AEROACOUSTIC WIND TUNNEL

HIGH WIND, LOW CO₂
How aerodynamics reduces fuel consumption and lowers emissions
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SMALL, HOT, VIRTUAL
The three “siblings” of the Stuttgart wind tunnel are doing a great deal...
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The CLA. The four-door coupé from Mercedes-Benz with the lowest cd-value of any production vehicle.

Design that makes a bold statement: The CLA boasts a distinctive aesthetic and an excellent drag coefficient. The optional AMG line adds even more sportiness to its appearance.

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Fuel consumption combined: 7.1–3.9 l/100 km, combined CO₂ emissions: 165–99 g/km.

Figures do not relate to the specific emissions of vehicles manufactured only for off-road use, do not form part of offers for sale and are intended solely to aid comparison between different types of vehicles.

Provider: Daimler AG, Mercedesstraße 137, 70327 Stuttgart.

For more than 80 years, FKFS researchers have worked in close cooperation with colleagues from the automotive industry on reducing aerodynamic drag. They have achieved remarkable progress and successfully mastered many new challenges, for example, in the field of aeroacoustics.

Modernization of the vehicle wind tunnel under the leadership of FKFS enables industrial customers and university researchers to address today’s emerging issues. Research findings are transformed into developments aimed at significantly increasing efficiency.

With members from the science, industry and government communities, the board of trustees provides professional support for FKFS strategy development. We are pleased that the FKFS managing board has successfully completed the future-oriented modernization of the wind tunnel.

We are excited about the future and look forward to doing our part.

Prof. Jürgen Blum
Chair of the FKFS Board of Trustees

Research in Motion® is the slogan for the Research Institute of Automotive Engineering and Vehicle Engines Stuttgart (FKFS). And motion is the key to designing research that meets the needs of a rapidly-changing world and contributes to social progress.

The modernization of the University of Stuttgart vehicle wind tunnel, which is operated by FKFS, a public foundation, represents a giant step forward. This unique collaboration benefits all stakeholders. By working in close cooperation with FKFS, industry benefits from the availability of a state-of-the-art, independently operated wind tunnel. The university benefits because it can adapt its research to important real-world issues, such as climate protection and conservation of natural resources. Students benefit because, in the course of their training, they are challenged by issues that will be important in their professional lives.

We wish the FKFS every success in operating the new wind tunnel!

Prof. Wolfram Ressel
Rector, University of Stuttgart

Cover
Close to the ground in the new wind tunnel: simulated asphalt surface on the steel belt, expansion strip and suction system for boundary layer conditioning (from left to right). More details on pages 32/33.
While the focus of aerodynamics is still on the aircraft industry, FKFS starts conducting experiments with 1:5 scale car models in a tunnel that was originally designed for testing aircraft engines.

The K1, an FKFS prototype, achieves a cd of 0.23. At that time, the drag coefficient for a full-size car is typically 0.5 or higher. The car’s rear deck and wheel well trim are characterized by groundbreaking design.

FKFS launches operation of the first wind tunnel designed for testing complete vehicles. The facility is closed down after being heavily damaged in an air raid.

Many of the world’s dream cars have been tested in wind tunnels operated by FKFS. For the past 85 years, the research institute’s engineers have looked beyond beautiful bodywork to focus on technological progress.

Progress in measuring technology is the key to better aerodynamics. This reciprocal effect is a common thread that weaves its way through the history of a discipline that started to flourish in the 1930s. Fuel efficiency wasn’t always the main concern. The first oil crisis in 1973 triggered a quest to achieve the best possible mileage. After more stringent restrictions on greenhouse gases had been introduced in response to climate change, engineers started focusing their full attention on improving energy efficiency.

Engineers at FKFS have not only supported the development of aerodynamics, their work has helped shape this branch of science.

The Opel Calibra came onto the market in 1990 with a low 0.26 cd, and remained the world’s drag coefficient leader for many years.

AERODYNAMICS

THE EVOLUTION OF

The Opel Calibra came onto the market in 1990 with a low 0.26 cd, and remained the world’s drag coefficient leader for many years.
The aerodynamic drag of full-size vehicles is primarily measured in coast down tests. FKFS engineers learn how ambient wind can have a significant impact on the results.

The Mercedes-Benz C111 (Type 2) experimental vehicle was the big surprise of the Frankfurt Auto Show in 1969. Engineers in Stuttgart used a revolutionary approach to achieve maximum downforce on the front axle. Instead of a large spoiler, a front air dam directed airflow over the engine compartment to reduce aerodynamic lift.

Focusing more on its role as an engineering service provider, FKFS optimizes the aerodynamics of legendary vehicles, including the NSU Ro80 and Mercedes W113 (nickname: “Pagoda”).
FKFS takes over operation of a large new wind tunnel at the University of Stuttgart. Airflow in the plenum is extremely even with a maximum variation of only 0.12 percent.

FKFS optimizes a very unique “Opel” in the model wind tunnel. The automaker designs the bobsled used by (West) German athletes in the Winter Olympics in Lake Placid, New York.

FKFS engineers support the development of Porsche competition cars with ground effect aerodynamics that create road-holding downforce. The Porsche 956 became a consistent first-place winner at Le Mans.

Designed in collaboration with four universities, the “Uni Car” reduces fuel consumption by up to 33 percent. FKFS trims the aerodynamics down to a $c_d$ of 0.24.

The design of the NSU Ro80 unveiled in 1967 was years ahead of its time. Although the rotary engine concept developed by Felix Wankel (“Ro”) failed to gain widespread acceptance, the streamlined, wedge-shaped body influenced automotive styling until the 1980s. Still today, advanced design and excellent aerodynamics can be perfectly combined.
In the racing world, aerodynamics can make the difference between triumph and defeat. FKFS supported Porsche in the development of many of their competition cars. For example, the Porsche 956 had enough downforce to keep it virtually glued to the ground. Appearing on the track for the first time in 1982, the three factory-sponsored endurance racers took first, second and third-place honors at Le Mans.

