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The driver of the future?

Autonomous cars are coming: how will the art of vehicle dynamics have to adapt for their arrival?

Roll control

John Miles considers the importance of roll control systems, and how to achieve a well-engineered setup

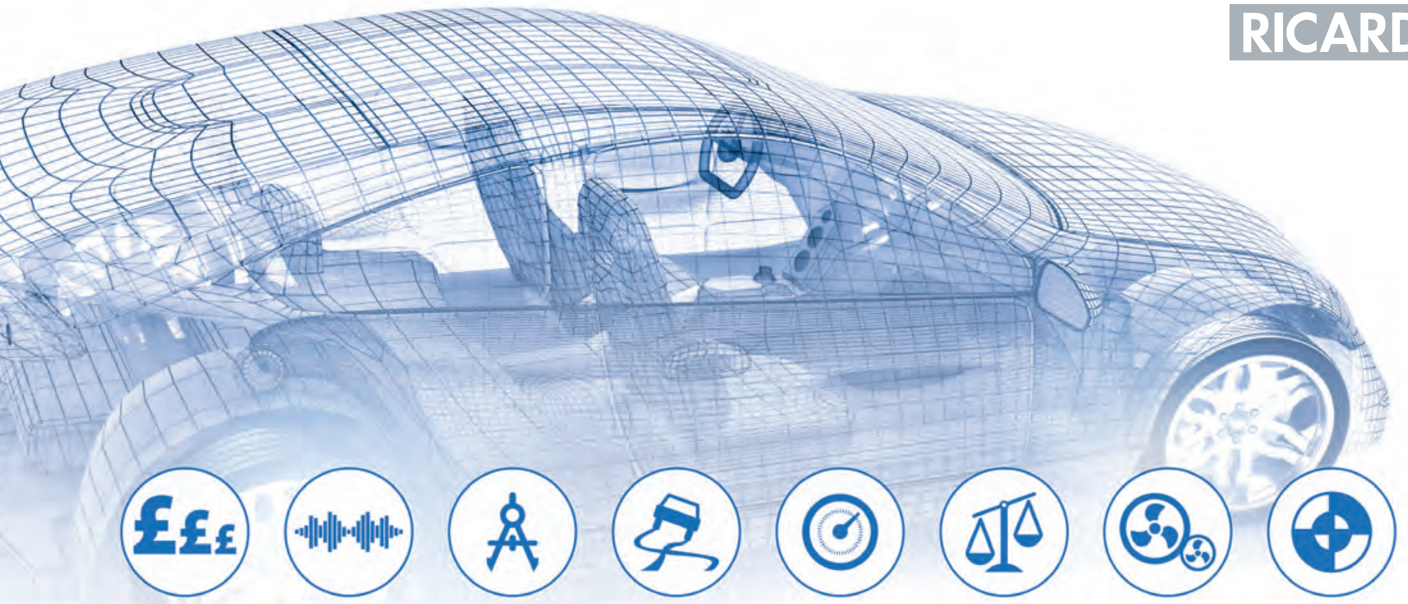
Hydro mounts

A team of academics has successfully modeled hydro mounts for ride comfort and dynamics simulation

Dynamic duo

Two oddities recently entered the dynamics sphere: a road car with ground effects, and a truly retro autonomous vehicle

ANNUAL SHOWCASE 2017



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24 Autonomous vehicles

What effects will driverless cars have on the vehicle dynamics industry? Will engineers and suppliers focus solely on comfort? Will they be less in demand? Vehicle dynamics experts have their say...

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"Dedicated work has to be done on the suspension to allow the driver to watch a film without experiencing travel sickness"

Vincent Abadie, expert leader, controlled chassis systems, PSA Group, p24

A note from the editor

A leisurely journey

Are you sitting comfortably? There is every chance that in the future, all road users will sit comfortably, with autonomous vehicles taking the strain of driving. However, in addition to major changes in lifestyle and the everyday travel experience for consumers, will autonomous vehicles herald a fundamental change in focus for the vehicle dynamics industry?

As roads around the world become increasingly congested, and with the resultant surface damage of that traffic, we are already seeing many car enthusiasts who previously demanded the ultimate no-compromise sporting experience now seeking that perfect balance of ride comfort and cornering performance to make their journeys a little more civilized. The step toward autonomy could see the sole dynamic focus of vehicles become traveling comfort, akin to today's chauffeur-driven fleets.

The art of dynamics will still come into play though, as achieving driverless comfort won't be as simple as creating a soft, wallowy ride in the vein of a 1970s Lincoln Continental. For one thing, the car will still have to be capable of swiftly and accurately responding to threats and obstacles on the road.

Another problem with blancmange-like ride and handling would be travel sickness. A bit of wallowing would be bearable if the vehicle occupants were looking at the road ahead, but as some concepts have suggested, passengers could be sitting in a circle facing the center of the vehicle, and are likely to be watching TV or movies, reading or gaming as they travel. When the body experiences movements that don't match what the eyes are seeing, it can result in nausea, headache and eye strain, and excessive movement during cornering events can further exacerbate these effects – not to mention the peril of meals and drinks being spilled on the carpet.

Roll control will remain a key dynamics attribute, and in this issue dynamics deity John Miles shares his expertise in achieving the ultimate setup on page 16, as does ex-Ford dynamics supremo and founder of Cayman Dynamics, John Heider, on page 12. Their thoughts are well worth investing the time to read, giving valuable insights into roll refinement that will be as relevant in the autonomous future as they are today.

We also gathered the thoughts of OEMs, consultants and academics on the implications of autonomous vehicles for the vehicle dynamics industry (see p24). There are some interesting views, from a rethink of standard dynamics approaches, to dynamicists evolving from being the artists of automotive engineering, into scientists. Some will lament the demise of driving fun in the autonomous future, but the world will appreciate dynamicists' efforts in making journeys and lives safer and more comfortable.

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Making the MARTY (Mc)Fly

MARTY was built in collaboration with Renovo Motors, an advanced EV startup based in Silicon Valley. Working closely together gave the Stanford team early access to a new platform derived from Renovo's electric supercar that delivers 4,000 lb-ft from on-motor gearboxes to the rear wheels in a fraction of a second – allowing precise control of the forces required to drift.

The original gasoline engine has been removed and replaced with the EV technology, managed by a central API. According to the partners, the platform itself is reliable enough that the Stanford team needs only focus its development work on the subsystems and algorithms most important to the research goals.

Other customization work included disassembling and upgrading the DeLorean's frame and suspension, adding a roll cage for safety and torsional rigidity, adding welded frame upgrades, and upgrading the steering system. MARTY has an appetite for rubber, but Bridgestone has offered to provide all the tires needed for the project.

Sideways thinking

A team from Stanford University has gone back to the future to develop an autonomous, electric, drifting automotive research vehicle with interesting potential. **Adam Gavine** meets MARTY, a remarkable DeLorean

An autonomous DeLorean that can drift? Has the engineering team at Stanford University, world-class researchers in autonomous vehicle research, been affected by fumes in the lab?

When Chris Gerdes, a professor of mechanical engineering at Stanford, and his team of students decided to adapt a 1981 DeLorean into a high-performance drifting testbed, it was with a sense of style and humor, but also serious intent, as it is a means for researching the physical limits of autonomous driving.

"We want to design automated vehicles that can take any action necessary to avoid an accident," Gerdes explains. "The laws of physics will limit what the car can do, but we think the software should be capable of any possible maneuver within those limits."

Nicknamed MARTY (Multiple Actuator Research Testbed for Yaw control) as a homage to Marty McFly, the lead character in *Back to the Future* – the cult 1980s film in which a DeLorean was also a star – the car is intended to demonstrate that when developing autonomous driving algorithms, sometimes you need to sacrifice stability to turn sharply and avoid accidents.

A DeLorean disappearing in a cloud of tire smoke of its own making is quite a sight. See the video on our website

"The very best rally car drivers do this all the time, sacrificing stability so they can use all of the car's capabilities to avoid obstacles and negotiate tight turns at speed. Their confidence in their ability to control the car opens up new possibilities for the car's motion," Gerdes states. "Current control systems designed to assist a human driver, however, don't allow this sort of maneuvering. We think that it is important to open up this design space in order to develop fully automated cars that are as safe as possible."

Thus the team is programming MARTY to autonomously decide when it is appropriate to sacrifice stability for safety, and to drive with the fluidity and precision of a professional driver, precisely controlling the path and angle of the car, coordinating throttle and steering to ensure that the car does not spin.

At present the car can autonomously lock itself into a continuous, precisely circular donut at a large drift angle, with the next step being to teach the car to race around a track using drifting techniques to negotiate tight turns around obstacles.

One of Gerdes' ultimate goals is for MARTY to drift alongside another car driven by a professional driver, demonstrating superior maneuvers, while also anticipating the driver's movements to avoid collisions.

"A drift competition is the perfect blend of our two most important research questions – how to control the car precisely and how to design automated vehicles that interact with humans," Gerdes adds. "While we aren't picturing a future where every car produces clouds of white tire smoke during the daily commute, we do want automated vehicles that can decipher the subtle cues drivers give when driving and incorporate this feedback when planning motion. Drifting is a way to study these larger questions, with style."

Squat **thrust**

Ariel is developing technology that creates massive downforce, even at standstill. Currently fitted to an Atom test mule, this innovation could have mainstream potential, finds **Adam Gavine**

The Atom is not a car known for compromised vehicle dynamics – or indeed any compromise in the pursuit of performance – but Ariel's engineers have devised a new concept version designed with innovative passive and active aero concepts intended to minimize aerodynamic drag, optimize cooling and airflow, as well as improve vehicle stability and safety. The result is the Aero-P, and Ariel says that this prototype generates downforce at any speed – including standstill – without the use of aerofoils.

"We're moving toward the point where traction and therefore acceleration, particularly from standstill, are limited by mechanical grip, so we're trying to come up with ways to overcome this," explains Ariel director Simon Saunders.

Inspiration for the concept came from racing cars with ground effects, including the 1970 Chaparral 2J 'sucker car' and the 1978 Brabham BT46B Fan Car.

The Aero-P's downforce system is powered by two small, high-speed fans, with a molding and rubber skirts added to the bottom of the tub, as well as ducting and a standalone battery pack.

The fans spin up very quickly, so the system can be activated when downforce is required – either manually or automatically – whether under acceleration, cornering or braking. The fans only run when needed, aiding vehicle efficiency during cruising and fast straights.

"When the system is turned on, the car visibly squats on the ground so you can see it working, which is pretty exciting," adds Saunders.

"We're already making about three times the downforce as our existing aerofoils, but this really is just the first step and a very early stage in what is a large and complex project to bring to a production reality, so we have a lot more work to do."

The Aero-P's downforce has led the Ariel engineering team to nickname the prototype 'the vacuum cleaner'

Greater potential

Simulated performance times and bench testing of full-size Aero-P prototypes is being carried out by Delta Motorsport, based at Silverstone, UK. Delta's engineering director, Nick Carpenter, believes the technology has potential beyond track-focused cars such as the Atom: "As with many of the projects we're working on today, we see the trickle down from high-performance vehicles to conventional passenger cars over time, so it's great to be ahead of the curve with these new technologies."

Turn to page 16 for a feature on roll control engineering

...Roman Bielak, technology development manager, BWI Group

"The challenge with passive dampers is to retain the price advantage while closing the performance gap on active systems"

Although adaptive suspension systems often capture the headlines, a great deal of further development on passive dampers goes on behind the scenes. *Vehicle Dynamics International* spoke to Roman Bielak, technology development manager at BWI Group, about some of the latest advances.

WHAT CAN BE DONE TO IMPROVE THE PERFORMANCE OF CONVENTIONAL PASSIVE DAMPERS?

The challenge with passive dampers is to retain the price advantage while closing the performance gap on adaptive systems. One way to do this is by cushioning the so-called 'spike' loads that normally occur at the limits of travel, allowing chassis designers to make greater use of the available damper movement to improve occupant comfort and chassis refinement.

WHY IS THIS IMPORTANT FOR VEHICLE MANUFACTURERS?

As manufacturers seek to differentiate their products without incurring additional cost, one of the most effective ways is to endow a vehicle with a 'premium' feel through improved refinement. For a damper manufacturer, this means improving ride comfort without impairing vehicle handling and control.

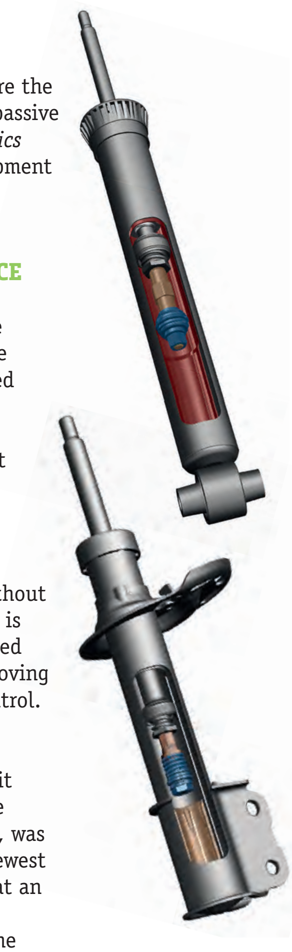
SO HOW HAVE YOU ACHIEVED THIS?

We have replaced the conventional hard stops at the limit of damper travel with hydraulic stops integrated into the damper. The first of these, HRS (hydraulic rebound stop), was introduced some time ago and is well-established. Our newest development, HCS (hydraulic compression stop), is now at an advanced stage of development.

Both HRS and HCS reduce the shocks transmitted to the vehicle body at the limits of suspension travel by dissipating the energy hydraulically in the damper fluid. This enables the damping to be better optimized over the whole wheel travel to secure better road isolation. HCS is being developed in two different configurations, to suit applications requiring either high or low damping levels.

WHY HAVE TWO VERSIONS?

We are developing two HCS technologies because different vehicle applications have specific priorities. Both approaches improve the comfort, refinement and durability of the vehicle, but one offers greater potential for fine tuning and the other provides higher levels of damping.



A new technology that replaces conventional hard bump stops with hydraulic compression stops integrated into the dampers is being developed by BWI Group: Low-level damping (top) and High-level damping (above)

HOW DO THE VERSIONS DIFFER?

The high damping arrangement is achieved by adding a sealed hydraulic chamber with a bypass to the damper's existing compression valve. The separate chamber permits very high damping forces to be generated without influencing the damping over the remainder of the suspension travel.

For applications requiring lower levels of damping, we swage the damper tube to give two different diameters. The larger diameter is for the main damper valve; the smaller engages a second valve at the chosen threshold of travel, before the limiting stroke is reached. This design gives greater opportunity for damper tuning, but the maximum damping force must be limited so that oil aeration does not degrade the base damper performance.

ARE YOU AIMING AT A PARTICULAR MARKET SECTOR?

Initially, we expect the greatest demand to come from medium-range premium passenger car applications, but HCS could be particularly helpful when applied to hybrid or electric vehicles that are derived from existing models, because it avoids any major suspension changes. The technology copes well with the additional weight of a large battery pack and satisfies the lower cabin noise levels required when driving in electric mode, by ensuring there are equally low levels of transmitted noise from the suspension.

The systems also appeal to manufacturers of vehicles whose gross weight varies significantly with payload; a heavily laden vehicle is more likely to bottom its suspension on bumpy or uneven roads. HCS prevents damaging loads from being transmitted into the body structure when bottoming occurs, which leads to a lighter vehicle.

WHEN WILL THE TECHNOLOGY REACH THE MARKET?

Several customers are currently evaluating the HCS systems and we will enter series production with this low damping architecture during 2018.

To learn more from BWI, visit www.ukipme.com/info/vdm ref. 001

Miles

Much has been learned from tuning anti-roll bars over the years, which has helped tame the RWD experience, recalls **John Miles**

It would be nice to pay a tribute to the inventor of the direct acting anti-roll bar (ARB), an elegant innovation first seen by this writer 35 years ago on a Peugeot 405. For little, if any, additional cost over existing systems, the concept transformed roll control of all strut suspension cars and has become yet another reason not to consider multilink front suspension, with its inherently mediocre anti-roll bar and damping ratios, plus displacement losses in the additional link bushes. Once the Lotus K&C rig was running, we also noted undesirable toe-in effects in roll as the ARB forces hauled the lower control arms around on their bushes.

Although I failed to recognize the true importance of the direct acting ARB at the time, I really grasped its worth about three years later when first working for Lotus Engineering to sports modify a US-spec GM V6 Cavalier. As received, it had an astonishingly rigid 24mm-diameter ARB, connected as was the fashion in those days to the lower control arms, and featured no less than 12°/m toe-out bump steer, which we did not understand at the time.

Let's admit it, in the early 1980s Lotus operated in a bit of a Colin Chapman racecar design inspired bubble. This meant that all Lotus's chassis were designed to eliminate bump steer altogether – a philosophy pursued to the extent that rear-wheel-drive Lotus Elan rack heights were individually adjusted on the production line to achieve zero steer. The fact was that by the early 1970s things had changed a lot. Lotus was 10 years behind in understanding subtle steer effects, whereas VW, GM and others had long since understood that to stabilize a car, zero bump/compliance steer is exactly what you do not want for disturbance rejection. They also strived for fluid yet damped steering responses at high speeds.

It was not long before I found this out for myself after 'correcting' the Cavalier's toe-out kinematics to zero with the aid of some machined parts and racecar-type ball joints. I was mortified to discover that the car was now nervous, over responsive to driver input, and seemed to react to every bump in the road.

Chapman was gone and none of the luminaries at Lotus could offer an explanation. It was 3am when it dawned on me that tires don't know how they are attached to the car – they can only respond to vertical load, camber change, track change, and thus most importantly, slip angle, whether applied by the driver or due to bumps/cambers/grooves in the road surface.

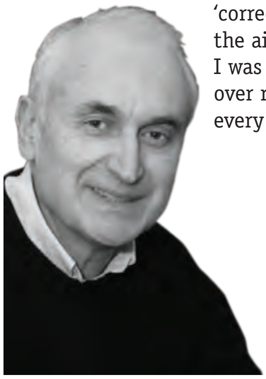
Zero bump steer might have been all right with cross-ply tires, but the much faster responses of low-profile radial tires had changed everything. Toe-out steer, whether kinematically or compliantly derived, is used on just about all modern road cars to automatically compensate for undesirable tire thrust and damp driver input without lowering steering ratios. For me this discovery was an almost religious experience, and changed Lotus's suspension design practice thereafter.

Having been highly impressed with the roll control and ride comfort of the Peugeot 405, we decided to package a Peugeot-type system on the Cavalier, guessing a 19mm ARB diameter as a starting point – around half the nominal stiffness and weight of the standard ARB. The result was astonishing, equalling or bettering the roll control of the donor vehicle, but with less understeer and finer control of steering inputs. Needless to say it stayed on the car.

And that was not the end of the story. The Cavalier project was a success and helped kickstart the possibility of FWD for the new Elan. Another influence was the plethora of turbo conversions for small hatchbacks, some of which were a bit wayward but ludicrously fast for the time, and always safe in the wet or dry, unlike so many RWD sports cars.

Lotus still had strong links with Toyota, which made the RWD Corolla and FWD Corolla at the time. Both cars had the same power-to-weight ratio and tires. In all back-to-back tests, wet or dry, the FWD Corolla was faster, and like all FWD cars was actually usable on snow and ice. Then there was the business case. With no north/south gearbox available we had to put a complete FWD powertrain in the front or back – in other words make a better Fiat X1/9 or something that could be driven rapidly and safety in all weather by people brought up with FWD experience. Perhaps the Elan ended up being too much of a touring car, but in a perverse way it helped lead to the creation of the Elise.

Technical editor John Miles is a major industry figure, known initially for motor racing in the 1960s, including F3, F2 and GT racing at Team Lotus, and F1 racing in the 1970s. He has vast experience, having spent 18 years at Lotus Engineering, three years at Aston Martin and 13 years at Multimatic Chassis Engineering



"For little, if any, additional cost, the direct acting anti-roll bar transformed roll control of all strut suspension cars"

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Car body flexibility influences the handling performance, including the subjective driving experience. Traditional approaches, such as body static stiffness tests, can objectively quantify the effect of reinforcements into a single static stiffness value. But when evaluating on the track in operational conditions, objective global vehicle performance quantities typically don't show significant changes for different body variants. Consequently, the possibilities to understand how body stiffness changes can impact the vehicle performance are limited.

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Realize innovation.

Heider

Times are changing fundamentally in the automotive world, and dynamicists must adjust their thinking, says **John Heider**

Kudos to Mazda for its current 'Driving Matters' television ad campaign, and BMW, whose 'The Ultimate Driving Machine' tag line normally appears in its advertising. These manufacturers, and a few others, still appear to care about driving. Chances are if you are reading *Vehicle Dynamics International* or have found your way to this column via the internet, you too care about driving. However, if we believe the crystal ball that mainstream media is staring into, the label of 'car enthusiast' will soon become a negative term, regarded in the same way as a 'Unix programmer' or a 'keen AM radio listener'.

On the off-chance that the mainstream media is accurate, we need to prepare ourselves for the vehicle dynamics world of the future. Driving may no longer matter, but riding – and ride comfort – certainly will. Having driven many premium luxury CUVs and SUVs over the past six months, it is apparent the current state-of-the-art in chassis design and vehicle dynamics development in the area of ride comfort needs significant improvement to satisfy the needs of future customers. Achieving a sense of plushness and a rolling feel (the sensation of riding on a piece of glass versus a textured road surface) has become a lost art; generally higher centers of gravity induce pitch, roll and head toss issues, and overall passenger ride comfort has not significantly improved in the past 10 years.

Continuously variable damping control (known as, among other things, CDC or CCD) is available on a number of vehicles. As in the case of many sophisticated electronic control systems, the opportunities to significantly overachieve and significantly underachieve, compared with a passive system, are great, and both solutions exist in the marketplace today. It is clear that some manufacturers have devoted the development resources necessary to successfully implement a CDC system, while others have not. Examples of opportunities missed include improperly sized upper and lower mounts not capable of reacting and isolating the range of damper forces present in a CDC system, suspension geometries with poor motion ratios through which no active or passive damper could be successful, or a general lack of development effort, resulting in a CDC-equipped vehicle that rides marginally better over a limited number of road surfaces than a passive vehicle.

Regardless of whether a vehicle has active or passive dampers, they are only one piece of the puzzle when it comes to ride comfort. Isolating the passengers from high-frequency vibrations and audible road inputs is primarily the function of the rubber components in the system – the tires, bushings, subframe or body mounts and powertrain mounts.

Tires are the single best road-induced vibration isolation component on the vehicle and are the subject of whole libraries of research papers. Like every other component in a vehicle, bushings and mounts are being squeezed for cost and weight reductions. The result can be undersized or under engineered designs which lack acceptable vibration isolation characteristics, given their load-carrying requirements. Many manufacturers fail to understand that powertrain mounts are required to isolate the high-frequency vibrations of a running powertrain from the passenger compartment, as well as being tuned in conjunction with the suspension of the vehicle to ensure that road-induced vibrations do not cause the 200-400kg powertrain to excessively vibrate, inducing additional lower frequency inputs into the body.

