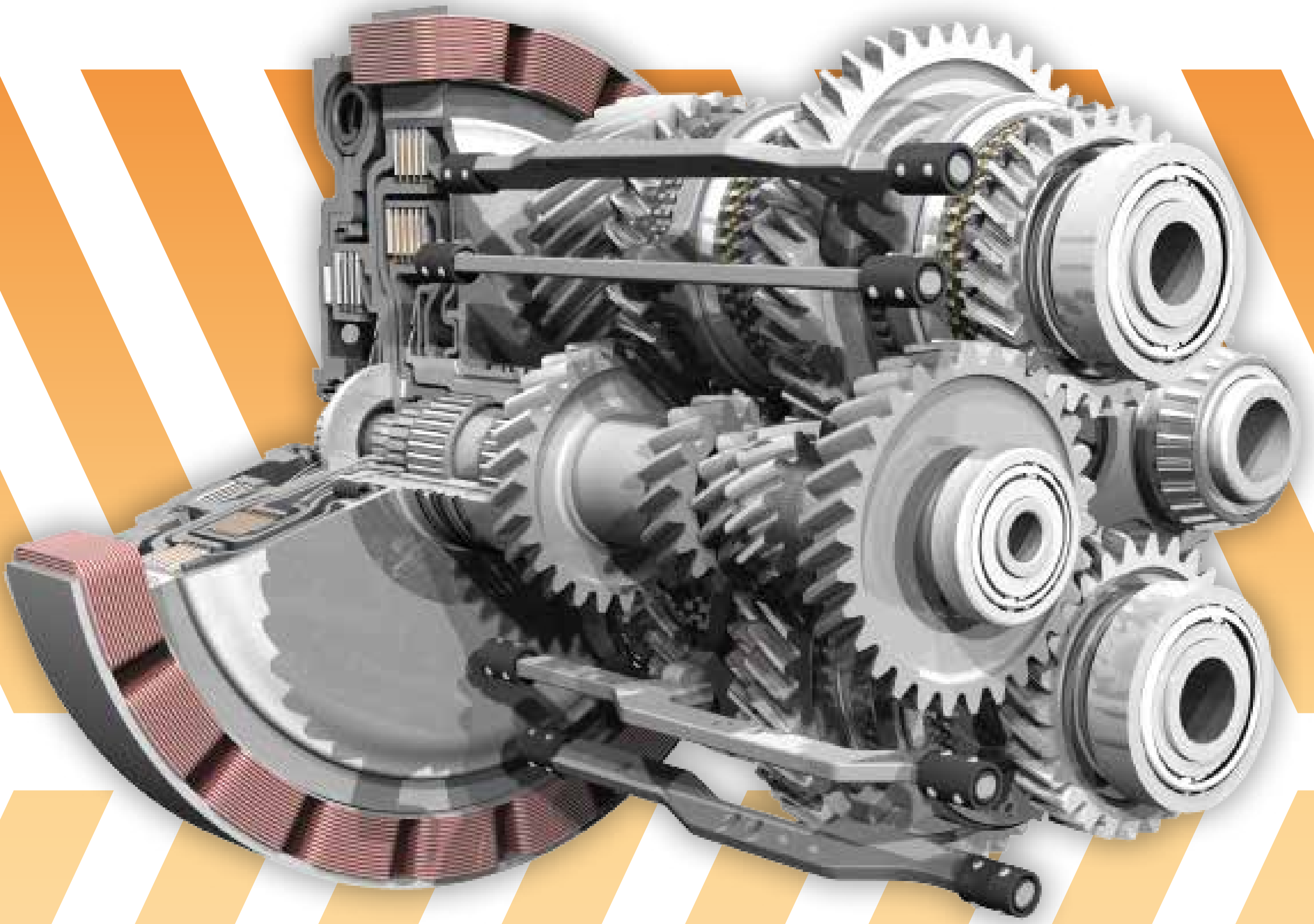
CTI MAG

The Automotive TM, HEV & EV Drives magazine by CTI

December 2016



A New Automatic Transmission Approach – a Suitable MT Replacement?

The Effect of Vehicle Electrification on Transmissions and the Transmission Market

Interview with John Juriga
Director Powertrain,
Hyundai America Technical Center

What Chinese Customer is Expecting


DRIVING EXCELLENCE.
INSPIRING INNOVATION.

CTI MAG Contents

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Dear readers,

Welcome to the seventh issue of CTI Mag! With 22 contributions, it's the biggest since our launch in 2013. Starting with an IHS market analysis, we've covered a wide range of current developments on your behalf in the field of transmissions and drives.

In this issue well-known manufacturers and suppliers talk about their latest electrification concepts, but also about new developments in conventional transmissions and individual drive components in terms of efficiency, performance and costs. The latest insights in development methods and drive component production are another key topic, with contributions from AVL, Getrag, GKN, BorgWarner, Oerlikon and many more besides.

To give you the bigger picture, we also interviewed high-calibre experts from the automobile industry. Read for yourself what Hyundai's John Juriga has to say about full and plug-in HEVs for the medium segment, and how Eaton's Jeff Carpenter answers the latest questions on DCT.

And for everyone who was there (and those who couldn't make it), we've included a follow-up report on our recent CTI Symposium China too.

Our special thanks to everyone who helped to make this issue happen.

Happy reading!
Your CTI Mag Team

PS: The eighth issue of CTI Mag will be published in May 2017.
The submission deadline for articles and adverts is 1 March 2017.
To get all the details, just send a brief email to michael.follmann@car-training-institute.com.

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The Effect of Vehicle Electrification on Transmissions and the Transmission Market

It is clear that the electrification of on-highway vehicles is now very much a reality. But what are the implications for transmissions, and the transmission market, as governments, OEMs, suppliers and customers all strive for lower CO2 emissions/fuel costs?

■ Chris Guile, Principal Analyst, IHS Automotive

Introduction

From a technical perspective, there is a broad range of possible configurations for OEMs and suppliers to consider, when thinking about vehicle electrification. Whilst we cannot evaluate all of these possibilities in such a short article, what we can do is look at some of the broader market trends which are emerging, during this 'embryonic' period. Let us start by looking at the implications for the different types of electrified vehicle:

Electric Vehicles

For Electric Vehicles (EVs), there are many simple reduction transmissions/systems, which are available for the OEMs to use. However, the volumes for EVs are not expected to represent a significant share of the global market (see graph below). In this respect they do not yet pose a threat to the existing transmission suppliers/supply chain. Having said that, the high torques available from electric motors are making EVs increasingly attractive to customers, for sporty/performance applications. For the moment, most of these vehicles use single-speed transmissions, but IHS Automotive does expect multi-speed transmissions to be used in the future.

Stop-Start/Mild Hybrids

At the other end of the electrification spectrum we have the stop-start vehicles, and the slightly more complicated mild hybrids. Here we have much higher volumes to consider, but for these applications conventional transmission technologies will be used, in most cases.

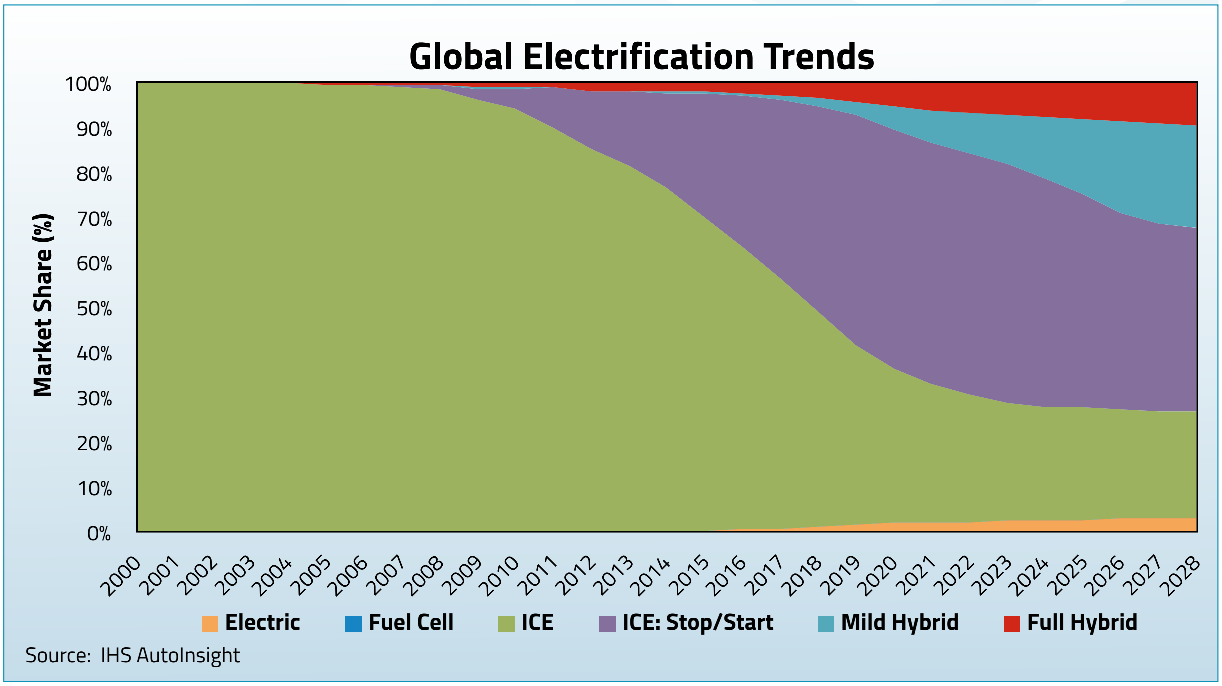
Usually, an additional sensor is all that is required to confirm when the transmission is in neutral, for the stop-start operation. Most non-manuals also need some way to maintain oil pressure, usually in the form of an electric oil pump, or an oil storage system. Manual transmissions will also be offered on mild hybrids, particular in Europe, some of which will switch to e-clutches.

With so much investment in the existing supply chain and production equipment, leading to high levels of inertia, this slow 'evolution' of an existing technology is a story we have seen many times, in the automotive industry.

Full Hybrids

But the most interesting question arises when we consider the full hybrids. Despite their current low share, this is an important part of the market, and involves much more complex powertrain systems which always require some kind of transmission.

For the full hybrids, OEMs have to ask themselves: 'Should we retain conventional transmissions, or should we develop/use some kind of



Dedicated Hybrid Transmission (DHT)?' For some, the costs involved in developing a DHT are prohibitive, at this stage, whilst for others the need to build up knowledge and experience is paramount.

As the first OEM to bring full hybrids to the market, Toyota initially offered products which featured a CVT or a DHT, but they quickly dropped the P210 CVT in favour of the DHTs. And with the significant volumes which they have been able to achieve, have stuck with that technology ever since.

Fast forward to 2016, and we now have many more full hybrids using DHTs (or 'EVTs' in the IHS terminology), but we also have many using 'standard' transmission types, as well. These typically feature some kind of add-on electric motor, to achieve a cost-effective modular strategy.

As you can see from the following graph, IHS Automotive is currently forecasting about 5 million EVTs (= DHTs) per year, by 2028, which represents just 5 % of the global market.

In the following sections, we review some of the transmission systems already employed in full hybrids, including those OEMs who have already invested in DHTs:

Hybridised AMT Transmissions

Despite their relatively simple, and cost-effective design, AMTs are not generally used for full hybrid applications. At first sight, the torque infill available from an electric motor may appear to be attractive. But in reality, the electric motors are not usually able to provide enough torque between the lower gears, where the torque interruption is most obvious to customers. Of those systems in use, the PSA MCPH4 is probably the best known example, but this will be phased out in favour of an automatic transmission, as PSA launches its new PHEV applications. Suzuki is also known to be working on an AMT-based full hybrid system, although it may have been delayed, or possibly even dropped.

Hybridised CVT Transmissions

Another early adopter of full hybrid technology was Honda, with CVT-based systems, although these have recently been replaced by DCT/DHT-based systems. In the last few years, Subaru has started to offer full hybrids, based on the TH58 CVT from Fuji Heavy Industries. And more recently, Jatco has seen its CVTs used in Nissan hybrid applications. But despite only being favoured by a few OEMs, the volumes for full hybrid CVT systems are expected to rise.

Hybridised DCT Transmissions

The volumes for DCTs in full hybrids are rising quite significantly, and are being used by many different OEMs. The VW Group is already using the transverse DQ400, and will soon launch a hybrid version of the longitudinal DL382. Porsche has already used the ZF 7DT75 in the 918 Spyder hybrid, with more Porsche applications expected in the future, using the recently announced ZF 8DT. Hyundai has recently launched DCT-based full hybrids, using its D6KF1.

Many other OEMs, particularly in China, will be launching similar applications in the next few years, whilst here in Europe Getrag is offering OEMs a broader range of hybridised DCTs. IHS Automotive also expects that Daimler will offer DCT-based hybrids on its various FWD (i.e. MFA platform) applications, whilst Volvo/Geely is known to be developing a DCT-based hybrid system, for its smaller CMA platform applications.

Hybridised Automatic Transmissions

Full hybrids based on classic automatic transmission designs are also growing significantly. One reason for this is the ease with which the torque converter can be replaced by an electric motor and clutches, with only a modest increase in package length. OEMs like Hyundai and Daimler have already embraced this technology, whilst suppliers like Aisin, Jatco and ZF are also supplying automatics to many OEMs such as BMW, Nissan and Volvo. Other OEMs are, of course, expected to follow using similar systems.

Dedicated Hybrid Transmissions

The design and structure of DHTs, which are characterized by having the electric motor/s fully integrated into the transmission, is just as varied as the number of potential hybrid configurations.

The Aisin/Toyota DHTs are the most established in the market, making up the majority of all DHTs manufactured to date, and are based around a planetary gearset. In these applications, one input of the planetary gearset is driven by the combustion engine, the second input is driven by the electric motor, giving a variable speed drive at the output to connect to the wheels.

Since 2013, Honda has offered full hybrid applications on the market, which feature planetary DHTs. Volumes are still quite low, but it is anticipated that this may become the hybrid technology of choice at Honda, in the longer term.

Back in 2006 we saw the evolution of the Advanced Hybrid System 2 (or AHS2) – a joint venture project between GM, Daimler and BMW. However, both of the German OEMs quickly backed away from the project after very short production runs, preferring instead to pursue more established technologies. This left just GM, which has subsequently developed several variants, with more expected in the future.

Ford introduced its HF35 DHT to the market in 2012, based on a planetary gearset arrangement, which is used in a handful of applications. A revised HF45 version is understood to be under development, and IHS Automotive expects this to be offered in many more applications, with much higher volumes in the future.

Another existing hybrid, which uses the GKN 'Multi-Mode' DHT on the front axle, is the Mitsubishi Outlander. This transmission has just three operating modes: EV, parallel and series. But in the parallel mode just a single fixed ratio is used, when the combustion engine is connected mechanically to the wheels.

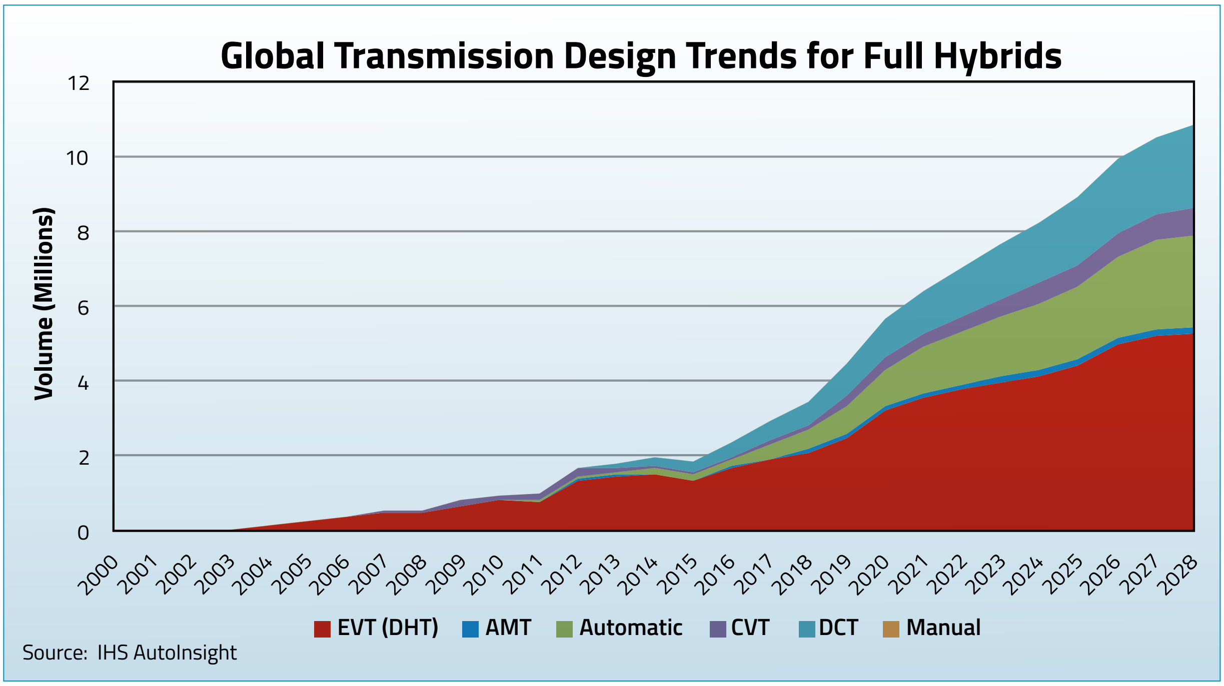
Finally, we have the new Chrysler EVT, or rather SI-EVT (Single Input, Electrically Variable Transmission), which has been announced for use in the Chrysler Pacifica minivan. Like so many of the others, this is based on a planetary gearset, but uses two electric motors – both of which can be used to propel the front wheels. Other applications will almost certainly follow the Pacifica.

One DHT which is currently under development, is the Renault 'LocoBox', which was first seen in the Renault EOLAB concept car. But Renault is probably also considering hybrid versions of the Getrag DCTs, which Renault already uses in many applications. So is Renault currently at a crossroads, regarding their transmission strategy for full hybrids? Perhaps they will decide to hedge their technology bets, by adopting both strategies until a clear winner becomes apparent. Or perhaps different systems will become optimal in different types of hybrid, or vehicle segment, or regions of the world. Even with extensive computer analysis and simulation, there is no substitute for trying something out, to see how it works in practice. Whilst it may be possible to predict the expected vehicle CO_2 emissions, it is much harder to predict how real customers will react to a particular technology, and its driving feel.

Transmission Suppliers

Another interesting way to observe the market, is to look at the different strategies adopted by the large independent transmission suppliers. Some, like Getrag, Jatco and ZF, have chosen to engineer variants of their standard transmission products, so that they can offer the OEMs a hybrid system, complete with an electric motor and sometimes more. Contrast this with Aisin, which seems content to offer its standard automatic transmissions, for OEMs to engineer into their own hybrid configurations.

The first strategy offers OEMs a simple and probably cost-effective solution, but may limit their ability to tailor the system to their own



exact requirements, or strategy. The Aisin route, on the other hand, gives the OEMs much more control over the system design, but would incur higher development costs. Aisin does of course offer some DHTs, but these are now only used in Toyota/Lexus applications.

What is curious is that most of these independent suppliers, who could probably garner greater volumes through multiple customers, have yet to bring DHTs to the market – at least so far. Is this another example of the inertia in the industry, leading to evolutionary, rather than revolutionary technology trends?

Final Thoughts

As is frequently the case, it is all about having the right technology at the right time. We can probably all think of examples where a technology was introduced too early to the market, resulting in low volumes and a short production run. Toyota, on the other hand, developed DHTs for its early full-hybrids, and has steadily increased penetration rates, to the extent that more than 90 % of Lexus vehicles, and more than 30 % of Toyota vehicles sold in Europe, are now full hybrids.

We are also beginning to see the number of physical/mechanical gear ratios, in a transmission, becoming less of a defining characteristic. This is because manufactures are cascading gears to create virtual ratios (e.g. DCTs from Getrag and Punch Powertrain), or because some gears/operating modes rely on the electric motors only, as seen on the Renault and GKN DHTs. So, the number of gears/modes, which may be apparent to the vehicle driver, could end up being characterized more by the transmission control software, than the physical hardware.

We are often asked to speculate on what might replace the hugely popular ZF 8-speed 8HP – which uses an add-on motor for hybrid applications – and in particular how many forward speeds it would have. But I can't help thinking that by then, something much more integrated (i.e. a DHT) may be more appropriate, and that the number of speeds will have largely become irrelevant.

Conclusions

So, is it time for the OEMs to launch DHTs? Well not just yet – in most cases. But it is certainly time for them to start looking seriously at DHTs, to see where, and perhaps more importantly when, they logically fit into their electrification strategies.

But whilst DHTs are the most interesting from an engineering perspective, we also have to consider if full hybrids will ever take a significant share of the market. The automotive market has long been known to go through evolutions, rather than revolutions, and with mild hybrids offering a simple and cost-effective option for high volume applications, the question then becomes what will replace the mild hybrids – more full hybrids, or more electric vehicles?

The graph above currently shows a broadly equal split between the DHTs and the add-on transmissions, in the outer years. This is based on IHS Automotive's current understanding of the OEMs' productions plans. However, with most of the powertrain consultancies and several OEMs already working on DHTs, we fully expect that the trend will begin to favour the DHTs, in the longer term.

Either way, there are no wrong answers at this stage.

What Chinese Customer is Expecting

- Dr Jiang Hong, Managing Director, AVL China
- Mario Brunner, Head of PC transmission, AVL List GmbH Austria
- Fuchun Zhao, Business Development Transmission China, AVL China
- Dr Frank Beste, General Manager Shanghai Tech Center, AVL China

After 10 years fast growth of passenger car market in China, the main growth moves to Tier3/4 cities due to major cities' restriction on new cars registration. Customers expect high ends equipment option normally bonded with automotive transmission. They also expect transmission with lower noise and vibration, smoother shift behavior and better reliability. The regulations on fuel consumption and emission provides new challenges on powertrain. Other than add on hybrid module on traditional automatic transmission, The Dedicated Hybrid Transmission (DHT) provides another option for vehicle powertrain electrification and hybridization.

Developed and Developing China

According the vehicle registration data, the new passenger car sales have experienced a continuously in last 5 years more than 10 % with an exception in 2011. In the year of 2015, the new passenger car sales reach 18.9 M with 11.05 % growth compared to the new car sales in 2014. For prediction of future growth models can be based on China's per capita GDP and vehicle ownership per 1000 people. Of course, there is not much historical data on China's automotive development, but when assuming an analogy with industrial countries, China is with 128 motored vehicles per 1.000 people and a GDP of 7.99 USD in 2015 still at the beginning of automotive development. This analogy suggests a further rather linear growth of automotive sales with GDP development until saturation effects as they are known in the industrial countries become effective. But reduced growth by local car-population control actions can already be observed in the most populated and economically strong Tier 1 and 2 mega cities. The share of automotive sales growth shifts away towards the very high number of also large and developing Tier 3 and 4 cities. These cities are spread across the country and are often not known outside China. But they include by far the majority of Chinese households, income value and further growth opportunities.

By now China already has become the world's largest automotive market and provides the main growth opportunities to the industry. But the large cities noxious smog is a permanent reminder of why China needs to further step up investment in clean energy. New legislation developments are promoting ambitious fuel efficiency targets, in parallel the world strictest emission legislation and changed but continued promotion for NEV production. This will push China into a pivotal role for future evolution of the automotive powertrain system.

To combat air pollution and significant traffic congestion, Shanghai started to introduce new vehicle sales restriction in the year of 1994. Beijing followed the sales restriction in 2010. Currently 7 major cities in China introduced the new car sales restriction measures including:

- Set quota for annual new car license plates and very high license plate fees
- Introduce traffic restrictions – cars will be not allowed to enter the city center on certain days depending on license plate numbers
- For the given quota, city governments either distribute the license plates through auction or lottery

In some cities NEVs are already exempted from these restrictions and can receive special license plates for free. The combination of Central China government incentives and local regulations are substantial and have proven to be very effective to push NEV sales. In summary for the example of a typical C-segment Sedan in Shanghai this NEV promotion results in an about 30 % lower customer payment for a PHEV car which is 65 % more expensive in MSRP compared to a conventionally propelled alternative:

- Taxation: 10 % purchase tax exempted, no annual vehicle tax, no consumption tax for BEVs
- Central and local incentives
- Avoidance of lottery and auctions
- Electric power is provided at residential pricing

The fastest growth vehicle segment is SUV. The year to year growth is 46.97 % in 2015 and almost reaches the sales volume of compact cars. MPV segment gets the growth of 41.05 % though the absolute sales

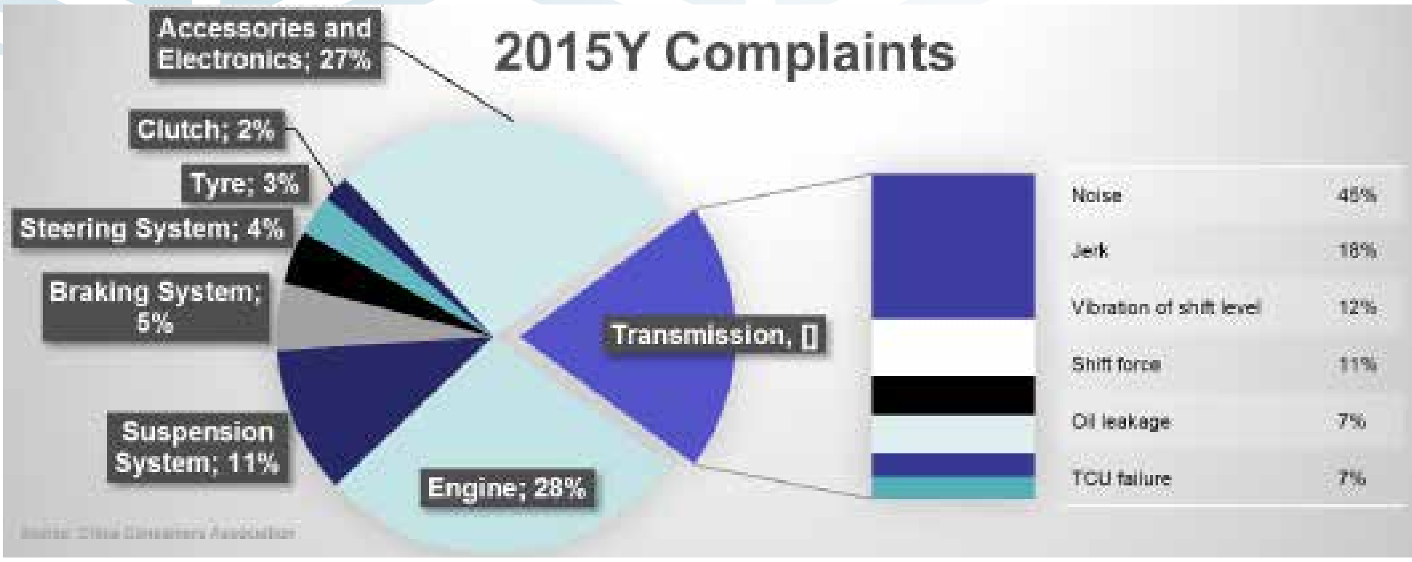


Figure 1 Customer complains in China

volume are much lower. Significant of the bestselling vehicles and the new launch vehicles in 2016 are equipping of high end interiors and options including: Open roof, large front display and leather seats. As the high end interiors and options were always bonded with automatic transmission vehicles in last decades in China, it is also pushing up the automatic transmission vehicle sales together with trend of pursuing comfort driving under traffic congestion.

Transmission in Chinese Market

Four of the five largest cities in China have more than 60 % of passenger cars equipped with automatic transmissions. Foreign Joint ventures companies sell more automatic transmission cars than manual transmission cars but local brands companies still have more manual transmission vehicle sales than automatic transmission vehicle sales. There is clear trend towards automatic transmission in China together with trend of more varieties in vehicle types and growth in larger size vehicles such as SUV and MPV.

Due to the size of the country, the vehicles and their transmissions in China need to be ready for much broader application conditions such as extreme temperature and altitude range, and varying road and traffic conditions.

What are the Chinese customer's expectations for vehicles and transmissions? The information published by China Consumer Association shows that automotive product has the 2nd highest complains right after IT product at the last quarter of 2015 from end consumer. Among those complains, 58 % of them are for foreign JV brand products and 40 % are for local brand products.

28 % of those complains are Engine problems and 20 % complains are Transmission problems (see Figure 1). The detail breakdown of complains about transmission is as the following figure. According to the breakdown data, NVH, Shift quality and Reliability are the top 3 issues are concerned by the end consumers.

Chinese Driving Conditions

Often reported is that Chinese driver's prefer to shift at extremely low engine speeds.

The AVL DRIVE readings show this preference for high gas-pedal positions and about 500–700 rpm lower engine speeds at slow driving conditions. The full engine speed range is not utilized. Besides NVH effects at low rpms also further development focus regarding electric load balancing, AC system performance, slower engine heat up and power-brake function might be needed.

For Chinese city driving with low average speed, idle conditions and very little constant pedal and velocity driving are dominant. In this situation the AVL DRIVE study shows, that there is a Chinese driver tendency towards gas-pedal pumping. Good vehicle drivabilty and spontaneousity might require to adapt transmission shift strategy by using a Busy-Shift-Avoiding Function at these low vehicle speed.

Also at the traffic light or stop and go, Chinese automatic transmission drivers tend to shift into N during standstill. While in Europe the little number of D-N-D engagements per trip is not significant regarding drivability assessment, this frequent use of the N-position in China might require to pay more attention to transmission engagement and idle function during calibration. Also and different from markets like US the neutral idle function does have Chinese customer acceptance and can help to reduce fuel consumption.

Some new challenges: Does fuel consumption regulation and electrification incentives drive to DHT

Chinese environmental reforms and regulations (CN6 and China Stage 4 FC) and also the government and local city incentives for NEVs continue strongly influence the Chinese automotive market. The LD CN6a and CN6b emission legislation is based on but is expected to become more stringent than EU6c emission legislation. It includes RDE and

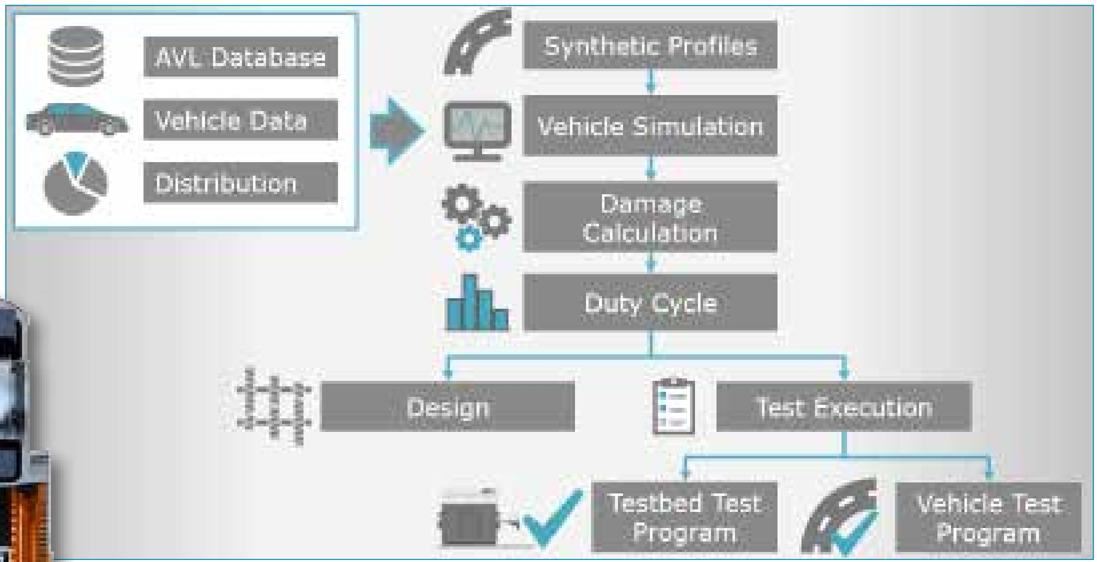


Figure 2 AVL duty cycle workflow

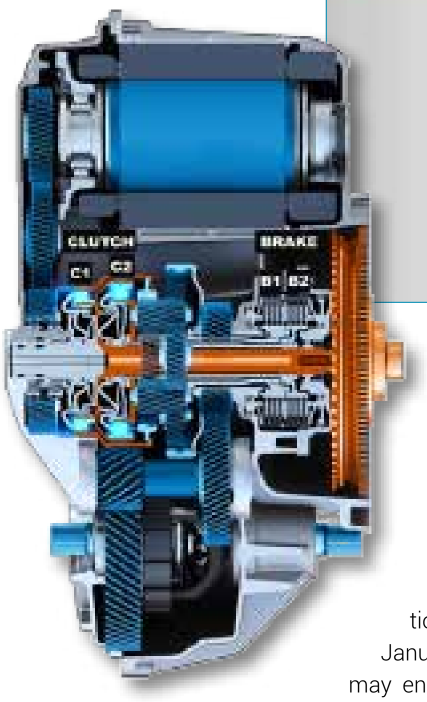


Figure 3
AVL Future Hybrid
Gen 2–8 Mode

also elements of the US emission legislation (e.g. ORVR, OBD) and is expected to be released until end 2016 with nationwide enforcement for January 2020. Tier 1 cities may enforce earlier. RDE will be optional until 2022. This emission enforcement is expected within a short period and in parallel to the new China Stage IV fuel consumption requirements which will become mandatory by 2020. Based on these announcements China is preparing to introduce the worldwide most stringent emission legislation in parallel to very ambitious fuel consumption targets.

