OFFICIAL MAGAZINE OF VEHICLE DYNAMICS EXPO 2011, MAY 17-19, MESSE STUTTGART

VEHICLE DYNAMICS INTERNATIONAL

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ANNUAL SHOWCASE 2011

MINI WRC

How complex analysis led to the simple models behind the John Cooper Works rally car

Supercar chassis
The latest cars from Pagani and Lamborghini

Research focus
University papers from Cambridge and Virginia Tech

Prize winners
All the results from the VDI Awards 2011

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Vehicle Dynamics International
Abinger House, Church Street,
Dorking, Surrey, RH4 1DF, UK
editorial tel: +44 1306 743744
editorial fax: +44 1306 875824
sales tel: +44 1306 741200
sales fax: +44 1306 743755
email: vehicledynamics@ukipme.com

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EDITORIAL
Editor **Graham Heeps**
Proofreaders
Aubrey Jacobs-Tyson, Frank Millard
Chief sub editor **Alex Bradley**
Sub editors **William Baker, Sarah Lee**
Contributors this issue
David Cole, Matt Davis, Adam Gavine, Stefan Gies, Damian Harty, John Heider, John Miles, Phil Morse, Keith Read, Saied Taheri, Derek Ward, Steve Williams

ADVERTISING
Publication manager
Mike Robinson
Project manager
Aboobaker Tayub

DESIGN & PRODUCTION
Head of production & logistics
Ian Donovan
Production team
Carole Doran, Lewis Hopkins, Cassie Inns, Robyn Skalsky
Art director **Craig Marshall**
Design team **Louise Adams, Andy Bass, Anna Davie, James Sutcliffe, Nicola Turner, Julie Welby, Ben White**

CIRCULATION
contact **Adam Frost**
a.frost@ukipme.com

CEO
Tony Robinson
Managing director
Graham Johnson
Editorial director
Anthony James

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A NOTE FROM THE EDITOR

In the 1950s, Ford's designers envisaged a car of the future called the Nucleon. This space-age machine was powered by a nuclear reactor similar to those used to this day in submarines, and had a predicted range of 5,000 miles (8,000km) or more. Now, that would have killed 'range anxiety' for good!

Sadly the Nucleon never made it beyond a 3/8-scale model, but the 'car of the future' is a concept that lives on in vehicles such as GM's EN-Vs, a trio of 'pods' suited to the megacities where, we're told, most of us will be living in 2050. Personally, I plan to remain domiciled in a place where trees aren't endangered species and there's still space for my old Alfa in the garage, provided it hasn't completely oxidized to dust by then...

But the chances are our 'daily drivers' will all incorporate electric powertrains of various shapes and sizes by 2050. Such vehicles will provide new challenges for dynamicists; in one of the fascinating articles in this special research edition of *VDI*, Lotus Engineering explores the impact of hub motors (*p38*). Indeed, having been fortunate to drive several prototype or early production EVs recently, I know that great progress is already being made in this field.

Don't forget that electric vehicles will be just one of the topics under discussion at Vehicle Dynamics Expo, which returns to Messe Stuttgart on May 17-19. See you there!

Graham Heeps

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CONTRIBUTORS


DAMIAN HARTY

The MINI World Rally project has loomed large in Damian's 'in-tray' these past two years, with the Prodrive engineer having been on board even before the Countryman base car was confirmed (*p22*)


JOHN HEIDER

John's Cayman Dynamics concern goes from strength to strength, with extra staff on board and a new lab/office/garage facility in Dearborn. He's not planning to buy a proving ground, but there are several for sale! (*p78*)


JOHN MILES

Austin Seven Specials have occupied much of John's time these past months, with not one but two in the Miles garage. One is being fully rebuilt; the body is back on and the engine should be done by June. John hopes it will run later in 2011


PHIL MORSE

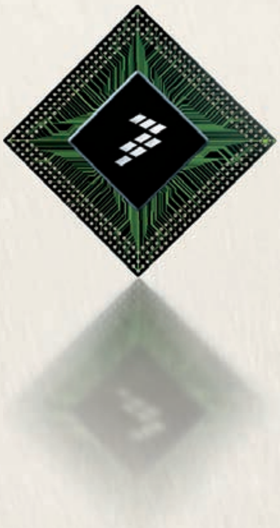
Phil has worked with a number of OEMs, as well as for open-wheel, stock-car, and sportscar racing teams. He now runs the Concord, NC-based consultancy, Energy Balance LLC and found time to explore shaker rig testing for this issue (*p42*)


KEITH READ

Keith has moved into the world of alternative fuels with his most recent purchase, a Fordson EN27 tractor from the late-1940s/early-1950s. It runs on TVO (tractor vaporizing oil), a cocktail of mainly paraffin (kerosene) plus gasoline and diesel!

Freescale Xtrinsic Sensors: HARMEMS Technology

Freescale, as the number one supplier of automotive MEMS inertial sensors, now offers intelligent active safety solutions to help prevent accidents from occurring. The new Xtrinsic MMA6900Q and MMA6901Q inertial sensors for electronic stability control (ESC) are designed to proactively help safeguard passengers by monitoring the driving environment.



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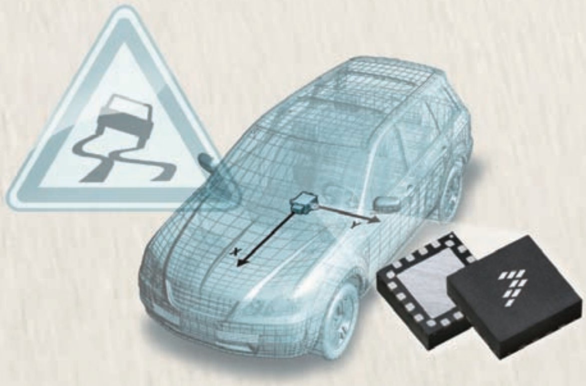
Based on Freescale's next-generation, high-aspect-ratio micro-electromechanical systems (HARMEMS) technology, the Xtrinsic MMA6900Q and MMA6901Q accelerometers offer a wide dynamic range of sensing, with exceptionally high resolution. These inertial sensors have robust design and temperature stability that are suitable for automotive applications, to help keep drivers safe.



Access the Tower Sensor Pak TWRPI-MMA6900 with complimentary software at freescale.com/towersensorpak

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Raging bull

ITS MAKERS CLAIM IT HAS PERFECT DYNAMICS IN ALL CONDITIONS. **MATT DAVIS** AND **GRAHAM HEEPS** HAVE THE STORY ON THE DESIRABLE NEW LAMBORGHINI AVENTADOR

TORQUE VECTORING UNNECESSARY, SAYS LAMBORGHINI, BECAUSE HALDEX AWD TAKES CARE OF OVER-/ UNDERSTEER AND STABILITY

SPECIFICATIONS

Lamborghini Aventador LP 700-4

Dimensions: 4,780mm (L) x 1,136mm (H) x 2,030mm (W). Wheelbase 2,700mm, track 1,720mm (F), 1,700mm (R)

Dry weight: 1,575kg

Chassis: Carbon-fiber monocoque with aluminum front and rear subframes

Suspension: Front and rear horizontal Öhlins monotube dampers with pushrod activation. Standard spring rates: 60N/mm (F), 70N/mm (R)

Geometry: camber 1°(F), 1°30′ (R); castor 5° 50′

Brakes: Ventilated carbon discs, Ø 400 x 38mm (F), 380 x 38mm (R). Six-piston calipers (F), four-piston (R). Multimode ESC/ABS

Steering: Three-mode Servotronic hydraulically assisted rack-and-pinion. Turning circle curb-to-curb 12.5m, ratio 16.5:1

Wheels/tires: 19in x 9J (F), 20in x 12J (R); Pirelli 255/35 ZR19 (F), 335/30 ZR20 (R)

Maximum speed: 217mph (350km/h)

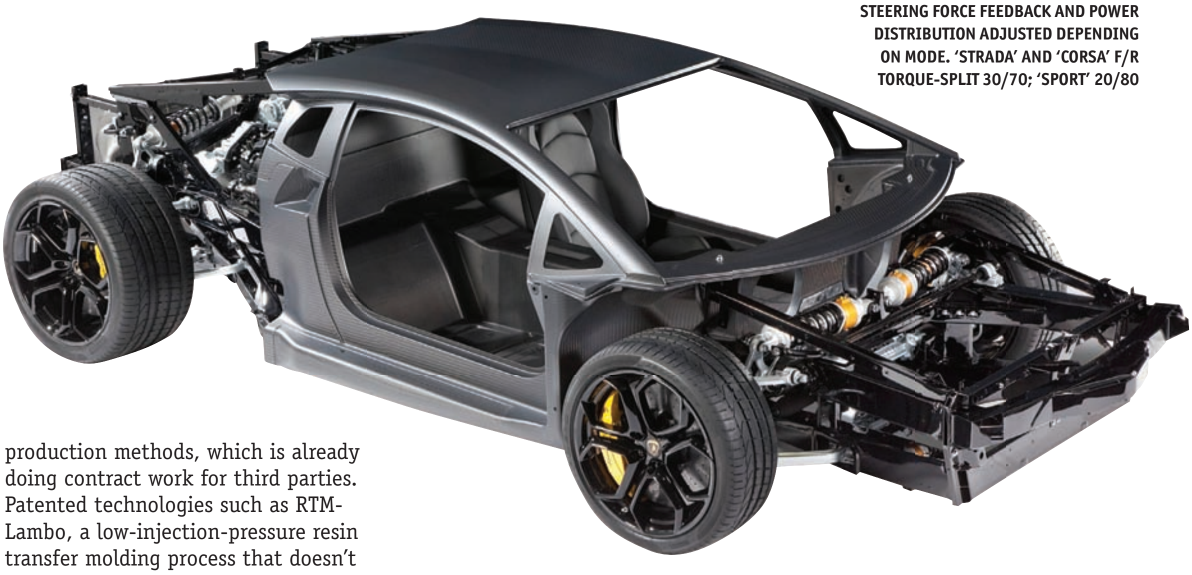
Acceleration zero-62mph (100km/h): 2.9 sec

Walking through the sliding front doors in Sant'Agata Bolognese, the energy is pretty infectious as the world awaits the official full-on drive launch of the new Italian dominator, the Lamborghini Aventador LP700-4. Truly big production-car news has been trickling in over the past few years as the company relied on versions of the Gallardo LP570-4 V10 and rare Murciélago LP670-4 sound bites. All of that is about to change dramatically.

Buzz on the Aventador is already swollen to a significant fever among supercar aficionados, and the promised technology and dynamics are tantalizing. After an early set of prototype drives at the high-speed oval and new handling circuit at Nardò, a lightweight workshop shared between mother company Audi AG and Lamborghini that focused on the latest on-site CFRP production capabilities, and a one-on-one with technical boss Maurizio Reggiani, we pretty much know what we're getting ourselves into already. Time for details…

The car is based around a CFRP structure of the type previewed in the Sesto Elemento technology demonstrator. Lamborghini is making a big noise about its future composites capabilities, and has set up a dedicated Advanced Composite Research Center for the purpose, complete with highly industrialized

COMPARED WITH ITS PREDECESSOR, AVENTADOR IS SAID TO BOAST LESS CABIN VIBRATION AND NO LONGER HAVE MASSIVELY OFFSET PEDALS. REAR WING EXTENDS TO A MAXIMUM ANGLE OF 11°, BUT RETRACTS TO 5° FOR HIGH-SPEED RUNNING



STEERING FORCE FEEDBACK AND POWER DISTRIBUTION ADJUSTED DEPENDING ON MODE. 'STRADA' AND 'CORSA' F/R TORQUE-SPLIT 30/70; 'SPORT' 20/80

NEWS-IN-BRIEF

NRG Wheels in the UK recently produced a carbon/magnesium car wheel said to be 40% lighter than the lightest aluminum or magnesium wheel. The carbon composite wheel rim was developed and produced with a Huntsman Araldite resin system that was especially adapted for resin transfer molding, and to deliver better impact resistance.

With assembly of the TF roadster now ended, production of the MG6 'sports fastback' began on April 13 – the first all-new MG to come out of MG Motor's factory in Birmingham, UK in 16 years. A team of around 300 engineers and designers from SAIC's technical center on the Birmingham site was responsible for the design and engineering development of the MG6, which is already on sale in China.

Mercedes-Benz's attractive Concept A-Class was launched at the Auto Shanghai Show. A precursor to the future production version, this is a more conventional compact-class car than the outgoing, sandwich-floor model. As a first in the segment, claim its makers, the A-Class offers Collision Prevention Assist, a radar-based collision warning system with adaptive Brake Assist that lowers the risk of rear-end collisions.

production methods, which is already doing contract work for third parties. Patented technologies such as RTM-Lambo, a low-injection-pressure resin transfer molding process that doesn't require expensive equipment, are a key part of the mix.

"We have already started work on future technologies where we can work more and more on the efficiency of the manufacturing time," promises Reggiani.

For Aventador, the carbon monocoque means torsional stiffness of 35,000Nm/deg, or approaching twice that of the outgoing Murciélago. This is symptomatic of the fact that the newcomer, which has the stated goal of reclaiming Lamborghini's place at the top of the supersports pile, is two generations on from its predecessor in terms of technology and development. In fact, Reggiani goes as far as to arbitrarily estimate that in all capacities and parameters the Aventador is "50 times better than the Murciélago".

"Normally during development of a new car you start with the basis of the existing car and try to improve the point that you judge to be the state-of-the-art," Reggiani continues. "With the Aventador we scrapped the [existing] engine, suspension, chassis, gearbox, and 4WD, and have redefined everything [based on] what can be the best performance possible. This means we were able to make a completely new car without compromise, without the constraints of using something already existing from a previous car."

At 1,575kg, the car is more than 90kg lighter than its forebear. A desire to keep the weight down was one reason behind the decision to go for a new, Oerlikon Graziano AMT gearbox (called ISR – Independent Shifting Rods) instead of the twin-clutch technology popular elsewhere in the Volkswagen Group. A wish to be "competition-ready in spirit" was another.

One high-tech feature the car codenamed 'LP834' will get, in time, is a version of Audi Magnetic Ride (BWI MagneRide, we assume), but for the time being the passively damped, forged aluminum suspension is in a pushrod setup (another Lamborghini first) and was developed with Öhlins. The spring and damper mounting points are now on the bodyshell, not at the wheel mounts, so wheel control and damping are separated. Reggiani says the spring rates are around 5-10% softer than on the Murciélago, but that damper/spring calibrations are together a bit harder.

The key proving ground for handling development was Nardò, but the Aventador has also run at Hockenheim, Nürburgring, and Imola. In terms of handling, the car should be in a different league to the Murciélago; certainly the dynamic fundamentals were set in stone early on. After decisions on a new V12 and then the scissor doors (!) came the discussion on the exact placement of the engine in the chassis. Meanwhile the whole car returns an effective 30mm lower center of gravity than the Murciélago.

"The reduced mass and increased stiffness are really important in terms of handling," Reggiani stresses. "I also think we are the only non-race car to adopt a pushrod suspension in the front and rear. This allows us to reduce the unsprung mass of the suspension, so it is light and has a more direct ratio in terms of damping. This has allowed us to have a perfect dynamic vehicle in every condition the car will be used in. We have realized a car that is extremely easy to use in busy city traffic, but can also be the most aggressive car when you want to use it on a proving ground or in special conditions."

The multimode transmission and three-mode Servotronic steering add further flexibility to the mix.

Additional reporting by Adam Gavine

VDI SAYS

There seems to be a sense with the Aventador that Lamborghini is affirming its independence within the VW Group – this car is most certainly not a souped-up Audi. With the might of Porsche joining the Group, that seems like a pretty sensible approach on Lambo's part.

AVENTADOR PRODUCES 105KG OF DOWNFORCE @ 174MPH (280KM/H)

Force of nature

ACTIVE AERODYNAMICS ARE JUST ONE OF THE HIGHLIGHTS OF PAGANI'S NEW HUAYRA HYPERCAR. **GRAHAM HEEPS** REPORTS ON AN EXCLUSIVE MACHINE

Even in the rarefied atmosphere of 200mph+ sports cars, the new Pagani Huayra promises to be an exceptional vehicle. With its bespoke, 6-liter, twin-turbocharged AMG engine, carbon-titanium monocoque structure, and active asymmetric aerodynamics, its select band of customers will get something different from anything else on the market when the first cars are delivered later this year.

Named after Huayra Tata, an ancient Andean god of wind, the new machine has been under development for the past five years. That timescale is no surprise when one considers that Pagani employs just 40 people, and that the 230mph (370km/h) Huayra will be the first of the company's cars to be homologated for sale in the USA, from 2012.

For the European version, IDIADA has handled the Huayra's homologation testing on Pagani's behalf. Another notable project partner has been Bosch, to whom Pagani supplied one of only four prototype vehicles in order to develop the braking- and stability-control electronics.

A DISTINCTIVE INTERIOR. NOTE SEQUENTIAL SHIFT

In addition to Bosch's proving grounds at Boxberg (Germany) and in northern Sweden, chief test driver Davide Testi and his colleagues (including Horacio Pagani himself) have undertaken dynamics work at Nardò (Italy), ATP Papenburg (Germany), and Upington Shuttle Airport (South Africa).

For handling development the emphasis has been on physical rather than digital testing. In design terms, Pagani says it sought to keep the weight of the rear overhang as low as possible in a bid to achieve neutral behavior at the limit. For this reason a dual-clutch gearbox – which would have brought a 70kg weight penalty – was rejected in favor of an Xtrac seven-speed sequential AMT.

The Huayra is based around a carbon-titanium monocoque to provide the requisite stiffness, despite the gullwing doors cutting deep into the roof. The design is new,

NEWS-IN-BRIEF

Bridgestone Corporation has received the General Motors Supplier of the Year Award for the thirteenth time. The Japanese tire giant supplies rubber to all four of GM's north American brands, as well as to GM facilities and subsidiaries in Brazil, Venezuela, Europe, Australia, India, Thailand, South Africa, China, and South Korea.

Simulation systems provider, IPG Automotive is about to release the latest version of its CarMaker integration and testing platform. A new Navigation-in-the-Loop feature in version 3.5 provides a plug-in for data transfer from navigation systems, facilitating the testing and development of predictive, map-based advanced driver assistance and energy management systems.

SPECIFICATIONS
Pagani Huayra
Dimensions: 4,605mm (L) x 1,169mm (H) x 2,036mm (W). Wheelbase 2,795mm, track 1,910mm (F), 2,010mm (R)
Engine: Mercedes-AMG M158, 5,980cc V12 twin-turbo. Power > 700bhp, torque > 1,000Nm
Suspension: Forged Avional double-wishbones. Pushrod-operated, adjustable Öhlins dampers
Steering rack: TRW
Brakes: Brembo carbon-ceramic with Bosch ABS/ESP
Tires: Bespoke Pirelli P Zero 255/35 ZR19 (F); 335/30 ZR20 (R)
Dry weight: 1,350kg

ADJUSTABLE WINGS VARY THE CAR'S DRAG COEFFICIENT FROM 0.31 TO 0.33

THE HUAYRA HAS BEEN SUBJECTED TO HIGH TEMPERATURES IN DEATH VALLEY AND SOUTH AFRICA, AND COLD-WEATHER RUNS IN NORTHERN SWEDEN. BY THE END OF 2011, IT WILL HAVE COVERED MORE THAN A MILLION TEST KILOMETERS

although Pagani first used this type of structure on the special-edition Zonda Cinque in 2009. Chrome Moly steel subframes are attached to the tub front and rear.

The double-wishbone suspension is largely carried over from the Zonda R, with geometry tweaks to account for the Huayra's 10mm of extra wheelbase; it features pushrod-operated, adjustable Öhlins dampers. The Brembo carbon-ceramic brake hardware is likewise adapted from the Zonda R, but recalibrated for the heavier Huayra (1,350kg compared with 1,070kg). A novel feature is the channeling of air from the side radiators to ducts cooling the brake discs and wheel hubs. With a temperature of around 50°C, this air warms up the brakes from cold, which Pagani says improves the first bite "significantly".

The friction braking can be supplemented by an airbrake, with the two wing flaps on the rear deck-lid extending upward for additional retardation. They're assisted by the front suspension, which raises the front of the car to counteract the weight transfer and balance the weight distribution between front and rear axles, for best use of the rear brakes. For the record, the Huayra's static weight distribution is 44% front, 56% rear.

The airbrake function forms part of the active aerodynamics that are the car's standout feature. A dedicated ECU (one of 15 on the car, compared with the Zonda's five) is fed information from the ABS and central ECU regarding the car's speed, yaw rate, lateral acceleration, steering angle, and throttle position. The aero controller then decides how to deploy the four control flaps (two front, two rear).

"A strategy defines how the wings move, dependent on the speed of the car," explains Davide Amerighi, technical department coordinator at Pagani. "In addition to the airbrake [function], there's an asymmetric mode, too: when you take a corner within a speed range defined in the software, the wings' control unit increases the incidence of the inner wing planes front and rear by 10° compared to the normal position, [adding downforce] so you can stop the roll and corner flat."

Working in conjunction with the sculpted underbody and rear diffuser, the system helps the car achieve more than 1.5*g* of lateral force, just one of several extreme performance figures for which tire supplier Pirelli developed Huayra's bespoke rubber.

Turning to more conventional technology, the steering is a hydraulically assisted setup with hardware from TRW.

"We've put a sensor on the steering to be able to vary the effort depending on the speed, but at the moment we don't need it because the feeling is good," says Amerighi. "We prefer our power steering without this type of electronic control."

VDI SAYS

Chances are we'll never get to drive the Huayra, but no matter. In an age when unusably high performance has reached even the humblest family hatchback, the Pagani is a properly exotic machine to excite your inner petrolhead!

NEWS-IN-BRIEF

Saab is establishing a sub-assembly plant in cooperation with ZF Chassis Systems. Located in Halvorstorp, 3km from Saab's Trollhättan factory, the just-in-time plant will supply front subframes and complete rear-axle assemblies for future Saabs based on the firm's new modular vehicle architecture, beginning with the successor to the 9-3 in 2012.

Leading Tier 1, Continental Automotive is investing €21 million in a new R&D center in Singapore. The new site will be located at Boon Keng Road with total land coverage of 4,500m². By April 2012 the facility will comprise a seven-storey office and R&D building with seating for 860 employees. A future phase could add a further storey to take the headcount past 1,000.

VI-grade has opened a new technical center dedicated to driving simulators at its premises in Tavagnacco (Udine, Italy). Two years in development, the 250m² VI-SimCenter features three driving simulators from the VI-DriveSim product line: two 'Static' models and one 'Dynamic' one with a moving platform, the latter being the first example of its kind. The same simulation engines for graphics and physics are used on all three machines, and race-car as well as passenger-car cockpits are available. Both types of simulators are available for purchase or lease, and can be customized to client needs.

Something to prove

CONTINENTAL'S UVALDE PROVING GROUND IN TEXAS HAS BEEN MADE EVEN MORE ATTRACTIVE FOR VEHICLE DYNAMICS DEVELOPMENT. BY **KEITH READ**

Recent major investments and improvements at Continental Tire the Americas (CTA's) vast 5,000-acre Uvalde proving ground have given the company's test and development site in the year-round warmth of Texas – originally constructed for General Tire in the late 1950s – a number of world-class facilities.

"Some are based on those at the world-famous Contidrome in Germany, while others are unique to the US facility," says test engineer, Christian Brielmaier.

Uvalde is used not only by Conti for development of its Continental and General Tire brands, but also external customers.

OEMs, component manufacturers, the military, law-enforcement agencies, independent test organizations and even rival tire companies – provided the facility they hire is not considered unique and giving Conti a competitive advantage – can all use Uvalde.

More than US$10 million has been invested in the upgrades and developments over the past decade, including a US$3.5-million resurfacing of Uvalde's vehicle dynamics area (VDA) 59,500m^2 (640,000ft^2) asphalt wet-handling pad.

Water depth is controllable from 1.25mm to 2.8mm with a 1% grade facilitating drainage. At maximum water depth, some 300 gallons per minute flows across the pad, which has straight approaches from each direction for stopping-tests from high-speed. However, the irrigation system can supply up to 800 gallons per minute. The entire pad is surrounded by a 100ft-wide run-off/recovery safety area.

"The wet-handling pad surface has been designed to produce real-world conditions, with surface texture emulating the type of surfaces that drivers can expect to encounter," adds Brielmaier.

Other vehicle dynamics features include a 1.1-mile dry handling course, a three-mile multi-surfaced oval for ride and noise evaluation, a 250ft hydroplaning test course, and a new underground footprint measuring laboratory, the ULab.

"The key to the new ULab is a plate-glass window set into the surface of the VDA – and the ceiling of the lab – through which tire footprints can be seen, filmed and measured dynamically," he explains.

"Uvalde's ULab operates under wet or dry test-surface conditions. The footprint and pressure distribution can be measured and filmed with high-speed cameras operating at 2,000fps."

Another new facility at Uvalde is the off-road course, which was used for the first time to host the "Off Road Challenge" event run by *auto motor und sport* magazine and Mercedes-Benz.

"It's a really amazing two-mile off-road course with a 70m rock-crawl, a 34m rock hillclimb, a 20m uphill climb with boulders, a 61m mud and water pit, and 35m of side-slope laid with telephone poles," says Brielmaier.

"It's very challenging and will be attractive to many of our customers."

There will be more new facilities in the future, with the enhancement of the Uvalde proving ground continuing. Conti is planning to widen its two-lane, 3-mile oval – known as the 'ride road' – this year, and will improve Uvalde's handling course.

CHRISTIAN BRIELMAIER (ABOVE) **AND AN AERIAL VIEW OF THE UVALDE SITE SHOWING THE RESURFACED VDA** (RIGHT)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On the job

Reverse logic

MAGNUS ROLAND'S REAR SUSPENSION PHILOSOPHY IMPRESSES **JOHN MILES**

Chassis guru Magnus Roland's history with Saab, GM, and now his consultancy S2AB continues to be all about a missionary zeal and passion in the field of vehicle dynamics, particularly in relation to rear suspension topology and kinematics. To put it bluntly, he wants to turn accepted thinking on its head, his ethos depending (as it always has) on the philosophy of 'reversed kinematic steer' at the rear axle; that is to say bump steer trajectories that tend toward slight toe-out, whereas the accepted norm is that a rear axle must toe-in with bump or lateral force, since it is claimed that this is the only way to inhibit yaw gain, and provide adequate lateral acceleration response at the rear axle.

This standard industry approach is usually combined with plenty of kinematic and compliance toe-out on the front axle, which normally gives a certain sense of 'stability' but often at the expense of numb steering, initial steering response delay, plus lane-change overshoot at the limit of adhesion, and excessively high lateral acceleration build-up in transient handling.

Years ago Roland made the point that the suspension system should be dedicated to optimizing the 'signal-to-noise ratio' – noise being the unwanted correction required to modify the car's path by the average driver operating at 0.5Hz, whereas the average car has a natural yaw frequency of 1.5Hz. Analysis will demonstrate that yaw damping is reduced with toe-in, and increased with toe-out kinematics, thus improving the STN ratio.

We are talking almost minute changes in sign from in to out. Reversal of the extremely small/stiff 18kN and 12kN/mm LCA bushes on the FWD Lotus Elan changed the smallest values of compliance toe-in to toe-out, dramatically affecting the car for the better regarding under/oversteer balance, tracking stability, steering center feel, and steering torque alignment characteristics. A 15mm height change on the very long Lotus Carlton/Omega rear-steer link performed the same trick.

That Roland's philosophy works in respect of disturbance rejection and platform stability was demonstrated to me more than 30 years ago in the Saab 9000, which could be driven virtually flat out on gravel, whereas the nervous Audi 100 definitely could not. The most graphic example was the 165mph Lotus Carlton/Omega, the most stable, yet gentle handling car in provoked oversteer I have driven. My understanding is that while at GM, Roland influenced the current Corvette rear suspension in the same direction.