The backbone of the vehicle continues to be the body structure. Regardless of how much technology or cost is thrown at a vehicle, inadequate body structure can easily curtail any potential positive outcomes. Most manufacturers have recognized this and have steadily and efficiently increased global and local stiffnesses. Unfortunately, customer desires such as full-length sunroofs and increased interior volumes continue to add to the pressure to reduce a vehicle's structural integrity.

Anyone who has tried to read a book in the back seat of a vehicle and experienced motion sickness can attest to the fact that not driving a vehicle does not automatically mean you are able to effortlessly work on a laptop or look at an e-reader. As we slowly march towards a riding- rather than driving-based transportation system, manufacturers must recognize that vehicles offering the greatest ride comfort to the occupants will have the competitive advantage.

John Heider spent 21 years at Ford in all areas of vehicle dynamics and is now principal at Cayman Dynamics, providing vehicle dynamics expertise

"Achieving the sensation of riding on a piece of glass versus a textured road surface has become a lost art"


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Roll control

Technical editor John Miles considers the importance of roll control systems, and how to achieve a well-engineered setup

WORDS BY **JOHN MILES**

ABOVE: Many of today's premium SUVs feature rotary actuator/split ARB systems

Controlling cornering roll is important because, as Lotus proved in the 1980s with its fully active suspension, it is the least-liked body mode, especially in a high-sided vehicle, and the one most likely to kill you in an emergency maneuver, due to the increased rollover potential as body roll accelerations build up.

A milestone in the development of vehicle roll control technologies was the direct acting front anti-roll bar (DAARB) system, introduced on the Peugeot 405 in the late 1970s. This system helped give intrinsically pro-roll strut front suspension designs another long lease of life.

The system, which saw the front anti-roll bar connected direct to the front struts using long ball-jointed links, when coupled with the resulting near 1:1 motion ratio, meant that compliance was effectively eradicated. The dynamic improvements in terms of response and control were dramatic, and all this was achieved with little, if any, increase in cost or weight. The bad news has been that DAARB actuation is virtually impossible to package on a multilink system.

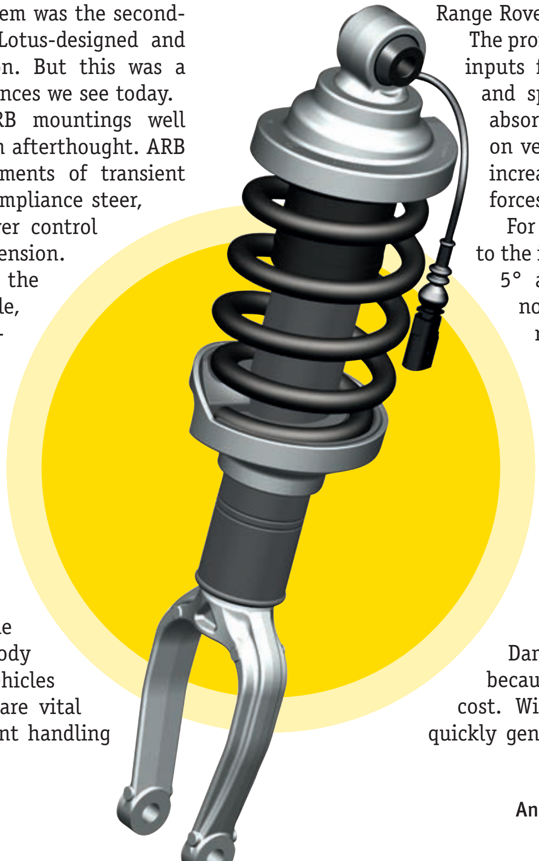
We also need to remember that bump stops usually control the final resting position of the body, so they also have a huge influence on roll angle and stability (see the May/June 2016 issue of *Vehicle Dynamics International*, available on our website, for more details on bump stop design).

CENTER OF GRAVITY ISSUES

The physics of high-sided (high CG) vehicles are, of course, well known, but the engineer is stuck with a dilemma. Very

ABOVE AND RIGHT: Drivers of large Jaguar saloons enjoy good roll damping provided by the Bilstein Damptronic system

BELOW: BWI's Magneride active damping valve system



high independent suspension roll centers and live axles (found on early Land Rover/Range Rover models, for example) work to reduce cornering roll, but naturally lead to unacceptable camber/track change and pronounced 'jacking' effects. There is also the famed 'stagecoach' effect (wriggling motion on single wheel bumps/head toss, etc), whereby a live axle moves laterally during roll.

Lower roll centers are achievable with solid axles by using special linkages, but they tend to be vulnerable to damage and you are back to square one with poor roll control. One notably successful live axle suspension system was the second-generation Isuzu Trooper, which used a Lotus-designed and -developed four-link live rear-axle location. But this was a working vehicle, not the glitzy 4x4 conveyances we see today.

While manufacturers execute front ARB mountings well enough, rear ARB systems often look like an afterthought. ARB response behavior controls important elements of transient stability, and can have major effects on compliance steer, especially if they are attached to the lower control arms, as in the case of a multilink suspension. These steer effects are almost always in the 'wrong' direction, especially on the front axle, so during a roll event, the ARB forces toe-in onto the laden wheel, thus tending to generate unintended steering response gain. These compliance steer effects (up to 4°/m) can be enough to eliminate any kinematic understeer (toe-out with bump travel) built in to stabilize the car in the first place. Rear ARBs are softer, so compliance steer effects tend to be less.

THE DOWNSIDE OF ARBs

The heavier and more upmarket the 4x4, the more ARBs are needed to support the body in corners, especially since some such vehicles now weigh well over 2.5 tons. The ARBs are vital in limiting body roll momentum in transient handling maneuvers, especially at high speed and when the car body is shoved around by cross-winds, but ARBs do have some real disadvantages, especially off road.

The across-car torsion-spring connection of an ARB will try to lift the opposing wheel off the deck, which is obviously not good for traction. Also, when there is an excessive difference between the double-wheel rate (ARB nominally not working) and single-wheel rate, body rocking or head toss will make its presence felt – dynamic conditions that have led to the development of the rotary actuator/split ARB systems seen on 4x4s from BMW, Range Rover and several other manufacturers.

The profound advantage of this development is that by using inputs from the usual basic accelerometer pack, steering and speed signals, single-wheel bumps are comfortably absorbed when driving straight ahead, or at low speed on very rough terrain, while roll stiffness can be greatly increased at high speeds by twisting the ARB against roll forces for a secure feel and transient stability.

For normal cars, the perception of roll is intimately tied to the initial roll rate. The Lotus Esprit leans approximately 5° at the limit of adhesion, but this roll is hardly noticeable by the occupants due to its extremely good roll damping. Jaguar uses Bilstein Damptronic to good effect in controlling body lean on its larger models. In this well-proven system, an 'active' valve block is mounted in series with the normal Bilstein double-digressive piston in the damper body. Both valves are first passively tuned with shim pack changes, followed by the solenoid-driven active valve via a laptop, all of which gives huge scope (almost too much!) for modifying damping force curves for a good compromise in comfort and control.

Active damping valve systems like Bilstein's Damptronic and BWI's MagneRide have a lot to offer because of their low inertia, fast response and tolerable cost. With these systems, very high forces can be very quickly generated to resist body motion in terms of both roll

and pitch. What they cannot do is displace the body hydraulically.

In the 1980s Lotus might have argued that fully active roll control was the ultimate solution. As a research tool it was fabulous, enabling many Lotus customers to drill down into a vehicle's dynamic modes by isolating each one in turn, and also to investigate roll-inward and pitch-up modes thanks to the available actuator authority. Negatives of such systems were the cost, complexity, very high-pressure hydraulics, awful NVH, friction and secondary ride. Plus there was the matter of dangerous fail states to consider.

It was soon realized that for body control, low bandwidth systems are sufficient, if only because body modes (roll/pitch/heave) frequencies on heavy vehicles are in the order of 1.5-2Hz, and only up to 7Hz for a Formula 1 car. This means that for body control you don't actually need the 30Hz-capable Lotus F1-type system – Williams and Nigel Mansell proved that with the F1 Championship-winning 1992 FW14B. On the other hand, Citroën's Hydropneumatic system, as with various other air-spring leveling systems, is far too lethargic to cope with more than static load leveling compensation.

"The quest for strong roll control without a ride penalty is still ongoing"

ACTIVE ROLL CONTROL

The quest for strong roll control without a ride penalty is still ongoing, and the latest development is the various powered 'active' roll control systems, where the ARBs are deleted from the vehicle altogether. For example, unlike Tenneco's original passive Kinetic Reversible Function Stabilizer (RFS), which Citroën licensed and which played a part in enabling Sébastien Loeb to win at least two World Rally Championships, Tenneco's latest H2 system is a powered system.

The hydraulic power for H2 – which is used by McLaren on all its current mid-engined hypercars – comes from the PAS pump,

ABOVE: McLaren uses Tenneco's H2 roll control system, powered by the PAS pump

LEFT: Tenneco's Kinetic Reversible Function Stabilizer helped Sébastien Loeb on his quest for WRC dominance. Photo: Blux-Denis

RIGHT: Low bandwidths were sufficient to help Williams to championship victory with the 1992 FW14B Formula 1 car. Photo: Jmex60

which supplies high-pressure oil stored in two accumulators. Somewhat like Lotus's active system, H2 generates suspension extension and compression displacements via a double-acting piston in the damper tube. Conventional damping functions are superimposed via an integral, electronically controlled side-valve unit, which is already in production in Tenneco's existing electronic damping systems.

H2's party trick is the cross-connection between the actuators and the hydraulic lines, which increases roll resistance potential with minimal additional power consumption. Tenneco has clearly mastered the development of H2 on the current line-up of McLaren hypercars – reportedly giving them unrivalled ride with extremely flat body control. Meanwhile we await Tenneco H2's appearance on a major manufacturer's heavy 4x4 – in other words when the system really has to perform on- and off-road.

ABOVE: Its direct acting front anti-roll bar (DAARB) system made the unassuming looking Peugeot 405 a milestone in vehicle roll control technologies

BELOW: Even for 'fashion' vehicles like the Evoque convertible, JLR runs a full off-road program, including roll refinement

RIGHT: The Isuzu Trooper featured a four-link live rear axle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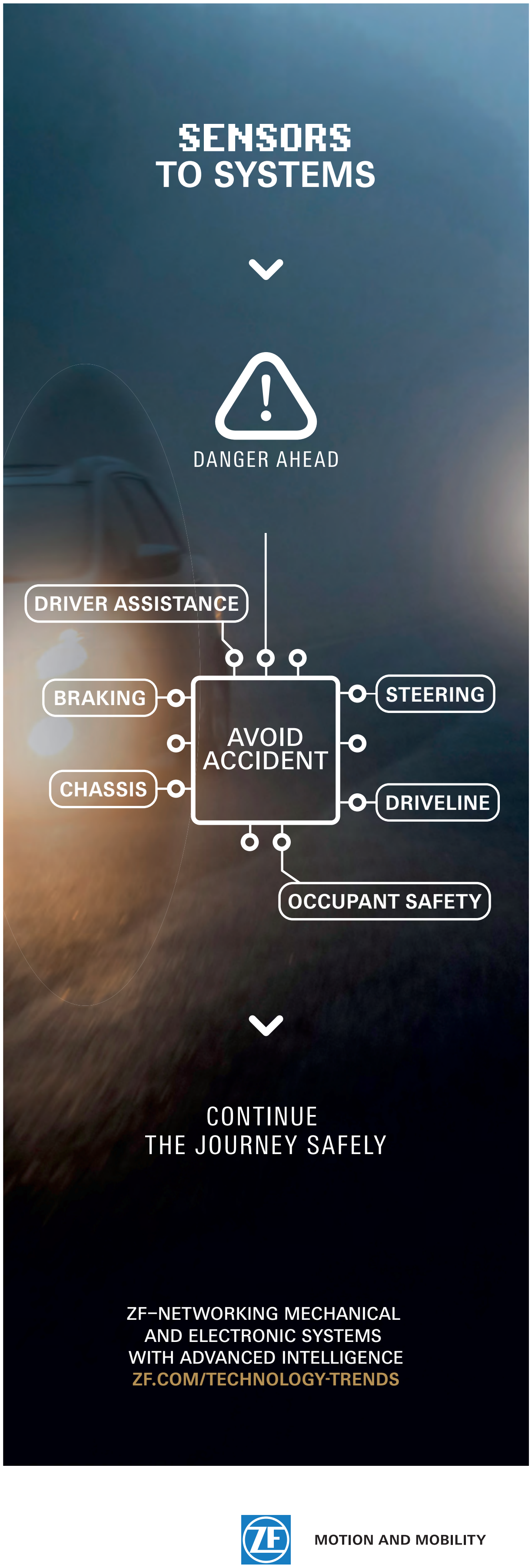
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The XchangE concept is Rinspeed's vision for an all-electric, autonomous touring sedan

With level-three self-driving vehicles on the horizon, what will the future hold for the vehicle dynamics industry? We asked experts from across the sector for their viewpoints on how the technology will influence vehicle dynamics

AVs MEAN BUSINESS

The AV market will be worth roughly US$42bn by 2025, according to global management consulting firm Boston Consulting Group (BCG)

Keen drivers become keen readers

Vincent Abadie, expert leader, controlled chassis systems, ADAS and autonomous vehicles at PSA Group, explains the implications of AVs for dynamics engineers.

"Driving automation impacts dynamics and chassis system design in several ways. AVs require failsafe operational systems, and chassis systems are key to delivering safety, especially braking and steering. In autonomous mode, the driver is out of the loop, so a backup system is required. The standard braking system (with ESC) has to evolve to include an active booster to deliver a fully effective braking system.

"For steering, especially at higher speeds, some components have to be backed up in parallel in case any parts are compromised.

"AVs also have other impacts on chassis design. Dedicated work has to be done on the suspension to allow the driver to read or watch a film without experiencing travel sickness. Chassis tuning may also have to be adapted to the autonomous mode. We can assume that all the controlled chassis system (steering, braking, dampers and even tires) will be optimized for AVs."

KEEPING THE THRILL OF DRIVING

"Driving is, for at least some of the time, exhilarating. The autonomous cars of the future will not stop driving enthusiasts enjoying the sensation. Autonomous driving and driving passion will co-exist."

Kia Foresight Study

How autonomous vehicles will develop

Level one: function-specific automation
Automation of specific control functions, such as cruise control, lane guidance and automated parallel parking. Drivers are fully engaged and responsible for overall vehicle control. This stage exists today.

Level two: combined function automation
Automation of multiple and integrated control functions, such as adaptive cruise control with lane changing. Drivers are responsible for monitoring the road and must be available to drive the car at all times, but under certain conditions can disengage from driving. This stage exists today and we are preparing for the next stage...

Level three: Limited self-driving automation
Drivers can cede all safety-critical functions under certain conditions and rely on the vehicle to monitor for changes in road conditions that will require driver control. Drivers are not expected to constantly monitor the road.

Level four: Full driverless automation
Vehicles can perform all driving functions and monitor roadway conditions for an entire trip, and so may operate with occupants who cannot drive, and even without human occupants.

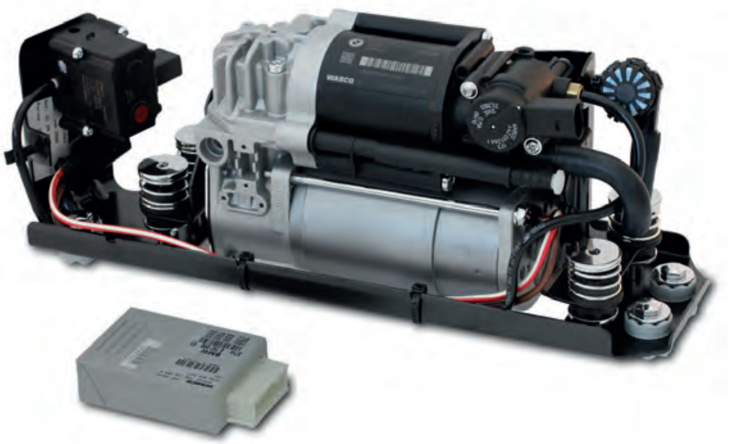
The road ahead for autonomous vehicles

2010s
Develop performance and data collection requirements for autonomous vehicles operating on public roadways

2020s
Support large-scale autonomous vehicle testing. Evaluate benefits and costs under actual operating conditions

AIR SUSPENSION FOR THE PERFECT RIDE

is an essential feature, not an option!



BMW X5 and X6 models can be equipped with WABCO's Air Suspension technology.

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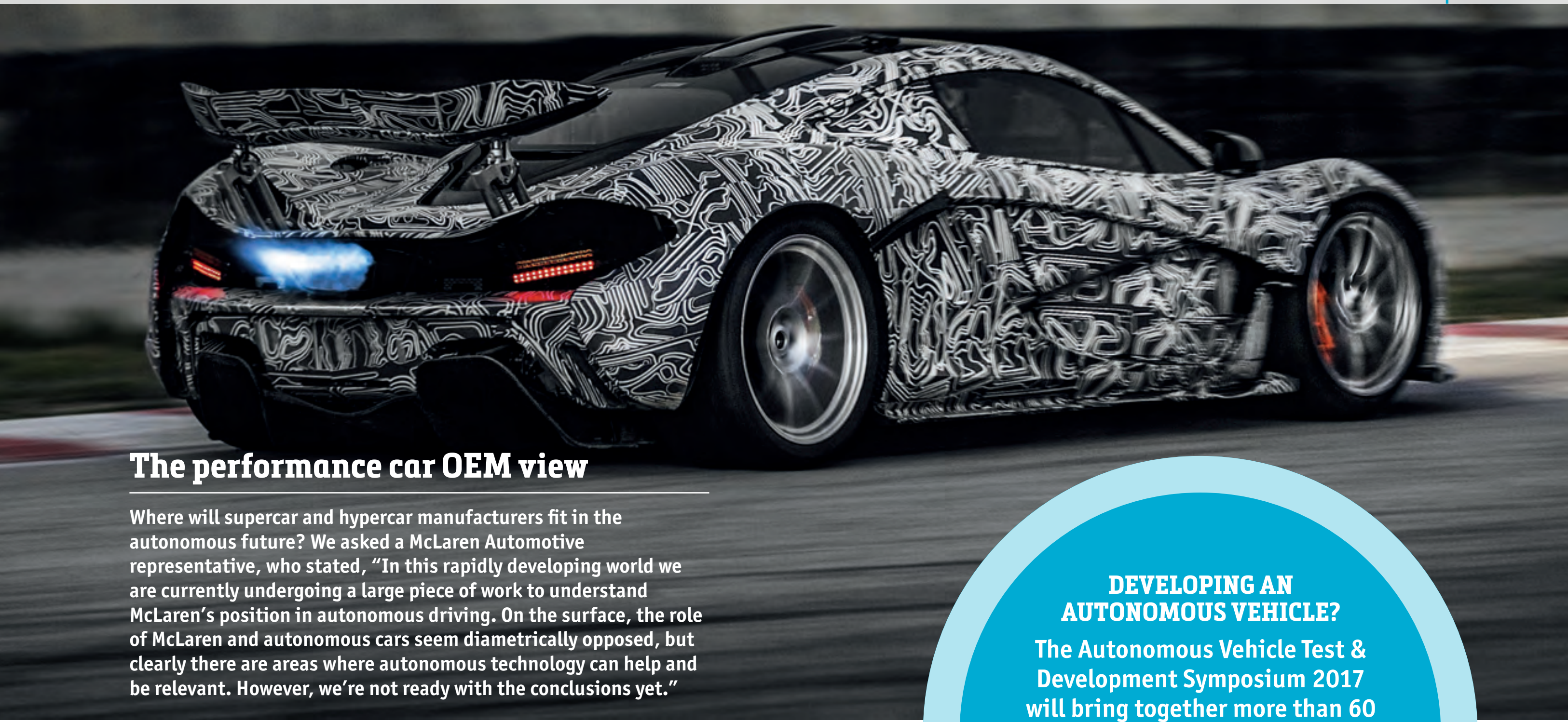


The performance car OEM view

Where will supercar and hypercar manufacturers fit in the autonomous future? We asked a McLaren Automotive representative, who stated, "In this rapidly developing world we are currently undergoing a large piece of work to understand McLaren's position in autonomous driving. On the surface, the role of McLaren and autonomous cars seem diametrically opposed, but clearly there are areas where autonomous technology can help and be relevant. However, we're not ready with the conclusions yet."

The academic view

An academic closely monitoring the area of AV dynamics is Simone Formentin, PhD, assistant professor at Politecnico di Milano. He explains, "The main dynamics issues for AVs are more complex than those for human-driven cars, and the standard approaches may no longer be effective.

"Path planning and tracking is widely studied in robotics, aerospace and other mechatronics applications, but it is novel for cars. In existing cars even the most cutting-edge technologies are dedicated to adjusting vehicle speed or acceleration to increase safety and performance, whereas trajectory tracking is a task always left to the driver (except for automatic parking).

"Nonetheless, most vehicle dynamics problems arise from the fact that the highly nonlinear road-tire characteristics are unknown and unmeasurable with existing (affordable) sensors. Therefore, keeping the driver within an outer (path tracking) control loop represents a great advantage in that she/he can manually handle the vehicle in critical conditions (at least to a certain extent) and make the overall system robust to road and tire interface changes. This is obviously not the case for AVs.

"Hence it seems that standard robust control for braking, traction and steering dynamics could turn out not to be robust enough for path tracking in AVs, because one can no longer rely on the intrinsic level of robustness provided by the driver feedback loop. In city and highway driving this fact may not be a problem, because the side-slip angles for the majority of maneuvers are low and easily controllable. However, in sudden maneuvers for obstacle avoidance, a robust controller for path tracking, exploiting the most recent developments in the field, could save lives.

"A few important questions still need to be answered by controls experts. For example, can we provide a sufficient level of robustness with respect to all roads and tire conditions without decreasing performance too much? Are we able to replicate the response of an expert driver to a sudden change in external conditions? How can we best exploit the information coming from additional sensors on board (e.g. cameras, sonar...)?

From artists to scientists

Ricardo has been working intensely on AV development, including dynamics aspects. Here's what Mark Simon, chief engineer for chassis dynamics and simulation at Ricardo, sees as the major dynamic implications.

"AVs are a paradigm shift in personal transportation. This is good news for dynamics engineers as their role will take on greater importance. As well as the obvious dynamics challenges – safety, environment and validation – ride comfort and NVH become more important with the released capacity of occupants' sensory perception. Supporting these challenges are some key opportunities for dynamicists to shape future vehicles: re-definition of user requirements, developing strategies to exploit dynamics for brand differentiation, and selection and tuning of complex technologies to personalize the 'chauffeured' experience. In recent years, dynamics has moved from art toward science, and autonomous vehicles will accelerate this trend."

The road ahead for autonomous vehicles

2030s
Study, and where appropriate support, autonomous vehicle implementation for specific applications such as taxis, car sharing and demand response services

2040s
Dedicated lanes on motorways for autonomous vehicles. AVs will account for approximately 50% of vehicle sales, 30% of vehicles and 40% of all vehicle travel

2050s
Most vehicles will be capable of automated driving at level four (see p27)

How will AVs roll?

Will AVs run on tires similar to today's 'green' models? Dean Tener, technical manager of the Smithers Ravenna Laboratory, Smithers Rapra's main center for tire testing in North America, gives his view.