For NEVs the current government subsidies for passenger cars are expected to reduce by 20 % in 2017–2018 and will reduce by 40 % between 2019–2020. Current policies will be replaced by the introduction of a national carbon emission credit trading scheme plus further industry promotion activities including tax incentives, infrastructure development and standardization starting from 2017. Relative to the CAFC (China Stage IV) fuel efficiency introduction policy the carbon trading scheme will result in positive credits for most companies until 2019. Subsequently negative credits will result from exceeding the more stringent China Stage IV fuel consumption limits. NEVs will remain in the range of positive credits since well-to-tank emissions are excluded. The resulting trading of carbon emission credits is expected to continuously promote NEV production in a similar range as today's policy. With this new policy established OEMs and also many new start-ups start to position themselves in the NEV field.

Besides BEVs especially for PHEV and Full Hybrid vehicles, transmission is becoming the one of the most essential component for technical solutions. Either applying the add-on P2 module to the existing automatic transmission or developing a complete new Dedicate Hybrid Transmission are under discussion with consideration of: overall investment, supplier base, product cost, time to market and so on.

The idea of dedicated hybrid transmissions is driven by the cost pressure with increasing production volumes of HEV and PHEV vehicles. DHTs are based on a very simple idea, if an e-motor is available, the e-motor may take over transmission functionality. In a HEV or PHEV the e-motor can as an example take over the launch of the vehicle. In this simple example, the torque converter or double clutch unit can be saved, which leads to lower overall costs, a reduction of weight and improves the package situation. Additionally driving in areas with low ICE efficiency is avoided, this regions are taken over by e-motor. This means, the number of gears for the ICE can be reduced. The most famous example for that is the Toyota Hybrid System (THS), the transmission complexity is reduced to a simple planetary gear set. With two e-motors Toyota invests a little bit more on the electrifications side. Another example is the GKN Multimode transmission, which was launched 2013 in the Mitsubishi Outlander. The system allows pure EV drive, a serial Hybrid mode, supported by the ICE via generator in situations with high-power-demand or low battery SOC and a parallel Hybrid with direct ICE support. For the parallel hybrid mode, only one gear ratio is available. AVL presented in 2012 the Future Hybrid 7 mode (3 parallel hybrid, 2 electric driving and 2 eCVT modes). 7 operating modes are provided with 3 clutches and one brake. The DHT is available in an AUDI A3 demonstrator vehicle. 2015 AVL presented the second generation of the Future Hybrid (see Figure 3), the 8 mode provides 5 parallel hybrid modes (load point shift and regeneration possible for all of them), 2 gears for electric driving and one eCVT mode. Additionally an efficient standstill charging is possible. The design is modular in terms of scaling the electric power, in terms of installation (transversal or a longitudinal installation) and in the meantime even in terms of electrification. That means the design is modular to convert the original DHT design into a 48 volt or even conventional transmission. This allows maximum flexibility to react on market and legislation trends.

HEV P2 Module Concepts for Different Transmission Architectures

- Brad Chamberlin, Technical Specialist, Innovation and New Concepts, BorgWarner
- Eckart Gold, Senior Manager, Advanced Engineering, BorgWarner
- Jörg Nitsche, Director, Business Programs, BorgWarner

Introduction

Driven by tough regulations and consumer demands for CO_2 reduction, efficiency and performance, automakers are accelerating the introduction of electrified and hybrid vehicle propulsion systems. Considerations such as system architecture, packaging, performance and cost are all critical aspects during development. By carefully evaluating the system trade-offs to maximize the value to the consumer, BorgWarner has developed P2 systems with an integrated clutch and E-motor.

Background

Hybrid concepts combine an electric motor (or E-motor) with an internal combustion engine (ICE). Common nomenclature defines the possible electric motor positions as P0 to P4, as shown in Figure 1. Depending on requirements for fuel savings, performance, cost, packaging space and other targets, automakers can choose between several technical solutions and arrangements, each with specific advantages and disadvantages.

A currently favored hybrid concept is the P2 arrangement, where the E-motor is placed between the ICE and the transmission. The cost-effective P2 concept allows producers of a step automatic transmission (AT), dual-clutch transmission (DCT), continuous variable transmission (CVT) and automated manual transmission (AMT) to transform an existing vehicle into a hybrid most easily. The main P2 elements are an E-motor, disconnect clutch and related actuation system elements.

P2 Module On-axis Arrangement

The P2 module is completely located between the ICE and transmission. The ICE crankshaft, damper element, P2 module (with disconnect clutch and E-motor) and transmission input shaft(s) are all on the same axis. The disconnect clutch is nested in the E-motor. On the input or ICE side, the disconnect clutch is connected to the damper element. The output side of the disconnect clutch is coupled directly to the rotor of the E-motor and the input of the launch and/or shift element. The stator of the E-motor is fixed in the module housing.

P2 Module Detail Configurations

When the strategy is to upgrade an existing transmission with P2 functionality, the design goal is to maximize the use of existing components. In this case, the disconnect clutch and E-motor are simply added in front of the existing transmission. (For a step AT, the torque converter might be omitted.) However, the transmission control system must be adjusted for control and lubrication of the disconnect clutch. This configuration is very popular due to its short development time and cost benefits.

The development of a completely new transmission architecture opens further opportunities to optimize packaging for the P2 module, especially in combination with a DCT. In this case, the two transmission clutches and the disconnect clutch can be integrated into a triple clutch module completely nested within the E-motor. Table 1 identifies the typical P2 configurations and the corresponding transmissions architectures that they can support.

Typical P2 Architectures	Step AT	DCT	CVT	AMT
P2 with Integrated Disconnect Clutch	X	X	X	X
P2 with Integrated Triple Clutch		X		

Table 1 Typical P2 Module Configurations

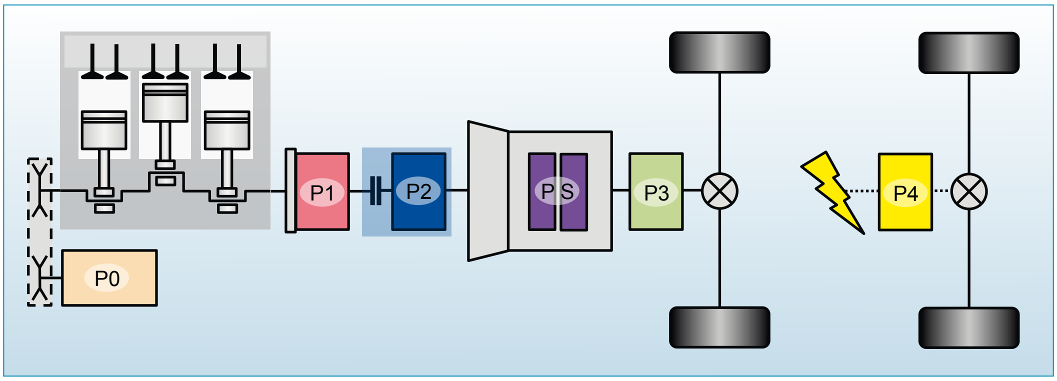


Figure 1 Common nomenclature for electric machine position P0 ~ P4.

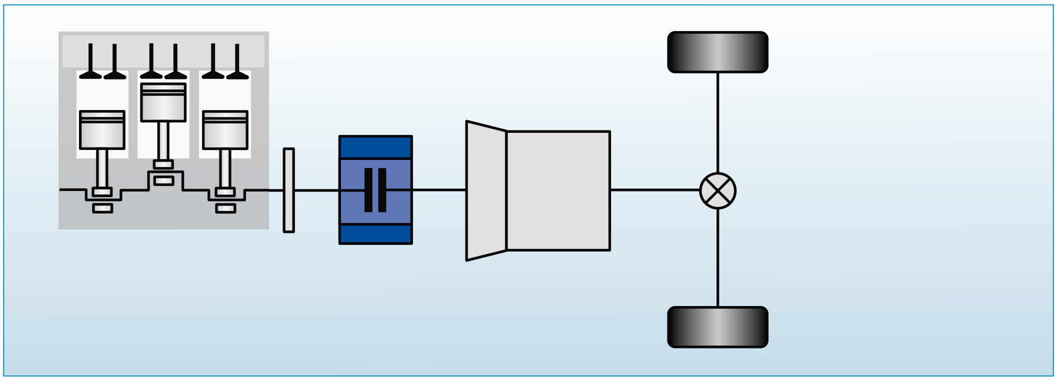


Figure 2 P2 module in-axis arrangement

P2 Module Clutch Design Considerations

Depending on the OEM's preferences for efficiency, performance, robustness, technical maturity and cost, the clutch actuation concept can vary significantly. The most popular variants are hydraulically (high pressure or low pressure) or electro-mechanically actuated.

The required torque capacity of the transmission clutches depends on the maximum torque of the ICE and E-motor, as well as their interaction. As ICE and E-motor can be operated simultaneously, the torque capacity of the transmission clutches could meet the summation of both maximum drive torques. If the maximum torque of the ICE and the maximum torque of the E-motor do not occur simultaneously, downsizing the clutches may be an option to save weight, inertia and cost. The torque capacity of the disconnect clutch must be adapted to support the maximum torque of the ICE to ensure that there is not any unintended slipping during operation.

The clutch friction technology used depends on the launch, shift and drive cycle strategy. If the disconnect clutch needs to provide full launch capability or must be used in a continuous slip mode, adequate friction materials must be selected to maintain the performance over the complete product life.

Due to the fact that the clutch(es) are nested inside the E-motor in an on-axis configuration, the lube oil, which is applied to cool the clutches to maintain high functionality and performance, can be guided to the E-motor for effective cooling of the rotor.

Depending on the pump concept itself (e-pump and possibly an additional conventional ICE-driven pump), the P2 module can also provide a clutch-integrated pump drive gear.

All of these design aspects are considered in the BorgWarner P2 module. Several products are available to best suit the OEM's specific demand. As an example, the on-axis triple clutch P2 module with an overall torque capacity of 500Nm and disconnect clutch torque capacity of about 350Nm can be packaged within an axial length of significantly less than 170mm.

P2 Module E-motor Design Considerations

A variety of design considerations need to be evaluated when designing the E-motor, both from the stator and rotor perspectives. Considerations such as torque or power density, thermal management, packaging space, and noise, vibration and harshness (NVH) related aspects (such as torque ripple) are evaluated to determine the best configuration.

Regarding the stator, the most common winding methodology is either a concentrated-wound or distributed-wound stator. These winding types can use either round or rectangular wire. Distributed-wound stators can also be bar wound, or concentric-wound.

With respect to the rotor assembly, common designs include induction and permanent magnet variants. Permanent magnet options can be either an interior permanent magnet (IPM) or a surface permanent magnet (SPM).

The chosen architecture of the BorgWarner P2 E-motor consists of a rectangular wire distributed-wound stator assembly with an IPM rotor for both the on-axis and off-axis solutions.

The distributed-wound stator assembly provides for extremely low (less than 5% in the on-axis configuration) torque ripple and cogging torque. This equates to lower NVH from the E-motor and reduces the overall system NVH by eliminating a significant portion of the pulsations from the E-motor. In comparison, an alternative concentrated-wound E-motor may have as much as 20% torque ripple, requiring additional controls and dampening from the system level to minimize the adverse impact of NVH.

The distributed-wound winding utilizes a rectangular cross-sectioned conductor to maximize current density, allowing the on-axis E-motor with an outside diameter of 270 mm to deliver peak performance in excess of 345 Nm of torque and 110 kW of electrical power as well as continuous performance of 170 Nm of torque and 60 kW of power. Increasing the surface area of the conductor in contact with the stator laminations improves the ability to transfer heat out of the conductor in a more efficient manner. Both analysis and testing have shown that an E-motor with a properly designed rectangular conductor can achieve far higher continuous performance levels compared with a round wire electric machine, all while maintaining the same packaging envelope and cooling methodology.

The optimal method for cooling depends upon the available medias and their corresponding temperatures. In general, a cooling system utilizing oil is the most effective for removing heat from the E-motor because it allows the coolant to be placed in direct contact with key thermal components of the electric machine, including the stator laminations and conductors, as well as the rotor laminations and the magnets. By allowing the oil to make direct contact with these components, the heat is efficiently removed by minimizing the conductive path that exists with other cooling methods.

In systems that have particularly high oil temperatures, high performance can be achieved by using a water ethylene glycol (WEG) system in combination with internally sprayed oil, if the WEG can be provided at a reduced temperature (typically 65 °C vs. 90 °C). In this case, optimal performance is achieved by combining cool WEG around the stator assembly with oil flow onto the rotor assembly. This combination allows for direct contact between the oil and the internal components of the E-motor assembly as well as a large temperature delta between the E-motor and the WEG coolant. Both cooling options are available with the BorgWarner P2 E-motor.

The IPM rotor balances the trade-offs between magnet retention, demagnetization resistance, magnet weight (and associated cost) and E-motor performance. By embedding the magnet into the lamination stack, the inertia of the system and the cogging torque can be minimized while improving the structural robustness and balance of the rotor assembly.

The BorgWarner P2 E-motor was designed specifically to be a compact, best-in-class electric machine providing high torque and power densities. The on-axis design accepts either single- or triple-clutch modules and easily packages in-line with the transmission.

BorgWarner's P2 Module Design Family Approach

Transmission manufacturers have different strategies for the system integration of their P2 modules, from their own in-house integration to purchasing complete pre-assembled and pre-tested P2 modules including the aluminum housing.

The challenge for component suppliers is to provide flexible technical solutions on one hand, and, on the other hand, keep a component family approach for cost efficiency.

From a value perspective, the E-motor is the most important element in the P2 module. Therefore, a standardized family of E-motors provides significant benefits. The dimensions of the E-motors define the design of other adjoining components in the P2 module, such as clutch housings and friction packages. Key E-motor characteristics are the motor performance data, rotor inner diameter, stator outer diameter and the axial length.

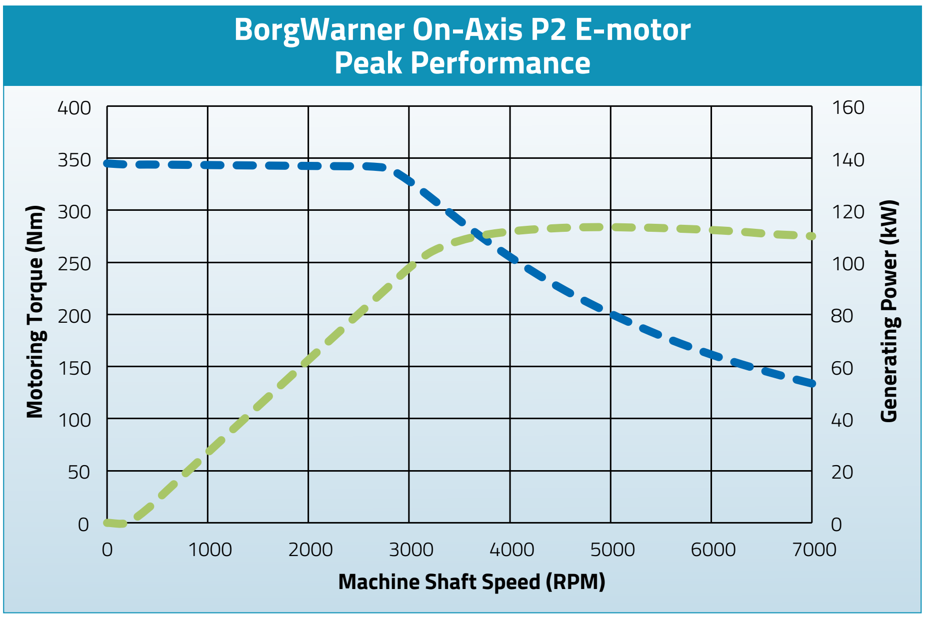


Figure 3
E-motor characteristic curves

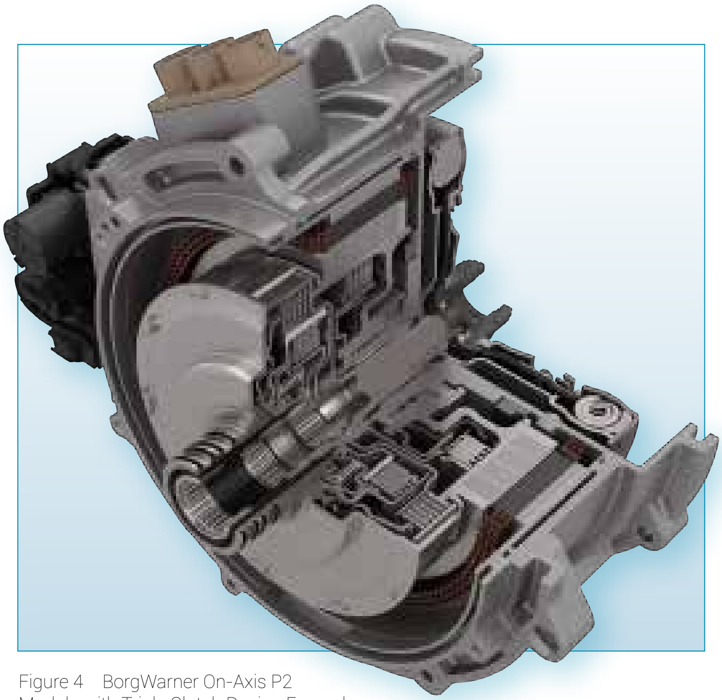


Figure 4 BorgWarner On-Axis P2 Module with Triple Clutch Design Example

Clutch design is mainly defined by the transmission concept, actuation concept, rotor inner diameter and targeted axial length. Standardized friction package dimensions can provide solutions for different torque levels by adjusting the number of plates.

Another aspect of the family approach is the possibility to integrate different kind of actuation systems, such as low-pressure conventional or high-pressure CSC type actuation.

Considering the variety of potential technical solutions for the specific applications, close collaboration is required to develop a tailored solution with optimized value.

BorgWarner is actively developing a family of E-motors and clutches for use in P2 modules. These products are configured specifically to maximize performance and benefits to the customer, at the same time being compact in size and allowing for flexible customer integration.

Dedicated Hybrid Transmission

Modular P2–P3 Dedicated Hybrid Transmission for 48V and HV applications

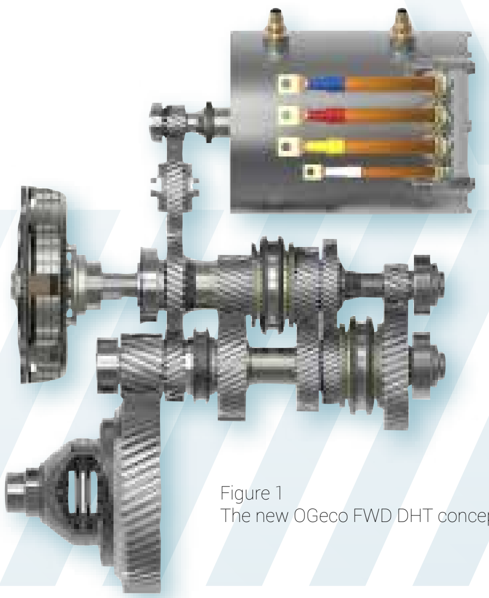


Figure 1
The new OGeco FWD DHT concept

The Oerlikon Graziano new OGeco FWD concept is a step ahead in compact and efficient systems on the way to electrification.

- Carlo Cavallino, Advanced Development Manager, Oerlikon Graziano
- Jacopo Rossi, Project Engineer, Oerlikon Graziano
- Marco Fracchia, Operations Manager, Vocis

The legislation limits for pollutant emissions are strongly pushing OEMs to electrification. This activity is seen from some manufacturers as an opportunity to increase the vehicle performance whilst also moving to more "green" powertrains. This means that the installation of electric power on the vehicle should, for sure, not affect negatively the performance of the internal combustion engine only model, but rather increase the performance while cutting the pollutant emissions. This is not an easy task, since the hybrid system (battery, inverter, electric motor) has a significant effect on the overall vehicle weight and thus its driving dynamics. In addition to this, most of the manufacturers look for synergies between hybrid and standard versions in order to minimise cost and investments of the overall vehicle platform. For the time being, all the above-mentioned concerns are even bigger because we consider hybrid car versions in the low to medium production volumes. Furthermore, the hybridisation of the standard vehicles should meet customer expectations, keeping then a good feeling in driving experience, otherwise a good green vehicle that is hard to sell won't help in decreasing the fleet emission level.

The Concept

Starting from these considerations, based on the experience grown in the last years thanks to the OGeco transmission (presented at CTI 2012), Oerlikon Graziano has designed and patented an elegant DHT concept. This has been achieved by continuous improvement activities ongoing on the demo vehicle and focusing on the market needs. The transmission is a modular concept that starts from a traditional 2-shaft single-clutch transmission. Thanks to a link between two main gears of the gearbox and the direct gearing between the electric machine and this linked gear arrangement, free-mounted on the primary shaft, the concept allows a very efficient electric path of the transmission, which presents two different gear ratios between the electric machine and the secondary shaft. The solution is particularly innovative, because keeping a very simple and well-known architecture (therefore cost effective), it allows the connections to be made with standard transmission components, selectively coupling the electric machine to either the primary or the secondary shaft. This feature, then, represents a mixed P2-P3 hybrid architecture and therefore takes the advantages of both (e.g. powershifting-P3, recuperation-P3, cranking-P2, standstill charging-P2). It allows a performance increase of up to 40 % on 0–100 kph and up to 25 % benefit on CO_2 emission, with a charge-sustaining strategy for the battery, with the installed electric power being 30 % of the total. Thanks to its scalability and to the possibility of having different power-split configurations the system can be used both as a mild-hybrid and as a full-hybrid solution, within a 48V or HV system. The new OGeco FWD concept is shown in figure 1.

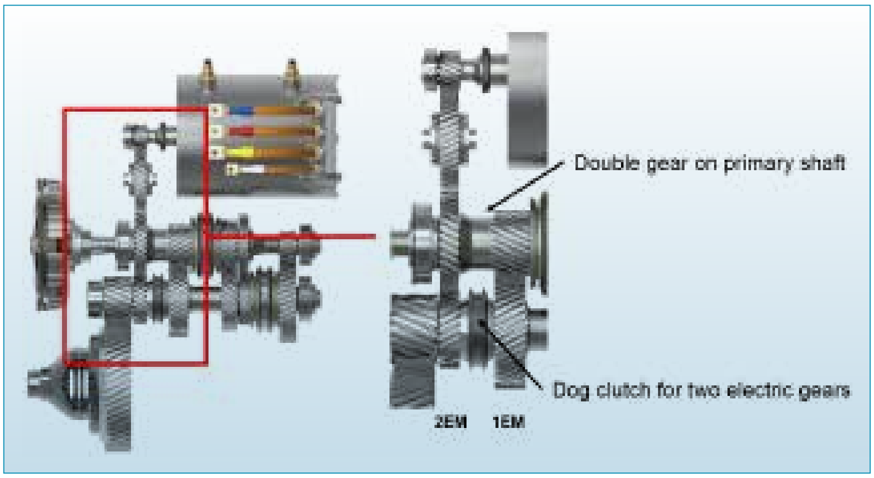


Figure 2 Hybrid coupling and electric gears detail

The concept developed is based on two electric gears and the two gears have different advantages from both a performance and efficiency point of view. The detail of the hybrid coupling and electric gears is shown in figure 2.

The electric first gear ratio allows consistent shift-infill assist and eBoost at low vehicle speed as well as a better uphill launch, which is a critical manoeuvre especially if the selected electric motor power is limited. It means also better drivability in fully electric mode thanks to the higher torque at the wheels, with the possibility to avoid the ICE mechanical reverse gear, because the electric torque at wheel is sufficient. The gear ratios are also dimensioned in order to drive in fully electric mode only in first gear up to a reasonable maximum speed, removing the need of shift gears in pure electric.

The second electric gear is then useful to allow the permanent connection of the electric motor to the wheel also at the maximum vehicle speed, additionally allowing the torque infill capability at high speed manoeuvres and the eBoost up to the maximum speed. Another benefit is that the motor can spin in its optimal efficiency zone also at high vehicle speeds.

In figure 3 a scheme with the analysis of the single electric speed version and the two speed version is presented illustrating the above-mentioned benefits.

The electric motor, customized for instance depending on electric voltage, required torque characteristic, package, technology (PMSM, ASM, ...), etc., is selectively connected via cylindrical gears directly to the primary and to the secondary shaft.

It enables then all the advantages of a P3 hybrid configuration, such as the higher efficiency from the electric machine to the wheels and the capability of a very strong eBoost at low speeds when in high ICE gears. For this purpose the graph in figure 4 shows how a P3 hybrid configuration, being independent from the ICE gearbox ratio, allows an important advantage in the eBoost torque at low vehicle speeds coupled with low combustion engines speeds with respect to a P2 system.

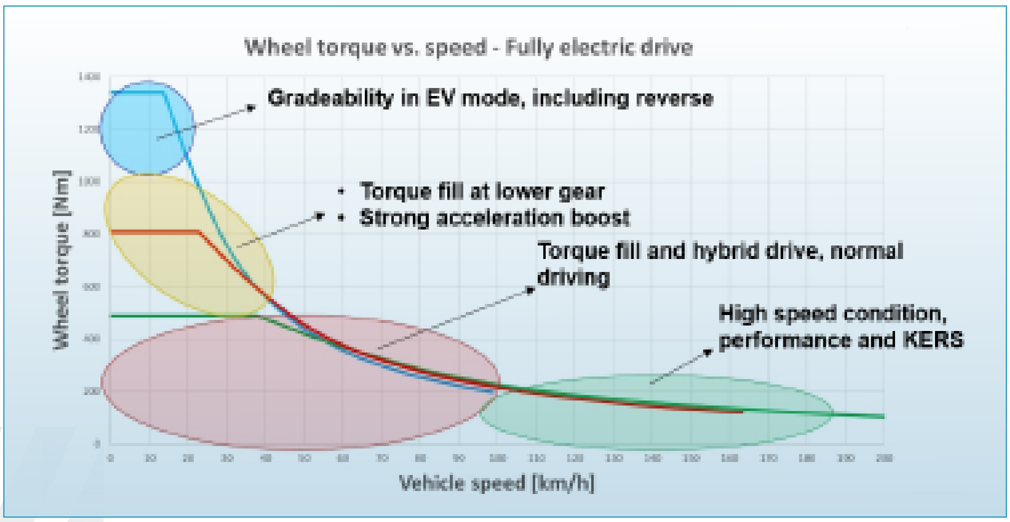


Figure 3 Single speed vs. two speed solution

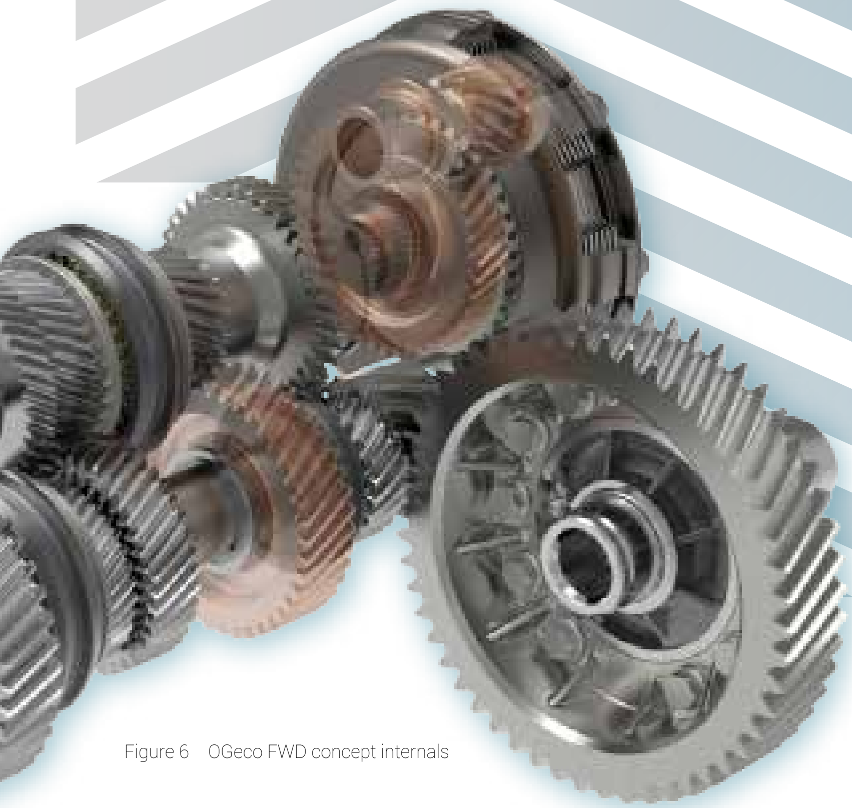


Figure 6 OGeco FWD concept internals

From a drivability point of view the advantage on the eBoost is then useful to have an important torque assist directly to the wheels in case of acceleration request without the need of downshifting on the ICE gearbox side. It can then provide immediate boost in case of kick down manoeuvre when the downshift is needed.

On the other hand, connecting the electric motor to the primary shaft it is possible to achieve all the P2 functionalities such as the possibility to recharge the battery while the vehicle is at standstill, achieved disconnecting the dog clutch on the secondary shaft, or the possibility to crank the internal combustion engine. All the possible driving modes are presented in the table of figure 5.

Summary

Oerlikon Graziano with his novel Dedicated Hybrid Transmission concept offers as a Tier 1 supplier a step forward on the path to electrification, with a compact and elegant package and full hybrid capabilities such as load point shifting, eBoost, KERS, regeneration, hybrid drive and full electric range.

The concept's distinctiveness is its compact nature and its simplicity, which makes it cost-effective and attractive for broad platforms.

A simple and efficient gearbox, capable of both P2 and P3 hybrid functionalities both in 48V and HV systems, makes the concept perfectly suitable for OEMs who want to accept the challenge of hybridisation without compromises on performances and cost.

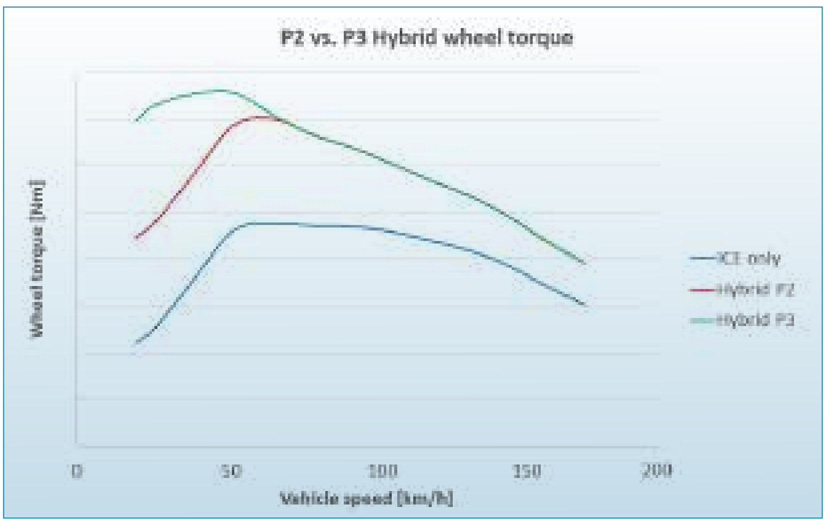


Figure 4 Example of P2 vs. P3 hybrid wheel torque in high gear

		ICE	1EM	2EM
HYBRID MODE	1st gear	x	x	x
	2nd gear	x	x	
	3rd gear	x	x	x
	4th gear	x	x	x
	5th gear	x		x
P3 EV MODE	Forward		x	x
	Reverse		x	x

Figure 5 OGeco FWD possible driving modes

Increased performance for hybrid vehicles

eTWINSTER – the First New-Generation Electric Axle System

The GKN-developed eTWINSTER is the first next-generation electrical axle system, providing a step-change in efficiency and dynamic performance of hybrid vehicles.