Happily, suspension topology on the foregoing cars had bump and lateral compliance steer trajectories that were extremely controllable to fine limits in production. This is important because lower/wider-profile tires mean that suspension systems have become even more sensitive to inappropriate dynamic slip angle (steer) characteristics and static setup. The Omega and Esprit had two and three links respectively, but Roland's current thinking demands that to independently control six degrees of freedom to fine limits, a five-link topology is required, especially if toe-in is to be retained for acceleration and braking. My experience suggests that achieving this with a suspension system that is made to a price, and is also adjustable in the field, might be a big challenge.

> "The 165mph Lotus Carlton/Omega remains to this day the most stable, yet gentle handling car in provoked oversteer I have ever driven"

Roland has spent most of his career working at understanding vehicle dynamics at a molecular level. He believes that an incredibly fast process of structural bonding is taking place between the tire and the road surface due to the light attraction of Van de Waal's forces, and this accounts for the fact that competition cars regularly exceed their theoretical maximum cornering and braking power for a given surface. He points out that at 87mph (140km/h), the average tire takes 1.25 milliseconds to compress by around 25mm, which, depending on the math, entails an acceleration of 500-1,000s of *g* at the outermost tread elements. This gives a vision of the high frequencies and energy involved at the tire/road interface, and in turn the necessity for the suspension topology to be optimized, because that part (the linkage) has the highest potential transmissibility. Or, in Roland's words, the response bandwidth of a passive suspension system is way beyond that achievable with the ESC that is sometimes used to "patch" the limit handling of cars. He also points out that gyroscopic effects inherent in a toe-out bump steer trajectory actually stiffen the wheel assembly in the camber mode, which increases grip and response just when you need it.

There is more to Roland's philosophy than just bump steer. All the kinematic and compliance characteristics are involved, but when his "reversed" rear axle steer works, steering feel, disturbance rejection, and cornering-security 'feel' at the limit, especially on slippery surfaces, become very seductive.


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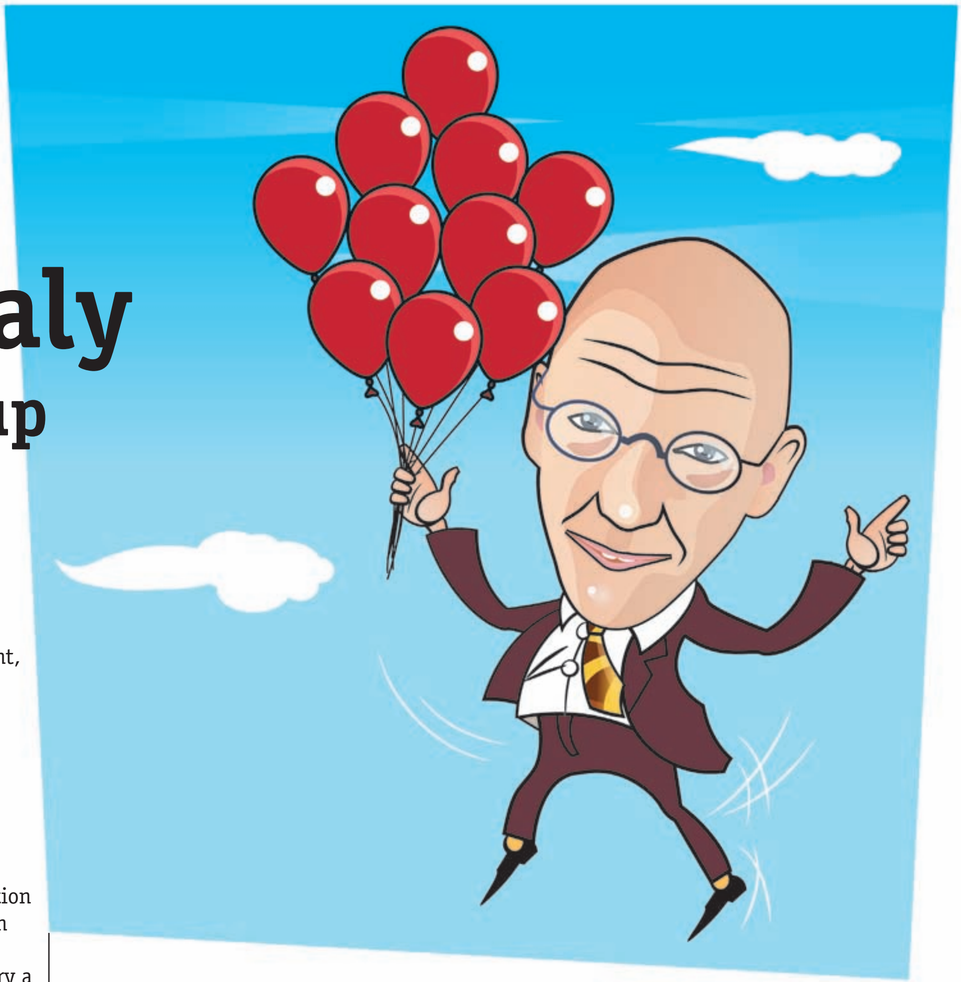

Made in Italy

Time to lighten up

LIGHTNESS SHOULDN'T BE CONFINED TO SUPERCARS, ARGUES **MATT DAVIS**

More than ever it seems the entire world of dynamics is stressing weight loss as a key to getting your car's behavior dialed in just right, as envisioned by the engineering team. This is certainly the direction being adopted by every high-performance car manufacturer.

This matters a lot because the halo effect of these attention-grabbing machines is a bit like free and very effective collateral advertising. And then we get the hoped-for trickle-down effect for all the rest of the manufacturer's lineup.

We'd been talking forever about lightweight construction as the holy grail for something, and then we were shown Ferrari's vision eco-concept in 2007, called Millechili. It weighed, yes, 1,000kg (2,200lb) and was intended to carry a 900hp V8. Maybe someday Maranello will get there for real.

This was at the dawn of the still ongoing green revolution, but nowadays the thing being stressed more is getting back to sheer dynamic performance through light weight while not compromising safety or comfort, and not making every sports car a million-dollar baby.

This transition is seemingly due to the human tendency to take it for granted after a while that enough effort has been spent cleaning up the planet (to at least meet Euro 5 or 6 goals). Now we can parley all this new green-lighted lightweight R&D investment into also making these cars stay faster, quicker-reacting and such, while also happening to pollute a bit less in the process. Sort of a budgetary chicken-and-egg game.

The holy grail now is making that Nm/d materials-use and weight loss a viable part of the everyday four-cylinder business case. I have, for instance, heard all the brake manufacturers preach to me about their consortium efforts to bring down the cost of ceramic discs, while also making them so that, when the calipers go into full-pinch mode, the discs don't squeal and send your dentures through the windscreen. This is just one way in which all-important rolling weight could be significantly dropped, automatically improving steering feel and everything else being communicated to my inner ear and the palms of my hands while just tooling around town. I'm convinced there's a conspiracy at this point to keep prices sky-high on ceramic brake discs, however, otherwise surely more civilian cars would be wearing them by now?

A further benefit of dropping weight is that entire suspension systems that once felt inadequate under elephant-heavy cars can now make a brilliant comeback. Although I do love magnetorheological dampers and adaptive chassis control systems, I am far more impressed with a much lighter traditional damper system that blows me away with how good it can be in all road circumstances.

> "The idea that we can save the planet with a car that weighs considerably more than the stock model on which it's based, is a joke"

I mention just one among several that are blossoming back to life: the Bilstein 46mm monotube dampers and Eibach springs mated to perfection (over an exhaustive length of time during development) at all four corners of the Lotus Evora.

Then comes the chassis challenge we all know too well. Currently we're seeing the big boys create full-CFRP passenger cells usually mated to front and rear bolted-on aluminum crash structures, and getting torsion and bending ratings that are double whatever model the new car is replacing. This is supreme good news, but I want more. I want us to stop being so impressed by a top-trim, everyday, warm hatchback coming standard with a fairy-dust-coated aluminum lower control arm in back. Big deal.

Meanwhile, dynamics has a whole new fish to fry when it comes to series or parallel hybrids, EVs and EVs with extended range engines. In this case, the current state of these vehicles is rather sad compared with how it should be in five to 10 years. The idea that we can save the planet with a car that routinely costs up to twice the price of the stock car on which it is based – and weighs anywhere between 300 and 500lb more – is a joke. All of these cars currently have the dynamics of a sea lion, apart from the limited-use sportier EVs we all know about. I'm talking bread-and-butter cars, folks. We can do so much better by just lightening up.

But, back to the main point: bring down the costs per pound lost and Nm/d gained – however we can – because this is the key to setting dynamics engineers really free to show off, instead of buying in a fancy optional multi-adaptive three-letter chassis pack to compensate. It's tough fighting product planners under pressure to create pork-belly profit margins with perceived drive-enhancing options, but dynamicists could fight harder for what is better long term. The future is light!

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Vehicle Dynamics International Awards 2011

THE VOTES ARE IN! **VEHICLE DYNAMICS INTERNATIONAL** IS PROUD TO PRESENT THE RESULTS OF ITS 2011 AWARDS, WHICH RECOGNIZE THE VERY BEST IN TECHNOLOGY, INNOVATION, AND HARD WORK IN THE FIELD OF VEHICLE DYNAMICS DEVELOPMENT

THE NEW MERCEDES DRIVING SIMULATOR IN SINDELFINGEN

DEVELOPMENT TOOL OF THE YEAR

Winner
Driving simulator – Mercedes-Benz/Moog
Highly Commended
SR60-Torus steering robot – Anthony Best Dynamics
(below)
Also shortlisted
WheelCam

It's been another year of impressive achievement from the vehicle dynamics community, and here at *VDI* we've once more assembled an expert judging panel to reward the very best that the industry has to offer.

The judging process took the same course as in previous years. From the nominations received from our readership, and with input of our own, the *VDI* editorial team selected a shortlist of finalists to be judged by the full jury. Once everybody had cast their votes, we added up the scores to determine the winner and a Highly Commended runner-up in each category.

If you feel your product, technology or achievement is worthy of recognition, don't forget to tell us about it. Then perhaps in 12 months' time, one of the coveted VDI Awards will be winging its way to a trophy cabinet near you!

Graham Heeps, editor

THE JURY

Jürgen Zöllter, freelance writer, Germany

"I have the best job on Earth!" says Zöllter, who contributes articles to more than 30 publications, including German titles *Focus*, *Welt am Sonntag*, *Autobild*, and *Autozeitung*, and *Car & Driver* in the USA, for which he is a European correspondent.

John Miles, vehicle dynamicist and journalist

From garage mechanic to F1 racer, and motoring journalist to respected chassis engineer, Miles has done it all in his 40 years in the auto industry. Now semi-retired, he continues to work for Multimatic while sharing his expertise with the readers of *Vehicle Dynamics International*.

Car of the Year

Opinion will always be divided as to whether a supercar that's out of reach of many ordinary car buyers is a worthy choice for a Car of the Year. But the McLaren MP4-12C won over the majority of the jury because, from a vehicle dynamics perspective, this is not just another supercar. In particular, McLaren Automotive's ambitious use of Tenneco's Kinetic H2 CES suspension system as the basis of its ProActive Chassis Control system breaks new ground for a roadgoing sports car, endowing it with ride comfort unheard of in this sector.

It was a solution that impressed journalists and dynamicists alike on the judging panel. "McLaren has produced an elegant solution to reduce the traditional compromise," said Peter Cambridge. "By not playing safe they have shown everybody the way forward."

CAR&Tecno's Alvaro Sauras was even more enthusiastic: "It is not just fast, not just nimble, not just clean. Giving drivers a carbon-fiber monocoque, revolutionary suspension, and more than 600bhp will give Ferrari, Porsche, Aston et al. plenty of headaches."

Accepting the award, Mark Vinnels, program director at McLaren Automotive, said, "This is an important award for us. Not only is it our first car of the year title, but it's in recognition of everything we have put into this car: an obsession with reducing weight, a commitment to using carbon fiber in a revolutionary way, and a thorough understanding of the best ways to integrate our Formula 1 expertise. The result is, we believe, the best car dynamically in all environments. That's the real breakthrough for us, that the car handles and rides beautifully on road or on track, in the hands of racing drivers or commuters."

Development Tool of the Year

Having won this Award in 2009, Anthony Best Dynamics came close again in 2011. But the winner this time around is Mercedes-Benz, which, with notable input from Moog, inaugurated perhaps the world's most advanced driving simulator at its Sindelfingen R&D base.

From the top down, it consists of a dome with a 360° projection screen, a full car model, a 6DOF Moog hexapod base, and a 12m-long sliding rail for lateral accelerations such as lane changes or, when swiveled through 90°, longitudinal motions. The complete motion system of the hexapod and lateral rail is controlled by Moog real-time software.

Dynamicist and awards judge Simon Newton is one of its many advocates: "This represents a great step forward in combining a hexapod ride comfort simulator with dynamics simulation now powerful enough, via the lateral rail, to replicate more aggressive maneuvers."

Daimler board member and Mercedes-Benz's head of development, Dr Thomas Weber, commented, "We are delighted to have received this award, as it also recognizes the work invested by our research and development team. As well as shortening our development times, the simulator also enables us to intermesh our research, development, design, planning, and production directly at our most important production and development location in Sindelfingen. The facility is not able or intended to replace real test drives completely, but the simulator makes it possible to test the systems and components of future Mercedes models in all development phases."

From a supplier perspective, Moog's business manager in Europe, Pim van den Dijssel, added, "The development of Daimler's latest dynamic driving simulator was very challenging in terms of the technologies required to meet the specifications. We were one of the committed partners to the project and we were able to bring new ideas and approaches to satisfy the technical requirements and meet the project specifications and objectives."

CAR OF THE YEAR

Winner
McLaren MP4-12C
Highly Commended
Chevrolet Volt *(right)*
Also shortlisted
Honda CR-Z

Alvaro Sauras, technical editor, *Car&Tecno*, Spain

An engineer by training, Sauras has been technical chief of the Spanish Luike group's car magazines since 2007, including the technically minded *CAR&Tecno*, and *Autofácil*, which is Spain's best-selling monthly car title.

Peter Cambridge, principal, Peter Cambridge & Associates

A former Prodrive engineer, Cambridge has just finished a stint as a freelance dynamicist in the automotive and defense sectors, and has recently accepted a role with Bilstein to develop more focused versions of standard production cars.

Graham Heeps, editor, ***Vehicle Dynamics International***

At the helm of *Vehicle Dynamics International* since 2005, Heeps has also been editor of *Professional Motorsport World* since its launch in 2006, and in 2009 oversaw the introduction of *Professional Motorsport Circuit*.

John Heider, principal, Cayman Dynamics

Formerly with Ford, *VDI* columnist Heider now runs the Cayman Dynamics consultancy, which works with OEMs, suppliers, and other companies in the transportation industry.

DYNAMICIST OF THE YEAR

Winner
Jürgen Pützschler, Ford

Highly Commended
Hidetoshi Kadota, Nissan *(below)*

Also shortlisted
Philippe Krief, Fiat Group Automobiles

Dynamicist of the Year

Ford has an enviable record in the VDI Awards, taking the Dynamics Team of the Year prize in 2008, and several other Highly Commended placings along the way. This year, Jürgen Pützschler (*pictured left*) has added the Dynamicist of the Year title to the Blue Oval's roll of honor, in recognition of his work as the vehicle dynamics supervisor for the new global C-Car platform.

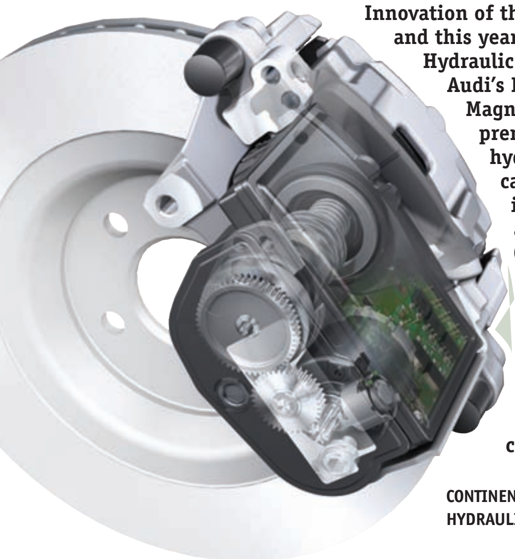
"This is truly a great honor and I am very pleased to receive this award on behalf of the entire Ford Vehicle Dynamics Team," he said. "With the new Ford Focus, we not only applied our 'attention to every detail' philosophy, but also went a step further in the integration of the attributes. This approach enabled us to effectively combine refinement, quality perception, and class-leading NVH characteristics with a high level of agility, precision, and confidence feel."

The jury shared the enthusiasm of Pützschler and his colleagues for the job done. "Ford's new C-Car platform is its most versatile yet: family cars, MPVs, SUVs, EVs, and performance cars will all derive from it, and with a remarkable degree of commonality between them," noted *VDI* editor Graham Heeps. "It can be a thankless task to serve so many masters, but on the evidence of the Focus and C-MAX, Pützschler has done a remarkable job."

Innovation of the Year

Innovation of the Year is always one of the hardest fought categories and this year was no exception. In the event, Continental's Electric Hydraulic Combi Brake (EHCB), which will hit the market on Audi's R8 e-tron EV, edged out the challenge from BWI's latest MagneRide damping system. EHCB is designed for use in premium vehicles and combines a friction-loss-minimized hydraulic setup at the front with a dry, electromechanical caliper at the rear. "Continental is taking a step forward in braking technology by making electrohydraulic a production reality," noted jury member Peter Cambridge. Indeed, EHCB could prove to be an important milestone on the road to full by-wire braking systems.

"Continental is very honored to receive the Innovation of the Year Award, which reflects an appreciation of the special achievement of our engineers," said Paul Linhoff, responsible for EHCB and dry brake-by-wire at Conti. "EHCB makes a significant contribution to reducing CO_2 emissions in cars and helps to further improve driving safety."



CONTINENTAL'S ELECTRIC HYDRAULIC COMBI BRAKE

INNOVATION OF THE YEAR

Winner
Electric hydraulic combi brake – Continental

Highly Commended
Third-generation MagneRide – BWI Group *(right)*

Also shortlisted
Ultralight front control arm – Magneti Marelli

THE JURY (continued)

Graham Johnson,
managing director,
UKIP Media & Events Ltd

Johnson was the launch editor of *Vehicle Dynamics International* in 2003 and continued to lead the magazine until mid-2005, when he became managing director of UKIP Media & Events Ltd, *VDI*'s publisher.

Matt Davis,
freelance writer, Italy

Italy-based, USA-born Davis has been in motoring journalism for 15 years. He is highly respected by news outlets worldwide, including *Auto Express*, *Genroq*, *Gente Motori*, and *Auto Week*, and of course *Vehicle Dynamics International*.

Simon Newton,
freelance vehicle
dynamicist, UK

Newton runs the UK-based Newton Dynamics consultancy and has spent the past few years contracted to Bentley's Vehicle Dynamics department, focusing on the Continental platform.

Dynamics Team of the Year

It's a debut win in the Dynamics Team of the Year category for McLaren Automotive. Key engineers including Paul Burnham (vehicle dynamics manager, *pictured right*), Mark Bolam (function group manager, chassis) and Dick Glover (formerly technical director, now research director) impressed the jury with the complex dynamics program for the MP4-12C supercar. Not only does the car boast an innovative chassis architecture, but to develop it, the engineers made extensive use of the same simulator technology that has served the McLaren Formula 1 team so well.

"With knowledge and agility superior to that of larger car manufacturers, the relatively small group of dynamicists working on the MP4-12C have done an exceptional job," commented awards judge Jonas Jarlmark.

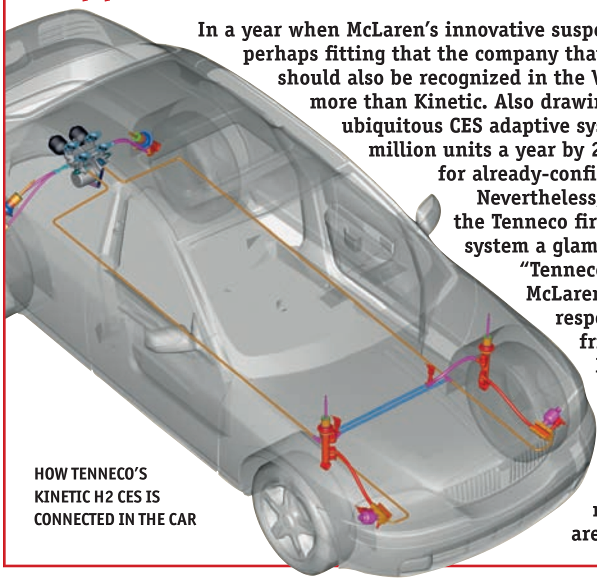
Accepting the award on behalf of his colleagues, Burnham said, "After moving into Automotive from McLaren Racing it was immediately obvious that everything was different, yet everything stayed the same. The dynamic challenges for a road car and a racing car are clearly poles apart, yet the integration of Formula 1 development technology, engineering know-how and a passion to win in the road car division was manifest. Our engineers have pushed beyond the normal rules and this award is a great reward for their endeavors."

DYNAMICS TEAM OF THE YEAR

Winner
McLaren Automotive
Highly Commended
Ford *(below)*
Also shortlisted
Suzuki

THE NEW C-MAX IS ONE OF THE LATEST PRODUCTS FROM FORD'S RENOWNED DYNAMICS DEPARTMENT

Supplier of the Year



HOW TENNECO'S KINETIC H2 CES IS CONNECTED IN THE CAR

In a year when McLaren's innovative suspension system has caught the eye, it's perhaps fitting that the company that supplies its core technology, Tenneco, should also be recognized in the VDI Awards. But this trophy is about more than Kinetic. Also drawing praise from the judges was Tenneco's ubiquitous CES adaptive systems, volumes for which are set to hit one million units a year by 2013, which is also when CES 2 production for already-confirmed customers is due to begin.

Nevertheless, Kinetic is perhaps the brightest star in the Tenneco firmament, and the McLaren has given the system a glamor that the Lexus RX 470 never managed! "Tenneco's electrohydraulic dampers in the McLaren's ProActive Chassis Control are responsible for much of the reason the car frightens both Ferrari and Porsche," noted Matt Davis. "They are a revelation."

Amid universal praise for the system, Tenneco can be rightly proud of its work. "This kind of innovation is what Tenneco is all about," concluded Sandro Paparelli, the Tier 1's vice president and general manager, Ride Control Europe, "and we are delighted to be recognized for it."

SUPPLIER OF THE YEAR

Winner
Tenneco
Highly Commended
TRW *(pictured)*
Also shortlisted
BWI Group

Jonas Jarlmark, freelance vehicle dynamicist and writer, Sweden

In 2011, Jarlmark is engineering Chevrolet Cruze race cars in the Scandinavian Touring Car Championship. He continues to contribute to *Automobil* as well as *VDI* and sister title *Professional Motorsport World*.

Gene Lukianov, freelance engineer, USA

Former Chrysler dynamicist, Lukianov is now a freelance dynamics consultant (via his VRAD Engineering business), amateur race car engineer and driver, and occasional technical writer with huge enthusiasm for engineering in all its forms.

John Heinricy, principal, Heinrocket Inc

The winner of the inaugural VDI Dynamicist of the Year Award in 2008, Heinricy then took early retirement from General Motors and now runs Heinrocket Inc, focusing on vehicle testing and development, and high-performance driver training.

Keep it simple

PRODRIVE'S TECHNICAL SPECIALIST, **DAMIAN HARTY**, REVEALS THE DESIGN PHILOSOPHY BEHIND THE NEW MINI JOHN COOPER WORKS WORLD RALLY CAR: SIMPLE MODELS, SMARTLY USED

With about 350km on a World Rally Championship (WRC) event and about five bends per kilometer, there are handsomely more than 1,000 bends in a weekend. In fact, the first two special stages alone have more than a circuit-racing season's worth of corners.

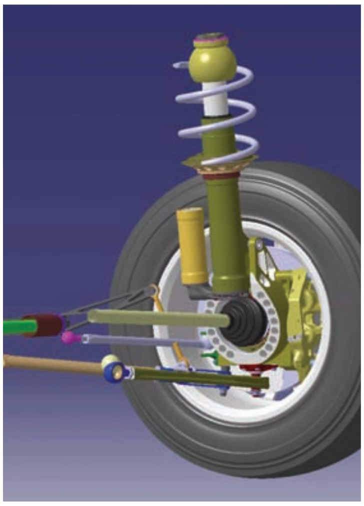
Rally driving is broadly not learnable, in a chaotic and unpredictable environment. Getting a grip on this problem using traditional methods can at first appear a little daunting.

Like most forms of motorsport, the task at hand is to deliver the car through a connected series of bends as quickly as possible in order to make our sponsorship space more valuable than other sponsorship space. Although the engine definitely plays a role, slowing down less for the corners makes a rather large difference to stage times, too.

From a vehicle dynamics perspective, the unrehearsed aspect to rallying is what makes it most compelling. The vehicle has to have the maximum possible corner speed ('grip') and also the shortest possible preview time to increase the odds of successfully judging the corner on the approach. Driving out of the corner, the engine power has to be delivered as effectively as possible to the road, for which all-wheel drive is indispensable.

Previous WRC cars have had sophisticated electronic control of the driveline with so-called 'active differentials' – electronically controlled clutches in parallel with traditional bevel or epicyclic differential gears – but current regulations in the sport forbid the use of active differentials and force the driveline's reversion to a rigid propeller shaft connecting two plate-and-ramp style, Salisbury differentials.

On very low grip surfaces, it is difficult to turn a vehicle with a stiff driveline, to which the traditional response is to use the handbrake. The handbrake on a World Rally car is a sophisticated hydraulic device and also incorporates actuation for a clutch in the rear end of the prop shaft to disconnect it and enable



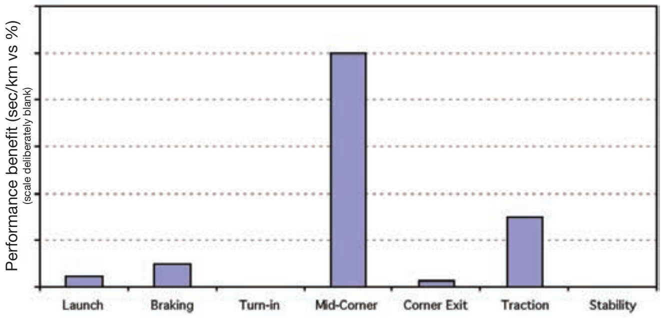


FIGURE 1 (LEFT): **MID-CORNER SPEED AND ACCELERATION OUT OF THE CORNER ARE THE KEYS TO DELIVERING THE FASTEST STAGE TIME**

LEFT AND INSET: **STRUT SUSPENSION ON ALL FOUR CORNERS IS ACCEPTED BEST PRACTICE IN WORLD RALLYING**

TOP: **SEPARATE RESERVOIRS FOR THE ÖHLINS DAMPERS.** ABOVE: **DURABLE SUSPENSION TOP MOUNTS ESSENTIAL**

the rear wheels to spin down when the handbrake is used. No electronic control is permitted.

Against this background there is a need to deliver dynamic performance that enables the driver to maneuver adroitly and yet gracefully recover from misjudgments, that enables the car to be driven at maximum pace over three days of event and yet does not deliver excessive fatigue, and that survives passage over territory that is at times shockingly rough.

Ambient temperatures can go over 40°C (104°F) for middle-eastern events, damper inputs are continuously up to 2.5m/sec. Braking events routinely average 250kW, which is nothing compared with the megawatt events in Formula 1 but is a lot of heat to dissipate from a closed-wheel car with 15in wheels.

And my favorite bit? There will always be a bigger rock. However much suspension travel there is, it will all get used up. Whatever loads are designed for, they will be exceeded. Welcome to my world!

For a car to survive over a season, it needs to be tough. For a car to succeed, it needs to have been designed intelligently, with compromises and priorities identified early and dispassionately quantified. The design of a completely new car, the car that became the MINI John Cooper Works WRC, gave a unique opportunity to go back and redefine the question.