"As autonomous vehicles become more viable, evaluations will be conducted by controls system engineers, and factors such as subjective handling and steering will be of less importance. Haptic feedback is currently through vibration in a steering wheel, so the lack of a steering wheel means that this feedback must be monitored and acted on differently. Ride will still be important, as passengers will be able to feel the impact of the road on tires, but aerodynamics, durability and rolling resistance will be more heavily emphasized than before.

"Designing tires for AVs will also depend on the structure of the vehicles themselves. Lightweight structures will put less weight on tires, but the tires will need to limit the force that is transmitted through them to the structure. If the tire is unable to absorb the force created by driving on rough surfaces, structural durability will be greatly affected.

"Another factor is aerodynamics. A narrower tire will be more beneficial in limiting drag, but will still require the same air cavity volume to achieve a suitable load capacity. This means that tires will need to be made taller to compensate. Increased tire diameter is generally better for ride, so it will not compromise comfort

"As well as diameter, the controller will need to be aware of other tire measurements, including cornering and braking stiffness, load transfer sensitivity, camber sensitivity and peak grip, to come up with quality initial steering and braking input."

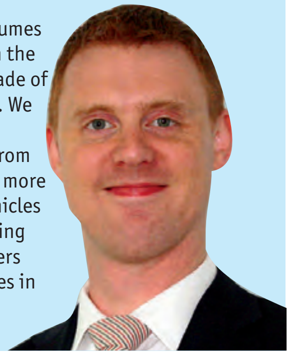
AVs to accelerate in 2025

Earlier this year the US DOT issued guidance on the development of AVs, including a 15-point safety assessment for manufacturers, developers and other organizations for the safe design, development, testing and deployment of autonomous vehicles.

Jeremy Carlson, principal automotive analyst for industry analysis company IHS Markit, gave us his thoughts on this move: "The federal guidance reflects a shift toward a more proactive regulatory approach – it covers not only how and where the vehicle is supposed to function, but also cybersecurity, privacy, human-machine interface, consumer education and a number of other relevant topics intended to be addressed from the early phases of design through to deployment. Such a wide approach to regulatory assessment reflects the rapid pace of innovation and complexity in the fast-moving mobility and transportation industries.

"The federal guidance also aligns to definitions from the SAE describing the levels of automation. This is a shift from NHTSA's 2013 policy, which was a competing standard in some ways. This creates a clearer and in some ways simpler framework for a conversation between industry stakeholders, advocates, and state and local governments that can help direct regulatory efforts as the industry continues to progress. This action is therefore a positive step in enabling progress in the development and deployment of autonomous vehicles.

"IHS Markit expects small volumes of autonomous vehicles through the next several years, before a decade of rapid growth beginning in 2025. We will see 76 million autonomous vehicles sold around the world from today through 2035. In the USA more than 18 million autonomous vehicles will be sold through 2035, creating new opportunities for auto makers and drivers as well as new choices in personal mobility."



The steering angle

For a viewpoint on steering, we asked Paul Poirel, chief engineer for Europe at Nexteer Automotive, what the move towards AVs means for his team.

"One of the main things to consider with the spread of ADAS into the automotive industry is how the EPS system dynamically responds to, and exchanges data with, other vehicle systems involved in ADAS. The EPS system must be tested extensively to ensure it can successfully be integrated with the vehicle, which means much of the early-stage testing is performed using vehicle-in-the-loop advanced simulation benches. Following that, EPS is tested in real vehicles for a variety of extreme steering maneuvers on multiple road surfaces. Here, the emphasis is on system stability and predictable steering response."

Comfort under consideration

With a bold plan to introduce partially autonomous cars by 2020 under its Drive Wise brand, and a fully autonomous car planned for launch by 2030, how does Kia foresee dynamics packages changing? A spokesperson from Kia's headquarters in Seoul explains, "One can imagine that drivers of fully autonomous driving vehicles in the future will still want to take over driving from time to time, depending on various needs and road situations. Thus, the fun driving dynamics of autonomous vehicles is a factor that OEMs cannot fully ignore.

"However, Kia Motors is still studying various aspects of autonomous driving technologies and has not yet made final decisions on the extent to which autonomous driving vehicles should focus on ride comfort and/or driving dynamics.

"A self-driving car is not an adaptation of the old-style human-driven one. It will in reality be a whole new class of product, just as the PC is completely different from a typewriter."

Hydro **mounts**

An in-depth look at modeling hydro mounts in vehicles for durability load analyses, ride comfort and vehicle dynamics simulation

WORDS BY **CHRISTIAN SCHEIBLEGGER & ANDREW HILLIS, UNIVERSITY OF BATH; NANTU ROY, FIAT-CHRYSLER-AUTOMOBILES; AND PETER PFEFFER, MUNICH UNIVERSITY OF APPLIED SCIENCES**

Reliability and robustness are key requirements for both heavy- and light-duty trucks, so the accurate prediction of durability under load is crucial during development. Multibody simulation tools are used to investigate the effect of different stiffnesses and the position of the mounts and bushings in the early phase of development. For analyses along the load path over the suspension and frame, into the body, the level of detail for all bushing elements needs to be increased.

Figure 2 shows the hydraulically damped cab mount that has been used for this survey. It is divided into the main rubber carrier on top, the hydraulic section with its fluid-filled rubber chambers, and the fluid channel.

Static stiffness k_{stat}, dynamic stiffness k_{dyn}, and loss angle δ are widely used to characterize mounts and bushings. This experimental data is used to derive model parameters for mount models within full-vehicle simulation. The mount's static stiffness, k_{stat}, depends on the loading conditions. The following characteristics may therefore depend on the preload. The main rubber part carries the gravitational load of the cab and offers some damping. Under dynamic excitation, a pressure difference from the upper to the lower chamber forces the fluid to flow within the spiral fluid channel. Oil or a water-glycerin mix are used as the fluid.

Hydraulically damped mounts and bushings use the tuned mass damping (TMD) effect with additional fluid damping to generate high dynamic stiffness and high damping around the tuned resonance frequency. Hydro mounts change dynamic stiffness and damping properties substantially over frequency and amplitude (Figure 3).

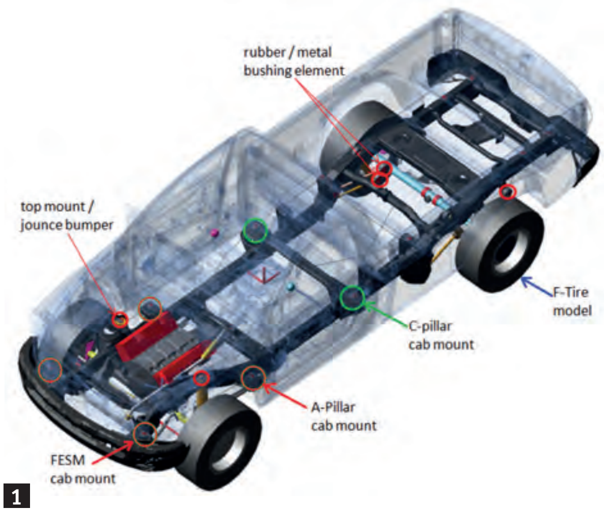


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FIGURE 1: The ADAMS model of a full-size pickup truck with a hydro cab mount (C-pillar) and several elastomer mounts

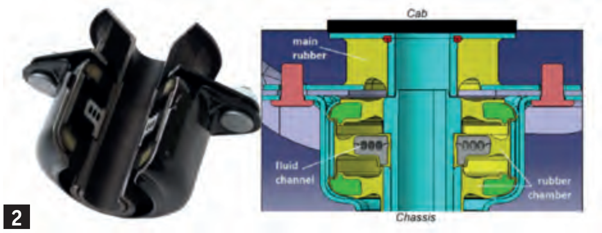

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FIGURE 2: Hydraulically damped cab mount with its main components

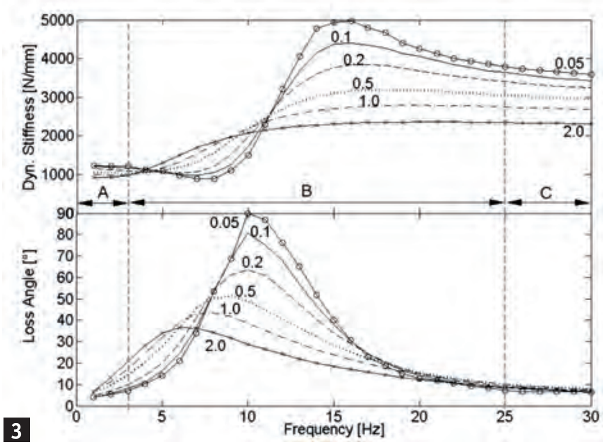

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FIGURE 3: Measured dynamic stiffness and loss angle of hydro cab mount for amplitude 0.05-2.0mm

Measurement data at low frequency (A) already shows a difference in stiffness, due to amplitude dependence of the main rubber. Fluid damping in the orifice and fluid friction lead to additional damping in the resonance frequency range (B). The internal damping also restricts the fluid flow at high frequencies (C). At high frequency, fluid pulsation stops, so the overall stiffness can be assumed to be main rubber stiffness plus stiffness against chamber compliance. The hydro mount's typical resonance peak goes back to the TMD effect.

Under certain operating conditions, the fluid inside the channel pulsates counterphase-wise to the excitation. The rubber chambers act as a spring with volumetric stiffness to restrict chamber compliance. The fluid mass inside the channel is amplified by the hydraulic lever arm and acts as TMD mass. At high excitation the movement of the cab or powertrain is limited and damped at the same time. The fluid mass inside the channel, the rubber stiffness and chamber compliance are tuned to give high damping at certain resonance frequencies.

Model structure

The principal hydro mount phenomena are discussed with the model approach as shown in Figure 4. The model presented is of a modular structure, where the hydro mount model behavior is a superposition of three elements.

First, the elastomer behavior of its underlying rubber parts, where c_T represents the main rubber stiffness (in the vertical direction). The chamber stiffness c_B represents the resistance against puffing of the chamber when pressure increases (chamber compliance, volumetric stiffness). Both springs for main rubber c_T and chamber rubber c_B are to be calculated from a sub-model for the elastomer that takes into account amplitude dependence due to the Payne effects. c_T and c_B are to be regarded as complex stiffness and depend on the current preload, frequency and amplitude.

Second, the TMD effect with chamber compliance c_B, main rubber stiffness c_T and fluid mass m_K as the main factors. The virtual fluid mass m_K is known from the channel length l_K, channel area A_K and fluid density ρ_F. The pulsation in the fluid channel is amplified over the hydraulic lever arm, where the areas of the main spring A_0, the chamber A_B and fluid channel area A_K are relevant.

Third, additional fluid damping in the channel and orifice depends on the velocity of fluid flow, and damping coefficients d and β for fluid damping. Physically meaningful parameters are used to model the mount. A force on top of the hydro mount caused by gravitational load leads to deflection u_0 of the main rubber spring c_T and increase of pressure in upper chamber p_0:

$$F = c_T \cdot u_0 + p_0 \cdot A_B \quad [1]$$

When pressure p_0 increases due to the force F, the chamber displacement (deflection) u_B results from the pressure in the upper chamber p_0:

$$p_0 \cdot A_B = u_B \cdot c_B \quad [2]$$

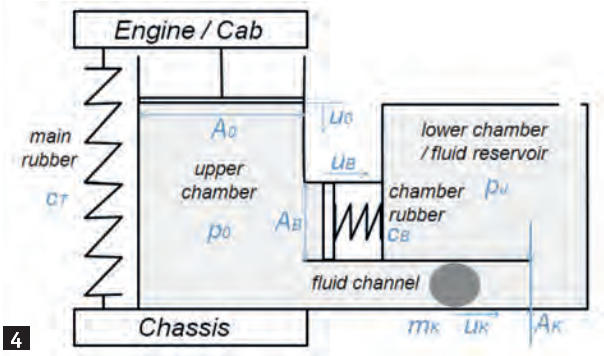

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FIGURE 4: Simple hydro mount model for principal investigations. Springs represent complete non-linear amplitude-dependent elastomer sub-models

The fluid (mass m_K and displacement U_K) flows through the channel with length l_K and cross-sectional area A_K. d and β are damping coefficients for linear and non-linear fluid damping in the channel, respectively:

$$m_K \cdot \ddot{u}_K = p_0 \cdot A_K - d \cdot \dot{u}_K - d \cdot \beta \cdot \dot{u}_K^{\,2} \cdot sign(\dot{u}_K) \quad [3]$$

In simple passive engine mounts, the lower chamber consists of a flexible rubber diaphragm membrane and acts as a fluid reservoir with atmospheric pressure p_u=0. Even if the lower chamber is physically closed and under pressure, the assumption p_u=0 still gives a good agreement to experimental data, as discussed below. For further simplification it is assumed that the main rubber area is the same as chamber area.

$$A_0 \approx A_B \quad [4]$$

A change of input displacement at slow excitation does not affect the pressure p_0 inside the mount because fluid flows freely through the channel without relevant damping and mass inertia. Therefore, input displacement u_0 only goes into the calculation of F_T due to the rubber spring c_T. Chamber deflection u_B is calculated from the integral of velocity du_0 over time, thereby eliminating a constant displacement offset due to static gravitational load onto the mount.

$$u_B = \int\left(\dot{u}_0 - \dot{u}_K \frac{A_K}{A_B}\right) \quad [5]$$

Pressure can be calculated as:

$$p_0 = \frac{u_B \cdot c_B}{A_B} = \int\left(\dot{u}_0 - \dot{u}_K \frac{A_K}{A_B}\right) \cdot \frac{c_B}{A_B} \quad [6]$$

The model approach shown in Figure 4 has been implemented into the multibody simulation (MBS) environment; a software plug-in for MSC.Adams/Car is available from VI-grade. Sophisticated graphical user interfaces have been developed for importing measurement data, parameter estimation and export into parameter files.

These tools include a virtual mount test rig and have been used for the following hydro mount design analyses. All sub-functionalities of the hydro mount model can be deactivated.

In addition to the fluid mass's inertia, a velocity-proportional term with damping coefficient d and an additional non-linear damping term with coefficient ß contribute to the damping in the fluid channel. It may be suggested that linear and non-linear parts should be regarded entirely separately, so:

$$p_0 \cdot A_K = m_K \cdot \ddot{u}_K + d \cdot \dot{u}_K + \beta \cdot \dot{u}_K^{\,2} \cdot sign(\dot{u}_K) \qquad [7]$$

However, numerous tests where the mount model parameters were identified for different sorts of hydro mounts (and hydro bushings) proved that it is beneficial to assume the main damping coefficient d also has an effect on the non-linear damping term ß.

$$p_0 \cdot A_K = m_K \cdot \ddot{u}_K + d \cdot \left(\dot{u}_K + \beta \cdot \dot{u}_K^{\,2} \cdot sign(\dot{u}_K)\right) \qquad [8]$$

This way the main characteristics can be estimated easily and fast via the damping coefficient d. Parameter variation for ß then gives fine-tuning of the behavior.

This coupling of linear and non-linear damping leads to significant simplifications and improved stability for a semi-automatic parameter estimation process where internal model parameters are varied for a good fit to experimental data. For model implementation into a practical tool for hydro mount simulation and design studies, several options for fluid damping are useful. So, a more general formulation is used, where

$$F_{fluid} = p_0 \cdot A_K = F_{TMD} + F_{damp1} + F_{damp2} \qquad [9]$$

with

$$F_{TMD} = m_K \cdot \ddot{u}_K \text{ and } F_{damp1} = d \cdot \dot{u}_K \qquad [10]$$

plus additional non-linear damping

$$F_{damp2} = \beta \cdot \dot{u}_K^{\,2} \cdot sign(\dot{u}_K) \qquad [11]$$

or alternatively

$$F_{damp2} = \beta \cdot \dot{u}_K^{\,3} \qquad [12]$$

For the final model implementation, the grade of nonlinearity can be changed via exponential coefficient n_{POW}, where n_{POW} = 1, 2 or 3. A continuous formulation for changing signs for velocity is needed to ensure low computing times when variable time step solvers are used. The sign of the velocity is therefore calculated using a hyperbolic tangent function with gradient factor k_{SignD}. The discontinuous sign function and its derivative is thereby replaced with a continuous function.

$$F_{damp2} = \beta \cdot \dot{u}_K^{\,n_{POW}} \cdot \tanh(k_{SignD} \cdot \dot{u}_K) \qquad [13]$$

Elastomer model

For hydro mount models it is often assumed that main rubber stiffness and chamber stiffness are constant. In reality main rubber stiffness c_T and chamber rubber stiffness c_B change over frequency and over amplitude.

Table 1 shows model parameters for the cab mount for the basic model approach when main rubber c_T and chamber compliance c_B are assumed to be constant springs, and fluid damping non-linear.

Due to such simplifications, the table values may not be equal to physical part's geometry. Instead, model parameters are estimated first and then automatically tuned for a good fit to experimental data. Figure 6 gives measurement for three amplitudes (markers) and simulation results (in solid lines) using the table values below derived from automatic parameter optimization.

Simulation results look good at first glance, but such a simplified model reveals the following drawbacks because stiffness for main rubber c_T and chamber rubber c_B are considered to be constant:

- The stiffness of main rubber is constant, so the static and dynamic stiffness are the same. The static stiffness is estimated too high if c_T is tuned for good results under dynamic excitation.

Table 1. Model parameters for basic hydro mount model with constant stiffness for main rubber and chamber rubber

Parameter	Symbol	Value
Stiffness top mount (main rubber)	c_T	$1e^3$ kN/m
Effective piston area chamber	A_B	$8.586e^{-3}$ m²
Area of fluid channel	A_K	$8.191e^{-5}$ m²
Length of fluid channel	l_K	0.248428m
Fluid damping coefficient linear	d	0.333 Ns/m
Non-linear fluid damping coefficient	β	1.393 Ns²/m²
Effective channel fluid mass	m_K	0.019333kg
Chamber stiffness	c_B	$1643e^3$ N/m

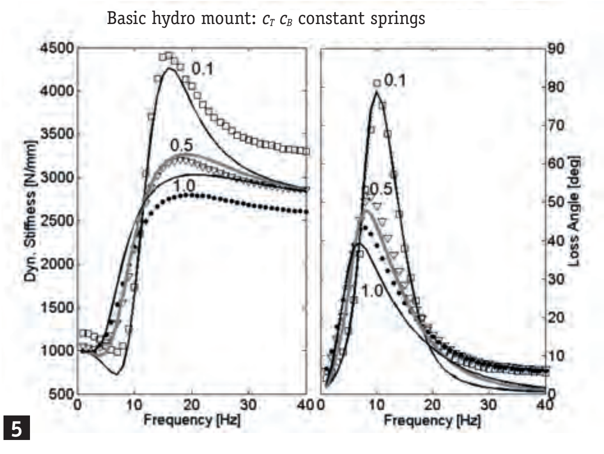

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FIGURE 5: Simulation (solid lines) assuming constant springs for main rubber and chamber rubber


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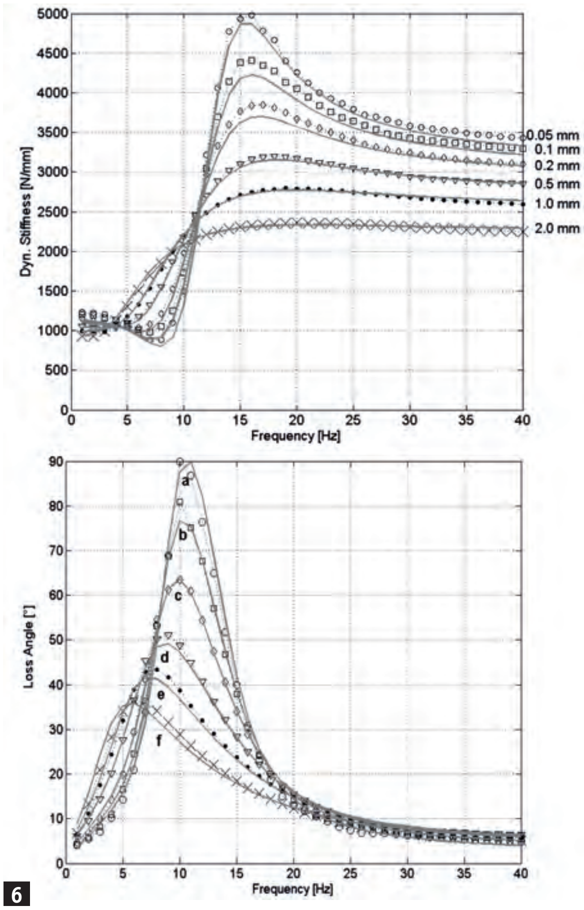

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FIGURE 6: Hydro mount model evaluation under sinusoidal excitation: Simulation (solid lines) and measurement for amplitudes 0.05mm (a), 0.1mm (b), 0.2mm (c), 0.5mm (d), 1.0mm (e) and 2.0mm (f)

The static equilibrium of the full vehicle model will be inaccurate, leading to severe drawbacks if the simulation runs for complex 3D excitation.

• The calculated stiffness is the same for all amplitudes at low frequency (1Hz) and at high frequency (>30Hz). In contrast, measurements show relevant differences due to the elastomer behavior.

• The simulation behavior at transient excitation might be different from the real parts, due to simplifications.

For better results and to make the hydro mount model flexible for all sorts of different hydro mounts and hydro bushings, it is vital to accurately model the elastomer's amplitude dependence and frequency dependence.

Standard bushing models in MBS environments do not take the elastomer amplitude dependence due to the Payne effect into account. For accurate results, it is crucial that the hydro mount's elastomer parts are modeled in detail. For the simulation of durability loads, high amplitudes and changing preloads are of interest, so special care has to be taken in terms of modeling the elastomer parts of a hydro mount.

There are many papers on this topic, but few models have been implemented into the MBS environment with full functionality to prove practical use and numerical stability. Others lack easy-to-use tools for fast parameter identification.

The main outcome of this research is that all sorts of passive hydraulically damped mounts and bushings can be simulated equally well as long as the underlying model approaches for the elastomer parts are accurate.

Sinusoidal excitation

The cab mount shown in Figure 1 is used for further validation. Figure 6 presents actual simulation results for the full non-linear model, including amplitude dependence for elastomer parts. The springs for c_T and c_B in the principal model scheme (Figure 4) are represented by a full non-linear elastomer model, including amplitude dependence. All measured amplitudes – 0.05mm, 0.1mm, 0.2mm, 0.5mm, 1.0mm and 2.0mm – have been used during the automatic parameter optimization routine.

Error values are calculated for each amplitude and frequency for loss angle, as well as frequency during parameter optimization. In this case, the error sums for dynamic stiffness and loss angle have been weighted as equally important.

Results at sinusoidal excitation are very accurate over the whole amplitude range if amplitude-dependent effects due to the underlying rubber parts are taken into account. This type of mount has no decoupler or bypass valve, so it can be compared with most passive hydraulic engine mounts.

Transient behavior / reaching steady state

For most tests on the component test rig, transient phenomena are neglected because the mount is fixed to the test rig on both sides. In accordance with the test definition, the mount is allowed to reach a steady state before force displacement loops are recorded and dynamic stiffness and loss angle calculated.