- Dipl.-Ing. Jan Haupt, Advanced Engineering Driveline Systems, GKN Driveline International
- Co-Autor Dr-Ing. Dirk Güth, Advanced Engineering Driveline Systems, GKN Driveline International

A look at the current registrations of hybrid and electric cars clearly shows that these vehicle categories are gaining essentially more importance worldwide. GKN supports this growth with a broad portfolio of electrical transmissions and axles, and advances the development of increasingly powerful and efficient driving units. Now, with the development of the GKN eTWINSTER, another fantastic development stage has been achieved in electric drive systems, significantly improving the drive performance of hybrid vehicles.

Many electric axle systems currently available on the market must be disconnected at high driving speeds because of the maximum permissible rotational speed of the electric motor and the applied gear ratio, whereby even drag torque of up to 2.5 Nm on the axle can remain (see Figure 1). The result is a significantly negative influence on the overall efficiency of the drive system, in particular at high speeds.

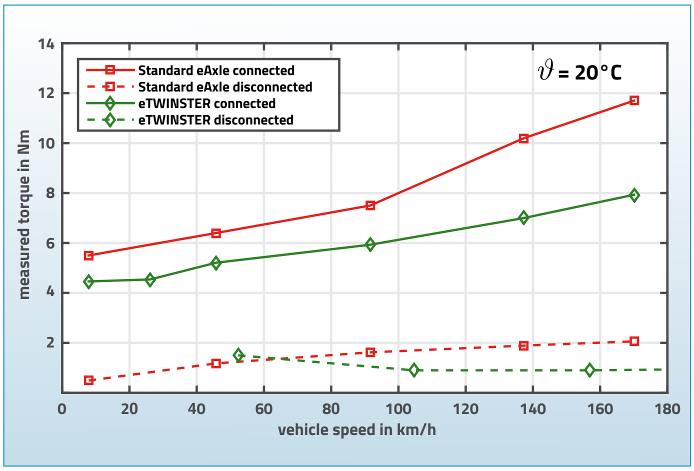


Figure 1 Drag torque disconnection unit comparison

Due to the increased system weight (caused by battery, electric motor, inverter, etc.) the driving dynamics of a hybrid vehicle are clearly affected in comparison to a corresponding conventionally-powered (all wheel driven) vehicle, which is primarily noticeable by means of reinforced understeering. Ultimately, it is the traction of the vehicle through the use of open differentials that is limited.

The GKN eTWINSTER acts exactly on these weaknesses: one key feature is the integration of the GKN TWINSTER technology, already introduced successfully to the market in AWD rear axle systems (for example, in the drive train of the JLR Evoque).

Structure

The electric axle for the Volvo SPA Platform serves as the basis for the system, developed and produced in series since mid-2015 by GKN. Among others, this is built into the new Volvo XC90 T8 Twin Engine Plug-In and is helping the flagship of the Volvo Group to achieve an average fuel consumption of 2.1 litres/100 km and an acceleration of 0 to 100 kph in just 5.9 seconds. Due to the work that took place on the vehicle during series development, GKN very well knows the vehicles and other areas surrounding electronic rear axles. For these reasons, the XC90 was chosen as the experimental vehicle for the development of eTWINSTER.

The electric rear axle is built coaxially, with the hollow motor shaft of the electric motor and the differential being positioned concentrically together (see Figure 2). By means of a countershaft, the output of the electric motor is connected with the final drive. The right rear drive shaft travels centrally through the electric motor. In the current series version, the electric drive axle is disconnected at a speed of 160 kph using a patented electromagnetic actuated disconnect differential.

For the newly developed GKN eTWINSTER, the fundamental architecture of this axis (coaxial layout, arrangement of the countershaft) has been taken over. As a key differentiator, however, the disconnect differential has been replaced by two side-by-side TWINSTER clutches with hydraulically actuated pistons. These could essentially be put in the same installation space as the outgoing design. The requirement was the integration of the final drive into the outer disc carrier and the space-saving positioning of the clutch disks below it.

In order to build up the required system pressure, an actuator, consisting of a BLDC motor, pump and valves, was integrated into the main housing. The transmission and the actuators share a common oil circuit and therefore use the same oil. The oil circuit is at the same time the basis for the applied dry sump of the transmission. The BLDC motor and pump have therefore been arranged in the area under the transmission in the common oil sump. Due to available package space, the hydraulic valves were also integrated in this area.

In total, the GKN eTWINSTER uses three valves. Two valves spread the oil on the right and left clutch pistons, the third valve controls the lubrication of the bearings, gears and cooling of the clutch. This allows not only the clutch pressure, but also the lubricant flow to be regulated on demand. Distribution of the oil on the individual lubrication points is adjusted through different orifices.

The key elements of the GKN TWINSTER clutches, such as the actuator, the clutch disks and the hydraulic pistons, are GKN-standardised system elements with fully defined physical, logical and material interfaces, the so-called "building blocks". This common-part strategy makes it possible to robustly develop and create a complex system such as the GKN eTWINSTER within a short period of time.

Function

The power generated from the electric motor will be delivered from the drive pinion of the electric motor to the gear of the countershaft. From there, the power flows over the shaft pinion to the final drive. By applying pressure on the clutch pistons, an axial force is exerted on the disk packs and the inner disk carrier is connected to the outer disc carrier. The maximum clutch pressure is 35 bar. Depending on the chosen clutch pressure, (in the design shown here) up to 1200 Nm drive torque can be applied to each rear wheel. For other applications the clutch torque is scalable through changing the number of disk plates.

In accordance with the driving situation, both clutches can be completely independently controlled and thus the torque can be distributed freely on the rear axle between the right and left wheel. This distribution is regulated by GKN's own vehicle dynamic controller, the

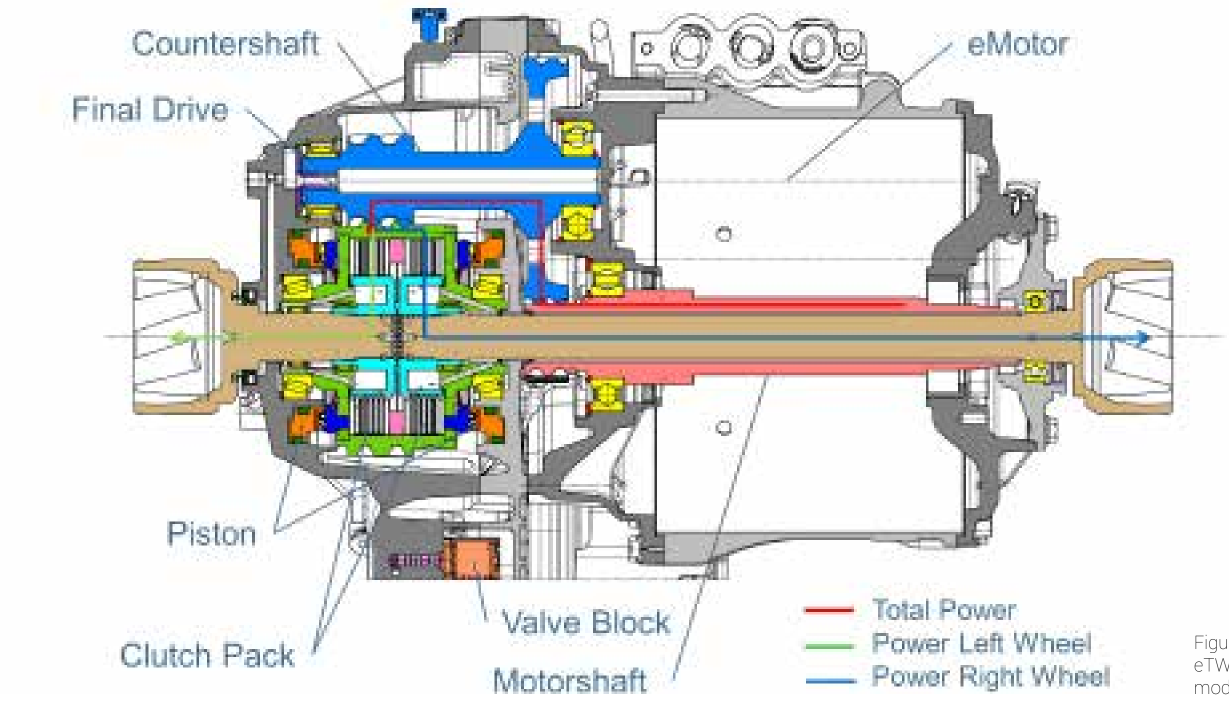


Figure 2
eTWINSTER rear axle module

so-called TASC (traction and stability control). Dependent on various input signals, such as wheel speeds and steering wheel angles, the controller calculates the required torques at the rear wheels and transmits these to the hardware controller for the BLDC motor and valves. The flexible structure of the software and the division into hardware and vehicle dynamic controller enables a quick and easy implementation in a variety of applications.

Benefits

Due to the targeted controllable distribution of torque between the rear wheels, the eTWINSTER offers the opportunity of torque vectoring on the electrically driven rear axle. When cornering, the outer wheels will be supplied with more torque than the inside wheels. This comes as part of a dynamic tuning of the vehicle being specifically exploited, in order to reduce understeering of the vehicle by a positive yaw moment.

Furthermore, the vehicle dynamics can be even more positively influenced by a controlled speed difference between the front and rear of the electrically-driven rear axle.

In addition, the eTWINSTER concept has a particular advantage compared to conventional four-wheel drive concepts. Even in deceleration, targeted torques can be lead to the wheels of the rear axle by taking advantage of the regeneration function. This situation is comparable to torque vectoring via brake intervention, during which the inside wheel brakes. Only in the case of the GKN eTWINSTER driving power is not lost in the brakes, but rather won back through regeneration.

Depending on the tuning of the vehicle, with the measures described, a neutral or even oversteering behaviour of the vehicle can be achieved. The vehicle becomes entirely more agile, the result is reflected in a smaller cornering radius and an increased lateral acceleration.

The GKN eTWINSTER as further function offers the opportunity to lock the rear axle. Comparable to a limited slip differential, the two rear wheels can be connected together by synchronous actuation of the clutches. This leads to significantly improved traction and can be used as yaw damping in the upper speed range.

The efficiency of the GKN eTWINSTER is better as well as in coupled state and disconnected state than the conventional electric rear axle. The input of the dry sump and the associated reduction in the splashing loss will improve efficiency in operation. In disconnected state the remaining drag torque of the eTWINSTER is significantly lower than the drag torque of the conventional axle (equipped with differential and disconnect device). This was achieved through targeted measures towards fast and effective de-lubrication of the clutch packs (see figure 1).

Summary

The integration of the TWINSTER technology in electric drive axles provides a step-change for electric drive train systems in terms of efficiency and vehicle dynamics whilst setting new standards.

With its torque vectoring and LSD function, the eTWINSTER creates more agile and safer hybrid and electric vehicles and ensures, through the use of the TWINSTER clutches in combination with further optimisation measures, such as the dry sump, a significant increase in efficiency of the entire system.

Jeffrey Carpenter, Engineering Manager,
Commercial Powertrain Truck, Eaton Corporation

Interview

"You Need a Software System that Reacts to All Driving Situations"

With their combination of shift comfort, efficiency and a customizable launch and shift element, dual-clutch transmissions have become successful – especially in Europe and China. Eaton has now transferred the technology to the medium-duty segment. We asked Chief Engineer **Jeffrey Carpenter** about the specific challenges involved.

Mr. Carpenter, the Procision 7-speed DCT entered the market early in 2016. Which market segments is it intended for?

There is a wide range of potential applications. The first applications we launched are for pick-up and delivery, wrecker recovery, school bus, and refrigerated scenarios. We see more vocational applications initially, but the product's scope can extend quickly – for example to Utility and heavier-duty applications such as Off-road. To give us the flexibility we need for this wide range, we designed this transmission as a wet DCT, not a dry DCT. If you want low-speed manoeuvrability, which customers demand in loading dock situations, parking situations etc., and if you want to perform better than with a torque converter, you need a wet clutch. ▸

Why is the comparison to torque converters so important?

In the medium-duty commercial sector, the vast majority of the market consists of home rentals. So you see less educated drivers, drivers who are coming from passenger cars to larger trucks, and their demand or expectation is that the vehicle drives like a car. Our dual clutch offers as much launch performance as a torque converter, plus even more flexible low speed manoeuvrability, and similar performance and acceleration to the six-speed AT we used as our reference.

How did you handle the missing torque multiplication of a torque converter?

First we gathered requirements for our acceleration – when you do a zero to 1, zero to 2.5 zero to 5, or zero to 10 miles per hour. Traction force had to be as good as or better than a torque converter can provide. We offer a 6.5 first gear – a half-ratio increase compared to our reference AT. We added the ratio coverage of more than 10 for some advantage, and the fact that we can operate at lower speed more than compensates for the effect of the torque multiplication. When driving uphill, the shorter first gears always ensure high enough engine rpm with a locked-up clutch. Moreover, we can adapt the clutch and shift behaviour to any requirement. We have multiple inputs to determine shift points, multiple shift tables based on sensor input. If you´re on a mountain heavily loaded, we go to another shift table automatically. That's one of the things the Procision does dynamically to adapt.

Generally speaking, how do requirements differ from those in car applications?

We needed more flexibility. There are very different requirements across various duty cycles, weights and vehicle applications. In our opinion, control algorithms need to more adaptable and robust. For example, you need to be able to adapt to the vehicle loading; is it half loaded, fully loaded, on a hill, not on a hill – and is it minus 40 or 105 degrees outside. To deliver the same experience to the driver in all possible situations, you have to be able to detect these various conditions, and you need a software system that reacts accordingly. We've developed a highly capable software system that offers different modes for low-speed manoeuvrability, according to the customer´s needs.

How does your dual-clutch transmission perform in terms of fuel consumption, and compared to an automated manual?

I think we stack up very favourably to an AMT. Testing of European AMT systems has shown comparable fuel economy to be achievable. In some situations like driving up hills, the missing torque interrupts can even be an advantage, because there is no loss of traction force between shifts. Compared to a six-speed AT, results are 5 to 10 percent better, varying by cycle, and even better in some specific scenarios. In perspective, we see some more headroom to get even more efficiency out of this transmission. You can have algorithms that adapt faster, so there are some more ways to further improve efficiency through optimized software. The inherent advantage of a DCT is that it combines these minimum parasitic losses with great control and flexibility for many different use cases.

This dual-clutch transmission is a young product – which applications come next?

Excitement is building around the product, and demand is exceeding our current capabilities. We are getting application extension requests, demand for higher torque capacity and global requests. So we go into a prioritization scheme, share all the information that we receive, analyse and prioritize where we want to go next and what steers us. We are pursuing all applications where value is needed in terms of better fuel economy, continuous torque delivery, application flexibility and superior low speed control and manoeuvrability.

Interview: Gernot Goppelt, CTI Correspondent

Development of a three-speed electric drivetrain

High Speed Electric Drive with a Three-Speed Gearbox

Development of a weight, volume and efficiency optimized powertrain for a Battery Electric Vehicle (BEV) with high speed transmission.

- Dipl.-Ing. Uwe Reichert, Scientific Assistant, Research Group Drive Systems, Karlsruhe Institute of Technology, Institute of Product Engineering
- Dipl.-Ing. Torsten Epskamp, Scientific Assistant, Research Group Hybrid Electric Vehicles, Karlsruhe Institute of Technology, Institute of Electrical Engineering
- Dipl.-Ing. Aline Radimersky, Scientific Assistant, Research Group Drive Systems, Karlsruhe Institute of Technology, Institute of Product Engineering
- Dipl.-Ing. Sascha Ott, Managing Director, Karlsruhe Institute of Technology, Institute of Product Engineering

Introduction

Increasingly more stringent regulations of CO_2 and fine dust in urban and interurban areas emphasize the need for clean mobility. Vehicles without local emissions provide a serious opportunity to avoid the local production of fine dust and pollution of the environment with exhaust gases.

Therefore, research and development focusses electric vehicles. While most vehicle manufacturers provide some electric vehicles in series production, there are still many aspects to optimize within the electric drive system. The main weakness is the low range of actual electric vehicles combined with high costs of electric cars in comparison to conventional cars. One solution of this matter could be battery cells with a higher ratio of energy per mass. Beside improvement of energy density of the batteries there are also approaches to improve the energy efficiency of the powertrain by raising the power density and reducing the total mass of the powertrain. An approach to increase the power density is to increase the maximum speed of the electric machine. Current machines in electric vehicles have a maximum speed of about 15 000 rpm. By raising the maximum speed at the same maximum power, the space and the mass of electric drives could be significantly reduced. But raising the maximum speed often leads to decreasing the maximum torque because of limitations regarding the maximal possible rotor-diameter at high speed as well as the limited possible current of the power electronics. In order to match all performance-requirements of the vehicle, a multi speed gearbox is needed. It enables the electric machine to operate in an efficient point, leading to new requirements for the electric machine and the gearbox and to more degrees of freedom in the design of the powertrain. Thus giving raise to the question of how to find suitable combinations of electric machine and gearboxes for different vehicles.

Research Project Effect 360°

The Karlsruhe Institute of Technology (KIT) develops a high speed electric machine with a maximum speed of 30 000 rpm in combination with a loss reduced three-speed gearbox without traction interruption. For the overall system integration of the complete drivetrain, Daimler AG and Robert Bosch GmbH are also part of the research project. This article presents the approach implemented in the project as well as the developed drivetrain concept. In this context, special attention is given to the functional interactions in the development of the whole drivetrain. Through the mixed physical and virtual approach of the development and verification of the drivetrain, the fulfilment of the vehicle requirements is continuously under consideration. The comparison in virtual simulations of the high speed drivetrain with a single speed reference drivetrain with lower speed shows a higher power density by competitive overall system efficiency of the three-speed gearbox. Initial simulation (virtual testing) is then gradually changed into physical tests on test rig with remaining system being modelled virtually (mixed physical and virtual tests). New findings of the subsystem experiments enter in the holistic conception and dimensioning of the drivetrain.

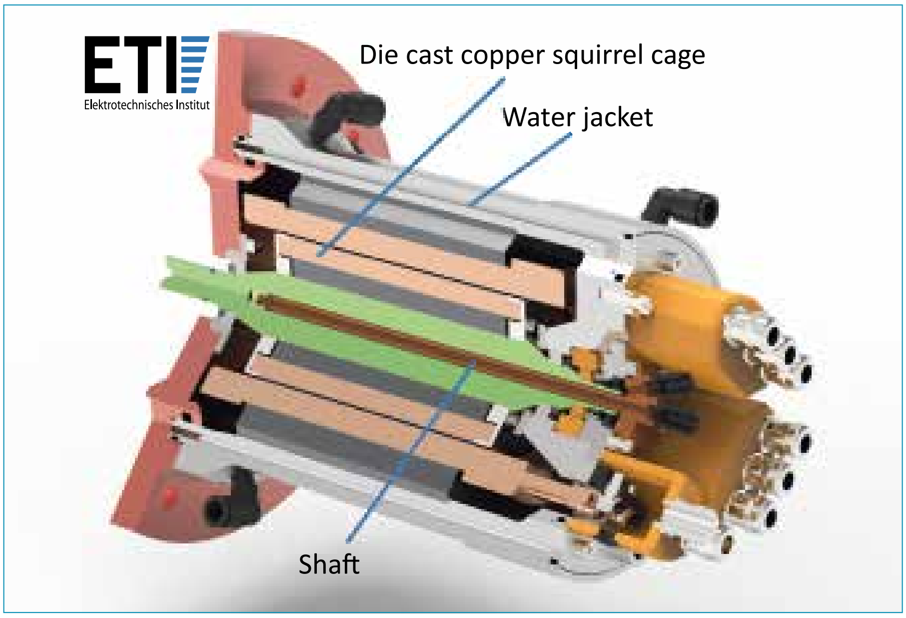


Figure 1 High-speed induction machine

High Speed Electric Machine

Today, the majority of electrical machines used in full electric and in hybrid electric vehicles are permanent magnet (PM) synchronous machines. But in the past years the prices for PM materials were subject to vast changes due to market restrictions. Additionally, the typical losses of such electric machines under zero load are considered to be unfavorable. In contrast, induction machines (IM) are known as a reliable and cost-efficient alternative. Thus, in this project a high-speed induction machine with die-cast copper squirrel cage was designed (Figure 1). High-speed operation bears additional challenges for the mechanical firmness of the rotor, especially the mechanical stability of the copper cage and the shaft-hub-joint. Therefore, to satisfy the requirements of high torque output at low speed and high continuous-power at maximum speed, a close combination of electromagnetic, thermal and mechanical simulations is necessary. The most important design parameters for the electrical machine are the ratio of inner to outer diameter, stator slot heights and width, rotor slot heights and width and the winding number of turns. For each possible design, the operation points are shifted in the torque-speed plane of the electrical machine, so the gear ratio is another parameter that has to be considered. In Figure 2 the operation points of WLTP drive cycle are plotted into the efficiency map of the electrical machine for three different gear ratios. It shows how the cloud of operation points for each gear is shifted from high speed and low torque to low speed and high torque. For each operation point the gear ratio with the best efficiency can be chosen.

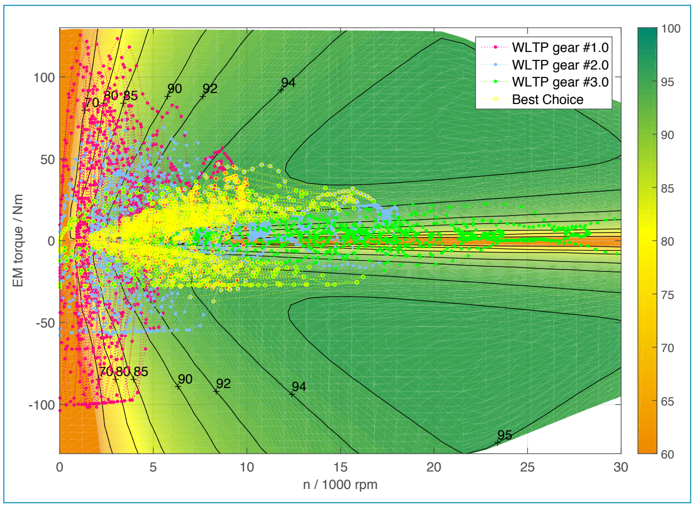


Figure 2 Drive cycle WLTP operation points for different gear ratios in torque-speed plane

Limitation of the Gear Ratio

The determination of an energy efficient gearbox design depends on several requirements, for example the number of gears, the gear ratio and the driving performance. The limitation of gear ratio and number of gears is based on efficiency and drivability. For the efficiency based determination, the gear ratios are varied in CVT-functionality with a fixed increment size in a prescribed range. Thereby, the efficiency-optimal operating points as a function of the characteristic map of the electric machine are determined. Input parameters are the characteristic map of the electric machine, the shifting strategy and the driving cycle, for example WLTP or NEFZ, according to the vehicle class and the preferred driving environment. With these boundary conditions and by means of simulation tools, the efficiency optimal gear ratio can be defined. The optimal gear ratio depends on the number of gears and is independent of the gearbox design for an assigned constant gearbox efficiency of 95 %. Further, gear ratio is limited by the maximum velocity and acceleration as a function of the maximum speed and torque of the electric machine. The result is the efficiency-optimal gear ratio for a single-speed, two-speed and three-speed transmission, which achieve minimal losses in the electric machine. It is important to note that the electric machine of the one-speed gearbox is different in comparison to the electric machine of the multi speed gearboxes. The electric machine of the one-speed gearbox has higher torque and lower speed. It is important to develop the electric machine and the gearbox under consideration of the interactions.

Gearbox Design

Based on the defined number of gears, the gear ratio, the maximum input torque and speed of the gearbox allow the specification of a suitable design of one-speed and multi-speed gearboxes. Due to these requirements along with the multi-speed gearboxes, shifting elements and a central drive for one vehicle axle, the choice for all gearboxes is a spur gear design.

Further investigations of the efficiency and power density for detailed design and dimensioning of the three gearboxes is carried out. The dimensioning includes the axles, gearings, bearings, seals, shifting elements and the housing. Thereby, it is possible to determine the exact mass and design space of the gearbox. Through the detailed dimensioning of the gearbox components, all parameters can be transferred to a simulation model to calculate the losses and the exact gearbox efficiency. The simulation model considers all load-dependent and independent losses, the clutch and drag losses, the actuator losses and the losses of the electric machine and the power electronics. The simulation results of the energy demand for a one-speed, two-speed and three-speed gearbox with different electric machines & power electronics for a medium sized car and the drive cycle WLTP are shown in Figure 3.

Through the approximate efficiency of the one-speed gearbox and the three-speed loss-reduced gearbox, the reduced mass of the three-speed powertrain including the power electronics, the electric machine and the gearbox against the one-speed powertrain are set to 20 %. Despite the gearbox being bigger, the reduction of mass of the electric machine through a lower torque output compared to the electric machine of the one-speed gearbox is large enough for a mass reduction of 20 % to be achieved. Hence in the research project Effect

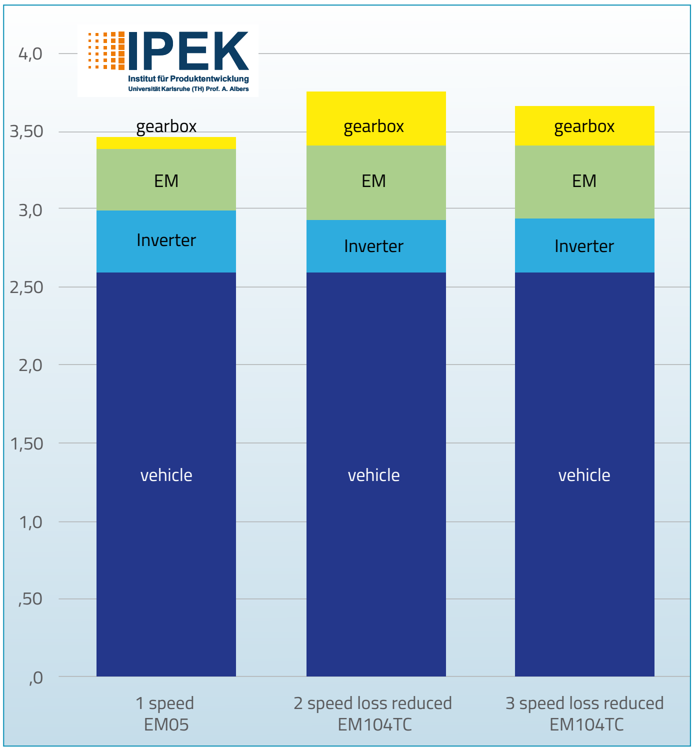


Figure 3 Energy demand for a medium sized car

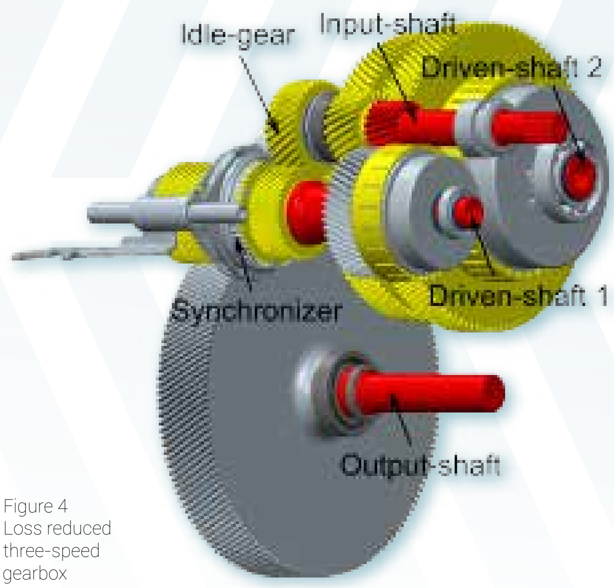


Figure 4
Loss reduced three-speed gearbox

360 °, the loss reduced three-speed gearbox was chosen. The final wheel set of the gearbox is shown in Figure 4.

The input-shaft is connected to the electric machine. Both the driven-shafts are connected over gearings with the input shaft. The two gearings are again connected respectively with a wet multi-plate clutch to the driven shafts ensuring shifting without traction loss. The driven-shaft 1 has a synchronizer to preselect the first or third gear during up or down shifting. The second gear is installed on the driven-shaft 2. Due to the high ratio of the first gear, power is transmitted from the input shaft to the driven-shaft 1 und over the idle-gear wheel on the input shaft to the driven-shaft 2 and finally to the output-shaft. The differential is a simplified construction of a rigid axle with huge gear-wheel.

Verification of the Gearbox

In the first step, only the gearbox and the electric machine, and in the second step the whole powertrain is verified with the IPEK-X-in-the-Loop approach on a suitable test bench. This means, the system in development, in the first case the gearbox or electric machine is fixed on a test bench as a physical system and the connected system, consisting of driver, environment and residual vehicle is virtually simulated. Aim of this validation is to confirm the simulation results, for example the efficiency or the energy demand for a drive cycle and to fulfil the vehicle requirements, like the maximum acceleration of the car.

Summary

The article elaborates on the development of the components of an electric drivetrain. By considering the interaction of these components, it is possible to increase the power density and the efficiency of the whole drivetrain. The methodology is applicable to all one and multi speed drivetrains for different vehicles and requirements.

Acknowledgements
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Modular and Scalable Layshaft Transmission Design

For today's worldwide applications, scalability of transmissions has a vertical as well as a horizontal dimension. Getrag pursues several modular and scalable design approaches that reflect typical market and OEM requirements.

- Dr-Ing. Jörg Willert, Director Central Core Engineering, GETRAG, Magna Powertrain
- Dr-Ing. Carsten Bünder, Senior Manager Product Engineering, GETRAG, Magna Powertrain

Introduction

Not too long ago, transmissions were mostly closed solutions with little potential for being adapted to different applications. The major concern was to design a universal product that enables largest possible economies of scale with the whole transmission. Currently, the boundary conditions for transmission development are significantly changing, Figure 1. Many vehicles are intended for different global use cases, resulting in much more complex and diverse requirement profiles. Efficient Transmission designs should on one hand enable large production numbers, on the other hand be suitable for different performance levels and market-specific requirements. After all, future fleet consumption and CO2 regulations do not allow any compromises with regard to package, weight and efficiency.

These new requirements lead to a new understanding of modularity, where a universal "closed system" would be replaced by a functionally scalable system, while maintaining economies of scale. The task is to resolve this seeming contradiction.

Figure 1 Requirements for designing transmission architectures

Benefits of Modularity and Scalability

Generally spoken, the requirements for modular and scalable transmissions are economies of scale of whole transmissions and functional components as well as scalability for market-specific functions, different performance levels and improved quality assurance.

In practice, these requirements often correlate. Functional modules are on one hand necessary to enable economies of scale. For example, these can be shift and clutch actuation modules that are used across a whole family of transmissions. On the other hand, functional modules can be the basis for scaling market specific features or product performance. The latter is for example represented by scalable e-machines, which allow for mild, full or plug-in hybrids within the same base transmission. Another advantage of defining functional modules is enhanced quality assurance: The more integrated components can be used across different transmissions, the easier it is to control quality and to transfer improvements or even new generations of functional modules to every application affected.

Generally spoken, the intrinsic high efficiency of layshaft transmissions, plus the high potential to define functional modules, Figure 2, allows for efficient products with high economies of scale and functional scalability. This applies for MTs as well as for AMTs and DCTs as well as their hybrid derivate.

Small Manual Transmission for High-Volume Production

A good example for today's global market requirements is the segment of small cars with low to mid torque engines. OEMs operating worldwide need manual transmissions that suit different markets like Europe, China, India or South America. Getrag has developed the MT family MX65, Figure 3, which reflects the diverse needs. It covers different torque segments, as different engine technologies are used regionally: Having emerged from Europe initially, small displacement turbocharged three-cylinder engines deliver comparably high torque of more than 200 Nm. In some markets, small four-cylinder engines are still being favoured for cost reasons, delivering significant lower torque. Furthermore, versions with five or six gears are available to meet different driving conditions in areas like Europe and Asia.

