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W ORLDWIDE

12 | December 2009 Volume 111

The New Opel Astra

High-strength Aluminium Profiles for Next Generation Spaceframes

Wet Starting Clutch for **Automatic Transmissions**

Electro-hydraulic Steering Systems for Light Commercial Vehicles

The Next Generation **Park Assist Systems**

Modular System for Methodological Design of Body Assemblies

INTERVIEW

»The SuperLightCar Has Boosted Confidence in Multi-material Design **Concepts**« Martin Goede, Tino Laue, **Volkswagen AG**

SPECIAL FKFS

20 Years of Vehicle Wind Tunnels at IVK



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COVER STORY

The New Opel Astra



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In the compact size class, the **Opel Astra** aims to offer technical innovations such as mechatronics chassis, adaptive headlights or traffic sign detection. ATZ presents the vehicle and the new six-speed automatic transmission for front-wheel drives for 175, 240 and 380 Nm maximum input torque.

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Where Do We Go from Here?

Dear Reader,

On a dull November day, I am writing this editorial for our magazine's final issue of 2009. Probably like many of you, I will be pleased when this difficult year is over. I plan to use the somewhat calmer time before Christmas and especially over the New Year period to focus once again on my long-term aims, after a year that has been so often marked by short-term, emergency activities.

But nevertheless, when I think back on the crisis, my emotions are not all negative. On the contrary, it revealed the true solidarity of many of our customers. 95 percent of our readers chose to renew their subscription even in these difficult times, because they know that knowledge is always the most important resource. In spite of short-time working, most of our authors delivered their articles on time and in their usual high quality. And more than two thirds of all advertising customers continued to advertise, because, especially in a crisis, communication is not a disposable quantity. I promise that I will not forget your loyalty.

In the midst of the crisis, we have been working on a relaunch of ATZ. The first issue of the new ATZ will be arriving in four weeks' time. I wouldn't like to reveal too much at the moment. But you can be sure that, even after 111 years, our commitment and excitement in creating this magazine is as great as ever. The next "model generation" will show even more clearly the fascination that good engineering can produce. I look forward to the first issue of the new ATZ – and to the year ahead.

I hope that you too have cause to be optimistic about 2010. We will be happy to accompany you.

laus Why

Johannes Winterhagen Bad Gögging, 10 November 2010



Johannes Winterhagen Editor-in-Chief

ATZ worldwide 1212009

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Opel Astra



Technical Portrait The New Opel Astra

The Astra is the most important high-volume model for "New Opel", as this platform makes up one third of all vehicle sales. The compact model, which was launched in autumn 2009, aims to offer technical innovations at a moderate cost. What is more, many of the systems familiar from the Insignia are now being installed in the compact class for the first time. Above all, Rüsselsheim intends to impress the public with the car's driving dynamics, acoustics and variability.



Technical Portrait The New Opel Astra



Adaptive Suspension System

The new Astra features an electronically controlled adaptive suspension system called "FlexRide". Drivers can preselect three basic settings: Standard, Tour or Sport. Sport mode not only stiffens the shock absorbers but also makes the accelerator and power steering characteristics more progressive. In cars fitted with an automatic transmission, the up-shift points are raised to a higher engine speed. To underline the sporty character, the instrument panel illumination changes from white to red. The development partner for FlexRide was ZF Sachs.

Watt's Link Rear Axle

To further improve driving dynamics and comfort without having to develop a complicated multi-link axle, Opel has rediscovered a tried and tested technical principle: Watt's linkage, which is based on Watt's Parallelogram, a machine element tested for the first time on a steam engine in 1784 by the renowned engineer James Watt. The Astra features an innovative combination of a compound crank axle and a Watt's link mounted at the centre of a small cross-member directly behind the rear wheel centre line. As a result, lateral forces acting on a rear wheel are applied in the opposite direction to the other wheel, thus neutralising about 80 % of the lateral loadings. This design allows the use of softer axle bushings, thus improving comfort, road noise and isolation.





Engines

The nine engine versions for the Astra have in some cases being significantly revised. On average, CO_2 emissions have been cut by 12 % compared to the predecessor versions. Of particular interest is the 1.4 l turbocharged petrol engine with 103 kW, which replaces the 1.8 l naturally aspirated unit with the same output. This downsizing by almost 25 % has also resulted in an increase in torque by 25 Nm to 200 Nm, which is now available at 1850 rpm. The 1.4 l engine, which is also offered as a naturally aspirated version, benefits from reinforced pistons and con rods and has a compression ratio of 9.5:1.

Front Camera System

The new Astra is the first vehicle in the compact class to be fitted with a camera system used for two driver assistance functions: Traffic Sign Recognition and Lane Departure Warning. The latter system does not actively intervene in the steering – although this would actually be possible with the electromechanical steering system – but gives an acoustic and visual warning when the driver unintentionally veers out of a traffic lane without indicating and if the speed is at least 60 km/h. The camera system also uses software to read speed limit or no overtaking traffic signs and displays them in the instrument panel. The camera is integrated into the interior rear-view mirror.





Technical Portrait The New Opel Astra



Seat Ergonomics

Special equipment for the new Astra includes ergonomically designed sports seats that won the coveted seal of approval from "Aktion Gesunder Rücken e.V." (Action for Healthy Backs), an independent panel of ergonomics experts and doctors in Germany. The front seats are adjustable for length, height and tilt, while the lumbar support can be adjusted for height and stiffness to adapt to the contours of the back. The driver's seat also has an extendable seat cushion. According to Opel, the fore and aft adjustment range of 280 mm is the best in class.



Integrated Bicycle Carrier

An Opel speciality, but one that has not yet been available in the compact class, is the "FlexFix" bike carrier, which is integrated into the rear bumper. It can carry either one or two bicycles and has a maximum weight capacity of 40 kg. When not required, it can be pushed back into the car with one hand. Opel says that the space-saving compound crank rear axle concept was the pre-requisite for the adoption of FlexFix.



Electronic Travel Guide

The DVD 800 satellite navigation system features an electronic travel guide developed in cooperation with Merian Scout. More than 100,000 "Points of Interest" from 26 countries are stored on the 2 GB flash memory card, in some cases with very detailed information such as opening hours and prices. A digital restaurant guide is also included. The information is displayed on 7-inch TFT monitor.



Technical Portrait The New Opel Astra



Automatic Transmission

The new six-speed automatic transmission from GM Powertrain is being installed for the first time in an Opel, although at first only in combination with the 2.0 I diesel engine. The transmission developed by GM uses three planet gear sets with two clutches and two brakes, thus making it very compact. All gear wheels are on the engine's crankshaft axle. The gear ratio spread is 6.1:1. The transmission is described in detail in the following report.

Technical Data

Engines						
	Output in kW at rpm	Torque in Nm at rpm	Displacement in cm³	Acceleration 0-100 km/h in s	Fuel consumption (NEDC) in I/100 km	CO ₂ emission in g/km
1.4 ecoFLEX	64/5,600	130/4,000	1,398	14.7	5.5	129
1.4	74/6,000	130/4,000	1,398	14.2	5.5	129
1.6 – MT5	85/6,000	155/4,000	1,598	11.7	6.3	147
1.6 - AT6	85/6,000	155/4,000	1,598	13.3	7.1	167
1.4 Turbo – MT6	103/4,900	200/1,850	1,364	9.7	5.9	139
1.4 Turbo – AT6	103/4,900	200/1,850	1,364	9.8	7.0	164
1.6 Turbo – MT6	132/5,500	230/2,200	1,598	8.5	6.8	159
1.6 Turbo – AT6	132/5,500	230/2,200	1,598	9.0	7.5	176
1.3 CDTI ecoFLEX	70/4,000	190/1,750	1,248	14.7	4.2	109
1.7 CDTI 81 kW – MT6	81/3,800	260/1,800	1,686	12.6	4.7	124
1.7 CDTI 92 kW – MT6	92/4,000	280/2,300	1,686	11.5	4.7	124
2.0 CDTI – MT6	118/4,000	350/1,750	1,956	9.0	4.9	129
2.0 CDTI – AT6	118/4,000	350/1,750	1,956	9.2	5.8	154
Dimensions and Weights Car dimensions in mm					Five-door version	
Length					4,419	
Width (with retracted / extended externa	al rear-view mirrors)				1,814/2,013	
Height (at curb weight)				1,510		
Wheelbase				2,685		
Track, front				1,544		
Track, rear						
Irack, rear					1,558	
Luggage compartment capacity in I	(according to ECIE)				1,558	
Luggage compartment capacity in I Luggage compartment only, up to luggage	(according to ECIE) le compartment cover				1,558	
Luggage compartment capacity in I Luggage compartment only, up to luggage With rear seats folded forward, up to roo	(according to ECIE) le compartment cover				1,558 370 1,235	
Luggage compartment capacity in I Luggage compartment only, up to luggage With rear seats folded forward, up to roo Weights and axle loads in kg (accor	(according to ECIE) le compartment cover of ding to 70/156/EEC)				1,558 370 1,235	
Luggage compartment capacity in I Luggage compartment only, up to luggage With rear seats folded forward, up to roo Weights and axle loads in kg (accor Curb weight including driver (basic mode	(according to ECIE) le compartment cover of ding to 70/156/EEC) el)				1,558 370 1,235 1,373	
Luggage compartment capacity in I Luggage compartment only, up to luggage With rear seats folded forward, up to roo Weights and axle loads in kg (accor Curb weight including driver (basic mode Gross vehicle weight	(according to ECIE) le compartment cover of ding to 70/156/EEC) el)				1,558 370 1,235 1,373 1,870	
Luggage compartment capacity in I Luggage compartment only, up to luggage With rear seats folded forward, up to roo Weights and axle loads in kg (accor Curb weight including driver (basic mode Gross vehicle weight Payload	(according to ECIE) le compartment cover of ding to 70/156/EEC) el)				1,558 370 1,235 1,373 1,870 497	



Six-speed Automatic Transmission in the Opel Astra and for the Global Market

General Motors Powertrain has developed a new six-speed FWD family of automatic transmissions for compact and midsize vehicles. These are also used for the European market, as they are put into the new Opel Astra since October 2009. Due to its compact shape, high quality and good value-for-money level, this transmission can be integrated in all vehicle platforms and is thus suitable for global markets. As compared to the four- and five-speed transmissions which it replaces, the new six-speed transmission excels by its improved fuel economy as well as its improved performance.

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proved manufacturing efficiency and flexible production volumes, as well as it reduces production costs. All variants are based on the same architecture and share identical electro-hydraulic control units. Using the same components, again results in a reduction of unit costs and of development and validation time. All of the variants will be applied in the new Opel Astra.

2 Development in a Global Team

Given the global presence of General Motors on all markets of the world, the technological development of the new transmission demanded likewise global standards. In support of the US Headquarters, GM development centres in South Korea, China, Germany, France, and Sweden were involved with specific tasks; those tasks comprised not just market specific integration work, rather, each developing centre contributed to the project by way of its knowledge of regional requirements as much as by its long-time experience. Figure 2 gives an illustration of which centres were involved with the project, including the first production sites in China and South Korea; additionally, new US and Mexican production modules will soon further increase production output. More than one million units of this family of transmissions will be produced in 2010 already. The transmissions for the

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The new family of transversal automatic transmissions is marked by a notably wide ratio spread as much as by different variants. These variants are meant to handle different levels of engine torque in order to allow a wide range of applications for different vehicle platforms, according to market demands. The maximum ranges for engine torque and engine horsepower of the variants of GM's new global automatic transmissions family for transversal engines are shown in Figure 1. The new transmissions were designed to offer the best technology to customers such as six speeds for a competitive cost-benefits relation.

All variants are built on the same production line; this fact allows for im-



Figure 1: Maximum torque and horsepower range of the new family of GM Powertrain six-speed automatic transmissions for 175, 240 and 380 Nm maximum input torque

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Figure 2: GM's global integrated development system for the new six-speed automatic transmission

new Opel Astra will be built in the production plant in Yantai, China.

The GM development centre in Pontiac, Michigan (USA), has ensured that all gobal and regional requirements were taken into account. One example of the specific requirements for markets in Europe and the Near East is testing the cooling system at maximum speed. A specific North American requirement is 'dinghy towing', that means trailering your passenger car long distance behind your motorhome. On the other hand, there is the problem of individual customer habits such as frequent changes of gear between 'N' and 'D' of South Korean drivers, despite for example 'neutral idle', which has to be taken into consideration while developing calibration.

It is clearly an advantage of this global project that transmissions from other production sites can be built in without further validation or change of calibration. A likewise global employment of families of engines helps to minimize variants, the number of converter housings, and to keep the number of powertrains manageable.

A joint development with several locations was a particular challenge for the team. On the other hand, this situation held many opportunities to further improve the product. Surely one challenge was communicating across differing time zones, by phone or network connections. An American colleague has to get up early, Asian colleagues have to work overtime and Europeans have to postpone their lunch break. Communicating in English is no longer a problem for either of the teams. Mutual understanding of cultural backgrounds grows as the project progresses; regional diversity of cultures and of ways of thinking allows to pursue divers options and solutions which prolongs the process of decisionmaking, but which quite often leads to better thought-out and more efficient solutions, with fewer intermediate steps. A management trained in international cooperation is a valuable factor here as it will know how to profit from cultural diversity. A well-tuned coordination of responsibilities will lead to success. Regular briefings, temporary cooperation and a rigorous change management process,



Figure 3: Schematic view of power flow

not just for transmission parts but also for processes themselves, have led to successful global teamwork. One of the greatest challenges has been the almost synchronic beginning in the different production plants related to a speedy product introduction on various markets and for various vehicle platforms.

3 Power Flow

In order to reduce the number of components and thus the complexity of the new six-speed automatic transmissions and still gain high efficiency, GM developed a new power flow concept. It uses three planetary gear sets together with two rotating and three stationary clutches plus a one-way clutch. Advanced electronics enables a simultaneous clutch control with the precision needed for optimum shifting. The one-way clutch is used for maximum comfort while shifting from first into second gear. A schematic view of the power flow is shown in **Figure 3**.

The new GM six-speed family of automatic transmissions has been tuned for optimum launch and efficient long travel speed using low engine revolutions. The new transmissions have a wide overall ratio spread of 6.1:1 which allows for optimum adaptation of the powertrain for various categories of vehicles [2]. The transmissions have a short first gear with a ratio of *i* = 4.58, improving acceleration from 0 to 100 km/h up to 7 % as against current four-speed automatic transmissions. A long overdrive sixth gear allows for low engine revolutions during highway driving, and thus for reduced engine friction and throttling losses as much as for a reduction of the interior noise level. As against four-speed automatic transmissions, fuel consumption for constant speed driving could be lowered up to 4 %. Figure 4 shows the sequence in which shifting elements are applied relative to increased vehicle speed.

4 Innovative Construction

In order to reduce the installed length of transmissions in transversal installation, the new automatic transmissions have all their gear sets on the crankshaft axis

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of the engine. By way of this compact construction the length of the required engine compartment and the distance between axle shafts and crankshaft is reduced. The key installation dimensions are shown in Figure 5. With this compact construction more free space for vehicle design is achieved. The Table shows all data of the family of transmissions with all gear ratios. Most important measures aiming at the reduction of the package size are an output chain with a planetary final drive gearset, a low aspect ratio torus torque converter, an integrated electro-hydraulic control unit, and a onepiece case. The innovative construction with these components is shown in Figure 6. The architecture and the optimized integration of components/subsystems result in a reduction of weight and high power density as compared to other six-speed automatic transmissions with transversally installed engines. Variants of the new GM six-speed family of automatic transmissions are built with an internal gear pump. It excels through high hydraulic efficiency, low noise level and yet compact dimensions and lowers the noise level. Its volumetric efficiency reaches up to 95 %.