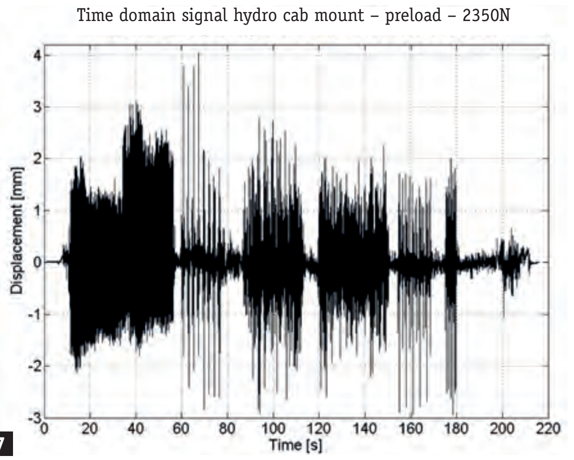
In contrast, for real-world excitation, the behavior before reaching a steady state is crucial for tuning the mounts and bushings. In addition to the dynamic stiffness and loss angle (or other parameters to characterize the damping properties) the actual transient response at freely damped vibration is relevant.

For model evaluation in this study, transient test rig signals have been derived from real on-road tests as input to the mount test rig. In this paper, the dynamic characteristics are mainly studied from dynamic stiffness and loss angle because these are the most commonly used parameters for standard dynamic measurement data. The calculation of complex stiffness is based on the assumption of elliptical hysteresis loops, but that is not always the case. Therefore, transient signals have also been used for the model evaluation.

Durability loads from experiment

Model parameter identification is based only on quasi-static and sinusoidal excitation after the bushing has reached a steady state. However, it is known that elastomeric parts exhibit different behavior under transient excitation. Here, the mount will vibrate mainly at a certain resonance frequency but the excitation amplitude is declining from its maximum value to zero after each single obstacle or input.

To evaluate the accuracy of the full-vehicle model using the new non-linear bushing models under transient excitation,



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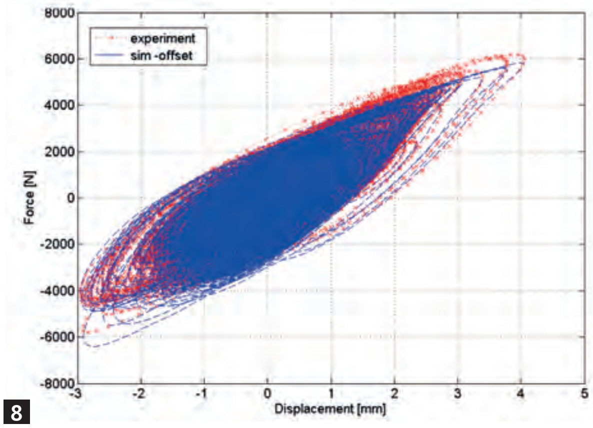

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FIGURE 7: Input of transient durability load signal without offset due to preload

FIGURE 8: Model validation: Force-displacement loop of transient durability load signal

FIGURE 9: Model validation at transient input signal

FIGURE 10: Model validation at transient input signal: detail

the mount loads have been measured during on-road tests for durability. Based on this data a transient displacement signal has been generated as input for the mount test rig. The measured resulting forces from the test rig are qualitatively very similar to the loads measured during on-road tests.

Figure 9 gives the resulting simulated and measured force over the displacement. The resulting force offset due to preload has been terminated for the following plots. The preload for parameter identification was much lower than during the durability load signal for model validation. Nevertheless, simulation results are very accurate. Please note that the overall force-displacement loops are not purely elliptical because the internal pressure inside the mount's chamber is limited during decompression after high deflections; damping is much higher under compression. The good results prove that the pressure inside the upper chamber was modeled correctly and accurately.

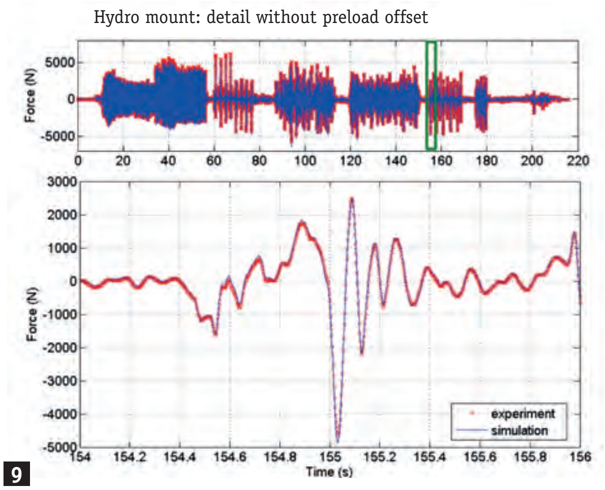
Figures 10 and 11 present the mount's load over time. Overall, the simulation results for the mounts are very accurate. The model evaluation under sinusoidal excitation proved a very high-performance model over a wide amplitude range. The evaluation with a transient time signal on the mount test rig also confirms a very high level of accuracy.

Summary / conclusions

The main conclusion of this investigation is that hydro mount behavior is only mapped accurately if the amplitude dependence of the underlying elastomer parts is taken into account. To improve accuracy of other existing mount models in MBS it is recommended that the amplitude-dependent characteristic of the underlying elastomer parts be implemented.

The model evaluation under transient excitations covered a wider amplitude range; the simulation showed good agreement with the measured loads. With the model for the hydro cab mount, the full vehicle simulation accuracy was improved greatly. This means that testing times and numbers of prototypes can be reduced, saving cost and time.

This paper was previously published in the Proceedings of the 13th International Symposium on Advanced Vehicle Control – AVEC 2016, CRC press/Balkema – Taylor & Francis Group, September 13-16, 2016, Munich, Germany



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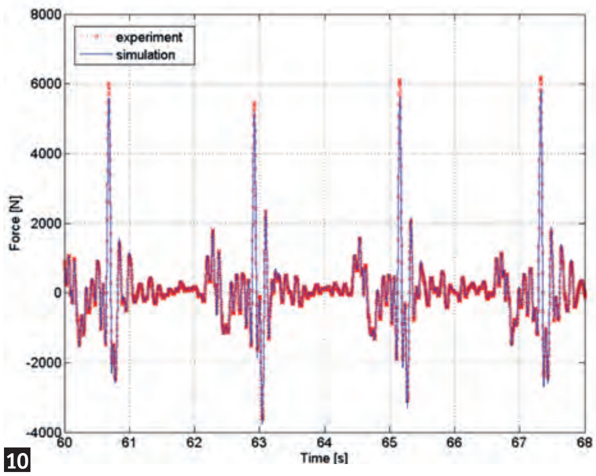

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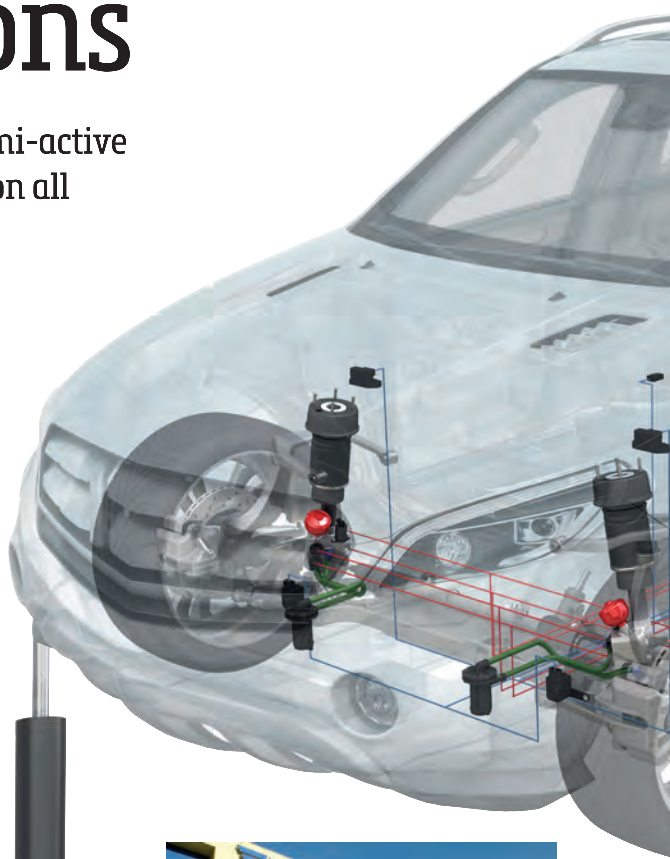
Scalable suspensions

Tenneco uses a flexible actuator design to easily scale up semi-active suspension systems into advanced and fully active systems on all models and powertrains within a single platform



Earlier this year, Tenneco announced that its Scalable Suspension Architecture can provide car manufacturers with a highly differentiated range of vehicles within one single platform.

The Scalable Suspension concept leverages the Monroe intelligent suspension portfolio of semi-active and active suspension technologies to offer car manufacturers enhanced suspension systems using a flexible actuator design to scale up semi-active suspensions to advanced and fully active applications.

"Scalable Suspension responds to the increasing need for differentiation as car manufacturers seek to offer a wide variety of different driving experiences on multiple car types within a single vehicle platform," says Rudi Schurmans, executive director of global engineering, Tenneco Ride Performance.

ABOVE: The Scalable Suspension simplifies the customization of driving experiences for different models based on a common platform

ABOVE RIGHT: The Tenneco/Monroe R&D center in Belgium

CVSA2

The Scalable Suspension options start with the latest generation of continuously variable semi-active suspension systems (CVSA2), which continuously adjust shock absorber damping levels to road conditions and vehicle dynamics inputs, including speed, turning, cornering and driver inputs. The system provides optimum driving safety and improves ride smoothness and NVH (noise, vibration and harshness), achieving the optimal balance between ride comfort and handling. The continuously controlled damping works with the 'skyhook' principle for body control, using additional algorithms for better road contact, steering and braking.

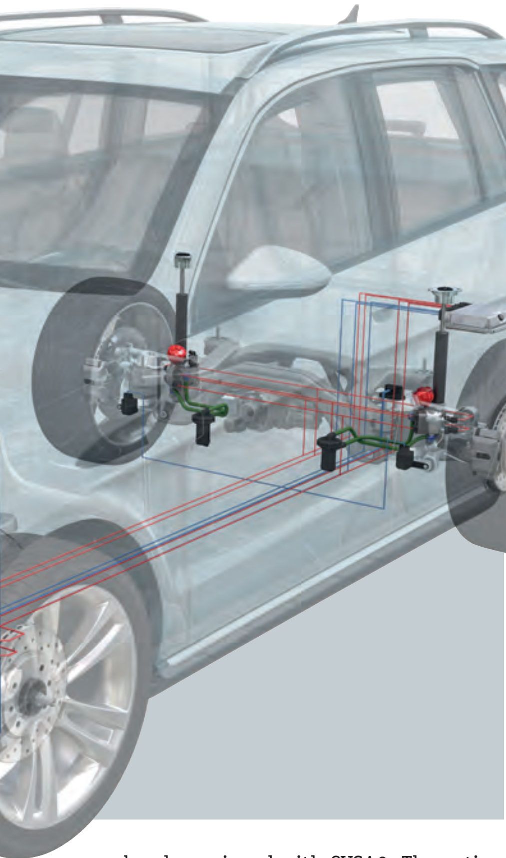
The CVSA2 system is controlled by a powerful electronic control unit (ECU) designed to exploit the full potential of the electrohydraulic valve system by processing input data sent from sensors placed at key locations around the vehicle. Further input signals are provided from the in-car network.

The CVSA2 control software processes sensor information on wheel motion, steering wheel angle, vehicle speed, brake pressure and other chassis control factors, and sends signals that independently adjust the damping level of each shock absorber. CVSA2 dampers allow a large separation between maximum and minimum damping levels and adjust instantaneously to ensure optimal ride comfort and vehicle control.

CVSA2/Kinetic

CVSA2/Kinetic combines the CVSA2 technology with an interconnected hydraulic roll control system to improve the comfort and handling performance of sports cars, while also delivering superb on-road comfort, off-road traction and articulation performance on SUVs. In addition, the CVSA2/Kinetic solution is low in weight and energy consumption, helping to reduce CO_2 emissions through reduced fuel consumption.

Using the Scalable Suspension concept, CVSA2/Kinetic can be easily implemented as an option on platforms



already equipped with CVSA2. The anti-roll bars are replaced with hydraulic connections between the corners, and the system can be extended with a variety of hydraulic ride height systems including discrete lifting, continuous leveling or hydro-pneumatic.

Acocar

The third option – the fully-active Acocar system – provides ultimate comfort with flying carpet-like control of body and wheel motion. By independently supplying hydraulic pump flow to the corners, Acocar can generate active force in addition to damping.

This replaces the anti-roll bars and keeps the car body flat at all times, while controlling wheel movements to improve tire-to-road contact. As a result, the Acocar system allows independent control of roll, pitch and heave,

ABOVE LEFT: Tenneco's Dual Mode adaptive damping technology

ABOVE AND BELOW LEFT: Reliability and durability for the Scalable Suspension has been ensured through thorough in-house testing and evaluation

providing superior handling and safety while optimizing comfort.

Acocar can easily be implemented as an option on platforms already equipped with CVSA2 by replacing the anti-roll bars by electrohydraulic power packs on each corner. As with CVSA2/Kinetic, the system can be extended with a variety of hydraulic ride-height systems including discrete lifting, continuous leveling or hydro-pneumatic.

The Scalable Suspension offers OEMs a unique product differentiation strategy. Each combination of the three Scalable Suspension solutions can be efficiently engineered on a single OEM platform as the actuator designs share the same vehicle interfaces, several common components, production processes, sensors and ECU. By using CVSA2 as its standard premium suspension technology, an OEM can add Kinetic roll control as an option for sports cars and/or SUVs and propose Acocar as the ultimate comfort and handling solution on luxury saloons or SUVs.

READER INQUIRY SERVICE

To learn more from Tenneco, visit www.ukipme.com/info/vdm ref. 002

Dynamics performance analysis

Siemens has developed a new load identification technique to accurately analyze vehicle dynamics performance

FIGURE 1: Limited instrumentation on suspension

Car manufacturers are prompted to design ever-lighter vehicles, while maintaining high standards for handling, NVH, and more. To reconcile these seemingly contradictory demands, a comprehensive understanding of vehicle loads is required.

Suspension-to-body interface loads are commonly used for identifying which suspension paths contribute most to a target response level. This information can be used for analyzing vehicle performance or for troubleshooting, and is typically performed for different attributes, using frequency-domain loads for (quasi-)stationary performances such as NVH and secondary ride or time-domain loads for transient performances such as impact harshness.

To aid vehicle dynamic performance or low-frequency comfort (primary ride) work, suspension-to-body loads help manufacturers to understand specific vehicle performance issues. They are also used to compare different vehicle suspension layouts and to identify potential weaknesses in the suspension or the body structure design. However, a major concern when identifying suspension-to-body interface loads, either in the time or frequency domain, is the significant effort required for the vehicle instrumentation, as well as the calibration transfer function tests needed for the load identification.

The LMS Engineering expert team at Siemens PLM Software developed a new load identification technique that deploys faster and more efficient vehicle performance evaluation for vehicle dynamics and primary ride phenomena. This technique is based on a limited amount of instrumentation (up to 50% compared with classic methods) and does not require load calibration frequency response function (FRF) measurements. Instead of FRF measurements, the vehicle instrumentation responses are combined with the output of a vehicle model, enabling an efficient and robust calibration of the vehicle instrumentation for load estimation. Especially for scenarios where different vehicles or a series of vehicle variants are to be studied, significant effort reductions can be achieved in the entire process of vehicle instrumentation, testing and analysis.

Innovative approaches

Two innovative approaches distinguish this new load identification technique from conventional methods.

First, the vehicle instrumentation is fitted to the suspension components instead of the body structure (Figure 1). The structure of suspension components is less complicated than the car body structure, and therefore the required amount of instrumentation is reduced.

Second, no calibration transfer function tests are carried out, which saves a significant amount of testing time in disassembling vehicles for evaluation. Instead, a short series of dedicated full vehicle tests are performed, both with the physical vehicle and with a basic model of the vehicle in a simulation environment. From these tests, the vehicle instrumentation responses and the vehicle model outputs are used to construct a robust calibration definition between vehicle instrumentation and the suspension interface loads of interest.

As a result, efficient and robust load identification for vehicle performance analysis is performed with limited instrumentation and calibration effort. By combining test and simulation data, many typical load identification complexities (such as cross-coupling between loads) are avoided.

Use scenarios

A typical scenario for applying the load identification technique is comparing the handling performance of two vehicles with different suspension layouts on an undulating road. Doing so, LMS Engineering experts investigate how a different suspension layout, geometry or setting affects the vehicle's stability, and by extension the driver's confidence.

First, the suspension components of vehicles A and B are instrumented with strain gauges, then full vehicle calibration tests are performed on both physical vehicles and on basic vehicle models in a simulation environment. These tests provide the required output to construct a robust calibration matrix for both vehicles, enabling load identification for full vehicle maneuvers on a chosen track or road.

In our example, objective vehicle evaluations on an undulating road demonstrate that vehicle A has a different vehicle behavior (yaw motion, roll motion) from vehicle B. This is shown in the oscillatory vehicle motion (Figure 2), as well as in different phasing of the body response to a road disturbance. These variances result in a very different subjective appreciation of vehicle A versus vehicle B.

Using the suspension strain-responses acquired during the tests on the undulating track, suspension-to-body loads are estimated for both vehicles. Loads are available in vertical direction, and also in lateral direction. These

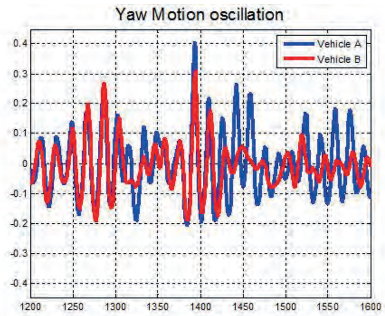


FIGURE 2: Different vehicle yaw motion behavior on undulating road

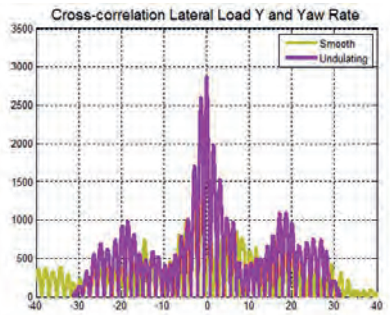


FIGURE 3: For smooth road, a negligible correlation of suspension component 'K' lateral load and the yaw motion. For undulating road, this correlation is far higher, pointing out the reason for the higher vehicle A yaw motion oscillation as shown in Figure 2

loads allow in-depth study of how a certain road undulation is absorbed by the suspension when the vehicle is cornering. It also gives insights into how and why the front suspension handles undulations differently from the rear.

For example, to understand why vehicle A shows more oscillatory yaw motion on an undulating road than vehicle B, the lateral loads – the loads related to the vehicle yaw motion – acting on both vehicles are compared in detail. This comparison reveals that the front suspension (which is similar for vehicles A and B) shows no relevant differences in how a road undulation introduces lateral disturbances into the suspension, which can lead to the undesired yaw oscillations. However, when looking at the rear suspension (having a different layout for vehicles A and B), a clear dissimilarity can be detected. To illustrate the divergence, correlation values are calculated between specific suspension loads and the oscillations in the vehicle yaw motion for the vehicle while cornering on a smooth and undulating road (Figure 3).

As demonstrated in Figure 3, it is clear that there are significant differences in the suspension design choices for vehicle A versus vehicle B. For vehicle A, the suspension component 'K' lateral load has no correlation with the yaw motion on smooth roads, while on undulating roads a clear correlation of this suspension load with the vehicle oscillatory yaw motion can be seen. For vehicle B, suspension component K does not correlate with the yaw motion on a smooth road nor on an undulating road. Further exploration of the identified suspension loads for both vehicles gives more insights into how both rear suspensions deal with road undulations.

This application example illustrates how the load identification technique enables automotive manufacturers to compare vehicles and suspension layouts for different dynamic performances and simultaneously identify potential suspension weaknesses. Based on the suspension-to-body load comparisons, the improvement potential for vehicle A is identified and modification recommendations for the suspension are made. The implementation of these modifications in a simulation environment, as well as on the physical car, proved to significantly enhance the vehicle performance on undulating road.

In summary

This load identification approach smartly combines the use of limited vehicle instrumentation and basic vehicle models to deploy a faster and more efficient vehicle performance analysis, suitable for different applications. As shown in the example, the suspension performance can be studied in detail because identified loads are available for each relevant suspension component. This allows for benchmarking of different vehicles or suspension layouts, but also for troubleshooting specific problems. In addition, the identified loads can be used for model correlation and validation, and can provide support in target-setting procedures.

Finally, this load identification approach has also been proven to allow objective quantification of the effects of body rigidity changes on vehicle dynamic performance.

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To learn more from Siemens, visit www.ukipme.com/info/vdm ref. 003

Innovative evaluation software

The VBOX Test Suite, **Racelogic**'s latest software package, is simple to use, yet ensures that dynamicists' software capabilities match their hardware capabilities

The versatility of Racelogic's VBOX GPS dataloggers, together with the various modules, inertial units and displays that accompany and enhance them, has led to their extensive use within virtually every sector of the automotive testing industry.

Test engineers can only take full advantage of high-quality hardware if the software being used alongside it is of the same standard. The software needs to be every bit as capable and versatile as the hardware it supports.

This balance is difficult to achieve: a supporting program that can be used to analyze just about any kind of test can itself be tiresomely long-winded and complex to set up and use. When pressure is mounting for evaluation to be conducted in as short a time as possible – whether due to cost restrictions, limited track time, or production deadlines – having to spend lengthy periods setting up the software, with lots of time needed for post-processing and reporting, is counterproductive and may even undermine the reasons for acquiring top-of-the-range hardware in the first place.

ABOVE: The latest version of the VBOX Test Suite enables dynamicists to evaluate tire performance in aquaplaning conditions

VBOX Test Suite

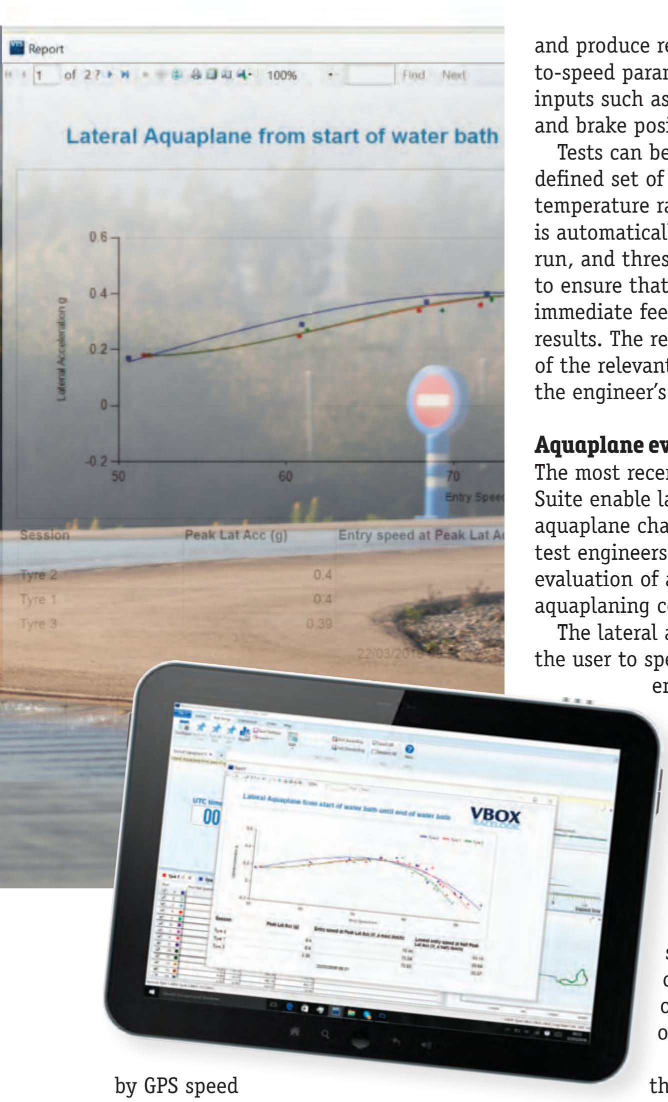
Racelogic has now created a software package, VBOX Test Suite, to solve the conflict between advanced features and ease of use. The company recognizes the fact that, although VBOX units around the world are used in hugely varying test environments, most of them are still purchased by individual departments to do one job.