With support from Mercedes and Opel, the full scale wind tunnel is upgraded for acoustic testing. A peak noise level of only 69 dB(A) at 140 kph (87 mph) makes it the world’s quietest wind tunnel – a record held for many years.

The full scale wind tunnel is equipped with a new five-belt rolling road simulation system that enables vehicle testing with spinning wheels. Running at full capacity, the facility starts operating in two shifts within the first year.

The Intergovernmental Panel on Climate Change publishes its first report indicating that global warming is most likely caused by human activities. Reducing CO2 emissions becomes a key issue in automotive engineering – along with improving drag.

Following reconstruction, the Stuttgart wind tunnel is capable of simulating actual road conditions. Reducing fuel consumption in everyday driving conditions becomes a primary objective for FKFS.
HIGH WIND, LOW CO₂

FKFS engineers are lowering aerodynamic drag to decrease new vehicles’ fuel consumption. At the same time, they are ensuring continued high levels of stability and acoustic comfort.

370 kph – 230 mph. It wasn’t on the Bonneville Salt Flats, but on an autobahn straightaway between Frankfurt and Darmstadt. Race driver Rudolf Caracciola set the speed record in 1936 in a modified Mercedes Silver Arrow. The car’s streamlined shape was measured and optimized at a Zeppelin construction yard in Friedrichshafen. In the 1930s, breaking land speed records was a sign of technical advancement. Today, engineers around the world are committed to lowering fuel consumption. The core issue is essentially the same: Use as little energy as possible to overcome driving resistance – primarily aerodynamic drag resulting from the vehicle’s front surface and drag coefficient.

Europe’s premium automakers are under pressure to meet future CO₂ restrictions with their large, relatively heavy vehicles. But the fleet average of 95 grams CO₂ per kilometer required for all manufacturers by 2021 is not absolute. Depending on the average weight of vehicles sold, manufacturers can slightly exceed this limit. Nevertheless, premium automakers will need to lower fuel consumption by an average of 25 percent. This can’t be achieved with lightweight construction alone. Most manufacturers are using a mixture of high-strength steel, aluminum and plastic. Using high-priced composite materials is probably the only viable solution to further reducing vehicle weight.

Automotive designers look at improving aerodynamics as an attractive low-cost – or no-cost – solution. Many of the details that lower the drag coefficient go unnoticed by the average driver. One proven solution is to use taillights with tiny airfoils on station wagons and SUVs. Engineers are fighting for every tenth of a gram of CO₂. It is no longer simply the shape of the bodywork that ensures good...
"GOOD DESIGN AND PERFECT AERODYNAMICS ARE ANYTHING BUT CONTRADICTORY. AND FOR A SPORTS CAR, PERFECT AERODYNAMICS MEANS Much More THAN A LOW DRAG COEFFICIENT. OUR FOCUS IS ON INTELLIGENT DYNAMICS."
Michael Pfadenhauer, Porsche

Aerodynamics. A growing number of vehicles are designed with enclosed underbodies. Airflow through the wheels – which function like fans when the vehicle is in motion – and wheel wells is another area in which progress is currently being made.

REALISTIC WIND TUNNEL TECHNOLOGY

Wind tunnels have become established as an important tool for refining aerodynamics. Using advanced measuring technology they can test vehicle airflow at practically any speed. But all wind tunnels are not created equal. Depending on the technical equipment, drag coefficients measured in two different tunnels can vary greatly. At the same time, the conditions in an artificial environment never really match the situation on the road. All you can do is approximate – and that’s exactly what the engineers at the Stuttgart research institute have been doing for decades. FKFS contributed groundbreaking information in the 1960s when it was discovered that the airflow around a vehicle can only be precisely measured when there is relative movement to the road surface in the testing lab.

Following reconstruction of the large wind tunnel, FKFS is moving forward into the realm of realistic wind tunnel technology. The Side Wind Generator (FKFS swing) developed in Stuttgart now makes it...
selected driving program. This can be done by raising or lowering an adjustable rear spoiler. “These active systems are still in the early stages of development,” Wiedemann explains. But despite the high costs, he thinks this technology may someday be found on series production models. “More research needs to be conducted on active systems,” he says. The interchangeable steel belt system FKFS first (Fully Interchangeable Road Simulation Technology) enables the research institute to create the conditions for measuring fast vehicles at high wind speeds to ensure the test results in the new wind tunnel come very close to real-world environments.

FOCUSING ON AEROACOUSTICS

Passenger comfort in the interior is just as important as vehicle dynamics. Producing eco-friendly cars that no one buys benefits neither the manufacturers nor the environment. Interior acoustics is an important element of passenger comfort. Even at moderate highway speeds, wind noise can be very annoying, because it exponentially increases by five or six in relation to vehicle speed. With this in mind, FKFS has focused intensely on aeroacoustics since the early 1990s. A primary objective for the

possible to not only measure the drag coefficient in a steady airflow. The system can also be used to reproduce wind gusts similar to those found in natural conditions or simulate wake turbulence created by other vehicles on the road. Professor Jochen Wiedemann, an FKFS board member who is also responsible for the wind tunnel, explains: “Under real conditions, the most efficient vehicle isn’t necessarily the one with the lowest drag coefficient in still air.” Good results achieved at various airflow angles are the prerequisites for optimal real-world fuel consumption.

Regardless of whether the wind is dynamic or constant, in an era when engineers battle for every gram of CO₂, the precision of each measurement is crucial. With this in mind, FKFS researchers develop more than concepts for improving automotive aerodynamics. They continuously scrutinize their own measuring technology. Where physical laws prevent it from being modified, the researchers develop correction procedures. These include the Pad Correction Procedure (FKFS pace) developed at the Stuttgart-based institute. The process considers the fact that the tire patch contact area is smaller than the belt system of the wheel drive unit.