By breaking the stage down into a series of phases – launch, braking, turn-in, mid-corner, throttle reapply, traction, high-speed stability – each can be considered in the light of historic data sets and reviewed for their contribution to actual stage time performance.

The results from this exercise are very different to popular belief. Despite the driver's impressions, braking and turn-in are not the key to delivering stage time. Of most importance is the ability to carry mid-corner speed and next on the list is the ability to put speed on after the bend.

From a vehicle dynamics point of view these questions are remarkably similar to those asked on a circuit – lateral acceleration and longitudinal drive out of the corner.

Having identified the question, the car can be considered as a large number of design variables, some of which influence either or both of the two main goals and some of which don't really move the needle. What also emerges is the existence of a panoply of factors that, if wrongly set, can slow the car down but can't really speed it up. A good example of this is the crew intercom; if the driver can't hear the pace notes then performance is obviously reduced. However, once the intercom is loud enough and clear enough, then making it louder or clearer doesn't bring any improvement in stage time.

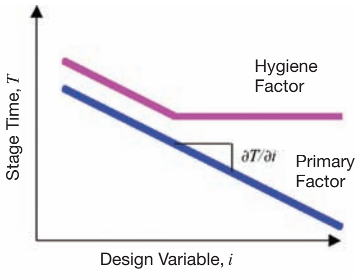
We refer to this class of variables as 'hygiene factors' – taken from management theory in which an item can degrade motivation if it is set wrongly but once it is clear of some threshold does not influence motivation anymore.

With a finite engineering resource it's absolutely crucial to identify which of the design variables are the ones that can genuinely improve the performance of the car – let's call them 'primary factors' – and to give them lots of engineering time. The hygiene factors deserve enough attention to get them into the right place and then they should be left alone (*see Figure 2, next page*).

"Once we abandon the search for a perfect stage simulation, we free ourselves of the burden of feeding such a monster"
Damian Harty, technical specialist, Prodrive

ABOVE RIGHT: **GRAVEL TESTING IN PORTUGAL IN THE HANDS OF DRIVERS KRIS MEEKE AND DANI SORDO**

FIGURE 2 (RIGHT): **PRIMARY FACTORS ARE DESIGN VARIABLES THAT GENUINELY IMPROVE THE CAR'S PERFORMANCE; HYGIENE FACTORS CAN ULTIMATELY BE LEFT ALONE**



BOTH S2000 AND FULL WRC VERSIONS OF THE MINI JCW ARE AVAILABLE TO CUSTOMERS FROM THIS YEAR

While the crew intercom is easy to imagine as a hygiene factor, some hygiene factors are surprising to the obsessive and dedicated vehicle dynamicist. Can great steering feel really make the car faster than merely 'good' steering feel? When the structure of the car is stiff enough, can making it stiffer make it faster? Perhaps most contentiously of all, if the car turns in well enough, does making it turn in better – whatever 'better' might mean – actually make the car faster through the stage?

The need to aggressively and dispassionately rank design variables sets the challenge for predictive methods to identify the knee-point for hygiene factors and usefully rank the design sensitivities for the primary factors; numerical models are the tool of choice given the ubiquity of digital computing. Consisting largely of the integration of differential equations to predict the time-domain performance of systems and subsystems on the vehicle, these models have a long and respectable pedigree, going back to the Manhattan project in the USA and, more recently – and less destructively – the Apollo space program.

Models are great when used honestly, but some overstate their value while others reject them unhesitatingly – and the two camps are often at loggerheads. The statistician, George Box is reputed to have said, 'All models are wrong, some models are useful.' This sentiment is vital to getting something useful out of a predictive modeling exercise.

The fear of a model being wrong can lead to getting suckered into thinking that the most accurate possible model is what's needed. Many people have in mind that a more accurate model is more useful in a fairly direct fashion. This isn't necessarily true, though.

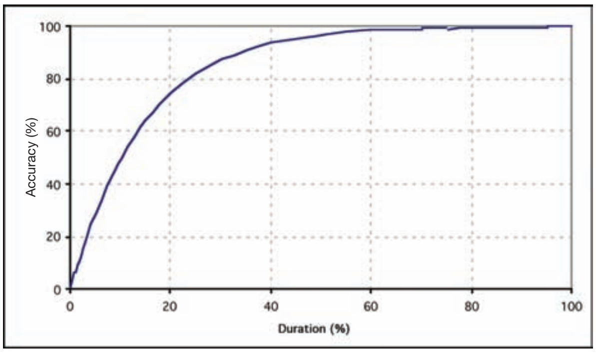
To prepare a very accurate model is something of a 'diminishing returns' proposition – the last 20% of accuracy costs about 80% of the effort.

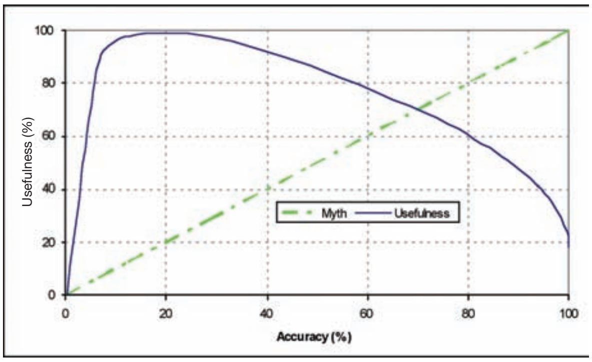
If we think about 'usefulness' – the degree to which predictions can be used advantageously in the design process – it may reasonably be suggested that a quicker prediction is more useful than a slow one. We might, for the sake of argument, suggest that Accuracy/Duration is some surrogate measure for usefulness. If:

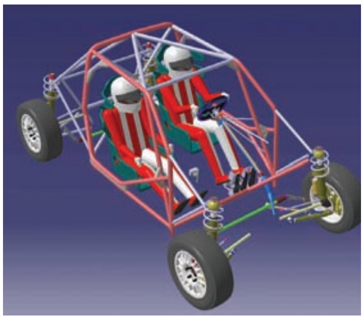
$$Accuracy = 1 - e^{-duration}$$

(the expression which produced the sketch graph in Figure 3, top) then it could be suggested that:

$$Use = \frac{Accuracy}{-1n^{(1-Accuracy)}}$$







FAR LEFT: FIGURE 3 (TOP): **ACCURACY/ DURATION CAN BE A SURROGATE MEASURE FOR USEFULNESS.** FIGURE 4 (BELOW): **THE MOST USEFUL MODEL IS THE LEAST ACCURATE ONE THAT SUPPORTS THE DECISION AT HAND**

LEFT: **SIMPLE CAD VIEW OF THE CAR'S ROLLCAGE, CORNERS AND CREW**

This slightly strange piece of algebra produces the result that is shown in the graph in Figure 4, above; *actually, the most useful model is the least accurate one that supports the decision at hand*.

What this analysis appears to suggest is that, 'I'd rather be simple-and-wrong than complicated-and-wrong' – seemingly obvious and yet often overlooked.

Once we abandon the search for a perfect stage simulation, we free ourselves of the burden of feeding such a monster. Where would the data for the surface come from? Would it be first or second pass? Can we account for the effect of different cars passing over the surface – the so-called 'road position' effect? All of these questions and more recede when we say our task is to identify hygiene factors, position them with a useful level of accuracy, identify primary factors, rank them, and then spend all our time improving the things that we know for certain move the needle.

Unsurprisingly, these turn out to be weight, horsepower, and grip.

Weight seems at first glance to be quite easy but on events with a clay-based soil and a level of moisture, the ability of mud to cling to the car has to be seen to be believed. Many, many tens of kilograms of mud can cling to every crevice, modifying overall weight, weight distribution, inertia, ride height, and suspension geometry.

Using experience we can estimate what these amounts will be and use a classical vehicle model to ensure that our car is not tuned to some knife edge of perfection but rather is unthreatening and friendly over a range of weight conditions – quite like a road car.

Horsepower can be measured on a dynamometer but of course it varies widely between Sweden, Mexico, and Africa. Nevertheless, we can generally know that more is more, and without a great deal of effort ensure we give ourselves something robust that won't self-destruct the moment the coolant temperature moves from 85°C to 86°C (185°F to 187°F). Controlled fuel substantially eases the task compared with road cars.

Grip is particularly interesting, because the rally environment presents enormous challenges to maintaining wheel contact.

The world can be thought of as a broadly immovable object that repeatedly imparts a distortion on the tire. The tire stores strain energy as a result of this distortion, being in general quite lightly damped. This energy is turned into kinetic energy upward in the unsprung mass, which in turn is converted to strain energy in the road spring. Given that the road spring is about 1/10th of the tire stiffness, a moment's reflection shows that any obstacle more than about one-third (1√10) of the suspension travel would fire the wheel up to full travel, were it not for the intervention of the suspension damper to dissipate energy.

Consideration of the energy exchange shows that the wheel and tire is incessantly prone to jumping clear of the road, a conclusion that can be tested by simply rolling a wheel and tire down a hill. As the speed comes up the wheel seems to 'sniff out' imperfections and begins to jump off the floor over apparently invisible obstacles.

It is easy to imagine that there is some optimum damping level that eases the problem of the wheel jumping clear of the road, and discovering the best level of damping turns out not to be so difficult. However, to focus on grip alone delivers poor performance under a number of other circumstances – jump landings, end-of-travel events, and so on. To get these aspects of the car right requires a number of other measures to be balanced against maintaining wheel contact – something usefully assessed and understood with a simple-and-wrong model but easy to drown trying with a complicated-and-wrong model.

The results of this luxuriously large study – the most comprehensive ever performed by Prodrive – were carried into the design process with eyes wide open about which effects were big, which were small, which were primary factors, and which were hygiene. Design decisions could be rapidly reviewed in the light of the pre-existing results of the sensitivity study rather than waiting for a detailed analysis to grind through.

'Do we care about the length of this bit?'

'No, it's on the floor and if it gets lighter it will only be replaced with ballast – but make sure it doesn't break.'

An apparently intractable, chaotic, complex design problem was reduced to a large number of simple questions, posed, queued, and solved using some good old-fashioned judgment, the math of Sir Isaac Newton, and modern engineering software. The models were relatively simple but were used thoughtfully and rapidly – smartly in both senses of the word.

Have we got it right? We'll know only once the MINI makes its WRC debut in Sardinia, on May 6!

WORKS MINIS ENJOYED NOTABLE RALLYING SUCCESS IN THE 1960s

Game theory

SEYED HOSSEIN TAMADDONI, **SAIED TAHERI** AND **MEHDI AHMADIAN** FROM THE MECHANICAL ENGINEERING DEPARTMENT AT VIRGINIA TECH HAVE BEEN RESEARCHING THE CONCEPT OF VEHICLE CONTROL DESIGN BASED ON GAME THEORY

> "Many driver models try to approximate the real driver's road tracking performance, assuming certain driver inputs and outputs"

Stability in a vehicle system is determined by the total performance of all dynamics subsystems. Among different subsystems, vehicle driver, and vehicle stability control systems share the most significant responsibility in providing stability in severe handling maneuvers. A rational driver tends to keep the vehicle stable throughout the maneuver; however, during unexpected or uncontrolled events, vehicle stability is jeopardized and the driver is unable to control the vehicle. It is in these scenarios that the vehicle stability control (VSC) system plays a crucial role in stabilizing the vehicle.

Vehicle active safety systems are designed to improve driving safety while the driver is still in control of the vehicle. The advancement of new VSC systems that can augment the driver input necessitates a better understanding of how the vehicle and driver can coexist in a manner that is complementary, not contradictory. The literature on interaction modeling of the vehicle driver and control system is classified in two categories.

In the first and the most popular category, the vehicle driver and the vehicle stability controller are two independent subsystems of the vehicle, in which the performance and strategy of each system does not significantly affect the performance and strategy of the other system. For example, most existing driver models ignore the fact that human drivers respond differently as the vehicle control system is changed, and most vehicle control literature has reported control designs that assume a predetermined steering input, thus ignoring the driver's transient response to the current event.

The second category includes research that considers vehicle stability as a collaboration between driver and the vehicle stability control system. Wenzel showed that considering a combination of a driver model and active front steering control may result in improved vehicle stability and performance. Regardless of the complexity, cooperative control of the driver's input and vehicle control system control actions results in a globally optimal solution to vehicle stability problems.

For vehicle directional control, the steering wheel is the primary means for control actuation. Many driver models try to approximate the real driver's road tracking performance, assuming certain driver inputs and outputs. If the controller is aware of the driver's intentions, the driver mathematical model can be traced back iteratively to determine its most important factors.

Accordingly, establishing a technique for detecting the driver's intentions or for recognizing driver model has been a challenging problem for vehicle system researchers. Kuge [2000] developed a driver behavior recognition method based on hidden Markov models to characterize and detect driving maneuvers and place it in the framework of a cognitive model of human behavior. In another piece of research by McCall and his colleagues [McCall, 2007], driver's behavior and the lane change intent is analyzed using robust sparse Bayesian learning methodology; it is shown that by incorporating a state-of-the-art Sparse Bayesian Learning classifier with well-motivated evaluation metrics, the likelihood of driver intent inference system algorithmic failure reduces.

In the research presented here, a novel optimal driver-controller interaction strategy is developed based on linear quadratic game theory. The model includes the driver's directional control through introducing steering wheel angle, and the vehicle direct yaw control (DYC) system through imposing a corrective yaw moment using differential braking of the four wheels. As a result, it is shown that globally optimal performance is obtained when the effects of driver's decision making on the controller and vice versa are taken into account, and the interactions are correctly modeled.

In continuous time interaction modeling of driver steering and vehicle direct yaw control as a dynamic game between driver and controller, the driver (player/agent 1) and the vehicle controller (player/agent 2) play cooperatively through their control actions, namely, the steering wheel angle δ_{sw} and the corrective yaw moment M_{zc}. To model such interactions, the linear bicycle model is extended to introduce the corrective yaw moment as

$$\dot{x}(t) = \mathbf{A}_c x(t) + \mathbf{B}_{c1} \underbrace{\delta_{sw}(t)}_{u_1} + \mathbf{B}_{c2} \underbrace{M_{zc}(t)}_{u_2} \qquad (1)$$

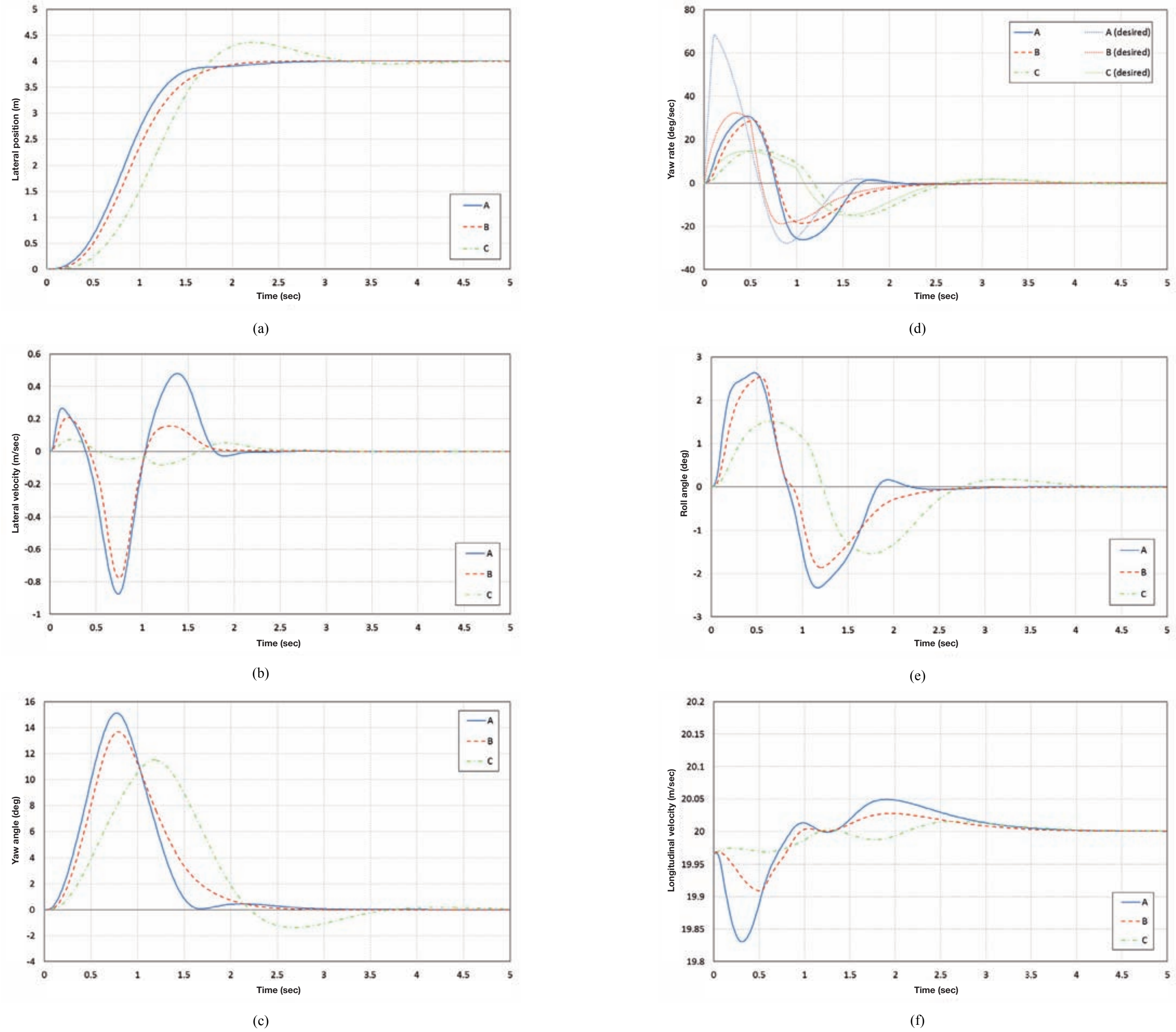
where $x_c(t)$ represents the time-continuous state, and

$$\mathbf{A}_c = \begin{bmatrix} 0 & 1 & V_x & 0 \\ 0 & -\dfrac{C_{\alpha F} + C_{\alpha B}}{MV_x} & 0 & -V_x - \dfrac{L_F C_{\alpha F} - L_B C_{\alpha B}}{MV_x} \\ 0 & 0 & 0 & 1 \\ 0 & \dfrac{L_F C_{\alpha F} - L_B C_{\alpha B}}{I_z V_x} & 0 & -\dfrac{L_F^2 C_{\alpha F} + L_R^2 C_{\alpha B}}{I_z V_x} \end{bmatrix}, \mathbf{B}_{c1} = \begin{bmatrix} 0 \\ \dfrac{C_{\alpha F}}{r_{st} M} \\ 0 \\ \dfrac{L_F C_{\alpha F}}{r_{st} I_z} \end{bmatrix}, \mathbf{B}_{c2} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dfrac{1}{I_z} \end{bmatrix}$$

The tire cornering stiffness for front and rear axles are given by $C_{\alpha F}$ and $C_{\alpha B}$, respectively, and steering gear ratio r_{st} is defined by the ratio between the steering wheel angle and the steering angle at the front wheels as $r_{st} = \delta_{sw} / \delta_{sF}$

The cooperative actions of the two players, namely human driver and vehicle stability controller, are assumed to have the tendency to minimize the corresponding sum of squares of attitude angle differences and to minimize the higher-order dynamics, typical terms that can be found analytically. Hence, it is assumed that the control priorities of the driver and the vehicle direct yaw controller are characterized in a form of quadratic cost functions given as

$$J_i(u_1, u_2) = \int_0^t \left(x^T \mathbf{Q}_i x + u_1^T \mathbf{R}_{i1} u_1 + u_2^T \mathbf{R}_{i2} u_2 \right) dt \qquad (2)$$



(a) (d) (b) (e) (c) (f)

FIGURE 1: **CONTINUOUS TIME INTERACTION MODEL; VEHICLE STATES: (A) LATERAL POSITION, (B) LATERAL VELOCITY, (C) YAW ANGLE, (D) YAW RATE, (E) ROLL ANGLE, (F) LONGITUDINAL VELOCITY**

where all weighting matrices are constant and symmetric with $Q_i \geq 0$, $R_{ij} = DT_{ij}D_{ij} \geq 0$ and $R_{ii} = D_i^T D_i > 0$, and $i = 1,2$ is the player number.

In Nash (1951), the Nash equilibrium concept was introduced; in Basar and Olsder (1995) and Starr (1969) it was defined as the pair (u_1*, u_2*) that corresponds to a Nash equilibrium if the following relations are satisfied for each admissible strategy (u_1, u_2):

$$\begin{cases} J_1(u_1, u_2^*) \geq J_1(u_1^*, u_2^*), \\ J_2(u_1^*, u_2) \geq J_2(u_1^*, u_2^*). \end{cases} \tag{3}$$

The Nash equilibrium is defined such that it has the property that there is no incentive for any unilateral deviation by any one of the players. In the other words, at Nash equilibrium with (u_1^*, u_2^*), the player who chooses to change his/her strategy cannot improve his/her payoff.

The problem of continuous time vehicle-driver interaction model is now reduced to finding the Nash equilibrium for the continuous-time model of (1). The following theorem was modified from Ho et al [1965] according to the game model (1):

Theorem 1

Consider the game system (1) with the cost functions defined in (2). Let the strategies $u_1^* = \delta_{sw}^*$, $u_2^* = \tau_{zc}^*$ be such that there exist solutions (P_1, P_2) to the differential equations

$$\frac{d}{dt}\mathbf{P}_i = -\frac{\partial}{\partial x}\mathbf{H}_i\left(x^*, u_1^*, u_2^*, \mathbf{P}_i\right) - \frac{\partial}{\partial u_i}\mathbf{H}_i\left(x^*, u_1^*, u_2^*, \mathbf{P}_i\right).\frac{\partial u_j^*}{\partial x}, \quad (i = 1,2) \tag{4}$$

where

$$\mathbf{H}_i\left(x, u_1, u_2, \mathbf{P}_i\right) = x^T\mathbf{Q}_i x + u_1^T\mathbf{R}_{i1}u_1 + u_2^T\mathbf{R}_{i2}u_2 + \mathbf{P}_i^T\left(\mathbf{A}_c x + \mathbf{B}_{c1}u_1 + \mathbf{B}_{c2}u_2\right) \tag{5}$$

such that for :

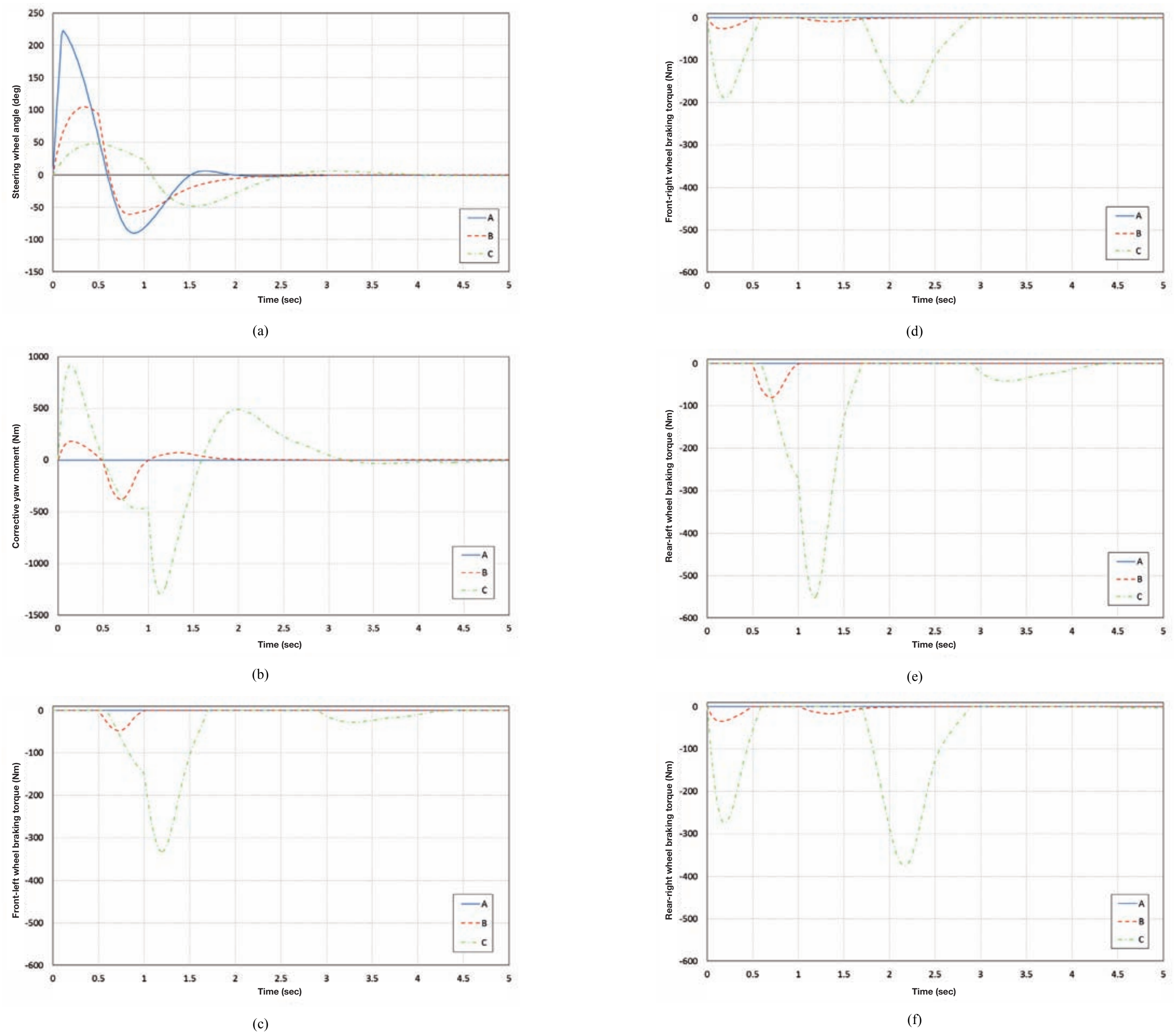


FIGURE 2 (ABOVE): **CONTINUOUS TIME INTERACTION MODEL; CONTROL INPUTS: (A) STEERING WHEEL ANGLE, (B) CORRECTIVE YAW MOMENT, (C)-(F) WHEEL BRAKING TORQUES CALCULATED USING THE DIFFERENTIAL BRAKING SYSTEM**

$$\frac{\partial}{\partial u_i}\mathbf{H}_i\left(x^*, u_1^*, u_2^*, \mathbf{P}_i\right) = 0 \qquad (6)$$

and x^* satisfies

$$\dot{x}^*(t) = \mathbf{A}_c x^*(t) + \mathbf{B}_{c1} u_1^* + \mathbf{B}_c \qquad (7)$$

then (u_1^*, u_2^*) is Nash equilibrium with respect to the memory-less perfect state information structure, and the following equalities hold:

$$u_i^* = -\mathbf{R}_{ii}^{-1}\mathbf{B}_{ci}^T\mathbf{P}_i(t) \qquad (8)$$

Since the driver steering control and the vehicle yaw controller are restricted to the class of linear time-invariant feedback strategies, the admissible strategies are defined as

$$\Gamma_i^{fd} = \left\{u_i \in \Gamma_i \,\middle|\, u_i(x;t) = \mathbf{G}_i x(t)\right\}, \qquad (9)$$

There exists a generically unique linear feedback Nash equilibrium [Ho, 1965; Basar, 1974] where the functions of Theorem 1 are given by $P_i(t) = K_i x(t)$.