Developed based on feedback from engineers who use a VBOX at the sharp end of vehicle development every day, the ethos behind the new software is to significantly reduce the time it takes to conduct specific tests to exacting modern standards, and therefore cater to specialized applications.

By creating an adaptable working space that allows for multiple sets of data to be compared via separate tabs, the software is as simple to use as it is capable, and it produces reports that present results clearly enough for complex data to be displayed and easily understood, no matter who is looking at them. The automation of much of the reporting is a key factor in getting results together, so quickly, in a meaningful manner.

The software also includes video integration for use with Racelogic's Video VBOX range: customizable graphs, compatibility with satellite imagery so that a positional trace can be overlaid, and live or post-test analysis. Context-sensitive menus mean that managing several data sets doesn't get too complicated.

On first release, VBOX Test Suite allowed for basic performance testing – acceleration and deceleration, triggered



by GPS speed or a vehicle CAN input. It has now been updated, however, to include plug-ins for specific types of testing.

Brake testing

As brake testing has always been one of Racelogic's core competencies, it made sense that the first additional component to the software should cater for engineers conducting brake stops. The system can be used by any VBOX 3i user in the world who carries out braking development, as the software is configured so that it conforms to regulations in all regions. The brake test plug-in can carry out auto-calibration of wheel speeds, calculate wheel slip, and produce results based on a speed-to-speed parameter or via alternative inputs such as trigger, brake pressure and brake position values.

Tests can be run within a tightly defined set of criteria, such as between temperature ranges. Centerline deviation is automatically calculated during each run, and thresholds can be applied to ensure that the operative gets immediate feedback on the validity of results. The report produced includes all of the relevant information, along with the engineer's notes.

Aquaplane evaluation

The most recent additions to VBOX Test Suite enable lateral and longitudinal aquaplane characterization to allow tire test engineers to perform a complete evaluation of a tire's performance in aquaplaning conditions.

The lateral aquaplane plug-in allows the user to specify entry criteria, to ensure that the vehicle is fully settled and in as steady a state as possible before entering the water bath, where the test begins. Then, by closely monitoring the vehicle's lateral acceleration at varying entry speeds, the software produces a comprehensive report of the acceleration obtained during each run.

This report then allows the engineer to understand the peak acceleration value that can be achieved by a given tire, as well as the rate at which grip decreases once aquaplane has occurred. This data can be directly compared with other tire compounds to provide engineers with the information needed to grade tire performance in wet corner conditions.

The longitudinal aquaplane plug-in employs a user-definable threshold slip value for each wheel, allowing the user to choose between reaching the aquaplane condition when one, or all, of the tires exceed this value. Wheel speeds can be automatically calibrated in comparison with GPS speed, but this doesn't need to be done in the actual test area – it can be done anywhere, further reducing pressure on track time. Pre-entry test conditions are also user-definable, to ensure the vehicle is in a steady state before the test begins.

LEFT: The lateral aquaplane plug-in for the VBOX Test Suite allows the user to specify entry criteria

Coast-down testing

Another recent addition to the VBOX Test Suite is a specific feature for coast-down testing, again designed for engineers to conduct tests to comply with international regulations. Given that the data produced forms the basis of a manufacturer's emissions values of a new model, enormous importance is attached to coast-down results.

One standard in particular – the American J2263 – has traditionally required highly complex post-processing work to produce these results, as well as demanding the use of onboard anemometer readings. Any automation of the process therefore brings considerable time savings. VBOX Test Suite integrates the wind speed via an analog signal into the VBOX itself and produces a road force measurement which completely removes the need for heavy-duty, time-consuming calculations after the track tests have been completed.

Coast-down testing to the new European GTR15 standard has pass criteria, not just from a start to end speed, but also in 10km/h (6.2mph) decrements and in opposing directions. (For instance, a 115km/h (71mph) to 15km/h (9.3mph) test requires an overall result as well as from speeds of 115-105km/h, 105-95km/h and so on, with each section having to fall within a 3% tolerance to pass).

The new software automatically grades each section of each individual run, and stitches each of the full runs together to form a comprehensive set of results – again massively reducing the amount of time needed to complete a set of coast-down tests meeting the new European regulations.

Further VBOX Test Suite plug-ins are also in development and will include AEB and pass-by noise (R41 and R51) tests.

A new breed of SUV

Dynamik Technological Alliance's luxury SUV project has come of age: a plug-in series hybrid, combined with an interconnected suspension modular platform chassis

Want to hear some impressive numbers for a vehicle? How about having ample space for nine people, 39cm of ground clearance in off-road mode, 30cm of suspension travel, 20cm of ride height adjustment, a turning radius of less than 9m, and 400bhp from four in-wheel hub motors? It is certainly a radical departure from the accepted luxury SUV setup. So what was the reasoning behind the design team's decisions?

"We analyzed the market for a vehicle of this type in detail, and came to the conclusion that a new paradigm was required if we were going to compete," explains Iván Platas, chief technical director at Dynamik Technological Alliance. "It was also important for us to demonstrate the expertise of our company and the team that makes it all possible."

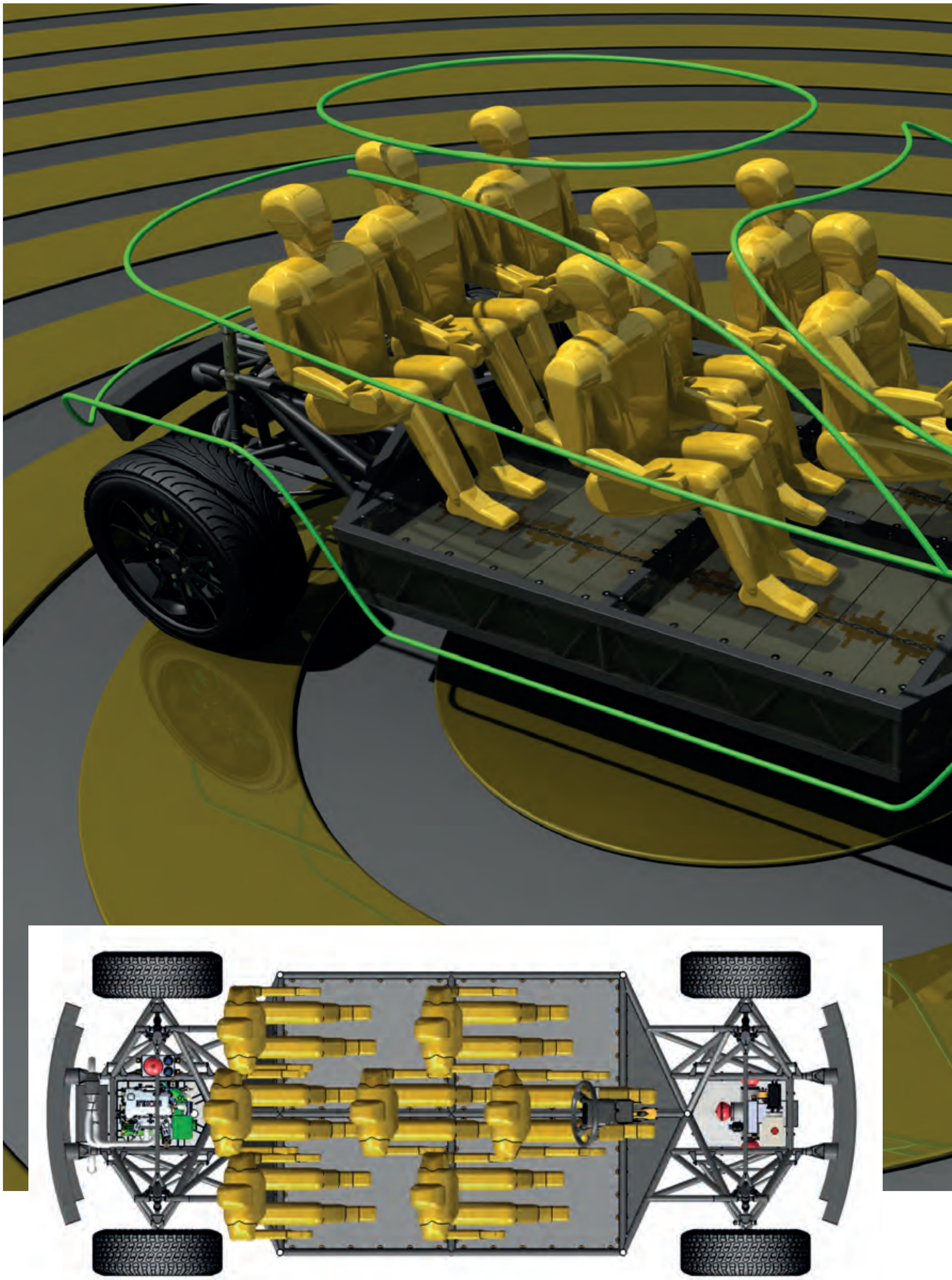
How were the unusual specifications of this SUV decided? "The requirements were succinct: the vehicle has to carry seven adults in complete luxury and have a true off-road capability," explains Karl Niklass, consultant vehicle dynamicist at the company. "Apart from that, we had a free hand."

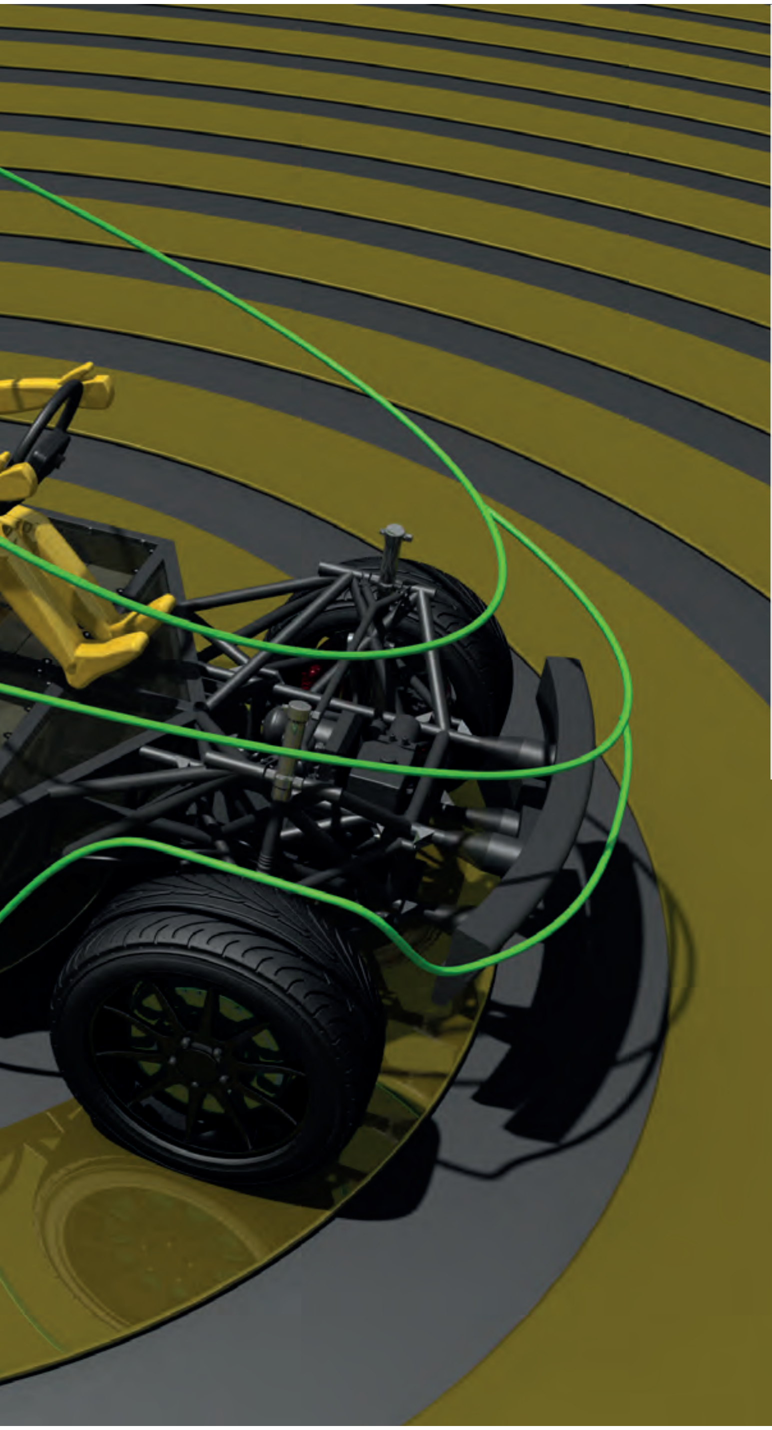
There were six principal goals for the vehicle: maximized passenger space; an efficient hybrid powertrain; an interconnected suspension; in-wheel hub motors; all-wheel steering; and a new type of suspension design.

"One of the key aims of our team was to approach this project using holistic methodology. Each of the technologies must complement the others – that is what makes this concept work," continues Niklass.

An example is how the interconnected suspension system interacts with the vehicle geometry. In this system, every movement of the body of the vehicle can be adjusted separately.

"We can place more damping and stiffness into roll, a lesser amount into pitch, and make the heave damping and stiffness optimized for ride comfort. Not only that, by cross-coupling front to rear, warp stiffness can be reduced to





Tech specs: Dynamik Luxury SUV

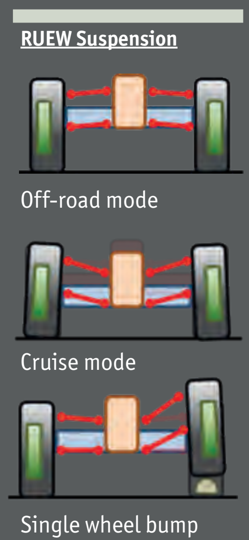
Width: 2.0m
Length: 5.0m
Wheelbase: 3.6m
Track: 1.7m
Turning radius: <9m
Ground clearance: 390mm
Approach/depart angle: 45°

Suspension:
Overall travel: 300mm
RUEW geometry
Interconnected suspension

Powertrain:
Range extender
In-wheel motors
Batteries
Ultracapacitors

Brakes:
Double-caliper brake system
+ 85% regenerative

Wheels and tires:
Equal diameter on-road and off-road tires to choose from:
285/50 R20
285/40 R22
295/30 R24



MAIN IMAGE: A complete rethinking of the dynamic setup has enabled a spacious and comfortable seven-seat cabin concept

BOTTOM LEFT: The interconnected suspension system lets each element of body movement be adjusted separately

a minimum," adds Niklass. "This is most important for an SUV traveling over irregular surfaces."

From the outset the intention was for the vehicle to have the robustness of a solid axle with the independence of a double-wishbone design. This arrangement allowed the upright to be connected to the wheel motors in a raised position. No suspension components hang below the undertray of the vehicle, which helps to create an exceptional ground clearance of 39cm in off-road mode.

"In this raised upright extended wishbone (RUEW) design, the wishbones are mounted longitudinally parallel to each other, so trunnions can be used for the wishbone, actuator and upright articulation," says Niklass. "The whole is a rugged but very lightweight design. The actuators connect directly to the upright and the steering geometry is set by swivel bearings, in a similar manner to a live solid axle.

"By removing the conventional engine and powertrain, and by implementing regenerative braking, efficiency is increased, the center of gravity is lowered and the cabin volume is increased," concludes Niklass. "This all adds up to a safer vehicle with improved dynamics."

The future of torque vectoring

BorgWarner's innovative 48V electric rear drive module (eRDM) facilitates torque vectoring and hybrid driving modes for excellent dynamics and enhanced safety, as well as reduced CO_2 emissions

FIGURE 1: A prototype eRDM undergoing extreme driving conditions in a series production vehicle available with torque vectoring

Mechanical torque vectoring axle systems are typically combined with an all-wheel drive (AWD) system and are available on some of today's premium vehicles. The systems have proved very capable in generating high levels of yaw authority, which results in outstanding control of vehicle dynamics, but their high mass and low efficiency have a negative impact on fuel economy and CO_2 emissions.

For this reason, BorgWarner has developed an innovative 48V electric rear drive module (eRDM) (Figure 1) to deliver outstanding electric torque vectoring performance combined with full-function mechanical AWD. The module combines excellent driving dynamics provided by torque vectoring via direct 48V electric motor control, with major CO_2 savings through 48V hybridization in a P3 configuration, with no compromises on AWD performance due to its mechanical connection to the driveline.

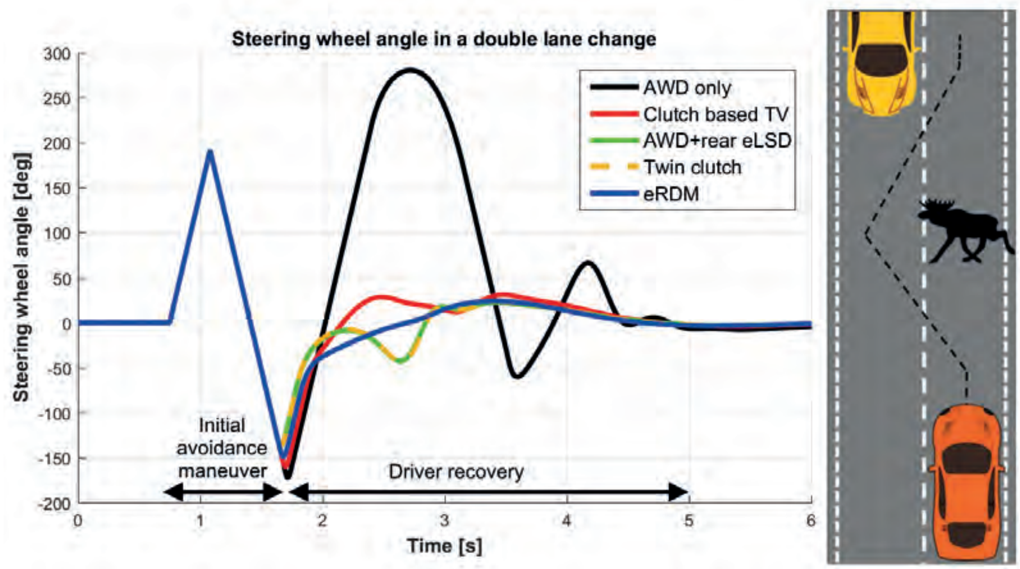
System specifications

The eRDM's system specification is based on vehicle-level modeling used to optimize system performance and value. This is why BorgWarner has run multiple simulations based on the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light-Duty Vehicle Test Procedure (WLTC) to determine the best balance between system cost and hybrid functionality. Additional simulations compared the performance of a two-speed and a single-speed gearbox.

The simulations showed that a maximum operating speed in hybrid mode of around 50mph (80km/h) would recover most of the available regenerative energy. Moreover, a maximum operating speed of around 80mph (130km/h) would maximize the regeneration potential, which is why it was chosen as a suitable speed for the demonstration vehicle.

Additional simulation results show that a wheel torque capacity of 700Nm provided electrically would recover most of the available regenerative energy. An increase in torque capacity in hybrid mode would mean little or no improvement in the regeneration function.

Moreover, higher electric power increases the amount of regenerative energy that can be recovered, but incremental improvements decrease at higher power. In accordance with these test results, as well as the fact that the



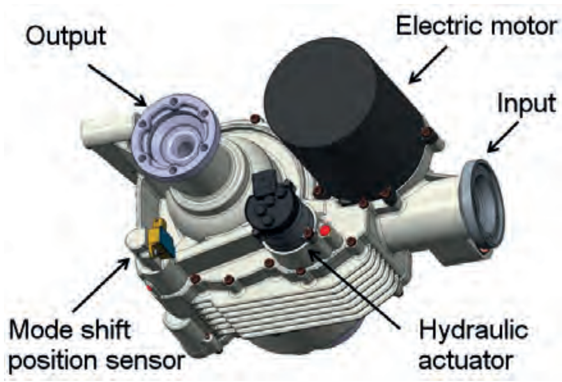
power of a 48V system is usually limited to 8-15kW by the vehicle's power supply and the battery, BorgWarner chose 12kW as the peak power for the investigations.

Performance comparisons of a two-speed and single-speed gearbox showed slight advantages for the former with regard to the regenerative energy recovered during the drive cycles. However, BorgWarner used a single-speed box due to its overall higher value.

Advanced system design

The eRDM has an input from the rear propshaft and includes the components of a traditional RDM (Figure 3). In addition, it uses a 48V motor that drives two planetary gearsets. A gerotor pump is used to supply the 48V motor with cooling lubricant and provide for hydraulic control of the shift mechanism. The system also features fins for passive heat rejection, requiring no external heat exchanger, thus greatly reducing system costs.

The eRDM can operate in torque vectoring and hybrid mode. Additionally, the 48V motor can be disengaged from the system. In hybrid mode, the motor is connected to the differential case by a double-reduction helical gearset. As a result, the motor can be used to add torque to the differential case for torque assist or in regenerative mode to recover kinetic energy, facilitating functions such as electrical sailing, regenerative braking, and boosting for CO_2 reduction and enhanced fuel efficiency. In torque vectoring mode, the motor is connected to the sun gear of the double planetary gear, allowing it to actively distribute the torque between the two wheels depending on vehicle signals such as yaw rate, wheel speed, steering wheel angle and throttle position, for excellent driving dynamics and stability.



Highly efficient performance

Using an electric motor to deliver up to 1,200Nm of torque vectoring function delivers multiple advantages, such as better actuation torque accuracy compared with most clutch-based systems. Moreover, a torque step response much shorter than 100ms is possible with an electric motor, whereas most clutch-based systems struggle to go below 100ms in some scenarios. Another improvement in the controllability of the eRDM compared with a clutch-based system is that it can operate in all four quadrants and is able to move between them smoothly.

Most clutch-based torque vectoring systems use two clutches in combination with a step-up/down transmission, with the clutches spinning at a differential speed of 10% of the absolute wheel speed. Even with an inactive system and clutches, and lubrication management optimized with regard to drag losses, the inherent losses due to the always present differential speed over the clutches have a great impact on fuel economy, which means a considerable advantage for the eRDM solution, which uses direct electric actuation.