TOWARDS ACTIVE AERODYNAMICS

SUVs and race cars need to be more than fuel efficient. One objective of aerodynamics is to minimize airflow under the car that creates positive lift and reduces road adhesion. Ideally, a downforce is created to press the vehicle to the road surface and enable faster cornering. Large rear spoilers or wings are mainly for the racetrack. This is why manufacturers are starting to focus on active aerodynamics. Air at the front and rear of the vehicle is channeled according to the vehicle speed and

“THE NEW FUEL ECONOMY CYCLES AND A FUTURE WLTP WITH HIGHER AVERAGE SPEEDS WILL INTENSIFY THE FOCUS ON AERODYNAMICS.”

Holger Winkelmann, BMW

"WE’RE PULLING OUT ALL THE STOPS IN AERODYNAMICS AND STILL SEE POTENTIAL FOR WHEELS, COOL AIR FLOW THROUGH AND AROUND THE VEHICLE, AND FOR THE UNDERBODY IN GENERAL.”

Dr. Moni Islam, Audi

“ANALYSIS OF AIRFLOW ON A NEW VEHICLE ALSO EXTENDS TO OTHER FACTORS THAT ARE IMPORTANT FOR CUSTOMER SATISFACTION, SUCH AS VENTILATION AND DEMISTER PERFORMANCE, AND WATER MANAGEMENT AND SOILING REDUCTION ON EXTERNAL SURFACES.”

Andy Scrimshire, Jaguar Land Rover

With electrically driven vehicles, aerodynamics can help reduce battery costs.

With recuperation

Without recuperation

Less resistance, more distance:

In the New European Driving Cycle (NEDC), a one-percent improvement of the aerodynamic drag coefficient saves € 39 in battery costs, if recuperation is taken into account. By comparison, lowering vehicle weight by one percent saves € 52, but costs the same – or more.
Climate change can only improve from cars that customers will accept. That’s why acoustic measurement is important.

Large rear spoilers are now almost obligatory in Formula Student — at least if you want to win, like the up-and-coming engineers from Stuttgart.
WE STILL HAVE A LOT TO LEARN

Aerodynamics is facing new challenges. Future vehicle generations need to be more efficient – despite real-world road conditions. An interview with Professor Jochen Wiedemann from the University of Stuttgart clarifies some of the key issues.

Today’s passenger cars achieve drag coefficients that were only possible with experimental vehicles 25 years ago. Have we reached the limit of aerodynamics?

Of course not. There is probably a point at which it is no longer possible to achieve a better drag coefficient, but this is debatable. Some say that a \( c_d \) of 0.20 is the limit for series production cars. Nevertheless, we need to look beyond the drag coefficient and focus on lift and the forces exerted on the sides of a vehicle.

Why is there so little mention of this?

Because we still don’t fully understand the implications of different coefficients. Industry specifications usually stipulate a maximum lift coefficient of 0.1. But no one can explain this. As engineers, we need to take a critical look at the issue. Aerodynamics is an element in overall vehicle dynamics. Both aerodynamics and vehicle dynamics involve the forces an occupant senses and reacts to in the vehicle. To study a driver’s reaction in a simulator we need the right forces as input parameters – and this brings us to the tests we conduct in the wind tunnel.

But forces in the wind tunnel are measured under constant driving conditions.

Yes, this has been the case up until now. Generations of aerodynamics engineers have worked to make the inflow of air over the vehicle in the wind tunnel as uniform as possible. But on the road, airflow is anything but uniform. This is a result of meteorological conditions, but is also due to traffic conditions: other vehicles on the road create wake turbulence. We can now demonstrate this in our new wind tunnel by creating a transient inflow of air with a side wind generator and then measuring it. The resulting forces can be made available as measurement data or used in the simulator to give the driver a realistic impression.

What is the goal of this technology?

It is basically possible to influence the forces and momentum that affect the vehicle by modifying the bodywork. This can also be achieved by changing the weight distribution and center of gravity. We still have a lot to learn about what the average driver perceives as comfortable or uncomfortable. Our assumption is that it’s not so much a matter of a
vehicle that doesn’t react. It’s a matter of ensuring the reaction can be anticipated, so that the driver remains in control of the vehicle at all times.

Can the technology be used to design safer vehicles that are also more efficient?

Similar to aerodynamics, the data currently used to measure efficiency is not measured under realistic conditions. Wind tunnel construction is based on the principles of aeronautics – and there is hardly any turbulence at a high altitude. Simulating conditions on the road requires a vortex generator, which we now have with the FKFS swing. This system is designed to reproduce the spectrum of conditions we have established in long-term driving tests. And this affects how we determine the drag coefficient. A model has been established in the U.S. where the drag coefficient for trucks is measured by factoring in the average wind angle based on the wind direction. A vehicle that exhibits the lowest coefficient with a 0° angle of inflow may not be the most efficient. A minimum range is perhaps more important than an absolute lowest minimum.

What about future comparability of measurement data from different wind tunnels?

This is already a tough problem. Wind tunnels have been set up to analyze vehicles with rotating wheels since the mid-1990s. A measurement with motionless wheels doesn’t really make sense. But there is no standard procedure. It is still a long way until uniform measurement parameters are specified for inflow with transient wind.

What role does the changeover to WLTP (Worldwide harmonized Light vehicles Test Procedures) play for the further development of aerodynamics?

There is a demand for more wind tunnel time. In the future, the additional fuel consumption resulting from certain add-on parts or wheel/tire combinations must also be measured. However, the surge in demand also lies in the stronger segmentation of what is available.

Where do you see potential for using aerodynamics to improve the fuel efficiency of modern vehicles?

There is potential everywhere. Options for improving drag coefficient can be found in the underbody, wheels and wheel wells. You also have to be able to correctly determine the ventilation factors. This is something we can do with our new system. The potential for improvement largely depends on fuel prices. In the face of higher prices, car buyers are more likely to accept things that they would otherwise reject. This includes, for example, a smaller frontal area and restrictions in the design.

But in reality, the frontal area is becoming bigger with the growing popularity of SUVs.