The case of the transmissions is built in such a way that it minimizes struc-



Figure 4: Shifting chart for the six-speed automatic transmission



Figure 5: Compact dimensions for an optimized construction space (packaging)

Table: Technicaldata of the newfamily of GF6 six-speed automatictransmissions6T30, 6T40 und6T45 for frontwheel drive

Descriptive	Unit	6130	6140	6145
Transmission model		6-speed, FWD, transaxle	6-speed, FWD, transaxle	6-speed, FWD, transaxle
Appearance by design		On crank shaft axis (2 axes)	On crank shaft axis (2 axes)	On crank shaft axis (2 axes)
Maximum engine torque		175 Nm (Gasoline), 200 Nm (Diesel)	240 Nm (Gasoline), 280 Nm (Diesel)	315 Nm (Gasoline), 380 Nm (Diesel)
Maximum engine power		140 Hp (Gasoline), 95 Hp (Diesel)	180 Hp (Gasoline), 125 Hp (Diesel)	215 Hp (Gasoline), 175 Hp (Diesel
Dimensions and Weight				
Wet mass	kg	71.5	81.4 - 82.5	84.3 - 83.5
Length	mm	352	351	357
Center distance	mm	185.9	197	197
Vertical drop	mm	65	75	75
Transmission Specifications				
1 st Gear ratio (1 st – 2 st gear step)		4.449 (1.530)	4.584 (1.55)	4.584 (1.55)
2 nd Gear ratio (2 nd – 3 nd gear step)		2.908 (1.536)	2.964 (1.55)	2.964 (1.55)
3 rd Gear ratio (3 rd – 4 th gear step)		1.893 (1.309)	1.912 (1.32)	1.912 (1.32)
4 th Gear ratio (4 th – 5 th gear step)		1.446 (1.446)	1.446 (1.45))	1.446 (1.45))
5 th Gear ratio (5 th - 6 th gear step)		1 (1.348)	1 (1.34)	1 (1.34)
6 th Gear ratio		0.742	0.746	0.746
Reverse gear ratio		-2.871 (0.645)	-2.94 (0.64)	-2.94 (0.64)
Ratio spread		6.00	6.14	6.14
Effective final drive ratio (EFDR)		2.84/3.14/3.37/3.72/4.11	2.29 / 2.52 / 2.74 / 2.64 / 2.89 / 3.17 / 3.23 / 3.53 / 3.87	2.29 / 2.52 / 2.74 / 2.64 / 2.89 / 3.17 / 3.23 / 3.53 / 3.87
Torque converter dispeter	-	220	216	236

Opel Astra

Figure 6: Components of applied compact architecture



ture- and air-borne noise. The first bending frequency of the power train exceeds 260 Hz which means a considerable improvement of noise reduction. The planetary gear sets have been designed with low mesh frequency and a decoupled vibration path to the case structure.

4.1 Clutch to Clutch Control with Internal Electro-hydraulic Module

The core of the integrated electro-hydraulic control unit (transmission electro-hydraulic control module, TEHCM) of the transmission is a 32-bit processor. The internal unit, bathed in transmission fluid, reduces the number of cable joints and improves the system's pressure control. The thermal management of the system has been optimized in order to ensure the optimal operation temperature of the TEHCM.

The control unit also monitors the synchronic clutch control which is essential for a perfect transmission performance. Unnoticed by the customer, manufacturing tolerances and clutch wear affecting transmission durability are levelled out.

20 mm	Hyper-Elliptical Torque Converter Diameter Maximum Efficiency	236 mm 90%
	Torque Ratio Round circuit Torque Converter	1.78
	Diameter Maximum Efficiency Torque Ratio	245 mm 88% 2.4

Figure 7: Comparison of elliptical to conventional torque converter

4.2 Elliptical Torque Converter

The transmission's torque converter is 236 mm in hydraulic diameter and is designed with an elliptical cross-section shape. It uses a single plate lockup clutch to enable direct drive. The oval shape provides an axial space saving of 30 mm, improved on-axis packaging of all planetary sets and clutches, and it reduces overall mass. In **Figure 7** the design of the elliptical torque converter is shown compared with a conventional torque converter.

While optimizing the package, the maximum efficiency could be improved. The reduction of torque multiplication could be balanced by ratio spread and a short first gear. The single-plate lockup clutch is controlled by GM's electronic clutch control (electronic controlled capacity clutch, ECCC).

4.3 Chain System

The new six-speed automatic transmissions use an output chain and sprocket system in order to eliminate the third axis and further reduce package space. Mass can also be reduced without negative impact on the noise level of the transmission, compared to gear set drive. The design of the output chain also allows flexibility in torque handling capability between standard and heavy duty variants: 6T40 uses a 25.4 mm wide chain, versus 31.75 mm for 6T45.

In order to keep a low level of transmission fluid aeration the new GM automatic transmissions have integrated output chain baffle plate/lip seal and output chain-scoop snubber systems, as shown in **Figure 8**. Through this design, improved transmission fluid pressure stability and durability as much as reduced spin loss is achieved. The baffle plate system is mass optimized and designed for easy assembly; it can also be used for chains with different width.

Long distance dinghy-towing – a requirement of the US market – is enabled by an integrated chain scoop and snubber system, as shown in Figure 8. The scoop provides lubrication while towing, captures and channels away oil from the chain and prevents exceeding oil aeration. Thus a passenger car can be trailered long distances behind a motorhome.

5 Oil Management System

The rather flat oil sump of the new GM automatic transmissions requires minimum package space and increases ground clearance. A sufficient amount of oil is provided for cold temperature operation. For high temperature operation the oil level is optimally maintained by a thermal oil level control unit; its construction and mode of operation is shown in Figure 9. Depending on the oil temperature, the oil level control unit opens or closes an extra oil reservoir. At temperatures below 60° C a thermal element opens the reservoir which is connected to the oil return flow. At higher temperatures the control unit closes the reservoir so that a defined amount of oil is retained. The reservoir has a spillage device preventing return flow blockage. Controlling oil capacity in circulation and the transmission's oil sump provides an always optimal oil level and thus optimal performance.

The new GM six-speed automatic transmissions for front-transversal installation are filled for life with premium Dexron-VI transmission fluid. Dexron-VI has been designed specifically for the sixspeed family of transmissions in order to provide a constant viscosity profile and optimal anti-vibration performance. Internal GM research with friction tests has revealed that compared to existing transmission fluids Dexron-VI provides



longer stability and durability. In addition, Dexron-VI has other excellent qualities such as improved oxidation stability, decreased tendency to oil aeration, improved shear stability and wear control of transmission parts.

6 Improved Efficiency through Electronic Converter Clutch Slip Control

The new GM six-speed automatic transmissions are equipped with torque converter lockup clutch with electronically



Figure 9: Design and operating mode of the oil level control unit

Opel Astra



Figure 10: Comparison between open torque converter clutch and electronically controlled slip in the fifth gear

controlled slip. This leads to better fuel economy for vehicles with automatic transmission. In conventional calibration of automatic transmissions the converter lockup clutch will be opened directly when falling below a certain speed threshold. In transmissions presented here the converter lockup clutch will be opened only to allow for controlled slip. Slip here is small, as it is only 12 rpm in some ranges of operation. Only at very low engine speeds the converter lockup clutch will be opened completely. Figure 10 shows, statically, the difference in engine revolutions with an opened converter lockup clutch and with electronic slip control. The example of fifth gear which is shown represents direct transmission, but a comparable strategy is calibrated for other gears. A complete opening of the converter lockup clutch only occurs below 1300 rpm and is calibrated for comfortable transitions.

Conversion losses can thus be minimized across a broad speed-range. The engine speed at which a downshift is commanded is load-dependent, that means when reaching maximum engine torque. In addition the engine speed reduction effects a more comfortable noise level. The aim for future transmission design is to further lower the speed level and subsequently improve fuel economy, and to bring the lower rpm-limit for the electronically slip controlled torque converter lockup clutch down to 1100 rpm.

7 Summary and Outlook

General Motors Powertrain has developed a new family of six-speed automatic transmissions for compact and midsize cars with front wheel drive. For Opel and Vauxhall Brands, the transmission is first used in the Astra (model year 2010). Due to compact design, high quality and an excellent value-for-money relation this transmission can be installed in all vehicle platforms and offered on all global markets. As against the existing four- and five-speed automatic transmissions which it will replace, fuel economy will be improved up to 4 % and vehicle performance will be increased.

The three variants of the transmission family cover a wide range of torque. Each variant uses the same architecture and identical control components; also a large number of components is used in several variants. In many details the transmission is optimized to minimum package space with maximum performance, yet uncompromising in efficiency. Essential measures concerning package space reduction are output chain, planetary final drive gear set, elliptical torque converter, integrated electro-hydraulic control module, and a one-piece case. Other remarkable qualities are a 6.1:1 ratio spread, neutral idle, torque converter lockup clutch with electronic slip control and all-wheel-drive compatibility.

At present the new family of transmissions is being introduced on all global markets and production capacity will be increased over the next years (first production sites are located in China and South Korea). The global development team is already working at the next evolutionary stage and at pushing the upper limits of the input torque of the transmission even further.

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Lightweight Design





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"The SuperLightCar Has Boosted Confidence in Multi-material Design Concepts"

In order to reduce traffic-related CO₂ emissions, the EU has introduced phased legislation to reduce fuel consumption. Vehicle weight plays a decisive role in this. This year, the conclusion of the EU project "SuperLightCar" (SLC) saw the presentation for the first time of a lightweight car body with an innovative multi-material construction that is 30 % lighter than its series-production counterpart. ATZ spoke to Dr. Martin Goede and Tino Laue at Volkswagen in Wolfsburg about SLC and the future of lightweight body design.

ATZ Martin Goede, Tino Laue, Volkswagen played a leading role in the EU's SLC project. Based on the example of the VW Golf V, it was shown that a series-production car body can be made 35 % lighter. What precise objectives were behind this project?

Goede The aim of SLC was to show how much lighter a passenger car body-inwhite in the high-volume segment can become, also from a cost perspective. It was not so much about the pure substitution of steel by aluminium but rather about intelligent multi-material design. The use of aluminium allows a weight advantage of up to 40 % compared to steel, but an aluminium design is linked with high additional costs. SLC not only considered new material combinations but also looked for innovative solutions. In this process, the important core competences in body design, such as material and manufacturing technologies, construction methods and functional and economic requirements, were considered all together. **ATZ** What were the concrete results? **Goede** Lightweight design solutions that may be very interesting for future series-production projects were developed. Above all, we can see the growing use of hot-formed steels and selected aluminium solutions. The results of the SLC project concerning the use of magnesium and fibre reinforced plastics confirm the lightweight design potentials and the fulfilment of structural requirements. However, we do not believe that these technologies can be used in large-volume series-production vehicles in the short and medium term. In this respect, the consortium has identified the need for further research.

ATZ Are the results transferable, or is the project only a demonstration of what is possible for the Golf V?

Goede The results certainly show the direction for the future. However, we must remember that, in the EU project, the focus was on pre-competitive developments, which means that it studied innovative lightweight design concepts that cannot be employed as a whole in series production in the short term. SLC has established a body structure as hardware. It represents a promising technological compromise between various lightweight design solutions and demonstrates the fundamental feasibility of the SLC concept.

Laue The body only represents a favoured multi-material version to meet the requirements of "large-volume production capability for the future". Transferring this concept to Volkswagen development projects is not directly possible, as competition-relevant design criteria were not considered.

ATZ Which aspects were considered in the SLC project?

Goede The SLC project allowed us to answer decisive questions on multi-material body design, such as structural performance, manufacturing processes, costs and life cycle assessment. Other requirements such as operational durability, acoustics or repair concepts were considered thematically but not quantitatively. Further series-relevant design criteria were not examined within the SLC project. The SLC results offer all project partners a very good basis on which to develop further aspects of multi-material body structures in follow-up projects.

ATZ Which consequences will be drawn from this at VW?

Goede SLC has given major impetus to concept developers and designers and has boosted confidence in multi-material concepts. When we started on SLC in 2005, the issue of multi-material design had long since become established in ex-

pert circles. We were familiar with lightweight steel and aluminium designs, the Audi A2 and A8 had long since been in series production and aluminium solutions are already being used by other competitors. As early as 2002, Volkswagen's "one-litre car" also demonstrated intelligent lightweight multi-material design solutions. Nevertheless, many issues were still unclear concerning the potential of multi-material design in large-volume lightweight body construction. SLC has delivered important new findings.

ATZ Let us consider the main materials aluminium and steel, the development of which has been mutually advanced by the project. Which potentials do you see for these materials?

Goede I wouldn't actually relate these developments to a certain material. Continuous material developments are the most important thing for progress in all areas. Metallurgists have been setting the course of development for many years and that will also continue with regard to aluminium, steel or magnesium.

ATZ You also mentioned magnesium. Aren't there still plenty of issues to be addressed with regard to this material?

Goede As far as large-scale series production is concerned, it will still remain very difficult to employ magnesium structures in body construction over the next few years. Nevertheless, we decided to show with the SLC body that it makes sense to continue working on it. Magnesium still has a significant lightweight design advantage over aluminium. However, magnesium is very susceptible to corrosion when used for outer body panels and areas subject to moisture, and therefore requires reliable surface protection systems. No new solutions were developed for this problem in the SLC project.

Laue From a technical point of view, the vehicle interior is more interesting for magnesium applications. Possibilities include the use of magnesium in selected seat structure components or for mounting structures. Applications for higher production volumes are still ruled out in particular due to the high additional costs involved.

Dr.-Ing. Dipl.-Chem. Martin Goede

studied engineering chemistry and mechanical engineering at the University of Hannover (1986 to 1994). From 1992 to 2001, he worked at the Laser-Zentrum Hannover, where he was Head of the Materials and Production Technology division for many years. In 1999, he completed his doctorate at the University of Hannover, Faculty of Mechanical Engineering. He joined Volkswagen AG in 2002. Since 2005, he has been Head of Lightweight Vehicle Design and CO₂ Concepts in Group Research at Volkswagen AG in Wolfsburg.

Dipl.-Ing. (FH) Tino Laue

joined Volkswagen AG in 2001, having previously studied mechanical engineering at the University of Applied Sciences Braunschweig-Wolfenbüttel. Since 2005, he has worked in Group Research at Volkswagen AG in the Vehicle Technology division and has been Project Leader for Lightweight Multi-material Structures since 2008. **ATZ** We haven't yet spoken about plastics or composites.

Goede These material systems have in some cases already proven that they are also suitable for structural components. The strategic question is: is it also possible to produce thermoplastic and thermoset structural components in large production volumes? In the SLC project, the specified requirement was 1,000 units per day. Fibre plastic composites do not yet completely fulfil this requirement. In the SLC project, we were able to fulfil this production volume requirement for the first time with a CFRP roof cross member as a pultruded component. For 1000 units a day, cycle times of one minute are usually required. Higher process times are generally not accepted from an economic point of view.

ATZ The material mix includes different materials that have to be joined. Which trends are becoming apparent in joining technology?

Goede Adhesive bonding is the favoured joining technology for multi-material construction. Wherever materials need to be joined with clean material separation for corrosion protection reasons, adhesive bonding is an excellent technology. And as far as the quality and strength of modern structural adhesives are concerned, they can be reliably used today. In the production of the body-in-white, there is always a need for suitable lowheat and mechanical joining techniques for multi-material structures.

ATZ Customers are hardly able to experience the lightweight design progress in the product. Are there other reasons for an OEM to use lightweight construction apart from the threat of CO₂ penalties by the EU?

Goede It is indeed the case that the EU has set high penalties for those manufacturers that do not meet fleet fuel consumption limits, and these will come into force from 2012. In the first phase, 65 % of each manufacturer's newly registered cars will be used to calculate the fleet fuel consumption. From 2015, all newly registered cars will be considered. Lightweight design is an important core competence for fulfilling these and future regulations – and not only in body design.

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Laue Lightweight design will become particularly important due to the new EU legislation because the individual fleet limit value for the manufacturer (OEM) will be derived from the fleet weight of its newly registered vehicles, and the manufacturer will have to fulfil a limit of 130 g CO₂/km in the NEDC from 2012 by applying powertrain and vehicle measures. According to the EU legislation, for every 100 kg reduction in fleet weight, the limit will be reduced by 4.57 g CO₂/km. The potential for reducing fuel consumption due to lightweight construction is fundamentally higher when considering an adapted vehicle design, which represents an additional motivation for reducing vehicle weight.

ATZ But there are also other ways of reducing fuel consumption.

Goede We consider lightweight design to be one component of a comprehensive CO₂ reduction strategy. We see the greatest potentials in the area of powertrain technology, right through to electrification. As far as the vehicle is concerned, lightweight design has the greatest influence on fuel consumption, ahead of rolling resistance and aerodynamics. The decisive strategic question is which measures have the most attractive cost/benefit effect. On its own, lightweight design is not always the cheapest measure, but it initiates far-reaching secondary CO₂ reduction potentials. For that reason, lightweight design remains a strategically very important discipline in vehicle construction - also for future drive concepts.

ATZ Martin Goede, Tino Laue, thank you very much for this interview.

The interview was conducted by Ulrich Knorra.

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High-strength Aluminium Profiles for Next Generation Spaceframes

Spaceframe bodies made of aluminium have considerable potential to make cars lighter and thus more economical, because they weigh about 40 % less than conventional bodies made of sheet steel. Honsel has been developing aluminium extrusion profiles for spaceframe structures since 1992 and has been supplying them in series production since 1994. An innovative alloy developed by Honsel and Trimet will give the profiles more strength. The extrusions can be dimensioned thinner, thus saving additional weight of up to 17 %.