The small transmission family currently is made up of three models, the 5MTT152, 5MTT215 and 6MTT215. To enable large economies of scale, they use many common parts like identical synchronisers and seals, a standard differential, common gearset parts etc. For specific market needs, there is a choice of different synchronisers. Assembly efficiency has been significantly improved: All loose gears are mounted on the same shaft for easier assembly. The two torque categories of 150 and 215 Nm are designed for small four-cylinder and turbocharged three-cylinder engines respectively, the five- and six-gear versions for different regional traffic conditions. The 5MTT215 is achieved by simply omitting the 6th gear of the otherwise identical 6MTT215. Generally, there is an option for an AMT version, featuring an actuation module that integrates shift and clutch actuation as well as the TCU in just one add-on module.

Small-Volume Manual Transmissions with Scalable Torque Density

While there is a stable worldwide demand for small front-transverse manuals, it is on the decrease for inline applications in higher torque segments. Beginning with the C to D segment, cars are being more and more automated. Even in Europe, most E segment cars and upwards have automatic transmissions. Manual transmissions for rear wheel applications have mainly become niche applications for sports cars – on the other hand they can be found in light commercial vehicles that deliver lower torque but handle high cargo load.

The MTI Next Generation integrates these seemingly opposing application types into one transmission concept that can be scaled internally from around 350 to 800 Nm. According to the intended torque density, the gear wheels width can be varied. Synchronisers can be chosen according to load and comfort requirements, through to carbon synchronisers. Gear spread can be up to 8.0 for high-speed applications and a 7th gear module is available, again for high-speed use – or to achieve smaller gear steps for higher wheel torque and lower life-cycle fuel cost with commercial vehicles.

There is an option for all-wheel drive and for an e-clutch. The e-clutch is useful to improve comfort and prevent from misuse, because the system is able to override the driver's action. Moreover, it is an enabler for less fuel consumption via a sailing function. The wet e-clutch can be an in-house solution based on components of the 3rd generation DCTs, namely on-demand pump actuators.

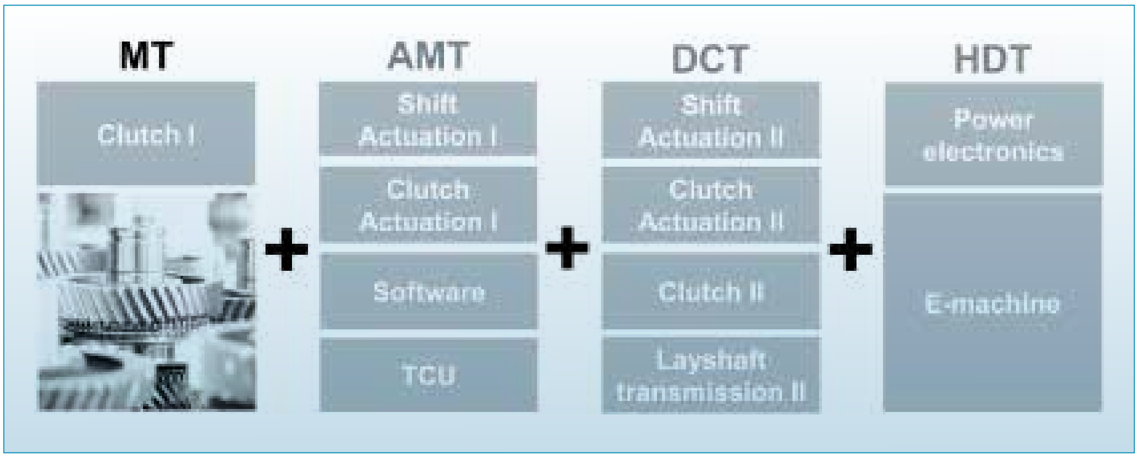


Figure 2
Module add-ons from manual to hybrid transmissions

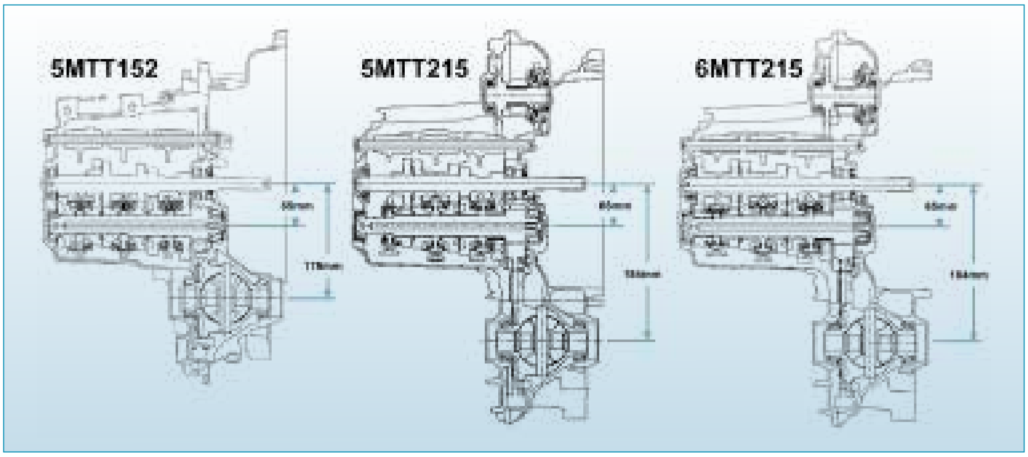


Figure 3 MX65: two transmission sizes for three variants

Corporate DCT Architecture

The path from standard products to the current corporate architecture took just a few years. The explicit goal was to define functional modules that enable better economies of scale, while increasing flexibility in terms of market-tailored characteristics and scalable performance.

1st generation dual-clutch transmissions were largely restricted to specific applications. Besides the inherent option to vary the ratio layout, they were largely "closed systems". This is represented by a specifically designed hydraulic actuation system with a mechanically driven oil pump. In the 2nd generation, Getrag went for a full on-demand system with electromechanical shift drums and clutch actuation, omitting the engine-driven hydraulics. While this architecture is proven and on-demand actuation has dramatically reduced power consumption, the completely "dry" design with a dry dual-clutch is limited to about 280 Nm.

For the 3rd DCT generation, Getrag retained the shift drums but opted for wet clutches for several reasons. Firstly, their higher torque density allowed for a flexible clutch use in different torque segments. Secondly, the resulting lower mass reduced inertia, thus increasing flexibility in conjunction with different engine technologies, including modern downsizing engines. Thirdly, it added application flexibility in terms of improved shift and launch behaviour and low-speed refinement. Overall, the wet clutch allows for considerably more functional flexibility and scalability along a wider torque bandwidth.

Another key feature of the 3rd generation is the electrohydraulic pump actuation for clutch actuation and cooling, Figure 4. Pump actuation is the enabler for the efficient use of wet clutches, consuming just 25 W for clutch actuation (7DCT300, NEDC). The entire power consumption including shift and clutch actuation, clutch cooling and TCU operation is 31 W. Just as important is the modular layout: the pump actuators merge a motor and a gerotor pump into a module, providing functional modules that are used for a whole family of 3rd generation dual-clutch transmissions, currently spanning 150 to 300 Nm and being suitable for higher torque use. As functional modules, pump actuators can be placed anywhere within the transmission, depending on package requirements.

The 3rd generation DCT corporate architecture for the current products 6DCT150, 6DCT200 and 7DCT300 is essentially made up of the following interchangeable components: wet clutches, pump actuators for clutch actuation, pump modules (with different pump geometry) for clutch cooling, shift drums, TCU and software module.

Other than in the 1st generation, these core components are suitable for a transmission family that fits applications from A to E segment. While they can be universally applied, their characteristics are designed by a common software module. Furthermore, the components are suitable for hybrid transmission derivatives – and even manuals (e-clutch) and automated manual transmissions – thus broadening scaling effects across several transmissions types.

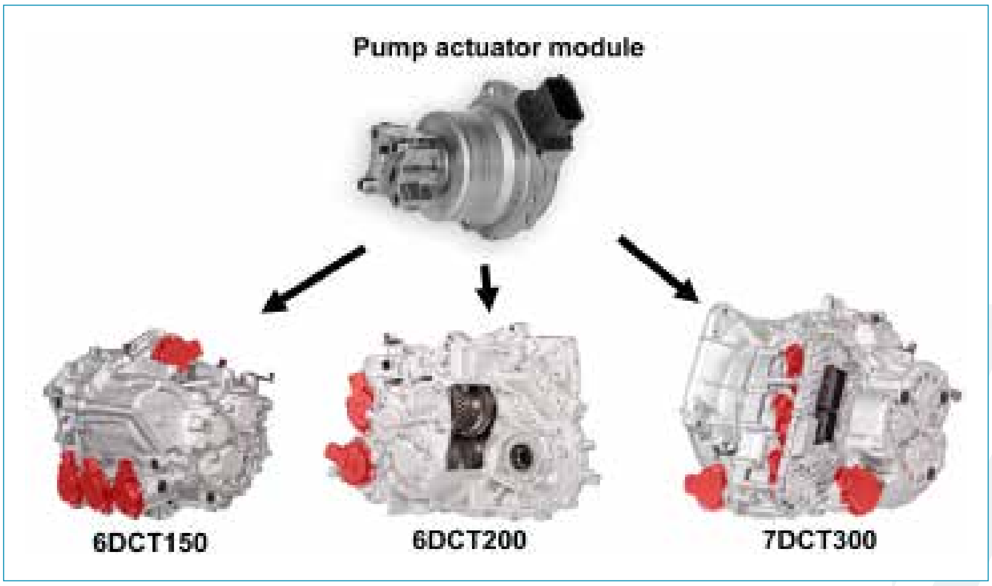


Figure 4 Modular pump actuation concept

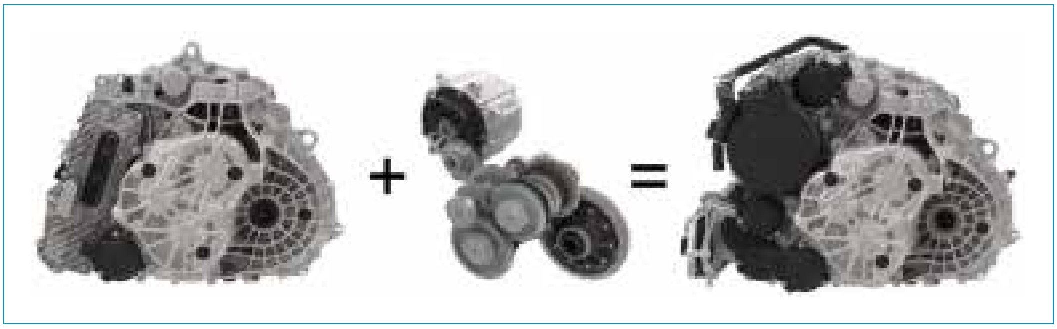


Figure 5
Torque-split hybridisation for dual-clutch transmissions (7DCT300 to 7HDT300)

Corporate Scalable Hybrid Architecture

Given that Getrag Hybrid DCTs are based on otherwise identical dual-clutch transmissions, they build on the same corporate architecture and its characteristics. Hybridisation adds additional interchangeable components to the corporate architecture, Figure 5: high-speed e-machine for torque-split use, inverter for 48 V version and power electronics interfaces.

These components are identically laid-out for the hybrid transmission models 6HDT200 and 7HDT300. In contrast to conventional parallel hybrid drives, the e-machine is arranged side-by-side to one of the sub-transmissions and connected via a reduction gear set. Thus, it can be designed very small, having little effect on the transmission size, while the installation length of the engine-transmission unit remains untouched. With regard to performance, the torque split architecture currently enables scaling the e-machine from mild hybrid (≈15 kW) to plug-in hybrid applications (≈75 kW) without changing the given installation space.

Actuation of the hybrid transmissions is done by the same pump actuation as in the dual-clutch transmissions they are based on. The flow path of the cooling oil pump is complemented by a second path for the oil-cooled e-machine via a separator, thus requiring no additional pump. Besides the scalable e-machine, pump actuation proves to be another enabler for scalable performance, covering the whole range from dual-clutch transmissions to mild, full and plug-in hybrid drives.

Figure 6
Modularity and scalability of the GETRAG corporate architecture

Summary

In contrast to other transmission technologies, layshaft transmissions can cover the whole range from manual, automated manual, dual-clutch and advanced hybrid transmissions, while maintaining their inherent efficiency advantages and many identical base technologies. Put simply, the development path from a manual to a hybrid dual-clutch transmission resembles gradually adding new components to the base technology while having in mind opportunities for modular and scalable solutions, Figure 6.

Automation and hybridisation have gained more and more importance in Getrag's product-portfolio in just a few years. Consequently, there was a strong motivation to develop a scalable corporate architecture for dual-clutch and hybrid transmissions with these goals:

- improved economies of scale of whole transmissions and functional components
- scalability for market-specific functions and different performance levels

Key technologies to achieve these goals were the electrohydraulic pump actuation, standard clutches and software modules; and not least, a scalable hybrid architecture from mild to plug-in based on the Getrag Torquesplit architecture. As a welcome additional effect, the corporate architecture affects other transmission types, in that the modular pump actuation technology can be used for any other transmission type for example. Within Magna Powertrain, further synergies will be possible in terms of vertical integration of single components as well as for example advanced hybrid architectures including rear-axle electrification as well as functional integration of other Driveline products and complete system integration, including controls and software.

Acceptable automatic shifting – with all benefits of a manual transmission

A New Automatic Transmission Approach – a Suitable MT Replacement?

Driver's comfort and safety, reduced fuel-consumption and emission as environment requirements and the wish of connectivity are demanding automatic shifting transmissions. Solutions are known: AT, DCT, ... not suitable to replace a MT – being cheap, simple, robust, producible anywhere with common production technology – new, even unusual ideas are needed!

■ Günther Priwitzer, Chief Engineer Driveline and Transmission System, Ricardo Deutschland

Requirements

On one side we can see a clear demand / wish for an automatic shifting transmission. From legal side for emission (efficiency powertrain, base for more gears and higher spread), from driver side for fuel consumption and comfort with high expectations for shift performance. We still had a similar approach with an AMT as "cheap" solution but this was not accepted by the end user because of long shift-times and long torque interruption and cost as well.

On the other side automotive products need to fulfill strong commercial demands. The MT still is the cheapest existing transmission type. Even a „cheap" AMT nearly doubles the costs for the vehicle. AT and DCT approximately triple costs. And last but not least nobody can ignore the demand of emerging nations to produce, maintain and repair these automotive products local. The general need of a cheap and robust vehicle as entrance to a "mobile" life will be valid for the next decades. Technology should be able to create a competitive "automised" solution for cleaner and more comfortable vehicles to replace the MT (also light trucks for distribution function can benefit) – creating new ideas, using new ways and unusual thinking.

Targets

1. No on-costs for the vehicle compared with a MT solution
2. Producible with common MT production technology
3. Mechanical efficiency equal or better than a comparable MT solution
4. Automatic shifting with an acceptable shift performance – short shift time, no or short torque interruption, smooth shifts
5. optimised power train efficiency equal or better than a comparable dry DCT solution

Approach

Till now there is no solution for this requirements known – after several attempts. To be successful a strict target oriented thinking is needed as well as thinking outside of the traditional transmission ways:

- Base is a dual transmission. The architecture is similar to a DCT with two transmission parts – the "odd" transmission and the "even" transmission. Gears are preselected and the shift time felt by the user is reduced to the torque transfer from one transmission to the other. (figure 1.1)
- Torque can be transferred via clutch (figure 1.2) and directly via the clutch housing (figure 1.3)
- Usual torque transfer is directly via the clutch housing
- A torque distribution system can shift optional the clutch to "odd" or "even" and independent also the direct line via the clutch housing to "odd" or "even"
- As clutch a hydrodynamic clutch is used, enables the transmission to launch the vehicle without complexe control devices.
- The HD-clutch also allows to shift two gears at the same time – one gear direct, one gear via the HD-clutch.
- The HD-clutch is used for launch and shift support – otherwise inactive, means no efficiency reduction
- Distribution system and main transmission are controlled by a control cylinder each (figure 4) or
- Equivalent systems powered by e-motors
- Because of lowest costs both transmission parts (odd and even) are controlled by one control cylinder, this means strict sequencial shifts have to be accepted (if not – an additional control cylinder is needed).
- Further in this article the approach is shown for a transvers application, an inline application evt. for commercial vehicles is also available.

Function

- In each part of the dual transmission always a gear has to be shifted – starting with figure 2-1, where the 1st gear in the "odd" part and the 2nd in the "even" part is shifted.
- Connecting the "odd" part to the HD-clutch (figure 2-2) engine power is transferrable via HD-clutch and 1st gear to the wheels – the vehicle is launching smoothly.
- To transfer torque via a HD-clutch the input speed has to be higher than the output speed. When reducing the engine speed to 1st gear speed the direct connection to the "odd" part can be shifted (figure 2-3) – 1st gear is form-fit shifted.
- In the "even" part the 2nd gear is still engaged. Shifting 2nd gear starts with connecting the HD-clutch to "even" (figure 2-4). Now two gears are shifted, one not solid via HD-clutch – the output torque decreases, qualitative shown in figure 3-1 point 3.
- Now the direct connection to "odd" is released – 2nd gear and engine is connected via HD-clutch (figure 2-5). The HD-clutch alignes the engine speed to 2nd gear speed smoothly when having a speed difference 10
- – engine control alignes engine speed to target-gear speed, HD-clutch is supporting – when speeds are aligned, the target-gear is connecting to direct drive. The qualitative torque-behaviour is shown in figure 3

Figure 1 architecture

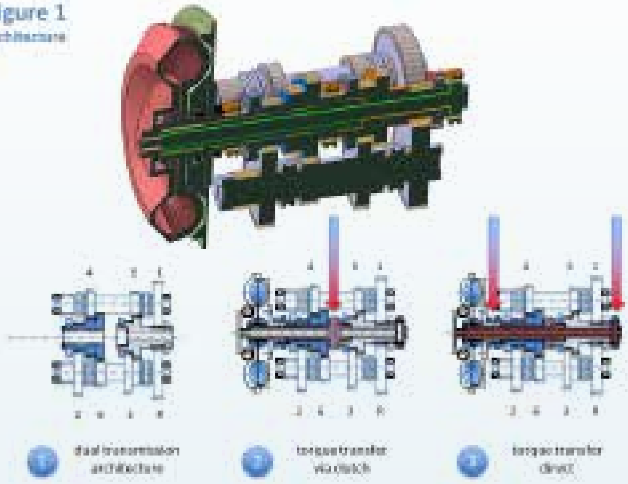


Figure 2 shift procedures

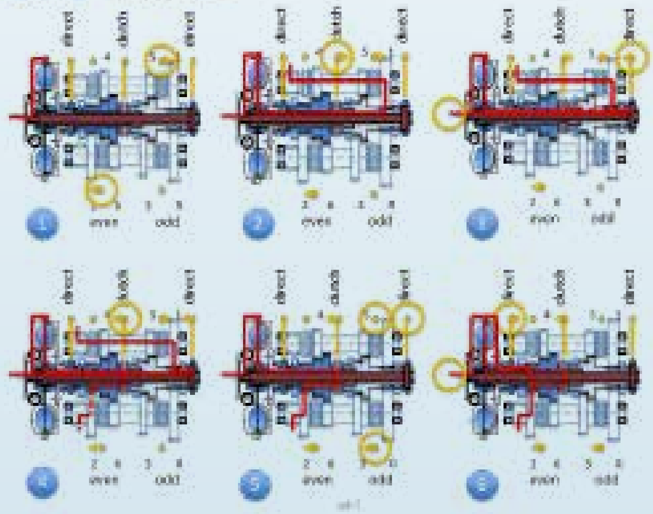
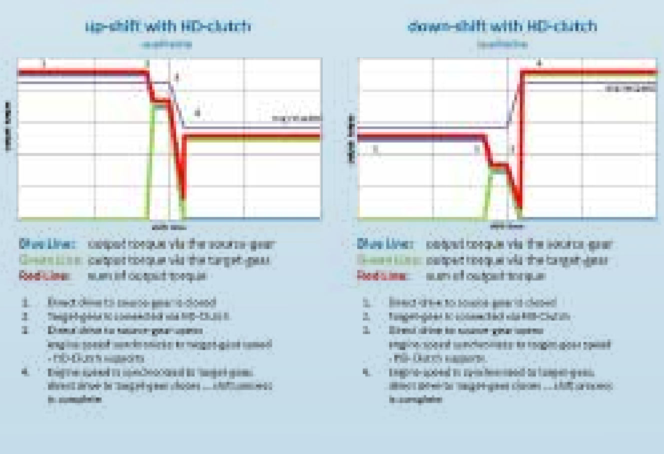


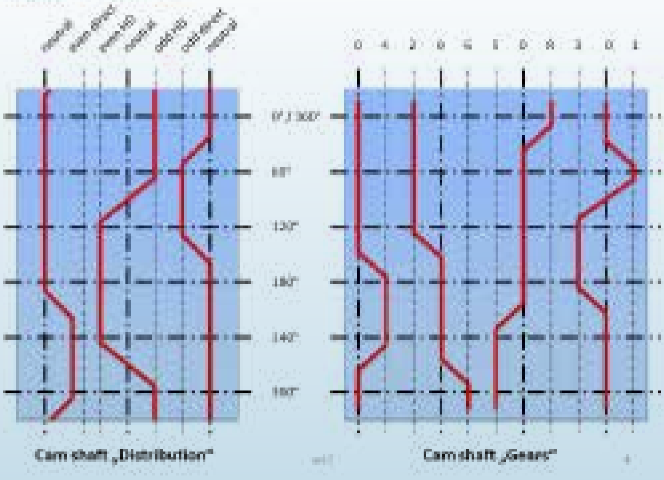
Figure 3 shift behaviour qualitative



Components

- TCU: to control the transmission needs to know the input speed (available from engine control), output speed (available from speedometer) and position of cam shafts for transmission and distribution system (new). The transmission control is confined to on-off shift, launch control is done by the HD-clutch. The function to modify the engine speed is still implemented in the engine control system.
- HD-clutch: the HD-clutch is used for launch and shift support. The clutch behaviour is influenced by the max. diameter, the inner geometry and the oil volume. For this application a permanent filled clutch is usable. This gives us a simple powertrain component. A housing with straight vanes, a rotor with straight vanes (aluminium pressure diecasting), a cover, two bearings and two seals. For serial production this can be produced simple and cheap.

Figure 4 – control cams



- Dog shift distribution system: used as shift element for the HD-clutch (both side shiftable) in the middle of the input shaft and as shift element (one side shift only) for the direct
- connection to the engine, on both sides of the input shaft. Dogs with a draft angle of appr. 3 ° are required as practicable compromise between axial forces and self disengagement in an active cam system. Independent of finding the correct speed difference for shifting, every dog clutch has a risk of a shift clonk. As back up, Ricardo is developping a simple combined dog/roller clamping clutch to get a shift without clonk.
- Control cylinder distribution system + e-motor: the shift procedures of the distribution system, from "odd" to "even" and "even" to "odd" are permanently recurring sequences
- and can be controlled by a continuous rotating control cylinder. Dog shifts need less power than a synchroniser shift (1000 – 1200 N), 400 N are sufficient – smaller e-motor – compared to a synchroniser shift.
- Dog shift main transmission: according the shift procedure the main transmission (odd and even) is shifted with decoupled clutch inertia. The internal transmission inertia only has to be synchronised to the shifted speed. All shift elements can be simplified to dog clutches as used for truck transmission (with heeling). As backup for shift clonk a simple elastic friction ring is sufficiant.
- Control cylinder main transmission (odd+even) + e-motor: the main transmission can be controlled by one control cylinder. Dog shifts less power than a synchroniser shift (1000 – 1200 N), 400 N are sufficient – smaller e-motor – compared to a synchroniser shift.
- Shift forks: also all shift forks need to tranfer these lower shift forces only. They can have a simple and small design.
- All other components are standard transmission parts as: gears, shafts, bearings, seals and housing parts.

Figure 5 part / cost comparison

5.1

	description	quant.	cost
add	Simple TCU, able to modify eng. speed	1	[illegible]
add	Dog shift elements	7	[illegible]
add	Shift forks, simple	7	[illegible]
add	Control cylinder	2	[illegible]
add	Position sensor	2	[illegible]
add	E-motor (low torque)	2	[illegible]
add	Input shaft „odd" – 3 gears	1	[illegible]
add	Input shaft „even" – 3 gears	1	+35
add	Input shaft HD-clutch	1	[illegible]
add	Input shaft direct „odd"	1	+11
add	HD-clutch, permanent filled	1	[illegible]
add	Main bearing	1	+4
add	NRB	4	+6
add	total		+411

5.2

	description	quant.	cost
leave	Clutch housing	1	[illegible]
leave	Clutch disc	1	-18
leave	Master cylinder	1	-10
leave	Slave cylinder	1	-10
leave	Clutch release bearing	1	-3
leave	Clutch actuation lever	1	-3
leave	Clutch wire and pedal - vehicle	1	[illegible]
leave	Input shaft – 6 gears	1	[illegible]
leave	Synchroniser system (single, double, 3) cone on driven gear	4	[illegible]
leave	Shift fork, complete	4	[illegible]
leave	Shift dome / shift actuation, shift lock	1	[illegible]
leave	Shift wires and lever - vehicle	1	[illegible]
leave	total		[illegible]

Cost-comparison to MT

Comparing a 6-speed transvers ad-T as shown in the pictures with a 6-speed transvers MT in similar architecture. Base is a 6-speed MT. To get an ad-T the following additional components have to be added, viewing the complete vehicle (see figure 5.1). And the following components can be deleted, viewing the complete vehicle (see figure 5.2).

To remember for ad-T:

- no friction clutch – no clutch control – no clutch actuation
- for shifting dog clutches only
- simple shift control, on-off functions only
- shift control by 2 electric driven control cylinders

All these components have different requirements, different evaluations in each company. So please evaluate it for your personal situation. The Ricardo estimation shows: the requirements regarding costs are not reached perfectly now but not too far away.

Conclusion

Please evaluate yourself how good this approach is able to fulfill the requirements. Some of them are clear, others expected but not prooven.

- Cost: The approch is anxious creating new components simple, simplifying existing components like replacing synchronisers by dogs – less cost, less friction- and preparing all components for high volume production.
- Shift performance: with HD-clutch and dogs all preconditions are given for as fast and smooth shift.
- Risk: shift clonk – back-ups available.
- Efficiency: no friction elements, HD-clutch used for launch and shift support only.
- Producibility: all parts are producible with common MT production technology.
  - ✔ No on-costs for the vehicle compared with a MT solution
  - ✔ Producible with common MT production technology
  - ✔ Mechanical efficiency equal or better than a comparable MT solution
  - ✔ Automatic shifting with an acceptable shift performance – short shift time, no or short torque interruption, smooth shifts
  - ✔ Optimised power train efficiency equal or better than a comparable dry DCT solution

We are confident having bright prospects to reach or be very close to the requirements – isn't is worth to try? And as outlook: a low cost hybrid with the same conception is in concept phase.

More information
www.ricardo.com/en-GB/What-we-do/Technical-Consulting/Driveline--Transmission-Systems/
or email to guenther.priwitzer@ricardo.com

Interview

“There is no *Eigenvalue* of a Single Solution”

Hyundai/Kia enters the market with a family of medium-segment full and plug-in hybrid cars based on a six-speed DCT. We discussed the new hybrid architecture with **John Juriga**, Director Powertrain at Hyundai America.

Mr Juriga, why did you choose a six-speed DCT for the new Hyundai Ioniq and Kia Niro?

We had various DCTs in production, but decided on a six-speed version as we do not actually need the seventh gear for this application. And by staying with six speeds we can keep the mass down, keep the cost down, and still optimize the gear ratios for full hybrid requirements. The NIro is a little larger and heavier, so we have a different spread using the same transmission. Compared to non-hybrid applications, we use the same type of engagement for the shift control, the solenoids, electronics and control – so it is the same type of architecture.

John Juriga, Director Powertrain, Hyundai America Technical Center

You could have chosen a powersplit architecture instead. Why did you go for a parallel design?

There are obviously many configurations you could put in place; our focus was to provide the most value with compatible hardware. We wanted to keep the cost down and provide the best benefit for the customer. So this configuration, which we call TMED, which stands for “Transmission Mounted Electric Device”, is our trademark architecture for our hybrid configurations. We use it in the Sonata, as well as in the new Ionic and the new Niro.

American customers sometimes criticize the launch feel of DCTs. How would you overcome that?

Especially in the States, our customers are more sensitive to launch characteristics with the dual-clutch transmission. And it's always a challenge with a conventional internal combustion engine to make that launch satisfactory for the customer. We do not have a torque converter in the system. But because we have the electric motor, it gives us additional flexibility to get the vehicle launching better and make it more fun to drive. It is actually a nice marriage between the DCT, the electric motor and the 1.6 litre Atkinson type engine. In general, I think for many customers, DCT, CVT or AT are just letters; but they understand the feel. The electric motor with 32 kW in the Niro and Ioniq gives you very instant low rpm torque, it's a wonderful launch device.

Does electrification of your DCTs improve shift behaviour in terms of NVH?

One of the key tricks in any shifting operation is to make sure you have the right amount of torque to engage and disengage the gear sets smoothly at the right speed. If I have an electric motor, it gives me more fine tuning capability. The ICE will produce a certain amount of fixed torque at a certain speed, and the electric motor allows me to fine-control the combined torque input. Obviously, this makes control schemes very complicated, but being able to coordinate and manage these different inputs enables more shift comfort as well.

What does the on-board power supply look like, especially in terms of low and high voltage distribution?

We have an integrated system with 12 Volt and high voltage, both based on Li-Ion battery technology. I think this is an industry first for a 12 Volt system. We were able to integrate this combined battery pack between the low and high voltage system, which helped from a packaging standpoint, as well as from a cost standpoint. The challenge for any new vehicle is making sure you get the volume up wherever possible. We believe the Ioniq is currently a stand-alone type in the market alongside full hybrid, plug-in hybrid and all-electric. The modular Li-Ion battery technology enables further synergies within this architecture, even though the hybrid and EV versions require different sized batteries.

Another first in this segment is the use of topographical navigation data. How does this support the driving strategy?

Using topography to improve efficiency and the driving experience is a relatively new technology. Knowing what lies ahead helps us to optimize powertrain efficiency and minimize interference from upshifts and downshifts. If we know a hill is coming and we know our current state of charge, we can go below the normal threshold because we know how much we'll be able to recuperate going down the next gradient. We will benefit even more as navigation data mapping systems become more accurate – for example on side roads or in terms of higher information density. So technology is available, algorithms are available, and with more accurate data from the service provider, we'll be able to expand the functionality further still.

You are scaling up from a full hybrid. What do you think about 48 Volt solutions?

The challenge with full hybrid systems is of course the cost, but customers definitely have big benefits in terms of fuel economy. However, we're also looking at solutions in between 12 Volt and high voltage, and we see some companies gravitating towards that. One 48 Volt benefit will be to provide more voltage for components like electric water pumps, air conditioning etc. These systems run more efficiently with more voltage, and you can reduce weight and size. But there are many solutions. It's always a balance between the voltage system I use, the energy level, the storage capacity of my battery, and what is the best overall balance for a given vehicle in a given customer segment. There is no single eigenvalue of a single solution.

You offer an all-electric Ioniq too. Which levels of electrification do you expect in different vehicle segments?

Obviously small vehicles have less room for the battery pack, but they are lighter and require smaller batteries to enable sufficient range for their typical field of use. I think in general, that still holds true. And you have other technologies such as fuel cell technology, where you don't have the range anxiety providing we have the infrastructure. Hydrogen fuel cell vehicles may be more acceptable in larger vehicles and even SUVs. In really general terms you could say EVs may be for smaller vehicles, and fuel cells for larger vehicles. But as with hybrid powertrains there are all kinds of configurations, so that generalization won't always hold water. We are all trying to figure out the most efficient, economical way to provide affordable solutions to the customer.

Interview: Gernot Goppelt, CTI Correspondent

Innovative transmission bearing from NSK contributes to vehicle fuel efficiency and reliability

New Transmission Bearing Reduces Housing Wear

NSK has developed an automotive transmission bearing with a solid lubricant film that protects against housing wear and supports the approach of weight reduction.

- Cem Yoldjou, Product Manager Drivetrain, NSK Deutschland
- Peter Kohl, Engineering Manager Automotive Bearings, NSK Deutschland

Wear Due to Creep

Intended for use in automatic transmissions (AT), Dual Clutch Transmissions (DCT), Manual Transmissions (MT) and continuously variable transmissions (CVT), NSK has developed an innovative bearing solution for the automotive industry that features a solid lubricant film. The new bearing contributes to higher vehicle reliability by reducing wear due to creep, a phenomenon where the outer ring of the bearing starts to shift in the transmission housing.