Theorem 2

Suppose K_i satisfy the coupled Riccati equations given by

$$\mathbf{A}_c^T\mathbf{K}_i + \mathbf{K}_i\mathbf{A}_c + \mathbf{Q}_i - \mathbf{K}_i\mathbf{S}_i\mathbf{K}_i - \mathbf{K}_i\mathbf{S}_{\hat{i}}\mathbf{K}_{\hat{i}} - \mathbf{K}_{\hat{i}}\mathbf{S}_{\hat{i}}\mathbf{K}_i + \mathbf{K}_{\hat{i}}\mathbf{S}_{i\hat{i}}\mathbf{K}_{\hat{i}} = \mathbf{0}_n \qquad (10)$$

where $i = (1,2)$ and i^ is the counter-coalition, i.e. the player counter-acting to the player with index i, and

$$\mathbf{S}_i = \mathbf{B}_{ci}\mathbf{R}_{ii}^{-1}\mathbf{B}_{ci}^T \;,\; \mathbf{S}_{i\hat{i}} = \mathbf{B}_{c\hat{i}}\mathbf{R}_{\hat{i}\hat{i}}^{-1}\mathbf{R}_{i\hat{i}}\mathbf{R}_{\hat{i}\hat{i}}^{-1}\mathbf{B}_{c\hat{i}}^T \qquad (11)$$

then the following strategy

$$u_i^*(t) = -\mathbf{R}_{ii}^{-1}\mathbf{B}_{ci}^T\mathbf{K}_i x(t) \qquad (12)$$

is linear feedback Nash equilibrium for the game system (1) with the cost functions defined in (2).

The coupled Riccati equation (10) is hard to solve due to the presence of quadratic coupling terms between K_1 and K_2. To the best of our knowledge there are no explicit conditions guaranteeing the existence of solutions to equation (10). Implicit conditions and special cases are provided in Weeren et al (1999) and Jungers et al (2008). Only numerical algorithms without proof of convergence are available to solve these equations (Freiling et al, 1996; Jungers et al, 2008). If there exists a solution to the coupled Riccati equation (10), it can be best found by iterative search of the following modified equation (13) until it converges to a stationary state:

$$\frac{d}{dt}\mathbf{K}_i = -\mathbf{A}_c^T\mathbf{K}_i - \mathbf{K}_i\mathbf{A}_c - \mathbf{Q}_i + \mathbf{K}_i\mathbf{S}_i\mathbf{K}_i + \mathbf{K}_i\mathbf{S}_{\hat{i}}\mathbf{K}_{\hat{i}} + \mathbf{K}_{\hat{i}}\mathbf{S}_{\hat{i}}\mathbf{K}_i - \mathbf{K}_{\hat{i}}\mathbf{S}_{i\hat{i}}\mathbf{K}_{\hat{i}} \tag{13}$$

where i = (1,2) and i^ is the counter-coalition, i.e. the player counter-acting to the player with index i, and S_i, $S_{i\hat{i}}$ are defined the same as in equation (10).

Considering the cooperative control actions $u_1 = \delta_{sw}$ and $u_2 = M_{zc}$ representing the driver's steering control and the vehicle controller's corrective yaw moment, the globally optimal set of actions by game theory are defined as:

$$\delta_{sw}^* = -\mathbf{R}_{11}^{-1}\mathbf{B}_{c1}^T\mathbf{K}_1\left(x - x_{des}\right) = \mathbf{G}_1\left(x - x_{des}\right) \tag{14}$$

$$\tau_{zc}^* = -\mathbf{R}_{22}^{-1}\mathbf{B}_{c2}^T\mathbf{K}_2\left(x - x_{des}\right) = \mathbf{G}_2\left(x - x_{des}\right) \tag{15}$$

where K_1, K_2 are the solutions of the coupled Riccati equation (10).

Computer simulations are then carried out to verify the effectiveness of the proposed continuous time interaction model. The presented driver and controller models are therefore evaluated using the nonlinear model that was developed as part of this research, with the objective to stably steer the vehicle through a single lane change of four meters. The following defines the desired states in non-dimensional form for the evaluation maneuver:

$$x_{des} = \begin{pmatrix} 5 & 0 & 0 & \dot{\theta}_{z,des} \end{pmatrix}^T, \tag{16}$$

The desired value of yaw rate in order to provide handling comfort is obtained from

$$\dot{\theta}_{z,des} = \frac{V_x}{r_{st}\left(L_F + L_B\right)\left(1 + K_{us}V_x^2\right)}\delta_{sw} \tag{17}$$

where k_{us} is understeer coefficient.

To better assess the performance of the proposed driver-controller interaction framework based on game theory, an independent model of vehicle driver and direct yaw control (DYC) system are also simulated in the same scenario. These independent models are assumed in the form of linear feedback controllers and their corresponding feedback gains are obtained by the linear quadratic regulation (LQR) strategy. In both cases, i.e. game theory (GT) and linear quadratic regulation (LQR), the control priorities for the driver and the controller are defined based on the following gains:

$$Driver: \ \mathbf{Q}_1 = \begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 0.01 & 0 & 0 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.01 \end{bmatrix}, \ \mathbf{R}_{11} = 1, \ \mathbf{R}_{12} = 0 \tag{18}$$

$$DYC: \ \mathbf{Q}_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \ \mathbf{R}_{21} = 10, \ \mathbf{R}_{22} = 10^{-7} \tag{19}$$

Using the same Q and R matrices, the final state feedback gains for both strategies are calculated from Theorem 4.2 and listed as follows;

• Game Theory:

$$\begin{cases} \mathbf{G}_{1(GT)} = \begin{bmatrix} -0.809 & -0.146 & -8.624 & -0.713 \end{bmatrix} \\ \mathbf{G}_{2(GT)} = \begin{bmatrix} 0 & 504.08 & 0 & -10696 \end{bmatrix} \end{cases} \tag{20}$$

• LQR:

$$\begin{cases} \mathbf{G}_{1(LQR)} = \begin{bmatrix} -1.0 & -0.215 & -13.63 & -1.286 \end{bmatrix} \\ \mathbf{G}_{2(LQR)} = \begin{bmatrix} 0 & 129.93 & 0 & -599 \end{bmatrix} \end{cases} \tag{21}$$

where G_1, G_2 are the driver and the vehicle controller feedback gains, respectively.

The simulation is done using the built-in vehicle mathematics model in Vehicle System Simulator for three different scenarios:

• Scenario A: the driver is supposed to act as an ideal linear quadratic regulator with the feedback gain $G_{1(LQR)}$ defined in (20), and the vehicle controller is turned off

• Scenario B: the driver and the vehicle controller are both supposed to act as ideal linear quadratic regulators with the feedback gain $G_{1(LQR)}$ and $G_{2(LQR)}$, respectively

• Scenario C: the driver and the vehicle controller are both supposed to act as ideal feedback controller with the feedback gain $G_{1(GT)}$ and $G_{1(GT)}$ obtained from the game theory-based framework as defined in (13) and (14), respectively

Figures 1 and 2 show the simulation results. Figure 1(a) shows that the vehicle successfully performs a single lane-change maneuver of 4m in all three cases; however, the vehicle in case C, i.e. the game theory framework, exhibits slower response with an overshoot of about 10%. Case A has the fastest response, which implies that the vehicle DYC system slows down the vehicle response and, in the other words, increases the settling time.

In spite of slower response, Figures 1(b and e) show that the lateral and roll motions of the vehicle are more stable in case C with the game theory-based driver and controller models compared with case A and B, and they are more stable in case B compared with case A. This implies the performance of the vehicle stability control in limiting the lateral velocity and roll angle to prevent the undesired rollover. Figure 1(c) shows the yaw angle throughout the lane change. Again, it reflects the slower response time and the overshoot characteristics in case C.

Figure 1(d) indicates that the vehicle controller in cases B and C tends to provide the desired handling performance; however, the game theory framework keeps the vehicle yaw rate closer to its corresponding value of the desired yaw rate compared with the independently controlled models in case B. Figure 1(f) shows that in all cases the vehicle speed was almost kept at 20m/sec to ensure the validity of the system linearization.

Figure 2 shows the driver's steering wheel angle and the corrective yaw moment required to maneuver the vehicle in a single lane change. It is concluded that as the vehicle controller is more engaged, the steering effort is more smoothed and the driver seems to be more relaxed, i.e. the peak value of the steering angle reduces. Figure 2(c-f) shows the wheel braking torques that are calculated using the differential braking system developed but not discussed here.

To include the preview-time characteristics of human drivers a discrete version of this controller was also developed where the driver and controller interact in a form of discrete difference game. A sensitivity analysis was also conducted and a robust controller was also developed. These could be the subjects of future technical notes.

Torque on corners

FORD HAS INTRODUCED AN ESC-BASED 'TORQUE VECTORING' SYSTEM WITH ITS NEW C-CAR PLATFORM. GLOBAL ADVANCED VEHICLE DYNAMICS RESEARCH ENGINEERS **DEREK WARD**, **JENS DORNHEGE** AND **LUCIAN LIPPOK** EXPLAIN HOW IT WORKS

Traction control has long been offered in motor vehicles to combat wheelspin, particularly in slippery conditions, but the system does have one slight drawback. Traditional systems primarily limit wheel slip by reducing engine power, which is effective but can feel frustrating, particularly for a keen driver who is 'pressing on'.

To overcome this, Ford has developed torque vectoring control, which uses advanced brake technology to dial out wheelspin without strangling the engine. It's completely automatic, virtually impossible to detect, and has been tested in some of the most extreme locations on the planet.

Torque vectoring is the term used to describe a system that adjusts the drive torque side-to-side on an axle to influence the turning behavior of a vehicle. It was developed as a performance feature to increase the corner exit speed by allowing higher corner apex speeds together with reduced vehicle understeer during the corner exit acceleration phase. The first vehicles on the market with torque vectoring systems used mechanical torque vectoring differentials to carry out the drive torque distribution.

Vehicle weight is a very sensitive theme in the current fuel-economy-conscious climate and any increase in vehicle weight is frowned upon. The

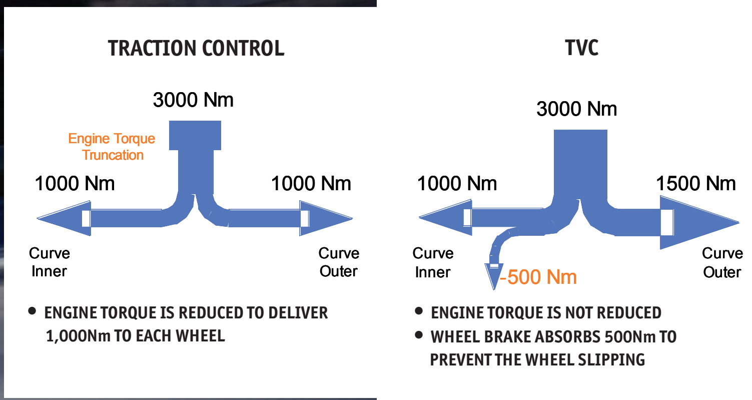


FIGURE 1: **EXAMPLE CASE – IN A LEFT-HAND TURN THE GEARBOX DELIVERS 3,000Nm OF DRIVING TORQUE AND THE INSIDE WHEEL CAN TRANSFER 1,000Nm**

"Ford's system relies on special software in the electronic brake system to control the torque distribution via careful application of single-wheel brake forces"

TVC vs TV differential

TV differential

(source: ATZ 12/2007)

- Possibly better acceleration in first gear because some of the engine torque is not being consumed by a braking torque – the energy loss in the clutches is lower than in the brakes
- Possibly more environmentally friendly during operation because it is not burning fuel to create 'side force' to enable more acceleration, but comes with a weight penalty (approx. 20kg)
- Increased transmission weight increases front-driven vehicles understeer tendency
- Increased fuel consumption (CO_2) when 'passive'
- Expensive hardware
- Limited modulation range

TVC

- Cost-efficient solution – software only
- No vehicle weight increase due to system
- The vectoring torque can be modulated over a large range
- Simple integration/harmonization with an existing ESC system
- No fuel consumption increase when not in use
- Slightly reduces engine power available for acceleration when active, but increases the ability to get available power on the road

mechanical torque vectoring systems are typically heavy and expensive. Because of this, Ford has developed Torque Vectoring Control (TVC), a system that relies on special software in the electronic brake system to control the torque distribution via careful application of single-wheel brake forces. It is not, however, a substitute for the normal ESC emergency understeer engine and brake intervention during the corner entry phase.

Torque vectoring is currently a very popular theme, especially in high-performance vehicles. Some vehicle manufacturers have mechanical torque vectoring systems in series production. These systems typically use a pair of clutches and planetary gearsets to increase the speed (and torque) of the outside driven wheel and decrease the speed (and torque) of an inside driven wheel. TVC is a concept that creates the same effect through use of the electronic braking system only. The *TVC vs TV differential* box (above) compares the two concepts.

The primary use case for TVC is acceleration in a turn. During this maneuver, there is a lateral load transfer to the curve outside wheels and the curve inside wheels are unloaded. This causes the curve inside drive wheels to slip more readily, limiting the drive torque that can be applied to the road surface. Traditional traction control typically reduces engine power to prevent wheel slip. This limits power to both wheels because a standard open differential works as a torque balance and divides the input torque evenly between both drive wheels. However, the more highly loaded curve outside wheel still has capacity to transmit additional drive torque.

If TVC detects that a wheel is about to spin, the system brakes that wheel back down to the optimum speed. It is a very gentle brake intervention. You don't need a lot of brake torque to do it and it will kick in only when the driver is driving in a sporty manner so it is not going to have a noticeable effect on brake wear or fuel consumption.

Traditional traction control and TVC are compared in Figure 1.

In this example, 25% more drive torque can be transferred to the drive wheels with TVC than without and the extra torque is all on the curve outside wheel, which improves turn-in. A torque vectoring effect has been created across the axle, providing more drive torque to the curve outer wheel. This creates an additional turn-in moment that turns the vehicle in to the corner.

Contrary to ESC understeer interventions, TVC does not slow down the vehicle. TVC prevents excessive wheelspin during high-throttle or wide-open-throttle maneuvers, before ESC thresholds are reached. It controls the speed of the curve inside wheel so that it doesn't slip, but doesn't brake the wheel hard enough to create negative drive forces at the tire contact patch.

ADVANTAGES OF TVC

Primary customer benefits:

- Improved cornering agility – improved turn-in and self-steer behavior
- Driver assistance in mid- to close-to-limit handling maneuvers
- Later ESC intervention (an active yaw increase is provided before the ESC activation limit is reached) leading to improved comfort
- Low cost – only software required (no additional hardware)
- Less wheelspin

Some other, beneficial, side effects are created by the system:

- Strongly reduced power-on understeer (especially in FWD vehicles)
- Increased power-off stability 'at the limit' (reduced slip angle overshoot)
- Lower roll angle change in power-on/power-off transitions due to consistent cornering behavior

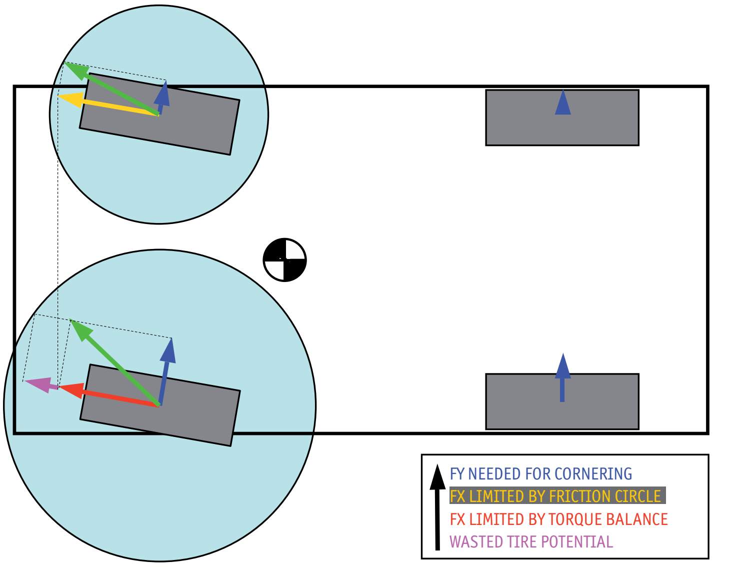
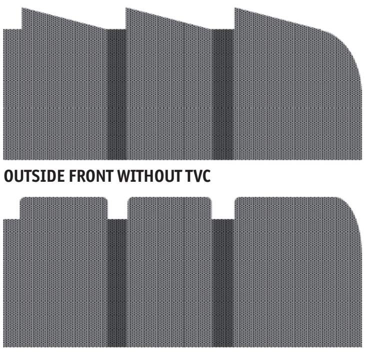


FIGURE 2 (FAR RIGHT): **TIRE FORCE POTENTIAL IN A TURN AS DEFINED BY KAMM'S FRICTION CIRCLE**



OUTSIDE FRONT WITH TVC

FIGURE 3 (RIGHT): **TIRE WEAR PATTERN WITH AND WITHOUT TORQUE VECTORING CONTROL**

During power-on, TVC increases traction and agility over uncontrolled vehicles or engine torque truncation.

Figure 2 shows that, assuming the same side forces in the tires with TVC on and TVC off, the tire friction can be better utilized for longitudinal acceleration with the system on. With the system off, the capacity of the curve outside tire is under-utilized.

The system provides several primary customer benefits, as shown above in *Advantages of TVC*.

Measurements during constant radius and limit handling maneuvers showed relatively low increases in brake temperature as a direct result of the torque vectoring activity. The majority of the temperature increase during enthusiastic driving could be attributed to normal driver braking; TVC has only a minimal effect.

It has also been observed that, although you can drive faster with TVC, it causes less wear to the tire edge and sidewall than a similar driving style without the feature. The tire wear differences observed are indicated in Figure 3.

This occurs because deep understeer is avoided. The tire slip angle is less than on a vehicle without TVC and as there is less lateral slip across the tire. Thus the wear pattern changes.

Although the slip-control-based TVC concept works very well for FWD vehicles, it has some limitations in AWD vehicles due to its dependence on a wheel slip calculation. In FWD vehicles, the speeds of the undriven rear wheels are used as a reference for calculating wheel slip. In AWD vehicles, all four wheels are driven and as such the rear wheel speeds cannot always be relied upon to be running slip-free for a reliable slip calculation. Addition of a yaw-based control algorithm can improve system performance in these situations. TVC is very effective in FWD vehicles, but addition of a yaw controller could improve performance even further.

Development is ongoing and enhancements to the system currently available in the Fiesta, C-MAX, and new Focus can be expected in the near future.

Driver steering control behavior

AT THE UNIVERSITY OF CAMBRIDGE'S DEPARTMENT OF ENGINEERING, **DAVID COLE, ANDREW ODHAMS, AND STEVEN KEEN** HAVE CONDUCTED RESEARCH TO IDENTIFY DRIVER STEERING CONTROL BEHAVIOR

"The aim is to measure, understand, and model human driving behavior and thereby enable improvements in the vehicle and its development process"

The Driver-Vehicle Dynamics (DVD) group at Cambridge University Engineering Department is using knowledge of vehicle dynamics, control theory, neuroscience, and machine learning to improve understanding of driver-vehicle dynamic interaction. The aim is to measure, understand, and model human driving behavior and thereby enable improvements in the vehicle and its development process.

Figure 1 shows the structure of the driver model being developed by the DVD group. This is a highly simplified representation of the model but serves to illustrate the main features. The vehicle is in the top right corner; the remaining blocks are the driver. The driver steers the vehicle by actuating the neuromuscular system (NMS) of the arms, which are mechanically coupled to the vehicle at the handwheel. A similar coupling exists between the NMS of the legs and the pedals, but this is omitted for clarity.

The NMS is actuated by neural control signals from the brain. The brain receives information on the motion of the vehicle and on the road ahead from the sensory system, including the eyes and the motion-sensing vestibular organs. The brain also stores an "internal" model of the vehicle and NMS, which is learnt over time by comparing the predictions of the internal model with the sensed responses. The brain uses the sensed responses and the internal model to generate the neural control signals necessary to turn the handwheel and steer the vehicle along the road path.

This article gives an overview of work undertaken by the authors to identify the driver's steering control strategy: how is the handwheel angle related to the road path ahead and to the vehicle responses? To answer this question some aspects of the driver model were simplified by making the following assumptions: (i) the driver has a perfect sensory system and thus has accurate and complete knowledge of the vehicle motion and of the road path ahead; (ii) the NMS is represented by a simple low-pass filter without steering torque feedback; and (iii) the internal model is fixed so that there is no learning. Technical details of the identification work are given in the publications listed at www.vehicledynamics.org.

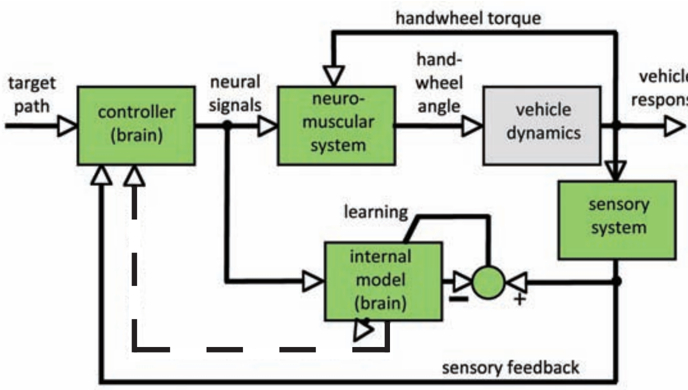


FIGURE 1: **SCHEMATIC OF DRIVER MODEL**

The hypothesis is that model predictive control theory (MPC) is a suitable basis for representing a driver's steering control strategy. MPC applied to steering control involves specifying: (i) a target path for the vehicle; (ii) a model, possibly nonlinear, of how the vehicle and NMS behave; and (iii) the objective of the control, in the form of a mathematical cost function. MPC theory also allows constraints to be imposed on responses and control actions. This feature was not exploited in the work described here, but is being used in related work.

Figure 2 shows the principle of MPC applied to steering control. At a moment in time the driver looks at the road ahead (up to a defined horizon) and specifies the target path of the vehicle. In the present work the target path is assumed to be the centerline of the road. The driver's internal model of the vehicle and NMS is then used to determine the sequence of handwheel angles necessary to follow the target path. The internal model and resulting handwheel angle account for any nonlinear tire behavior encountered as the friction limit is approached.

In determining the control action there is a trade-off between path-following error (lateral and angular deviation from the target path) and handwheel activity (angular displacement or velocity). So path error can be reduced by increasing handwheel activity, but the driver may decide to trade larger error for reduced activity. A cost function allows this trade-off to be specified by setting weighting values for path error and handwheel activity. The weighting values provide a way of representing different driving styles.

As the vehicle moves forwards, so does the horizon. The horizon

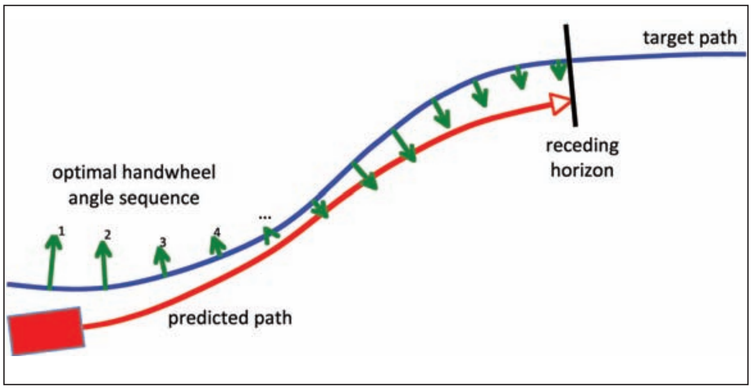


FIGURE 2 (LEFT): **MODEL PREDICTIVE STEERING CONTROL**

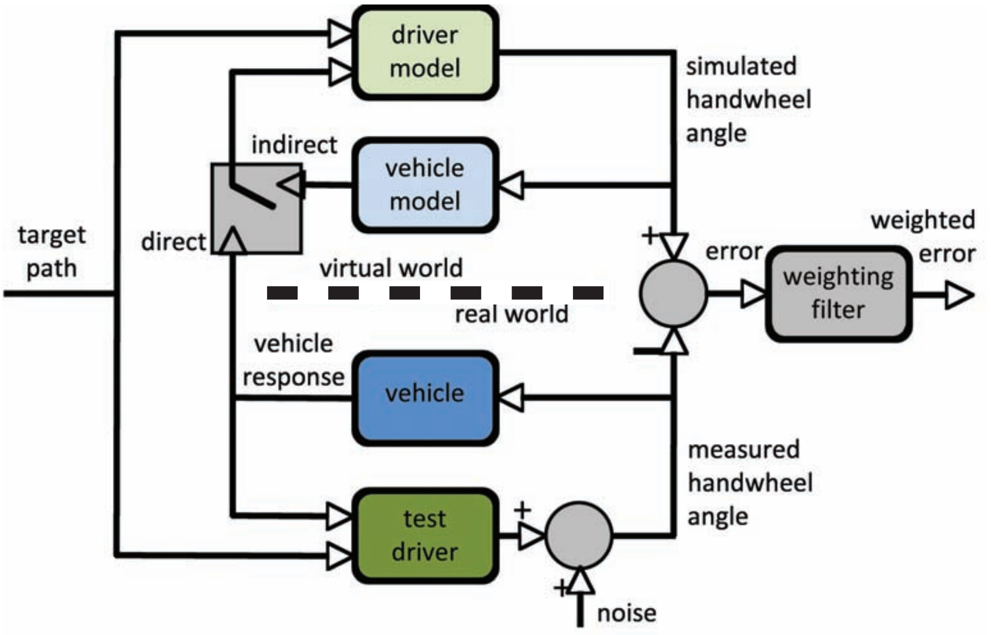
is therefore known as a receding horizon, and allows the driver to receive new information on the road path ahead and to update his steering control action. In the computer simulation this update is performed 20 times a second.

Note that the MPC approach differs from some other driver models currently in use that measure the target path at one fixed distance ahead of the vehicle. In MPC the driver is assumed to have available information on the target path from the current position of the vehicle right up to the horizon, which might typically be five seconds ahead of the vehicle. If the horizon is set conservatively far ahead, the choice of horizon does not affect the optimal handwheel angle sequence.

The MPC strategy presented here assumes that the road centerline is the target path. In some driving situations, such as race driving, this will not be the case. In a related research project, MPC with constraints has been used in a computationally efficient way to find simultaneously the optimum path and corresponding control action.

Having proposed a model of the driver's steering control strategy, the next problem is to identify the parameters of the model from measured steering behavior. Figure 3 shows the identification procedure. The bottom half of the diagram shows the real-world driver-vehicle system. The driver is human and the vehicle is either an instrumented test vehicle or a driving simulator. The target path is either a line painted on the test track or a virtual representation of the line displayed by the driving simulator.

The aim of the identification procedure is to find values for the parameters of the driver model (principally the cost function weighting values) that result in minimum difference between the simulated and measured handwheel angles. A trial and error approach involving manual adjustment of the cost function weights is possible, but this becomes increasingly unsatisfactory as the number of parameters in the model and the amount of test data increase. A better approach is to perform an automatic search of the parameter values to minimize the mean square



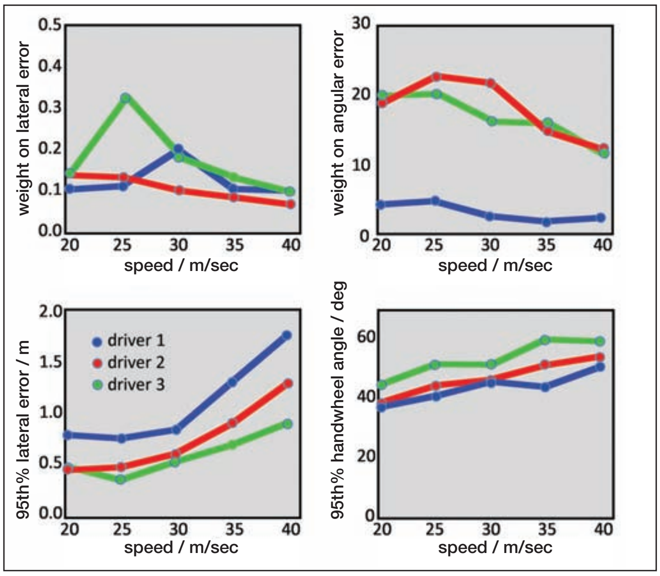


FIGURE 3 (TOP): **IDENTIFICATION PROCEDURE**

FIGURE 4 (ABOVE): **IDENTIFIED COST FUNCTION WEIGHTS AND MEASURED 95TH PERCENTILE LATERAL ERROR AND HANDWHEEL ANGLE FOR THREE DRIVERS FOLLOWING A RANDOMLY CURVED PATH**

difference between the simulated and measured handwheel angles.