Indeed, the size of the frontal area is continuously increasing. This makes a favorable drag coefficient even more important. At the same time, a taller silhouette makes the vehicle more susceptible to crosswinds. This is important because current demographics indicate that drivers are becoming older. There is a growing demand for cars that handle well – which is why many of today’s cars are equipped with self-correcting steering systems.

How important is aerodynamics for electric vehicles?

When it comes to increasing the range of electric vehicles, improving aerodynamics is much more cost effective than installing bigger batteries. In the New European Driving Cycle (NEDC), a one percent improvement of the aerodynamic drag coefficient saves € 39 in battery costs if recuperation is taken into account. By comparison, lowering vehicle weight by one percent saves an average € 52, but costs the same amount – or more. In many cases, improving vehicle aerodynamics doesn’t cost anything.

In other words, as an aerodynamics engineer, you will have plenty of work in the future.

Definitely! Research on transient inflow is still in the early stages. At the same time, we are just starting to develop active systems that can influence vehicle aerodynamics based on specific driving conditions. Our goal is to continuously develop measurement technologies. This means that we need to clearly understand and correct the errors in wind tunnel measurements.

**WE NEED TO LOOK BEYOND THE DRAG COEFFICIENT AND FOCUS ON LIFT AND THE FORCES EXERTED ON THE SIDES OF A VEHICLE.**

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**“WHEN IT COMES TO INCREASING THE RANGE OF ELECTRIC VEHICLES, IMPROVING AERODYNAMICS IS MUCH MORE COST EFFECTIVE THAN INSTALLING BIGGER BATTERIES.”**

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Excited about the job and focused on detail — that’s how FKFS engineers and employees felt when planning, building and commissioning the new wind tunnel. They’re seldom satisfied with what they’ve achieved, because there is always something to improve. With this attitude, they constantly drive aerodynamic development forward.

Following reconstruction by operator FKFS, testing conditions in the reopened University of Stuttgart wind tunnel are closer to real-world than ever before. Along with updated measuring technology, a newly installed system simulates gusting road winds.

“Planning replaces coincidence with error.” This witticism is scrawled on a board amid project drawings and schedules in Reinhard Blumrich’s office. As the aeroacoustic wind tunnel consulting manager at FKFS, Blumrich shares project coordination responsibility with operations manager Armin Michelbach. A physicist with a PhD in acoustic engineering, Blumrich is quick to point out that coincidence and error are not his cup of tea. At the same time, he makes it clear that an upgrade project as complex as the one undertaken by FKFS demands nerves of steel and lots of flexibility.

Twenty-five years after the wind tunnel went into operation in 1989, the project that started in December 2013 aims at bringing vehicle testing in line with real-world conditions. The engineers want to create reproducible conditions and bring measuring technology as close as possible to typical on-the-road conditions.

Completed in 1993, the first major update of the wind tunnel had essentially the same goals. Originally designed as a purely aerodynamic wind tunnel, acoustic damping of the airflow in the testing chamber made it possible to take aeroacoustic measurements. A traversing gear installed below the ceiling was used to precisely position microphones and other instruments. The upgrade was successful. Prior to modernization, the wind tunnel noise level was 91 dB(A). After the aeroacoustic conversion was completed, the noise level dropped to 69 dB(A) at 140 kph. The wind tunnel was among the world’s quietest for many years.

A second upgrade project completed at the start of the new millennium was aimed at improving on-road simulation. This involved the integration of a steel belt and wheel rotating system on the wind tunnel floor. The center belt on the five-belt system simulates the roadway. Two shorter belts left and right of the center belt drive the car wheels and can be adjusted for vehicle wheelbase and track width. For many years, the moving belt and boundary layer control systems were among the wind tunnel’s unique advantages.

The modernization work completed in 2014 integrates advanced measurement technologies in an innovative environment for scientific research and customer operations. Special attention was focused on optimizing wind tunnel acoustics to accommodate quieter cars and meet the demand for aeroacoustic testing. Thus, the wind tunnel background noise has been reduced in several ways.
steps from 73 dB(A) at 160 kph to 68 dB(A) at 160 kph. The initial design concept and planning began in 2008. Professional planners were brought onboard in 2009 to coordinate the various optimization measures. It soon became apparent that in-depth modernization was needed at the heart of the wind tunnel, the electromechanical weighing system that records airflow-related forces on the vehicle. Nearly a quarter century of measuring operations had left its mark on the old system. It was becoming more difficult to obtain replacement parts and the data recording system was no longer state-of-the-art.

It was also important to improve on-road simulation with a universal modular steel belt system that covered more ground area on a larger turntable. The specially designed system combining a steel belt, weighing balance and turntable was ordered in 2011 so that it would be ready for the reconstruction project scheduled to start in December 2013.

NEW WIND TUNNEL HIGHLIGHTS:
• FKFS **Swing** (Side Wind Generator) to simulate driving in a transient crosswind
• FKFS **besst** (Beland Silent Stabilizer) for aerodynamics and aeroacoustic measurements without buffeting
• FKFS **First** (Fully Interchangeable Road Simulation Technology) based on three/five belt ground system

The FKFS **First** road simulation system is designed for testing series production vehicles and race cars (see page 30). The FKFS **besst** system features vaulted airflow guide elements positioned at the nozzle exit. This system suppresses buffeting and reduces wind tunnel noise (see page 40).

The Side Wind Generator (FKFS **Swing**) is an FKFS innovation that makes it possible to quantify and model transient effects on aerodynamics, vehicle dynamics and aeroacoustics and map this information in the wind tunnel. This represents a further step toward simulating real-world conditions.

The people who played a key role in developing the FKFS **Swing** include Matthias Riegel, group leader for acoustic measurement and analysis technology at FKFS, aerodynamics engineer Daniel Stoll and former PhD engineer David Schröck. These three men refused to be satisfied with the conventional aerodynamic and aeroacoustic development process based on stationary parameters established in the wind tunnel with low-turbulence airflow. For measuring aerodynamic forces, momentum and aeroacoustic noise during a crosswind, the vehicle is simply rotated in the wind tunnel relative to the airflow to achieve a stationary flow angle.