1 Introduction

The energy requirement of a vehicle and thus its fuel consumption are considerably affected by the vehicle's weight. Lightweight construction leads to much better fuel economy. A rule of thumb says that a weight reduction of 100 kg means a fuel saving of 0.3 l over 100 km. However, new vehicle models are generally not lighter than their predecessors. They are, in fact, heavier, particularly due to the additional system components and deformation structures resulting from higher demands regarding safety and convenience. This ever-increasing weight gain can be reversed only by means of intelligent lightweight design using innovative materials. Since the body makes up 40 % of the total weight of a vehicle, it offers the greatest potential to reduce weight while still maintaining identical performance.

Today, conventional bodies are manufactured from steel. Replacing the steel by aluminium would make a body more than 60 % lighter. However, it would no longer be rigid enough to meet today's requirements regarding crash protection and driving performance. In particular, the high degree of passive safety of today's vehicles can only be achieved by very rigid body structures that are also subject to plastic deformation. Innovative aluminium spaceframe bodies provide the solution.

A spaceframe is a frame structure made of extruded profiles and cast parts

that form the framework of the body. The body sheets are assembled onto it. These have two functions: in the first place, they provide reinforcement to the frame structure and, secondly, they give the body its actual shape. Spaceframe bodies in modern series-production vehicles are about 40 % lighter than comparable conventionally constructed bodies made of sheet steel. At the same time, they even increase body rigidity to provide optimum support for passive vehicle safety.

2 Development of the Technology

Audi is the pioneer for the large-scale use of the spaceframe design. The International Motor Show in Frankfurt (IAA) in 1993 saw the Ingolstadt-based company presenting the so-called "Audi Space Frame Concept Car", ASF. It very largely corresponded to the Audi A8 model, which in 1994 was the world's first large scale production vehicle with an aluminium body. In association with other suppliers and Audi, Honsel had already been working on its development since 1992, and has been supplying Audi with aluminium profiles for the spaceframe since 1994.

Following the Audi A8, there were further models using this technology in Volkswagen group, such as the Audi A2 and the Audi R8 as well as the Lamborghini Gallardo. But other OEMs also exploit the potential of the spaceframe

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Figure 1: In the event of a crash, aluminium profiles absorb the energy very well, thus supporting passive safety



Figure 2: The strength requirements for the body result in aluminium profiles with a complex geometry (Source: Karmann)

Lightweight Design

design. In all applications, hybrid construction has become established, using extruded profiles as well as cast and sheet parts, although the percentage of individual components in the overall body structure varies and is dependent on the production scale and the design.

3 Construction of Extruded Profiles

Aluminium profiles manufactured in an extrusion process have proven to be best as structural elements for a spaceframe. They can be produced in large numbers with very high precision and can be joined mechanically or thermally. Additionally, in spite of their high strength, the profiles deform very well when compressed, thus absorbing energy very successfully in the event of a crash, Figure 1. As a result of the thickness of the profile walls as well as the design configuration of the walls, this characteristic can be adjusted very precisely to requirements at every point of the body, Figure 2. Singlechamber and multi-chamber hollow profiles are especially suitable for these cases, as, due to their enclosed form, they have greater torsional rigidity than open sheet metal designs. Moreover, additional functionalities such as assembly elements, fastening elements or channels for electrical and hydraulic lines can be integrated very easily into the profile design.

Compared to other manufacturing processes, the dies for the extrusion process cost only a fraction of the tools for sheet metal shaping or of high pressure die casting moulds. Since the profiles are produced from the very beginning on standard dies, the manufacturing process is unchanged from the first part to the start of series production. Thus, the time between the first runs with a new extrusion design and the production ramp-up can be kept very short. In addition, the dies used for extrusion can be manufactured relatively quickly, so that design modifications of the profiles can be implemented rapidly. These advantages make extrusion profiles very interesting compared to alternative manufacturing processes.

Aluminium alloys of the so-called 6xxx series have become established as the material for spaceframe profiles. They have medium strength, can be eas-

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ily extruded and, in addition, show good resistance to corrosion. This group of alloys is widespread in many areas of use, which means that they can be recycled without difficulty. Magnesium and silicon as the main alloy elements ensure their basic strength. Additional elements make the structure fine-grained and insensitive to quenching. The composition of the aluminium alloy must correspond very precisely to the technical reference in order to fulfil all the product characteristics required.

Figure 3: Simulation of

the tool deflection

The technological requirements for modern cars are constantly increasing and so are those for aluminium profiles. There is a clear tendency towards higher strength alloys: stronger materials allow the profile walls to be made thinner, resulting in even lighter components. The profiles must still, however, be easily foldable. In the light of these contradictory demands, conventional alloys run up against the limits of their possibilities. Therefore, Honsel and Trimet jointly developed a new aluminium alloy and registered it to be patented. This new aluminium alloy is specially geared to the requirements of future spaceframe profiles. The composition of this special alloy differs from those already established on the market as it contains a certain ratio of silicon and magnesium. With this new alloy, Honsel increased the profile strength considerably. Whereas the first-generation spaceframe profiles had strengths of 220 to 260 MPa, the new material achieves strengths of more than 300 MPa. In addition, the yield strength was increased from 200 to more than 280 MPa. With these characteristics, the required crumple behaviour of the profiles becomes a particular challenge. With an A_5 elongation at fracture of 11 to 13 %, the new material shows an outstanding behaviour. In comparison with conventional alloys, it provides higher component strengths with the same wall thickness of the profiles or, at the same strength, the wall thickness can be reduced, thus allowing the component weight to be reduced by about 17 %. The new alloy from Honsel can be used very flexibly to achieve different dimensioning objectives in spaceframe development.

The production of spaceframe bodies involves a number of process stages that have to be carried out under heat, such as in cathodic immersion coating of the structures. Temperature stability is therefore of great importance for spaceframe extrusions and component strength must not decrease during treatment. Honsel proved by research that the high strength of the new alloy is fully retained during these process stages. A two-hour cathodic immersion coating process at a temperature of 200 °C is no problem at all.



4 Design of the Profiles

Aluminium profiles for spaceframe bodies are generally single-chamber and multi-chamber cavity profiles with halfcircumferences of up to 250 mm. The wall thicknesses are between 1.8 and 3.0 mm. In general, the profiles are designed by using FEM programs. Compiling these typically involves "frameworktype" designs with nodes at which three or more internal webs meet. The profiles are developed to grant optimum strength and rigidity in the spaceframe composite construction. To achieve this, the walls of the component around the nodes that are exposed to a higher load are therefore thicker than the areas that are subject to lower load. The shape of these profiles makes them difficult to extrude. The different material thickness leads to a non-uniform material flow in the extrusion die, which can only be managed with a great deal of experience and expertise. This applies especially to alloys that have higher strengths and lower extrudability.

Moreover, the mandrels of the extrusion die that form the cavities of a profile are subject to very great loading as a result of the unevenly flowing material. In this case, the simulation programs that allow the material flow in the tool as well as the die load to be calculated are very useful. The deflection of the tool and thus the dimensional accuracy of the profiles can also be estimated from this loading, **Figure 3**. Although the programs are not yet fully developed, the simulations allow initial estimates of the possible extrusion result. Thus, development time and tool costs can be further reduced.

5 Manufacturing

During the extrusion process, heated aluminium billets made from the selected alloy are extruded through the die. In this way, the profile with the desired shape is produced and can be finally cut to the required length. The billets are produced in the "direct chill" casting process. Before being extruded, they must be heated to temperatures of more than 500 °C in the homogenization annealing process. This has two advantages: on one hand, an optimum microstructure for the alloy is achieved. On the other hand, differences in the concentration of the alloy elements, which might appear during the casting and solidifying process, are compensated for. For extrusion, the billets are heated up to more than 430 °C and pushed through the tool, which is



also hot. Due to deformation work and friction, the aluminium is heated up further, **Figure 4**. In this process, it has to reach the necessary temperature for solution annealing. This is the precondition for the profile to reach its maximum strength and for the potential of the aluminium alloy to be fully exploited.

To ensure uniform material characteristics of the finished profile over its entire length, Honsel manufactures the spaceframe profiles by isothermal extrusion. Therefore, the temperature of the profile has to be maintained at a uniform level throughout the entire extrusion process. The profiles may be cooled using air or, alternatively, water, depending on the type of the alloy. In the case of water cooling, Honsel uses a special cooling device that prevents the profiles from warping and becoming unusable when they are cooled very rapidly. After being cooled, the profiles are cut to the required length and, depending on their application, are bent or formed in the hydroforming process. The extruded aluminium profiles receive their actual strength in the final heat treatment, during which the agehardening temperatures must be observed very strictly. The finished profiles then are delivered ready-to-install.

6 Summary and Prospects

In order to increase the lightweight construction potential of spaceframe bodies to the maximum, all stages in the manufacturing process of the product - from the selection of materials and design of components through to production must be optimized to their application. This requires a great deal of expertise, which Honsel has gained in a way that hardly any other company has. As a further development of the spaceframe body profiles, which have been successfully introduced onto the market, Honsel now supplies structured profiles made of a new alloy which was developed together with Trimet. Thanks to the outstanding specific characteristics of the innovative aluminium material, the profiles can be about 17 % lighter or can be even stronger, depending on the requirements for the components. There is already a first prototype order, which means that a series launch in 2010 is realistic.



Wet Starting Clutch for Automatic Transmissions with Innovative Cooling Approach

Fuel consumption, comfort and dynamics more and more depend on the characteristics of starting device and automatic transmission. That is why ZF Sachs developed a new wet starting clutch. An innovative cooling principle allows for a compact design and the transfer of high input torques. The first series production application was realized for the "AMG Speedshift MCT", the seven-speed automatic transmission of the Mercedes-Benz SL 63 AMG. But also in front-transverse transmissions, this new type of clutch creates additional space for enhanced torsional vibration dampers – another option to reduce fuel consumption.

1 Basic Concept

It was the basic idea for the Hydrodynamically Cooled Clutch (HCC) to combine the advantages of a hydrodynamic torque converter and a wet clutch. The first series production application of the HCC was realized in the "AMG Speedshift MCT", the seven-speed sports transmission of the Mercedes-Benz SL 63 AMG [1].

Over the last 60 years, hydrodynamic starting devices, the hydraulic clutch based on the operating principle of Föttinger, and the torque converter, have become indispensable in the world of transmissions for all types of vehicle due to their high power density and their comfortable, vibration-decoupling torque transmission. One of the most important advantages of the hydrodynamic operating principle - the total lack of wear - is often forgotten in the process. There needs to be no grinding between the components during the starting process; the impulse exchange of the impellers through the oil transfers the incidental power loss as smoothly as possible to the oil. Wet clutches must, however, be carefully designed and applied within their various limitations in order to avoid incurring problems regarding comfort and service life resulting from damaged friction linings and "cracked" oils along with the associated decreasing friction coefficient characteristics, Figure 1.

Despite more and more improvements, the converter in its modern design with a lock-up clutch requires radial installation space between the engine and the transmission, which is meanwhile also needed by the electric motors for transmission hybridization. In addition, the mass moment of inertia of a converter cannot be reduced arbitrarily. These conditions are not desirable for a sports transmission where the engine should run up to speed quickly, and gear-changing times must be short. But it is especially the strategy compatibility, that means the ability to call up different start characteristics as required, that is limited with today's standard converters.

In summary, the aim was to match the thermal and mechanical robustness of the hydrodynamic power transfer with the strategy compatibility and the radially small, compact design of a wet clutch.

2 Operating Principle

Derived from the Euler turbine equation for hydrodynamic torque

$$M_{Hvd} \sim \rho \cdot \dot{V} \cdot \Delta (r \cdot c_{II}) \qquad \text{Eq. (1)}$$

the law of similarity is derived for the torque converter for the speed n and the hydraulic diameter D:

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$M_{_{Hyd}} \sim n^2 \cdot D^5$	Eq. (2)
$\dot{V}_{_{Hyd}} \sim n \cdot D^3$	Eq. (3)

Thus it was the objective to pair the converter with a wet clutch in order to keep the hydrodynamic torque M_{Hyd} as small as possible, since it restricts the desired controllability of torque transfer, and, on the other hand, to still obtain the largest possible volume flow \dot{V}_{Hyd} that could be utilized for cooling the wet clutch. This apparent contradiction, that $M \sim \dot{V}$ (see Eq. (1), for D = const.), is, fortunately, not one. Inordinate volume flows occur with torque converters for impulse exchange for torque transmission that are certainly not required on this scale for cooling a wet



Figure 1: Characteristics of torque converters and wet clutches

clutch, so that a reduction in the size of the hydrodynamics should be possible if they are only required for cooling. This is shown by a numerical example from the new generation of torque converter (TC) for the ZF automatic transmission 8HP [6].

If the assumption is made that present-day wet clutches, all of which are dependent on the performance of the external cooling pump/hydraulics, must cope with up to 30 l/min, the cooling power of a hydrodynamic converter with a volume flow of 10,000 l/min, Figure 2, would bring any wet clutch to "freezing point". Thermal damage to oil or linings would be a thing of the past; the capacity of this clutch would barely impose a constraint on this application. In future, the expectation for conventionally designed wet clutches is more likely to be for less cooling oil. Since the transmission pump required here partly determines the total efficiency of the transmission, the pump is more likely to be designed smaller in the future. If we assume that a volume flow smaller by a factor of 33, that means approximately 300 l/min, still has sufficient cooling potential under "stall" conditions (engine speed 3000 rpm, stationary vehicle) - after all, it is still a factor of 10 higher than state-of-the-art wet clutches. This results in the following diameter for a new hydraulic circuit derived from Eq. (3):

$$D_{Neu} = D_{Alt} \cdot \sqrt[3]{\vec{V}_{Neu} | \vec{V}_{Alt}} =$$

 $235 \text{ mm} \cdot \sqrt[3]{300/10.0000} = 75 \text{ mm}$ Eq. (4)

With this diameter the former hydrodynamic torque of 540 Nm would clearly collapse as visible in Eq. (2):

 $M_{_{Neu}} = M_{_{Alt}} \cdot (D_{_{Neu}}/D_{_{Alt}})^5 =$ Eq. (5) 540 Nm · (75 mm/235 mm)⁵ = 1,8 Nm

This initial computational result shows that a very small diameter still allows for the realization of a high volume flow, despite the very small hydrodynamic torque, which is likewise desirable. Now the challenge is to find a design that directs this volume flow over the friction surfaces of a wet clutch where the cooling is required. A very sophisticated approach is to place the plate kit of a wet clutch into a radially-sectioned pump or



Figure 2: Performance data and volume flow \dot{V} of the newest torque converter (TC) generation in the ZF automatic transmission 8HP



Figure 3: Crossing of TC and wet clutch – first ideas for a hybridization

turbine of a converter. Considering the so-called Euler clutch with radial cascades rather than the axially-oriented cascades (as with a converter and hydroclutch) [7], elements of a simpler solution are recognizable: The disk-shaped surfaces, which limit the blade channels, can transmit a friction torque like a wet clutch if they are bonded with a lining and an axially-directed force is applied. TC and wet clutch are "crossed", **Figure 3**.

In a next evolutionary step, the socalled pump and turbine plates were designed with meander-shaped steel disks that form radial channels and which are partially bonded using lining pads. The pump plates, like the converter pump, are directly connected with the engine, and radially pump out the oil in the filled HCC, **Figure 4**. The oil subsequently reaches the turbine plates that are directly hung on the transmission input shaft through deflection gaps, that means openings in the internal and external flow path. This occurs in a similar way to a hydrodynamic clutch until the pump and the turbine rotate at the same speeds. Only then does the circulating volume flow, which also cools the friction surfaces, collapse to zero. The resulting cooling oil volume flow is therefore appropriately at its peak when starting and remains present until the starting process is completed.

The last evolutionary step in the plate design was ultimately a single-side plate with radial slots and reliefs in the steel support on the external and internal flow paths providing deflection of the volume flow in order to achieve a simple design capable of manufacture using current manufacturing systems. The pump and turbine plates alternate, so that a six-plate design produces three small hydraulic clutches connected in parallel. These are then pressed together or unloaded using a piston controlled by a third line, comparable with the converter clutch of a triple-line converter. In



Figure 4: Crossing of TC and wet clutch – design of serial steel plates



Figure 5: Comparison of thermal efficiency of wet clutch, torque converter (TC) and HCC

order to be able to transport the power losses at start-up from the HCC, just as with the converter, an external cooling circuit is superimposed on the internal circuit. However, this is dimensioned essentially in the same way as current multi-ratio transmissions, so that the transmission pump need not be changed.

Due to its high velocity, the internal volume flow affords an almost ideal heat transfer from the steel of the tribological contact to the oil, so that even at high power the temperature of the steel barely exceeds that of the oil, thereby avoiding, for example hot spots that could result in lining or oil damage. Thus, thermal robustness is attainable that is closer to that of the converter than any established wet clutches until now, **Figure 5**.