FIGURE 2: The eRDM offers major benefits in terms of stability and requires less steering effort during dangerous evasive maneuvers

FIGURE 3: Through an innovative design in which a 48V electric motor is added to the traditional RDM, BorgWarner's eRDM combines torque vectoring and hybrid functionality

The eRDM's performance with respect to peak and average losses during sporty driving is another advantage. Since clutch-based systems feature a typical 10% overspeeding on the clutches, power losses can reach several tens of kilowatts at moderate or high speeds, and this can force the system to limit or degrade performance due to thermal limits. In contrast, with the eRDM the energy is simply transferred to or from the battery, considerably improving system availability in sporty driving and in hot climates.

BorgWarner has also simulated a double lane-change evasive maneuver at 60mph (100km/h) to compare the eRDM's performance with that of AWD, clutch-based torque vectoring and twin-clutch systems, as well as with an AWD system with rear-axle electronic limited slip differential (Figure 2). Following the initial avoidance maneuver, the eRDM does not require as much steering input by the driver to stabilize the car as the other systems. This is a major advantage, since even average drivers can now resolve dangerous situations more easily, which improves comfort and safety. The eRDM also provides better cornering behavior than most other systems, independent from clutch friction characteristics. In terms of understeering, the behavior of an eRDM-equipped vehicle is much more predictable since it operates independently of throttle position and acceleration.

Even though the eRDM is initially being designed for a mechanical AWD vehicle, the principle of electrical torque vectoring is also applicable to electrically driven axles on hybrid electric and electric vehicles.

Mechatronic test benches

Test drive evaluation of steering behavior in a closed loop is made possible with highly dynamic mechatronic test benches from **dSPACE**

ABOVE: The mechatronic test bench, including the operator workstation with ControlDesk for controlling the tests (left) and MotionDesk for visualizing driving maneuvers (right)

ABOVE: Expansion of the test bench by a cockpit with force feedback steering wheel for realistic test drives with haptic feedback

Today's complex steering systems' main functionalities are implemented as the control and function software of the electronic control unit (ECU). Integrating mechanical, electronic and information technology components is therefore a major part of the development process.

The essential role of control and function software necessitates switching from a classic mechanical product development process to the mechatronic process described by the V-cycle. One major task in developing a steering system is to define precise requirements. Ideally, this is done by using objective criteria or comparisons with existing products that are well accepted by customers and proven in practice. With steering systems, this is difficult because the overall driving feel is a very subjective experience that depends on the individual driver. A test driver's evaluation therefore always plays a central role. However, this is not possible until the controller and function software has been integrated at the end of the development process. To get a first subjective impression of a steering system early on, a hardware-in-the-loop (HIL) test bench for the steering function is combined with a static driving simulator (mechanical setup).

In this test environment, virtual test drives can be used to analyze and evaluate the real steering system with various control and function algorithms. This means that even before vehicle integration, requirements on the steering feel, sense of safety, and ergonomics can be evaluated both objectively and subjectively. Advantages are the high reproducibility and adaptability of the automated tests, and the broad range of uses for the test bench.

This type of test bench also increases development efficiency and helps engineers perform the growing number of tests, which are necessitated by the many vehicle variants and shorter development times.

Flexible test bench setup

dSPACE's steering test benches can include a complete steering system, with the steering column, servomotors, racks, and tie rods. A special feature of these benches is the variable clamping plate with various scales for positioning the individual components. The systems also provide interfaces for energy and signal transmission between the steering system and the test bench. All this makes the test bench highly flexible, letting users adapt it perfectly to various steering systems while ensuring extremely low setup times and, thus, efficient operation.

Efficient electric drives

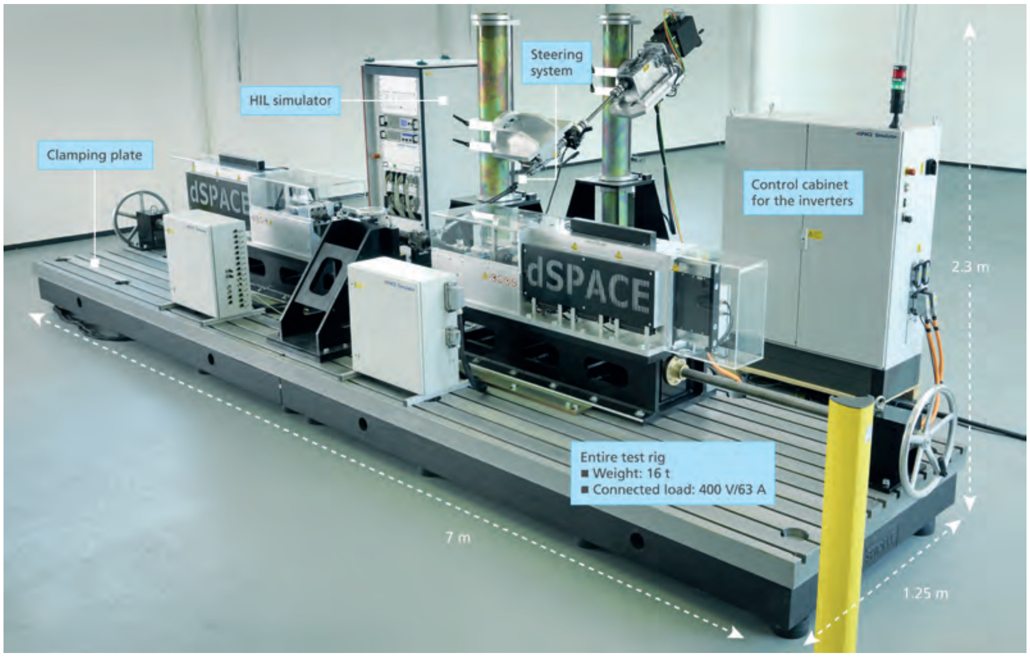
The dynamic electric drives, consisting of two linear motors that mechanically stimulate the steering system, are at the heart of the test bench. The drives simulate forces that, in a real vehicle, are transmitted from the wheels to the two tie rods. The steering actuator at the other end of the steering column dynamically sets the steering angle, thus imitating a driver. Controlled servo-inverters supply power to the two linear motors and the steering actuator. The low-latency control of the linear motors is designed so they can dynamically represent high forces and precise resolutions. The inverters of all the motors are connected by a shared voltage DC link. The DC link is fed energy from the electrical grid via an active feed-in unit.

Because the inverters are connected, only the current losses of the test bench have to be covered. The majority of the energy continues to flow in the circuit. This makes the test bench more energy-efficient than hydraulic test benches. The external power supply works with only a standard three-phase plug (63A). Other materials, such as coolant and compressed air, are not needed.

Setup and function of the simulator

The motor control, test bench monitoring and measurement data capturing are all performed by a dSPACE HIL simulator. The simulator contains a real-time processor, the required I/O, and the appropriate signal conditioning. The drive inverters are controlled via the TWINsync protocol by LTi, which ensures that the setpoints are transmitted to the inverters in intervals of 125µs. This control concept provides high accuracy, even for highly dynamic stimuli up to 30Hz, which corresponds to a fast drive on a cobblestone road.

The simulator also simulates the restbus, which can be either CAN or FlexRay, depending on the steering type. The dSPACE Automotive Simulation Models (ASM) tool suite is used to simulate the dynamics of a vehicle in real time. The real steering system can be connected to the ASM Vehicle Dynamics Model for real closed-loop operation. ASM Vehicle Dynamics provides models for a wide range of vehicle types, such as passenger cars and trucks. The models can be extended by rear-axle steering if needed. The graphical user interface of dSPACE ModelDesk is used to parameterize the various vehicle models, and the software also lets developers define roads and maneuvers for the virtual test drives. The 3D dSPACE MotionDesk animation software can be used to immediately visualize the vehicle behavior, and the dSPACE ControlDesk experiment and instrumentation software is used to control the test bench. With the dSPACE AutomationDesk test automation software, users can also automate their test sequences for more convenience.



ABOVE: Setup and technical data of the steering system test bench

Use cases and evaluation

The modular structure of the test bench and the software opens up a broad range of applications in the development of steering functions at steering system level and also at vehicle level: from classic open-loop driving maneuvers, to subjective assessment of feedback, to the development of driver assistance functions with longitudinal and lateral dynamics. This structure has the advantage that the entire system, consisting of the real steering system, the control and function software plus the vehicle, can be evaluated and analyzed. For example, the results from open-loop test drives can be used to identify objective variables for describing steering feel and driving behavior.

The driving simulator makes it possible to perform various closed-loop tests, such as slalom tests, and assess them objectively as well as subjectively. This gives users a way to analyze feedback behavior, for example when driving over cobblestones, modify it with the aid of the control software, and evaluate it. A camera can be added to the existing HIL system to test camera-based driver assistance systems, with the restbus data necessary for running the camera provided by the vehicle simulation model and sent to the camera's ECU via CAN. The assistance torque calculated from the camera and vehicle data is provided via the torque interface. This makes it possible to combine the real steering system and the real camera system in order to test them together and adjust the steering assistant functions and driver assistant functions to each other.

Features and application areas:

- Closed-loop testing of steering systems
- Complete validation of steering systems
- Tests of steering mechanisms, ECUs, sensors and actuators
- Reproducible tests
- Replay of vehicle dynamics measurement values
- Early tests throughout the development cycle
- Release tests of steering system components
- Benchmark tests
- Adjustments of the steering feel
- Tests of steering character
- Identification of mechanical steering parameters
- Analysis of transmission behavior

Summary

With a highly dynamic mechatronic test bench, it is possible to use HIL simulation to test drive the steering behavior of a vehicle realistically under laboratory conditions. This means manufacturers can now efficiently test and optimize the behavior, feel and function of new steering systems, even in early development phases. Mechatronic steering test benches give users more flexibility and enable them to reproduce tests with high precision by means of automation, making the development and validation of steering systems more efficient.

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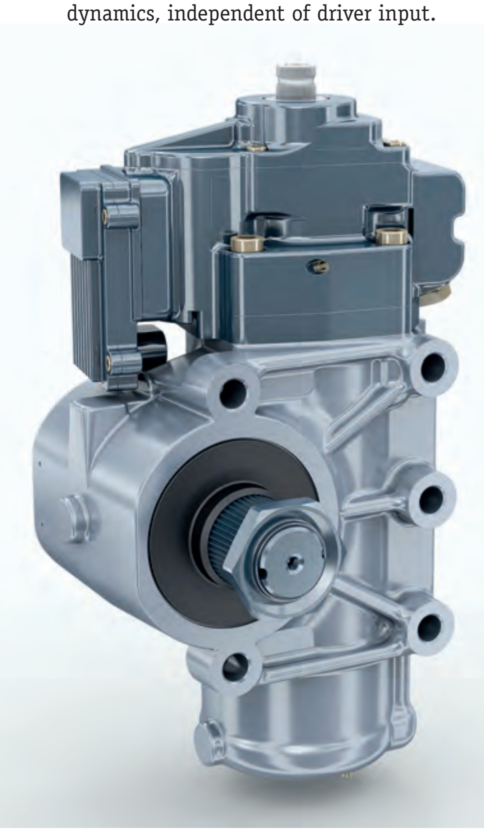
Autonomous yard maneuvering

Knorr-Bremse and **Tedrive Steering** have successfully integrated active steering into the braking system of commercial vehicles

Through its recent acquisition of Tedrive Steering Systems, Knorr-Bremse has added innovative steering technologies for commercial vehicles to its product portfolio and paved the way toward offering an integrated longitudinal and lateral guidance system for automated driving in heavy-duty commercial vehicles.

Tedrive Steering Systems is a manufacturer and development partner for steering systems for all axle loads, with base recirculating ball steering gears that are suitable for vehicles with front-axle loads between 2.5 tons and 9 tons. One key product in the company's range is the iHSA (intelligent hydraulic steering assist) technology. Automated driving predicates control of the longitudinal and lateral vehicle dynamics, independent of driver input.



LEFT: With the intelligent steering system (iHSA), Knorr-Bremse is paving the way for automated driving

Today, Knorr-Bremse's electronic brake control systems can already control the longitudinal motion of the vehicle and at the same time ensure its dynamic stability. Integration of iHSA steering will mean that the system can now also control the vehicle's lateral dynamics. Knorr-Bremse is thereby putting in place one of the key prerequisites for implementation of automated driving in the commercial vehicle sector.

Steering systems for all axle loads

In the recirculating ball steering segment, Tedrive Steering has three basic systems in its portfolio – the C300, C500 and C700 – which are suitable for vehicles with front-axle loads from 2.5 tons (C300) to 9 tons (C700). The specifications of the iHSA control module are identical for all Tedrive recirculating ball steering gears.

The robust, modular design of the recirculating ball steering gears, as well as their high hydraulic power-to-weight ratios and compact dimensions make for maximum flexibility in terms of applications engineering. The recirculating ball steering gears are also available in a two-circuit version and for two-axle systems as a master/slave application. The company also develops and delivers special applications for very high axle loads. When developing its commercial vehicle steering systems, Tedrive Steering applies a balanced blend of proven and innovative technology.

System integration

"In our very first joint projects, connecting up the brake control system from Knorr-Bremse and iHSA technology to form a control network rapidly revealed the benefits of genuine system integration," says Bernd Spies, chairman of Knorr-Bremse.

"Driver assistance and automated driving functions can be channeled through a common interface, and then synchronized between the steering and braking systems. Added to which,

the more advanced levels of automated driving require a backup function for the steering, and this can be provided efficiently by the brakes," he adds.

With iHSA technology, Knorr-Bremse will be able to realize numerous optimized solutions for driver assistance systems and automated driving functions. By adding the iHSA control module to a Tedrive base recirculating ball steering gear, all safety, comfort and convenience functions, such as congestion assist, platooning or autonomous yard maneuvering, can be implemented in heavy-duty vehicles.

Autonomous yard maneuvering

Trucks maneuvering around the depot with no driver can now be a reality: Knorr-Bremse has built an autonomous semi-trailer rig that can drive itself to the loading bay and back across the yard with no driver. The company demonstrated this system in a test truck at the IAA 2016 transportation show in Hannover.

"Everyone's talking about Highway Pilot, the truck that drives onto the autobahn and handles everything automatically. And while that will certainly happen, it's a long-term prospect. For our part, we will be actively shaping the route to the

How iHSA works

The iHSA steering module combines the familiar advantages of electric steering – the possibility of driver-independent torque overlay – with those of conventional hydraulic steering gear, while also presenting a robust overall design suitable for use in light commercial vehicles, heavy-duty trucks, buses and special-purpose vehicles with high front-axle loads.

In conventional steering systems, the steering torque initiated by driver controls the hydraulic power steering via a hydraulic valve. The iHSA steering system uses the existing hydraulic valve as well, but also addresses it, independent of driver input, via a compact electric motor, thus generating steering torque independently of the driver. The motor can be kept very small because it doesn't have to deliver any steering torque itself, but simply serves to control the hydraulic valve.

As a result, the power uptake of the iHSA control module is low and there is no need to modify the vehicle's electrical system. The steering system can be controlled by the driver assistance systems in conjunction with the steering torque applied by the driver. In highly automated driving functions, this can take place without driver involvement.

Along with its base recirculating ball steering gears, Tedrive Steering is an established manufacturer of rack-and-pinion systems for passenger cars. The company has also been supplying these for LCV applications with higher axle loads for many years now. As a key differentiator and USP in this area, Tedrive Steering offers proprietary steel housing technology that delivers tangible benefits in terms of steering feel.

ABOVE: At the 2016 IAA fair, Knorr-Bremse demonstrated a semitrailer rig that can perform autonomous maneuvers in depots off the public roads

Highway Pilot and continuously expanding our portfolio in the field of driver assistance systems and automated driving," explains Dr Peter Laier, member of the executive board of Knorr-Bremse, and is responsible for the commercial vehicle systems division.

Trucks capable of autonomous yard maneuvering make for greater efficiency. This complex autonomous driving function is made possible by interaction of the powertrain, the iHSA steering gear and the braking system, supported by simultaneous detection of the vehicle environment by radar and ultrasonic sensors, cameras and GPS. Smart system connectivity enables the truck to maneuver autonomously to and from the loading bay with great precision, stopping automatically if danger is detected. This way, there is less risk of minor damage being caused during complex maneuvering, and no time is lost because of errors in bay selection. Drivers are free to carry out other duties or take their statutory rest hours.

Through this demonstration of autonomous yard maneuvering, Knorr-Bremse is showing what is currently technically feasible, as well as underlining its own systems integration expertise. In the specific context of a depot, with its low speeds and fenced-off spaces, the legal framework for rapid realization is also given.

En route to Highway Pilot

The first steps have already been taken: lane departure warning, adaptive cruise control and autonomous emergency brake systems from Knorr-Bremse have already been installed in trucks being driven on the road today. The next steps are turn-off assist, congestion assist and autobahn assist. Following the acquisition of Tedrive Steering Systems and its iHSA system, Knorr-Bremse will be able to offer numerous proprietary driver assistance systems and automated driving functions from a single source.

In this context, the company's Global Scalable Brake Control (GSBC) system provides an efficient integration platform for future driver assistance functions. In addition, GSBC and iHSA together form a control network for the longitudinal and lateral guidance of the vehicle in automated driving functions. The backup function required to cover component failure in automated driving is already built into this system. As a result, highly automated driving functions in the commercial vehicle sector can be realized efficiently.

Along with autonomous yard maneuvering, at the IAA fair Knorr-Bremse also presented its Turn-off Assist system, which has the potential to substantially reduce the number of accidents at urban intersections. The near-side door mirror is replaced by a camera which, together with a side-mounted radar, scans the relevant environment. When the vehicle is on the road, a monitor in the A-pillar shows what would appear in a conventional mirror. If a collision threat is sensed, the driver receives acoustic and visual warnings and the monitor displays the blind spot on the right-hand side of the vehicle. This way, the driver can assess critical situations more accurately and react accordingly.

Knorr-Bremse's aim is to generate added value for its customers, be they vehicle manufacturers or operators, in the development, production and operation of commercial vehicles. In the interests of greater safety and of reducing vehicle and operating costs, Knorr-Bremse has been systematically pursuing this course for many years now, particularly against the backdrop of the growing market penetration of driver assistance and automation functions.

Fit for purpose

Cutting-edge facilities and expertise can refine vehicle testing for real-life applications. **Millbrook** considers the bus sector...

ABOVE: Millbrook's 9m x 3.3m tilt platform can tilt vehicles weighing up to 42,000kg at an angle of up to 45°

Millbrook provides assessment and development expertise across all aspects of vehicle, tire and component testing. The company's sites, in the UK and Finland, boast a reputation for adaptability, a broad range of facilities and experienced engineering staff. Covering the full range of safety, powertrain and vehicle development, the company has become adept at creating bespoke testing programs that put vehicles through their paces. These programs are devised with a view to assessing how successful a vehicle is likely to be in the market, as well as whether it will be legally compliant.

Product development testing is all about the consistency, repeatability and reliability of testing procedures, but there is an increasing demand for applying a more subjective approach to R&D. By understanding the inner workings of testing procedures, and why a vehicle or component performs the way that it does, the team at Millbrook is in a unique position to add value through informed consultation.

Some aspects of Millbrook's work in the bus, truck and off-highway sector are well documented, particularly in relation to emissions and fuel economy testing. Millbrook works alongside Transport for London (TfL), and performs testing for emissions, to equivalent Euro VI legislation criteria, noise, acceleration and stability. Benefitting consumers directly, trials with First Bus have led to improvements in fuel efficiency and reduced carbon emissions, as manufacturers strive for the top level of performance.

The testing work undertaken at Millbrook for the public transport sector is reasonably well understood, unlike Millbrook's work in the more dynamic areas of bus product development. In July 2015, Millbrook announced its new noise, vibration and harshness (NVH) measurement facilities, supporting customers as they refine vehicles beyond the usual testing metrics, while following regulatory processes. The facilities are particularly relevant for new technologies, including electric and hybrid vehicles. By measuring acoustics and vibration inside a vehicle, and syncing it with data recorded outside, engineers can better understand the cause of excessive noise and vibration. This enables the development of vehicles for quieter, smoother and more comfortable journeys.

Advanced capabilities

Millbrook has invested in state-of-the-art hardware, software and databases to provide these capabilities. These have proved to be of enormous value to public transportation manufacturers who are seeking independent expertise in the key areas of impact on end-user experience.

Much of the consultation also focuses on broader aspects of passenger comfort, such as convenience, space, practicality and utility, and safety. Objective or subjective, Millbrook has ways of quantifying comfort variables.

The supply of vehicles in the transportation sector is very different from the supply of mainstream

ABOVE: First Bus vehicles being evaluated on Millbrook's Hill Route

passenger vehicles due to the unique mix of customer needs. The primary customers are bus operators working to specifications, targets and requirements set locally in the areas in which they are active. The needs of the end user are also very important. The understanding of these differing priorities is fundamental to establishing a base design requirement for a new product, or a modification of a current product to fit specific markets.

Specific issues

Millbrook works with bus manufacturers to assess, report and modify the base vehicle construction and make-up. Taking into account known requirements such as energy consumption, operating range and performance specifications, the engineering team can focus on the more intangible elements of vehicle development, those that look at consumer needs.

In looking at dynamic elements of hybrid or fully electric vehicles, the team assesses and refines take-off performance, particularly in the first acceleration phase from 0-5km/h. The emphasis is put on refinement, rather than benefitting fully from 'instant' performance when starting from rest. In public transportation the initial acceleration is critical to passenger comfort – as anyone who has ever been on a crowded bus knows.

The impact of rapid standing-start acceleration will lead to instability in the body of standing passengers, and has been known to lead to injuries and damage to cargo. This is unique in a public transportation situation; in passenger cars the occupants are seated and belted, with cargo safely stowed.

With drive-by-wire technology, the acceleration from rest (and smooth braking to a stop) can be adjusted in the calibration of vehicle response. The vehicle can be much improved with appropriate modifications. The Millbrook team looks hard for comparable transportation modes that offer smooth acceleration from rest. Mainline trains, trams and cars on part throttle are all benchmarked for performance and the most effective characteristics adopted into the calibration.

Balance and optimization are most important, and can only be tested in a safe and repeatable environment, which Millbrook is well-placed to provide. A gentle increase of acceleration is good for the passengers, but the initial take-off needs to be very responsive to throttle input in a city application. The drivers need to be confident that the vehicle will respond instantly; otherwise, safety can be compromised or the journeys can suffer from delays at roundabouts and junctions, when drivers may feel unable to 'make the gap'. This can impact confidence in the vehicle and lead to knock-on effects in depots, such as schedules not being adhered to, increasing costs, disgruntled customers and low morale in the workforce. The driver may prioritize different performance and refinement attributes to those the passengers value most. Hitting the right balance between these two sets of conflicting requirements is one of Millbrook's areas of expertise.

When it comes to braking, except in an emergency-stop situation, calibration of smooth brake-to-rest can be adjusted by refinement of the regeneration strategy on the vehicle, resorting to friction brakes for the very last second. The reverse applies for passenger loading, helping to minimize the forward momentum at the stopping point.

An uphill challenge

Other aspects of vehicle dynamics are often less clear with larger vehicles. Using Millbrook's unique topography, with hill gradients ranging from 7% to 26%, engineers can ensure vehicles are able to perform in real-world situations and meet the challenges they present. In addition to ensuring a vehicle can physically climb when fully loaded (worst case), the shift strategy of the gearbox can be developed in real time to ensure optimum fuel consumption, as well as perceived refinement from the passengers' point of view.