A significant difficulty arises due to the closed-loop nature of the driver-vehicle system. The presence of noise in the real world, particularly from the human driver, can result in the identified values being biased from the true values. The bias can be minimized by simultaneously identifying a model of the noise. The noise model can then be used to frequency-weight the prediction error before calculating the mean square error.

An important choice to be made is whether to perform a direct or an indirect identification. For direct identification the prediction of the driver model is calculated using the known target path and the measured vehicle responses. This method works well if accurate and complete measurements of the vehicle responses are available, but often this is difficult to achieve on a test vehicle. However, direct identification is particularly suitable for a driving simulator experiment where the vehicle responses are available directly from the simulator's vehicle model.

When accurate measurements from the vehicle are not available, the indirect method may be a better choice. A validated model of the test vehicle is used to predict the measured vehicle responses. These predictions are then used as the inputs to the driver model. The switch in Figure 3 denotes the difference between the direct and indirect methods.

A fixed-based driving simulator was used to measure the steering control behavior of five test subjects with a range of driving experience, from an unlicensed novice to an experienced driver of cars and trucks. The steering task involved following a randomly curving path at a constant speed between 20m/sec and 40m/sec. Each test subject drove a total distance of 120km. The vehicle in the simulator had lateral and yaw degrees of freedom and linear tires.

The measured data from the simulator was used to identify a steering control model based on MPC. An NMS low-pass filter and a cognitive time delay were included, and the driver's internal model was assumed to be identical to the vehicle in the simulator. A direct identification method was used. A noise model was identified simultaneously with the steering control model in order to minimise bias. The parameters identified included the cost function weights (lateral path error and angular path error) and the time delay.

The time delay was identified to be in the range 200ms to 300ms for all drivers, the longer delay belonging to the novice driver. The cost function weights were found to vary with vehicle speed and with driver. Figure 4 shows the weights identified for three of the drivers. There is a trend for the weights to reduce with speed, suggesting that these drivers permit greater path error as the vehicle speed increases in order to limit the increase in handwheel activity.

The plots of 95th percentile lateral path error and handwheel angle shown in the bottom part of Figure 4 are consistent with this strategy. Driver 1 (blue line) stands out by having a much lower weighting on angular path error than the other two drivers. Driver 1 was a novice, and further analysis pointed to this driver's internal model being simpler than that employed by the other, experienced, drivers.

The driving simulator study confirmed that the MPC steering control model was able to satisfactorily represent the measured behavior of drivers steering a linear vehicle, and to distinguish between the steering behavior of different drivers and different speeds.

An instrumented vehicle running on a test track was used to collect further data for validating the MPC steering control model. Fourteen test subjects ranging from novices to professional vehicle development drivers repeatedly performed an ISO 3888-1 double lane change (DLC) maneuver. The speed was 18m/sec and the maximum lateral acceleration was 4m/sec^2, so the tires were within their linear regime. All drivers performed the maneuver well, but significant inter- and intra-driver variation in steering action was observed.

An indirect identification method was used to identify the steering control model. Identified parameters included the cost function weights and the time delay. A noise model was also identified for each driver. Figure 5 shows measured and simulated handwheel angle time histories for drivers numbered 3 and 5. The steering control strategy is clearly different for each driver, yet by suitable setting of the cost function weights the model was able to simulate these different strategies. Comparing the cost function weights identified for the two drivers, driver 5 placed more emphasis on minimizing angular path error than driver 3, which is consistent with the differences in handwheel activity observed in Figure 5.

These results gave further evidence of the suitability of the MPC steering control model for representing human steering control behavior in the linear operating regime of the vehicle,

Having established the validity of the driver model in the linear operating regime of the vehicle, instrumented vehicle tests were performed for a severe maneuver, an ISO 3888-2 elk test at 18m/sec, which resulted in lateral accelerations up to 10m/sec^2. In contrast to the DLC maneuver, about half the drivers found the test difficult to perform, the elk test being outside their previous experience. However, the performance of the drivers who initially performed poorly improved with successive maneuvers, indicating a learning process. Four of the drivers demonstrated very good performance from the start and negligible subsequent improvement.

The change in handwheel angle required for a given change in lateral tire force tends to increase as the tire approaches the friction limit. The MPC steering controller accounts for this nonlinear effect. However, if the cost function weights are fixed, the bandwidth of the MPC steering control tends to decrease as the tires approach the friction limit. A parameter to vary the cost function weights in order to maintain the control bandwidth was introduced to the MPC steering controller. In addition, it was postulated that novice drivers might not have complete knowledge of the nonlinear tire behavior, and base their steering control on the linear behavior of the tire at small lateral acceleration. To account for this, another parameter was introduced to the MPC steering controller that limited the extent of the nonlinearity in the internal model. With these two additions to the controller the parameters of the model were identified from the measured data using an indirect identification method.

The model had some success in simulating the measured steering performance. Figure 6 shows measured and simulated handwheel angles for two of the four expert drivers. All drivers were found to modify their cost function weights to deal with the change in control bandwidth as the friction limit was approached. However, the identified values of the parameter representing the extent of the nonlinearity in the internal model did not vary in the expected way. Of the expert drivers, some were identified as knowing the full range of tire nonlinear behavior, while others used a more limited range. The measured steering action of the non-expert group of drivers (not shown) was thought to be affected by learning action, which was not a feature included in the MPC steering controller.

These MPC steering control model and validation studies are believed to have significantly progressed the field of driver-vehicle simulation. In the linear operating regime the model is able to represent the range of steering control behavior observed in measurements. Steering control behavior of expert drivers in an extreme maneuver is also predicted well. Further improvements are being sought by investigating learning mechanisms and internal model representations. A feature of the DVD group's approach is the experimental validation of driver models that are based on neuroscience principles and appropriate control theory. Such an approach is thought essential to deliver driver models that can be used with confidence in the vehicle development process. An up-to-date list of publications can be found at www.vehicledynamics.org.

Acknowledgement

The authors are pleased to acknowledge the support of EPSRC (studentship for Odhams) and TRW Automotive (studentship and test facilities for Keen).

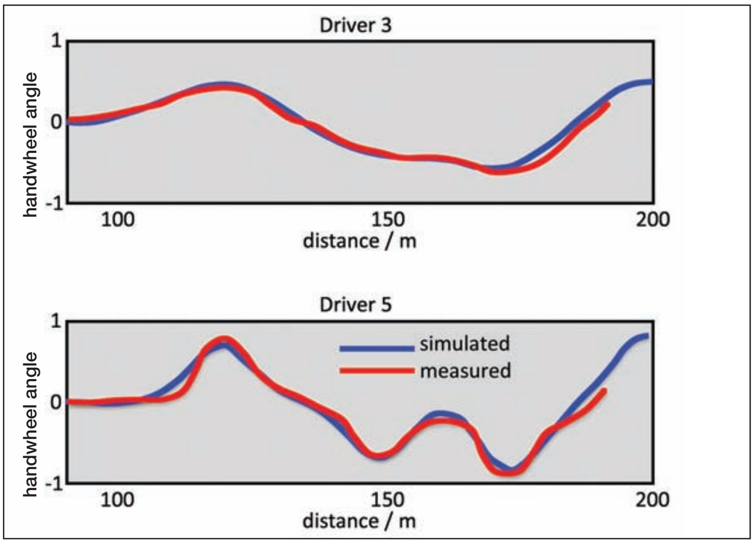


FIGURE 5 (LEFT): **SIMULATED AND AVERAGE MEASURED HANDWHEEL ANGLES FOR TWO DRIVERS PERFORMING A DOUBLE LANE CHANGE**

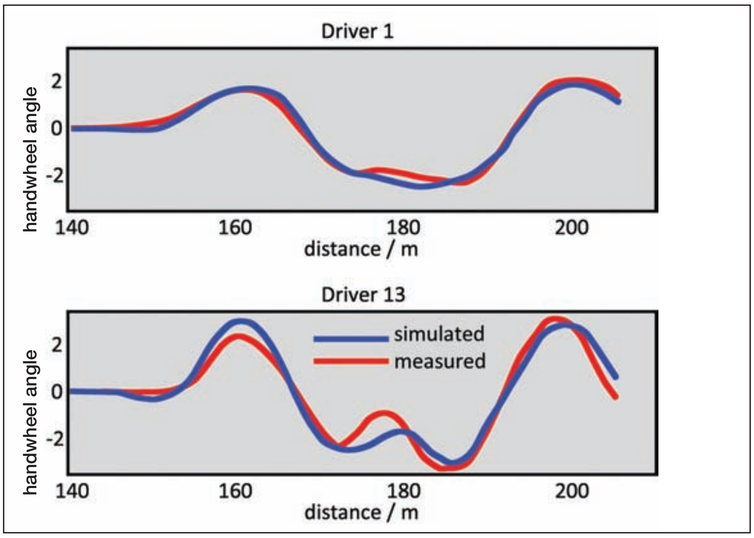
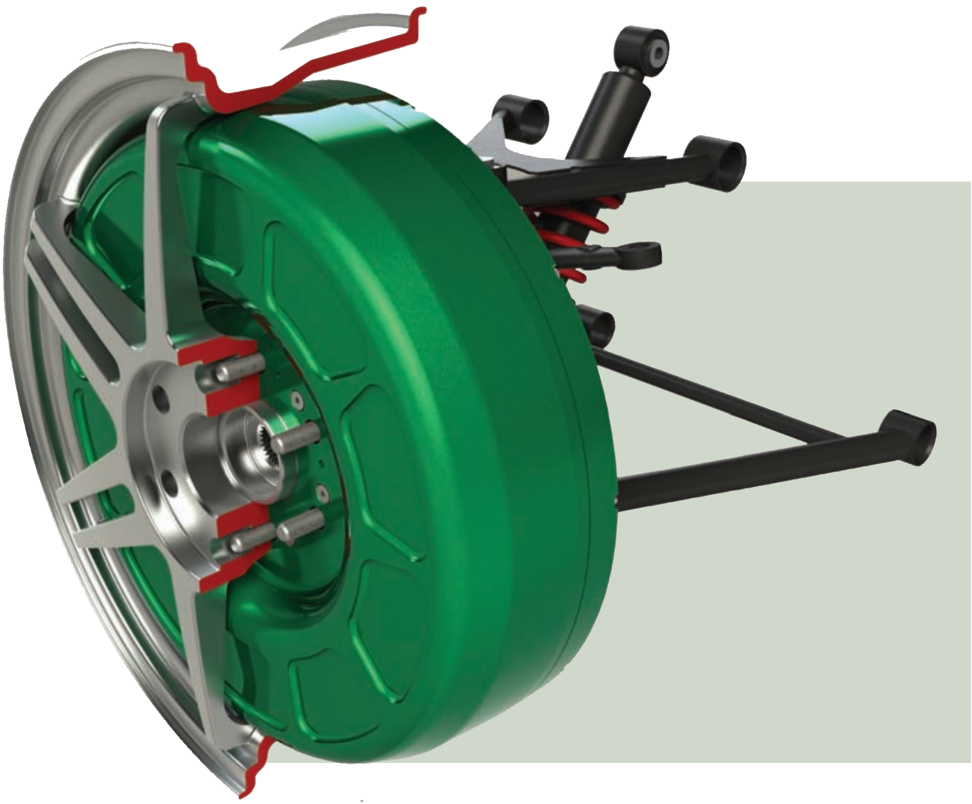


FIGURE 6 (BELOW LEFT): **SIMULATED AND AVERAGE MEASURED HANDWHEEL ANGLES FOR TWO DRIVERS PERFORMING AN ELK TEST**

Hub motor dynamics

INTEREST IN EVs AND HEVs HAS LED TO CONSIDERABLE DISCUSSION ABOUT THE RELATIVE MERITS OF CHASSIS- OR HUB-MOUNTED MOTORS. **STEVE WILLIAMS** AT LOTUS ENGINEERING INVESTIGATES THE DYNAMIC IMPLICATIONS



MAIN IMAGE: **RENDER OF A PROTEAN ELECTRIC IN-WHEEL DRIVE MOTOR**

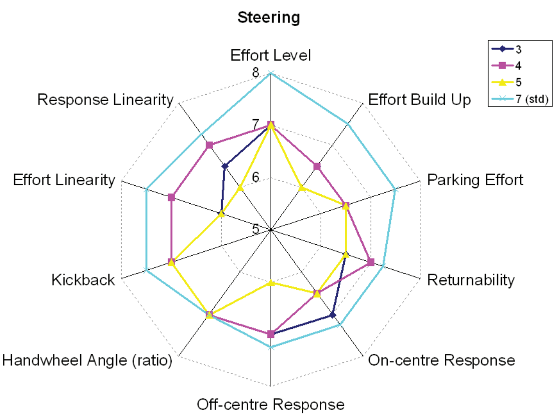
Much of the debate about electric vehicles (EVs) and hybrid electric vehicles (HEVs) has focused on the issues of vehicle package, cost, and driveline efficiency. However, the effect on vehicle dynamics has also emerged as a key factor, with apparently conflicting attributes making the potential advantages of one powertrain configuration over another difficult to define.

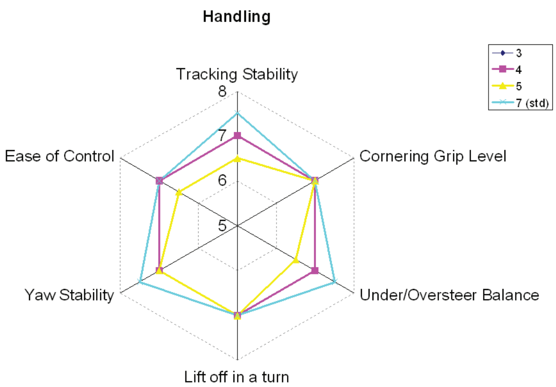
On the face of it, hub motors appear to offer real benefits over chassis-mounted motors. However, the transfer of the vehicle's powertrain from the chassis to the hubs represents a significant shift in the ratio of sprung to unsprung mass, and as every vehicle dynamics engineer knows, high unsprung mass is not desirable.

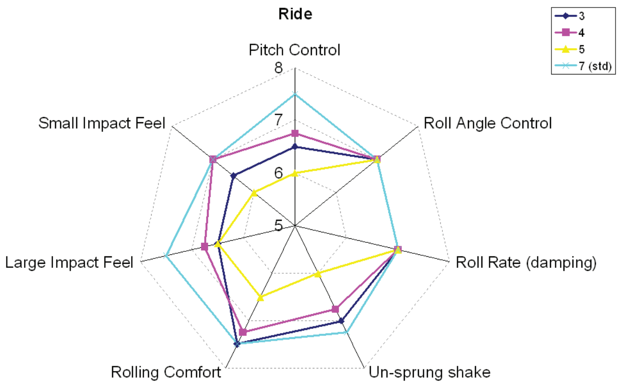
In the hub motor's favor, we have the advantage of independent control of drive torque to two or even all four wheels, without the cost, complexity, and packaging implications of controlled differentials and driveshafts. This makes hub motors the obvious choice for torque vectoring control of the vehicle's response and stability, as well as four-wheel-drive traction. In addition, an EV's body package is freed from all requirements to accommodate the vehicle's powertrain, and a hybrid may retain the conventional IC powertrain package, with EVs and HEVs both needing extra space for batteries only.

With such a powerful argument for the use of hub motors, Lotus decided to conduct a unique study to evaluate the real-world impact of the increase to unsprung mass.

Working with Protean Electric, Lotus took a mid-segment sedan with class-leading vehicle dynamics and replicated the unsprung mass and inertia characteristics of a range of Protean's hub motor designs by adding ballast to the wheels and knuckles. Lotus then commenced a







Assessment Number	Front Hub	Front Wheel	Rear Hub	Rear Wheel
3	23kg	7.5kg	23kg	7.5kg
4	15kg	5kg	15kg	5kg
5	10kg	5kg	10kg	5kg
7	Std	Std	Std	Std

LEFT AND OPPOSITE PAGE, BOTTOM: **SUBJECTIVE VEHICLE EVALUATION RATINGS FOR STANDARD AND INCREASED HUB MASS CONDITIONS**

vigorous program of benchmarking the vehicle dynamic performance of the 'massed up' vehicle.

Lotus ride and handling engineers recorded subjective evaluations of the vehicle's steering, handling, stability, ride comfort, and NVH, before collecting objective measurements of the same vehicle attributes. Finally, Lotus generated a comprehensive vehicle dynamics CAE model using its RAVEN software, and shadowed the physical benchmarking with a parallel virtual study.

A total of seven conditions were investigated, representing different levels of mass increase. Initial subjective assessments identified four that were considered to offer sufficient separation in perceived performance to merit objective measurement. The vehicle was subjectively assessed for steering, handling and ride comfort, with detailed Vehicle Evaluation Rating scores given to different aspects of each category.

The standard vehicle was characterized by its overall very good steering attributes, which lead the market sector, and its good overall handling capabilities, which were considered to be responsive and well pitched within its target market. Ride comfort, while firm, was felt to be well controlled.

The increased unsprung mass brought about a small reduction in agility and a reasonable increase in overall steering efforts. Ride comfort with the highest unsprung mass was actually found to be as good as the standard vehicle for rolling comfort, but, as expected, unsprung mass shake was more apparent, which reduced the subjective rating for impact feel even though initial impacts were softer.

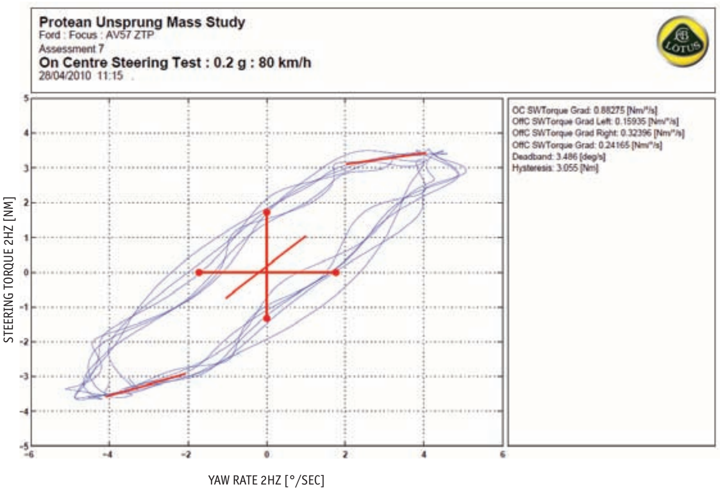
Contrary to expectations, the vehicle behavior was found to exhibit the greatest degradation not when the unsprung mass was at its greatest, but at the intermediate conditions. Subsequent objective measurements would reveal the reason for this apparent anomaly.

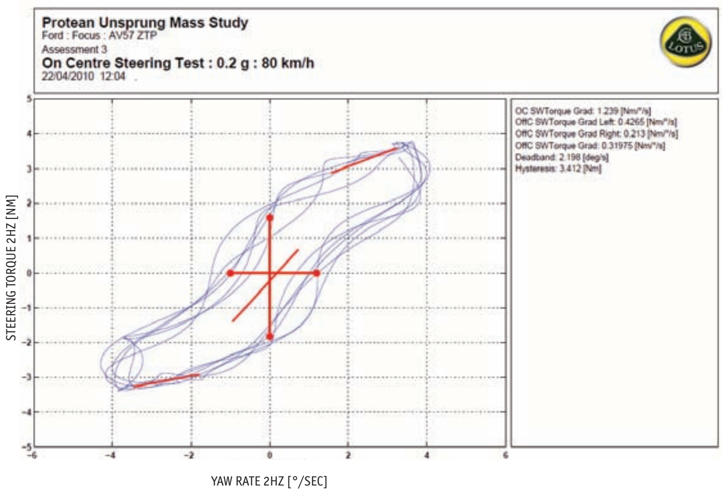
Following on from the findings of the subjective assessment, objective steering and handling measurements were conducted using an 'on-center' steering maneuver. This test highlights the dynamic response of the vehicle to a continuous sinusoidal steering input, the test being run at different steering input magnitudes in order to highlight non-linearities in the vehicle behavior.

Small differences in lateral acceleration and yaw velocity response were identified, with a slight increase in yaw response phase lag. The changes were considered to be consistent with the increase in vehicle yaw inertia associated with the mass added at each wheel. The steering torque build-up was found to be less linear with the increased unsprung mass. The initial rate of torque increase relative to yaw rate was increased, but then reduced off center. The characteristic was considered to be consistent with the combined effects of the yaw response lag, increased steering friction and increased wheel and hub inertia about the steering axis.

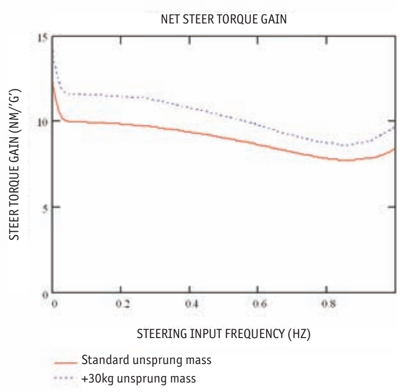
CAE models were used to better understand the dynamic mechanisms responsible for the observed differences in the vehicle responses. Steady-state cornering analysis revealed a small reduction in the vehicle's lateral acceleration limit,

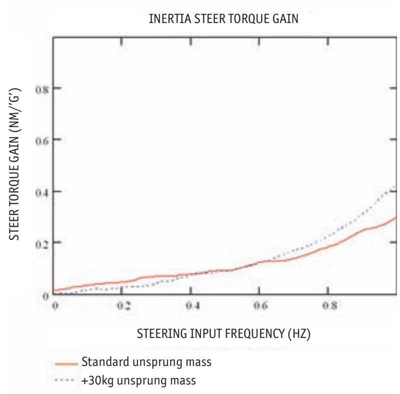
BELOW: **ON-CENTER STEERING RESPONSE COMPARISON, STANDARD AND +30KG HUB MASS**

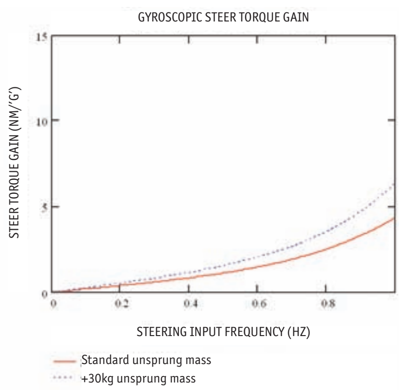




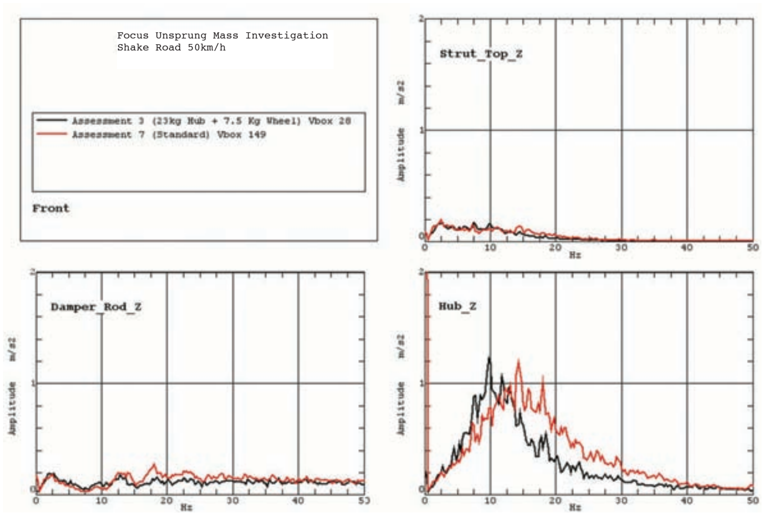
RIGHT: **INERTIAL AND GYROSCOPIC CONTRIBUTIONS TO STEERING TORQUE, STANDARD AND +30KG HUB MASS**







RIGHT: **SECONDARY RIDE RESPONSE COMPARISON (SHAKE), STANDARD AND +30KG HUB MASS**



and body roll and side slip were also found to increase as one might expect with a 132kg increase in total vehicle mass, sprung or unsprung.

Steering input swept-sine analysis highlighted the differences in the vehicle's transient response as a function of input frequency. Here the CAE confirmed the slight yaw response delay observed in the objective vehicle measurements. The CAE models also enabled the effects of the increased unsprung inertia and gyroscopic torques to be quantified. It had been expected that these may have a significant effect upon transient steering efforts.

The steering torques generated by unsprung inertia are dependent upon steer velocity (the rate of change of steer angle) and wheel rotational velocity. Typical vehicle response to transient steering inputs has a bandwidth of around 1Hz; beyond this frequency, vehicle response is completely out of phase with steering and is not within the operating range normally experienced by the vehicle user. Steering wheel input rates may reach 750°/sec in exceptional circumstances. With a typical steering ratio of 16:1, this relates to a peak roadwheel angular acceleration of 2.6 radians/sec^2 for a 0.5Hz excitation.

Even at this extreme steer acceleration, the transient resisting torque due to the unsprung mass inertia of a typical car is about 1.56Nm. Reduced by the mechanical advantage of the steering gear, this results in just 0.1Nm felt by the driver. With the added inertia of the heaviest hub motor, the contribution to steering effort from a transient steering input increases to 0.17Nm, a figure that is still negligible compared with the total steering effort.

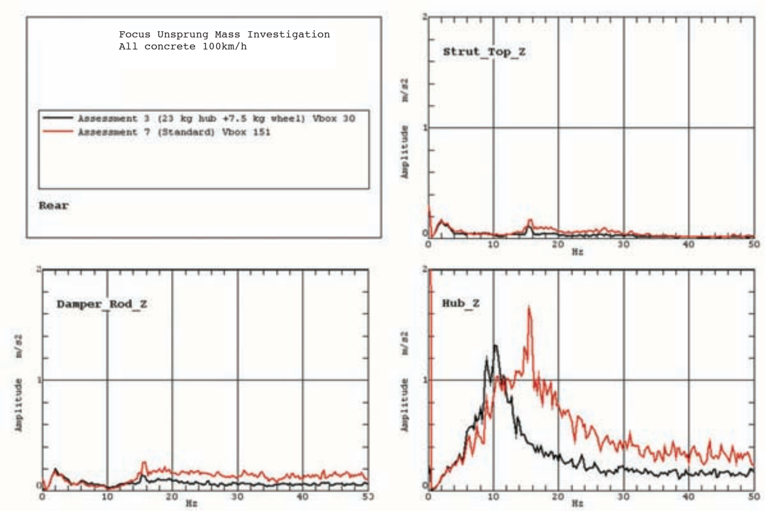
Gyroscopic steer torque is a function of both wheel camber velocity and wheel rolling velocity. For cornering maneuvers, wheel camber velocity for a typical passenger car does not exceed 15°/sec even in extreme maneuvers such as the previous example. When combined with a road speed of 90km/h, the resulting gyroscopic steer torque may reach a peak of 20Nm at the road wheel, contributing about 20% of the total steer torque. With the increased rotational inertia of the heaviest unsprung mass, this contribution increases to about 23%. So, although the gyroscopic effect is greater than that of the increased inertia about the steer axis, neither has a particularly detrimental effect on steering effort build-up.

Ride comfort is the aspect of vehicle dynamics traditionally considered to be most affected by unsprung mass. Lotus conducted road measurements on surfaces deliberately chosen to excite the natural frequencies of the unsprung mass in order to emphasize any differences due to the unsprung mass increase. Accelerations were measured at strut tops, damper rod, and wheel hubs to give a clear picture of vehicle body disturbance, as well as insight into the suspension behavior.