For a full-load start with a conventional wet clutch the flowing oil only heats up moderately with regard to the imported power losses, that means a lot of this power leads to considerable heating of the steel plate supports. In contrast, significantly higher oil outlet temperatures are measured with the HCC, evidence that the imported power loss is rapidly removed and only heats up the plates to a small degree. This principle is also used to call up sports functions with very low peak temperatures, such as the race start with the Mercedes-Benz SL 63 AMG, **Figure 6**.

3 First Series Application

The HCC concept described was ultimately realized in two variants, in a six-plate variant providing up to 700 Nm (HCC185-6), in series production since April 2008, **Figure 7**. It is applied at the same hardware interfaces in the direction of the engine and transmission at which the torque converter would otherwise sit (plug and play). The application of a four-steel plate or a eightsteel plate variant with respective torques is also possible, **Figure 8**. Since a wet clutch cannot be opened in an emergency in response to vibration problems, as is possible with a converter, good dampers are required. A two-stage torsional damper was selected. Comparable with a turbine torsional damper for a converter, it is located with its stiffness directly in front of the transmission input shaft and thus offers good prerequisites for vibration decoupling. It was possible to select a radial, internally-located damper that is, for reasons of friction and inertial mass, ideal.

The value $\dot{V}_{Hyd, Stall}$ is of the same order of magnitude for both clutches as in the numerical example given in Chapter 2 and therefore exceeds the existing wet clutches ten times in terms of cooling power. The height of the channels (1 mm) corresponds to a still reasonable lining thickness. The high surface stress of 4 N/mm² of the friction lining with maximum torque capacity, which is considerably higher than the established values for dual clutches, sets a benchmark. The high figures are only due to the cooling principle, as the lining used is conventional. In addition to the strategic capability, the second main objective of the transmission development was to reduce the mass moment of inertia when turning a multi-ratio transmission into a thoroughbred sports transmission. With a reduction of more than 50 % compared to the converter, **Figure 9**, this aim was achieved and the preconditions were created for short gearshift times.

A further, technical feature of the HCC is the drag torque present in the clutch, for example at idling speed. The cooling ,lives' from the fact that the clutch is permanently 100 % filled with oil. On the other hand this means that, even if the clutch is not actuated, drag torques induced by shear forces from the oil are created between the plate pairs. Due to the small diameter of the HCC however, these are significantly smaller than for torque converters, not only at operating temperature but also at very low temperatures. But they are still greater than in totally refillable wet dual clutches.

4 Further Application Possibilities

With the new product HCC, presented here, vehicle manufacturers must decide for sporty applications whether they want to offer an already available multi-ratio transmission with HCC or a dual clutch transmission. With the HCC they can draw on identical basic transmissions to save costs in contrast to the development of a maybe completely new dual clutch transmission. Besides the premium sport transmission segment there are further application scenarios in the driveline hybridization. Thanks to its compact design, the HCC can provide sufficient installation space for the electric motor in the driveline.

The application of HCC in combination with a multi-ratio transmission creates enormous advantages in fronttransverse applications, too. In these applications, space for the starting element is very limited. But here too, very powerful assemblies will be required for vibration decoupling, among other because of the engines used. The application of HCC allows for the absence of hydrodynamic devices and increased space for the installation of vibration decoupling elements. Such a starting system is called HCN in order to hint at the fact that HCN derives from HCC, on the other hand to demonstrate the aim of the starting element (N for NVH - noise, vibration, harshness) to reduce torsional vibrations.

In **Figure 10** different starting elements are compared in terms of their space requirements and available space for vibration decoupling and torque converter. Comparing HCN and front-transverse torque converters – both operate in the same space – the space potential for vibration decoupling elements through deletion of devices for hydrodynamics becomes obvious.

In Figure 11 the comparison between starting elements in the hill-holding mode (uphill gradient of 12 %, 2.7 t vehicle mass) is extended based on simulation results. One can see clearly that the thermal performance of HCN is comparable to the performance of HCC. This result is explained by the internal coolant flow rate which is comparable to that of the HCC. It is only the hydrodynamic elements located in the torque converter that create more efficiency, which is no longer required to this extent in modern applications, though. Dual clutches have a relatively poor thermal performance because of the



Time [s] Figure 6: Comparison of temperature of a typical wet clutch to the HCC

Figure 7: Design of the series clutch HCC185-6 in six-plate variant for 700 Nm



HCC	185-6	185-8
Hydrodynamic diameter D	185 mm	185 mm
Number of friction surfaces/ plates	6	8
Max. net specific friction lining pressure	4 N/mm ^a	4 N/mm ¹
M _{trophs, max}	700 Nm	1000 Nm
Max. engine speed	7500 rpm	7600 rpm
Race start speed	4000 rpm	4000 rpm
Max. power input at start	175 kW	228 kW
$\hat{V}_{\mu_{0},t,hut}$ (at 3000 rpm)	300 l/min	340 l/min
Total inertia (kom ²)	0.0823	0.083

Figure 8: Performance data of the types 185-6 and 185-8 with six respectively eight plates in the HCC modular design principle

	ZF Sachs W270 (series)	ZF Sachs W300 (etd)	External TC W272	Daimler W270	ZF Sachs HCC 185-8
Engine torque [Nm]	700	1000	750	700	1000
Inertia (kgm²)	0.179	0.29	0.21	0.168	0.083
Δ in %	+6	+72	+25	Base	-50
Mass [kg]	15.9	22.8	19.0	16.5	13.5
Δ in %	-4	+ 38	+15	Base	-20
\longrightarrow		HCC: - 50 %	inertia		
\longrightarrow					

Figure 9: Torque converters TC (W270, W300, TC W272, W270) in comparison to HCC 185-8 regarding mass moments of inertia (with oil)



Istallation space used for torque transfer





Figure 11: Comparison of starting devices in hill-holding mode

missing internal cooling circuits. As comparisons show, the HCC effect allows for more installation space and thus a significant development leap in vibration decoupling and fuel savings, also in front-transverse applications.

5 Summary

The first series production application of the HCC by ZF Sachs was realized in the "AMG Speedshift MCT", the seven-speed sports transmission of the Mercedes-Benz SL 63 AMG as front-longitudinal application. An innovative cooling principle allows for a compact design and the transfer of high input torques. This starting element is available as a six-plate variant providing up to 700 Nm (HCC185-6) and a eight-plate variant for 1000 Nm maximum input torque (HCC185-8).

The application of HCC in combination with an torque converter automatic transmission creates enormous advantages also in front-transverse applications. In these applications, space for the starting element is very limited. The application of HCC allows for the absence of hydrodynamic devices and increased space for the installation of vibration decoupling elements against NVH.

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FEA-optimized Lightweight Hollow Shafts for the Transmission

When it comes to transmissions, considerable weight savings may be made by using hollow transmission shafts. Hirschvogel achieved success in transferring the same high loads in spite of less material use. These forged lightweight shafts may be used both in manual transmissions as well as in axle drives and transfer gearboxes of passenger cars or trucks.

The Authors

1 Introduction

Currently there are three objectives when optimizing transmission components. These are to decrease CO_2 emissions, to reduce costs and to retain good mechanical properties. The reduction in CO_2 emissions is achieved primarily by lightweight design measures, as the lower the vehicle weight, the lower the fuel consumption. When it comes to transmissions, considerable weight savings may be made by using hollow transmission shafts. These lighter parts still need to transfer the same high loads, however.

In order to keep the mechanical properties at the high level required, stiffness and strength analyses need to be carried out using FEA when designing the hollow geometry. Besides weight reduction the cost factor also needs to be considered. To achieve lower costs it is essential to reduce bar material usage and to design the process chain in a skillful way [1].

2 Lightweight Design

Hollow lightweight shafts, Figure 1, may be used both in manual transmissions as well as in axle drives and transfer gearboxes. Particularly in the case of bevel gear shafts hollow design allows a considerable weight reduction of over 1 kg per shaft in passenger cars without compromising strength. Heavy shafts for commercial vehicles yield material savings of between 4 and 6 kg. Halfshafts, too, may be produced with a hollow geometry if the available space allows such a design. Front wheel drives require a long and a short halfshaft. The design of the long shaft, with a length of approximately 600 mm, provides excellent opportunities for reducing weight while increasing torsional stiffness.

Production of lightweight shafts often requires a combination of special manufacturing processes such as deephole drilling and swaging. The flange with intricate geometry is produced by hot forging. In some applications shafts



Figure 1: Types of hollow shafts for transmission applications



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Machined part, ready-to-install



Figure 2: Cost-optimized production process for a disk carrier – from the warm forged raw part (left) over the cold forged part with gearing (center) to the ready to install machined part (right)

with closed ends are needed. This requirement can be met with a two-piece joined part. The production costs in this case increase to such a considerable extent, however, that the use of a plug represents a possible alternative.

3 Cost Reduction

It is already apparent from these initial examples that the cost situation in the case of hollow shafts needs to be viewed with a critical eye. Producing the hollow space by means of drilling, forging or by tube rolling in steelworks represents an additional process step involving extra costs. In order to reduce the costs, it is therefore important to minimize the volume of material used on the one hand and to consistently exploit the benefits in the process chain on the other. Forging, in particular, allows additional geometrical elements to be integrated into the forming process without additional costs.

Figure 2 shows a cost-optimized disk carrier with shaft and internal splines. Originally this component consisted of three individual pieces that were welded together. Design optimizations resulted in a single-piece forged design. The omission of the joining process as well as of the cutting operation to produce the



Figure 3: FEA forging simulation with excellent forged part (right)

splines or gearing led to a significant reduction in production costs. As strain hardening occurs when forging the splines, the target strength of the disk splines is achieved without the need for expensive heat treatment.

When producing such complicated dimensionally accurate geometrical elements such as splines or teeth for lamellae, the forging quality is monitored and optimized in advance using FEA material flow simulations. **Figure 3** shows the forging of a spline with and without process optimization. On the left it may be seen that, during the production of splines, material is pushed up, leading to a disruption of the fiber flow and a reduction in part quality. On the right of Figure 3, the simulation result of the zero-defect forged part is shown.

4 Design Optimization by FEA

Prior to material flow optimization, the part geometry is optimally designed using linear-elastic FEA analyses. When carrying out part design, good mechanical properties need to be achieved while at the same time attaining reductions in weight and in production costs.

In **Figure 4**, left, the classic geometry of an intermediate shaft is shown. At a torsional load of 2400 Nm, a maximum equivalent stress of 690 MPa and a maximum torsion of 0.65 mm occur. The goal of optimization efforts is to achieve higher strength at the same load. After checking the space available, it may be possi-



Figure 4: Design optimization of an intermediate shaft into optimized design (right)



Figure 5: Weight optimization of an axle drive shaft of 20 % or 500 g

ble to enlarge the outer diameter of the shaft. In order to limit increases in weight, the inner hollow space also needs to be extended, that is the wall thickness needs to be reduced. The optimized design is shown in Figure 4, right. It demonstrates lower stress values of a maximum of 500 MPa and torsional distortion of below 0.45 mm. Furthermore, a weight reduction of 13.6 % is achieved and ultimately also a decrease in production costs, as the machining efforts on the outside are lower, and the deep-hole drilling on the inside is omitted.

A similar case can be described in the example axle drive shaft. This drive shaft is driven on the left flange via a surrounding ring gear that has been welded on and subjected to a torque of 2000 Nm up to the right spline. Here, too, the space limitations need to be defined at the start of the design optimization process, as the enhanced part geometry generally leads to a reduction in wall thickness and to an enlargement of the outer diameter of the shaft.

Figure 5 shows the FEA results of the stiffness/strength analyses for the classic design (left) of the axle drive shaft and the weight-optimized geometry (right). The highest load is generated on the spline. However, the diameter and the wall thickness cannot be varied here due to reasons of packaging. The bearing diameters, too, remain unchanged. Variable design can be achieved for the inner contour and the wall thickness between the bearing and the ring gear seat.

In the classic design the wall thickness beneath the bearing seat is barely subjected to load and is thus overdimensioned. In the weight-optimized geometry, this wall thickness is reduced and designed appropriate to load, so that noncritical stresses of a maximum of 250 MPa are generated. Up to the ring gear seat, the space available is fully exploited and the shaft contour has grown radially. This leads to a reduction in stress to below 120 MPa. Theoretically the wall thickness could thus be reduced even further in this area. The production process renders this impossible, however. The hollow space cannot be produced efficiently using cutting processes. Such a contour can only be generated using forging. The main advantage of the optimized geometry is the reduction in part weight amounting to 20 % or 500 g.

5 Summary

In the examples Hirschvogel outlined that transmission shafts hold considerable optimization potential with respect to weight and costs, without the need to compromise the good mechanical properties of the part. Forging, deep-hole drilling and swaging lead to dimensionally accurate hollow lightweight shafts for cars and trucks.

Such optimized designs need to be defined jointly by the user and the supplier at the earliest possible development stage. This is because any changes made at a later point – following production release – are mostly associated with high costs. Only if the part design, the material and the production process are harmonized comprehensive optimization measures can be achieved. In order to develop such optimized products at an early stage, the Hirschvogel Automotive Group can assist its customers with modern development tools, experienced employees and innovative ideas across the globe.

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Electro-hydraulic Steering Systems for Light Commercial Vehicles

In 2007 the average CO_2 emission of light commercial vehicles was approximately 203 grams per kilometer. As part of its overall European strategy, the EU environment commission is planning to drastically reduce the carbon dioxide emissions from delivery vans, mini busses and trucks. Targets of 175 g in 2014 – decreasing to 135 g in 2020 could also mean additional costs of several thousand Euros per vehicle. TRW's high performance electro-hydraulic steering systems are able to make a cost effective value contribution to achieve the overall target of reduced CO_2 emissions.

1 Introduction

Electrically Powered Hydraulic Steering Systems (EPHS) have successfully competed in the market for approximately ten years. The application of EPHS has thus far been universally applied - having started in compact cars - and following the development of high power motorpump-units continued in luxury class vehicles and sport-utility vehicles (SUV). Electro-hydraulic steering systems consist of a so-called motor-pump-unit (MPU) which can modularly be combined with a steering gear, Figure 1. The motor-pumpunit comprises a hydraulic part with an outer gear pump, a resonator with combined check and pressure relief valve and an electric motor with ECU. The motor is a brushless permanent magnetic synchronous machine which is controlled without Hall sensors (sensorless control). Starting at a stand-by speed of 750/min the motor achieves a maximum speed of 6000/min (according to 12 l/min) within less than 100 ms. Therefore, low energy consumption (stand by speed for straight ahead driving) und high dynamic (avoidance maneuver, fast steering) can be combined [1]. The motor-pump-unit is controlled via vehicle CAN. For activation, a signal from the power train is used. For example, this can be information which represents a stable operation of the combustion engine or which indicates the general driving readiness - something which is realized in Hybrid Electric Vehicles, for example. The steering map which provides the speed demand of the motor-pump-unit and thus the steering assist as a function of different variables usually makes use of vehicle speed and steering rate. It is possible to use further parameters for the control of the steering assist (for example the vehicle's load condition [2] or the steering angle (4-D map)). Further functions concerning energy, comfort and self protection are listed in extracts. The most powerful system with a hydraulic output power of 1000 W currently represents the highest power limit of electric steering systems on a 12 V basis technically realised today. Due to the required high electrical input current of approximately 115 A, the thermal layout of motor and ECU is of high importance. For the driver, the question is how long they can use the system under

high loads (number of consecutive high load parking cycles) and, respectively, how long the system can remain in endlock condition before a thermal protection mode is activated (critical time). The MPU has a special design using a wet running motor, i. e. the hydraulic fluid is used for the cooling of the windings and the ECU. Compared to a dry running variant, the critical time can be doubled. The effect results from the improvement of the convective heat transport (approx. factor 100 compared to air) and also from the additional thermal mass (thermal capacity of the hydraulic fluid). The hydraulic steering gear includes a hydraulic valve which is designed for low volume flows (e.g. 3.5 l/min) and the actual hydraulic cylinder. In contrast to pure hydraulic power steering, an oil cooler is no longer required because the system is designed to be energy efficient and provides power only on demand (small stand by volume flow, no internal pump volume flow, steering map control). The normal operating temperature is approx. 40 to 50 °C and therefore is significantly lower than in conventional hydraulic steering systems. This increases the system's reliability which especially concerns the durability of elastomers such as sealing elements [3]. With a temperature decrease of 80 °C to 50 °C, the endurance of static sealings will increase five to ten times, for example.