Regulations and internal specifications for stability and reactions in emergency conditions apply, as increasingly do those affecting primary and secondary rides. Traditionally, steel ladder frame chassis were available to body builders, and these were generally set for steel upper-body structures.

With the drive toward lower fuel and energy consumption, it has been said that these setups are no longer applicable to the next generation of lightweight bodies being engineered and applied to standard chassis builds. As a result, the ride conditions are not optimized. For instance, the tuning work and modification to suit specific road conditions typically do not receive the attention they require in order to provide a comfortable ride.

Millbrook is able to offer tuning and design setup advice to customers supplying the European market. It has the ability to benchmark, set targets and produce differing tunes of suspension damper, springs and roll bars (where fitted) in order to produce a vehicle that is much better suited to local conditions.

Autonomous vehicle simulation

Dominic Gallello, president and CEO of **MSC Software**, considers the building blocks of autonomous vehicle simulation

What would it take for us to get to the point where driverless vehicles are the 'expected' technology, just as cellphones are today? MSC Software has spent a lot of time perfecting the software tools that help engineers design faster, lighter and safer vehicles through computer simulation. Yet, making the transition from simulating the car and leaving the driving to the human brain, to simulating both the car and the brain of the vehicle, requires closing a large gap in the current vehicle design process.

In this new and very complex world of driverless vehicles, vehicle-to-vehicle communication between myriad different car brands will be the norm. A Ford van, for example, will have to communicate with a Toyota sedan. It will also have to process a variety of outside sensor input data while still interacting with the rest of the road infrastructure, such as street lights, traffic signs, and so on.

To predict certainty in the performance of driverless vehicles, and to ensure safety, automotive companies will have to extend their use of simulation technologies and embrace new ones.

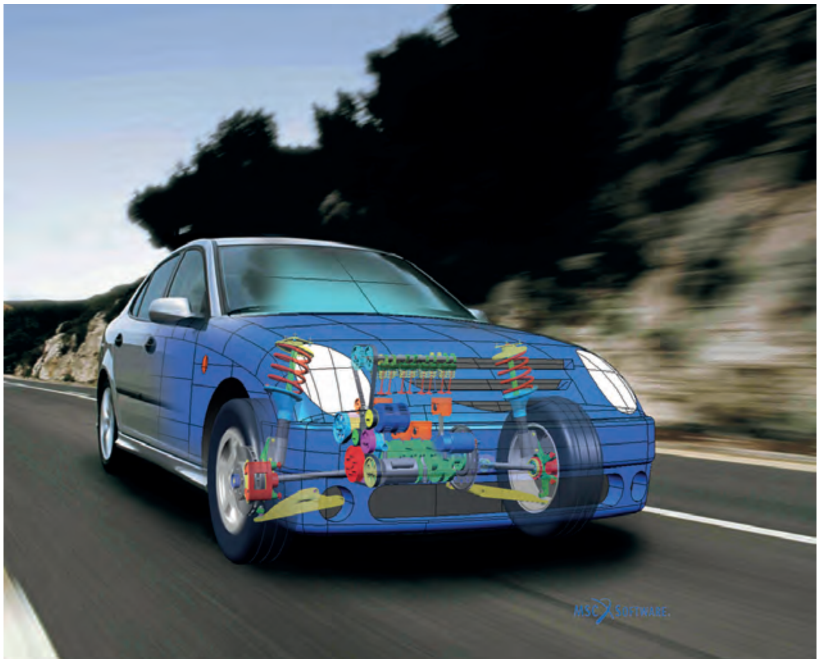
MSC Software predicts that the following five building blocks will be the key to success when it comes to total simulation of driverless vehicles.

Off-line to real time

Real-time simulation is absolutely key when it comes to realistic validation of increasingly complex automotive systems. Although off-line solutions will continue to solve sophisticated models with high degrees of complexity, there are two main reasons why the need for real-time simulation is ever increasing.

First, the requirement to connect virtual models to physical hardware such as sensors, controllers, driving simulators, etc: so-called hardware-in-the-loop. These physical assets have a defined communication speed, and the associated simulation model must be able to keep up with this communication speed. This connection between the physical and simulation world is what defines a real-time model.

Second, vehicle development (including dynamics) has traditionally been targeted at validating the machine. The human driver, either following the test instructions or making numerous on-the-fly decisions, was not considered a 'system' that required validation (aside from passing a driving test). The concept of autonomous vehicles completely flips this paradigm on its head. Now, the 'driver', undoubtedly the most complex system on the vehicle, has to be validated as well. Just imagine how many more simulated scenarios an autonomous school bus 'driver' will have to undergo to be deemed safe and reliable.



RIGHT: All components that affect vehicle dynamics can be simulated, helping in the safe and swift development of driverless vehicles

Sensing the environment

Now that we have an accurate representation of the vehicle response, the vehicle can be introduced to a computer simulation of a real-world driving environment, which would include other cars, trees, people, buildings, etc. To 'read' this environment, the autonomous vehicle model is equipped with a variety of sensors (radar, lidar, vision, infrared, etc.) that continually monitor the surroundings. Based on this feedback, the vehicle calculates what to do next and then sends appropriate signals to actuators (steering, throttle, brakes, etc.) to drive the car. This behavior is then coded onto the vehicle chassis controller.

Until now, the vehicle dynamics model has been effectively a 'black box' representation of vehicle behavior. That is, sensor and controls developers have not been interested in why a vehicle behaves as it does, only how it behaves.

Although response behavior can be hard-wired into a controller, this will always be limited to the situations that were preconceived by the designers. Making a vehicle dynamics model that resides on the vehicle controller and learns the difference between predicted and actual response would allow driverless cars to navigate through situations that might not have originally been predicted by the design team. This approach can then capture the effects of worn components, improper tire pressures, low grip due to standing water, etc. and better inform the vehicle of the most appropriate next step.

The data explosion

To continuously sense the surrounding environment in real time, the autonomous car will also have to access historical data stores containing weather, obstacles, traffic and road conditions. This would provide the necessary framework for quality control and forensic analysis. These enormous data dumps, accounting for every minute, hour, day and year that a driverless car is out on the road, will have to be managed and stored.

Of course, a large part of a driverless car's environment will be other vehicles. Thus, the driverless car will have to come equipped with myriad sensors creating and transferring machine-to-machine data, with speeds of up to 1GB per second. Big data storage will then be an absolute necessity along with smart management of the data feed, and its sensor and vehicle libraries.

The design and engineering teams will also have to manage model libraries with multiple assemblies and model variations. They also need to ensure that different representations, such as MATLAB and Adams, are consistent across all of these variations.

Big data stores

These massive persisting raw sensor feeds, as well as simulated sensor data, will have to eventually transition from modeled data storage to big data lakes.

These stores must include multiple benefits, such as: storing many types of data in the same repository; applying a variety of transformations on the data; creating schema on read-based analytics; and new types of data processing as well as single subject analytics only controlled by specific use cases providing a low cost and huge scalability.

Independent of the storage structure, the problem of 'data ingestion' would also have to be addressed: in other words, loading the data into the system before it can be queried or processed. After the data becomes available to process, performance optimizations will apply techniques such as vectorization in the query evaluation to interoperate, extrapolate and optimize car behaviors.

Machine learning

Of course, the topic of AI cannot go untouched when discussing autonomous vehicles. Even the most extensive, most brilliant groups of vehicle designers and engineers cannot predict and program ahead for every possible scenario that a driverless car will have to navigate.

A self-supervised machine-learning approach is an option currently being explored. Surface points in the vehicle's environment are acquired with a laser, which can be so sparse that significant information for comparison is not available or their accuracy might be low, based on latency or error in the estimation. The terrain in the supervised learning process can be learned by generating labels against actual shocks when driving.

Another approach is so-called 'obstacle avoidance' with reinforcement learning. A case for this approach would be a self-driving vehicle, driving at higher speeds through unstructured outdoor environments. A supervised learning algorithm will then accurately estimate the distance to the nearest obstacle by using only monocular visual cues or multi-sensor feeds.

Autonomous vehicle systems use visual and robotic techniques for navigation, among them image processing and pattern recognition. Under real-world conditions, the noise and variability of scenes creates significant problems. Artificial neural networks have been shown to perform very well in environments with high degrees of noise and variability.

Models for regression and classification based on linear combination of fixed basic functions face significant limitations due to dimensionality. There is the need to fix the number of basic functions in advance, while at the same time allowing them to be adaptive. It requires the use of parametric forms for the basic functions in which the parameter values are adapted during training. A successful model of operations for this type is the feed-forward neural network. An alternative name for it is 'multilayer perception'.

Another machine learning technique that is moving into the autonomous driving space is deep learning. This technology allows vehicle navigation algorithms to learn complex mapping functions. Deep learning is one of the few, if not the only, machine learning algorithms to leverage huge amounts of training data from various sensors, specifically from camera systems. It covers almost the entire scope of challenges including pedestrian detection, lane detection, road sign recognition, traffic lights, cars, various obstacles, environmental and road surface detection, as well as human action recognition.

Finally, one other extension being explored is that of replacing fixed features with efficient algorithms for unsupervised or semi-supervised learning and hierarchical feature extraction and flow patterns.

The global automotive industry is committed to the development of the driverless car. It is also apparent that OEMs and their suppliers are, so far, more advanced in their ability to create the technology than they are in their ability to validate that technology as foolproof, tamperproof and stable. We have a long way to go to standardize communication formats, agree on liability and provide the infrastructure to handle the massive amount of data transfer that will be required.

How do we make sense of this sea of new information and emerging technologies? Computer simulation has to be the only way to test all of the potential combinations of conditions, and the structured process described here is aimed at supporting the goal of safe and reliable autonomy. MSC Software will be there to ensure that happens.

ABOVE: The BIT algorithm is flashed into a dedicated microcontroller used to test the technology on the road

Intelligent tires

BhaiTech's Intelligent Tyre technology can enable the next generation of intelligent vehicle systems and bring fuel economy and energy savings

The automotive market has never been more competitive, and in this highly saturated market, vehicle safety and embedded technology are playing a crucial role as OEMs seek to attract customers. In addition to increasing customer expectations, global trends toward cleaner mobility are further fuelling the need for innovation.

One of the most prominent aspects of this innovation process is that of intelligent onboard systems. These systems enhance vehicle interaction and communication capabilities with the driver, other vehicle occupants and the external world. Vehicle interactivity can happen at different levels: safety, performance, fuel economy, convenience, entertainment and personalization.

Intelligent systems have become not just an integral part of modern vehicles, but also a distinguishing feature of OEM brand identities. Intelligent safety and intelligent performance capabilities, together with 'green' properties, are therefore used as an important part of OEM marketing campaigns.

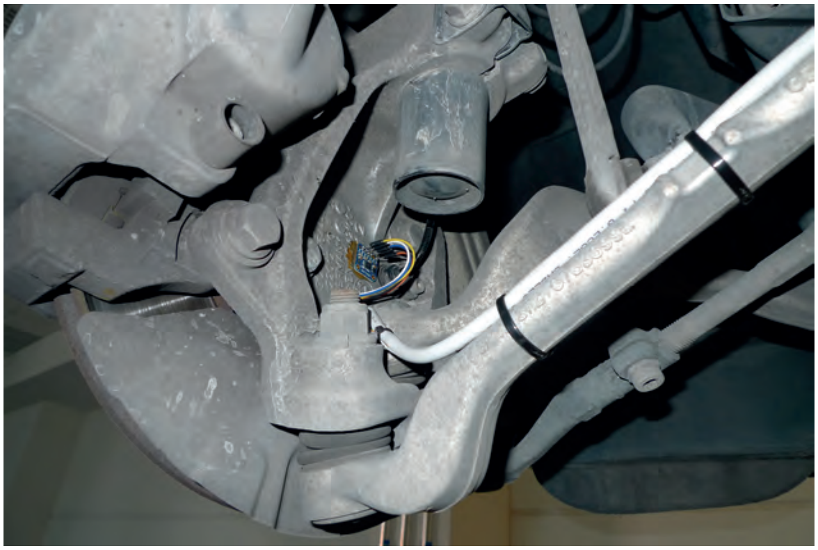
It should be noted that even in the era of intelligent systems, the tire still governs vehicle dynamics as the primary source of active safety and vehicle performance. The tire is also a critical component in terms of fuel economy as it can dramatically affect consumption.

It is well known that tire response and therefore vehicle response are highly sensitive to operating conditions. As an example, a change in tire inflation pressure can dramatically shift nominal car ride and handling response. In addition to operating conditions, a change in a tire's structural properties following a replacement can have an even greater impact.

The efficiency of all embedded systems controlling vehicle dynamics is thus affected by the tire characterization in use by such systems. A new stage of intelligence for vehicle embedded systems can be then represented by their ability to adapt to changes in tire properties and operating conditions. If this becomes possible, then the expected driving flavor can be experienced consistently by the driver, together with the vehicle's native safety and performance levels.

Based on these considerations, at the end of 2015 BhaiTech, an automotive technology consultancy, decided to start development of an intelligent tire technology. BhaiTech Intelligent Tyre (BIT) is a software technology that evaluates the real-time mechanical properties and response of tires in real vehicle operating conditions.

Due to the increasing demand for flexibility in vehicle systems, great effort has been put into the development of an intelligent technology that is also scalable. This software technology can be shared across any vehicle segment and is not limited to high-end applications such as supercars. Tire information and even surface friction measurements are



ABOVE AND LEFT: The system is non-intrusive, requiring only small instrumentation devices to be fitted to the test vehicle

derived from existing vehicle sensors, using BIT algorithms running on existing processors on the vehicle.

Examples of mechanical properties evaluated by BIT are tire vertical stiffness and tire vertical damping.

Indirect TPMS is probably one of the most obvious applications of real-time monitoring of tire mechanical properties. Real-time identification of tire properties can also have other important applications such as those requiring an accurate evaluation of tire loads. For example, tire loads are a key quantity in the control strategy of active suspension systems, which aim to improve vehicle ride and handling characteristics.

Instant tire response in the form of instant road-tire friction coefficient is also delivered. This information provides the basis for the detection of road condition changes caused by different types of asphalt or changing weather.

A fundamental piece of information for active vehicle dynamics systems and driver assistance systems dealing with vehicle safety and/or vehicle limit performance is certainly represented by the limit road-tire friction coefficient. BIT technology delivers information to these systems about the limit of the road-tire friction coefficient in the current operating conditions.

The production code implementing BIT's algorithms can run in real time at high frequencies (KHz order), with the bottleneck represented by the sampling rate at which useful signals are actually acquired on the vehicle, which is generally much lower.

When it comes to the evaluation of the limit of the road-tire friction coefficient, the BIT system buffers a certain amount of information before providing its estimate. This approach is needed if accurate and robust information about current tire operating conditions is to be delivered to all the vehicle systems. The dimension of the buffer determines the frequency at which the road-tire friction coefficient information is available.

After months of virtual testing and tuning of the BIT technology, BhaiTech has recently started an experimental testing campaign to prove the encouraging results obtained so far.

The green side of this technology is also under development. "Being aware of the impact that this technology can also bring to fuel economy or energy savings, BhaiTech is looking into possible options to use the instantaneous information about road-tire friction as the primary control variable for a system that shifts the vehicle toward an overall lower friction operating region whenever this is permitted by the vehicle safety margins and maneuvering resources needed," says Giuseppe Callea, head of technology at BhaiTech.

"The most straightforward way to control road-tire friction is by acting on the tire inflation pressure, and therefore we are investigating this option first. The technology to change internal tire pressures in real time is not the only factor to be solved, since the change of tire pressure will also affect vehicle dynamics. If we are to be successful in the development of the hardware and in finding a system strategy that does not affect vehicle safety or performance, then we could move from current TPMS to more sophisticated tire pressure control systems," adds Callea.

If this advance is possible, then potentially all vehicles that run on tires could benefit from BIT technology and the dynamic control of tire inflation pressures to reduce their fuel or energy consumption.

Steering a safer future

ZF TRW's comprehensive range of dynamic enhancing components benefit not only driving enjoyment, but occupant safety too

To generate systems that help to shape and influence key automotive megatrends like automated driving, safety and efficiency, combining technologies in new ways has become a decisive factor for success. For ZF and its active and passive safety division, ZF TRW, this means combining the different fields of competence of the two formerly independent companies.

It also involves bringing together advanced mechanics, electronics and software in one integrated system. Finally, it means connecting various automotive systems intelligently to create innovative functions with added value. A ZF steering system that was recently showcased during winter testing of a prototype compact car in northern Sweden is testament to all these factors.

The vehicle features progressive, already existing ZF technologies. It is equipped with dual-pinion electrically powered steering (DP EPS) from ZF TRW on the front axle and – from the ZF chassis systems unit – active kinematics control (AKC) at the rear. The latter provides steering on demand by wire, with a steering angle of up to 5°. Because both systems are connected via joint control electronics systems – also developed and manufactured in-house by ZF – the driving safety and dynamics of the vehicle are clearly enhanced. Even on packed snow and ice surfaces, the ZF system keeps the prototype vehicle perfectly on track, even when changing lanes or overtaking.

The connection of the two ECU-controlled electromechanical systems also offers advantages for partially or fully automated vehicles. This uses an additional control element in the vehicle cockpit's center console, whereby the systems at the front and rear axles can be steered completely electronically. Such a steer-by-wire concept could be used in the future to control partially, as well as fully, automated steering maneuvers, especially overtaking and lane changing. Having the AKC's support at the rear also greatly improves overall lateral dynamics, as driver assistance systems such as stability control can intervene much later than in conventionally equipped vehicles – if needed at all.

ABOVE: The ZF prototype compact car features a dual-pinion electrically powered steering system on the front axle, with active kinematics control on the rear axle

In addition, this setup also provides system redundancy, which is critical for automated driving. At highway speeds, for instance, AKC can direct a vehicle without necessarily needing DP EPS at the front.

The test vehicle also features a newly developed ZF modular rear-axle concept that enables easy integration, not only of AKC, but also of an electric or conventional drive module. The basic axle features a development of a semi-trailing arm rear suspension setup. As part of this design, the rear of the two outboard kinematics points of the lower control arm were replaced with an integral link and an added toe link. As an alternative to a suspension strut, which tends to be used on semi-trailing link axles, the integral link in an extreme outboard position enables a space-saving layout with separate springs and dampers.

At low vehicle speeds, AKC supports the front steering by moving the rear wheels in the opposite direction to the front wheel's steering angle. This improves the vehicle's agility and reduces the turning radius, helping to increase driver comfort. At higher speeds, the rear and front wheels steer in the same direction, improving the vehicle's stability. In this case, the vehicle's rotation around the vertical axis is reduced, enabling safer driving.

The connected AKC and DP EPS concept shown in the compact prototype represents a technology integration milestone for ZF and ZF TRW – as well as a high-value solution.

In the future, safety and comfort can be further increased when the company's steering and active chassis systems are combined with other ZF technologies, such as braking, as well as camera and radar systems. This will enable the next generation of automated driving and driver assistance.

READER INQUIRY SERVICE

To learn more from ZF TRW, visit www.ukipme.com/info/vdm **ref. 012**

Damper modeling

Ricardo has found that high fidelity damper modeling is a missing piece in the jigsaw of accurate vehicle dynamics simulation

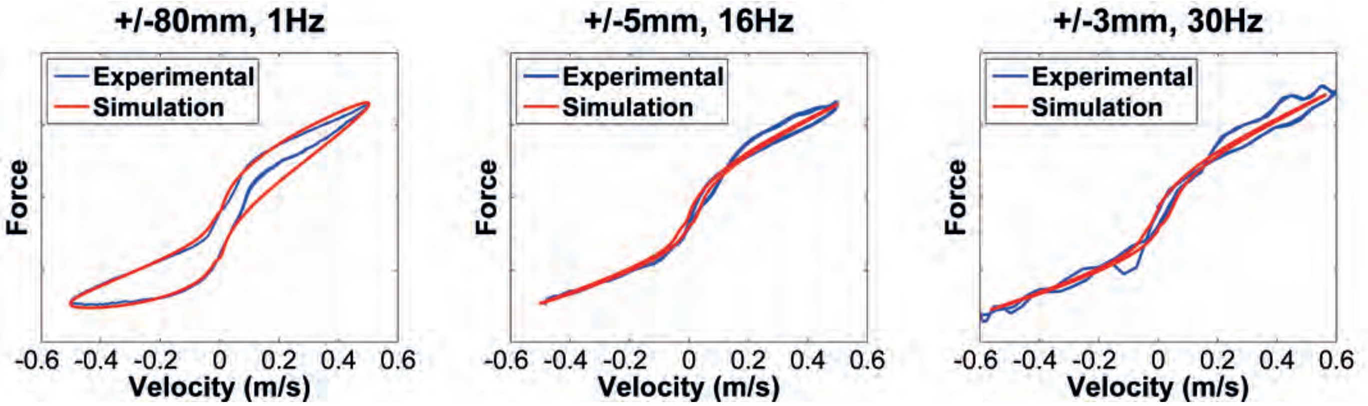


FIGURE 1: Example of twin-tube comparison of measured versus simulated damper characteristics at 1Hz, 16Hz and 30Hz

It is often said that the devil lies in the detail. This is certainly true of many of the most challenging engineering problems, and vehicle dynamics simulation is very much a case in point. The financial investment in physical prototype vehicles is considerable, while the time taken to build, develop, test and modify a design can represent the critical path of a new product's journey to market.

It is unsurprising, therefore, that considerable effort has gone into the development of high-fidelity virtual vehicle models that can be used to simulate many aspects of vehicle dynamics, NVH, durability and driveability. Indeed, anything that can be developed, optimized and validated in a virtual environment will almost always save the auto maker's hard-pressed vehicle engineering team both time and resources in prototype programs.

While the current state-of-the-art in the simulation of ride, handling and NVH attribute performances are well advanced, the modeling fidelity of the suspension damper is limiting the finer detail of ride and NVH predictions.

The main challenge with simulating dampers is in the non-linear hysteresis forces arising from friction, gas spring and fluid compressibility effects, all of which are heavily influenced by varying operating temperatures. Typically, these hysteresis effects are not well represented by commercially available damper simulation models. This is an important deficiency as such hysteresis effects contribute to many of the gaps with model correlation for ride, handling and NVH performance. Some commercial 'black box' type models aim to replicate the non-linear effects. However, these tend to be non-parametric, non-tuneable models that are reliant upon the physical test data of an already developed damper. In effect, a pre-existing prototype is needed to create the model; therefore the ride, handling and NVH simulation is limited to that damper specification.

The availability of a reliable simulation model able to accurately capture such hysteresis effects without resort to prototype hardware, is thus a significant step on the path to creating a truly predictive simulation capability. For this reason, Ricardo has developed a Matlab/Simulink-based physical damper model, which is fully parameterized and accurately simulates the hysteresis effects of the gas spring, fluid viscosity and compressibility and rod guide bush seal friction, in addition to the conventional peak velocity/force characteristics.