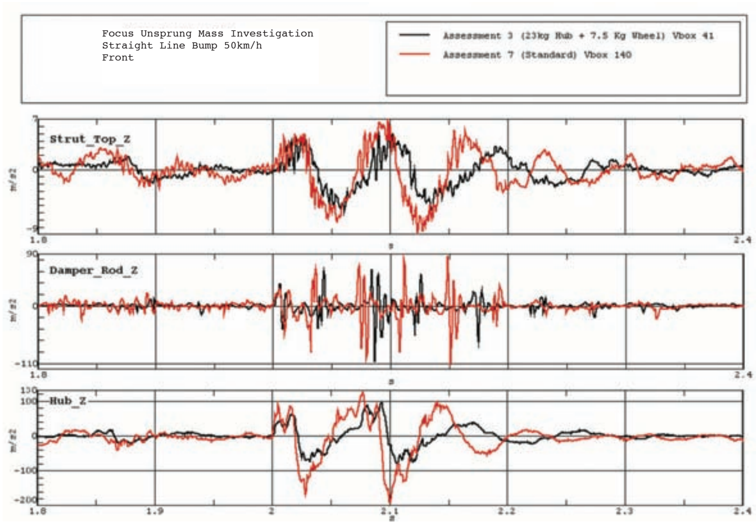
The results showed a shift in the frequency at which peak hub acceleration occurred; this wheel hop frequency is primarily a function of unsprung mass and tire radial stiffness. Although the difference in hub acceleration is clear, the resulting change in body accelerations is small and was subjectively assessed as unlikely to be noticeable beyond a direct, back-to-back comparison of the standard and high-unsprung-mass vehicles.

Further testing was conducted on a concrete highway surface at higher vehicle speeds. This test highlights the vehicle's response to higher frequency excitation. From this testing it can clearly be seen that the higher unsprung mass reduces the acceleration response of the vehicle body at frequencies above the wheel hop frequency, giving improved higher frequency noise and vibration attenuation.

The final road testing used a purpose-built double-bump to measure the vehicle response to an impact event. The test clearly shows



LEFT: **COMPARISON OF HIGH-SPEED HIGHWAY RIDE ISOLATION, STANDARD AND +30KG HUB MASS**



LEFT: **COMPARISON OF RIDE IMPACT ISOLATION, STANDARD AND +30KG HUB MASS**

that the increased unsprung mass enables the suspension to absorb the bump impact better, resulting in reduced accelerations on the vehicle body.

Lab testing of the vehicle using two-post rigs produced good correlation of the road measurement results, and clearly highlighted the shift in wheel hop mode frequency, from around 14Hz down to 10.5Hz. The measurements also showed the vehicle to have a powertrain vertical mode of 12.75Hz. This explains why the subjective performance is worse for the intermediate unsprung masses rather than the highest unsprung mass. For the intermediate unsprung mass conditions, the wheel hop mode was close to the powertrain vertical mode, giving a coupling of the two modes. Normal powertrain mounting design practice would avoid this type of coupling.

CAE modeling was again used to correlate the findings of the physical testing, as well as providing Lotus with valuable insight into how tuning of suspension components could be use to mitigate the effects of the increased unsprung mass and recover the vehicle's performance.

Although the vehicle dynamic performance was degraded by the increase in unsprung mass, the degree to which this was noticeable was small and could be said to have moved from class-leading to mid-class. Furthermore, the understanding gained from the study has led Lotus to believe that the small performance deficit could be largely recovered through design changes to suspension compliance bushings, top mounts, PAS characteristics, and damping – all part of a typical new-vehicle tuning program.

Add the powerful benefits of active torque control and Lotus's findings make a strong argument for the vehicle dynamic benefits of hub motors as an EV drivetrain.

FROM FOUR-POST RIGS TO SEVEN TO EIGHT AND MORE: ENGINEERING CONSULTANT, **PHIL MORSE** TAKES AN IN-DEPTH LOOK AT SHAKER RIG TESTING IN MOTORSPORT

Shakedown

Shaker rig testing, it seems, has truly entered the vernacular. It is often featured during racing broadcasts' technical asides and it receives a reasonable amount of print coverage. So perhaps now is a good time to dig a little deeper, and expose some of the technical nuances of this rather specialized form of vehicle testing.

Considering the investment required, it may be surprising to learn just how many shaker rigs are actually in operation. For example, within a two-hour drive from the author's office in Charlotte, North Carolina, USA, there are more than a dozen operational shaker rigs. Most are owned by individual race teams, and are used for their own internal research purposes. A few are for-hire facilities. Either way, these machines are in vogue and in demand.

"It takes time to learn how to absorb the data that a seven-post provides, to learn how to really integrate the knowledge into [vehicle] developments," notes Joe Berardi, managing director of RaceWorks, one of the for-hire seven-post test facilities near Charlotte. "But those who do this successfully reap the rewards – you can see it on the track. Those who have not are scrambling to catch the wave, to find out what all the fuss is about."

There are a number of measurements that can be extracted from shaker rigs. For example, simple heave, pitch and roll tests can be processed to estimate sprung and unsprung masses, sprung mass pitch and roll inertias, effective suspension stiffness and damping rates, effective tire stiffness and damping rates, and natural frequencies and damping ratios of various subsystems. Shaker rigs can also provide input excitations for structural (modal) testing and various subsystem analysis work.

HISTORY

The use of shaker rigs in racing dates back to the mid-1980s. This was an era of intense vehicle suspension research and development, particularly in Formula 1. Inexorably tied to the story is Dave Williams, famed developer of the first Lotus active suspension control systems.

"I became involved in the physics of race vehicles when I modeled the porpoising problem that was a by-product of ground-effect aerodynamics," recounts Williams. "There was little that could be done (legally) to manipulate modal responses to stabilize a vehicle, so I then became drawn into devising other potential solutions: mass dampers, the twin-chassis Lotus 88, and ultimately, active suspension. With much help from Lotus [Team & Engineering], the active system came to be reasonably successful.

"In 1984/5, I installed a four-post rig at Cranfield University, where I worked at the time, mainly because I came to realize that the cockpit was not the place from which to understand vehicle dynamics problems. The rig at Cranfield gathered dust after the end of our involvement with active suspension, until an engineer from Reynard approached me in 1993 flourishing a graph and asking, 'Can we do this?'. The idea caught my interest and, in short, it is how I came to be doing what I do now."

In the USA, the use of shaker rigs in racing followed the second, mid-1990s burst described above. NASCAR teams were certainly relying upon the shaker rig facilities at their parent manufacturers during this timeframe.

Dave Charpentier, director of Earnhardt Technologies Group's vehicle dynamics test center in Mooresville, North Carolina, has been in the trenches of NASCAR racing long enough to provide this account: "By late 1994, the capabilities of the Ford facilities [in Dearborn, Michigan] were already being stretched. We wanted to add bungee cords and load cells to their four-post rig, and try new things. NASCAR vehicles, even at that time, were making 800lb (363kg) of downforce, and we wanted to get the vehicles properly loaded and run sine sweeps with specific energy content.

"We eventually devised some unique testing methods, and we were finding gains – especially at 'high energy' tracks such as Bristol, Dover, and so on. And right in the midst of all this came the Bilstein and Penske revolutions, where all of a sudden we had the ability to change [damper] shims and perform our own [damper] rebuilds in our own shops. All of a sudden we had a million things we wanted to try on the cars, and all eyes fell upon shaker tests as a way to efficiently do that."

"Our test methods are well-proven, but it is always a learning process on both sides, every time"

Tony Yardley, manager rig testing, Multimatic Markham facility, Canada

MAIN IMAGE: **INITIALIZATION RUNS ON A ROBERT YATES STOCK CAR AT THE ÖHLINS USA FACILITY IN HENDERSONVILLE, NORTH CAROLINA, USA**

RIGHT: **MUSTANG BOSS 302R GETS A WORKOUT ON MULTIMATIC'S ENHANCED FOUR-POST TEST RIG IN MARKHAM, ONTARIO, CANADA**

But, in truth, extracting these measurements is rarely the focus of a shaker rig test session conducted by a race team. More typical pursuits are quantifications of grip disturbance and body control metrics.

Grip disturbance is a measurement that denotes contact patch vertical force variation. Sometimes this might be as simple as the root mean square (RMS) or mean of a rig-measured, time-varying contact patch force signal for a given run over a specific track segment or input frequency band. Less is considered better, because it might directly correlate to more consistency in a tire's lateral or longitudinal force generation capability.

Body control is any measurement that describes sprung/unsprung mass and aerodynamic platform (pitch) responses to shaker rig inputs. Sometimes ride height measurements are included in this measurement category, but values are typically derived from the amplitude peaks of transfer functions of mass movements (heave, pitch, roll) to actuator inputs for a given run, over a specific track segment or input frequency band. Less is considered better, denoting attenuation of inputs, absorption of road irregularities, and so on.

Embedded in these definitions are references to 'specific track segments or input frequency bands'. This is a not-so-subtle reference to the two most popular types of shaker rig testing approaches: drive-file-based track mapping, and sine sweep testing. A particular approach leads to a distinct path and sets the stage for suspension-tuning philosophies.

Further discussion lends itself to a description of some of the test methods employed by various for-hire shaker rig test facilities. This is by no means a comprehensive survey of available for-hire facilities, but the intention is to provide an overview of

ABOVE: **DR KEVIN KEFAUVER PREPARES TO LAUNCH A TRACK SIMULATION ON EARNHARDT TECHNOLOGIES' SEVEN-POST RIG IN MOORESVILLE, NORTH CAROLINA, USA. AMERICAN STOCK CARS, SUCH AS THIS CAMPING WORLD TRUCK SERIES CHEVROLET, HAVE UNIQUE AERODYNAMIC CHARACTERISTICS THAT DEMAND CAREFULLY DEVELOPED SETUPS – WITH SPECIAL ATTENTION TO BODY CONTROL METRICS**

testing philosophies – which can be adequately described in the context of the particular facilities referenced in the following pages.

Although the common goal of 'making cars faster' is shared by all shaker rig users in racing, there is very little standardization of testing philosophies. Everyone, it seems, has their own way of looking at information and making assessments. And rightly so.

This may at first seem surprising, perhaps because the level of technical sophistication involved could lead one to believe that conclusions must be scientific, born of some strict methodology, some rigid protocol. But people have been building automobiles for around 120 years, and *the solution* is yet to be found – most likely because there simply isn't one.

RaceWorks Inc

At RaceWorks, an independent for-hire seven-post test facility in Cornelius, North Carolina, the philosophy is one of 'anything goes'. Although the centerpiece is a seven-post test rig, capabilities also include a bevy of standalone actuators for subsystem evaluation, durability tests, and multi-axis testing.

"We often support special projects – building custom test fixtures, sorting out specialty load applications and measurements, testing non-traditional vehicles," says Berardi.

After several years of working for successful NASCAR teams, Berardi ventured out on his own, determined to bring the science of seven-post testing to the masses. The booking schedule at RaceWorks shows that he has been successful.

"We are on top of our machine day and night, making sure that it has the best repeatability, the lowest [aerodynamic load] residuals possible," says Berardi.

As shaker rig track mapping methods gain in popularity, sine sweep testing is sometimes relegated to the back seat, but RaceWorks understands that this is not necessarily a good idea.

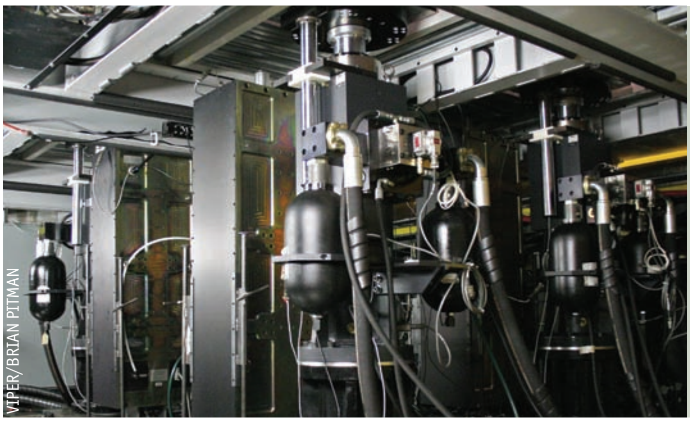
"What we're talking about here is a comparative process, one of iteration and learning," explains Berardi. "Teams that are new to this testing are sometimes hungry to get in here and start building drive files [track maps] right away. They assume that's how everyone else is doing it and seeing such big gains.

"Don't get me wrong, we love building and running drive files and pushing data out into someone's Pi or MoTeC system, but we gently suggest to our clients to have a look at sine sweeps and some vehicle fundamentals. There is so much to learn there, it shouldn't be ignored."

Figures 1 and 2 (overleaf) show sample results from three sine sweep tests conducted at RaceWorks, each corresponding to a suspension tuning change. Here, the nature of a sine sweep test becomes evident – it is merely a rig displacement profile that oscillates in time, in this case from low frequency to high frequency. With a quick glance it is easy enough to see the improvements made to the vehicle's left front suspension, progressing from Run 1 to Run 3.

One might even guess the changes that were made to achieve this… As is typical in some stock car classes, if left to their own devices front setups can migrate toward progressively stiff springs (sometimes to the point of coil collapse) with heavy rebound

BELOW: **AT VIPER'S EIGHT-POST TEST RIG IN ALTON, VIRGINIA, USA, ELECTROMECHANICAL AEROLOADERS, SPECIALLY DEVELOPED BY ROEHRIG ENGINEERING, PROVIDE EXCELLENT DYNAMIC CONTROL**

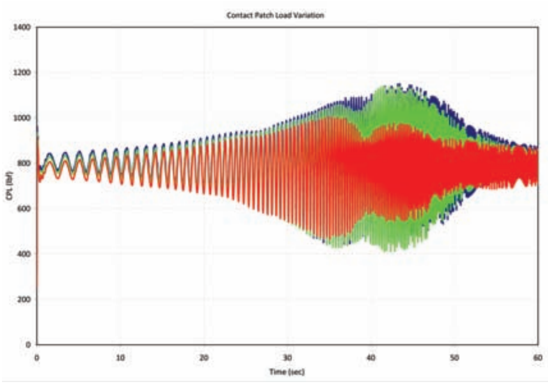


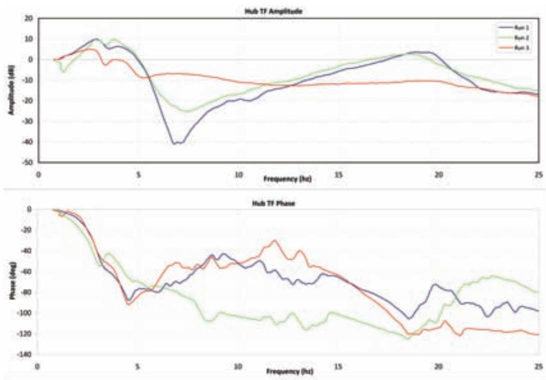
Choices, choices

Within the broad classification of what might best be termed multipost vertical test rigs, the following sub-categories can be identified. These rigs, regardless of classification, are complex pieces of laboratory measurement equipment, and the installation and operation of these rigs does not come cheap or easy. Spending US$2 million may get you some but not all of the goodies.

FOUR-POST RIGS

Four independently controlled vertical actuators, typically electrohydraulic. One actuator is located beneath each tire contact patch. Vehicle chassis is not restrained, except perhaps by limit travel tethers or safety stops, which are not engaged during test runs. Standard instrumentation includes sensors at each wheel platen to measure vertical force, acceleration, and displacement. This type of rig is the norm among vehicle manufacturers where it is used to assess durability, squeak/rattle, ride, and NVH.





RACEWORKS USA

FIGURE 1 (FAR LEFT): **CONTACT PATCH LOAD VARIATION (CPL) VERSUS TIME FOR A LEFT FRONT STOCK CAR TIRE**

FIGURE 2 (LEFT): **VERTICAL HUB ACCELERATION FROM VERTICAL INPUT ACTUATOR ACCELERATION FOR A LEFT FRONT STOCK CAR HUB**

damping. The blue traces in the figures describe just such a case.

Knowing the definition of grip disturbance, we can readily see the improvements in the time domain – visibly, the red trace has much less variation. Improvements are evident in the frequency domain as well – the red setup (Run 3) is evidence of good road disturbance attenuation, without the inconsistencies of the blue setup (Run 1). Trends like this can often be adequately captured by single numbers in summary tables and run logs.

"Reducing run data to a single number can have risks, and it is always wise to take time for deeper analysis," Berardi is quick to suggest.

Tire construction subtleties, for example, can sometimes muddy the waters. Depending on excitation frequency and amplitude – specific ranges of which might be of particular interest on a given racetrack – increases in tire vertical load may actually (and counterintuitively) decrease lateral load capability, and vice versa.

This happens when the rate of compression force on the tire acts to relax or tighten the carcass and the internal load-supporting cords. In cases like this, single number grip disturbance metrics can be very misleading.

Multimatic Inc

Both of Multimatic's enhanced, for-hire four-post rigs (one in Thetford, UK, and another in Markham, Ontario) are the brainchild of Dave Williams, principal of Flight Systems and Measurement Ltd, a company contracted to Multimatic Inc to support vehicle dynamics activities.

The (exclusively) sine sweep methodologies used for studying race cars are a product of Williams' vast experience in vehicle and aerospace engineering.

"My methodology is one of vehicle characterization," states Williams. "It is very much founded on the idea that 'optimally' damping a vehicle solves many problems – with caveats. To that end my methods are based on identifying mathematical models of the vehicle, and using them to iterate to a 'good' suspension setup.

"Originally 'deliverables' were damper settings to match various spring selections – still the case today, in essence, but I now also supply information to try to help race engineers to make better-informed calls at a racetrack.

"Interestingly, perhaps, this was stimulated by one of my [Touring Car] customers. He noticed that I was using a 'cost function' as a personal aid during a test, and asked for a copy. He eventually returned and said that the cost function I had put together correlated reasonably well with laptimes."

These 'cost functions' have developed over the last 20 years into a robust library of performance indices for many different production and racing vehicle types. Each performance index is built upon modal damping, contact patch load, and body control cost functions, and each can be thought of as an ideal vehicle response characteristic (in terms of mechanical grip and handling).

For example, results from a 0-40Hz sine sweep test with applied front/rear aero loads can be viewed as shown in Figures 3 and 4 (overleaf) – where performance index (z) is plotted as a function of front (x) and rear (y) damping levels. The

ENHANCED FOUR-POST RIGS

Same as above with the addition of at least two passive or quasi-static vertical chassis restraints for the application of constant aerodynamic downforce during test runs. Other sensors record applied vertical chassis forces. These were the first shaker rigs to find a regular place in motorsport.

SEVEN-POST RIGS

Four-post rig plus three independently controlled chassis vertical actuators, typically electrohydraulic, but sometimes pneumatic. The three chassis actuators, often called aeroloaders, provide more than just aerodynamic downforce during test runs; they control three chassis degrees of freedom (DOF): heave, pitch, and roll. Additional sensors record applied vertical chassis forces.

X-POST RIGS

Seven-post rig plus additional independently controlled chassis vertical actuators, typically electrohydraulic, but sometimes pneumatic or electromechanical. Additional actuators provide additional DOF control for chassis and/or mechanical subsystems. These rigs are the latest and greatest. Eight-post rigs, for example, are beginning to have a presence in motorsport.

BELOW: **FORMULA MAZDA TEST/DEVELOPMENT CHASSIS ON VIPER'S EIGHT-POST TEST RIG**

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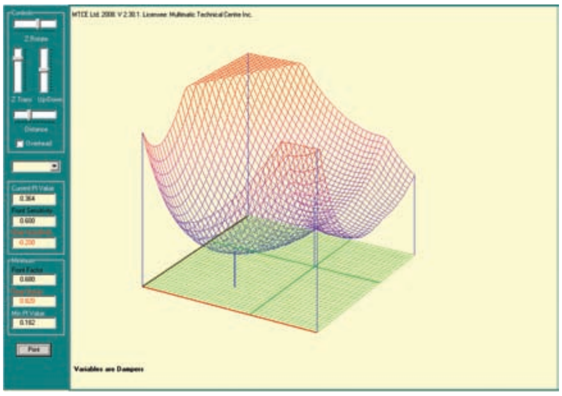


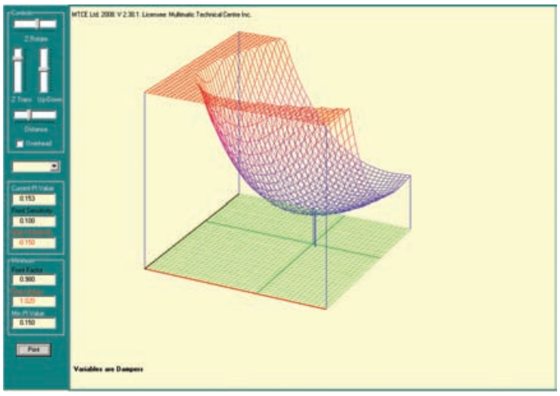


FIGURE 3 (FAR LEFT): **A NON-OPTIMAL CAR, EVIDENCED BY THE RESPONSE SURFACE MINIMUM LYING AWAY FROM THE CURRENT TUNING AT THE CROSS-HAIRS IN THE FRONT/REAR DAMPING PLANE. DECREASING THE FRONT AND REAR DAMPING MAY LEAD TO IMPROVEMENT**

FIGURE 4 (LEFT): **THE SAME CAR AS IN FIGURE 3, OPTIMALLY TUNED. DAMPER ADJUSTMENTS HAVE MOVED THE CURRENT TUNING (CROSS-HAIRS) TO BE AT THE RESPONSE SURFACE MINIMUM**

beauty of this test method and data visualization approach is that it does not impose suspension-tuning solutions that are event/driving line/driver-specific.

If a team can learn and understand the vehicle changes that are required to alter these response surfaces, they have learned how to approach tuning their vehicle for any racetrack or situation. Each Multimatic rig employs two pneumatic aeroloaders (one front and one rear) that have received special attention from a controls perspective.

"Our aeroloaders are very pure," says Tony Yardley, who oversees rig testing at the facility in Markham, Canada. "You can clearly see the damping of the car, uncorrupted. Dave [Williams] is famous for saying that the aeroloaders on most shaker rigs are typically the most effective dampers in the building. And we, of course, want to avoid that."

Tony's perspective is a healthy one, in that he understands that teams want answers they can trust, and they want them fast.

"Our test methods are well proven, but it is always a learning process on both sides, every time," he says. "Our approach is not geared toward finding solutions for a single racetrack. But because of this, if there are fundamental vehicle limitations due to, say, damper installation stiffness, we will most certainly find them. Our goal is to have teams walk away with an excellent understanding of what the car likes [for a setup], and why it likes it."

Öhlins USA

When Kenth Öhlin announced his intentions to install a for-hire seven-post shaker rig in western North Carolina in 1998, some thought he was crazy. As it turns out, he was a visionary, and for some years Öhlins was the only game in town.

Since this time the Öhlins USA rig has just about seen it all: testing race vehicles of all types; special test fixtures that replace tires and subvert the above-mentioned rolling tire issue; and rigorous OEM-style testing to support their own and others' product developments.

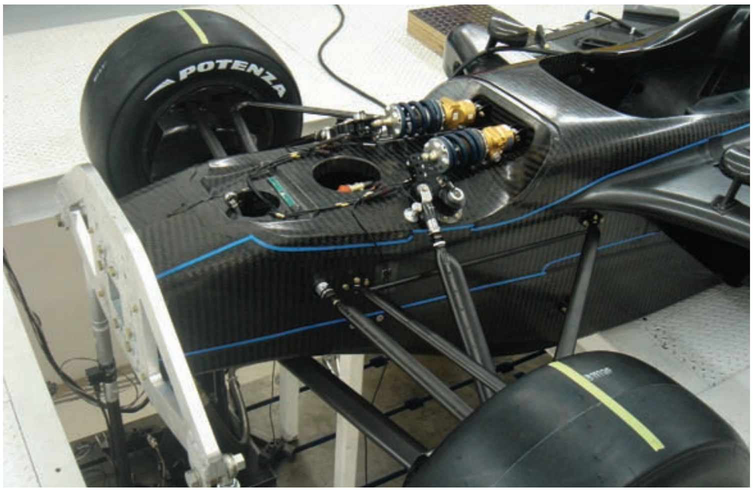
Öhlins' original test methodologies for race teams involved running long duration (maybe 90-second) random velocity profiles that were used to produce various grip disturbance maps. Except in a few rare cases, this has now been largely abandoned in favor of drive file generation and track mapping. According to Christer Lööw, the automotive group manager, this has been primarily due to the demands of motorsport clients.

"We began looking at specific on-track events such as curb strikes to see if we could improve segment times through rough sections," he says. "We had success. In the Champ Car days, tracks such as Long Beach, Toronto, and Surfer's Paradise – that one used to be the worst – would change their curbing every year to keep the cars chicaned, but it would just lead to more aggressive driving lines. Rig time helped teams a great deal in these segments."

Lööw also alludes to the special track-mapping experience gained by studying specific track segments when he says, "If one front wheel lifts, suddenly all the roll stiffness moves to the rear. A rig controller appropriate for this case is not appropriate for a more general case."

It is through statements like this that the subtleties (and dangers!) of drive file creation can be speculated upon. In the most general sense, drive files are time histories of specific racetracks that can be played through a shaker rig. From a rig perspective, the trick is to develop an open-loop rig input command script (aeroloaders in force control, and wheel platens in displacement control) that causes a vehicle to behave in the same manner as it would on the racetrack.

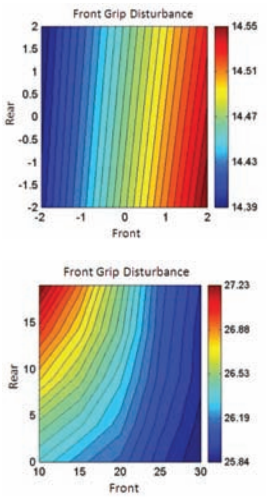
If the same vehicle equipped with sensors (typically four damper displacement potentiometers, and four wheel hub vertical accelerometers) were tested back-to-back on a racetrack and then on a



LEFT: **CHAMP CAR ON TEST AT ÖHLINS USA. TWO FRONT AERODYNAMIC LOADERS ARE ATTACHED TO THE CHASSIS VIA A SPECIAL BULKHEAD PLATE. SPECIAL WHEEL PLATENS REDUCE GROUND PLANE FRICTION (SCRUB) DURING TESTING**

FIGURE 5 (FAR RIGHT): **CREATING A 'DRIVE FILE' USING MTS'S RPC SOFTWARE**

FIGURE 6A&B (BELOW): **SEVEN-POST DATA REPRESENTATIONS THAT SUMMARIZE MULTIPLE PART CHANGES**



ÖHLINS USA

shaker rig, in an ideal situation the sensors would not be able to detect the difference, and the drive file would be a 'keeper'.

In reality, of course, this is never the case due to fundamental shortcomings mentioned above. Öhlins' drive file creation, not unlike the process on other test rigs, begins with sorting out the low-frequency aeroloaders. Lööw prefers 'low stiffness' aeroloaders.

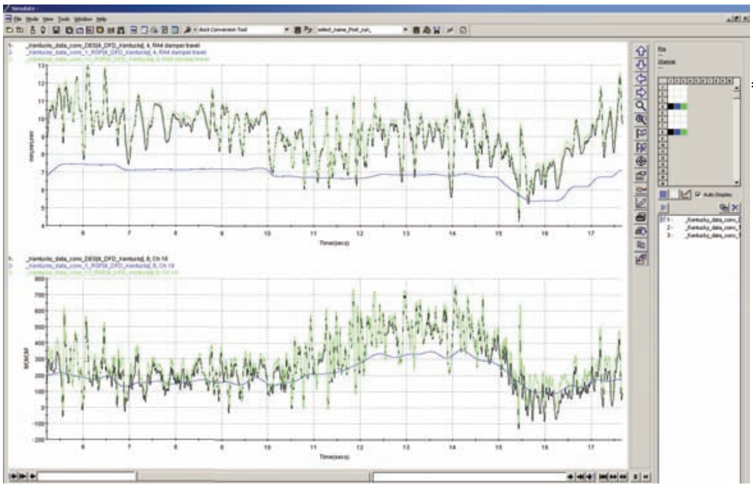
"We want the aeroloaders to influence only, say, sub-2Hz body control. High stiffness aeroloaders can cause you to trick yourself. For instance, in a severe bump situation, the car responds quickly – but we must introduce loads in the way that the car sees them, through the tire contact patch, then up through the suspension. We do not want to artificially control the relative displacement of sprung and unsprung mass by using the aeroloaders."