2 Target Vehicles and CO₂ Regulations

Since smaller commercial vehicles are directly derived from passenger cars and due to the fact that electro-hydraulic steering systems are already established, they will not be considered as target vehicles in this article. New possible applications arise from heavier vehicles up to about 3.5 t GVW. For these vehicles, the two most powerful motorpump-units 89-C (890 W) and 100-C (1000 W) which are suitable for up to about 18 kN rack force come into consideration. Further performance data is shown in Table 1 in table form. The legislative objectives describe the achievable CO₂ emissions as being linear dependent on the utility value of the vehicles. For the utility value the vehicle weight

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Steering



Figure 1: System architecture Electrically Powered Hydraulic Steering

is considered which correlates to the CO_2 emission [4]. For an average new vehicle fleet of an OEM registered in the EU, the following CO_2 targets for a reference weight (weight average for the whole of vehicles of all OEMs) apply:

- passenger car legislation (M1): from 2012: 130 g/km, from 2020: 95 g/km
- light Commercial Vehicles legislation proposal (N1, N2, M2 with a reference weight smaller than 2610 kg): from 2014: 175 g/km, from 2020: 135 g/km

will be required.

Light Commercial Vehicles are a subset of vehicle class M (passenger cars) and also N (commercial vehicles) according to their registration [5]. In class N over 85 % are represented, but depending on the OEM the share can also be significantly smaller, e.g. in case specific models are primarily registered as passenger cars. Therefore, light commercial vehicles will not only be subject to the Europe-wide directive for the CO_2 emission of passenger cars but

presumably they will also be subject to the legislation for light commercial vehicles [6] which is being prepared and refers to the regulation for passenger cars. When considering the background of an average CO_2 reduction target of 25 g/km and with the technical boundaries (especially the high percentage of diesel engines and the need for robust solutions which are proven in mass production), the challenge becomes apparent.

3 CO, Reduction

With the help of a model calculation, the impact of ancillary units such as the power steering system on the energy consumption should be investigated. For this, a balance of power under consideration of all resistances and the combustion engine is set up [7], Figure 2. An arbitrary vehicle speed is chosen as the input signal which means a certain gear selection and thus a combustion engine speed nCrank. The driving resistances, ie. the rolling resistance and the aerodynamic resistance, are considered as well as the power drain of the ancillary units. With the efficiencies involved (e.g. generator, belt drive, etc.) the balance of power is set up so that the current operating point (speed, torque) of the combustion engine is found and the input power and the fuel supply per time interval can be calculated. By calculating the difference of two trials - one with installed hydraulic pump (HPS) and the other one with electro-hydraulic power steering (EPHS), the energy saving potential can be identified. Figure 3 shows the reduction of fuel consumption of the electro-hydraulic power steering system in comparison to the hydraulic power steering system as a function of vehicle speed. As further reference points, the calculated values for a driving cycle are shown including a vehicle speed profile.

In addition to these calculations, various light commercial vehicles with diesel engines (3.5 t) were measured on a roller dynamometer test bench supporting the simulation results. The average value for the NEDC revealed a potential saving of 0.3 to 0.4 l/100 km – and for a city cycle a difference of approx. 1 l/100 km was reported. Table 1: New target vehicle group for Electrically Powered Hydraulic Steering

Target Vehicles		
Max. Kerb Weight	2200 kg	2500 kg
Max. Gross Vehicle Weight	3.0 t	3.5 t
Max. Vehicle Payload	1000 kg	1500 kg
Max. Loading Volume	9,3 m ³	17 m³
Max. Loading Volume	1575 kg	1800 kg
Typical Diesel Engine	2.0 I / 84 kW	2.5 l / 120 kW
Typical CO ₂ Emission	220 g CO ₂ /km	260 g CO ₂ /km
EPHS	89-C	100-C
Nom. Hydr. Output Power	890 W	1000 W
Max. Pressure / Max. Flow	128 bar / 10.3 l/min	128 bar / 12.0 l/min
Max. Current / Standby Current	< 98 A / < 2.5 A	< 115 A / < 2.5 A
Nom. Voltage	13.5 V	13.5 V
Max. Assist Force	14,5 kN	18 kN
Force at 540 °/s & 50 mm/rev	10,9 kN	11,6 kN

4 Value Proposition

An improvement of the CO_2 emissions (and the fuel consumption respectively) can be achieved by the implementation of various technologies. Among these, there are typically modifications to the power train, aerodynamic improvements or the reduction of friction [8]. Looking at the cost-benefit ratio of single technologies, electro-hydraulic steering systems can be found on the first ranks, **Table 2**. The derived CO_2 index reflects a standardized value which is proportional to the relation between the reduction of CO_2 emissions and costs.

The reality is more complex however, because when implementing one tech-

nology the individual value proposition will change due to the non-linear interactions. Furthermore, in order to achieve the above mentioned CO₂ reduction target it might also be required to implement more expensive (smaller index) modifications such as adjustments to the power train. This leads to a progressive cost curve, Figure 4. It is possible to make this relationship clearer by inverting and cumulating the values in Table 2: the more technologies are implemented, the steeper the cost curve becomes because with increasing CO₂ reduction, disproportionate costs arise for a constant difference of CO₂ reduction. Figure 4 exemplifies such a progressive curve



Figure 2: Calculation flow down

Steering



Figure 3: Calculated CO₂-/fuel reduction for EPHS against hydraulic power steering (HPS) under consideration of the combustion engine characteristic (2.5 | 128 kW Diesel engine, 12 l/min HPS pump vs. 100-C EPHS)

Table 2: Cost-value ratio of different technical measures

Average CO Reduction and CO Saving per Incremental Spend

Techn	Technology		CO ₂ /EUR Index
1	Reduced mechanical friction components	4.0	10
2	Improved aerodynamic	3.0	7.5
3	Elecrically Powered Hydraulic Steering	3.9	4.9
4	Downsizing engine capacity	12.5	3.5
5	Low rolling resistance tyres	3.0	2.5
6	Direct injection and lean burn	11.5	2.4
7	Variable valve actuation	6.0	1.8
8	Lightweighting	10.0	1.6
9	Stop-start	3.5	1.5
10	Stop-start with regenerative braking	7.0	1.1
11	Dual clutch transmission	4.5	0.6
12	Dual clutch transmission	7.0	0.5



which refers to [6]. The black curve comprises various packages "Pk1 to Pk3". The content of these packages are:

- package 1: low friction components, tyres, aerodynamic measures
- package 2: Package 1 + downsizing, stop/start, weight reduction
- package 3: Package 2 + automatic gearbox, regenerative brakes, further weight reduction.

By implementing package 3, a CO₂ reduction of about 36 g at costs of CRef can be achieved. These reference costs may represent several thousand euros per vehicle.

The implementation of the electro-hydraulic steering system in package 1 by keeping the technologies from package 2 leads to a different - namely more cost effective - content of package 3. This can be explained by the shift of the cost curve, indicated by the slope triangle which represents the ratio between 5.9 % of the reference costs and a CO₂ reduction of 8 g. Due to the non-linearity of the cost curve, a significant cost reduction of about 37 % of the reference value can be achieved. Point Pk3 shifts to Pk3** [9].

The grey dashed line indicates an alternative steering technology which has a better CO₂ index (3 g for 1 % of the reference costs). It can be seen that the implementation saves only 16 % however, and therefore represents a significantly worse balance.

Another value proposition results from the reduced fuel consumption. Assuming a price per liter of 1.20 Euros, the equivalent values can be directly derived from the above explained calculation results. These add up to approximately 180 Euros per year for inner city driving modes (assuming 20,000 km/year) or 270 Euros for a transit haulage modes (70,000 km/year in outer city modes).

5 Summary

per vehicle to achieve

CO₂-target - holistic

value consideration

With its electro-hydraulic high power motor-pump-units up to 1000 W hydraulic output power, TRW offers solutions which are proven in mass production and can realize high rack forces up to about 18 kN if combined with standardized hydraulic steering gears. Based on an average emission of about 200 g/km, a CO₂ saving of about 4 % can be achieved which already amounts to one third of the required efforts that will likely be mandated in the future. Therefore, this application is very eligible for light commercial vehicles up to about 3.5 t GVW.

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Steering



The Next Generation Park Assist Systems Development Steps, Studies and Trends

Fundamental principles of park assist systems have not changed significantly since the first generation: They inform the driver about distances between close objects during the parking manoeuvre. Valeo has played the role of an outrider and introduced the first parking assistance system based on ultrasonic technology in 1991 in the BMW 7-Series. In the following the development steps, market studies, customer wishes for future parking systems and their technological realisation are being described.

1 Preface

Considering the improvements which took place in today's vehicles compared with the previous versions, focus was put on driver security, environmental friendliness, driving dynamics, convenience, etc. As a result only few driving tasks became more complex during all these optimisations; parking and manoeuvring is one of them. Making vehicles more aerodynamic had a negative impact on their all-round visibility especially to the back of the car. Bumpers are no longer pure functional extension but also styling elements now. At the same time, free parking spots are hard to find and if you are in a lucky situation that you have found one, they are very small. Without a park assist system an accident-free parking has become very challenging, at least if you briskly want to complete the manoeuvre.

Park assist systems based on ultrasonic technology and providing the driver with optical and/or acoustic information about the distance between his vehicle (bumper) and objects in its path were introduced in 1991 by BMW and ITT Automotive (today Valeo) in the 7-Series (E32). At first they were considered options for luxury models at premium OEMs. Several years passed before such assistance systems won recognition on a broader scale, **Figure 1**. Since the year 2000 more and more vehicles in all market segments are offered with park assist systems; in parallel the equipment rate has also increased. frequency allocation (to reach a comparable distance resolution radar sensors need a frequency bandwidth of 5 GHz) and comparatively high costs. Purely camera-based systems are expensive as well, do not provide any distance information, do not cover the vehicle's edges and do have system-immanent limits in some environment conditions.

Fundamental principles of park assist systems have not changed significantly since the first generation. They have to inform the driver about distances between close objects during the parking manoeuvre. It is hard to imagine a modern car without park assist and in some vehicle variants park assist is standard equipment already. The user gets familiar with the function and trusts in it. Consequently there is room for new, additional functions which make the parking manoeuvre even easier. A major breakthrough was the introduction of the active "Parklenkassistent" on the Volkswagen Touran in 2007. Supplier of the system called "Park4U" is Valeo. When passing a parking slot, an ultrasonic sensor measures its length and depth. If the parking slot is found sufficient in size, the driver can initiate a semi-autonomous parking process. Based on the slot dimensions and vehicle position, the slightly modified park assist ECU calculates the optimal parking trajectory and takes control of the steering during the parking manoeuvre. The driver operates accelerator, brake and

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when applicable the clutch pedal in the usual fashion, determining the vehicle's direction and speed. Therefore he remains in control during the complete manoeuvre. He can for example override the system at any time and end the automatic

2 Development Steps of Today's Park Assist Systems

2.1 Park Assist Systems

Park assist systems which can be found on the market today have passed several evolution steps. Valeo's ultrasonic park assist is currently into its fifth generation. Targets for the continuous improvements were "better", "smaller", "more beautiful" (more elegant integration in the bumper) and "more cost effective". The trend continues permanently. The ultrasonic time-of-flight measurement has established itself as the preferred technology due to the fact that it offers the best compromise of sensor signal quality, robustness and costs. At the moment radar-based systems fail because of



Figure 1: Market development of the ultrasonic park assist

steering by simply taking hold of the steering wheel. The well-known assistance by the park assist sensors provides additional safety and confidence which helps to build trust in the feature.

Besides the active semi-autonomous parking, other systems are offered which either inform the driver by indicating the slot length (parking space measurement) or remain passive while provide steering instructions to the driver (guided parking). Whether an active or a passive system is offered mainly depends – beside other requirements – on the availability of an adequate steering system in the vehicle.

2.2 Feedback and Customer Requests Regarding "Park4U"

The reaction of end consumers, the market and the media regarding "Park4U" is very positive. Professional media conclude consistently: "very recommendable", "really useful investment", "easy to handle". The high level of acceptance and the resulting market success for this kind of assistance have played a major role in the fact that the function was introduced in many other vehicles within a short time. By June 2009 car buyers are able to order the semi-autonomous park assistance in cars from Volkswagen (eight), Audi (three), Skoda (two), Mercedes (two) and Lancia. The function is also available in North America with Lincoln (two), Ford (two) and Mercury cars. Further brands will launch the system shortly.

Valeo frequently conducts worldwide end-user surveys and consumer clinics (involving practical experience of the system) to evaluate opinions, acceptance and readiness to pay by the end costumer. Generally speaking one can say that "ease of use" is most important to the driver. This means the function shall be simple to handle thus needs as few operation steps as possible and adapts itself to the individual driver behaviour. Furthermore it should be easy to understand, meaning the driver can perceive the information quickly and deduce the correct reaction intuitively. Related to "Park4U" it can be said that the parking manoeuvre should be finished at least as quickly as a skilled driver could do whereas that the expectation regarding the precision of the parking result deviates, depending on the perceived level of difficulty of the parking situation. Another important aspect is that



Figure 2: In- and output signals of the semi-autonomous "Parklenkassistent"



Figure 3: Functional model of the ultrasonic park assist

the parking manoeuvre must be successfully completed whenever the system reports the driver an adequate parking place. Contrary to this is the request that the system shall be able to make use of the smallest possible parking spaces while the acceptance of the fact that a specific short parking slot is not offered mainly depends on the given availability of parking slots in the certain situation. Consequently Valeo's focus for the further system development is the reduction of the required length of gap as well as improving the function for non-standard situations. A quantum leap will be the transition from the current semi-autonomous to fully autonomous systems.

3 Parking and Manoeuvring

3.1 System Architecture

Regarding to the used components the semi-autonomous park assist is based on the standard system. It utilises an extended version of the already existing ECU. "Park4U" needs just two more sensors in the corners of the front bumper and a push button in addition. However the feature generates completely new requirements regarding the system development, the vehicle integration and the functional validation. For example there is significantly more data to process, **Figure 2**, and the amount of application specific parameters is several times higher. While it is

sufficient for a normal park assist system to measure the radial distance to the next object with a precision of 10 %, "Park4U" requires a much more detailed knowledge about the environment of the vehicle. The system uses its own coordinate system (with the centre of the rear axle as point of origin) and relies on several computational models for determining the exact vehicle position (odometry).

While park assist is merely an informative system, **Figure 3**, "Park4U" includes own awareness of the situation in addition to the pure signal processing. The system must be able to interpret the sensor data according to the given situation and – if wished – to take over a part of the driver's tasks (lateral vehicle control), **Figure 4**.

3.2 Semi-autonomous Park Assist

3.2.1 System Performance

The basic task is to get into every parking slot which could be entered by a trained driver as well. Although this requirement relates to the minimal useful slot length, the assistant as well has to correctly handle complex parking situations such as slots in a curve or in a narrow road or when the space is confined by an object different from a passenger car. Sensor technology, data processing, situation modelling, trajectory calculation and vehicle odometry have to be designed accordingly.

While the first generation can make use of parking slots with a length of 1.4 m in addition to the vehicle, the current system can manage it with a length of no more than vehicle +1.1 m. Costumer studies show that many drivers would pass such a parking slot under normal conditions without making an attempt to park. Valeo sees a limit at a value of + 0.8 m, which means 40 cm in the front and 40 cm in the rear. This is done by using more sensor signals and a more intelligent analysis to get a more detailed view of the reality. The odometry will use more particularly redundant vehicle models in future which include the analysis of the signals of the wheel speed sensors at all four wheels. With the first generation one to two movements where sufficient to get into the parking space, but with a decreasing slot length additional movements are required to park the car. In case the length of the gap is just 80 cm longer than the vehicle the manoeuvre will generally consist of four to six movements. The calculated parking trajectory is getting more complex while the amount of movements depends on the size of gap, the vehicle geometry and the characteristic of the steering system. On the other hand it depends on the driving behaviour of the respective driver. The park assist must have the ability to react flexibly on different turning points between forward and backward movements. While the first generation's parking path was inflexible and consisted of predefined fix circular arcs, the next generation will react far more flexible to the given situation. As a result the parking manoeuvre will become more comfortable and natural.

The system's next generation will also introduce semi-autonomous parking for spaces perpendicular to the driving lane. In general this is realised by the already established system components whereby gap measurement, trajectory calculation and odometry had to be adapted or even developed completely new. At the moment the system can use gaps rectangular to the lane. To enhance the function to angular parking slots as well the system will require further ultrasonic sensors to collect the additional information about the environment required for this.

3.2.2 Functional Enhancements

The short term functional extensions of the current park system are primary based on modifications of the already existing software modules plus a few new modules. Beside rather invisible improvements which enable the system to park in more complex parking situations in addition to standard situations, the next step will be an assistant to leave the parking space. This will particularly make sense when the vehicle is placed in a very tight parking slot. This function is frequently requested by end-users and is in general quite similar to the parking-in function. On the basis of the available space in front and behind the car, the steering is controlled to get out of the gap with as few movements as possible. Once leaving is possible, the steering is returned to the driver. It is important to mention that this feature can be used any time, even if the vehicle has been parked manually without using of the park assist.