This process does not take into account the fact that wind velocity and direction continuously change. Unlike the conventional method, FKFS **Swing** simulates natural wind gusts. Instead of rotating the vehicle, flow deflection occurs dynamically with eight wing profiles arranged vertically on the air flow path. In the basic application, the system creates a flow field which is uniform in lateral direction in order to simulate typical airflow conditions on the road.

Preparatory work in the scale model wind tunnel demonstrated the effectiveness of the new concept. It also showed that the four-meter-long wing profiles must be lightweight and extremely rigid. This is why Riegel and Stoll requested assistance from two other institutes at the University of Stuttgart. The aerodynamic design of the wing system was developed by the Institute for Aerodynamics and Gas Dynamics in the Aerospace Technology and Geodesics department. The Institute for Aircraft Engineering managed construction of the wing profiles made from carbon fiber reinforced composite materials. Another complicated task involved optimizing the wings’ electric drive system to minimize interference frequencies and oscillations.

The new process will improve research and assessment of vehicle crosswind behavior in the future. Matthias Riegel also sees opportunities to use the system for developing new testing and analysis processes for measuring transient wind noise. This brings aerodynamics and aeroacoustics experts at the university another step closer to simulating real-world conditions.
WORLD first TECHNOLOGY

The new FKFS first interchangeable steel belt system in the University of Stuttgart wind tunnel features world-leading technology that enables FKFS engineers to measure more precisely than ever.

People who deal with large masses and tight tolerances all day don’t believe in compromises. This is the principle followed by Armin Michelbach, chief operating engineer since 1988 and FKFS wind tunnel operations manager since 1998. The mechanical engineer and self-confessed rivet head is not only a witness to the continuous optimization of the Stuttgart wind tunnel over time. He is a driving force behind the move toward more precise and realistic measuring techniques.

BENEFIT FROM THE SHOWER MAT

This conversion to a steel belt system in 2001 contributed to improving measuring precision. The old rubber belts reacted to the downforce beneath the vehicle underbody by slightly arching, which affected the measurement results. The 0.8 mm steel belt system currently in use has a special adhesive film similar to an anti-slip shower mat that provides a textured surface that simulates a more realistic tire/road contact surface.

The recently completed upgrade of the large wind tunnel in Stuttgart with steel belt technology goes a step further. New installations include the patented new FKFS first (Fully Interchangeable Road Simulation Technology) moving belt system and a new weighing system—the heart of any wind tunnel. Other updates include a turntable device for measuring performance at different angles to the wind direction. The balance and all other devices which are necessary for ground simulation form a unit.

BENEATH THE TURNTABLE

More than 100 tons of components delivered in 16 shipping containers were assembled over the months of reconstruction. In the process, FKFS engineers combined the best of two worlds. A to the maximum improved five-belt system used for testing passenger cars mostly can be converted to a three-belt system that is long and wide enough to test race cars. The two systems differ in their structure. In the five-belt system, a 7.80 m long center belt simulates the road surface. Water-cooled 80 kW drive motors are capable of belt speeds up to 80 m/s (288 kph). Four small belts, each driven by 35 kW motors serve as the contact surface and drive units for the wheels.
The FKFS aeroacoustic wind tunnel has a horizontal air path with an open jet test section. In order to simulate airflow conditions of a vehicle driving on a road surface as realistically as possible, the test is conducted with turning wheels and moving ground in the wind tunnel. This is done by using a five-belt system with one center belt and four wheel drive units, or by a three-belt system which comes with one center belt and two side belts, depending on the required testing specifications. The largest proportion of the 100 tons delivery of structural parts is located below the stainless test section plates, including the highly dynamic and precision balance, drive units and suction system for boundary layer conditioning.
With the three-belt system, two lateral belts, 1.10 m and 5.70 m long, are installed left and right of the center belt and serve as a rotating device for the wheels while providing additional ground coverage.

In the design phase, it became apparent that a five-belt system reaches its limits with certain vehicles—especially those with automatic ride height adjustment systems. The reason is the flow conditions of the ground boundary layer. With FKFS’s five-belt system, it is now possible to combine and compare measurements on a five-belt system and a three-belt system in a full scale wind tunnel, without unreasonable changeover expenses. Since only the ground changes and all other external conditions remain the same, the limiting conditions can be regarded as constants. This makes the measurement results comparable and therefore more meaningful.

HIGHLY SENSITIVE MAMMOTH DEVICE

Comparability is also enhanced by the new, highly-dynamic scale system. Based on strain gauge measuring technology, it uses load cells to determine within micrometers the pressure changes that cause path alterations on the strain gauges. The sensitivity of the multi-ton device is demonstrated by the following: with a load from zero to four tons, the length of the measurement strips changes by only five micrometers. In other words, the mammoth device is as sensitive as the scales used for weighing letters.

The scale simultaneously tracks six aerodynamic factors: flow resistance in the direction of travel, crosswind components, lift, roll, pitch and yaw. According to Michelbach, the static precision represents the limits of what is technically feasible.

Dynamic testing can also be performed on different designs. This is important for the future because optimizing vehicles for constant incoming flow conditions when driving straight forward is no longer regarded as an important factor. These conditions are real, but only significant for a small fraction of driving situations. In most cases, flows are most angled from the front of the vehicle with an impact on both dynamics and comfort. Using the FKFS’s five-belt system in combination with the FKFS’s swing dynamic crosswind generator enables FKFS to more realistically simulate and research these load conditions.

Perfect test results are not simply a question of technological excellence. They are also a product of the careful attention to detail by the technicians and mechanics responsible for daily operation of the Stuttgart University wind tunnel.
When André Nagel starts his morning or afternoon shift, he never knows for sure what awaits him. He has testing schedules and configuration plans to give him an overview of his daily activities, but this is where all predictability ends. Is the car to be tested arriving via air cargo from the desert? If so, it will have to be carefully washed before it heads for the wind tunnel. Or will a component part break away and fly through the tunnel? That may require some heavy-duty tape and creative improvisation.