After the aeroloaders are sorted, and the vehicle chassis is loaded into a typical condition, the rig is used to drive 'random' wheel platen inputs for several minutes. This can get violent, and it is not for the faint of heart. The purpose here is to create a mathematical model of the vehicle, a frequency domain transfer function (or FRF, frequency response function) relating system outputs to inputs.

For example, the outputs might be the eight vehicle measurements mentioned above, and the inputs would be the seven command signals given to the seven posts on the rig. This mathematical vehicle model can then be inverted, turned on its head, so that inputs can be predicted from known outputs. The inputs, after all, are the goal – the command signals to the rig that constitute a drive file.

In a perfect world, this would be a one-shot deal: a drive file would spit right out, and vehicle testing could commence. However, the mathematical inversion is not perfect, primarily due to non-linearities in the vehicle.

"There is really no such thing as a non-linear FRF," explains assistant professor of non-linear dynamics at the University of Portland, Dr Timothy Doughty. "A non-linear system like a vehicle, with its tires, energy dissipation mechanisms, and its inherent flexibilities, does not respond in an obvious way to a given input. Depending upon initial conditions, there may be different output



ÖHLINS USA

responses. And the initial conditions themselves may well be moving targets, as we are already operating inside a dynamic realm."

And so the process becomes one of iteration. This is where Lööw's experience comes into play. Having been through the process a number of times, and, in effect, knowing which 'knobs to turn' he can use software tools designed to support the relaxed pace of OEMs (two weeks to develop a drive file) to develop a usable drive file in about three hours.

An example of the drive file creation process is shown in Figure 5, where a mere 12 iterations have shifted measured rig data to very closely match data acquired at a racetrack. A drive file such as this can be replayed through the rig again and again, subjecting the vehicle with associated component changes to a repeatable representation of on-track conditions.

To help engineers assess vehicle performance, Öhlins can create alternative data representations such as that shown in Figure 6. These are simply colored graphs (red = bad, blue = good) that condense a great number of tuning changes into a single reference graph. In each plot, a suspension parameter is being changed through its available tuning range, normalized to ±2 in the upper plot, and about 0-20 in the lower.

The nearly vertical lines in the upper plot demonstrate that parameter changes in the front have very little effect on the rear grip disturbance level, and vice versa. However, the lower plot shows a strong coupling effect in that grip disturbance modifications can be achieved only by simultaneous tuning of front and rear suspension parameters. This can sometimes be overlooked, as engineers are keen to change only one thing at a time. It may well be that this notion is correct. However, perhaps that 'thing' is a system-level parameter, not an individual component or setting.

Future trends

Shaker rigs do have shortcomings. Two primary ones are the inability to account for horizontal tire contact patch forces, and the inability to include rolling tire dynamics. But engineers are currently hard at work to remedy and/or sidestep them.

Based on the sheer number of data analysis methods discussed above and speculated to exist elsewhere, there is no limit to the direction one might take. Facilities such as VIPER in Virginia, USA, are already imagining 'inter-platform communication' links that might enable a human driver in its simulator to pilot a tele-operated vehicle around nearby Virginia International Raceway, or join its simulators to its eight-post rig.

The pioneering Dave Williams arguably has the broadest perspective on the subject.

"I think much remains to be achieved by combining, in a more realistic way, information that can be gained from hardware-in-the-loop tests with mathematical modeling, which has the potential for predicting more realistically the performance of a vehicle around a specific racetrack," he says. "Many of the required elements are already in place, arguably, but much remains to be accomplished to improve vehicle, driver and (particularly) tire models, track mapping, and so on. Even then it will remain a tool that can be used or abused."

Traction controlled

FACED WITH EVER-MORE POWERFUL FRONT-WHEEL-DRIVE VEHICLES, VOLKSWAGEN AND HALDEX HAVE READIED AN ELECTRONICALLY CONTROLLED LIMITED-SLIP DIFFERENTIAL FOR PRODUCTION. **PROF DR STEFAN GIES** FROM VW AND **GRAHAM HEEPS** EXPLAIN THE THINKING BEHIND THE SYSTEM

In 2008, the Volkswagen Group launched XDS (eXtended Differential Sperre – see *Sunny delight*, November 2008 issue, p8). This ESC-based technology predicts the onset of understeer and acts to prevent it, and has since been successfully fitted to numerous vehicles across the Volkswagen Group.

In parallel, however, Volkswagen's chassis group had been evaluating an electronically controlled mechanical limited-slip differential for front-wheel-drive applications.

Work began in the fall of 2003 with the goal to build a car up for winter testing in Sweden in February 2004. The triggers were: the appearance at that time of increasingly powerful engines in front-drive Volkswagen Group vehicles; the use of mechanically locking differentials in competing transverse installations; and the development of a sportingly controlled powertrain with standard drive.

The targets were: the further dynamic development of front-wheel drive; to demonstrate the possible interplay with stability control; and to discover the limits of the steering's influence on VW's front axles, including of EPS, which had been in production for two years at that point.

The eLSD technology and supplier were different at the beginning to now, but enabled a fast start toward demonstrating the system's potential.

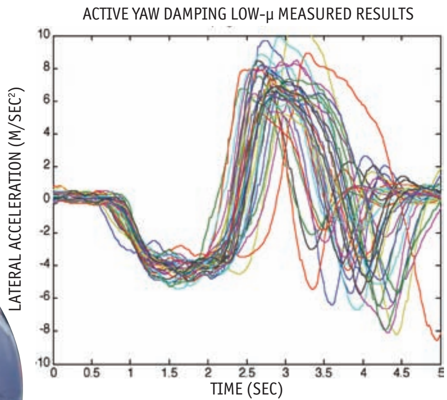
Features and benefits

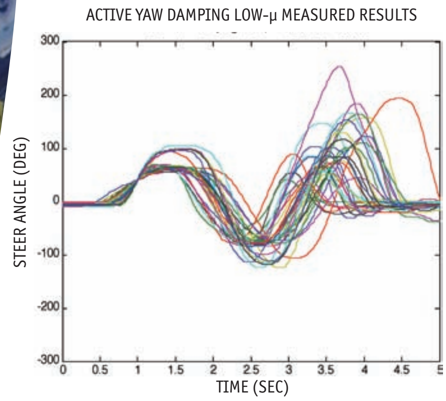
The eLSD technology that has been investigated by Volkswagen is known by Haldex as FXD. Its makers say that FXD, which automatically engages differential lock by means of a slip controller, enhances traction in a number of ways. First of all, it offers pre-emptive lock torque for a better getaway. Improved split-µ traction is another benefit, along with intervention on brake lock-up. An adjustable degree of intervention reduces steering wheel 'fight', and there is the ability to modify engine torque to make the best use of the available grip.

On the handling front, FXD prevents the inner wheel from spinning during cornering and can reduce power understeer at the limit. Haldex also claims reduced understeer during normal cornering compared with torque-locking LSDs, and slip utilization monitoring of both front wheels prevents a front axle skid, another area in which FXD should offer a benefit over a passive LSD.

Yaw damping – the ability to counteract a rate of change in yaw velocity – is also possible with the FXD. This is accomplished by creating an understeering yaw moment across the front axle at the right time and in the right magnitude. Because yaw damping is a transient property but understeer a steady-state condition, understeer should be unaffected by the yaw damping function.

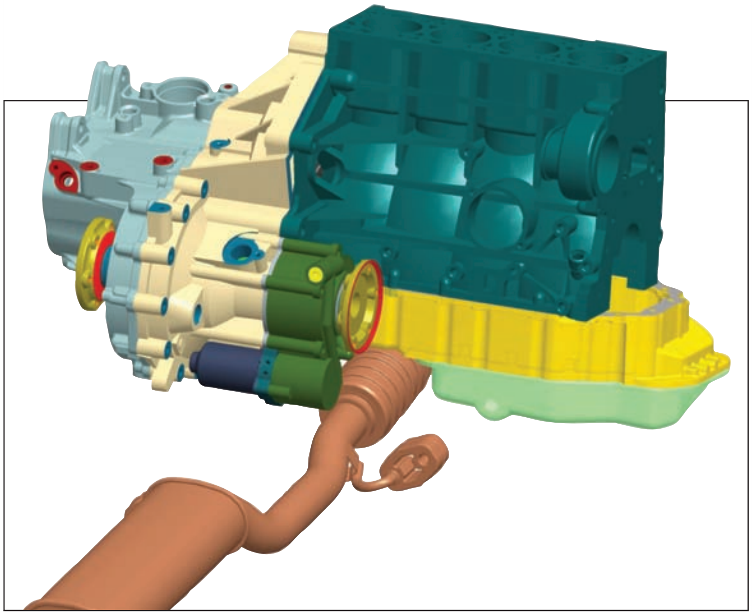
Finally, FXD is designed to remain robust against variations in tire properties or road surface.





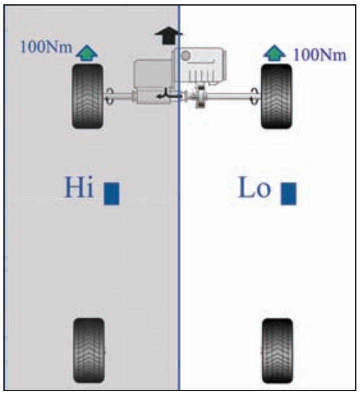
MAIN IMAGE: **SCIROCCO RACE CAR WITH eLSD AT THE NÜRBURGRING.** ABOVE: **RESULTS FOR ACCIDENT AVOIDANCE MANEUVER ON LOW-MU – HAND WHEEL ANGLE** (TOP) **AND LATERAL ACCELERATION (YAW RATE TIMES VELOCITY,** ABOVE**)**

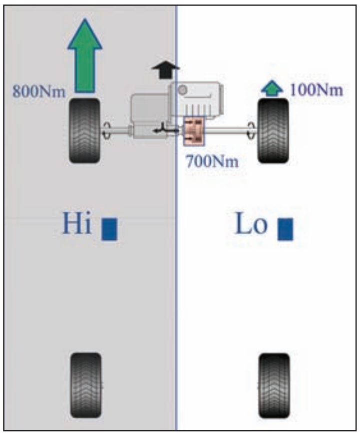
"The idea retained its appeal because the eLSD still has a certain sense of innovation now that systems such as XDS have become common"



LEFT: **HALDEX'S FXD TECHNOLOGY FORMS THE BASIS FOR VW'S eLSD**

BELOW: **SPLIT-MU GETAWAY WITH** (BOTTOM) **AND WITHOUT FXD FITTED**





Volkswagen engineers had to determine conceptually how the unit could be accommodated into the available front-end architecture and how the function and architecture of the accompanying software would look, because the diff and stability control were supplied by different companies.

The first measurable proof of the system's function was the improvement in laptime recorded by a professional driver at the Oschersleben race circuit in Germany. The laptime was around 1.5 seconds less than the non-eLSD time, and an increase in corner exit speed of around 10% was also recorded.

A period followed in 2007 that was defined by cost pressures and cost-optimization, so that to begin with a route to a production vehicle for the technology could not be found. The difficult sales climate and above all a 'free' alternative in the form of the XDS system made justifying the application of eLSD harder still. The cost-effective further development of XDS, which simulates the intervention of an eLSD using the brakes, was a success, with a production application in the Golf and its specification in other vehicles.

But the idea retained its appeal because the eLSD still has a certain sense of innovation now that systems such as XDS have become common. Today's carryover of existing production technology from the AWD longitudinal diff application to a transverse one has opened new possibilities and led to the current thoughts of adoption for series production. In fact, the all-wheel-drive gearbox could be used for this front-wheel-drive car to install the eLSD without further modifications in the area.

Beyond that, the electronically controlled, transverse limited-slip differential, in comparison to the XDS brake intervention system, offers the advantage of a torque split with considerably lower losses. This gives higher available engine power for acceleration, and it is not reduced by brake interventions.

In the meantime, Volkswagen Motorsport deployed the eLSD to great effect in the natural-gas powered Scirocco GT24-CNG race car, where the drivers were excited by the steering precision and the cornering confidence of this 325bhp, FWD machine.

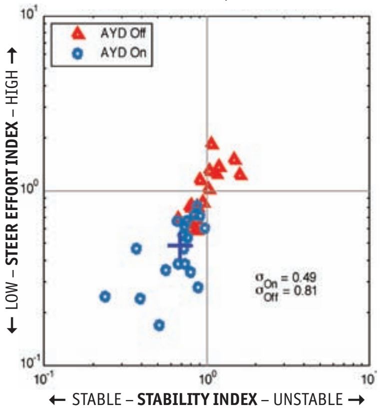
In 2010, one of these Sciroccos was raced by senior Volkswagen engineers Dr Ulrich Hackenberg (head of technical development) and Prof Dr Stefan Gies (head of chassis development), who tested the eLSD under the harsh conditions of the 24-hour race at the Nürburgring.

The evidence is that the eLSD clearly improves the driving experience for the ambitious driver, and Volkswagen is keen to find a business case for its application in a sporty car.

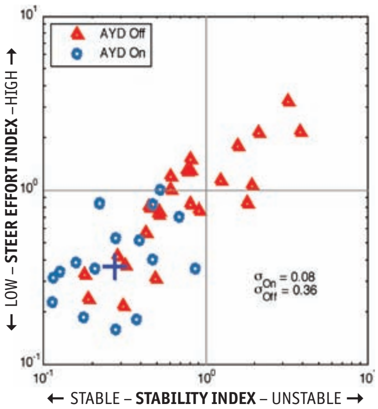
RIGHT: **YAW DAMPING FUNCTION, ACCIDENT AVOIDANCE MANEUVER ON LOW-MU. LESS STEERING EFFORT (50%), LARGER STABILITY MARGIN (30%)**

FAR RIGHT: **YAW DAMPING FUNCTION, ACCIDENT AVOIDANCE MANEUVER ON HIGH-MU. LESS STEERING EFFORT (65%), LARGER STABILITY MARGIN (70%)**

ACTIVE YAW DAMPING LOW-μ MEASURED RESULTS



ACTIVE YAW DAMPING HIGH-μ MEASURED RESULTS



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Vehicle Dynamics Expo 2011

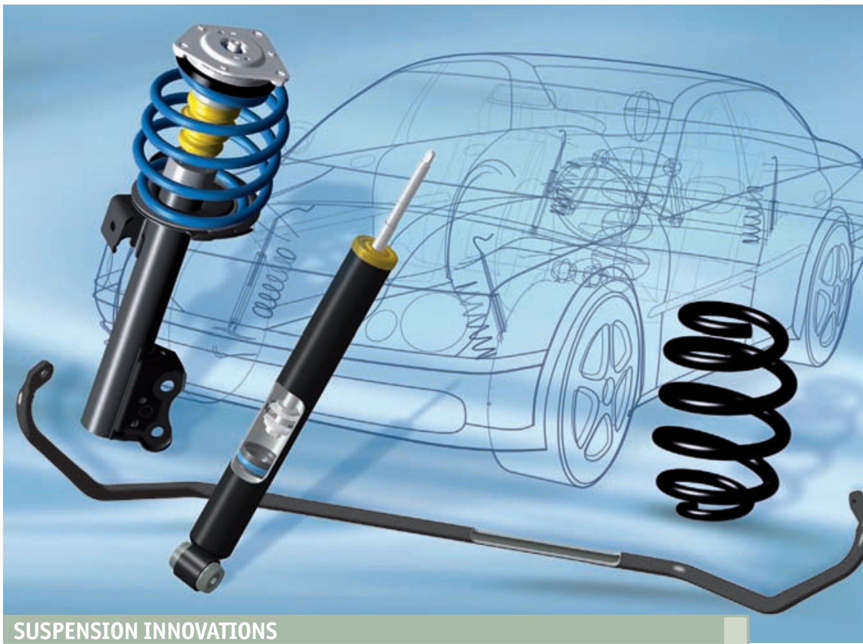
IT'S ALMOST HERE! **VEHICLE DYNAMICS EXPO 2011** TAKES PLACE IN THE MESSE STUTTGART ON MAY 17-19. READ ON FOR OUR SHOW PREVIEW...

Vehicle Dynamics Expo returns to Messe Stuttgart on May 17-19. As usual at this most focused of events, visitors will be able to see the latest product and service technologies from industry-leading companies in the field of chassis development. There will also be a superb, free-to-attend Open Technology Forum (*see page 58*). Nowhere else is there such a concentration of the latest innovations in chassis, suspension, steering, braking, and ride and handling!

A highlight of this year's show will be the chance to discuss some of the latest suspension technologies with the engineers who have created them. Among the exhibitors is Tenneco, whose Kinetic interconnected suspension system forms the basis of the ProActive Chassis Control that McLaren has developed for its *VDI* award-winning new MP4-12C supercar.

Elsewhere in the exhibition is BWI Group, which will be showing the brand new, third generation of its innovative MagneRide damping system. This technology is making its production debut in the Range Rover Evoque this summer.

Entry to Vehicle Dynamics Expo – in Hall 3 at Stuttgart's New Trade Fair Center – also includes complimentary access to the adjoining exhibitions of Automotive Testing Expo, European Automotive Components Expo, and Engine Expo. It all adds up to make this the key event in 2011 for anyone involved in chassis engineering and tuning. Don't miss it!



SUSPENSION INNOVATIONS

ThyssenKrupp Bilstein Suspension's display will include two of its latest innovations: the ThermoTec Spring (a weight-optimized coil spring made using high-strength steel) and tubular stabilizer bars with varying wall thickness. Bilstein's adjustable damping portfolio will be represented by several systems, including the new two-state system, DampTronic select, and the high-end DampTronic sky system, with independent adjustment of rebound and compression.

VB and Fludicon hook up

VB-Airsuspension BV (VBA) will be exhibiting in conjunction with Fludicon. Together the two companies will be showing the VB-eRRIde technology, backed up by a joint presentation at the Open Technology Forum. In addition, VBA will be showing its new VB-FullAir and VB-ASCM systems. Based in Varsseveld, in the Netherlands, VB-Airsuspension develops, manufactures, and markets components for OEMs and is an aftermarket solution supplier. Its range of products includes LCV (1.5-7.5 metric tons GVW) air suspension systems and other suspension-related parts. Using a range of modules developed over the years, these parts are controlled by a VB-ASCU (VB-Air Suspension Control Unit). Furthermore, the company develops LCV front- and rear-axle air suspension systems.

RINGS AND BEARINGS

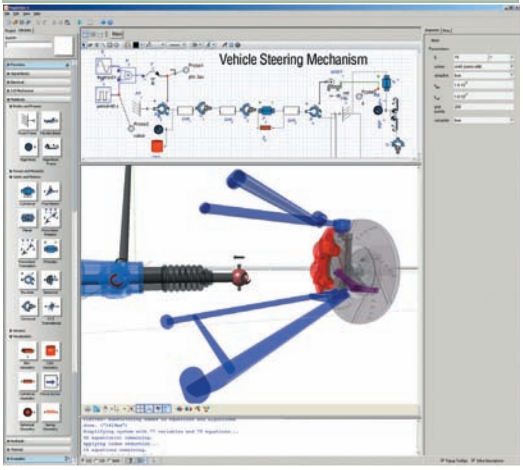
Saint-Gobain Performance Plastics will be showcasing its Norglide bearings and Rencol tolerance rings at the expo. Its sister company, Seals Business Unit, will also be on hand to discuss its sealing rings for steering and suspension systems.

Cellasto expansion

BASF is expanding its business with Cellasto automotive spring aids and top mounts made of microcellular polyurethane (PU). "With our existing sites in North and South America, Asia, and Europe, we have strengthened our market position in the past years," comments Kenneth Lane, senior vice president, strategic marketing polyurethanes. Moreover, a new Shanghai site is scheduled for completion imminently. "Producing and supplying products in the same region that our customer is located is critical to our long-term success," adds Lane. Cellasto has gained market share especially in the PU top mounts and spring isolators business. Examples include new global platforms for cars such as Opel Astra and the new Citroën C4, or the new global GM platforms such as Delta, Epsilon and Gamma, which will all be fitted worldwide with BASF top mounts from 2011 onward.

NEW SOFTWARE LAUNCH

Maplesoft will launch the newest version of MapleSim at Vehicle Dynamics Expo 2011. MapleSim is a physical modeling tool built on a foundation of symbolic computation technology. It efficiently manages all the complex mathematics involved in the development of engineering system models, including multi-domain systems and plant models for control applications. The newest version of MapleSim includes many enhancements to help engineers manage the complexity of their models. Due to its broader application scope, streamlined modeling environment, and ability to efficiently simulate even more systems, MapleSim's creators say the new package makes it even easier to tackle large projects and get results quickly.



Automotive Simulation Models

dSPACE's Automotive Simulation Models (ASM) are open Simulink models for the real-time simulation of passenger cars and trucks. They are used as plant models for the development and testing of vehicle dynamics controls and driver-assistance systems. The ASM concept consists of coordinated, combinable models of automotive components. There is a vehicle model with a trailer, plus other ASMs for engines, brake hydraulics, electrical systems, electric motors, environment sensors, roads, and traffic. The ASMs support a whole range of simulations from individual components to complex virtual traffic scenarios.

WHO TO MEET

Riender Happee (Delft University of Technology), DRIVOBS, stand 5255

Happee leads research and education in Automotive Human Machine Interfacing and Biomechanics at Delft University of Technology. Current research focuses on driver observation, driver modeling, extreme steering, cooperative driving, and neuromuscular stabilization of the neck and the lumbar spine.

AIR SUSPENSION EXPERTISE

For more than 30 years Continental has contributed air-suspension systems to luxury cars, premium SUVs, MPVs, vans and other vehicles. The principal reason for the widespread use of air springs is for vehicle leveling, with a considerable improvement achieved in ride comfort and driving dynamics at a relatively low cost. Customer benefits can very easily be realized with auxiliary functions such as an adaptive loading sill, or entry and trailer functions. The system's potential is far from having been exhausted. Continental is developing an air-suspension system with a switched auxiliary reservoir, making possible very comfortable and, at the push of a button, very sporty driving.

3D artist joins Mechanical Simulation

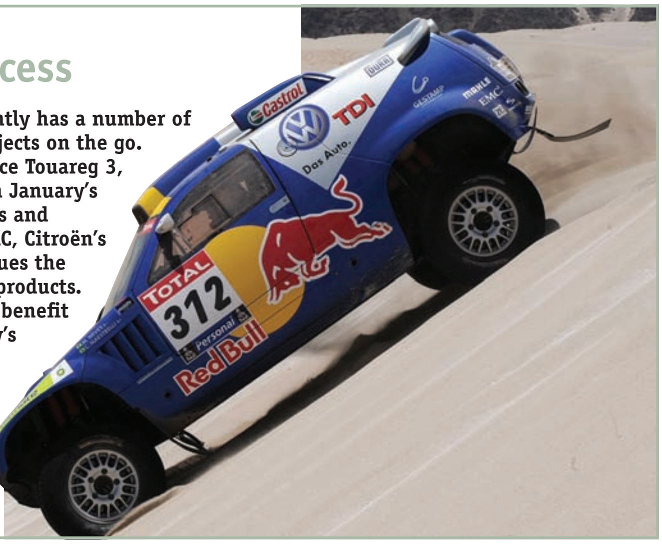
Mechanical Simulation Corporation has added a new member to its staff. Doug Champine is an artist who has been working in the gaming industry for more than 15 years, and has worked on many big-budget games such as Red Faction Armageddon, SaintsRow 2, NASCAR SimRacing, Madden NFL, and the F1 series. His recruitment gives Mechanical Simulation the specific capability to generate realistic vehicles and environments by using advanced computer rendering techniques. Customers will be able to make use of these realistic assets for presentations, marketing purposes, and driving simulators. Mechanical Simulation will be able to create custom vehicles and proving grounds to represent real-world situations and places. These new capabilities take full advantage of the company's new animation program, the Visualizer, due to be released later this year.

LIGHTWEIGHT CONCEPT

Magna Steyr unveiled its fifth concept vehicle from the MILA (Magna Innovative Lightweight Vehicle) innovation family at the recent Geneva Motor Show. MILA Aerolight is a compact, four-seat, natural-gas vehicle in the A segment that weighs 700kg and has maximum CO_2 emissions of 55g/km. A multimaterial system forms the basis of the concept car. The body consists of a structural frame optimally adapted to stress, and a polymer shell. Considerable reductions in weight are achieved due to the honeycomb structures and innovative composite materials. In this way, all safety requirements – especially with regard to protection of pedestrians – are fulfilled, while simultaneously improving insulation and acoustic properties. Furthermore, there are module solutions with integrated functions, such as an axle with stabilizers, a structurally embedded back seat and a digital viewing system.

Motorsport success

Brake supplier, Alcon currently has a number of high-profile motorsport projects on the go. First up, the Volkswagen Race Touareg 3, which took a 1-2-3 finish in January's Dakar Rally, uses Alcon discs and friction material. In the WRC, Citroën's all-new DS3 rally car continues the French team's use of Alcon products. And two Lotus projects also benefit from the UK-based company's hardware: the F1-like Type 125 track car, and the Evora Enduro endurance machine, which finished third-in-class in this year's 24 Hours of Dubai.



WHO TO MEET

Martijn de Mooj, Cruden, Stand 5060

As project manager and support engineer at Cruden, de Mooj provides operational support to Cruden's customers in motorsport, automotive, and entertainment, from simulator installation and training to ongoing maintenance.

SIMULATOR RESEARCH DEMONSTRATION

Visitors to the Cruden stand will be able to see the first demonstration of a new motion simulator research application by Cruden, Noldus, Smart Eye, the Delft University of Technology, TNO, and VTI, the Swedish National Road and Transport Research Institute. The DRIVOBS project aims to increase knowledge of the ways drivers use vision, motion, and other information to control vehicles. The result will eventually be a set of simulation products for the automotive market to aid the development of vehicle dynamic control systems, active safety systems, infotainment systems, and human machine interfaces, and for the training of professional test drivers. Driver behavior is observed using camera vision, physiological measurements and system identification in complex driving scenarios such as highway and city driving. Visitors can also drive the Cruden Hexatech motion simulator for themselves. There is a DRIVOBS stand opposite the Cruden stand, where all the DRIVOBS research partners will be able to discuss the project's findings to date and demonstrate driver reactions from the simulator, via a spectator view, operating in real time.

New ownership

In January 2011, the Georgsmarienhütte Group (GMH) acquired Bishop Steering Technology, strengthening its ability to supply integrated, engineered solutions to the steering market. Bishop complements two existing GMH businesses: fellow Vehicle Dynamics Expo exhibitors, Stahl Judenburg, which develops specialized materials for steering racks; and MVO, whose precision components include steering racks for low-volume prototypes, semi-finished rack blanks, and production-volume finished steering racks. Future investment will see steering racks with variable ratio teeth manufactured at MVO using the Bishop Warm Forging process. Bishop's Indianapolis location, meanwhile, will be expanded to produce not only prototypes, but semi-finished products and finished steering racks, too.

STRONG RESULTS FOR AAM

American Axle & Manufacturing (AAM) posted some excellent financial results for the full year 2010. AAM grew its sales by 50% to US$2.28 billion in 2010, of which non-GM sales were US$563 million, a 70% growth year-on-year. The gross margin of 17.6% of sales is a new company record for AAM, which posted net income of US$115.4 million, compared with a net loss of US$253.1 million in 2009. The firm also managed to reduce its net debt by more than US$125 million.