While during the parking manoeuvre all ten ultrasonic sensors are being used to determine distance information, for the parking slot measurement only the two sensors in the corners of the front bumper are active. This means that when passing the parking slot the normal park assist function is yet not available. As this is desirable in some situations, for example if a vehicle is parked in second row, the Valeo system will offer possibility of a simultaneous operation of gap measurement and the park assist function (concurrent mode).

A further clearly perceivable functional extension will be the introduction of brake interventions by the semi-autonomous park assistant. This will allow keeping the vehicle velocity within the speed range



Figure 4: Functional model of the semi-autonomous "Parklenkassistent"

Steering







Figure 6: Functional roadmap of park assistance

which is ideal for the steering system and prevent sudden system interventions due to an accidental exceeding of the permissible speed. Furthermore the car can be slowed down or completely stopped when getting close to the gap confinement.

Of course the last mentioned brake intervention can be used during the normal park assist function as well. A further functional extension basically independent from "Park4U" is the flank guard. Objects next to the driving path are recorded and their positions be tracked utilising the vehicle odometry when they have left the detection zone of the ultrasonic sensors. In case of any hazardous approach to this obstacle, for example because of a too early turn, the driver is alerted by acoustic and/or visual means alike the well known park assist.

3.3 Semi-autonomous Parking Assistance for Complex Environments

The currently used ultrasonic technology alone does not permit to make use of every parking slot that a skilled driver could use to park the car. A system which is solely based on ranging sensors has its limitations just because the system does not possess sufficient information for the perception of a complex environment. Using viewing cameras in addition to the ultrasonic sensors takes one nearer to the target. Through the analysis of the video images the system may identify markings on the ground as a further reference to calculate the parking manoeuvre. As an example the system will be able to park within a marked parking position even with no confining vehicles around, **Figure 5**.

Step by step the analysis of the visual information will be improved and extended and the combination with the ultrasonic ranging sensors further optimised to finally achieve the original requirement of performing a satisfactory parking manoeuvre in each and every single situation.

3.4 Fully-autonomous Parking Assistance

Fully-autonomous parked cars are known from different research projects but they operate in restricted and in controlled situations only. Before such a system is introduced in a series vehicle, one has to solve a wide range of technical challenges, the human-machine interface and the allocation of responsibilities.

Reliability of the sensor information ranks first among the technical challenges. On the one hand error signals caused by noise must be securely eliminated or at least be reduced to an acceptable level. On the other hand objects of any kind have to be detected reliably and their exact location should be determined as well as an object classification be executed in addition to the original measurement of their distance to the car. The reliability of the environmental model needs to undergo significant improvements. Besides the improvement of the single sensor and signal processing technologies, sensor/data fusion will play a major role, Figure 6. In a first step Valeo will merge ultrasonic and vision technology, which will be extended later by near range radar sensors. In all three mentioned technologies Valeo is one of the leading suppliers and is therefore in a good position for this development.

4 Abstract

Park assist systems have been introduced on the market in the beginning of the 1990s. But only with the evolution to the "Parklenkassistent" of Valeo (in the VW Touran 2007) it got real media attention. Although the used technology and hardware is similar to the "old" ultrasonic park assist, the semi-autonomous park assist is an entire new system development. End-users expect the system to park in every parking spot which can be used by a skilled driver as well. As the first generation is solely based on ultrasonic sensor technology providing only ranging information its usage in complex situations is limited. In a next step more detailed information about the environment and the parking situation will be obtained by the available sensors.

In future visual information will be used in addition to extend the perception of the environment. Currently fully autonomous parking cars are only available in research programmes to demonstrate the function. The technical challenge is to obtain all required information about the environment of the vehicle utilising robust and affordable sensor technology, for example ultrasonic, camera and radar.

Special FKFS 20 Years of Vehicle Wind Tunnels at IVK

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20 Years of Wind Tunnels at IVK



Twenty Years of Automotive Wind Tunnels at the Institute for Combustion Engines and Automotive Engineering of Universität Stuttgart 1989 – 2009 In 1989, the new automotive wind tunnel and model scale wind tunnel at the Institute for Combustion Engines and Automotive Engineering (IVK) of Universität Stuttgart in the district of Vaihingen in Stuttgart came into operation. Since then both wind tunnels have undergone comprehensive upgrades and further improvements are planned. The increasing use of numerical flow simulation has provided the impetus for developing an integrated approach to vehicle aerodynamic improvements, consisting of both experiments and simulation. It is clear that the future of automotive aerodynamics lies in the parallel use of experiments and simulations, with close links between the two areas.

1 The Wind Tunnel in Untertürkheim from 1933 to 1987

At the Research Institute of Automotive Engineering and Vehicle Engines (FKFS) of the Technical University of Stuttgart [1], founded by Wunibald Kamm in 1930, several automotive wind tunnels were established in Untertürkheim at short intervals from 1932/1933 onwards. The medium-sized wind tunnel for 1:5 models rapidly became the ideal on which all later vehicle wind tunnels were based. It had a 1.5 m² square nozzle. The bottom edge of the nozzle was flush with the floor plate and the integral two-roller belt, which reduced the floor boundary layer, covered the entire width and length of the test section, Figure 1. The vehicle wind tunnel completed in 1943, which was destined for the planned vehicle test facility, had a nozzle cross section area of 32.5 m². It represented the end of wind tunnel development at the FKFS. This tunnel had to be shut down in early 1944 following bomb damage.

The medium-sized wind tunnel was completely destroyed, but by 1950 it had been rebuilt and remained in operation in Untertürkheim until 1987, having

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Figure 1: Test section of the medium-sized FKFS wind tunnel in Stuttgart-Untertürkheim in 1938 with a 1:5.3 scale model of the partly enclosed MB racing car W 125 above the belt

been updated on several occasions. The large FKFS wind tunnel was repaired and came into operation in 1954. It was used for the first time for measuring the aerodynamic forces on vehicles. It was in full use for aerodynamic testing of helicopter rotors and V/STOL aircraft models and for measuring vehicles from almost all European manufacturers until 1974.

2 Events Leading up to the Construction of the New Wind Tunnel in Stuttgart-Vaihingen from 1970 to 1984

The majority of the FKFS buildings were situated on a leased site provided by the city of Stuttgart, next to the Daimler-Benz AG site. After the Second World War, the city of Stuttgart transferred the part of the site on which the large FKFS wind tunnel was to Daimler-Benz AG in exchange for other land. Daimler-Benz purchased

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the wind tunnel from the FKFS in 1970. As a result, the state of Baden-Württemberg was obliged to provide a new building for a new university institute and for the FKFS which would allow work to continue on the university site in Stuttgart-Vaihingen. As the proceeds from the sale of the building and the site, including the state subsidy under the terms of the Higher Education Institutions Construction Act, only covered the cost of building the new institute, the construction of the new wind tunnel was postponed for several years, despite the fact that the FKFS had made available funds from the sale of the old wind tunnel.

Numerous studies carried out on behalf of the FKFS and its own investigations soon indicated that a new wind tunnel could only be built with the participation of companies from the automotive industry. As the preconceptions of the interested parties about the purpose, size and performance figures of the new tunnel varied widely, at first it was not possible to find a solution that suited everyone.

The university and the state of Baden-Württemberg granted approval for the new vehicle wind tunnel in 1979 and funding was provided by the FKFS foundation, Adam Opel AG and Dr. Ing. h.c. F. Porsche AG. The official planning process began in 1980 and a provisional budget was drawn up which estimated the total cost of the tunnel to be DM 36.5 million. When the resolution to build a wind tunnel at the IVK was passed by the German council of ministers on 7 September 1982, the state of Baden-Württemberg agreed to supply the additional funds needed, which amounted to DM 14 million out of the total estimated building costs of DM 31 million [2].

The implementation plan for the wind tunnel facility, consisting of a full

scale aerodynamic automotive wind tunnel with a cross section of 22.45 m² and a 1:4/1:5 model scale wind tunnel with a cross sectional area of 1.65 m² was approved by the university building authorities on 28 November 1982. Work on the plan continued with the involvement of the companies responsible for the original plan, Weber & Schürmaier and H. R. Wallner, and the support of the IVK and the FKFS. Building work began on 12 May 1984, around 10 years after the large FKFS wind tunnel had been sold. The new wind tunnels came into operation in 1987/1988 and were taken over by the university on 19 May 1989. The university handed over responsibility for operating the wind tunnel facility to the FKFS foundation, in line with modern industrial practice, because a business with links to industry could not be operated by a public institution. The FKFS and Adam Opel AG agreed that all profits would be transferred to a "wind tunnel" cost

centre and would be used for the ongoing modernisation of the facility.

3 The IVK Automotive Aerodynamic Wind Tunnel from 1989 to 1992

3.1 The Air Duct of the Full Scale Wind Tunnel

As a result of conditions on site, a horizontal air duct of the Göttingen type had to be used in the wind tunnel. This allowed the model scale wind tunnel to be located under the large transverse axis of the full scale wind tunnel. The result was a verticaly structured bulding in which the open jet test section of the full scla etunnel was accessed by a vehicle lift. To keep noise emissions to a minimum, the air duct of the wind tunnel was made of concrete, while the model scale wind tunnel had a duct consisting of prefabricated sections of steel sheet, which were welded together on site. The duct system of the full scale wind tunnel had a traditional design without the common air/water heat exchanger in the settling chamber. The collector, the four 90° corners and the nozzle were made of steel sheet. As a result of the available length of the tunnel axis, the contraction of the nozzle was limited to 4.41:1 and the length of the open jet test section was restricted to 9.5 m.

The three turbulence grids in the settling chamber and a further mesh screen in the upstream wide angle diffuser allowed for very low non-uniformity in the velocity distribution, amounting to less than 0.12 %. Because of its dimensions, the plenum helped to prevent aerodynamic influences on the jet boundaries enlarged by the vehicle.

The separately mounted twelve-blade axial fan, which had an impeller with a diameter of 7.10 m, was driven via a torsionproof coupling by a shunt-wound DC motor with speed control in the impeller hub.



Figure 2: Test section of the IVK automotive wind tunnel in Stuttgart-Vaihingen after its start-up in 1989 with an FKFS calibration vehicle

3.2 Measuring Aerodynamic

Forces and Pressures in the Automotive Wind Tunnel

The electromechanical balance installed below the floor of the test section is characterised by a hydrostatic, non-interactive decomposition of forces. It can be switched to a six-component measurement with the formation of a large, rigid three-component platform or to a sevencomponent measurement with the formation of four small, separate platforms for measuring wheel load. Strain gauge load cells and integral digital voltmeters were used to record the measurements. The system error of the balance is less than 0.012 %.

In order to measure aerodynamic forces, the vehicle was positioned with its wheels on the measurement pads of the balance and its drive train blocked. The pads were flush with the floor of the turntable with radial clearance. The position of the boards could be adjusted to the wheelbase and track of the vehicle and their size could be adjusted in stages to fit the vehicle tyres. A fully retractable jack with four pillars, which was built into the turntable, could be used with wheel forks to lift vehicles up to 40 kN by 1.80 m [2]. The dynamic pressure of the free stream velocity was determined by taking differential pressure measurements with a pressure balance.

3.3 Data Acquisition and Processing in both IVK Wind Tunnels

The system that acquired the data and controlled the system was identical in both wind tunnels. The analogue signals from the force sensors were digitized in parallel, analog signals from the pressure measurement channels were amplified, and then processed by integral voltmeters with a shared integration start. The measurements from both wind tunnels were recorded independently in a fast process computer, processed and displayed online in the measuring stations. The software was developed by the IVK and the FKFS.

3.4 Starting up the IVK Full Scale Wind Tunnel

In order to minimise the longitudinal pressure oscillations which occurred in some velocity ranges, Seiferth wings had to be installed in front of the nozzle exit.

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The boundary layer thickness δ 99 %above the floor plate was 85.5 mm in the centre of the test section. Deviations of the flow angle were less than 0.12° for yaw and pitch. The turbulence intensity was 0.3 %. The maximum jet speed of 265 km/h was reached at a fan speed of 335 rpm using 2.95 MW of electricity, Figure 2.

During the years from 1989 onwards, when no full scale wind tunnel was available at the FKFS, many vehicle manufacturers were forced to use other vehicle wind tunnels (DB, DNW, Pininfarina, VW) or to establish their own wind tunnels (BMW, Ford). As a result, contracts for work were slow in coming in and amounted to around 1050 hours per year by the start of the aeroacoustic developments in 1992. In addition to development work on prototypes with aerodynamic forces, pressure distribution and rebound measurements, the focus of the activities in the wind tunnel was on functional and safety testing at high speeds. The average number of research hours per year was around 700 from 1989 to 1992.

4 The IVK Model Scale Wind **Tunnel from 1987 to 2001**

4.1 The Air Duct of the IVK Model Scale Wind Tunnel

As the model scale wind tunnel, which had a horizontal air duct system of the Göttingen type, was used as a pilot system for conversions and upgrades to the test section, it was important that it was similar in shape to the full scale wind tunnel. The air duct, which had a traditional design, was fitted with an air/water heat exchanger because of the temperature limit of 25 °C resulting from the frequent work with plasticine models. The contraction of the nozzle was slightly larger at 4.99:1 with a nozzle exit cross section of 1.645 m² and the length of the test section was 2.585 m which correlated with that of the full scale wind tunnel (on a scale of 1:3.683). The floor of the test section was connected to the bottom edge of the nozzle and consisted of a retractable test section table with an integrated turntable. Underneath was an electromechanical six-component balance. The twelve-blade axial fan with a diameter of 2.0 m was driven by a 315-kW shunt-wound DC motor. The impeller was mounted directly on the motor shaft. The drive control system, the regulation system and the processing of the nominal values were identical to those in the full scale wind tunnel.

4.2 Electromechanical Balance and Pressure Measurement System

The six-component balance was designed as a pyramid balance. A hydrostatically mounted universal joint with a virtual pivot point at the level of the test section floor allowed the moments to be measured directly. The hydrostatic decomposition of forces enabled the horizontal and vertical force components to be completely separated. As was the case with the full scale balance, strain gauge load cells with integral downstream digital voltmeters were used. The system error of the measurement system was less than 0.015 %. With the original configuration on start-up, the wheelbase and track could be continuously adjusted by altering the radial clearance around the exchangeable wheel pads using four double eccentric discs [2].

4.3 The Five-axis Traversing System

The essential five-axis traversing system was initially installed in the IVK model scale wind tunnel because of its future focus on research. The traverse paths of the linear X/Y/Z axeswere 2.40/4.45/1.0 m in length, and the rotation angles of the traversing system running across the plenum, which were 320° in the direction of the B and C axes, provide perfect coverage for the test sections. Every point in the cube described above can be reached by a CNC continuous path control to an accuracy of 0.05 mm at a maximum speed of 0.15 m/s.

4.4 Starting up the IVK Model Scale Wind Tunnel

Trial operation of the IVK model scale wind tunnel began on 31 July 1987, only a few days after the model scale wind tunnel in Untertürkheim was shut down. The wind tunnel was calibrated using the traversing system and the simple collector adjustment. This took so little time that the first customer tests could be carried out on 31 August 1987. During acceptance testing, the Seiferth wings fit-



Figure 3: Test section of the IVK aeroacoustic wind tunnel with the acoustic lining of the plenum, traversing system and four-axis manipulator for flow microphones in 1993

ted initially to stabilise the jet were replaced with lower-loss Delta wings in the nozzle opening. The non-uniformity in the velocity distribution of the jet was less than 0.10 %, with angle deviations on both axes of 0.085°. The maximum jet speed of 80 m/s was reached at a fan speed of 1050 rpm using 335 kW of electricity. The boundary layer thickness δ 99 % was 28 mm in the centre of the turn table. Comparisons of measurements of several vehicle models in the previous FKFS model wind tunnel in Untertürkheim and in the new IVK model scale wind tunnel showed that the old measurements could be correlated without restrictions.

The smooth transition from the FKFS model scale wind tunnel in Untertürkheim to the IVK model scale wind tunnel in Stuttgart-Vaihingen allowed existing regular customers to continue their aerodynamic development work on 1:4/1:5 scale models of future vehicles to the same extent as before. New customers were impressed by the increased maximum speed of 80 m/s and the lower air flow temperature of less than 25 °C. The average annual industrial usage of the model scale wind tunnel from 1990 to 1999 was around 1300 hours. During the same period the IVK model scale wind tunnel was used for research by the IVK and the FKFS for around 1250 hours per year.

5 Aeroacoustic Upgrade of the IVK Full Scale Wind Tunnel 1992/1993

When the new IVK wind tunnel complex was designed in 1984, the decision was made to delay the installation of acoustic treatment of the tunnel airpath for aeroacoustic tests for financial reasons. In 1992/1993 the FKFS had the opportunity to fit acoustic treatment to the air duct and the plenum and to install a traversing gear for microphone probes, with the support of Mercedes-Benz and Opel and a subsidy from the University of Stuttgart. The acoustic treatment of the IVK full scale wind tunnel was given priority over the planned installation of belt systems for road simulation because of the greater urgency and the expected improvement of the efficiency of the wind tunnel [3].