**TRAFFIC COMING AND GOING IN THE WIND TUNNEL**

Unpredictability is one of the things Nagel finds most exciting about his job as a measurement technician in the aeroacoustic wind tunnel operated by FKFS at the University of Stuttgart. Even when it requires shift work and overtime on Saturdays. To ensure the testing program runs as smoothly as possible, the four measurement technicians who operate the wind tunnel are joined by eight mechanics responsible for preparing the vehicles. One measurement technician and two mechanics are present during normal operations. If aeroacoustic measurements are on the job list, an acoustician joins the team and takes his place at a second master display across from Nagel’s control console.

With traffic coming and going on the ground floor of the wind tunnel building, the atmosphere is anything but relaxed. Two to four trucks a day drop off and pick up vehicles. The mechanics start off by spending three to five hours unloading and washing vehicles, changing tires and preparing for the test program. These are just a few of the steps required before a freight elevator transports the vehicles to a facility where they are set up for testing. These procedures differ for each measurement process and are precisely outlined in work instructions.

**30 SECONDS OF MEASUREMENT BRINGING LOTS OF NUMBERS**

Once all the steps are complete, Nagel starts up the wind tunnel fan, which reaches the testing velocity of 140 kph within 20 seconds. Measurements are taken and the procedure is over in three minutes. Depending on how many changes are required for a vehicle, 70 to 100 different measurements can be completed in a single day.

Aerodynamic force measurement is by far the most common task. For this, a prepared vehicle with rotating wheels – powertrain disengaged – is attached to the wind tunnel balance with four pillars. Sandbags are used to adjust the standing height. A short test run follows to see if everything moves freely and the wheels turn. Pressing the start button resets all systems to zero. Fans, belts and all other sub-devices come up to speed and are adjusted to a preset calibrated point, such as 140 kph. After about 20 seconds, everything is running smoothly and the measurement values are recorded for about 30 seconds. After the systems are powered down the test configuration is modified for the next task and the process starts anew. This results in Reynolds runs, yaw runs with increments of one degree or more and ride height sweeps.

**LASER BEAM REFLECTIONS AT A WHITE WALL**

For pressure distribution measurements, probes are positioned on the vehicle surface. They guide wind through tubes into a pressure measurement system. This provides information about flow conditions and is usually performed at various levels and angles. In less frequent configurations, a total pressure rig is placed behind the vehicle to measure the pressure deviation behind or beside a car. For measuring the front surface, the vehicle is scanned with low-power laser beams. This light is reflected
by the body and redirected to a white wall. In the following step, the projected images are digitally processed to determine the frontal area of the vehicle.

**DUMMY HEADS, MICROPHONES, AND PLENTY OF ADHESIVE TAPE**

When aeroacoustic measurements are required, the vehicle is set up with recording devices including plastic dummy heads and microphones. Measurements are taken at three standard speeds (90, 140 and 200 kph) and two different flow angles. This is usually done with the vehicle in delivery condition. Afterwards, adhesive tape is used to close up all of the vehicle’s joints and panel gaps. New tests are carried out and the strips of tape are gradually removed before further measurements are taken. If the sound level rises abruptly after a piece of tape is removed, the experts know that they have localized a significant source of noise.

Modernization of the wind tunnel not only improved measurement precision and variance. The highly complex upgrade and expansion also changed everyday work routines for André Nagel and his fellow team members. This is because special knowledge and skills are required to operate the new FKFS swing and FKFS first systems. Once this advanced technology is in full operation, things will return to business as usual. But there will still be a demand for close attention to detail, spotless work conditions, improvisational talent – and a plenty of adhesive tape.
Aerodynamic and aeroacoustic testing often focus on eliminating disturbance variables. The engineers at FKFS are always coming up with new ideas for more precise measuring.

Even when a civil engineer and an aerospace engineer look at a wind tunnel from the same angle, they see it from different perspectives. But Oliver Beland and Nils Widdecke still have one thing in common. Both managed to solve problems that aerodynamics experts had been working on for generations. They both contribute to high-quality wind tunnel testing at FKFS with their patents, which result in near real-world road conditions.

COPING WITH LOW PRESSURE
The careers of the two engineers are just as different as their contributions to wind tunnel technology. Widdecke, department head of vehicle aerodynamics and thermal management at FKFS, has long focused on issues directly related to measurement precision in the wind tunnel. The wheel drive units used in the tunnel do more than rotate wheels. They are also connected to the wind tunnel balance, which measures the forces in the tire contact area as well as the forces that act on the vehicle laterally or longitudinally.

The following scenario is a regular occurrence in the wind tunnel. When air flows around the vehicle, it causes a low pressure region between the vehicle and the ground, which dynamically creates downforce on the underside of the vehicle. However, because the surface of the wheel drive units is larger than the tire contact area, the low pressure acts on the uncovered part of the weighing elements. This shifts the measurement results, because additional lift force is measured that does not exist in a real driving situation.

This phenomenon has been known for a long time. In older wind tunnels with board or roller systems, it was partially ignored. Sometimes correction factors were determined and integrated into the measurements. But neither of these approaches proved satisfactory. The situation was aggravated by the introduction of wheel drive systems, because they increase the attack surface for the low pressure. Many attempts were made to resolve this unsatisfactory situation. However, there was no way to implement the idea of measuring the pressure on the moving surfaces of the wheel drive belts. Attempts to measure using similarity correspondences to stationary points proved unsuccessful.

BEYOND THE SEIFERTH WINGS
The solution occurred to Nils Widdecke on his way home from the institute. And the idea is as simple as it is impressive. It entails measuring twice and eliminating one of the influential factors during one of the test runs. In practice, this means that during the second test run the vehicle is no longer attached to the balance by the rocker panel struts but rather directly to the wind tunnel floor, so that all forces that are directed onto the vehicle are no longer detected by the balance. The difference between the two measurements provides the sought-after correction value. This patented process is now known as Pad Correction Procedure or FKFS pace. Extensive testing in the model wind tunnel has verified the idea, which has since led to more precise measurements.