Recent demands from automotive OEMs and TIERs for more compact, lightweight transmissions have been growing in line with greater requirements for vehicle fuel efficiency. The result of this design pressure has led to the evolution of thinner bearing housings, a characteristic that, in time, can lead to slight deformation.

Any deformation will create a gap between the housing and bearing, which in turn can cause the outer ring of the bearing to lose its fit. The upshot is creep, an undesirable effect that sees the outer ring begin to rotate very gradually when it should not. Eventually, this creep will start to generate wear on the aluminium housings.

Amplified Vibration

The effect of housing wear due to creep will amplify vibration with the transmission, what might cause NVH issues. Erratic rotation will then result, creating wear debris that can cause components within the transmission to malfunction. Both vehicle reliability and driver comfort will subsequently deteriorate.

The conventional solution to this problem typically entails a tight fit, fitting an O-ring and/or manufacturing a thicker outer ring. However, such measures are costly, time-consuming and make assembly more difficult.

With these issues in mind, NSK set out to develop a new generation of transmission bearings that would not cause housing wear, even if some creep occurred.

Figure 1 NSK´s new automotive transmission bearing with solid lubricant film reduces housing wear
Copyright: NSK

Figure 2 The latest bearing technology from NSK helps improve the performance of all transmission types
Copyright: Grau Schnittmodelle

Solid Lubricant Film

The new transmission bearing from NSK features a low-friction, solid lubricant film coating on the outer ring's external surface, lowering the coefficient of friction and reducing wear on the inner surface of the housing, even in the eventuality of creep. Importantly, this solution means there is no need to increase bearing size or increase the thickness of the bearing periphery, therefore maintaining simple assembly.

The solid lubricant film comprises a processed substrate on the bearing base surface and a bonded film coating on the substrate. This type of solution is already deployed successfully on other types of components, such as gears and valves, but its application on the new NSK transmission bearings raised a number of challenges that had to be overcome. For example, would it be able to offer the required level of wear resistance, or would it exhibit peeling? Furthermore, the high temperature tempering processes involved in applying the film might reduce the performance of the bearing steel. There were also cost implications that could ultimately hinder its success in the marketplace.

Overcoming the Challenges

The new NSK transmission bearing with solid lubricant film solves all of these issues in a number of innovative ways. For example, engineers at NSK optimised the design of the friction and wear adjusters (and solid lubricant agent), along with the grain size of the adjuster. As a consequence, the adjuster is able to resist wear for extended periods of time, even in tough automobile operating environments.

A further innovation related to finding an alternative to the high temperature tempering processes required to harden the bonded film. Without a suitable solution, the bearing steel could lose its hardness, which would reduce durability characteristics. However, NSK developed an optimised resin binder hardener that allows the bonded film to be hardened at lower temperatures. Furthermore, the company selected a resin binder that hardens quickly, thus keeping overall costs down.

About NSK

Established 100 years ago, NSK (Nippon Seiko Kabushiki Kaisha) is a Japanese-listed company that has evolved from a regional ball bearing supplier to a roller bearing specialist and automotive supplier with a global market presence. Today, NSK employs more than 31,500 employees in 30 countries. As per March 2016 NSK achieved a turnover of 975 billion Yen. This result has been driven by ever-increasing investment in research & development, enabling the company to continuously improve the quality of its products and services. This investment supports NSK's objective of "No. 1 in Total Quality". In addition to a complete rolling bearing portfolio, NSK develops and manufactures precision components and mechatronic products, as well as systems and components for the automotive industry, including wheel bearing units and electric power-steering systems.

In 1963, NSK's first European subsidiary, Düsseldorf, Germany, was opened and in 1976, the first European production facility in Peterlee, England. Today, NSK Europe supports pan-European sales with production locations in England, Poland and Germany, logistics centres in the Netherlands, Germany and England and technology centres in Germany, England and Poland. In 1990, NSK purchased the UPI Group including the renowned European bearing manufacturer RHP, with its factory in Newark (UK). Additionally, NSK has developed a comprehensive network of authorised sales distributors. NSK Europe is divided into application-based business divisions: Industry rolling bearing technologies & linear and precision technology (EIBU) as well as bearing modules and steering systems for the automotive industry (EABU & ESBU). In this organisation, NSK Europe's 3,500 employees achieved a turnover of over 1,000 million Euros as per March 2016.

For more information, visit www.nskeurope.com

Understanding of TIFF and TFF is required at the design stage of transmission systems

Evaluation of TIFF and TFF Load Carrying Capacities and Comparison Against Other Failure Modes

This paper consolidates validation of methodology and comparison of load carrying capacity to allowable loading conditions for bending and pitting fatigue failures.

- Baydu Al, Analyst/Software Engineer, Smart Manufacturing Technology
- Dr Paul Langlois, CAE Products Development Department Manager, Smart Manufacturing Technology

Examples from the open literature have been used to compare results with those obtained by a proposed methodology, as implemented in SMT's MASTA software, for analysis of TIFF and TFF in which loaded tooth contact analysis (LTCA) results have been utilized to determine load boundary conditions at a selected number of points in the gear tooth load cycle. The method is then used to extend existing understanding of TIFF and TFF load capacity and compare to the allowable loading conditions for bending and pitting fatigue failure based on the standard calculation procedures. Possible methods that could be used to mitigate TIFF risk are presented and the effect of these methods on the performance with respect to the other failure modes are quantified.

Overview of Failure Mode

Gears are case hardened to produce compressive residual stresses at and close to the surface, improving wear resistance, bending fatigue, and contact fatigue strength. These beneficial compressive stresses are balanced by tensile stresses within the core. This poses an increased risk of fatigue crack growth below the surface. Both Tooth Interior Fatigue Fracture (TIFF) and Tooth Flank Fracture (TFF, also known as Tooth Flank Breakage (TFB)) describe a failure mode where a subsurface fatigue crack initiates close to the case core boundary, at approximately mid-height of the tooth.

Previous research [1–8] has established that the direction in which the crack propagates and the appearance of the associated fracture is dependent on the flank loading (i.e. single stage loading versus idler usage). Although there does not appear to be total agreement in the literature, TIFF (failure with reverse loading) and TFF (failure with single flank loading) appear to have very similar characteristics and crack initiation mechanisms. However, as shown in Figure 1, the final fracture shape and distribution of total stresses are different, due to TIFF having near-symmetric total stresses along the tooth centreline (with two possible initiation points per tooth). The location of the crack initiation distinguishes this failure mode from other fatigue failure modes, where the crack initiates at or close to the surface.

TIFF and TFF failures can appear at loads below the allowable loading conditions for pitting and bending fatigue failure based on the interna-

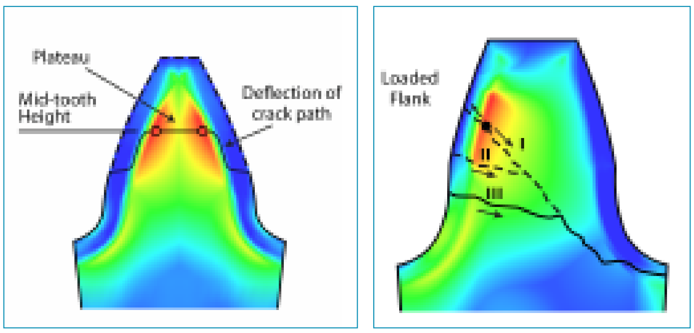


Figure 1 Expected crack propagation paths and intensity of total stresses for TIFF (left, adapted from [1]) and TFF (right, adapted from [4]).

	Author's method	Author's method with Lang [16] for residual stresses
Stress History	Calculated using 2D FE analysis where MASTA's LTCA model [15] has been utilized to obtain the load boundary conditions for the contact.	
Residual Stress State	Calculated using 2D FE with volume expansion specified as in MackAldener.	According to Lang [16] and used by Witzig [8]. Tensile stresses in the core are assumed negligible.
Equivalent Stresses	Calculated using Findley critical plane criterion. Fatigue sensitivity to normal stress assumed to vary continuously in the same manner as the hardness profile. As in MackAldener.	
Initiation Threshold	Calculated by dividing the maximum Findley plane stress by the permissible stress at a given point. Critical plane stress is assumed to vary continuously in the same manner as the hardness profile. As in MackAldener.	

Table 1 Summary of the author's calculation method

tionally accepted calculation procedures (such as ISO 6336 [9] and AGMA 2101-D04 [11]). Therefore, understanding of TIFF and TFF failure modes is required at the design stage to avoid durability issues in the field.

As of the time of writing, there is no accepted standardised method to assess the probability of this type of failure and the relative importance of the influencing factors. It is, however, worth noting that TFF is an active topic within the ISO gearing committee, which is currently working on a draft standard, ISO/DTR 19042, for the calculation of Tooth Flank Fracture performance.

Methodology

A review of existing calculation methods can be found in Al et al. [12]. The methodology used throughout the rest of this paper, and implemented in MASTA, is derived from MackAldener's finite element method and has been described in detail in our previous work [12-14]. Table 1 provides a brief summary of the methodology.

Validation Against TIFF Open Literature [2]

A parametric study initially conducted by MackAldener [2] to investigate which parameters influence the risk of TIFF has been repeated to validate the author's methodology, presented in [12, 13]. This study considered varying critical plane stress within the core (A), fatigue sensitivity to normal stress within the core (B), gear tooth geometry (C), total case depth (D), and torque on the pinion (E). The change in gear design in C is reflected mostly in the "slenderness ratio", defined as the ratio between the height of the involute and the tooth thickness (C- lower ratio, C+ higher slenderness ratio). For each of the designs, the Crack Initiation Risk Factor (CIRF) throughout the tooth was calculated. Al et al. [12] further investigated the effect of using Lang [16] to specify residual stresses, where residual tensile stresses within the core are not considered.

Figure 2 shows a comparison of the calculated maximum CIRF for all 32 designs. From **Figure 2**, it is clear that there is a good overall correlation between CIRF calculated by the author's method and that calculated by MackAldener [2].

Figure 3 displays the average CIRF results for each factor at its low and high level together with the average for some interactions. It can be seen that good agreement exists for factors A, B, D, and E, and reasonable agreement for factor C.

Details regarding these comparisons are discussed in [12]. One interesting observation here comes when examining the cases where the author's method is used with Lang [16] for residual stresses. In these calculations tensile stresses within the core are assumed negligible. As can clearly be seen from **Figure 2**, this approach underestimates the maximum CIRF in all designs investigated. Furthermore, using Lang [16] for residual stresses changes the relationships and some interactions expected from the factors (Figure 3). This change can be attributed to differences in the hardness profiles and/or neglected tensile residual stresses within the core.

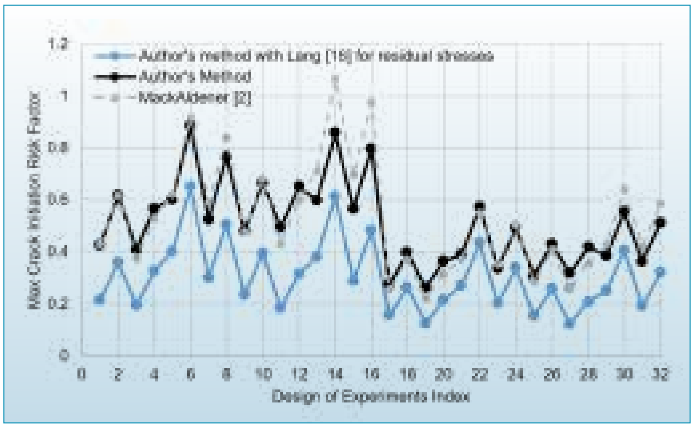


Figure 2 Comparison of the calculated Maximum CIRF's using the author's method, author's method with Lang [16] for residual stresses, and MackAldener's finite element calculations. Index values have been determined by first sorting according to factor (A through E) then sorting the values of each factor in ascending order. As shown in Al et al. [12]

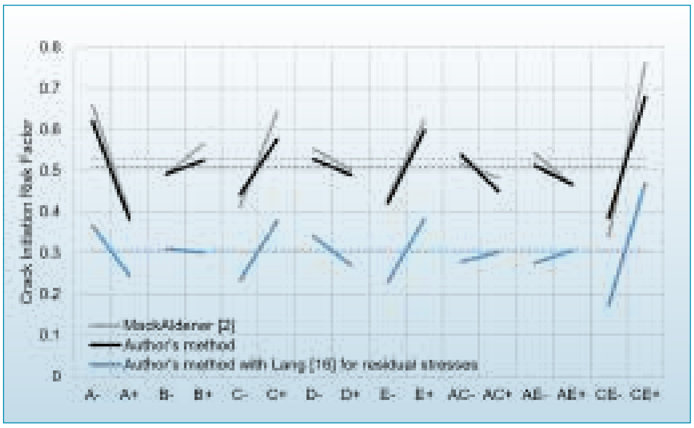


Figure 3 Comparison of the effects of individual factors and their interactions on CIRF response for author's method, author's method with Lang [16] for residual stresses, and MackAldener's FE calculations. The dotted lines represent the mean response from each method. As shown in Al et al. [12]

Effect of Factors on Pitting and Bending Safety Factors

Factor (C) gear design and Factor (E) torque on the pinion are two parameters investigated in the factorial design which would have a direct effect on pitting and bending fatigue calculations according to ISO 6336 [9]. It has been assumed all gears have a flank tolerance class of 5 according to ISO 1328-1 [10] and material quality grade of ME. It should be noted that the other parameters in the study could also potentially have an effect on the pitting and bending safety factors, however they are not directly reflected in the inputs of ISO 6336 which for the material properties has assumptions based on the ISO material type selected.

Figure 4 shows how crack initiation risk factor, bending safety factor, and pitting safety factor vary with the change in the common factors which affect all three calculations. It should be noted that resistance to all three failure types can be improved by reducing the torque. For the cases investigated, slender toothed gears show an improved safety against bending, however reduced safety for TIFF and pitting. As can be seen from Figure 4, both CIRF^{-1} and gear bending fatigue are more sensitive to both geometry and loading compared to pitting.

Validation Against TFF Open Literature [8]

Witzig [8] has run numerous experiments with test gears and validated their calculation model, suggesting a critical threshold of 1.2 for safety factor dependent on material exposure and calibration coefficient. These gear sets were designed to fail due to Tooth Flank Fracture and results were reproducible. It is important to note that failure analysis of these gear sets showed that, in the majority of cases, initial crack initiation occurred at an inclusion near the case-core boundary. However, the size and the effect of these inclusions are not included within the analysis (i.e. material is considered homogeneous).

Figure 5 summarizes the results from Witzig [8] for spur gear set 67/69 spur gear set. It should be noted that the y-axis on the right, for the TFF safety factor, is shifted to give comparable results (i.e. the critical value for the CIRF^{-1} is expected to be 1 while for Witzig TFF safety factor this critical value is 1.2).

Given the assumptions made, including the assumption that a critical CIRF^{-1} of 1 can be compared with a Witzig's TFF safety factor of 1.2,

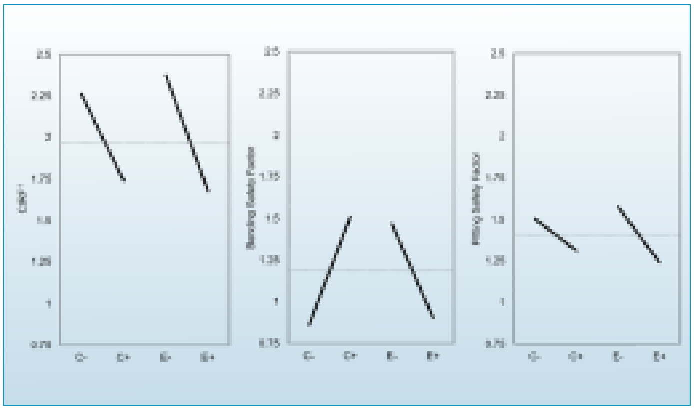


Figure 4 Comparison of geometry and load effects on CIRF, Bending Safety Factor, and Pitting Safety Factor. As shown in Al et al. [12]

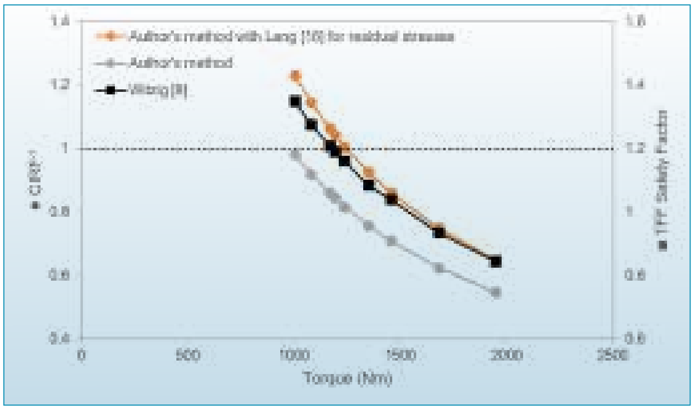


Figure 5 Comparison of calculated CIRF^{-1} and Witzig's method for 67/69 Spur Gear. It should be noted that y-axis of the TFF safety factor is shifted to give comparable results (i.e. threshold value for CIRF^{-1} is expected to be 1 and for TFF safety factor is 1.2 [8]). Adapted from Al, et al. [14]

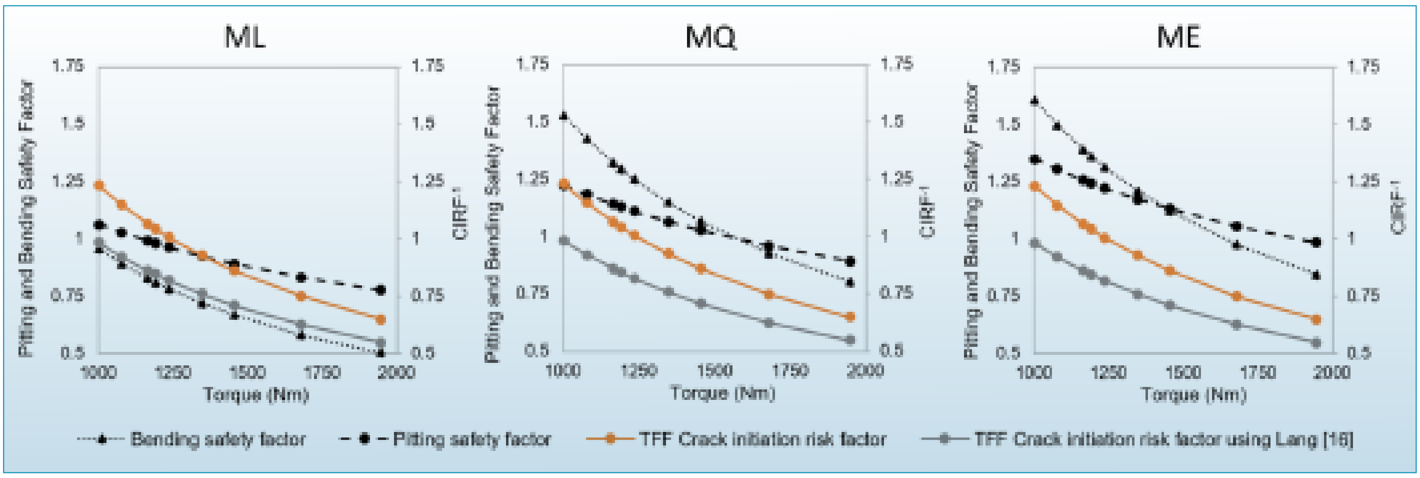


Figure 6 Comparison of TFF load capacity with safety factors for bending and pitting fatigue failures based on ISO 6336 [9], for 67/69 spur gear with different material qualities, from left to right ML, MQ, ME. As shown in Al et al. [12].

the results obtained show similar qualitative behaviour but some significant difference in the torque which leads to the critical metric values ($CIRF^{-1}$ or TFF Safety Factor) for different designs. Further investigation is required to understand whether this difference is down to the assumptions made in our inputs or a more fundamental difference in the formalism of the methods. The results in Figure 5 for the author's method with and without the use of Lang for residual stresses give some indication that differences relate to the inclusion or not of residual tensile stresses in the core.

Comparison of Load Carrying Capacity with Other Failure Mode

Calculated $CIRF^{-1}$ using the author's method with both residual stress calculation methods are extracted from Figure 5 and plotted together with pitting and bending fatigue safety factors in Figure 6. The figure shows results for the three different ISO 6336 material quality classes. As can be seen in Figure 6, according to the calculations the torque range over which TFF failure could occur changes, in comparison to pitting and bending failure. However, it should be noted that TIFF and TFF calculations, at present, do not take material quality into account. This is a significant shortcoming of the current procedures given the indications in the field that TIFF failures are often associated with crack initiation at material inclusions. Utilizing MackAldener's approach, this parameter could be included within the critical fatigue strength.

Conclusions

This paper aimed to consolidate the existing understanding of TIFF and TFF load capacity and its comparison to allowable loading conditions for bending and pitting fatigue based on standard calculation procedures.

The key conclusions from this study are:

- It is possible to replace a computationally expensive explicitly modelled FE-based contact analysis e.g.[2] with simple load boundary conditions obtained by a separate specialized gear Loaded Tooth Contact Analysis (LTCA), in order to apply MackAldener's methodology for the analysis of TIFF.
- It is possible to analyse the risk of TFF by applying a methodology based on MackAldener. However, as is to be expected, thresholds obtained from Witzig's method and Findley are different. The critical value has been found to be close to 1, but requires further investigation.
- The calculated CIRF is higher when tensile residual stresses are considered within the core compared to Lang. It has been found that for the cases investigated the effect of residual stresses increases with torque. It should be also noted that neglecting tensile stresses within the core modifies the expected relationships between factors resulting from the factorial design.
- The torque range across which TFF failure can be seen could be relatively small compared to the operating range.

Further understanding of residual tensile stresses within the core of a gear loaded on a single flank is required to determine the suitability of Lang [16] to these applications.

It is the author's opinion that the critical effect of material quality and inclusions is the key factor missing in the type of analyses presented. We would expect that this could be addressed as a factor applied to e.g. the material thresholds (utilizing MackAldener's approach, this parameter could be included within the critical fatigue strength), however significant field experience and further experimental studies are required to address this point.

More Information

The contents of this paper are consolidated from papers presented at British Gears Association (BGA) Gears 2015, Car Training Institute (CTI) Symposium USA 2016 and American Gear Manufacturers Association (AGMA) Fall Technical Meeting 2016.
For more information, see www.smartmt.com/Downloads/

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Software-based Load and Lifetime Monitoring for Automotive Components

Or when Big Data stand for proactive & lightweight design, intelligent operating strategies and predictive maintenance

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- Dr-Ing. Rafael Fietzek, EXIST-Spin-Off Project compLIFE, funded by the German Ministry for Economic Affairs and Energy, Executive Director, Business Developement, compredict

Even if emission and cost reductions, short development time and lightweight design are since more than two decades essential cornerstones in automotive engineering, the reality is quite different. In a recent intervention during the prize ceremony of the Johann Puch Automotive Awards 2016 which arwarded the first prize to the EXIST-Spin-Off project compLIFE, Karl Stracke, President Automotive Technology & Engineering by Magna Steyr, stated in this context that still today "cost and weight have to get out of the vehicles".

This is a fact: lightweight design based on new materials needs investments, vehicle development requires huge engineering time, endurance tests are cost-intensive. Nevertheless, components still break down and recall actions are always a risk. Obviously, the current state of the art in the automotive sector does not achieve its full potential with regard to component dimensioning, operating strategy and maintenance. This is mainly due to the limited knowledge about the actual component usage profiles under real operating conditions. Once the vehicles are designed, released and introduced in the market, the automotive manufacturers and suppliers only get a feedback, if field failures occur. Thus, most of the time, they do not get any feedback. How are the vehicles being driven by the customers? What are the real load profiles of the components? Are they able to fulfill the nominal lifetime requirements? Are the components overdesigned? Are they underdesigned? These questions raised cannot be satisfyingly answered nowadays.

But, what if the load profiles of vehicle components could be precisely determined and their lifetimes predicted? What if an analysis of these data could be achieved at the fleet level? And what if the real vehicle fleet would become a part of a knowledge-based and proactive development process in the framework of Smart Big Data? To make it possible, each vehicle should have to be monitored, meaning equipped with a load monitoring and lifetime prediction system. This is only feasible, if the relevant physical quantities (e.g. force, torque) are dynamically and accurately acquired. Series-production vehicles do not possess the necessary equipment to achieve this task and, from this point of view, the mounting of dedicated sensors points economic and technical issues. Therefore, the remaining possibility is to answer this practical problem with a software-based approach. And this is precisely what the Institute for Mechatronic Systems in Mechanical Engineering (IMS) of the Technical University of Darmstadt in Germany addressed in the past years at the example of the gearwheels of automotive transmissions and what the EXIST-Spin-Off project compLIFE funded by the German Ministry for Economic Affairs and Energy is now actively transferring to the industry and also extending to other components and systems such as clutch, synchronizers, suspension, brake, electric engine, accumulators, etc.

Motivation

For the dimensioning and the release of automotive components, a conservative approach is generally adopted in order to guarantee a high degree of reliability and avoid operating failures as much as possible. Usually, a 99.9 %-driver is taken as a reference, which covers theoretically 99.9 % of the usage profiles. For cost reasons, simulations and less and less field tests mainly determine this one. Moreover, for safety reasons and due to limited knowledge about real operating conditions, very demanding driving situations are taken into account, which do not necessarily represent the end user behavior, and often overestimate it. As a direct result, the components developed with standard industry procedures are overdesigned for the majority of the end-customers. This leads to superfluous weight, which in turn implies higher material costs and fuel consumption.

An additional aspect is that the load spectra of the components and the resulting service lifetimes are only considered during the development phase. This means that, after the market introduction, no data relating to the real driver profiles are generated. This brings three disadvantages. First, the future generations of components cannot be improved with regard to the real driver and damage behavior. Second, the cause of a field failure can only be identified with a lot of effort, because the load history of the respective components is not available and the load scenario is not reproducible. Third, the components cannot be operated under consideration of the component damage levels because the required inputs are missing. A damage-oriented operating strategy is advantageous to enhance the components service life for each individual driver during operation.

In this context, online and real-time condition prediction systems, so-called load & lifetime monitoring, are being currently developed at IMS, which are intended for implementation in standard control units of series production cars.

Load & Lifetime Monitoring Without Additional Hardware

Purely software-based, the load & lifetime monitoring acquires the dynamic component loads by sensor fusion and accumulates the induced partial damages in real-time. This way, the generated data provide a high quality and validity. So the component load spectra are computed continuously and under operating conditions, and the resulting remaining service life is predicted from the first day of vehicle use. In this sense, it is not supposed that a failure has already occurred or a fault is progressing, but a continuous comparison between design (load capacity) and operation (load) is achieved (so-called DO-4-LIFE-calculation for “Design vs. Operation FORecasts LIFEtime”). This is a significant distinction from usual Condition Monitoring methods. The application-oriented, easily adaptable and reliable lifetime monitoring system does not require any additional hardware and is based on already available vehicle sensors and signals running on the vehicle bus, such as a Controller Area Network (CAN). Furthermore, the amount of

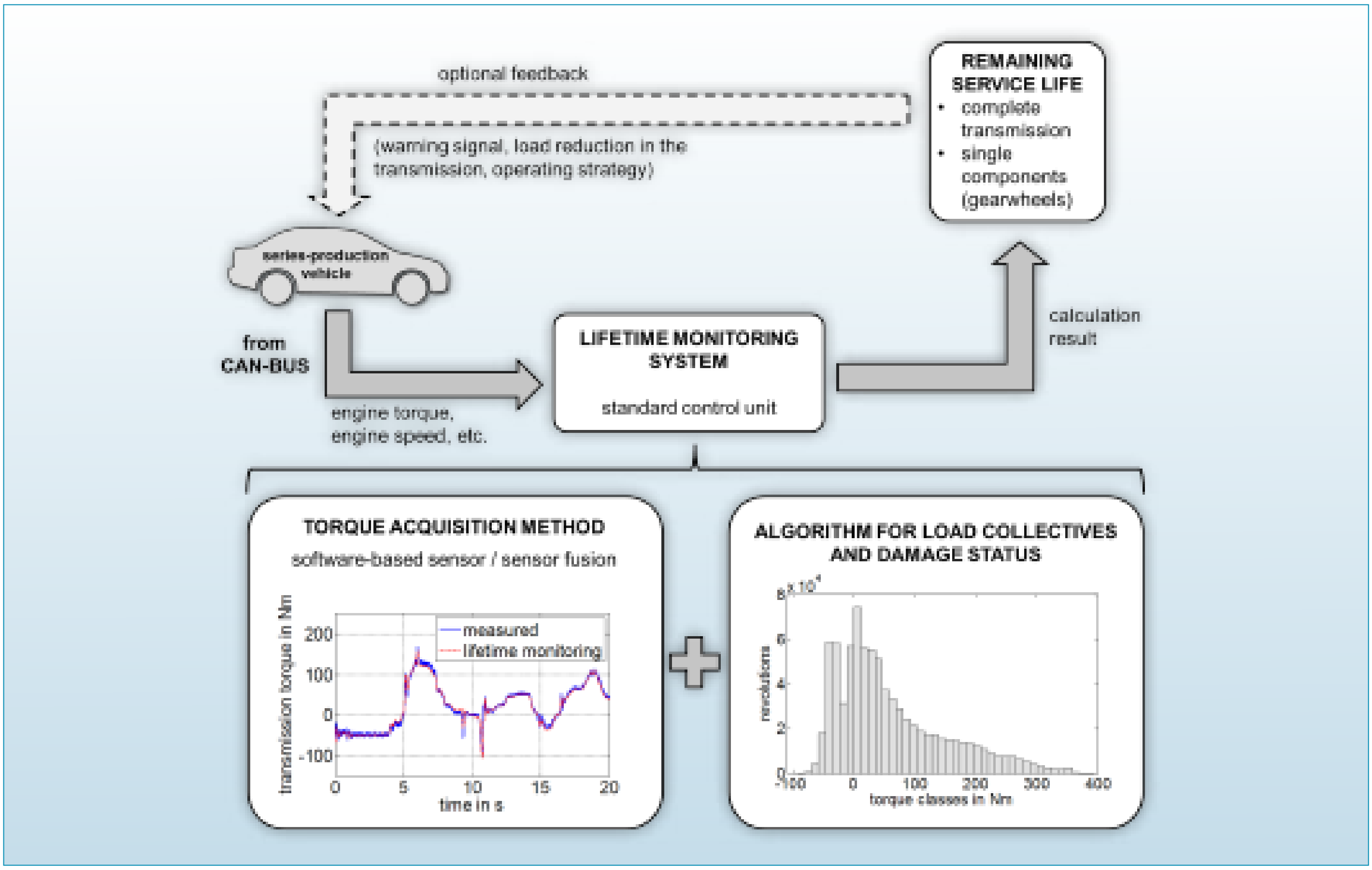


Figure 1 Example of load & lifetime monitoring for automotive transmissions

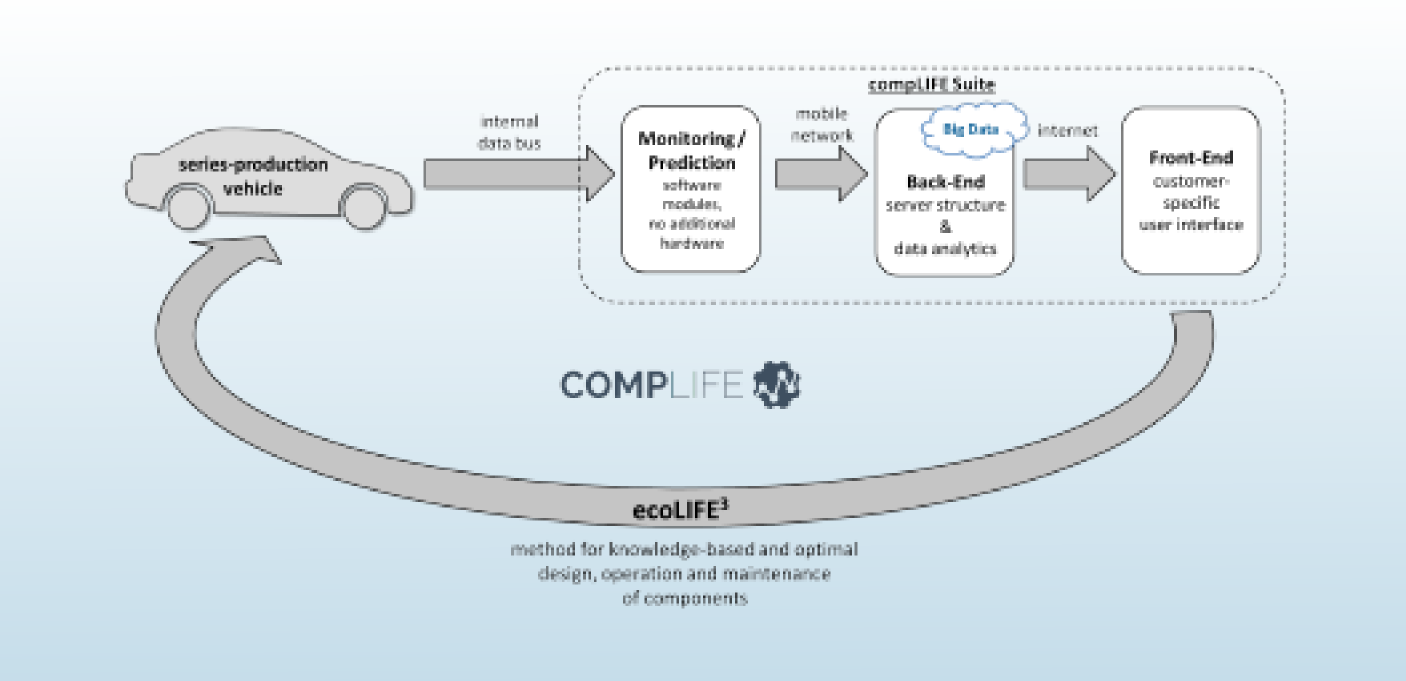


Figure 2 ecoLIFE³ as a part of the compLIFE Suite

generated data is kept low, and the limited computing power and storage capacity of standard Electronic Control Units (ECU) are considered, so that the system can be implemented in all vehicles without any special expense (Fig. 1).