The inherent noise level of the IVK full scale wind tunnel without acoustic treatment and without Seiferth wings at a flow speed of 150 km/h measured next to the open jet was 91 dB(A). A reduction to around 73 to 75 dB(A) at 150 km/h was regarded as absolutely necessary to allow external noise measurements on vehicles.

Following some tests by the Fraunhofer Institute for Building Physics in Stuttgart, which provided consultancy for the project, the requirement to keep the reduction in speed to a minimum was met using an innovative solution with a special absorber design. By dividing the



Figure 4: Test section of the 1:1 wind tunnel with belt system showing a competition vehicle above the centre belt and the FKFS guy rope restraint system in 2001

cross ducts of the air supply system into narrow subchannels with wall insulation in the form of membrane absorbers. "deflection silencers" were created between each of two cornerswith foam covered turning vanes. The requirement for a low noise level of 71 dB(A) at 150 km/h was fulfilled by lining the plenum with broadband absorbers which are 320 mm thick, consisting of membrane absorbers, foam panels and a coating on the shortened collector flaps (new test section length of 10 m). The sound absorption level of the hall lining is better than 0.98 from 200 Hz upwards. The reduction of 20 dB(A) in the sound pressure level in the open jet test section allowes reliable measurements to be made of the aerodynamic internal and external noise of vehicles. The IVK full scale wind tunnel was the world's first aeroacoustic wind tunnel to use an absorber design with no glass or mineral fibre which can cause damage to health.

The period during which the aeroacoustic upgrade was carried out was also used to make other improvements and, in particular, to fit a multi-axis traversing system covering the test section, **Figure 3**. The total cost was DM 13.5 million. In recent years, microphone probes for recording alternating pressure on surfaces, a laser scanning vibrometer, a microphone array for locating sound sources in the interior of vehicles (conformal mapping) and an acoustic holography system have been added to the basic measuring equipment.

With an inherent noise level of 69 dB(A) at 140 km/h, the IVK full scale wind tunnel was for many years the quietest acoustic wind tunnel available. As a result of the role played by the FKFS as a professional service provider, it had a high level of usage of around 1850 hours per year.

6 Installing Belt and Wheel Rotation Systems for Road Simulation 2000/2001

Studies by competitors, primarily using standard production vehicles in wind tunnels with belt systems, had highlighted several significant differences in the effect of aerodynamic configuration changes compared with measurements above the conventional wind tunnel floor without boundary layer influence. On the other hand, the proposal made by the FKFS in 1968 to restrict the system to a narrow belt between the tracks or wheels because of the aerodynamic influence on the air flow around the vehicle was reinforced [4].

Following extensive preliminary tests in the model scale wind tunnel, the FKFS decided to install five-belt systems in its wind tunnels which would allow continued use of the existing six-component underfloor balances. In five-belt systems, the narrow belt between the wheels is accompanied by two wheel drives with smaller belts on either side of the centre belt, where the vehicle's wheels stand and which can be adjusted to the wheelbase and the track of the vehicle [5].

6.1 The Centre Belt of the Full Scale Wind Tunnel

The central dual-roller belt system (centre belt) is supported by an enlarged floor turntable. It has a roller diameter of 0.42 m and allows for a maximum belt width of 1.210 m and an axle base between the two rollers of 6.0 m. Belts with a width of 1.00 m and 1.105 m can also be used to accommodate different tracks. The 0.6 mm thick steel belts have a bonded polymer coating which is similar in texture to the average roughness of the road surface. The belt is supported on an uncooled air bearing of varying width and is subjected to a vacuum of up to 10 kPa. This compensates for the pressure exerted by the vehicle on the floor and ensures that the belt surface is completely even under all operating conditions.

The rigid-mounted front roller is powered by two servo motors each with an output of 28 kW, which continuously match the belt speed with the free stream velocity in a speed range up to 250 km/h. The rear roller is responsible for tensioning and tracking the belt. The laser-optic edge tracking function, combined with the high quality of the cut edge of the steel belt and the rapid servo-hydraulic control system, keeps tracking deviations to less than 0.15 mm, **Figure 4**.

6.2 Wheel Rotation Units and Vehicle Restraint System in the Full Scale Wind Tunnel

The wheels are driven by four independent wheel rotation units located directly under the vehicle wheels. They are weighted components of the balance. The compact two-roller belt systems newly developed by MTS provide a smooth road surface under the wheel contact area, as the 0.30 mm thick steel belt is mounted on air bearings between the rollers. At air bearing pressures of up to 26 bar, the bearings can support 8 kN at speeds up to 250 km/h, which allows cars to be tested under full wheel load.

The standard system for measurements with wheel rotation is a four-point support for the vehicle on the jack points or production support points in the sills using balance-mounted, hydraulic supports which can be extended vertically. Given sufficient preload on the sill points, the height and pitch angle can be adjusted. In floating mode, the restraint in the Z direction is removed to allow the vehicle to adjust its own position. A special restraint system developed by FKFS using guy ropes is available for vehicles without sills. The wheel rotation units and the sill supports can be adjusted to the wheelbase and track and to the XY positions of the pivot points of the sill supports on the measurement platform of the six-component balance.

6.3 Centre Belt System, FKFS Wheel Rotation Units and Rocker Panel Struts in the Model Scale Wind Tunnel

For cost reasons, the FKFS and the vehicle developers working for car manufacturers agreed on a combined 1:4/1:5 belt system with a standard roller distance of 1.70 m and exchangeable belt widths of 0.225, 0.250 and 0.312 m. The steel belt, which is only 0.30 mm thick and has a rough coating, runs on two rollers with a diameter of 0.240 m up to a maximum speed of 80 m/s. The air bearing, drive and tracking systems are identical to those of

the system in the full scale wind tunnel.

For the wheel rotation units in the model scale wind tunnel, the FKFS used the concept of a ribbed V-belt running over a triangle of rollers which had been tested on a prototype in 1997 and 1998. The wheel, which runs on the belt between the two upper rollers and is not loaded, is not supported in any other way. In order to accommodate different wheel widths, three roller modules with belt widths of 69, 85 and 115 mm can be used. With a wheel load of 85 N, the system can be operated briefly at 80 m/s. For long-term operation, 75 m/s is permitted. The models are restrained in the three main axes in a similar way to the vehicles in the full scale wind tunnel using four balance-mounted rocker panel supports with linear actuators.

6.4 Four-axis Manipulator System in the IVK Model Scale Wind Tunnel

A four-axis manipulator above the open jet, which can be moved transversely in the main axis, automatically positions the models in the test section. The model is lifted off the modelling plate of the trolley using a grabber system, moved into the test section and placed on the four sill supports on the balance. The manipulator was also designed to lift the 350 kg centre belt outside the test section in order to allow the belt to be changed and to position a large 3D LDA system alongside the entire test section, **Figure 5**.

6.5 Boundary Layer Influence in both Wind Tunnels with Belts

The floor boundary layer which emerges from the nozzle in both wind tunnels is completely removed by the boundary layer suction system. The local drop in speed resulting from the combination of the floor flow and the belt drag flow from the front roller gap is compensated for by a thin flat jet of air directed at a tangent. This reproduces the block profile corresponding to the situation on the road above the centre belt moving at the velocity of approach (VA) shortly after the beginning of the belt.

In the wheel track area, the boundary layer displacement thickness is prevented from increasing from 2.3 mm to 4.8 mm until the end of the belt. To achieve this, a jet at a tangent is combined with two advance suction systems operating over two strips 0.85 m wide along the centre belt. Comparable measurements with and without boundary layer influence gave aerodynamic drag figures of 0.003 to 0.018 with approximately the same proportions of suction and belt operation. However, when lift is reduced, the influence of the centre belt prevails, in particular in the case of smaller ground clearance. The increase in aero-



Figure 5: Model manipulator with a 1:4 scale model above the belt test section of the IVK model scale wind tunnel in 2009

dynamic drag caused by the boundary layer suction system is partly a result of the influence of the longitudinal pressure gradient in front of the vehicle.

Simulating wheel rotation causes a reduction in the drag coefficient of 0.005 to 0.026 in the case of vehicles with wheel arches. The extent of the reduction is influenced by the shape of the tyre cross section, the wheel design and the space in the wheel arch and is dependent on the speed of travel.

Because of the lack of space in the model scale wind tunnel, the boundary layer influence system had to be simplified. In addition to the pre-suction system in front of the belt with the tangential blowing sytsem, the boundary layer suction systems on either side of the centre belt were continued to the end of the test section.

6.6 Data Processing in the Full Scale and Model Scale Wind Tunnels

While the system for recording forces and pressures remained unchanged, the data processing for both wind tunnels, together with the numerous new drive control systems was moved to desktop PCs. A Microsoft Windows-based graphical user interface is used, which provides all the input and output screens needed by the FKFS for the test process. The measuring systems and automated measurement processes are activated from the monitor on the main console, where the raw measurement data is also displayed. The online measurements are displayed on another operator screen in the form of non-dimensional coefficients and the aerodynamic coefficients are summarised in a measurement report.

The belt systems and the accompanying boundary layer conditioning systems were installed in 2000/2001 with the financial support of DaimlerChrysler AG and Adam Opel AG, on the basis of advance payments for future bookings. For many years they were unique selling points for the wind tunnel facility. As a result of the constant collaboration of the FKFS on the development of the facility, the institute has acquired unique skills in designing, operating and maintaining wind tunnels with belt systems. The belts at the FKFS were developed further in collaboration with MTS, which supplied the five-belt system, using the experience of the FKFS. The institute has therefore helped to influence the current status of development in road simulation systems. Since 2002, the full scale wind tunnel with the road simulation system has been in use in two shifts for up to 3500 hours per year.

7 Further Development of the FKFS Wind Tunnel Facility

Since 1998 the FKFS has focused more closely on the combination of experimental and numerical vehicle aerodynamics. This, together with the gradual integration of aerodynamics and aeroacoustics, the development of the links between vehicle thermodynamics and vehicle aerodynamics and the experience of cooperation with other parties, will ensure that the FKFS remains a competent service provider and effective partner in vehicle research and development. Below is a list outlining some of the current modernisation projects and problem areas in aeroacoustics and vehicle aerodynamics.

Aeroacoustics of the Full Scale Wind Tunnel

- Investigating and defining measures to reduce the inherent noise level by more than 5 dB(A) in the test section of the IVK aeroacoustic full scale wind tunnel, particularly in the higher frequency ranges
- improving the damping of low frequency pulsations of the open jet at around 2 and 4 Hz using active or passive measures
- in-depth investigations of a large number of aeroacoustic and aerodynamic issues using a 1:20 model of the current IVK aeroacoustic full scale wind tunnel created by the FKFS
- installing a microphone array to locate sources of noise on the outside of the vehicle.

Aerodynamics of the wind tunnels

 Reducing the influence of the sink/ source effect of the conventional floor boundary layer pre-suction system on the static longitudinal pressure in the open jet test section in front of the vehicle using a scoop

 analysing the speed dependence of aerodynamic drag with wheel rotation.
 Measurement and testing systems in the IVK wind tunnels

- Improving road simulation using a more universal, modular belt system

covering a larger floor area with an enlarged floor turntable and developing a new six-component underfloor balance with additional equipment for measuring aerodynamic forces and separating aerodynamic drag and rolling resistance

- converting the traversing system into a crane and vehicle manipulator while retaining its existing functions or installing a separate crane
- improving the mobility of the 3D laser system in the model scale wind tunnel including a reduction in the installation time and creating a 2D/3D laser system for measurements on original vehicles (external and internal flow of air)
- investigating the design of a high-performance, all-purpose PIV (particle image velocimetry) system for both wind tunnels
- adding a model turning device to the model manipulator of the model scale wind tunnel to make it easier to use in the case of underfloor modelling work on 1:4 scale clay models weighing up to 140 kg
- fitting the 3D measurement machine with electric axle drives for 1:4 scale models to automate frontal area measurement and with a 2D milling head for computer-controlled milling of plasticine and rigid foam models
- acquisition of a rapid prototyping system to allow add-on parts to be created quickly and internally for aerodynamic tests
- acquisition of a high-performance 3D surface mapping system from GOM, based on slit light projection, to document the current status of 1:1 and 1:4 scale clay models during vehicle optimisation and to increase the efficiency of the integration of CFD and experiments.

8 Numerical Methods in Vehicle Aerodynamics and Aeroacoustics

8.1 Aerodynamic Simulations Using FDI FIDAP 4.51

In early 1989, the IVK and the FKFS started their first efforts in numerical simulation of vehicle aerodynamics. Back then, the institute did not have its own high-performance computer and so the university's computing centre with a Cray 2 high-performance vector computer was used to run the commercial flow simulation program FIDAP 4.51. However, because the computer had just four processors and limited parallelization capabilities, it was only possible to use a fraction of the computing power, which resulted in significant increase of CPU time and therefore also in the costs involved [6].

The first numerical simulations were limited to flow fields around basic 2D bodies with different boundary layer conditions. The first 3D simulations used simplified body shells with smooth surfaces with or without wheels. These simple bodies were also suitable as 1:5 models for experimental verification. Simulation work with FIDAP came to an end in 1991 due to less available CPU time on the Cray 2 and the restrictions in grid resolution of the simulation program.

8.2 Numerical Simulation Using EXA PowerFLOW

In 1998/1999, after the institute built up its own simulation infrastructure in the form of a simulation server with 14 processors, numerical flow simulation in the field of vehicle aerodynamics were resumed. The server was replaced in 2003 by a high-performance Linux cluster with 64 processors. In 2007 the number of processors was increased to 192. This reduced the runtime for an average simulation of the external flow field around a vehicle by a factor of 8.

During validation tests on a saloon body shell with a critical rear window angle, the program EXA PowerFLOW release 3.2 produced pressure coefficients (CP) on the external skin which matched the experimental results very well. In order to validate a complex vehicle shape with a set-up consisting of 25.8 million fluid elements (voxels) and 3.3 million surface elements (surfels), 3500 processor hours were needed to simulate a period of 0.13 seconds [7]. The PowerFLOW results in both, the simulated flow field and the integral coefficients, corresponded closely with those of the experiment. Following a detailed validation phase, the aerodynamic simulation process was extended and additional capacities for pre- and postprocessing were created. The hardware at the FKFS was upgraded again in November 2008 to a total of 420 processors.

Nowadays, an integrated approach is taken for simulations throughout all aerodynamic and aeroacoustic research and development projects. The central philosophy behind these integrated simulation processes is the combined use of the results of experimental and numerical investigations, depending on which method can produce more useful or faster results [8]. In addition to the usage of simulations in research projects at the FKFS, numerical simulations are also used extensively in method development with OEMs and software developers.



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Figure 6: FKFS turbulence flaps in front of the nozzle of the IVK model scale wind tunnel with a 1:4 scale model in the open jet test section in 2009

8.3 Aeroacoustic Simulations

In the early 1990s, the FKFS began to develop a boundary element method (BEM) simulation tool to complement its technical measurement skills. On the basis of its expertise in this area, it is currently using commercially available software tools such as MSC Nastran (FEM), LMS Virtual.LAB (BEM), statistical energy analysis (SEA) and PowerFLOW.

Besides the experiments in the wind tunnel, the focus is currently on developing new simulation methods. This involves improving conventional procedures and creating new tools to investigate acoustic problems of vehicles, like the transmission of aerodynamically generated noise into the passenger cabin.

9 Summary and Future Prospects

9.1 The Current Research Environment

At present, the FKFS is one of the leading service providers in the field of vehicle aerodynamics and acoustics in Europe. Focus of its research and development activities are the wind tunnels at the Universität Stuttgart which are operated by the FKFS.

In the past the FKFS has become involved in industrial development projects when customers needed additional development capacity on a temporary or permanent basis or decided not to build

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their own wind tunnel because it would not be used to capacity. In the near future, work on expanding existing vehicle wind tunnels in industry will continue, together with the construction of new tunnels. Although this requires major investments and allows companies to enhance their development skills and prestige, it also provides additional capacity which will obviously be needed in the face of current CO₂ issues and the increasing importance of aerodynamics in vehicles with energy recovery systems. In the future, the success of the FKFS in the wind tunnel service providers market will depend on consistently meeting customers' requirements, developing innovative solutions for unexpected problems and, in particular, occupying niche markets in testing by offering a highly competent service and the latest technology. A decisive factor in the future success of the FKFS is its organisational structure as a non-profit-making foundation. This ensures that the profits made by the wind tunnels return to the foundation and are used for future modernisation, as has been the case in the past.