Oliver Beland, who works on FKFS interdisciplinary projects and high performance computing department, focused on a different issue dealing with...
the occurrence of low-frequency fluctuations of velocity and pressure in the wind tunnel’s plenum hall. This resonance excitation is known as “wind tunnel buffeting” and has long been suppressed by various means. One common approach is the use of Seiferth wings to influence the vortex structures at the nozzle edge. However, when air flows across these wings, they produce inherent noise and are therefore only suitable for aerodynamic measurements but not for aeroacoustic measurements. The recent reconstruction project called for a configuration that would be equally suitable for aerodynamic and aeroacoustic measurements. Therefore, a new solution had to be found.

INNOVATIONS REQUIRE TEAMWORK
Beland initially experimented with a 1:20 scale model wind tunnel and found a way to suppress the buffeting using vaulted airflow guide elements. These elements are arranged directly in front of the nozzle exit. If nothing is done, the pressure fluctuations at some airflow speeds surpass 4 percent of the prevailing dynamic pressure in the open jet. The airflow guide elements reduce this value to about 0.5 percent and are at least as effective as the conventional Seiferth wings – without producing additional noise. The invention has since been patented as the Beland Silent Stabilizer, or FKFS besst.

Innovations like these require teamwork. An FKFS innovation group routinely discusses emerging problems and explores possible solutions. The institute’s flat hierarchies support informal knowledge sharing. Certain aspects can be investigated by assigning theses to students working in bachelor’s or master’s degree programs. Nevertheless, the projects usually require a driving force, a person at the helm to give the innovation a name.
What a great driver! He spends hours behind the wheel on the highway and never gets tired. He reacts to potentially dangerous situations within a fraction of a second. He never makes a mistake and knows the exact limits of his car’s driving dynamics. Dozens of sensors keep him constantly aware of his surroundings. Traffic accidents? A thing of the past.

This is basically the vision of today’s premium automakers, who are working intensively on replacing the human driver with a computer. Not without reason. According to a Volkswagen research study, more than 93 percent of all accidents are attributed to human error. The number of accident victims in Europe has continuously declined in recent decades. It appears that we have reached a point where further progress is only possible through automated driving.

MAIN CHALLENGE: THE HUMAN FACTOR
A number of hurdles must be overcome before the vision can be implemented in series production technology. One of the most difficult challenges facing research institutions and engineering departments is the human element. For the foreseeable future – perhaps even for decades – human drivers will be able to overrule automatic functions in the automobile. The self-driving car will not suddenly appear someday on the showroom floor. To meet current regulatory guidelines, manufacturers are introducing semi-automated systems that only operate at moderate speeds on the highway. The driver must take control as soon as the vehicle leaves the predefined speed range.

“FKFS is successfully networking the driving simulator with its wind tunnel and other in-house testing facilities. This enables us to assess the driver’s reaction and the benefits of new assistance systems based on scientific criteria.”

Cars of the future will be capable of covering great distances – automatically! Engineers are already working on the technology and developing a new game plan for the relationship between drivers and automobiles. The networked testing technology developed by FKFS plays an important role.
seven meters. The system enables acceleration of up to 0.6x the force of gravity. In the simulator, an emergency stop on a wet road surface feels just like it does in real life: scary.

A camera installed in the passenger compartment monitors driver reaction in emergency situations and correlates this information with objective measurements. This is an important prerequisite for testing new driver assistance systems and autonomous driving functions. Twelve projectors inside the dome generate an overlapping 360° image without white spots or seams. Looking in the rear view mirrors the driver sees the exact same image he would see on the road. This requires enormous computing power that is handled by 25 PCs connected in parallel.

But how do the computers get their input? In order to design the driving routes realistically, FKFS engineers worked in cooperation with various carmakers to model the complete “Stuttgart Cycle” – including landscape images. However, this immense effort only makes sense if the virtual landscapes are also used for developing new vehicles equipped with the innovative technologies.

NETWORK OF TESTING FACILITIES
To achieve this, FKFS is successively networking the driving simulator with its wind tunnel and other in-house testing facilities. The dynamic forces that act on a new car body can be captured and precisely transferred to the driving simulator. “This enables us to assess the driver’s reaction and the benefits of new assistance systems based on scientific criteria,” explains Dr. Werner Krantz, who is responsible for these projects at FKFS.

The benefit of networking will become apparent when it comes to developing a vehicle that operates autonomously on all roads. According to a Bosch study, testing a self-driving car with the same thoroughness that today’s engineers use to assess an ABS blocking system would require more than one billion hours – a little more than 100,000 years. Even if this workload could be shared by many different players, it would exceed the capacity of even the largest engineering departments. Many experts see the only viable solution in a comprehensive model, the indefatigable autopilot could one day become a reality. And it may even be capable of compensating for the unpredictability of humans.

This leads to the question of how humans and technology interact. From the machine’s perspective, human behavior is unpredictable, or very random in nature. This has been a focus of research at FKFS for many years. A key tool in this respect is a large driving simulator unlike any other installed at a university anywhere else in the world. Uniquely realistic, it gives testers the sensation of driving on a genuine real-world road. This begins with the fact that the subject test person is sitting in a real car with a steering wheel, brakes and accelerator pedal. Except that the car is located in a dome, a type of 3D movie theater, which in turn can be moved freely in space.

Part of an effective testing network: The FKFS driving simulator – a kind of 3D movie theater, which can be moved freely in space.
The new wind tunnel at the University of Stuttgart Institute for Internal Combustion Engines and Automotive Engineering is anything but a standalone facility. Its performance potential unfolds in combination with scale model and thermal wind tunnels using advanced calculation methodologies.