Smart Big Data: Complife Suite and ecoLIFE³

By going beyond the vehicle level and considering the complete vehicle fleet, the possibility of a continuous optimization procedure on basis of the load & lifetime monitoring system emerges for a better control of user profile discrepancies, customer-optimized lightweight design, cost-efficiency and improved resource management. This is namely what the ecoLIFE³ approach developed at IMS aims at. The abbreviation is standing for **e**lectronic and **c**ontinuous **o**ptimization of **LIFE**time and **LI**gthweight **FE**atures based on **L**oad **I**dentification and **F**atigue **E**stimation. The basic idea of the ecoLIFE³ procedure is to involve the data generated by the load & lifetime monitoring system in the dimensioning routine, the operating strategy and the predictive maintenance of components. This way, the global vehicle fleet becomes a part of a continuously monitored optimization problem within a knowledge-based development process (Fig. 2).

For this purpose, the data generated by the load & lifetime monitoring system are transferred to external evaluation units for statistical analysis. The data transfer is realized during service inspections or wirelessly, if available. In any case, the data management is performed within the scope of a Smart Big Data approach. Regarding data security and confidentiality, no individual-related data is supposed to be generated. No time signal is recorded and only aggregated data are computed. The unique information is about the component load profiles and attained damage levels. This means that it cannot be determined, where, how or when a user drove or why one load or another was generated. However, it could certainly be deduced, if a component was aggressively loaded or not. But, from this point of view, this is the same kind of deduction which can be done today for an engine on basis of oil service intervals. At the end, this does not represent a critical point.

To make ecoLIFE³ possible, the Spin-Off project compLIFE is currently developing the first version of the compLIFE Suite. The overall goal is to propose a complete, customer-specific and turnkey solution for car manufacturers and suppliers which contains the load & lifetime monitoring algorithms for vehicle components ready to be implemented on control units, a back-end server structure to administrate and analyze the data, and a customer-specific user interface such as a client-software or web interface in order to prepare and represent the key results and information.

Towards Vehicle 5.0

The goals in automotive engineering are to make vehicles lightweight, environmental friendly and autonomous. In connection with these goals, car-to-car communication and the internet of things open up new ways to process and use operating data. As of now, there could be gained a lot additional knowledge by analyzing the operating data. The research cluster Vehicle 5.0 at TU Darmstadt, of which the Spin-Off project compLIFE is an important part, will focus on the development of scientific methods and a knowledge base to enable the continuous improvement and the intelligent operation of connected vehicles with the support of Big Data. The aim of the research cluster Vehicle 5.0 is to develop progressive methods, which will lead to a paradigm shift in the automotive industry.

Conclusion

The current state of the art in the automotive industry does not achieve its full potential regarding component dimensioning, operating strategy and maintenance. In this article a software-based method was described, which enables manufacturers and suppliers to get information about the real user profiles and load spectra under operating conditions without additional hardware costs. Based on sensor fusion, the relevant physical quantities (e.g. forces, torques) are calculated accurately. In combination with the ecoLIFE³ procedure the generated load spectra and user profiles are analyzed at global vehicle fleet level and become part of a continuously monitored optimization problem within a knowledge-based development process. In this way the dimensioning of components and the related operating strategy can be optimized at fleet level. The EXIST-Spin-Off project compLIFE funded by the German Ministry for Economic Affairs and Energy is now actively transferring these research results to the industry and proceeding the development of methods for systems such as gears, clutches, synchronizers, suspension parts, brakes, electric engines, accumulators, etc.

Interview

"Knowledge-Based Data is the Key"

Professor Rinderknecht, accurate load monitoring using real-life data requires a lot of sensor information from the car. Are today's data sufficient for the ecoLife method, or do we need new sensor types?

The data we get from cars today are sufficient to collect what we need, and process it in the lifetime monitoring software. We might think about additional sensors in future if they pay off by delivering even more exact data. But in transmissions, mechanical load is directly linked to criteria such as engine torque and the resulting loads in various transmission components. So we don't need a specific torque sensor, for instance. We already know how to reconstruct torque values in real time from existing sensor data. The ecoLife method requires no modifications to current hardware and software; not in-car, and not in terms of transmission design methods.

The benefit is that you gain an additional path within the development process that reduces the need for over-engineering by using data that are knowledge based, not rule based. Would redesigning transmissions within their lifecycle be an option?

That's quite unlikely in my opinion. It's not our intention to modify the development process itself –which incidentally, would increase costs too. But there may be other new opportunities. For example, real-life knowledge might reveal different load spectra at fleet level in different markets with different driving habits. So for instance, we could opt for a smaller transmission type in specific markets, and reduce overdesign at vehicle level using existing products. But that's only possible if we can make decisions based on knowledge; by opening every black box, if you will.

Prof. Dr-Ing. Stephan Rinderknecht, Head of the Institute for Mechatronic Systems in Mechanical Engineering (IMS), TU Darmstadt

If we have this kind of real-life data from the powertrain, would it make sense to modify the operating strategy to modulate the load within individual vehicles?

Generally speaking, that is possible using the aggregated information. To a certain extent, we can predict the remaining life of a transmission and then adapt the operating strategy individually within the powertrain. For example, we gain information about individual driving styles, and hence about the possible accumulation of load peaks and above-average lifetime loads. I think there are several possibilities for intelligent concepts. Of course, these ideas have to be acceptable for the car owner. That's one reason why we are teaming up_with psychologists and economists at TU Darmstadt to explore future use cases and their acceptance levels.

The idea of designing a product closer to its mechanical limits might raise a few eyebrows among car drivers. How would you convince them that they benefit from the ecoLife approach?

That's a very important point indeed. The purpose of ecoLife is not only to enable OEMs and suppliers to reduce costs, or produce vehicles that are more CO_2-efficient. We see our research as a contribution to overall resource conservation in society too. By using knowledge-based software – and without changing the product design approach itself – we can produce more efficient powertrains that pay off by reducing the number of build versions and our costs-per-unit. If we think further ahead, we might consider some kind of in-car feedback for resource-friendly drivers, or perhaps even bonus systems. This would enable car owners to effectively improve car reliability. On the other hand, cost savings from more efficient design could be passed on to car owners if a new transmission is needed.

What feedback are you getting from OEMs and suppliers?

Some of them may be a little skeptical at first, but in general the response is positive. One crucial aspect is that ecoLife requires no changes in the development processes; the only difference is that we use much more exact and specific knowledge-based data instead of empirical knowledge. The good thing is that we can proceed step by step, gaining more knowledge with each new step and shifting from vehicle 4.0 to 5.0 without having to abandon proven methods and processes. We have found some partners who say 'Let's get started and learn what we can do with it.' We might even discover completely new possibilities that we couldn't see before because we simply didn't have the real-life data.

Interview: Gernot Goppelt, CTI Correspondent

Efficient Development Process from Supplier Point of View

■ Stefan Beinkämpen, Head of Business Development, VOIT Automotive

Changes in the automotive powertrain are increasing significantly. Already more than half of all vehicles produced have automatic transmission concepts which are increasingly being electrified. In this process, future developments will change from the series installation of the electric machine in the powertrain to integrated and / or adaptive drive solutions.

What positive contribution can an automotive supplier actively make during the development phase?

From the point of view of a supplier of manufacturing technology, advantages are to be gained in taking a broader approach to the simultaneous engineering approach that is already familiar. Although it is quite common, when integrating complex systems in the automotive industry, to nominate a systems supplier at an early stage, in contrast, as a result of purchasing policy, there is often no early involvement of a manufacturing supplier for the production of sub-assemblies or individual components. However, it is intelligent component development which forms the basis of an economic production process which, together with customary provision of spare parts in the industry, may last more than 25 years. As far as the manufacturing process is concerned, intelligent component development is characterized by the fact that there is economical and high-quality production of the components over the whole life cycle. Risks concerning production are analysed together with the manufacturing supplier in extended simultaneous engineering, evaluated and, ideally, avoided (Figure 1). The result of this cooperation is an accelerated, economic and robust manufacturing process throughout the whole life-cycle of the components or assemblies.

During the development process, the requirements of the individual components are established together whereby the material and manufacturing process remain unimportant as long as the component meets the requirements. The functional components used in vehicle transmissions are made of various materials and therefore also very different manufacturing processes are implemented. Examples of this are rotationally symmetric structures or planet carriers. Both components are designed either as welded metal constructions or using an aluminium pressure die casting solution. Manufacturing suppliers who can supply several manufacturing processes simultaneously offer their customers a significant advantage since the consulting regarding the component development process is independent of the manufacturing process. Besides the core process, all further manufacturing steps such as mechanical processing, surface conditioning,

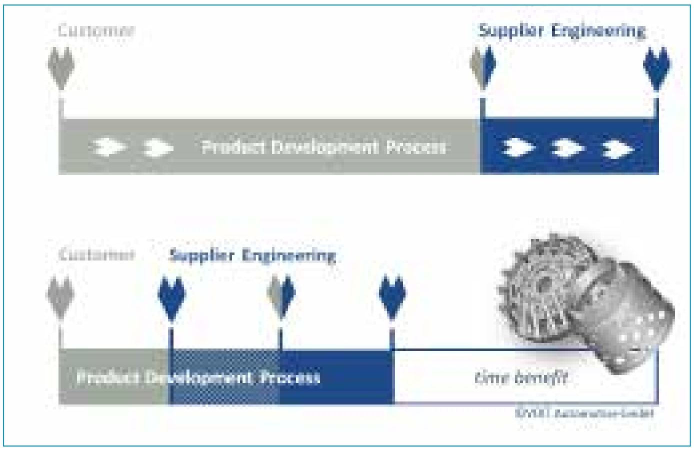


Figure 1 Extended simultaneous engineering process

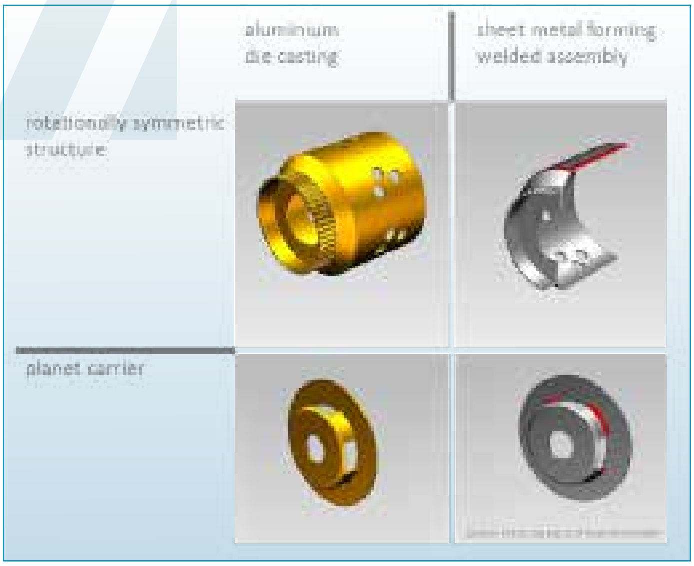


Figure 2 Material and process substitution for functional components in a vehicle transmission

assembly and testing can be analytically evaluated to the same degree with the result that the customer's requirements are fulfilled with a reliable process and ready-to-install components and / or assemblies are supplied dependably for many years.

Besides knowledge of manufacturing technology, it is also necessary to have comprehensive knowledge of the customers' products. For this purpose, the various drive concepts are studied and analysed in order to deduce the requirements of changed market demands from these. For example, narrow CO_2 targets increasingly require electrified power trains. Today's series applications will give way to more integrated, power-split solutions. Dedicated Hybrid Transmissions (DHT) are characterised in that the vehicle transmission system only functions where there is interaction between the electric and combustion engine. An important element in a DHT transmission is the power-splitting which is based on a planetary transmission. Depending on the demands during operation, the planet carriers are to be designed in such a way that the most economic manufacturing process is implemented.

This procedure can be explained in more detail using the example of toothed disk carriers. Just as with the current automatic converter transmissions, switching of driving statuses is carried out using internal friction clutches. Friction clutches are designed as a construction with inner and outer disk carriers. It is the task of the process supplier to create an economic process for these disk carriers. For instance, a process for the manufacture of disk carriers on transfer presses with pressing capacities of up to 2,400 t and table lengths of up to 6 m has proven itself and toothing is rolled into the disk directly in the tool.

Electric machines represent a new challenge for traditional suppliers in the transmission supply chain. Here, simple housing solutions in aluminium pressure die casting are predominant for the electric engines on the electrified axle. The electric machines integrated into DHT and hybrid transmissions with a high power density require cooled, ideally liquid cooled, housing structures due to the high temperatures which develop. Therefore, the advantages and disadvantages of any chosen cooling structure must be assessed between the manufacturer of the transmission and the production specialist.

Water-cooled electric engine housings are supplied to the customer as sophisticatedly processed assemblies. Cooling channels can be achieved using different production methods. Often solutions using two components are constructed (Figure 3) whereby an inner ring is screwed to an outer ring so that it is liquid-tight.

The manufacturing steps required to achieve this are:

- Pressure die cast component 1
- Pressure die cast component 2
- Mechanical processing component 1
- Mechanical processing component 2
- Drill a circle of screw-holes for connecting with screws
- Purchase sealing
- Purchase machine screws
- (12 machine screws distributed around circumference)
- Assembly of component 1 with component 2

For two reasons, the construction is not optimally designed; on the one hand, there is the effect of the large amount of material required (weight and costs), on the other hand, the whole assembly consists of numerous individual parts – the two main components, inner and outer ring as well as the sealing and screws. The large number of purchased parts as well as the large amount of material required has a negative effect on the cost-effectiveness and component weight of the whole assembly. The chosen design has a great overall effect on the cost of the component.

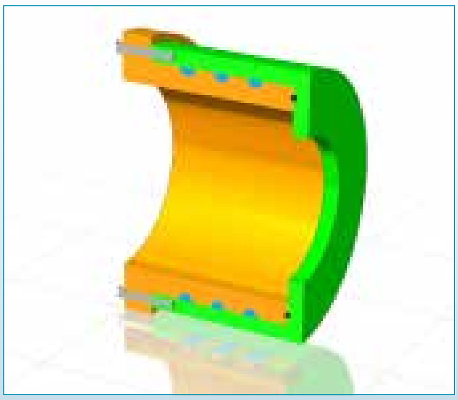


Figure 3 Structure of liquid-cooled engine housing with two pressure die cast components

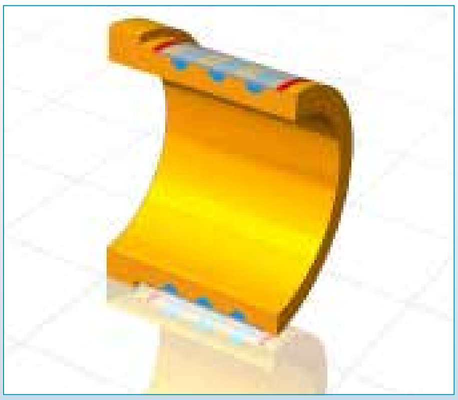


Figure 4 Structure of a liquid-cooled engine housing with substance-to-substance bonded metal sheet covering

An alternative manufacturing process is the substance-to-substance bonding of an inner component with a simple metal sheet covering (Figure 4)

To design the metal sheet covering and substance-to-substance bond, it is necessary to agree on the manufacturing process and define the requirements of the engine housing at an early stage, in particular with regard to the temperature and internal pressure in the system. The manufacturing complexity is reduced by approximately 50 % of the production steps and therefore also by around 50 % of the process time.

- Pressure die casting of component 1
- Mechanical processing of component 1
- Purchase of sheet metal covering
- Assembly of component 1 with metal sheet covering

The construction is optimally designed from the point of view of the manufacturing process, the manufacturing process can be fully automated in the cycles of pressure die casting and processing.

This lean manufacturing process can be represented throughout the whole life cycle, there is little dependency on purchased parts and the investment costs can also be significantly reduced with only one processed component.

Conclusion

If a component design has been laid down and there has already been effort and expenditure for trials, it is hardly possible to implement design changes at this stage. This design and cost trap can be avoided when there is early cooperation between the manufacturing specialist and the customer. Only joint development of the component leads to lean and economic processes. A precondition for this is that the customer has not yet reached the point of the "Design Freeze" and that design changes in favour of a cost-optimised manufacturing design are therefore still possible. The advantages achieved together influence both the cost of the component and the component weight in a way which is both direct and positive for the customer.

The author:
With over 15 years of automotive experience working in positions in consulting and in the supplier industry, **Stefan Beinkämpen** is Head of Business Development at VOIT Automotive GmbH.

Low-cost, low-maintenance, light-weight, multi-speed power shifting transmissions for electrified vehicles

Synchronisers and Hydraulics Become Redundant for Hybrid and EV with Innovative Actuation and Control Methods

The push for vehicle electrification creates many opportunities and challenges in terms of the transmission concept. Novel layouts, actuation and control techniques have a key role in meeting these challenges.

■ Dr Richard Taylor, Technical Director, Vocis

Background

As the scope for vehicle electrification increases across more vehicle sectors, the need for novel transmission concepts to meet the variety of challenges thrown up by this expansion is becoming clear. As always, key goals include the need to be cheap, light-weight and simple whilst still meeting the performance and efficiency goals for the vehicle itself. Whilst the initial promise of electric motors meant that single speed transmissions were sufficient, in reality such a decision has become much more complex when consideration is given to potentially conflicting goals such as pull-away performance, gradeability, top-speed, as well as maximising system efficiency and motor downsizing to increase range.

One way to try and resolve such conflicting requirements is to deploy multi-speed transmissions in the application. This approach however would normally be seen to be at odds with a desire for a simple, cheap and light-weight system. Vocis and Oerlikon Graziano have approached this problem by developing a patented transmission concept that offers a scalable, multi-speed, power shifting solution that is yet simple, cheap and light-weight. This concept however does require the application of novel control techniques and can be further optimised by using novel actuation methods.

4SED Transmission

The multi-speed, power shifting transmission concept developed by Vocis and Oerlikon Graziano can be considered as two transmissions in a single case, as can been seen in Figure 1. In the particular configuration shown, one input motor can be connected to the output via gears 1 and 3, whilst the second input motor can be connected to the output via gears 2 and 4. In this way, it is possible to drive the vehicle through a total of 7 different gear combinations. Seamless power shifting is achieved by increasing the torque on one of the motors whilst changing the gear connected to the other input machine. Once the new gear is engaged both motors can be returned to their nominal

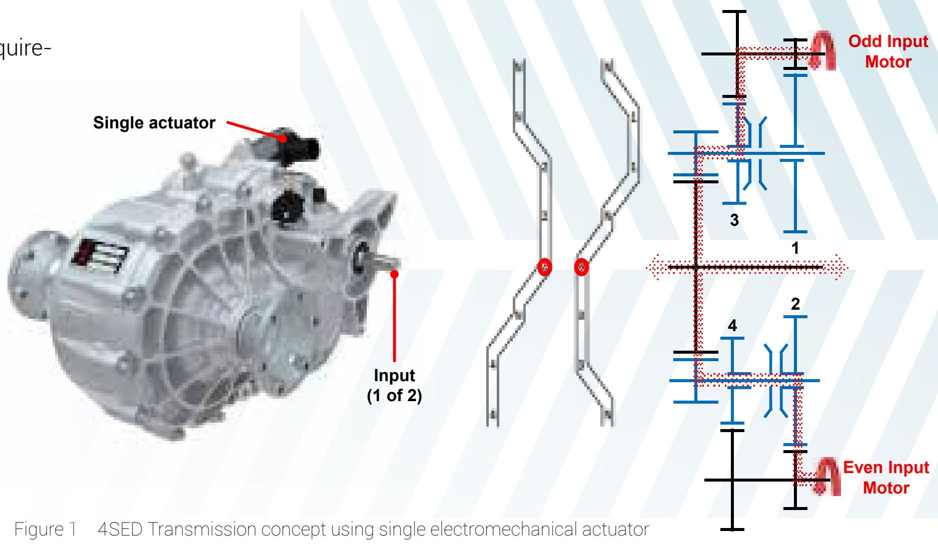


Figure 1 4SED Transmission concept using single electromechanical actuator torque as required by the driver demand. (CTi Berlin 2011, eDCT: Compact Seamless Clutch-less Transmission for Electric Vehicles, Bologna and Fracchia). Clearly the concept is highly scalable both in terms of motor size, but also in terms of the number of gears and chosen ratios in each 'half' of the transmission.

By applying such a concept, it is clear that the transmission will not need a launch clutch, will be able to satisfy the potentially conflicting requirements of pull-away performance and vehicle top-speed, whilst offering full disconnect functionality. The motors can be sized asymmetrically, and packaged in opposed or parallel configurations.

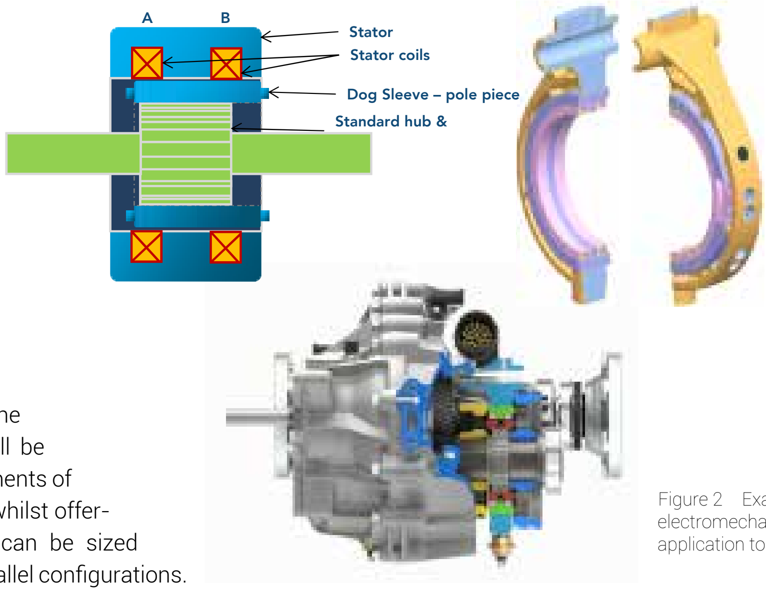


Figure 2 Example direct acting electromechanical actuator and application to 4SED transmission

There may remain a question mark of complexity hanging over such a transmission concept. An actuation system will be required for the gear selection and synchronisers may be needed to facilitate the gear change.

Why Use Hydraulics?

On electrified vehicles with an ample supply of electrical power, it seems somewhat counterintuitive to then add a hydraulic actuation system when it could be avoided. Hydraulics have generally been added to meet the speed of response and apply force requirements of the system, and where hydraulics are already present for clutch control for example then there is logic in that approach. In transmissions for electrified vehicles however, electric actuation can be used instead resulting in a simpler, cheaper transmission.

In the first version of the 4SED transmission a BLDC motor was used which performed the gear selection through rotation of a barrel cam (Figure 1). Although this worked perfectly well, it was felt that a more elegant solution could be found that further removed complexity. The proposed solution is a scheme of direct actuation of the selection sleeves themselves.

Electro-Mechanical Actuation

A concept has been developed whereby linear actuation of the selection sleeves can be achieved within the transmission casing. Such a scheme is as shown in Figure 2, whereby application of current to the coils A and B can be used to control the position of the selection sleeve directly, enabling engagement of the two opposing gears or the selection of a neutral position.

A real benefit of such an approach is that the system is extremely simple, with a minimum of moving parts making it much cheaper than the BLDC motor equivalent, as well as being much more reliable, low wear and low maintenance.

One key concern in this approach is in terms of the actuation speed, synchronisation force and controllability achievable when using coil currents and control methods sensibly available on-vehicle. As a proof of concept therefore, a test was developed to allow measurements using a representative test piece. Some results from this testing are shown in Figure 3.

From the results, it is clear that such an approach to actuation can give the speed of response and gear selection forces required for a transmission application.

In order to reduce the required size of the actuation elements and the drive current of the actuation system however, it would be ideal if the synchronisation forces required during gear selection could be reduced or even eliminated completely. This would allow the actuation system to be more easily packaged within the transmission, and perhaps the system voltage reduced to, for example, 48 V.

Why Use Synchronisers?

Continuing the theme of removing as much complexity from the concept as possible, it seemed obvious that the next step to take would be to remove the synchronisers from the transmission completely and rely solely on the input motor for the synchronisation. As described previously, the 4SED concept has two input motors, such that driving torque can be sustained on one input motor whilst the second motor is disengaged during the gear change. As a result, there is no reason not to make use of the disengaged motor for synchronisation of the new gear. The motor can be switched from a torque control to a speed

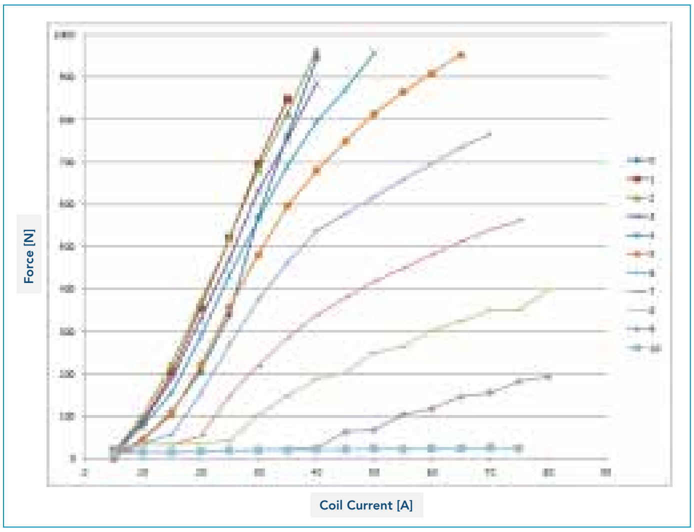


Figure 3 Actuator apply force versus coil current

control mode, and the ability of electric machines for fast and accurate speed control is well known.

As a result therefore , the transmission concept has now become one in which there are no clutches, no synchronisers and the actuation system is a direct actuating electro-mechanical system removing the need for either a separate hydraulic system or separate actuation motor.

A clear outcome of removing the synchronisers from the transmission is that the gear engagement now only involves dog clutches. On the assumption therefore that the two sides of the dogs are synchronised and there is no dog to dog contact requiring a re-try or a push and twist strategy, then the engagement force required of the actuation system resolves to being very low indeed. It only needs to displace the mass of the engagement sleeve into the engaged position in an appropriate timeframe. If it can be assured that the assumption regarding the dog engagement is always the case, it is perfectly valid to size the electro-mechanical actuation of the engagement sleeves to only meet this lower force requirement.

The question is therefore; is it possible to always ensure that synchronisation is achieved and there is no dog to dog contact?

Angular Control

In an ideal world, we would know the exact positions of the engagement dogs relative to the pockets and could control the disengaged motor to match the speed requirement of the new gear and at the same time align each engagement dog with an appropriate pocket. Surely however this would require expensive sensing technology?

Through its work on advanced production DCT transmissions, Vocis has developed techniques that allow for the derivation of the relative angular position between two rotating shafts, using only the standard speed sensors available within the transmission. In the case of DCT transmissions for example this has enabled Vocis to control clutch micro slip down to 1 RPM. This improves both the efficiency of the transmission and the positive feel to the driver during tip in/out transitions, whilst maintaining the benefits of running in micro slip (now coined nano slip by Vocis).

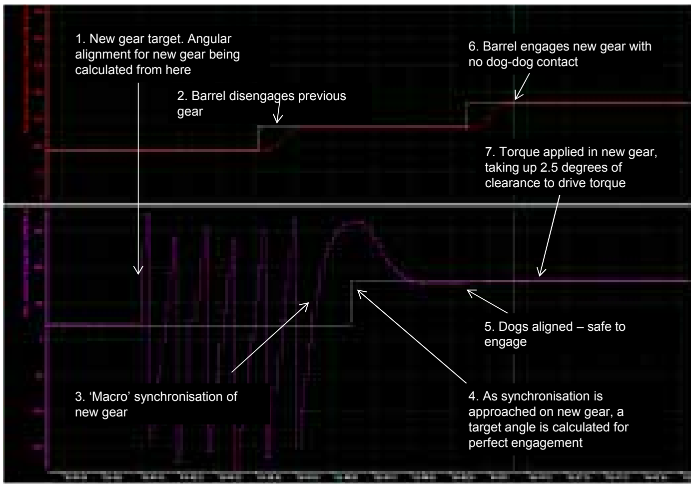


Figure 4 Dog engagement utilising angular position derivation

By applying this angular derivation technique to the 4SED type transmission it is also possible to accurately align the engagement dogs and pockets during the synchronisation process, thereby ensuring that dog on dog contact is never seen.

During initial testing of this technique on the first version of the 4SED transmission, being appropriately pessimistic about the accuracy of the technique meant that the parts were designed with an angular clearance of 6 degrees between the engagement dogs and pockets. As a result, although it was found that the gear engagement was never an issue, the angular clearance equated to a certain level of backlash across the transmission during tip in/out transitions. Subsequent development now means that the latest version of the 4SED only has 2 degrees of clearance between the engagement dogs and pockets, which is still perfectly acceptable from a gear engagement perspective but also significantly reduces the backlash across the transmission.

Figure 4 demonstrates the principle in operation using data measured from the first version of the 4SED transmission. It is clear that the technique allows the alignment of the dog and pocket to be guaranteed. It is also possible to see the level of detail revealed in the angular derivation technique, with the take-up in backlash visible in the trace as the motor is brought back to positive torque.

Conclusions

By applying a principle of removing as much mechanical complexity from the transmission as possible, whilst employing advanced actuation and control methods, Vocis and Oerlikon Graziano have developed a transmission system for electrified vehicles which satisfies the aims of being low-cost and low-weight whilst still offering multiple gear ratios, power shifting and disconnect capability.

The direct acting electro-mechanical actuation offers exciting possibilities not only in terms of gear selection but also in other areas such as disconnect and 4WD systems, the key being the removal of the need for hydraulic systems on the electrified vehicle whilst also simplifying the actuation to avoid the use of additional actuation motors and barrel cams for example.

The angular derivation and control techniques developed by Vocis have previously proven themselves in series production DCT control and have now done so again in terms of dog engagement control. Further developments of these techniques is also well underway to also cover backlash measurement, wear assessment, torque measurement, measurement of dual mass flywheel behaviour and in optimising the gear shift process in AMT and DCT transmissions.

Moving Towards Higher Powers – Electronic Control Units for the 48V Battery Network

Electrical loads (actuators, pumps, ...) with power demands higher than some hundred Watts needs them connected to the 48 V battery. MELECS has designed an Electronic Control Unit for evaluation purposes.

- Dipl.-Ing. Thomas Szelestey, HW Development Group Leader, MELECS EWS
- Dipl.-Ing. Dr techn. Alexander Schulz, Project Manager, MELECS EWS

How to Start?