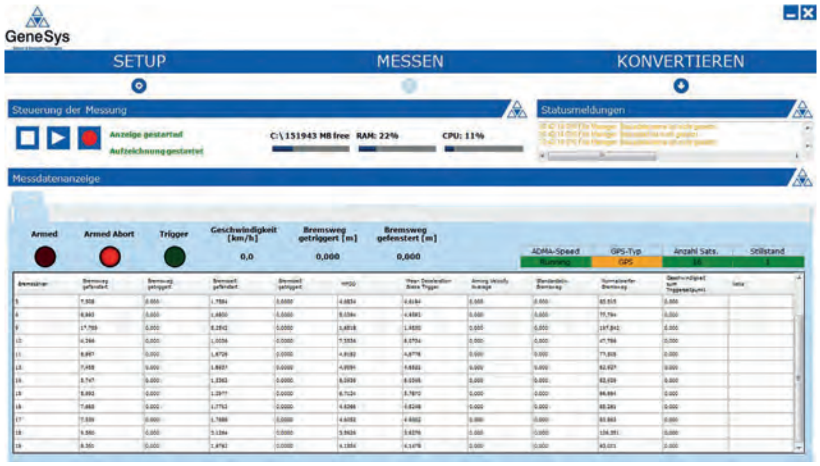
The Ricardo non-linear damper model is uniquely configured to allow adaptation of the damper characteristics by varying model parameters against temperature during CAE simulations.

In addition to deriving the damper final specification faster and more robustly, the Ricardo non-linear damper model enables improved design and specification of bushes, BIW structural characteristics, and interior trim designs for sound attenuation, reduced vehicle development work, and a higher confidence of virtual verification sign-off.

This model is part of the range of vehicle dynamics engineering and development services that Ricardo can provide, including the provision of consultancy, technology transfer, training and support. In summary, this advanced Ricardo model is part of a suite of advanced software and engineering capability that can be deployed by customers to improve product quality while also reducing time to market and opening the way to more cost-competitive vehicles.

Speed and braking sensor

Centimeter-accurate, speed-triggered braking distance measurements can be achieved with the compact ADMA-Speed sensor from **GeneSys**



LEFT: ADMA-Speed: the new speed and braking distance sensor with integrated inertial sensor-based technology is optimized for brake tests, but can do much more

RIGHT: Acceleration, speed and braking distance data is saved and displayed via the logger software for ADMA-Speed

ADMA-Speed (Automotive Dynamic Motion Analyzer) is a compact GPS speed sensor featuring inertial sensor-based technology. The braking distance sensor puts out a precise, smooth and continuous speed signal – even with poor GPS reception. Thus, centimeter-accurate and speed-triggered braking distance measurements are now possible.

The unit is optimized for brake tests and supplies exact acceleration, speed and braking distance data. The settings for braking distance calculation are configured easily via a web browser. With ADMA-Speed, parameter input is just as fast as the subsequent output of measured and braking distance data, and is achieved in real time and directly via CAN interface and Ethernet.

In addition to braking performance specifications according to DIN, software enhancements for acceleration tests and measuring of lateral deviation are available, also in real time. At any time, ADMA-Speed can be extended to a fully fledged GPS-aided inertial system. ADMA-Speed is small, compact and easy to install, and thanks to these characteristics it is ideal for braking distance measurements.

Further development of vehicle and brake technology places added demands on the measurement accuracy, quality and repeatability of the results and the need for enhanced technology. All vehicle movement data can be calculated reliably and precisely using ADMA technology from GeneSys.

ADMA-Speed is the little brother of the ADMA system and consists of an evaluation unit and a separate sensor unit. The evaluation unit, weighing roughly 2kg, houses tried-and-tested ADMA Kalman filter technology. This unit calculates the movement data of the vehicle at its center of gravity. Output of the acceleration, speed and braking distance data according to ISO standard occurs – in real time – via the CAN interface and simultaneously via Ethernet. Logger software for Windows is available for data storage and display of the braking distance data via Ethernet.

At the heart of ADMA-Speed is a speed and braking distance sensor unit with a GPS antenna and integrated inertial sensor-based technology. ADMA-Speed is very easy to handle as it weighs just 750g and is just 11cm long.

The standard GPS measuring method without inertial sensor-based technology has the disadvantage of requiring a clear view of the sky to ensure accurate results. In real-life situations, the GPS signals and the measurement accuracy are affected by buildings, trees, fences and vehicles. The inertial measuring unit suppresses signal interference during poor GPS reception or temporary GPS failure. The combination of GPS and inertial measuring unit in ADMA-Speed therefore provides a smooth and consistent speed signal compared with a standard GPS signal.

ADMA-Speed compensates GPS data latency and corrects acceleration-dependent GPS signal distortion. ADMA-Speed additionally uses GLONASS, which enhances satellite reception, even on wooded test routes. The typical accuracy of the braking distance measurement is 5cm, and the speed is measured with an accuracy of 0.05km/h.

Pitching movements, which inevitably occur during brake stop, are also taken into account by the speed and braking distance sensor. Signal inputs for a brake trigger or light barrier are integrated in the unit. In other words, a covered braking distance can be triggered via adjustable speed thresholds and via external signals using a physical switch on the brake pedal or a light barrier.

At any time, ADMA-Speed can be upgraded from a simple braking distance sensor to a complete GPS-aided inertial system without having to alter the hardware. The delta option even enables centimeter-accurate measurement of distances or relative angles between several vehicles. ADMA-Speed is thus also a cost-effective alternative for evaluating driver-assistance systems such as ACC, FCW, AEB and LDW. Moreover, ADMA-Speed allows for determination of deviations from a straight calibration line or path when braking and accelerating, or in case of cross wind. Yawing can therefore also be calculated. In addition, a function extension for acceleration tests will soon be available.

ADMA-Speed is a clear choice for centimeter-accurate speed-triggered braking distance measurement, especially with its attractive price and expandability to a fully fledged RTK GPS-aided inertial system for vehicle dynamics testing and ADAS evaluation.

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To learn more from GeneSys, visit www.ukipme.com/info/vdm ref. 014

Closing the loop

A recent project carried out with Hyundai and Applus+ IDIADA has demonstrated how **rFpro** software can be used for the more effective development of commercial vehicle dynamics

ABOVE: Advanced simulation systems allow dynamics engineers to 'feel' how a vehicle behaves, before it is even built

INSET: This is not a photograph, it is a screenshot of the incredibly realistic 3D test environment

State-of-the-art software from rFpro has helped to speed up the development of commercial vehicle chassis dynamics in a study for Hyundai carried out by a team from Applus+ IDIADA.

rFpro's software allowed IDIADA to link Hyundai's CarSim model with realistic graphics and a human driver to evaluate the benefits of using a simulator for chassis development. Once sufficiently developed using a workstation, the application was transferred to the eight-degrees-of-freedom Sim IV platform at the Swedish National Road and Transport Research Institute (VTI), which has been at the forefront of simulator development for more than 40 years.

"In the space of 10 days, we were able to evaluate around 25 different vehicle configurations using three professional drivers," explains Guido Tosolin, Applus+ IDIADA's product manager, chassis development and vehicle dynamics simulation. "More importantly, because of the high-fidelity visual cueing using rFpro software, driver immersion was very convincing, which led to good correlation between their subjective ratings and the objective data."

During the study, drivers correctly interpreted the direction and magnitude of various changes to kinematics, springs, dampers and anti-roll bars. An additional benefit was derived from the high volume of data produced, according to Tosolin. "For the first time, we have generated so much data that we are able to use statistical methods effectively to interpret the results," he says.

The IDIADA project is believed to be the first major application of a driving simulator to commercial vehicle chassis dynamics and required a suitable cabin arrangement and driving position to be effective. It also used rFpro's own virtual vehicle dynamics proving ground, which allows subjective and objective testing to take place just as it is done in real-world track testing.

"Our software is based on closing the loop as quickly as possible by providing very high-bandwidth video and audio feeds to the driver, and high-bandwidth road surface detail to the vehicle model. This provides the realism necessary to achieve good correlation between driver perceptions and objective vehicle changes," explains rFpro's technical director, Chris Hoyle.

The experience of the IDIADA team parallels that of AVL, the world's largest independent developer of automotive powertrain systems, which also uses simulator software from rFpro. AVL estimates that more than 30% of the costs incurred in developing driving attributes can be saved through front-loading the engineering activity on a driver-in-the-loop (DIL) simulator with subjective feedback, making better and more complete information available earlier in a vehicle program, before physical prototypes exist.

"Early in the development of new powertrain concepts, decisions are made regarding fundamental architecture, which have far-reaching consequences," says Erik Bogner, manager for driveability and simulation, engineering and technology, at AVL's powertrain systems department. "Many of those decisions influence the subjective feel of the vehicle and require driver feedback to supplement objective data, in order to ensure the optimum choices are made. Simulation software from rFpro not only provides the greatest possible graphical realism for the driver, but also the ability to 'feel' events such as gear shifts and vehicle movements and experience them in ways that are not possible with offline desktop simulation.

"AVL chose rFpro software because it provides seamless integration of the vehicle model and the best level of immersive experience for the driver conducting the assessment testing," Bogner continues. "rFpro's inherent strengths in low latency and high bandwidth make it the only viable solution for conducting DIL vehicle dynamics studies."

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To learn more from rFpro, visit www.ukipme.com/info/vdm ref. 015

Set the bar

MVO has discovered that warm forging creates many benefits for the manufacture of rack bars, including wider teeth and increased bending strength

In the past 15 years enormous advances have been made in the area of EPS. Problems such as noise, reliability and lack of steering feel that dominated the first EPS applications have largely been overcome. The solutions have involved simultaneous developments in both software and hardware; in the case of the latter it includes changing the component design to reflect new loading and performance requirements.

At the rack bar level there has been a focus on new steel grades, increased tooth size and lower – or at least more consistent – friction characteristics. Notably, steering gear mass has also tended to increase, which is not in line with the downsizing of the marketplace. Putting the different motor and drive systems aside, the rack bar has also contributed significantly to increased weight.

The only way to increase tooth size in conventional broached or milled rack bars with a set steering gear geometry is to increase the rack bar diameter, thereby making the teeth wider. Although the increase in tooth width is roughly proportional to the increase in diameter, mass increases with the square of the diameter. This increase in bar diameter therefore leads directly to an increase in mass as well as in housing size, which will also lead to greater mass. The extent of this weight increase is dependent on the size and type of steering gear; however, weight penalties in rack bars alone are of the order of 0.4-1.0kg. Accordingly, strategies for rack bar weight reduction that were fashionable 10 years ago for hydraulic power steering (HPS) are being considered again.

Broadly speaking, there are three strategies for reducing mass in rack bars. The first is deep hole drilling of the shaft, a process that is very well established for HPS. Depending on the size of the rack bar, mass reduction of 300-600g is typical, although the hole diameter tends to be limited by the internal tie-rod thread diameter. It is also a slow process, taking from three to five minutes.

The second strategy is to use composite or two-piece racks. The use of two-piece racks where the shaft is made of tube and welded to the solid tooth section leads to greater mass reduction than that achievable by deep hole drilling, but carries the cost penalty of a welding operation. The risk associated with a welded joint on a safety-critical part also has varying acceptance in the market.

ABOVE: Precision warm-forged rack bars (the bar on the right) have forged teeth, enabling a wider, deeper cross section

The third option is a precision warm-forged rack bar. The classical steering rack bar has the majority of its mass in the shaft, where stresses are accordingly lower. The smallest cross-section is in the area of the teeth and the maximum stresses are typically found here, so with respect to mass and stress loading, the rack bar is inherently unbalanced.

Precision warm-forging allows the process to start with a smaller shaft. By forging the teeth rather than machining them, material can be moved to make a wider and perhaps deeper cross-section, leading to the desired wider teeth as well as increasing bending strength.

Should weight reduction be of paramount importance, the shaft of a precision warm-forged rack bar can also be deep hole drilled, thereby achieving weight targets that are comparable to rack bars made purely from tube.

A distinguishing aspect of the forged lightweight rack bar technology is that all of the measures used lead to a fall in manufacturing costs in terms of reduced material purchase, elimination of process steps and less waste.

MVO is a specialized rack bar manufacturer that has been producing warm-forged racks since 2012 and launched the lightweight forged rack technology in 2014. Keeping pace with demand has been challenging, and a second forging line with a 30% reduction in cycle time will be commissioned at the end of 2016. As customers accumulate more experience with forged rack bars, they are also prepared to do some of the general machining and processing themselves as they are likely to have these processes in-house.

Offering semi-finished rack bars into the market allows for better utilization of existing resources and allows MVO to focus its investment on key processes with lower cost and higher output, again leading to a fall in costs, demonstrating that reduced weight and reduced cost do not have to be mutually exclusive.

READER INQUIRY SERVICE
To learn more from MVO, visit www.ukipme.com/info/vdm ref. 016

Helping hand

Driver-in-the-loop testing technologies from **Mechanical Simulation** enable accurate and effective ADAS validation

Advanced driver assistance systems (ADAS) play a pivotal role in the future of vehicle development. It is important to develop, test and deliver these systems in an efficient, robust manner. One effective way to achieve this is to have human drivers test these systems throughout the development process, especially before hardware hits the road.

This proactive approach was taken with the development of OnGuardACTIVE, a radar-based active safety system by Meritor Wabco that offers collision mitigation and adaptive cruise control (ACC). The system detects moving, stopped or stationary objects and vehicles ahead, and measures the vehicle's position in relation to those obstacles to warn the driver of a possible rear-end collision by providing audible, visual and haptic warnings. When appropriate, the system will apply the brakes to help avoid an impending collision or lessen the severity of an unavoidable collision.

The radar component of the system registers vehicles and classifies them in one of three ways. The first category is Moving, as in a vehicle that is currently and continuously in motion in the same direction as the ego vehicle. The second is Stopped, meaning a vehicle the radar has registered as moving but which is now at a stop, for example at a traffic light. The third classification is Stationary, meaning a vehicle the radar is picking up but has never seen move, such as a disabled car.

OnGuardACTIVE provides audible and visual warnings, a haptic warning, and active braking for all three classifications of object that the radar registers, even when cruise control is not enabled. The system employs haptic warnings in the form of short brake pulses, which cause the driver to respond faster. Additionally, the active braking system applies the vehicle's brakes to help avoid a collision or, failing that, to lessen its severity.

The ACC maintains the set speed while in cruise control mode when the lane ahead is clear, and will automatically adjust the vehicle's speed to maintain a set following distance when a vehicle ahead is detected. The system provides early warning feedback for improved safety and collision mitigation. The 'always on' feature means that feedback is provided to the driver even when ACC is not enabled. These features make cruise control a more useful tool in various traffic conditions, leaving drivers feeling more relaxed in heavy traffic and creating an improved driving experience.

BELOW: Mechanical Simulation's QuadDS driving simulator simulates dangerous scenarios that are difficult to create using real vehicles. This ADAS application includes environmental conditions such as fog and rain

Furthermore, this technology reduces driver fatigue in congested traffic.

In today's fast-paced development environment, it is imperative that engineers test these systems early and often during development to tune the systems for the complex human-machine interaction that occurs in the real world.

The aforementioned complex human-machine interactions can be studied using realistic driving simulators. Mechanical Simulation's QuadDS driving simulator runs CarSim or TruckSim, which can to be used to test and develop ADAS by putting the driver in the loop for a variety of vehicle architectures and applications.

A wide range of driving styles and behaviors can be tested, which results in more thorough validation and higher confidence in the ultimate calibration for production. This includes a variety of road and weather conditions.

"QuadDS helped us understand how drivers respond to our OnGuardACTIVE system without having to equip a vehicle. Also, OEMs can get a complete understanding of our technology quickly and easily. It is great to see people's eyes light up when they get it," says Michael Lambie, marketing manager at Meritor Wabco Vehicle Control Systems.

Accurate vehicle dynamics software and a realistic driving simulator environment are the cornerstones of demonstrating and testing ADAS technologies, thereby enabling engineers to get their product to market faster with the desired quality and robustness. CarSim and TruckSim vehicle dynamics software packages reduce the effort and cost associated with ADAS engineers creating realistic testing environments and events, and ensure high confidence going into final hardware validation. Coupling this software with the QuadDS driving simulator allows driver-in-the-loop testing for that real-world validation before hitting the road.

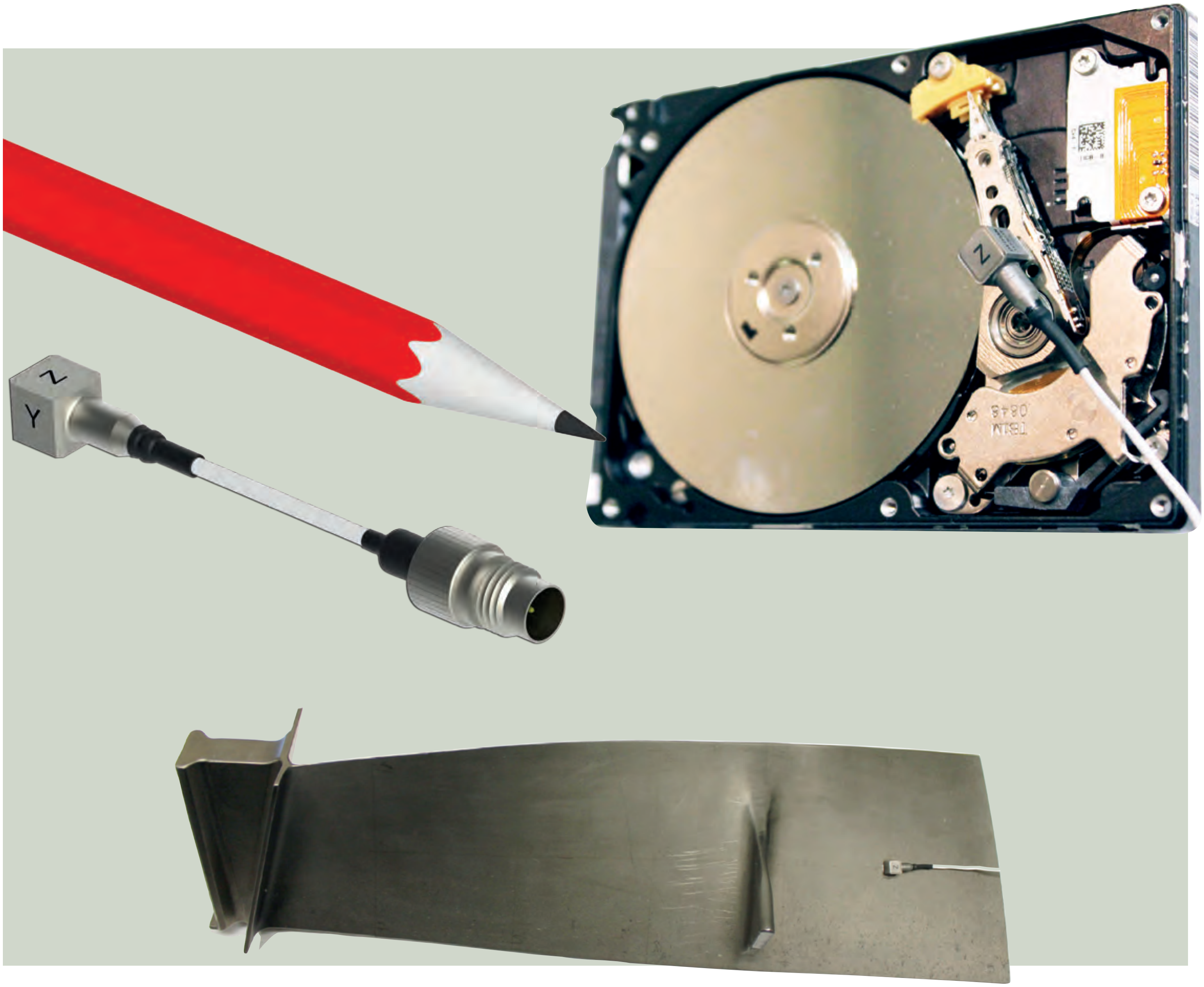
This testing improves productivity, ensures quality and lowers costs – a winning value proposition for organizations developing ADAS.

READER INQUIRY SERVICE

To learn more from Mechanical Simulation, visit www.ukipme.com/info/vdm ref. 017

Small victory

Dytran's 3133D Series is a new miniature accelerometer for product development testing



ABOVE: The 3133D is truly tiny. Here it is compared with a pencil, a hard drive and a turbine blade

Dytran has introduced the 3133D series, a line of ultra-miniature hermetically sealed IEPE triaxial accelerometers, weighing just 0.8g. Today's electronic devices continue to decrease in size, yet require more development testing than ever before to survive in rugged environments and harsh daily use.

Series 3133D is characterized by its exceptionally small size, which means it can be mounted in spaces that are inaccessible to other types of triaxial accelerometers. The low mass of the accelerometer has minimal impact on the natural frequency behavior of the test article.

Series 3133D is offered in several sensitivity ranges from 0.25mV/g to 10mV/g and is adhesive mounted. The accelerometers feature a permanently attached 3ft-long cable with a four-pin connector designed to mate with several models of extension cables for connection to IEPE power sources.

Performance specification features of the 3133D series include excellent low-frequency response and low base-strain sensitivity. Series 3133D meets the demand for a small-size (0.24in (L) x 0.24in (W) x 0.23in (H)), low-mass, three-axis accelerometer for HALT/HASS, drop test, vibration, survivability and end-of-line product testing.

A TEDS (transducer electronic data sheet) version of this series is also available for customers who need plug-and-play identification.

READER INQUIRY SERVICE

To learn more from Dytran, visit www.ukipme.com/info/vdm ref. 018

LCC Rocket

Gordon Murray's 1991 rocket design is still a benchmark in terms of lightweight design, and a masterclass in accessible driving fun writes **Adam Gavine**

"If ever you want to be reminded what light weight does for vehicle dynamics, you just need 30 minutes in the Rocket." No less an authority on dynamics than Gordon Murray said that to me, when discussing this remarkable car that he designed as the ultimate in lightweight driving thrills.

The Rocket was launched in 1991 by the Light Car Company, an enterprise of former endurance racer Chris Craft. The racing background of Murray and Craft is clear to see in the styling, with the Rocket's stubby shape recalling the lines of 1960s F1 cars. The design also recalls some dynamic features of those elegant, simple cars, with the composite body shrouding a tubular spaceframe, and the engine acting as a stressed member to support the rear double wishbone, coilover suspension with Bilstein dampers.

The car weighs in at an incredibly low 390kg – a standard Caterham 7 is 545kg – and to ensure it lives up to its name, a 1,002cc, 20-valve Yamaha FZR1000 motorcycle engine creates a power-to-weight ratio of 380bhp per metric ton and a 0-60mph time of around four seconds. The Rocket stops as well as it gets going, with Brembo drilled and ventilated discs front and rear. The only downside is that the incredibly low weight means it is difficult to develop heat in the tires.

As Murray said, "The Rocket was a bit ahead of its time." While today many enthusiasts will spend £45,000 (US$55,000) on a track car, when the Rocket launched in 1991, its £38,000 (US$47,000) price tag was considered quite outlandish for such a pared-back car.

The Rocket didn't offer buyers much metal for their money, but it did offer great value in terms of a visceral, immersive driving experience. As Murray says, "The Rocket can run all day without sweat – or brake fade – and as it has no downforce it can be four-wheel drifted at speeds as low as 18mph. It's really good fun and changes direction like a feather."

The Rocket still has a special place in Murray's heart, and in his garage, where it lives alongside his other dynamic masterpieces, including a McLaren F1 and SLR.

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