In late 1987, as final work was being completed on the large new aeroacoustic wind tunnel, its smaller sibling was already providing measurement results. These familiar roles continue today. Even though the small wind tunnel can only test models at 1:4 or 1:5 scale, it plays an important part in aerodynamic vehicle development. Among other things it is used to cost-effectively validate earlier design proposals. “The model wind tunnel plays a strategically important role,” says Armin Michelbach, operations manager for all FKFS wind tunnels.

The model wind tunnel has a dual identity as a tool for customers and for FKFS, which uses it for developing in-house testing and measuring technologies. Before the new FKFS swing system for simulating crosswind gusts on full-size vehicles was built, comprehensive testing in the model wind tunnel confirmed feasibility.

The model wind tunnel has been equipped with a five-belt system since 2001. This enables simulation of real-world conditions with oncoming flow conditions on a moving vehicle. It makes sense, because – contrary to what press photos showing clay models of new vehicles would make you think – only the body structure is made of clay. The underbody and chassis are usually constructed in great detail. This means that on-road driving with rotating wheels and moving ground can also be simulated in the model wind tunnel. Despite miniaturization, this provides astoundingly precise results. Michelbach figures that the $c_d$ values between the model wind tunnel and the large aeroacoustic wind tunnel deviate by no more than five drag counts. Another contributing factor is the highly dynamic balance from Japan, which was added in 2013. Aside from its dimensions, the model wind tunnel differs very little from the large FKFS wind tunnel.

The model wind tunnel has played a decisive role in Michelbach’s career. This is where he discovered his passion for aerodynamics as a student assistant. People who start out with small models can obviously work their way up.

*Preparation in a smaller world:*

The model wind tunnel is a testing tool for customers and FKFS.

LITTLE BROTHER

In great detail: Underbody and chassis of vehicle clay models (top) as well as modern measuring technologies in a miniaturized environment provide precise results.
Torturing vehicles is how Jens Neubeck and Wolfgang Mayer describe their work. More than just aerodynamic and aeroacoustic fine-tuning is on the list of things to do for Neubeck, head of vehicle technology and dynamics, and Mayer, who is in charge of the thermal wind tunnel. They manage a wide spectrum of tasks, ranging from engine water intake in rainy weather and accumulation of water droplets on the side windows, to airflow through the engine compartment and cooling under extreme conditions. Regardless of the season or weather, tests on drivetrain and brake behavior along with many other thermal, vibration and aerodynamic issues can be handled under reproducible conditions.

The thermal wind tunnel is a powerful two-axle roller test bed that is integrated into a chamber with a closed air duct. Adjustable wheelbase with custom anchoring options make it possible to test all standard vehicle models. System specifications: for each vehicle axle, the installed drive and braking power is up to 500 kW, the tractive force ranges to 20 kN, and the maximum oncoming airflow speed is 245 kph. A heat exchanger built into the air duct allows temperature control ranging from +20°C to +50°C.

For soiling tests, water droplets with fluorescent agents are added to the airflow and made visible using a black light. An FKFS patented process allows automatic evaluation and quantification of the resulting soiling. A variety of custom tests demonstrate the versatility of the thermal wind tunnel. Examples include stationary and cyclical driving performance measurements, simulation of towing operations, or tests of the transmission design. Neubeck and Mayer have also conducted tests on products other than vehicles, including shingles for water and wind resistance, tents designed for Antarctic expeditions and wind turbines. They even received a request for assistance on shooting a TV film on ski flying. But the true focus of their work is on automobiles, which must be capable of providing the right level of comfort at all temperatures and in any weather. Torturing cars clearly benefits the people who buy them.

Timo Kuthada is a passionate aerodynamics expert – even though he spends most of his days in front of a computer. This isn’t a matter of personal preference. Computational fluid dynamics (CFD) simulation is indispensable in modern aerodynamic development. While in many other engineering disciplines calculation is gradually supplanting hands-on testing, it can’t replace real wind tunnel tests in the engineering process.

Kuthada is in charge of transverse projects and high-performance calculations at FKFS. He sees CFD as a valuable tool that can support engineers in the product development process. For analyzing airflows, simulation can help in areas that are hard to assess with measurement technology. FKFS has a formula for this situation: combine digital simulation and real wind tunnel tests and use the best tool for each application. A good example of this principle can be found in the underhood area. Although the volume flow rate through the heat exchangers can be easily measured, CFD offers better options for flow analysis in the engine compartment.

FKFS is well equipped for using digital simulation effectively. The high-performance computer system in the wind tunnel building has gradually been expanded and now has more than 1,000 cores that calculate in eight queues of 128 cores. This allows a vehicle made up of 60 to 80 million simulation cells (voxels) to be calculated within one day. Fifteen years ago, the model with 18 million voxels per vehicle was considerably smaller, but simulation time could take up to seven days.

Aerodynamic simulation of virtual vehicle models is not the only thing that keeps the computers running at peak capacity. Vehicles are also simulated in the wind tunnel to optimize the system or to develop new test procedures. For example, before the scaled-down prototype of the wing for the FKFS swing system was built and tested for the first time in the model wind tunnel – in order to make its way to the wind tunnel plenum – CFD simulations had long confirmed the new system’s basic operation.
A BUMBLE BEE HAS A WING SURFACE OF 0.7 CENTIMETERS AND WEIGHS 1.2 GRAMS. ACCORDING TO THE LAWS OF AERODYNAMICS, IT IS IMPOSSIBLE TO FLY WITH THIS CONFIGURATION. THE BUMBLE BEE DOESN'T KNOW THIS.

Arthur Lassen, German motivation and success trainer

TODAY WE CAN BUILD CARS WITH C\textsubscript{D} VALUES BELOW 0.2. THEY LOOK DIFFERENT FROM TODAY’S VEHICLES. NONETHELESS, YOU CAN DRIVE THEM.

Dr. Teddy Woll, head of aerodynamics for Mercedes-Benz Cars. Inspired by the boxfish, in 2005 Mercedes-Benz presented a compact concept car with a c\textsubscript{D} value of 0.19.