When starting a project in the field of higher electric power there are a lot of questions to be answered: What is the mechanical power I need? Which motor fits these demands? What are the space needs? What is the power loss and how can I dissipate the respective heat?

To answer these questions tests in real environments are necessary. It is not possible to define realistic design requirements before the questions above are answered. To cope with these challenges MELECS has designed a "48 V Evaluation ECU" (Electronic Control Unit), which can be used in various motor and generator setups.

Design Goals

The ECU is able to drive brushless 3-phase motors up to 3 kVA electrical power – the three motor connections can deliver up to 100 Arms each. For best flexibility this Evaluation ECU is designed to be used with any 3 phase motor in the targeted power range and therefore developed as standalone device.

The complete voltage range for the 48 V battery, as defined in the VDA 320, is supported: Full power to the motor is delivered in the range of 36 V to 52 V, from 52 V to 60 V a power derating due to thermal reasons is carried out. The micro controller (CPU) works down to 24 V.

The ECU is controlled through a 500 kbit/s CAN interface, referred to the 12 V battery. One additional input switches the ECU on (drives it out of the "closed-circuit" state, typically connected to KL15), another one can be used to only stop the motor (e.g. in emergency cases).

Electronics

Figure 1 shows a block diagram of the ECU. Due to different PCB layer stacks the design is split onto two optimized PCBs. The Power PCB contains all high current parts and is optimized to distribute high currents horizontally and the dissipated power (mainly of the bridge FETs) vertically down to the heat sink. Besides the 3phase bridge and the necessary buffer capacitors the Power PCB carries an input filter and an inrush current limiter. Current sensing is done through low side shunt resistors.

The heart of the Controller PCB is a CPU with lock step architecture, which together with the system basis chip is able to support even

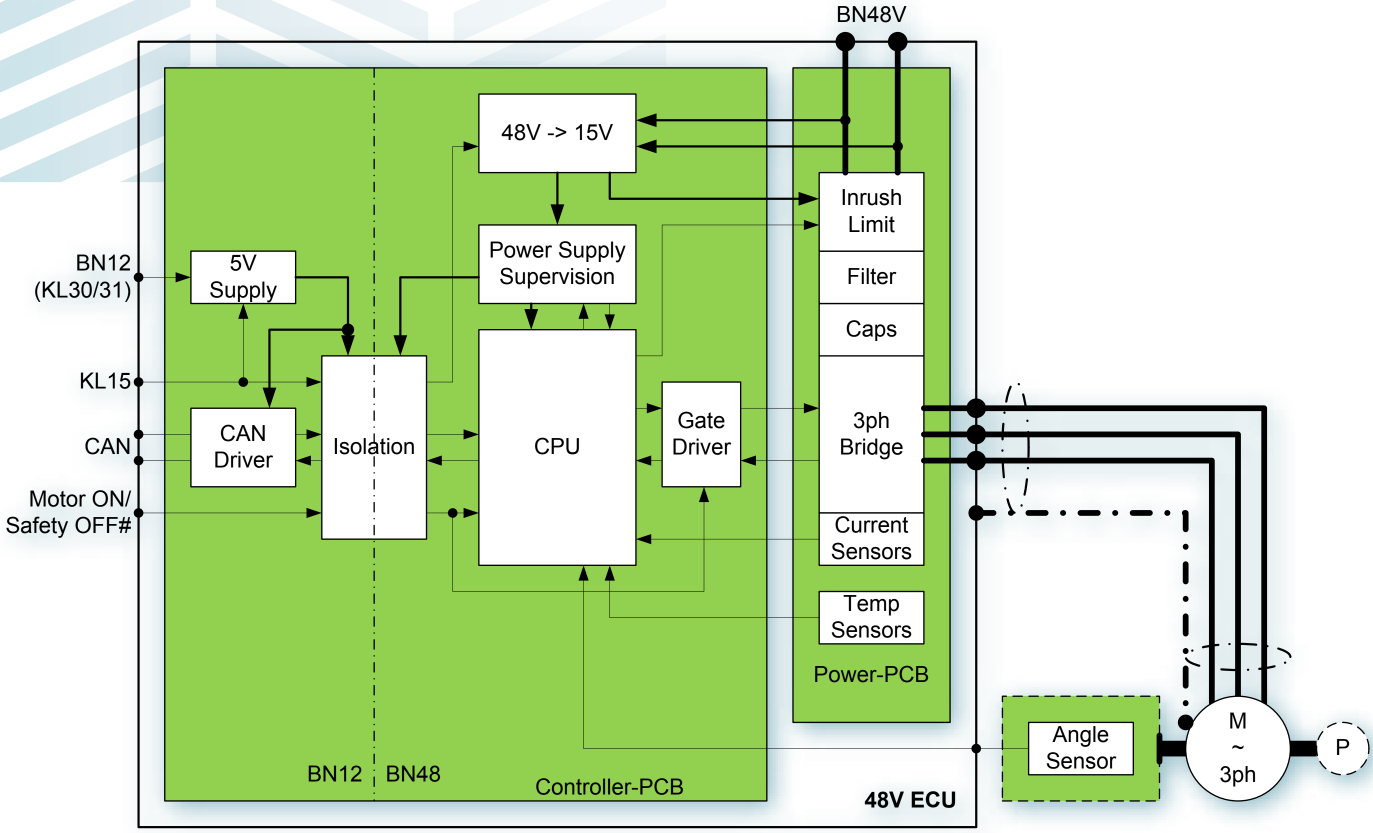


Figure 1 Block Diagram

safety relevant applications. The gate driver supports a number of supervising task, among them a V_{DS} supervision of the bridge FETs. The ECU has connections to both batteries and especially two different ground connections as required in the VDA 320. Internal data transfer between the CPU – related to the 48 V battery – and the communication and control interfaces – related to the 12 V battery – is done via an isolation barrier, to avoid disadvantageous effects when losing one of the grounds.

An angle sensor, which is necessary for controlling the motor at low speeds, has to be attached at the motor and is connected to the ECU through a separate connector.

Mechanics

The ECU is packed into a housing with a square base of 150 x 150 mm² and a height of 67 mm (without connectors). The base plate is made out of aluminum and can be mounted to any flat surface, which is able to dissipate the losses and keeps the temperature at an appropriate value to deliver the demanded power. The upper shell is made of plastic. Both the housing and the connectors are basically designed to be

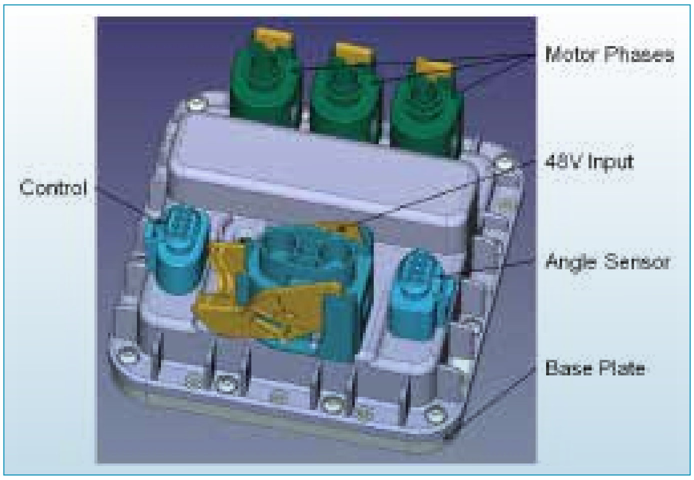


Figure 2 Mechanical Design

water proof and withstand vibrations as defined in profile D of the LV 124.

All interfaces are implemented as pluggable connectors (refer to Figure 2): The control interface (CAN) and the angle sensor interface use FEP connectors with 2 × 4 pins 1.5 × 0.64 mm²; the 48 V battery input uses a high power Delphi Ducon connector (to avoid reversed polarity of the BN48 system) with 9.5 × 1.2 mm² pins, and the motor is connected through three Kostal LSK8 connectors with 8 × 0.8 mm² pins.

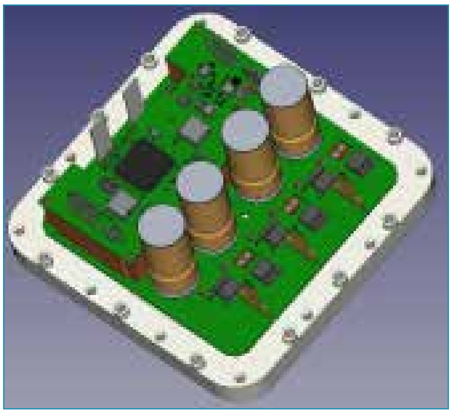


Figure 3 PCB Concept

Figure 4 Housing Prototype

Figure 5 Real PCBs

A Look Inside

As mentioned before the design contains two PCBs (refer to Figure 3). The Power PCB is tightly connected to the aluminum base plate to efficiently lead off the losses. The Controller PCB is in the "second floor" and distanced from the Power PCB by a plastic spacer. All parts are pressed towards the base plate by elastic elements in the shell: Especially the FETs – to ensure best thermal conditions by reducing the distance between PCB and base plate to a minimum – and the buffer capacitors – to fix them mechanically to avoid damage due to vibrations.

Controlling the ECU

Via the CANopen protocol the ECU can be configured, the output parameters set and the status read back. Basic output parameters are the motor speed (revolutions per minute) or the motor torque (given by a certain motor current) – depending on the configuration. Other configuration parameters are for example limits for current, speed, voltage and temperature. Status messages deliver the actual values of speed, current, DC voltage, output voltage, temperatures, errors, etc.

Further Features

Besides the main functions, the ECU is designed to fulfill most of the other requirements in the LV 124 and the VDA 320/LV 148. Among them are the idle current requirements, when the device is turned off, and the safe behavior, when one of the grounds is lost. Basically also mechanisms for safety functions are implemented (diagnosis, supervision, redundant turn off paths).

Usage

The ECU can be positioned on or near a motor or in a certain distance of it (using shielded wires). It just needs connections to the 48 V battery, to the motor (including an angle sensor), to a CAN bus and to a surface able to lead off the dissipated power.

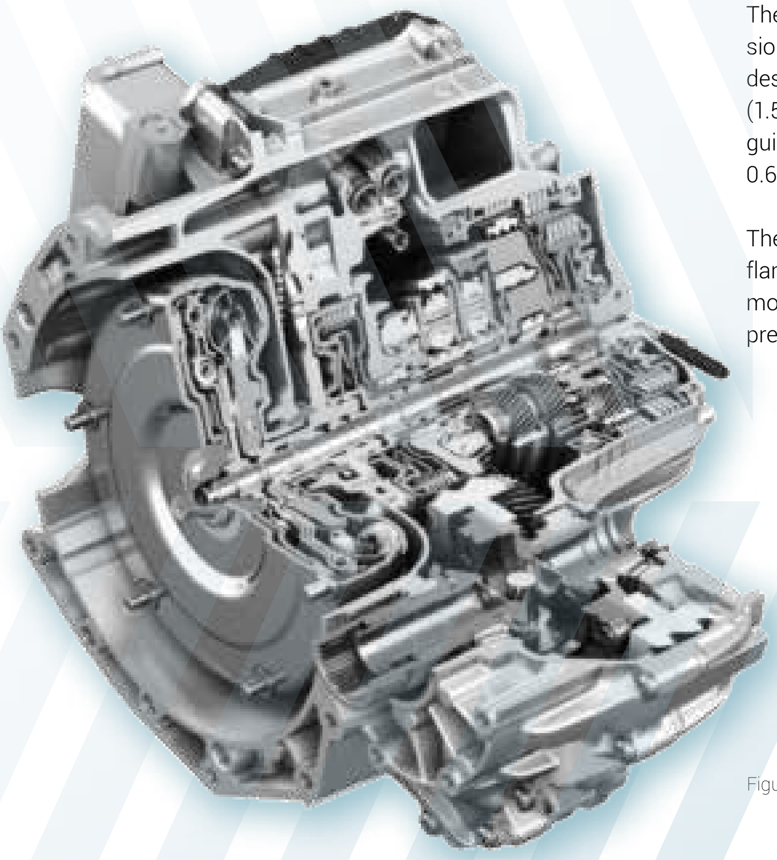
Optimized Designs for our Customers

After tests with this ECU under real conditions, the findings can be used to define the requirements for a motor including the feature to be driven (e.g. a pump) on the one side and the ECU on the other side. These requirements are the basis for a customized ECU design to exactly fit the electrical and mechanical demands – to get an optimum design for our customers.

Innovative Powder Metal Planetary Carrier Solution for World Class Automatic Transmission Recognized with 2016 EPMA PM Component Award

Planetary carriers are one of the key components of automatic transmissions. Stackpole International has significant market experience, with more than 80 million carriers produced. Stackpole International developed the award-winning powder metal, sinter-brazed solution for a high-performance automatic transmission with 9 speeds, 4 simple gears and 6 shift elements by one of the leading transmission suppliers. This is the first powder metal planetary carrier the customer has used for an automatic transmission.

- Semih Demir, P.Eng., MBA, Assistant General Manager – Engineering, Stackpole International
- Philipp Schaeflein, Dipl.-Ing., Business Development Manager – Powder Metal Europe, Stackpole Powertrain International
- Jochen Wagner, Dipl.-Ing., Business Development Manager – Powder Metal Europe, Stackpole Powertrain International



The planetary carrier for this high-performance automatic transmission is light-weight and feature integrated. Its sinter-brazed two-piece design is made out of a spider using FC0208 (D11) modified material (1.5–2.5 Cu, 0.7–0.9 C, 0.5 other elements, balance Fe) and a guide plate using FX1008 (D11, copper infiltrated) modified (Cu > 10, 0.6–0.8 C, 0.5 other elements, balance FE).

The component's shape complexity manifests itself in the form of thin flange sections, narrow spider legs with partially hollow sections, and most prominently all the net formed features and functional holes present in the guide plate (see Figure 2 – Note guide plate on top).

Figure 1 World class 9 speed automatic transmission

Figure 2 Planetary carrier

Figure 3 Thin sections

The thin cross sections and light construction of this planetary carrier required at least one high-density component to provide stiffness, reducing stress induced by deflection as well as pinion pin tilt. Stackpole International, Stratford Powder Metal Division, developed a world-class compacting process and tooling to provide uniform density throughout the varying sections, such as those between the functional holes and the center hole (see Figure 3).

Precise control of compacting densities and tooling was required for dimensional capability, as well as for material properties after copper infiltration and induction hardening. Copper infiltration takes place during the sintering process and improves mechanical properties such as yield, tensile and compressive strength, fatigue and impact strength, as well as apparent hardness. Induction hardening of spline segments had to be sufficient to provide wear resistance without compromising the impact and fatigue properties, while maintaining dynamic toughness in the highly loaded spline area.

The guide plate has "manufacturing" features designed for the placement of brazing pellets in the fully automated assembly cell and as locating features for the copper infiltrate slug so that infiltration marks or any residue can be removed during the pinion pin machining operation.

Figure 4 Spider, guide plate and spline

This planetary carrier is an excellent example of collaboration between teams with expertise in the powder metal process and in automotive transmission design. The customer and Stackpole's technical teams defined the engineering properties required for this application through joint reviews of initial bench test results and shortened the development cycle through successful simultaneous development. Stackpole International, although did not have design responsibility, undertook the bench testing and established better options for material selection.

Stackpole International proactively addressed design challenges and ensured a successful PM application, with the following benefits:

- Extended pinion gear life and improved efficiency by higher stiffness compared to aluminum die cast or sheet metal carriers.
- Integration of function including light weight design, pinion pin staking, couplings and oil slots for improved pinion gear lubrication.
- Material solutions tailored to functional requirements.

About Stackpole International

Stackpole International is a premier world manufacturer of innovative engine and transmission pumps and powder metal components to the global automotive original equipment manufacturers (OEMs).

More information

At our stand J17 during the CTI transmission congress in Berlin (06–07 Dec. 2016)

www.stackpole.com or e-mail to pschaeflein@stackpole.com

	Spider	Guide Plate	Spline
Density [g/cm³]	7.0	7.5	7.5
Tensile Strength [MPa]	510	730	760
Yield Strength [MPa]	420	520	760
Hardness	80 HRB	90 HRB	50 HRC
Elongation	1 %	3 %	n/a

Growth of e-mobility is shrinking electric motor size

Advanced Insulation Systems for Cost Effective, High Power Density E-Motors

Electrification is driving the automotive industry to investigate a variety of materials including high performance polymer film for e-motor insulation systems to meet today's requirements.

■ James Bonnett, Market Technology Manager Automotive, Victrex

Trends in E-Mobility

Global legislation is driving the Auto industry to adopt alternative powertrain systems for their products which deliver lower vehicle fleet emissions. As well as this technical challenge, the traditional model of personal transport is being challenged, creating multiple new markets for a range of mobility solutions and vehicle platforms. For traditional light vehicle manufacturers, they must maintain safe and cost-effective platforms, whilst not compromising on customer satisfaction (value for money and driver experience). Looking specifically at the electric powertrain, this brings many challenges for OEMs around, integration, power and energy density, cost of manufacture, and so on. This article looks at examples of how making a simple change in insulation can deliver multiple benefits on many of these levels.

E-Motor Designs and Challenges

Since Faraday first excited Victorian London with demonstrations of electromagnetic rotation and induction the electric motor has become increasingly used and optimised. For the automotive industry the first mainstream adoption came in 1997, with the Toyota Prius using two permanent magnet synchronous machines (PMSMs) integrated with a power split transmission system to create a ground-breaking vehicle. After this, the industry has investigated a series of complementary technologies to advance the sector, including increasingly efficient rare earth magnet technology, alternative winding styles (distributed and concentrated), and conductor profiles (round vs rectangular), as well as a range of cooling systems. The next generation of e-motor today could be a hybrid of PMSMs and synchronous reluctance induction motor (SynRelM), offering greater efficiency and reduced cost of manufacture (Calvo et al [1]). Today, it is still unclear if one design will win out above all others, but the challenges are constant regardless of motor architecture. They are:

- Increased motor power density
- Reduced cost of manufacture

Combine package size reductions with voltage, revolution per minute (RPM) and current density increases, and thermal management becomes key in achieving efficiency requirements across the torque output vs RPM curve.

Insulation Systems Requirements

Requirements of the e-motor insulation system have increased to meet the needs of Hybrid and Electric vehicles (H/EVs) in accordance with the key parameters of temperature, environment, electrical and mechanical properties. Temperature rating above 200 °C is now a more common need. Mechanical properties are also more demanding as manufacturers look to reduce the volume of insulation in the motor in order to maximise conductor content or Slot Fill Factor (SFF). In relation to environmental requirements, the insulation system often needs to be compatible with long term exposure to a mix of automotive transmission fluids (ATF) and water, and above all the dielectric strength of materials must be high for an effective insulator. For the slot liner and slot wedge components, this combination of properties is driving the Auto industry to investigate a wider variety of materials, including high performance polymer films (both in traditional laminates of meta-aramid papers and polymer film, or in a mono-film layer).

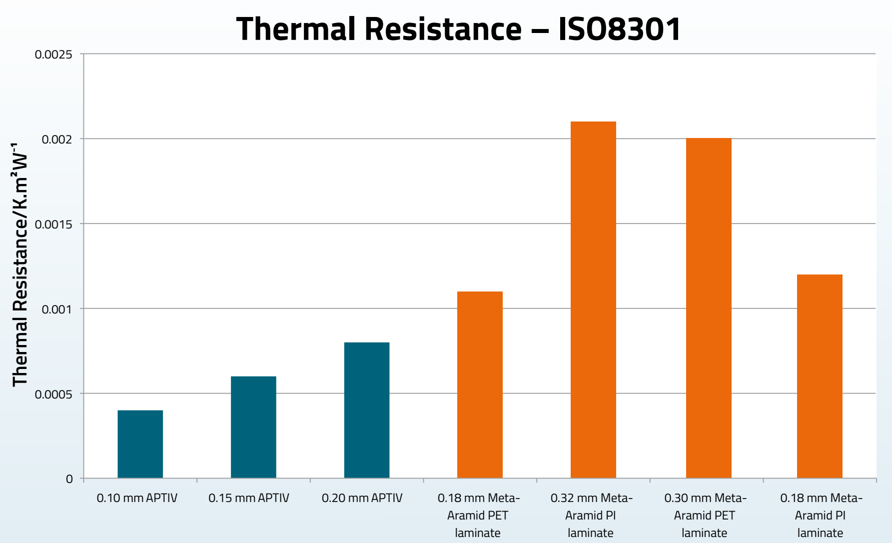


Figure 1

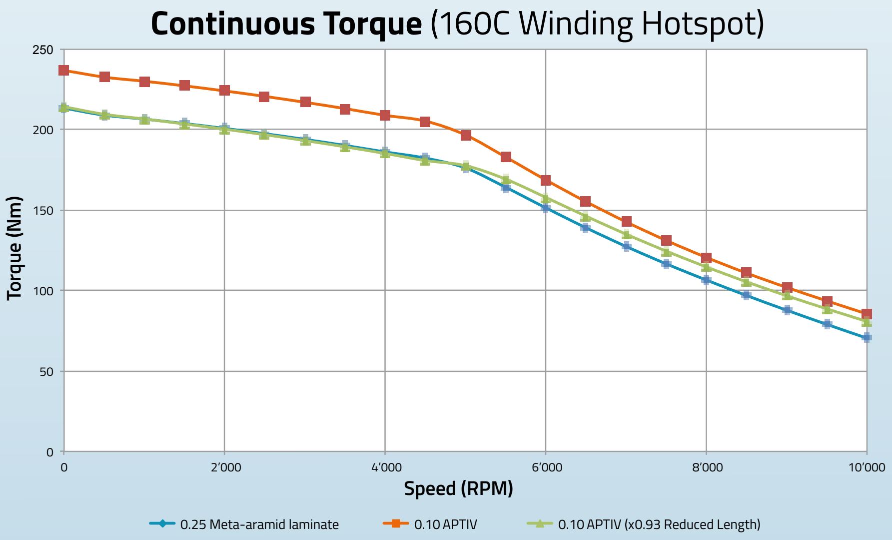


Figure 2

Popescu et al consider modern heat extraction systems for power traction machines [2] where they conclude that high quality materials as insulation systems and cooling fluids are essential to improving the cooling of electrical motors. High dielectric strength and low thermal resistance is not a common material characteristic, but the combination of properties offered by APTIV™ film can be an improvement over some of the traditional materials. The thermoplastic film from Victrex, a leading provider of high performance polymer solutions, is made from VICTREX™ PEEK polymer.

Notably, APTIV film is a potential material for a motor's slot liner. The slot liner, also known as a ground wall insulation, provides an insulating barrier layer between the wire of an electric motor's winding and the metal stator stack. It enables electrical isolation during operation and also protects the insulated wire during the assembly process at time of manufacture. Typically, a slot liner is made from paper or film or composites (including multi-layer options). The actual choice of material depends on the thermal, environmental, mechanical and dielectric parameters of the motor.

Figure 1 shows the thermal resistance of different slot liner materials taking into consideration their thermal conductivity and thickness. The material must work as part of an insulation system though and should be used in conjunction with a compatible impregnation system, as Godbhere et al point out in their study of Thermal stator modelling of AC Machines [3]. Whilst a range of impregnation systems are available, the right balance of adhesion, thermal conductivity, dielectric strength, processing and cost of manufacture should be found.

A Case Study

In order to demonstrate more convincingly the benefits of using APTIV film insulation, Victrex commissioned independent simulation analysis on a mainstream e-motor design; the model selected was an 80 kW (peak) Power 8 pole 3 phase PMSM with distributed winding design and water cooling jacket. This design is the same as that used in the 2012 Nissan Leaf platform and has 48 slots each wound with 120 round (0.88 mm diameter) conductor wires. There is significant published teardown information on this renowned electric vehicle platform and the Motor-CAD team used this public domain information inputted to their software to create an electromagnetic and thermal model in the Motor-CAD EMag and Therm modules. These models allowed simulation of output/performance based on two different slot liner insulation constructions.

Main assumptions:
- EM61 motor model rated to 80 kW / 107 Hp output
- Max Torque is 280 Nm with 10'390 RPM limit
- US06 drive cycle used to produce efficiency map
- Winding Temperature limited to 160 °C

The simulation analysis was carried out by Motor Design Ltd using their unique software packages Motor-CAD and Motor-LAB (lumped circuit modelling method used for electromagnetic performance, thermal mapping and efficiency on, for example, any AC permanent magnet motor).

Results:
- **ABA laminate slot liner of Meta-aramid paper and polymer film at 254micron thick**: copper slot fill = 52 %; Motor-CAD predicts the winding temperature will reach 88 °C; the wire slot fill ratio is 72 %;
- **100 micron APTIV™ slot liner**: enables enough space saving to increase slot copper content; the most effective way would likely be to add in an additional strand (previous 6 turns with 20 strands), so from 120 to 126 in total. Copper slot fill = 55 % (increase of 5 % more copper) and wire slot fill ratio remains at 71 %.

Results showed the same average motor efficiency, but with reduced winding temperatures of 3.5 °C on the APTIV™ insulation scenario. When considering the overall torque output potential from improved SFF and thermal management, Motor-CAD predicts an increase of 11 % usable torque over the full RPM range, which equates to potential 24 Nm / 11.5 Hp in power output for a same size of machine.

An alternative to having a higher torque output e-motor is to have the same output but with a smaller, lighter and more cost-effective machine. Figure 2 shows the torque output curves for different slot liner insulation (in red & green) with the same machine size, but includes a reduced axial length machine scenario where the torque output curve is matched as closely as possible to the original (in blue). The modelling predicted a potential 7 % reduction in length of the active (stator and rotor) assembly and overall reduction in weight close to 2 kg. According to Widmer et al [4] this should represent up to $ 20 material saving potential for this PMSM.

Summary: Benefits of Using Advanced Polymer Film Based Insulation Systems

Environmental concern in an increasingly mobile world is driving demand for more efficient electric motors. Used for their slot liners, VICTREX PEEK polymer based APTIV film can offer significant benefits:
- Higher torque output, improved SFF and ultimately smaller, lighter lower, cost PMSM design options
- Further investigations are on-going to understand the manufacturabilty and durability benefits of using APTIV films compared with meta-aramid paper/laminates in e-motor applications

Being able to use 5 % more copper due to the very thin high-performance polymer film for the e-motor insulation system, results in an increase in the power density of the motor. Having higher power density motors enables the same performance with package size, weight and cost reductions by up to US$ 20 per unit, offering the industry an attractive alternative compared with the materials used to date.

References
[1] Calvo et al: Synchronous reluctance motors with and without permanent magnets for high performance low cost electric drives
[2] Popescu et al: Modern heat extraction systems for power traction machines – A review
[3] Godbhere et al: Experimentally calibrated thermal stator modelling of AC machines for short-duty transient modelling
[4] Widmer et al: Low cost, high performance eMotors for traction applications

Manufacturing technology for assembling a rotor of an electric motor

Reduced Production Cost with Increased Performance

With its innovative joining technology "StackFix" the Hirschvogel Automotive Group presents a series-production method for manufacturing a rotor of an electric traction motor. This method promises reduced manufacturing cost while enabling the motor to deliver higher performance due to highly effective rotor-cooling and minimized induced stresses on the lamination stack of the rotor.

■ Robert Filgertshofer, Research & Development, Hirschvogel Automotive Group

Electric Mobility Trend

Current attempts for reducing the global CO_2 emission, the dramatic air pollution in some megacities, restricted access to many large cities and even the potential ban on selling conventional vehicles gave boost to the previously sluggish switch to electric mobility. Therefore, not only the hybrid vehicles but also battery-electric driven passenger cars will reach remarkable registration numbers in the near future. According to VW information in 2025 – which is less than 10 years from now – every fourth car produced by them will be driven by an electric motor. This prediction will open up a market of millions of battery electric vehicles (BEV) to Volkswagen alone. Such quantity forecasts therefore make large-scale production technologies increasingly attractive for the production of electric engines and therefore more and more manufacturing companies focus on it.

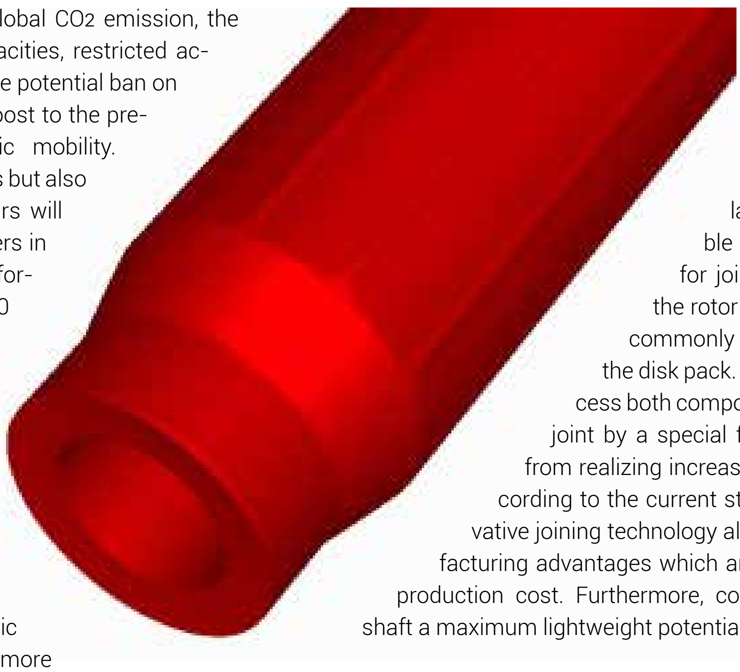


Figure 1 Rotor Shaft with Forged Protruding Elements (Forging Simulation)

In an advanced engineering project dealing with the production of a rotor of an electric motor the Hirschvogel Automotive Group developed the new large-series-production capable "StackFix" production method for joining the lamination stack and the rotor shaft. Nowadays a shrink fit is commonly used for joining the shaft and the disk pack. In the Hirschvogel favored process both components are force-fit and form-fit joint by a special forging process instead. Apart from realizing increased efficiency of the engine according to the current state of development, this innovative joining technology also promises significant manufacturing advantages which are also expected to reduce the production cost. Furthermore, combined with a forged hollow shaft a maximum lightweight potential might be accomplished.

Pressing instead of Shrinking

For the production of a rotor (e.g. for PSM) the single lamination stacks are fixed on the rotor shaft in order to transfer the torque induced by the stator. Shrink fit connections require very high dimensional and shape accuracy of the contact areas. To meet this high dimensional accuracy the relatively large diameters of the rotor shafts are usually ground or hard turned. In addition, the internal diameter and the sheared edge of the laminas need to be high precision to ensure a durable connection with the shaft. A time-consuming joining process follows wherein the shaft is cooled down and the stack of laminations is heated. After a final cooling period the joining is completed. The required high production quality and the time-consuming shrinkage process obviously involve high production cost.

With very high-performance e-motors it might also be possible, that the lateral forces achieved through the shrink joint are not sufficient to transfer the torque applied to the rotor in the long run. In order to avoid the result that the lamination stack slips through on the shaft an additional form fit is frequently applied.

The new Hirschvogel joining method is based on a force-fit and form-fit approach and can shorten the currently usual process chain significantly. The elaborate shrinkage process is replaced by simply joining a “special” rotor shaft and the lamination stack through forging. This rotor shaft has protruding shaped elements in the area of the joining surface in axial direction which are pressed into the lamination stack with oversize. This joining operation forces the protruding elements into the laminas and induces a plastic deformation which develops the force-fit and form-fit connection.

The production of the lengthwise oriented convex elements can be integrated into the forging process of the rotor shaft and can thus be realized in a cost-efficient way. (Fig.1). Machining the joining area of the rotor shaft and the internal diameter of the lamination stack – as required in the shrinkage process – can be omitted due to the new manufacturing method. Therefore a significant reduction of production cost is expected.

In their first comparative calculations the BRUSA Elektronik AG / Switzerland analyzed the transferable torque taking the motor rotation speed into account (Fig. 2). For the shrink fit they compared a standard design with minimum (0.02 mm/side) and maximum oversize (0.045 mm/side) to pressing with a grooving depth of 0.15 mm/side. In this, the StackFix approach with a 20 % higher torque looks very promising. This joining technology is very interesting due to the results regarding future high-speed concepts.