In contrast to large research organisations, the FKFS is not funded from taxes. This enables the FKFS to use its latest aerodynamic testing and simulation technology in engineering services provided to the industry and, for example, in pre-competitive projects which form part of collective industrial research (FAT, FW), as well as for pure academic research and teaching in a university environment.

9.2 Current Areas of Research

The focus of current research activities at the IVK and the FKFS is on reproducing realistic approaching flow conditions as found on road using suitable measures in the wind tunnel. This is based on numerous measurements of turbulence in the air flow around the vehicle travelling on the road [9]. Initial tests of an active system in front of the nozzle of the model scale wind tunnel to reproduce the flow conditions on the road have already been successful and also allow the generation of wind gusts, Figure 6. The effects on the model were measured with a highly dynamic six-component underfloor balance [10]. Using this and other similar processes, it will be possible in future to predict and to improve the unsteady aerodynamic characteristics of a vehicle, without the need for road-going prototypes and measurements on road. The results of these unsteady tests become significantly more important as a result of the installation of a high-performance, five-axis driving simulator at the IVK, the acquisition of a driving dynamics test bench for the behaviour of

personal buildup for Force Motors Ltd.

the vehicle and driver and the development of the man/machine interface.

9.3 The Future of the Wind Tunnel

In order to be able to compare the results of road driving and wind tunnel tests, further developments must be made to the wind tunnel corrections for the open jet test section [11], the testing methods on the road and the numerical verification of measurement results, taking into account the wind tunnel in the simulation of flows of air around the vehicle, Figure 7. Therefore, investigations are being carried out in collaboration with EXA Corporation and other partners into the influence of the wind tunnel test section on the air flow around the vehicle [12]. This will give a better understanding of the blocking effects in wind tunnels and will increase the comparability of measurements and simulation results with the objective of creating a digital wind tunnel.

Automotive wind tunnels will continue to be an essential tool in the future, as experiments are significantly faster than simulations, in particular when small details of the vehicle need to be improved. In addition, the final functional tests will always have to be carried out using a real vehicle, at least for the foreseeable future. The proof of this lies in the wind tunnels which have recently been opened or are currently in the planning stages in Germany, the USA, China and Japan.



Figure 7: Comparison of the static pressures behind the luggage compartment of a 1:4 scale model from an experiment (top left) and a simulation with (top right) and without (bottom left) taking into account the influence of the wind tunnel in 2009

Abbrevi	ations
DB	Daimler-Benz
DNW	Deutsch-Niederländischer Windkanal (German/Dutch wind tunnel)
FAT	Forschungsvereinigung Automobiltechnik e. V. (Research Association for Automotive Technology)
FKFS	Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren Stuttgart (Research Institute of Automotive Engineering and Vehicle Engines in Stuttgart)
FVV	Forschungsvereinigung Verbrennungskraftmaschinen e. V. (Research Association for Combustion Engines)
FWK	Fahrzeugwindkanal
IVK	Institut für Verbrennungsmotoren und Kraftfahrwesen der Universität Stuttgart (Univer- sity of Stuttgart Institute for Combustion Engines and Automotive Engineering)
V/STOL	Vertical/short take-off and landing

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Direct injection spark-ignition engines are becoming increasingly important, and their potential is still to be fully exploited. Increased power and torque coupled with further reductions in fuel consumption and emissions will be the clear trend for future developments. From today's perspective, the key technologies driving this development will be new fuel injection and combustion processes. The book presents the latest developments, illustrates and evaluates engine concepts such as downsizing and describes the requirements that have to be met by materials and operating fluids. The outlook at the end of the book discusses whether future spark-ignition engines will achieve the same level as diesel engines.

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TECHNIK BEWEGT.



Historical technical drawing for the body of a coupé coach [1]

Modular System for Methodological Design of Body Assemblies

The University of Applied Sciences (HAW) Hamburg and the University of Hertfordshire in collaboration with the automotive industry set up a R&D process to optimise the design methods in the "new" parametric associative approach. The objective with the parametric associative design was to develop new methods for task allocation and a more "structured" approach in the organisation of design processes while designing automotive body components. Groups consisting of four to seven students evaluated and developed body assemblies. 22 realistic projects were identified before by automotive companies. Here, important conclusions are presented for the example A-pillar.

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1 Introduction

Parametric associative design (PAD) models do not only contain geometric information, but also design intent in the form of dependencies between the various geometric elements. When certain design characteristics (parameters) are modified or replaced, the geometric model is automatically updated to reflect these changes. The automatic update process relies on the design intent which is stored in the form of relations and associative links. To achieve reliable and efficient updates, consistent dependencies and the re-use of existing CAD models are of paramount importance for economical use.

Especially during the working phase with many changes from concept design to design freeze in the product evolution process (PEP), **Figure 1**, where "new" product requirements often lead to several product variations the use of the parametric associative design has been tried and tested. In this phase it has shown that a zone based approach whereby in the concept phase a sole engineer designs large zones and principle layouts of the automotive body components instead of designing single parts has proved to be more reliable. During the detailing phase of the product most of the decisions are finalised and various product references have been clearly defined and frozen. Thus during this phase it is more appropriate to distribute the design work according to parts and subassemblies of the automotive body rather than according to the zones.

The hierachical structure of the PAD models can be defined in the concept design phase either according to the bill of materials (final products, assemblies and parts) in one product model or under the support of folders in one single part model.

In the first case, product models are controlled by multi model links (MML) of published references. Single part models structured by folders are also useful in the concept phase. In the second case single model links (SML) of unpublish references are used to control depended geometries. Mixed product models combine MML for existing parts and carry over parts with SML for new designs.

As underlying hypothesis and problems the following points were chosen: During the concept development stage of body structures there are still several occasions where breakage of the links in the associative process chain can occur.





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Figure 1: Distributed tasks in product evolution process (PEP) according to [5, 6]

One of these breakages is generated by the use of isolated master package sections.

In the early phases of PEP the package process optimises the space allocation for the various parts, Figure 1. To describe these space allocation cross-sections, previously defined section developments and competitors' data are used. These sections are often distorted in terms of their geometric integrity and therefore can not be utilised for dimensioning and surface derivation and extraction.

In this case a methodology of true most (radial) section and true (compound radial) sections should be used to design a specific zone to prove both the legal and functional requirements of the packaging department. With the aid of specific case studies this article describes the following three methodologies:

- methodology of developing true most radial section and true radial compound sections for the design of body parts
- methodology of zone-based design approach of body assemblies
- "new" methodology for creating parametric associative package sections.

Figure 2 shows the simplified model of an upper A-pillar with front door and front screen beds in a radial section. This parametric associative section was designed having as a basis a distorted package section. The upper A-pillar is built from Class-A, prismatic and functional surfaces of glass barrel (retractable window, door) or control surfaces of binocular obstruction. The A-pillar in Figure 2 shows three prismatic areas (surface bands with constant cross-section). These are the glass bed of the windscreen and the inner and outer bed of the front door. The design of prismatic surface areas is described in the following Section.

2 Methodology to Create Radial Section and Compound Radial Sections for the Design of Automotive Body Parts

In designing an upper A-pillar its position and orientation in packaging space is usually common. That is to say the Apillar assembly is inclined and curved in a compound angle in relation to the vehi-



Figure 2: Upper A-pillar cross-section

cle's standard xyz coordinate system. The spine curves of the three prismatic areas of the A-pillar are not parallel. The radial section is defined on a plane perpendicular to the theoretical intersection curve of the front and the sidewall Class A surfaces.

The fully constrained (dimensioned) section controls the dimensions of the true compound radial sections. Important parameters for the true most radial section are highlighted as explicit control parameters in the structural tree of the CAD model. **Figure 3** shows the radial section with yellow and green curves. Yellow curves are direct (for example cut with a plane) or indirect (for example offset curve) based on Class A or functional surfaces while the green curves are designed according to the yellow curves. The sheet thicknesses are shown in the form of offset curves.

From the radial section compound radial sections for the design of the pris-



Figure 3: Upper A-pillar true most radial section



Figure 4: Glass bedding of the windscreen

matic areas are derived. On the basis of the projected width of the prismatic profile a secant surface is designed. This secant surface should then be used as the reference surface for the orientation of the profile segments. Would the profile segments be orientated under the support of surface normals or tangents of the Class A surface there can be intersections between reference and prismatic surface when a large profile surface is designed on basis of a reference surface with a small radius of curvature.

Circumferential constant prismatic surfaces are modelled from profile curves which when drawn include all required radii. Generally most prismatic surfaces end up in a joint design. Therefore the prismatic profile without any radius representation is separated into segments. Every single segment is generating a curve for the development of a surface band. It is necessary to define generating curves of appropriate length to allow a precise delimitation or enable filleting between the two surface bands. This prolongation of surface bands also supports the definition of planar control curves for the modelling of surface blends in the joint area. The necessary prolongation of the profile segments can be delimited under support of boundary boxes (rectangles) or boundary circles, which are defined on the section plane of the profile. After investigation of several methods for the design of surface bands and joint areas the approach presented has proved to be most clearly traceable and updates save.

Figure 4 shows the glass bed front screen as a detail of the radial section

with an appropriate number of dimensions used to control the compound radial sections. All dimensions of the true section are linked with the dimensions of the controlling radial section. The bedding flange is inclined towards the wind screen (secant). The angle between the rebate and the flange surface is not constant. A control dimension between the glass and the end of the flange ensures that there are no intersections between flange and glass.

Parts of the prismatic glass bedding are the three flange surfaces of the three meeting surfaces and the four slope surfaces connected with the flanges. On basis of a single segment of the true section, a spine curve and a reference surface every surface band of the seven prismatic surface bands is designed.

The surface model of the upper A-pillar will be supplemented with offsets of Class A surface and functional surfaces and fillets once all three prismatic surfaces are completed. When the corresponding body zones are designed joint design can be completed and body parts, sub assemblies and assemblies can be derived from the zone based design. For the digital mock-up (DMU) process surface models will be supplied with sheet thickness and the solid models can be detailed in further design steps as required.

3 Methodology of the Zone-based Design for Body Assemblies

In this Section the zone-based design methodology shall be discussed. The zone of the upper A-pillar described before is part of the front door design. The complex functions of the side door drive the design of the corresponding body structure. This zone includes sub zones of the circumferential glass bed of the front screen, the A-pillar and the front door. The hypothesis and problem are: The distribution of design work can either be organised according to the single parts and sub assemblies or according to design zones of the front door and its corresponding parts (for example inner or outer door panel, inner or outer side wall etc.). In the concept phase of the design of a front door functional detail investigations are also needed which are integrated in the zone-based design directly or which are prepared in separate concept models.

In cooperation with the sponsors one of the two methods for the distribution of work was appointed for each project. A great amount of the 22 projects for automotive industry has shown that a zonebased approach leads to a more evenly and fair distribution of work when compared with that of distributing the work according to parts and sub-assemblies. A project study carried out by HAW Hamburg in collaboration with Volkswagen Commercial Vehicles the design of the tail gate and its corresponding parts was undertaken [2, 9, 10, 13]. University of



Figure 5: Layout of the door check trap

Applied Sciences (HAW) Hamburg adopted the zone based design approach and the OEM the single parts and subassemblies approach. The conclusions of this study were the following [8]:

The unequal complexity of the parts involved offer very different design resources. Every part oriented CAD model contains the design work from concept to detailing phase and is especially tailored for required modelling methods and details. Adapter model (contains all the references) and corresponding design models are closely constrained and therefore very unstable when it comes to larger changes and variations.

In the zone based approach the corresponding zones use a common adapter model which defines parameters and reference geometries and geometry where the transitions between the zones take place (for example planes). In addition to references used in zones a share of the same definitions for the denomination of sub surfaces, attributes and publications for the common design of every single part surface have to be allocated. The zonebased design models have a much higher





Figure 6: Insulated upper A-pillar master package section 105 – section (top) and position definition (bottom) according to [7] degree of reusability than that of highly specialised part models. The side effect is that a team leader must be responsible for the entire model with all corresponding design zones. For the update sequence of the zone models involved in the project model and for all single parts that are included in the zones a good working group has to be established.

In the example of a front door [11] the distribution of design work in a zone based methodology could be organised in the following CAD models:

- layout body-in-white (BIW) door opening flange (flange door entrance between inner and outer side wall)
- layout glass barrel, trimming door glass, window regulator
- lower A-pillar zone with layout of hinge axis and door gap
- layout door check, see **Figure 5**
- upper A-pillar zone (see Section 2)
- upper roof rail zone
- lower B-pillar zone with integration of door latch and seat-belt retractor
- upper B-pillar zone with the inclusion of belt height adjustment
- door belt and side mirror zone
- side impact carrier zone
- door sill zone.

Lessons learned at the HAW Hamburg in side door development projects have shown that the entire scope described cannot be undertaken by a team of seven students during one semester. Thus, in these cases the projects had to be limited to the area below the belt line.

The following second example describes the methodology that could be adopted for the development of a lower A-pillar zone with hinge axis layout and door gap. In general side door hinges are arranged to turn the door tip into the side wall as turn-in arrangement. Dependent upon the current reference geometry (for example door gap and outer surface, A-pillar) a corridor for the positioning of the hinge axis can be designed. Then the door gap can be designed and on the basis of the front corner of the door the outer surface of the A-pillar can be derived. The lower A-pillar zone shows three prismatic areas:

- 1. The door gap with first slope surface of the front wing and the crash-flange with its hemming flange of the door.
- 2. The body side door seal flange of the BIW and its opposite seal surface on

the door. Results of the BIW flange layout would be approved and updated in the zone model.

3. The door's side door seal with its seal surface on the corresponding pillar is positioned as far outside as possible inside the hinge axis.

The inner and outer door frame in the hinge area (hinge frame) and the opposite hinge surfaces of the pillar are defined as planar surfaces relative to the hinge axis. The door function does not necessarily need an inclined inner and outer hinge frame but for tooling purposes the surfaces are inclined relative to tooling directions of the parts involved.

The mounting surfaces of the hinges are positioned in grid direction. This allows an easy hinge adjustment for a flush outer panel and parallel door gap. The results of the separate layout of the door check are included in the zone model of the lower A-panel.

4 Methodology of Parametric Associative Package Sections

Isolated master package sections, Figure 6, are part of the Global Car Manufacturers Information Exchange Group (GCIE). At the moment in concept design phase master package sections are used [12] to describe the content of the modelled spaces. Hypothesis: Apart from some exceptions (for example Section Y0) these are often distorted sections and are not applicable for the design of surface models. However as soon as adaptive parametric associative models of body zones are designed, package sections can be derived as results of these zones. At any time these results can be adjusted according to new requirements controlled by a car line section.

The master package section of the upper A-pillar is a section on the height of the eye-points according to (EG) 77/649. For the design of parametric associative package sections a body segment with package sections will be derived from the presented example "design zone upper A-pillar", **Figure 7**. The segment is limited at the top and bottom by the two planes which are defined in EU directive (EG) 77/649 for the design of viewing beams. On the height of the eye points a third plane is defined for the approval according to the current legislation as

well as to the former stronger legislation regarding ergonomics and geometry. Figure 7 shows that a binocular obstruction of 2.586° is achieved and the current legislation is fulfilled.

But **Figure 8** shows that the allowed binocular obstruction of 6° is exceeded by 2.176° and the concept design has to be adjusted. Still the most German OEMs use this former legislation. The binocular obstruction not only depends on the size of the cross-section of the A-pillar (true radial section) but also on the inclination and bending of the A-pillar as well as on the distance between eye points and pillar.

The CAD model described allows the exchange of reference geometries (for ex-

ample Class A surface, spine curves etc.) changes of the seating position of the driver or of the parameters of the section at any time. The model consequently allows the automatic adaptation of new requirements and approval of the binocular obstruction. Compatibility for new references and flexibility for new requirements leads to a high degree of reusability of the CAD model.

5 Summary

The distribution of design work according to the methodology of re-usable zone and principle layout models (for example upper A-pillar zone with mating parts of



Figure 7: Parametric package-section with current binocular obstruction according to (EG) 77/649

Body



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Figure 8: Parametric associative package section with current binocular obstruction according to OEM specification

front door and front screen designed and modelled in a zone based approach for the development of the side door) leads to some advantages, as it is shown in the projects of the University of Applied Sciences (HAW) Hamburg and the University of Hertfordshire. Apart from the equal distribution of the work load this method defines a modular modelling and construction system of reusable zones and principle layouts. The zone and principle layouts can be combined and varied to generate not only one but several individual design solutions for the body assembly.

As soon as a modular modelling system is defined with alternative solutions for all zones of an automotive body assembly (for example side doors and corresponding body-in-white and joint designs and the derivation of parts and assemblies are completed by a design team one single engineer can handle the construction system of parametric associative designs and adjust the system according to new references or requirements to divert new parts or assemblies in an economical way.

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