Higher Motor Performance Reachable

Apart from the savings potential in production of the rotor remarkable advantages in application technology can be realized. Electromagnetic losses in the rotor emerging from operation of the engine are

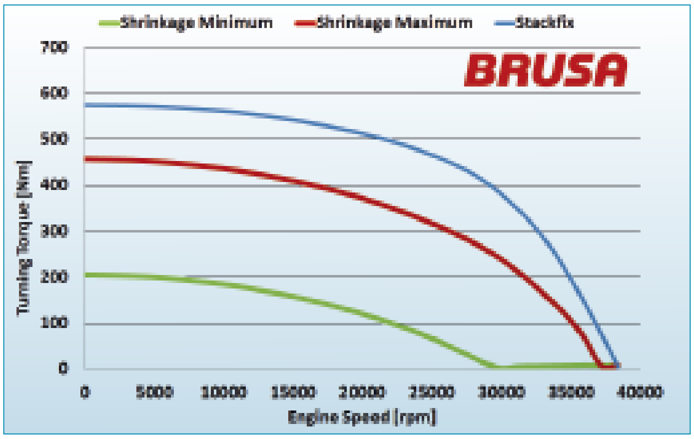


Figure 2 Comparative Calculation of the Transferable Torque (Source BRUSA)

mainly influenced by the prevailing stress condition inside the lamina. StackFix – in opposite to the shrink fit – has the advantage that, due to the joining operation in the area of the joints, tensile stresses are only partially induced into the lamina. In Fig. 3 a comparison by means of simulation was made to show the equivalent stresses inside the lamina that emerges from the respective joining process. The shrink fit generates high tensile stresses in the entire surface of the lamina. The lamella joint by means of the StackFix technology shows no noteworthy stress fields apart from the areas around the joints.

An accordingly reduced stress field inside the lamina promises the following advantages:

- Improved performance and efficiency of the engine due to less electromagnetic losses inside the lamination stack
- Higher mechanical load of the lamination stack possible because of greatly reduced assembly stresses
- Thereby higher motor rotation speed possible
- Relief of highly stressed areas such as magnetic pockets of an PSM engine
- Less mechanical strength requirements of the lamina material

Number and position of joints on the circumference are defined depending on mechanical and electromagnetic demands. It is the target to safely transfer the required torque and at the same time enable an undisturbed and thus optimized magnetic flow inside the lamina.

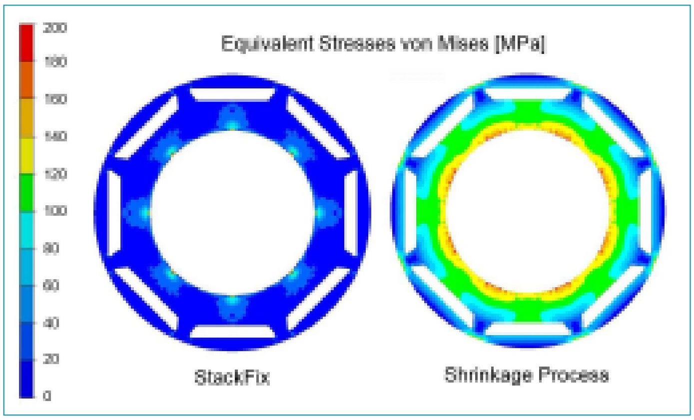


Figure 3 Comparison of the Stresses due to Joining Process

Direct Liquid Cooling of the Lamination Stack is Possible

Joints only punctually placed around the circumference of the shaft also provide the option to integrate liquid cooling inside the rotor. Such only partially existing contact points may generate cavities between the rotor shaft and the lamination stack which could be used for cooling of the rotor. The cooling liquid is supplied through a bore inside the rotor shaft – as shown in Fig. 4 – then it is led into the space between lamination stack and rotor shaft via guide elements and radially drilled holes. The crucial advantage of this cooling concept is the direct contact of the cooling medium with the component in which the heat emerges, namely the lamination stack. This facilitates a fast heat removal from the rotor and thereby reduces the heat influence on adjacent areas of the rotor, such as adjacent bearing zones. A two-part rotor shaft design, as illustrated in Fig. 4, preferably joined by laser welding is beneficial for this cooling concept.

Summary

With the presented joining method Hirschvogel demonstrates a new technology for joining rotor shaft and lamination stack which, from production and application view, provides many benefits. For future battery electric vehicles (BEV) generations the automobile manufacturers will bring the efficiency of the powertrain to perfection and outbid it. In order to achieve the performance targets a large number of e-motors will certainly need to be equipped with rotor cooling beside the currently used standard stator cooling. Combining the advantages of StackFix with a lightweight design hollow rotor shaft will definitely contribute to accomplish these goals.

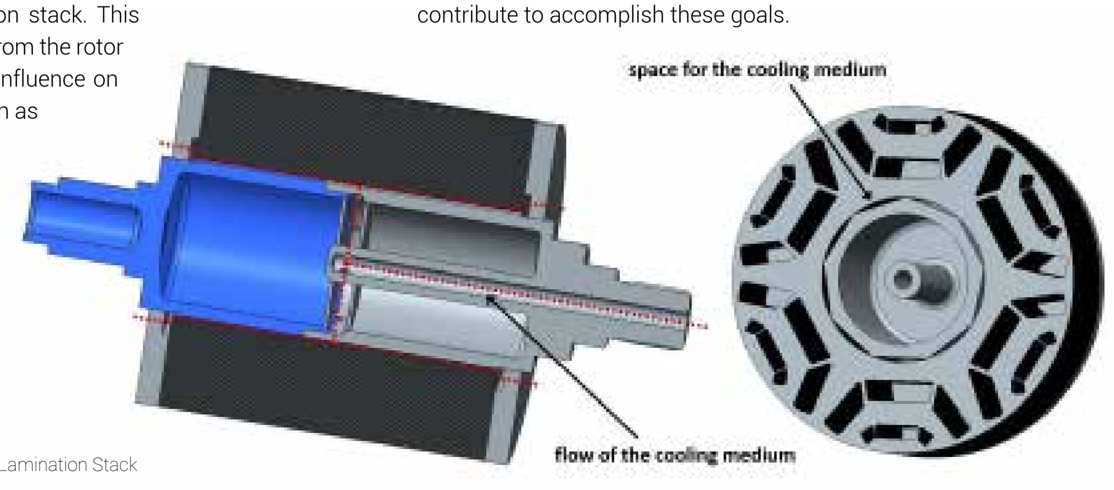


Figure 4 Direct Liquid Cooling of the Lamination Stack

World's 1st Production Selectable One-Way Clutches for Automatic Transmissions

Means Industries is launching four mass production Controllable Mechanical Diodes (CMDs) with three different customers in 2016. This is the first time Means' CMD technology will be integrated with its successful Mechanical Diode (MD) technology, and the first selectable one-way clutches (SOWCs) to be used in high-volume powertrain applications. Means CMDs are proven to facilitate improved fuel economy and reduced CO2 emissions. CMDs are highly configurable and have additional advantages over competing technology including: decreased packaging space, reduced mass, and system cost savings.

- Rob Fetting, Director of Engineering, North America, Means Industries
- Jeff Prout, Director of Engineering, Asia, Means Industries
- Carl Beiser, Technical Business Manager, Means Industries

Introduction

Means Industries manufactures its version of a one-way clutch (OWC) called the Mechanical Diode (MD). Similar to sprag and roller OWCs, MDs transmit torque when rotated in one direction and freewheel in the opposite direction. MDs are used in automatic transmissions to provide smooth 1st to 2nd gear shifts. To transmit torque in 1st gear, the MD uses locking elements called struts which passively engage by rotating the MD in the lock direction. When 2nd gear is commanded, the MD freewheels in the opposite direction, as the struts cannot transmit torque. The ability to smoothly transition from transmitting torque to freewheeling contributes to satisfactory shifting. Often, a low/reverse (L/R) clutch pack, which primarily transmits torque in reverse and low gear, is found adjacent to the MD. Simultaneously engaging the MD and L/R clutch pack creates a brake, which prevents rotation in either direction and is necessary for specific gear ratios to be achieved in a given powerflow.

After several successful MD product launches, Means began developing the Controllable Mechanical Diode (CMD). The CMD eliminates the need for the L/R clutch pack by having the ability to transmit torque in reverse and 1st gear. To accomplish this, a second set of locking elements (commonly referred to as reverse struts) are added to the basic MD architecture. The reverse struts are controllable and lock in the opposite direction to that of the passive struts (commonly called forward struts). The reverse struts can be turned on (uncovered) or off (covered) as needed as shown in Figure 1. By engaging both the forward and reverse struts, the CMD functions as a brake which is similar to simultaneously engaging the MD and L/R clutch pack.

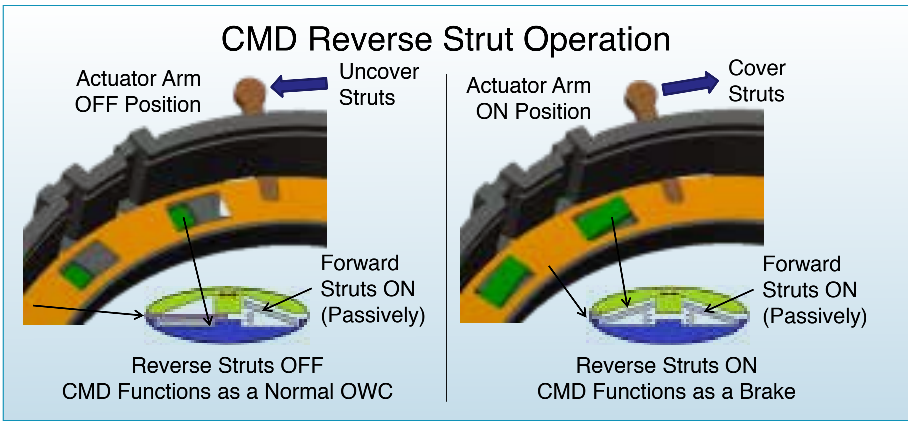


Figure 1 CMD Reverse Strut Operation

CMD Advantages over Competing Technology

The primary advantages of incorporating a CMD into a transmission include reduced spin loss resulting in improved fuel economy, decreased packaging size and mass, and systems cost savings.

The L/R clutch pack is a large spin loss contributor because it is disengaged (open) for most of the transmission's operation. The CMD primarily reduces spin loss by replacing the L/R clutch pack with the controllable reverse strut set. The reverse struts are off (covered) during freewheel, which allows the CMD to provide similar spin loss performance to that of the MD. Additional spin loss gains are achieved by integrating oil management features into CMD assembly. Spin loss advantages are reviewed later in this paper.

Additionally, eliminating the L/R clutch pack negates the need for a backing plate, apply piston, piston return spring, and all necessary secondary machining to the transmission case. Removing the components not only reduces packaging space and mass, but it also leads to a system cost savings.

Unlike conventional roller and sprag OWCs, Means' MDs and CMDs can use aluminum components to transmit torque because of the way engagement forces are reacted. Benefits are also realized through component integration, reductions in mass, decreases in rotating inertia, and the ability to incorporate complex part geometry.

A 2009 SAE publication titled Selectable One-Way Clutch in GM's RWD 6-Speed Automatic Transmission further explains the benefits of using a CMD at the vehicle-level. The paper describes hardware design, vehicle implementation, and control of a CMD in General Motors rear-wheel drive (RWD) 6-speed transmission. Figures 2 and 3 show the 6-speed RWD transmission cross section and actual hardware used in the comparison study.

After replacing the production roller OWC and L/R clutch pack with a CMD, GM concluded the CMD facilitated the following:

- No compromise in vehicle driveability
- System cost savings
- Fuel economy improvement of approximately 1.2 %
- Mass reduction of about 1.8 kg (4 lbs)

As development progressed, transmission designers better understood the design flexibility and functionality options CMDs create for a multitude of powertrain applications. Several global powertrain companies began developing new transmissions using CMD technology.

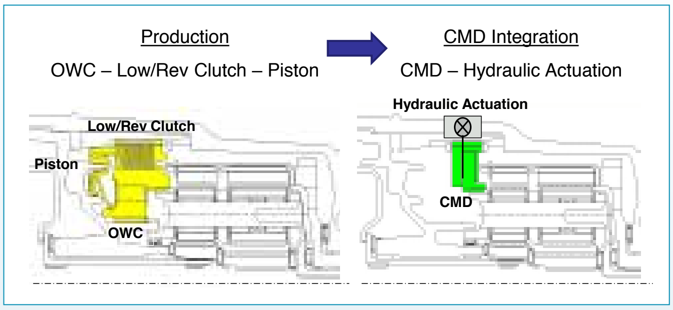


Figure 2 CMD Integrated into GM RWD 6-speed transmission

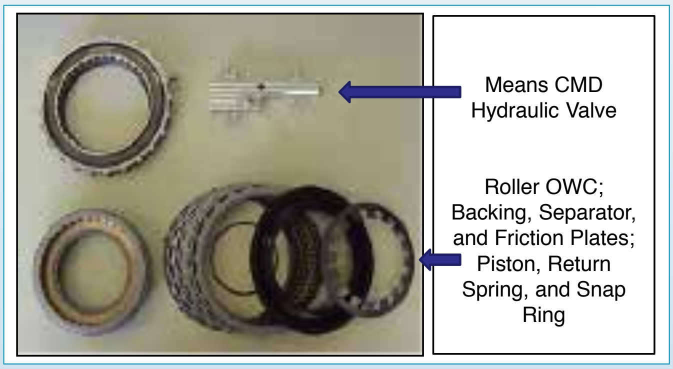


Figure 3 CMD and Actuation System vs. Production GM RWD 6-speed Transmission Components

Production CMD Comparisons

The production CMD application requirements are compared in Table 1. All four of Means' production CMDs are of the coplanar type, meaning three races are used to transmit torque, namely, the forward notch plate, forward/reverse (F/R) plate, and reverse pocket plate. Both applications have a selector plate which controls the reverse struts. Figure 4 and Figure 5 show the exploded view for each CMD. In each production application, the CMD created several advantages over competing technology which included the following: packaging space, spin loss, and actuation flexibility.

	Customer A & B	Customer C
Start of Production	June 2016	December 2016
Clutch Type	Coplanar CMD	Coplanar CMD
Outer Diameter	230 mm	200 mm
Inner Diameter	140 mm	155 mm
Forward Operating Torque	900 N-m	1200 N-m
Reverse Operating Torque	1600 N-m	2450 N-m
Freewheel Speed	7000 RPM	7000 RPM

Table 1 Production CMD Comparison

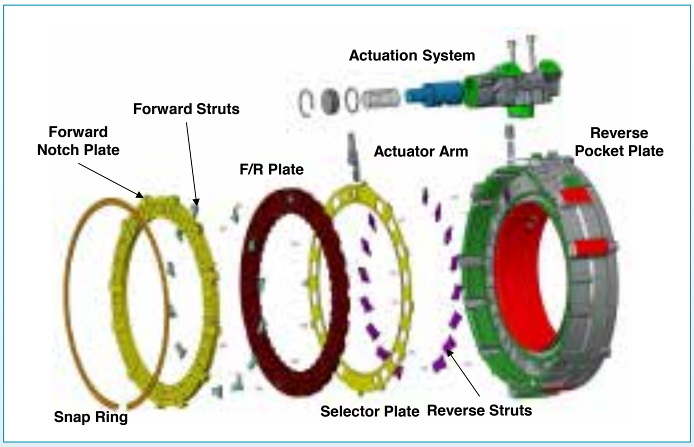


Figure 4 Customers A & B CMD (SOP June 2016)

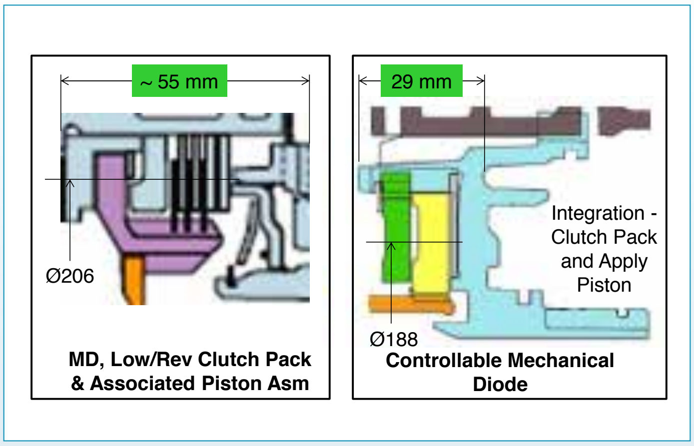


Figure 6 Customers A & B CMD – Axial Space Savings

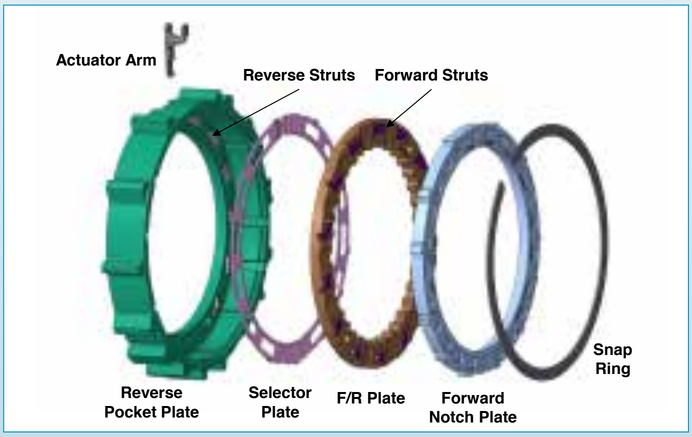


Figure 5
Customer C CMD
(SOP December 2016)

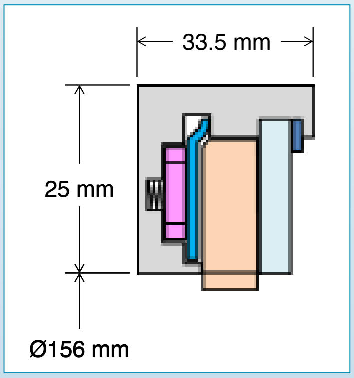


Figure 7 Customer C CMD – Axial Space Requirement

Packaging Space

In Customers A and B's application, the CMD's axial packaging space was reduced by 47 % compared to that of the conventional OWC and L/R clutch pack combination as shown in Figure 6. Furthermore, the reverse pocket plate and adjacent clutch pack assembly and housing were integrated into a single aluminum housing. Conventional OWCs would have required the clutch housing to remain a separate component. Moreover, integrating the adjacent clutch pack assembly into the CMD allowed Customers A and B to purchase one component from single supplier rather than 10 or more components from multiple suppliers.

Customer C's application required a more torque dense CMD solution and did not require integration with adjacent components. To transmit the increased reverse torque load, the reverse pocket plate was designed using high strength powder metal. Based on the torque requirement, it is estimated the packaging space required for a conventional OWC and L/R clutch pack combination is approximately 50 % greater than that of the CMD, which has an ultimate torque capacities of 6300 N-m and 6550 N-m for forward and reverse, respectively. Figure 7 shows Customer C's CMD and its axial packaging space.

Spin Loss

For aforementioned reasons above, both CMD solutions have lower spin loss than that of a conventional OWC and L/R clutch pack combination. The CMD designs also incorporate oil management features for improved performance. Unlike conventional roller and sprag OWCs and L/R clutch packs, which require high oil flow for lubrication and cooling, the CMD was designed to operate in low oil conditions to minimize spin loss. Furthermore, the oil management features help maintain durability at low oil flows by delivering oil where it is needed.

Figure 8 compares each CMD's spin loss advantage over that of a similarly size roller OWC and L/R clutch pack combination. The CMDs have significantly less spin loss at both city and highway speeds. These results are consistent with GM's findings published in its 2009 SAE paper, which states the CMD facilitated a 1.2 % fuel economy improvement. While Means does not have an exact fuel economy improvement for each production CMD application, customer feedback suggests the 1.2 % fuel economy improvement is understated.

Actuation Flexibility

Customers A and B required Means to design and validate a hydraulic actuation system integrated into their CMDs. This actuation system is a separate sub-assembly that is fastened to the reverse pocket plate. An actuator arm connects the selector plate to a valve internal to the actuation system sub-assembly. The valve contains a milled cam feature that converts axial valve displacement into rotary selector plate motion. Figure 9 details the ON and OFF ports that mate with the transmission valve body. Applying ON oil will turn on (uncover) the reverse struts allowing the CMD to transmit torque in the reverse direction. Conversely, applying OFF oil will turn off (cover) the reverse struts which allows the CMD to freewheel.

Customer C took a different approach and decided to design the CMD's actuation system. This required Means to design the end of the actuator arm to connect to the actuation system at transmission final assembly. Keeping the actuation separate from the CMD helped minimize package size and allowed the valve housing to be integrated into an existing aluminum casting. Figure 10 details how the actuator arm protrudes from the reverse pocket plate. The actuator arm converts tangential valve displacement to rotary selector plate motion.

Future CMDs

Means is also developing electronically-controlled CMDs (eCMD), which further improve transmission efficiency by reducing hydraulic control system capacity, or in some cases eliminating hydraulic controls altogether. As a result, eCMDs are an attractive option for hybrid and electric vehicle applications which usually lack intricate hydraulic systems needed for clutch control. Figure 11 shows two types of eCMDs currently under development.

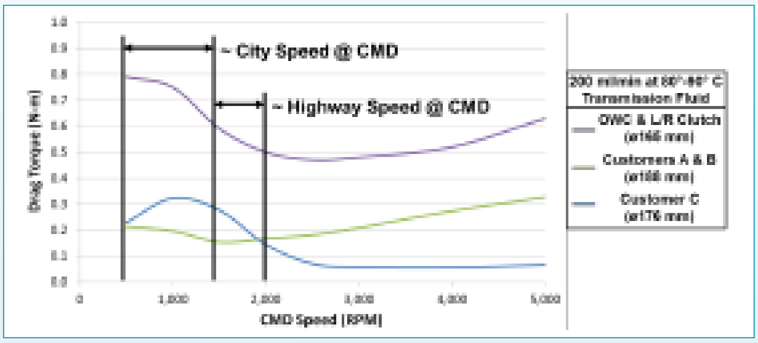


Figure 8 Drag Loss Comparison – Production CMDs vs. Roller OWC and L/R Clutch

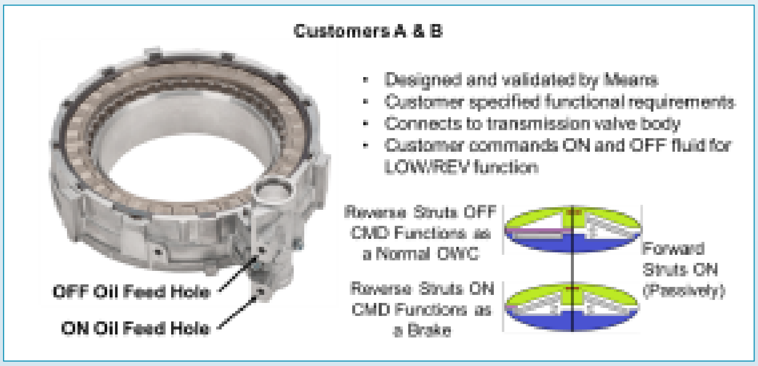


Figure 9 Customers A & B CMD – Actuation Methodology

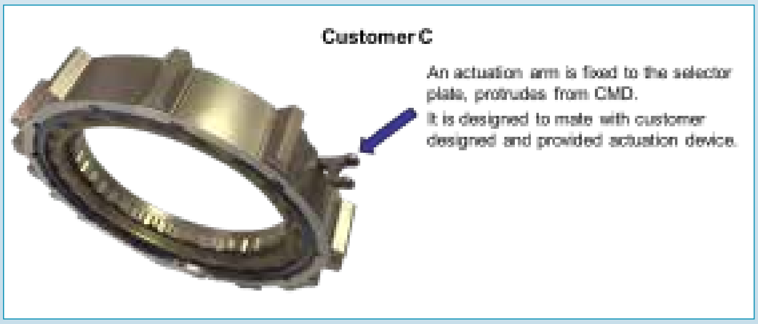


Figure 10 Customer C CMD – Actuation Methodology

Additionally, other CMDs configurations are being developed for application outside automatic transmissions. CMD technology is easily configurable to have different functionality, such as eAxle and eMotor couplers/disconnects, dynamic clutches, and brakes outside the production applications. CMDs currently in development range in sizes from 60 mm to over 300 mm, have torque capacities from 25 N-m to 5,000 N-m, and can freewheel up to 15,000 RPM.

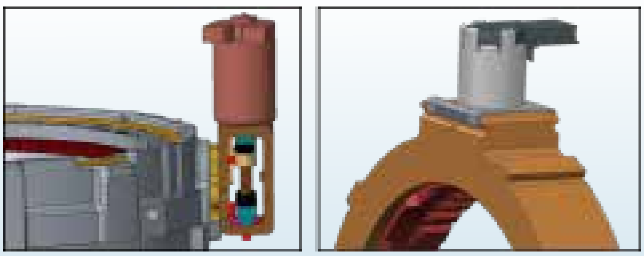


Figure 11 Electrically-Actuated CMDs (eCMD)

Conclusions

Using its CMD technology, Means Industries is launching four of the world's first selectable one-way clutches into high volume production for three large OEMs. While these applications differ in design, both CMDs function similarly, decrease packaging space, reduce mass by eliminating components, and provide a system cost savings. Unlike other one-way clutches, CMDs can also use lightweight materials, such as aluminum, to transmit torque which leads to further mass reduction. Lastly, CMDs are easily integrated into powerflows and highly configurable. Overall, Means CMDs are proven to facilitate improved fuel economy and reduced CO_2 emissions.

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Impressions of the CTI Symposium China, 21–23 September 2016

China Pushes Electrification

China is on the way to become a lead market for electromobility: more electric or plug-in hybrid cars are sold here than anywhere else. The CTI Symposium in Shanghai showed that the discussions on hybridization and electrification have become even more dominant, which in turn increases the interest in a new transmission category, the DHTs.

■ Gernot Goppelt, CTI Correspondent

"China invests a lot in the electrification of drivetrains", says Prof. Ferit Küçükay, Chairman of the Advisory Board, when asked about a memorable impression of this year's CTI Symposium China in Shanghai. With 570 participants from 17 countries, the conference has become an established event in addition to the CTI symposia in Germany and the US. 64 presentations discussed traditional topics, such as clutches, on-demand actuation, lubrication, functional development, calibration and solutions for commercial vehicles. But the programme of the CTI Symposium also reflects the increasing importance of electrification, for example in the "Dedicated Hybrid Transmission (DHT)" session and the two blocks on concepts and components for "New Energy Vehicles (NEV)" – in other words: three of eight sessions explicitly dealt with electrified powertrains.

How Much Electrification Do We Need?

NEVs and the required transmission concepts also characterised the panel discussion, chaired by Prof. Küçükay. Participants included Michael Schöffmann, Audi AG, Mario Brunner, AVL List GmbH, Dr. Frank Zhao, Tsinghua University, Dr. Rolf Gall, ZF (China) and Peter Hartman, FCA Powertrain Technologies R&D Shanghai. The first question Prof.

Küçükay asked: what are the electrification concepts China will focus on in the coming years – EV, PHEV or even FCEV, which are supported by the Chinese government under the general term NEV, or also full or 48V mild hybrids?

Prof. Zhao said that NEVs were heavily driven by regulations and that 48V hybrids were basically only a "quick fix", i.e. an intermediate step that would not be sufficient in the long term. The driving force for PHEV in China is the demand for zero-emission mobility in city centres in order to receive national and regional funding. Mario Brunner, AVL, countered that modern 48 V solutions already offered an advantage that was almost on the level of the first generation Toyota Prius full hybrid. Furthermore, there was a demand for hybridization of cars with manual transmissions, which still take a significant share of the market. Michael Schöffmann, Audi, considered it an advantage that no special infrastructure is required with regard to service. Peter Hartman, FCA Powertrain, believed that there would also be considerable diversification in the future: for the B segment and above, he expected PHEVs, and pure electric vehicles for urban use and car sharing. The FCEV played only a minor role in the discussion since, as Mr Schöffmann remarked, its future strongly depended on the infrastructure and the production costs of hydrogen.

Transmission Architectures – More Diversification

Given the variety of possibilities, the question which transmission designs and architectures will have the best chances with regard to increasing electrification remains an important issue. Michael Schöffmann explicitly excluded one design: the MT did not play a role anymore since autonomous driving would become more important with increasing electrification. Therefore, a powershift transmission was required. Rolf Gall put the idea into play that longitudinal architectures were not suitable anymore since the transmission tunnel did not match the usage behaviour in the interior of the car that would be expected with autonomous driving. With regard to vehicles with an electric range of at least 50 km, Frank Zhao considered the battery costs to be more important than the transmission concept. Mario Brunner favoured DHTs for high voltage hybrid vehicles, he even considered the idea that 48 V DHTs could be an option with future e-machines. With an eye on the future, Peter Hartman considered mild hybrid MT and AMT a reasonable solution in the low-cost range, for higher classes he still expected a wide range of transmission designs.

China as Lead Market for EVs and PHEVs

At the well-attended press conference chaired by Prof. Küçükay, the topic of electrification was even more in the focus than in the presen-

tations and the panel discussion. Prof. Küçükay explained to the journalists that there were already more than 30 different hybrid concepts today and that the number would increase rapidly in the future. According to him, there was a clear trend towards EVs and PHEVs in China. In the first half of 2016, 130,000 EVs and 45,000 PHEVs were sold – as opposed to North America and Europa where more PHEVs than pure electric vehicles were sold – of course in much smaller numbers. As Prof. Zhao already stated in the panel discussion, the incentives in China influenced the advancement of electromobility considerably since they made buying a NEV more attractive. By 2020, electric cars should reach a market share of 20 percent; however, there would be no more incentives by then, resulting in a self-supporting market.

Until then, there will undoubtedly be challenges ahead: the batteries are still too heavy, but a doubling of the energy density and halving of the costs for batteries and electric components is expected for the next ten years. Furthermore, complete recycling of the batteries is not yet possible – another challenge to be met. Electric cars are high voltage systems, so particularly the safety of the battery has to be guaranteed here. Last but not least, electric cars are still 20 to 30 percent more expensive than conventional vehicles. This is not only due to the drivetrain components, but also the increased demand for lightweight design. According to Prof. Küçükay, China will play an important and leading role as a global battery producer in the medium term and therefore affect the price and technology development considerably.

More Electrification – Less Mechanical Complexity

The journalists at the press conference showed great interest in the DHT, a new transmission category: after its first presentation at the CTI Symposium 2015 in Berlin, it has quickly been established in usage in the transmission industry. Prof. Küçükay once more presented the definition of the DHT, including the statement that the electric motor plays a central role here and that the transmission would not be functional without it. He explained that, provided that the units in production were high enough, a DHT could be cheaper than an add-on

hybrid transmission since it could be less complex due to less gears. In the future, manifold solutions could also be expected for the DHT. Mr Küçükay emphasized the advantages of architectures with two electric motors instead of one since more operating modes and therefore a particularly efficient operation were possible.

In terms of technology, China was more diversified nowadays than for instance Europe. For example, there were more than 100 Chinese suppliers of electric cars today. Here and with regard to the development of new hybrid concepts, it could be advantageous for China that it was easier for the large number of new market participants to develop new architectures "from scratch".

The DHT could therefore be a factor in the attempt to reduce costs and weight in order to develop efficient plug-in hybrids for the Chinese market. Toyota and GM are not the only ones providing standard applications of a DHT – Sidong Luo presented a DHT from SAIC Motor in Shanghai, which uses a very simple gear set with spur gears, and is installed in the Roewe models e550 and e950. The latter one has an electric range of 60 km and a hybrid range of 540 km. As of September 2016, more than 30,000 vehicles – according to Luo – of both plug-in hybrid models had been sold.

Tradition and Modern Technology

High units of EVs and PHEVs are characteristic for the Chinese market, but also a large number of manual transmission cars. Here, they currently have a market share of approx. 59 percent – 65 percent in Europe and only nine percent in North America. In the coming years, a decrease by about five percent is expected. As the discussions at the CTI Symposium China showed, the increasing automation will result in several development lines, which are eagerly observed by the development community. Mild hybrid MT and AMT could also be a cheap option for China to reduce CO_2 emissions. Pure electric vehicles are already much more popular than in Europe or the US. Plug-in hybrids, including solutions based on DHTs, have the potential in all markets to combine local zero-emission mobility and suitability for long-distance driving.

China has taken a leading role in the mass production of EVs and PHEVs. That does not necessarily mean that the technical solutions favoured in China can be transferred to other markets, but it will probably lead to a rapidly increasing expertise in the key areas of electromobility, such as battery technology and electric drivetrain components. On the other hand, the market offers great opportunities to participate in the market development with advanced plug-in hybrid concepts. Thus, China could in turn be a driving force for accelerated hybridization in Europe and North America.