Precise position determination

An important function of GeneSys Elektronik's Automotive Dynamic Motion Analyzer (ADMA) is to provide road data, including realistic height profiles. To ensure precise positioning even under difficult GPS reception conditions, the firm is now introducing the new ADMA-PP post-processing software, which allows optimization of ADMA data recordings and inclusion of GPS correction data after the test drive. The software's core is a Kalman filter, which perfectly combines GPS and inertial data. While the real-time option continues to be provided by the ADMA system, offline calculation has two decisive advantages. First, GPS correction data can be downloaded easily from the internet for the required test run. This facilitates installation work for the measurement process compared with the real-time mode, where GPS correction data must be supplied via a radio or GSM link from a private base station or an RTK network provider. Second, ADMA-PP is able to calculate position solutions forward and backward along the time axis, which improves positioning accuracy. The package is rounded off by an auxiliary module with a barometric altitude sensor, allowing accurate measurements of critical height-related data.

BOSCH HONORS BOURNS

The Automotive division of Bourns Inc recently received a Preferred Supplier award from Robert Bosch GmbH. Bourns last year consolidated its North American Automotive Division sales and technical support into a new facility in Auburn Hills, Michigan, and the award recognizes the company's quality and customer service performance in the supply of its position and angle sensors. "This award confirms Bourns' commitment to provide the highest quality and superior performing position and angle sensors available in the market, as well as to exceed customer expectations for service and support," said Jeff Pyle, vice president of Bourns Automotive Division. "We are honoured to be recognized as a Preferred Supplier of the Bosch Group, and have the chance to solidify a long-term relationship with this respected manufacturer."

WHO TO MEET

Paul Goossens, director, applications engineering, Maplesoft, stand 5350

Goossens directs the Applications Engineering Group that supports Maplesoft's new line of engineering modeling products. A mechanical engineer by background, he has over 20 years of experience in engineering and software business management.

Crossover applications

Expo exhibitor, BWI Group has developed larger, sturdier suspension modules to suit crossover vehicles developed on sporting and premium compact platforms. The upgrades to the gas-filled dampers provide greater all-terrain capability and increased load-carrying capacity while maintaining the inherent agility of the base vehicle. The first application is the MINI Countryman crossover. The front and rear dampers are larger with increased travel, which gives the Countryman the wider shock-absorbing capacity needed to cope with the demands of running on rough roads. This has also helped increase the Countryman's load-carrying capacity by 40kg to 470kg. The BWI dampers are part of a package that includes forged track control arms at the front and a multi-link axle at the rear. Another crossover, the new Range Rover Evoque, also features BWI technology in the form of the brand new, third-generation MagneRide adaptive damping system. BWI will be showcasing the benefits of MagneRide III at Expo; they include a reconfigured design for easier installation, and a twin, opposite-wound coil setup that increases the speed at which damping force can be removed.

Global Toyota Etios gets Tenneco suspension

Tenneco has begun producing suspension products for the Etios, Toyota's new global small car that was recently launched in India. Tenneco is supplying front struts and rear dampers, which use an adaptable valve technology, from its ride control plant in Hosur, India for delivery to Toyota's Kirloskar Motors plant in Bangalore.

The contract marks the latest step in the Tier 1's expansion into fast-growing automotive markets such as India, and symbolizes the company's ability to support OEMs on a global scale. Tenneco will supply Toyota's future compact car launch in Brazil as well. "We are proud to support Toyota on this strategic, new launch with our global manufacturing and engineering capabilities, including a strong footprint in India," said Jeff Jarrell, vice president and managing director, Tenneco Japan.

Open Technology Forum 2011

VEHICLE DYNAMICS EXPO 2011 ONCE AGAIN FEATURES AN EXCELLENT, **FREE-TO-ATTEND** CONFERENCE. HERE'S THE DRAFT SCHEDULE:

DAY 1
Tuesday, May 17

Simulation Development Tools and Chassis Tuning

10:30 Chassis management: advanced and integrated electronic suspension systems for vehicle dynamics and comfort
Dr Andreas Rohde, managing director, segment suspension systems, Continental, Germany

10:50 Vehicle dynamics control: an integrated approach
Daniel Lindvai-Soos, project engineer, Magna Steyr, Austria

11:10 Game theory approach to control vehicle lateral motion
Dr Saied Taheri, associate professor, Virginia Tech, USA

11:30 An advanced physical modeling approach for brake system performance analysis
Valerio Cibrario, manager automotive industry, LMS Italy, Italy

11:50 Steer-by-wire and testing: unlocking potential with Advanced Mechatronic Test Bench (AM-TB)
Dr Stefano Serra, managing director, Teseo SpA, Italy

12:10 Displacement comes first before acceleration: a preliminary study to correlate objective off-road ride measurements with subjective feedback
Syed Naveed Haider Zaidi, PhD, researcher, Cranfield University, UK

12:30-13:30 Lunch

13:30 Mechatronic MBS vehicle models for efficient vehicle handling simulations
Gerald Wölfel, MBS simulation expert, Magna Steyr Fahrzeugtechnik, Austria

13:50 Preparing for ESC homologation: how simulation can take the strain
Iginio Voorhorst, commercial and R&D director, VB-Airsuspension BV, Netherlands

14:10 Enabling vehicle subsystem development and validation early in the development cycle using MTS Mechanical Hardware-in-the-Loop (mHIL) technology
Ford Boone, systems engineer, MTS Systems, USA

14:30 Local non-linearity modeling requirements for dynamics simulation
Thomas Wissart, CAE engineer, Samtech Deutschland, Germany

14:50 MapleSim progress report: major initiatives showing promise for higher-fidelity physical models and faster HIL
Paul Goossens, director, Applications Engineering, Maplesoft, Canada

15:10 Magnetic conductivity vs. mechanical rigidity: a solvable contradiction?
Harald Burkart, head of design and engineering, Kendrion Binder Magnete GmbH, Germany

15:30 Driver observation in car simulators: added value of observation technologies such as eye tracking and driver model identification
Martijn de Mooj, project manager, Cruden BV, Netherlands

15:50 Expand the realms of automotive testing using Moog's versatile test systems
Peter Onesti, test system engineer, Moog, Netherlands

DAY 2
Wednesday, May 18

Safety first in vehicle dynamics

10:30 Evaluation methods for active safety systems: the eVALUE EU project
Marco Pesce, vehicle dynamics senior specialist, Centro Ricerche Fiat, Italy

10:50 Functional approach to vehicle integrated safety assessment
Václav Jirovský, researcher, Czech Technical University in Prague – Faculty of Mechanical Engineering, Czech Republic

11:10 The Nürburgring effect revisited: driver integration vs. isolation
Shields Bergstrom, professional race driver, SBA Motorsports, USA

11:30 Speed breaker severity index: a novel approach to develop a standard speed breaker based on market data
Hari Krishnan Mohankumar, deputy manager, Maruti Suzuki India Ltd, India

11:50 Prospects for safety sensors in automotive markets to 2015
Dr Richard Dixon, senior analyst MEMS and Sensors, IHS – iSuppli, Germany

12:10 A flexible axle mounting bracket to improve the ride-handling compromise inherent in twist-beam suspensions
Barney Gerrard, senior engineer, Magneti Marelli Sistemi Sospensioni, Italy

12:30 Application of a road scanner in vehicular dynamic studies
Dr Liborio Bortoni-Anzures, professor, Universidad Politecnica de Victoria, Mexico

12:50-14:00 Lunch

Innovation in chassis component design

14:00 Smart application of available chassis actuators – Ford Torque Vectoring Control
Jens Dornhege, development engineer – Advanced Vehicle Dynamics Technologies, Ford Research & Advanced Engineering, Germany

14:20 Use of low-bandwidth rear-axle toe variation to reduce chassis costs
Matthew Taylor, principal engineer, Prodrive Ltd, UK

14:40 Vehicle dynamics authority of a novel driveline electrification concept
Hans-Martin Duringhof, manager, vehicle dynamics & controls, e-AAM Driveline Systems AB, Sweden

15:00 Magneto-rheological powertrain mounts
Stephen Setty, product development engineer, BWI Group, USA

15:20 Cellasto: more than jounce bumpers – innovative solutions for the automotive industry
Andreas Horstmann, graduate engineer, BASF Polyurethanes GmbH, Germany

15:40 VB-eRRide: World's First ER Fluid-Based Semi-Active Suspension System for Light Commercial Vehicles (LCV)
Dr Alex Alexandridis, managing director, Fludicon GmbH, Germany
Dr Joachim Funke, general manager, Fludicon GmbH, Germany
Iginio Voorhorst, commercial and R&D director, VB-Airsuspension BV, Netherlands

DAY 3
Thursday, May 19

Developments in vehicle dynamics in one of the world's harshest, yet fastest growing markets

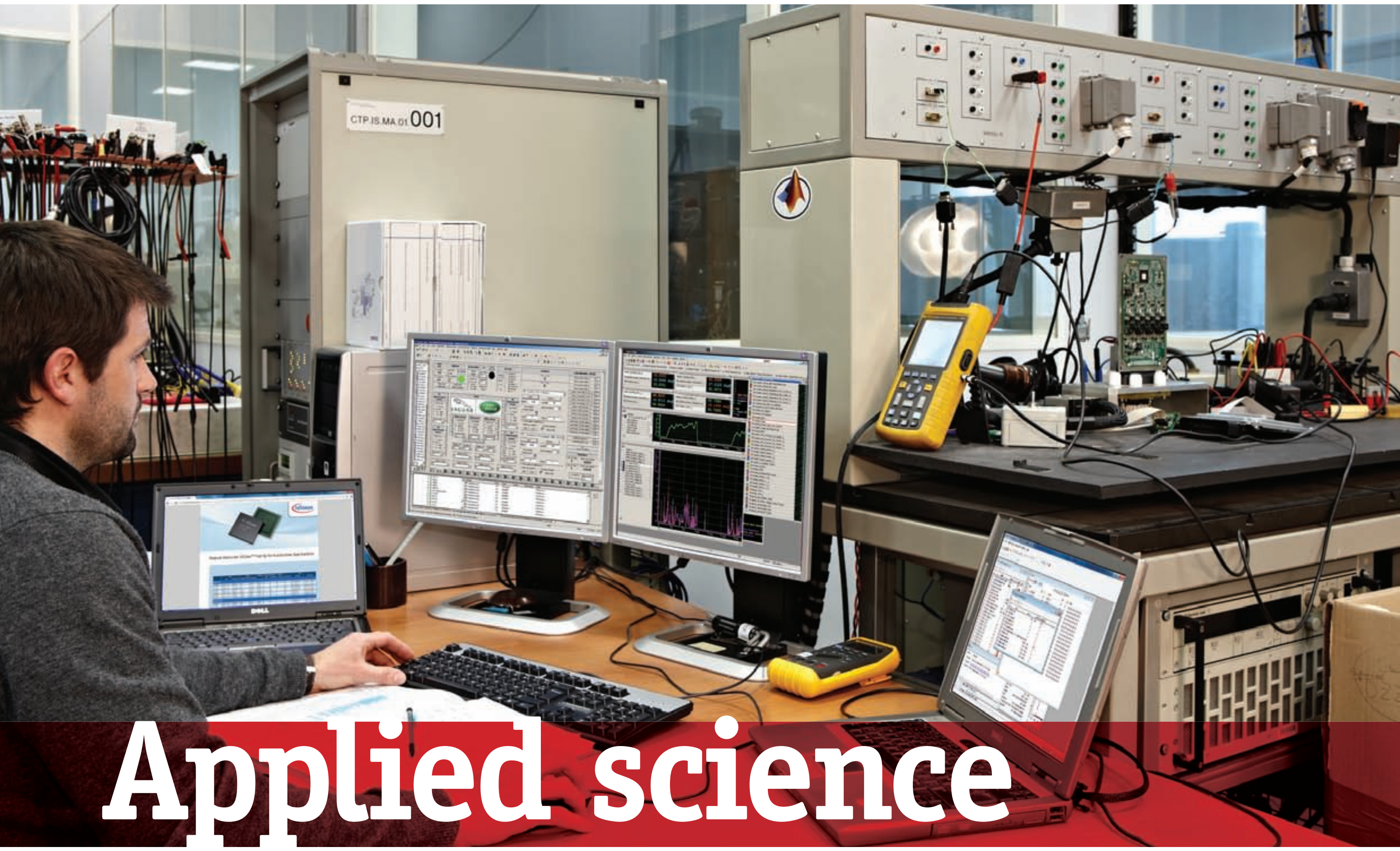
11:00 Composite ride comfort index for heavy commercial vehicles with vehicle and application-based weight-age
Dr Venkat Srinivas, general manager, Ashok Leyland Ltd, India

11:20 Use of road profile data for suspension development using HIL technology
Mangesh Saraf, deputy director, Automotive Research Association of India (ARAI), India

11:40 Front suspension modeling using an integrated FEM multibody approach
Amritashu Bardhan, deputy manager, Maruti Suzuki India Ltd, India

12:00 Virtual prototyping to predict the vehicle dynamics performance of an inter-city bus
Sharad Bhadgaonkar, deputy manager, vehicle design R&D, Mahindra Navistar Automotives Ltd, India

For the latest updates: www.vehicledynamics-expo.com



Applied science

GRAHAM HEEPS TOURS BWI GROUP'S TECHNICAL CENTER IN PARIS, THE DEVELOPMENT HOME FOR THE THIRD-GENERATION MAGNERIDE DAMPING SYSTEM

Since being spun off from the ailing Delphi concern back in November 2009, the suspension and braking business of BWI Group has been on an upward trajectory.

"As a new company we want to grow, and we plan to grow globally," asserts Frank Robinson, BWI's director of suspension product line.

That determination has been borne out in the sales figures. BWI has booked US$1 billion of new business since the change of ownership, including contracts with four new customers, while all previous customers have been retained. Chinese ownership is helping BWI to start conversations with domestic OEMs keen to boost the image and technology content of their vehicles. Globally, the company's revenue has now passed the US$600 million mark.

To take a look at some of the development work underpinning that success, *VDI* went to BWI's Technical Center Paris (TCP). Located in the district of Tremblay in a multibuilding complex once filled with Delphi employees, the facility is hard evidence of the changes in that supplier's structure over the past couple of years.

At one end of the site, one building is now completely vacant. Delphi powertrain engineers continue to work in another, and next door to that, BWI Group and Nexteer – the former Delphi steering business – share the space in a somewhat haphazard fashion via a series of swipe-card access doors. The arrangement is a legacy of the tight integration that previously existed within Delphi's chassis business; indeed, there's still plenty of communication between engineers in the two organizations on a day-to-day basis, who can also turn to their former colleagues for assistance on an informal basis if required.

Naturally enough, a costly and time-consuming reorganization of the site – which includes the relocation of substantial chunks of test equipment – has not been top of either party's agenda up to now, but the present setup is unlikely to persist in the long term.

MAIN IMAGE: **CONTROLS TESTING IN THE ELECTRONICS LABORATORY**
ABOVE: **THE SITE HAS A 500M^2 GARAGE SHARED WITH NEXTEER**

BWI currently has 43 engineers plus 10 contractors and a small support staff at TCP. That's still well short of the number of people Delphi employed at the unified facility pre-bankruptcy, but the numbers are slowly rising again, by about 10% annually, including making some of the contractors permanent.

Crucially, however, the facility retains all of its former capabilities. There is a prototype shop, an NVH lab, simulation and FEA facilities, an electronics and software lab, CAD and analysis suites, and a physical test laboratory. So, for example, a new iteration of a MagneRide damper can be designed, prototyped, unit and subsystem tested, and fitted to an

TAKE A BRAKE

Twenty-five years after Delphi created by-wire brakes for GM's EV1, OEMs remain reluctant to commit to all-electric braking. But BWI Group is continuing to develop products in this area for when the market picks up – as Olivier Raynauld, the TCP-based head of controlled suspensions forward engineering, firmly believes it will.

"You have to look at the issue as a whole," he explains. "It's not about braking better. It's about making cars simpler, cheaper, and having more functionality within the same envelope. It could be driven by other forces, such as recycling and dry cars, or maybe features that manufacturers value, such as not having to shift the vacuum booster assembly when you do an LHD/RHD conversion.

"There are other features too. Lane-keeping systems are now being advertised that use the brakes to keep you in line; that's easier to do with electric calipers than with electrohydraulic systems and ABS pumps. They're so much quicker than normal brakes: a standard hydraulic caliper reacts in about 200m; our electric caliper has a 20m reaction time. That might shave a meter off your stopping distance, but it also means you can regulate your ABS more comfortably at a much higher frequency."

Surely there are still some downsides to by-wire braking, though. How about the cost?

"The cost penalty's not that bad," Raynauld counters. "If you do the rear calipers only, you still have hydraulics for the front of the car and all of the drawbacks that go with them, so it's more expensive. It's cheaper if you can get rid of the 'apply' system between pedal and caliper.

"But to get rid of that means brake-by-wire, which is a leap of faith for the OEM," he acknowledges. "We do have millions of people's lives in our hands, and we don't want to get it wrong. As a development engineer it's easy to lose track of the fact that the average driver doesn't know what the car is capable of, or what to do when it doesn't behave normally. The microprocessor reliability is there now but we still need to make the wiring harnesses more reliable before we make that leap."

Generating sufficient braking force shouldn't be a problem either, he thinks, with BWI's famed Max Torque Brake (twin-disc) setup fitting the bill, even with 14V electrics.

It might take another five years, but according to Raynauld, "There will come a time when the manufacturers are willing to jump, when there will be enough functionality, and it will be easier to use an electric caliper. We are answering requests from OEMs and you already see electric calipers on the rear axle, so it won't be very long. Plus, the industry's had it with brake lines, and if nothing else, frustration from the engineers will drive this too!"

"It's about making cars simpler, cheaper, and having more functionality within the same envelope"

Olivier Raynauld, head of controlled suspensions forward engineering, BWI Group

instrumented vehicle for road testing, all at TCP. The nearby Mortefontaine proving ground, and its surrounding public roads, continue to be used for vehicle evaluation.

A tour of TCP's laboratories, with site manager Antonio de Matos underlines the breadth of capability at the site, which is used for advanced engineering (such as MagneRide), suspension pre-engineering, and application engineering for suspension and brakes. BWI's other technical centers around the world, notably at Krakow in Poland, and in Ohio in the USA, share the development workload.

We begin with the design office. BWI holds a generic component library in all the major CAE packages, such as CATIA v4 and v5 and NX, so that they don't have to be redrawn for each new customer project. There is also FEA capability via Abaqus, and electronics hardware- and software-design tools.

LAB TESTING A MAGNERIDE DAMPER AT BWI'S TCP

MagneRide's ECUs are built to print now, and across the building in the electronics lab there's a software test bench for different control strategies. Next door, an anechoic chamber is available for damper noise testing, and a metrology area has a number of coordinate measuring machines to check part measurements.

We were able to view a tear-down area, where sample MR dampers had been returned from customers as part of the validation process. These included units from Land Rover, which will be the first OEM to introduce third-generation MagneRide when the Range Rover Evoque goes on sale this summer. Meanwhile, some Audi R8 dampers were back from durability testing, together with a small number of field parts sent back for examination. In such cases, BWI can fit the components in question to its own R8 leased from Audi, as part of its investigations into whether the part is at fault.

In the prototype shop, a climatic chamber is available for performance testing to -20°C (-4°F) and +80°C (176°F) . There are a number of test rigs here from the likes of Schenck, Instron, MTS, and Zwick/Roell. Pseudo production parts can be built and tested to support early customer builds and prototypes for Olivier Raynauld's forward engineering group. In a neighboring area there's a brake dyno, and an electromagnetic shaker that can go up to 400Hz for noise and vibration testing.

A walk into the suspension test laboratory reveals a number of rigs for durability-type testing. A MagneRide unit was being evaluated at the time of our visit in a dual-frequency setup (12Hz on top of 1Hz), with water jackets around the damper to reduce overheating and sideloads being applied in addition to vertical strokes. The strokes are carried out with and without current to the damper, as they would in the car. TCP primarily tests new designs, performing concept validation on runs of around four to eight parts, before larger quantities are made for full validation in Krakow or the USA.

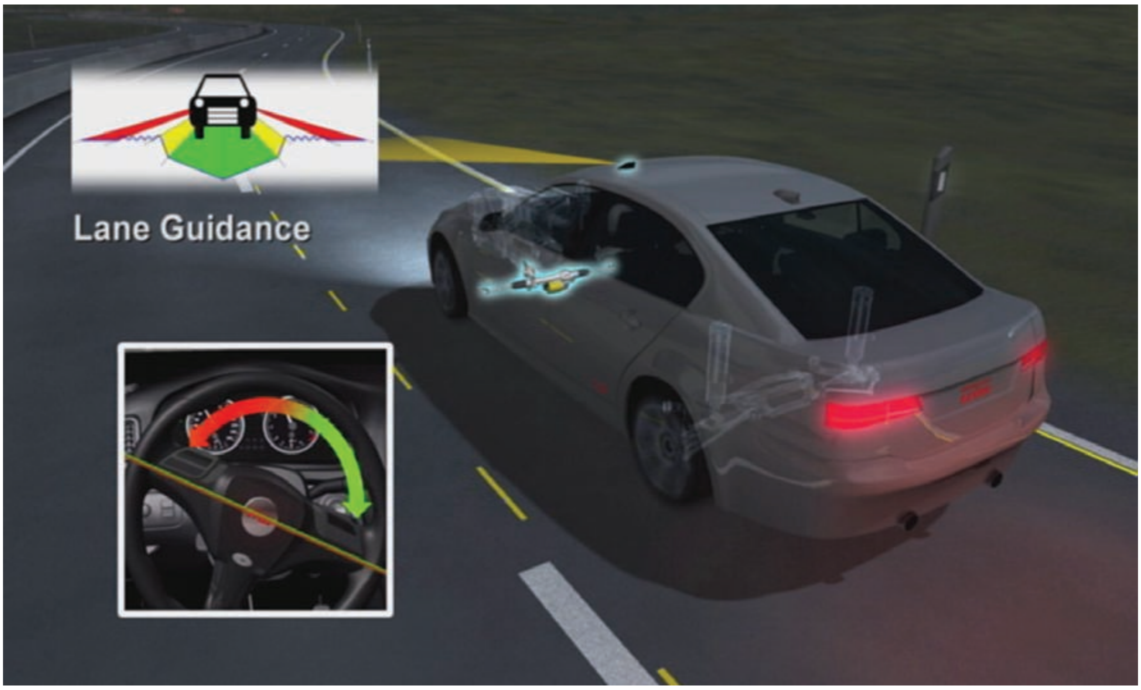
Some inverted monotube struts were also being tested at that time on a four-post rig. Close by, a similar machine has an environmental chamber for durability-type testing across a temperature range.

Once a part has been tested in isolation, a large rig at the end of the room is available for corner or full-axle system testing. An anti-roll bar, steering system, control arms and customer-supplied mounts can all be set up together with the correct geometry, and tested using customer road-load data. Load can also be applied to active roll control systems, such as BWI's active stabilizer bar.

From there, the part can be fitted to a development vehicle. The spacious garage area is shared with Nexteer, but each company has an access-controlled, single-car garage within it for confidential customer prototypes.

Steering feel regulation

TRW'S VIDEO CAMERA WORKS IN COMBINATION WITH THE EPS AND PROVIDES AN OVERLAY TORQUE TO GUIDE THE DRIVER ALONG A REFERENCE COURSE



Market drivers in the automotive industry for fuel economy, emissions reduction, and vehicle safety are leading to increased uptake in advanced vehicle technologies – in particular electrically powered steering (EPS) systems. In addition to offering a greener power-steering solution than conventional steering systems, EPS is a key building block for providing a number of vehicle safety features – both in terms of working together with other active systems, such as driver assist systems or electronic stability control, and in its ability to include new features to mitigate vehicle error-states.

EPS enables vehicle manufacturers to differentiate their offer through a host of features that can be programmed within the EPS software – a number of which are being enabled by TRW.

"With the given mechanical and hydraulic constraints of traditional hydraulic steering systems, there are limits to what can be achieved – compromising the ability to implement functions and steer feel characteristics beyond conventional physical boundaries," comments vice president of TRW steering engineering Frank Lubischer.

"One of the beauties of electric steering is that these functions are controlled through software – and can be programmed quickly to enable the desired outcome. For example the amount of power-steering assist can easily be varied – full assist at slower speeds for tight turning maneuvers such as parking, or a stiffer, sportier response at high speeds, such as highway driving, and these modes could be chosen by the driver.

"Likewise, the electric steering system can be programmed to intelligently respond to varying vehicle and environmental conditions, such as different tire types, payloads or road surfaces."

Using electronic control algorithms, TRW works in close collaboration with its customers to develop and implement several advanced steering functions. A number are in production, or are due to go into production within the next two to three years, in the areas of driver assist and safety.

"Electric steering plays an important role in TRW's driver assist systems technology road map, as it represents the one system in the vehicle that has a permanent connection with the driver, continuously translates the driver's directional commands, and directly provides feedback from the vehicle's tires to the driver's hands," adds Lubischer.

As such, TRW's driver assist functions can help the driver in unpleasant, but necessary, steering tasks such as when there are mitigating road and environmental conditions, as well as in support of parking maneuvers (see box, *TRW's driver assist functions*, right).

Safety functions are those that can detect and react to hazardous conditions, such as slippery or icy road surfaces and torque feedback that infers a driver's drowsiness or inattention. When coupled with sensors, surrounding or approaching vehicles can be detected, enabling the system to warn drivers of dangerous conditions.

"Electric steering safety enhancements are achievable through integration with other systems," continues Lubischer. "For example, driver steer recommendation functionality can be delivered

through the integration of EPS and ESC to help correct situations such as oversteer in hard cornering or when encountering a slippery surface on one side of the vehicle and dry pavement on the other. Tests have shown up to 8% reduction in stopping distance.

"When combined with driver assist technologies such as camera-based systems, electric power steering can help the driver stay in the intended lane by providing a torque through the steering wheel that guides the driver back toward the center of the lane. A full lane guide system can actively assist in keeping the vehicle in the center of the lane."

Looking ahead, TRW predicts significant adoption of its EPS technologies for non-premium vehicle platforms due to its performance, price, packaging, and of course fuel-efficiency advantages over conventional steering technologies. TRW has ongoing programs to continuously enhance and develop advanced driver interaction functions to improve driver safety and offer more customer choice.

TRW'S DRIVER ASSIST FUNCTIONS

Pull drift compensation (PDC) Detects if the vehicle is drifting to one side (through a suspension error or from a side wind or cambered road), and makes automatic adjustments, eliminating the need for constant steering wheel corrections.

Active disturbance and road shake compensation Help reduce vibration in the steering wheel caused by uneven road conditions and imbalanced torque at the wheels.

Torque steer compensation Corrects the tendency in some FWD vehicles to pull to one side under the influence of high engine torque.

Semi-automatic parking When linked to proximity sensors EPS can 'automate' the sometimes challenging task of parallel parking. Sensor information, along with algorithms, are used to calculate the best parking trajectory and EPS provides the assistance to steer the vehicle.

Personalization Enables the driver to switch from a different tuning of the steering system such as a 'city mode' with less steering effort, to a standard mode for faster driving conditions requiring a harder steering feel.

Arbitration and limitation A centralized function that arbitrates between feature requests and limits the sum of torque requests. If one system becomes active for example, another feature would be deactivated in order to avoid negative impacts.

Variable ratio Helps the vehicle to be more responsive in different driving situations. For example, it can respond more quickly when starting a turn or reduce the steering effort near the wheel's turning limits, such as during a parking maneuver.

Driver steer recommendation Provides an interface to the braking system to request an additional driver torque overlay to the steering system. Usually, brake tuning is a compromise – a shorter stopping distance means a more unstable vehicle. With driver steer recommendation, the brakes can minimize the stopping distance and simultaneously request a steering torque to stabilize the vehicle.

CONTACT

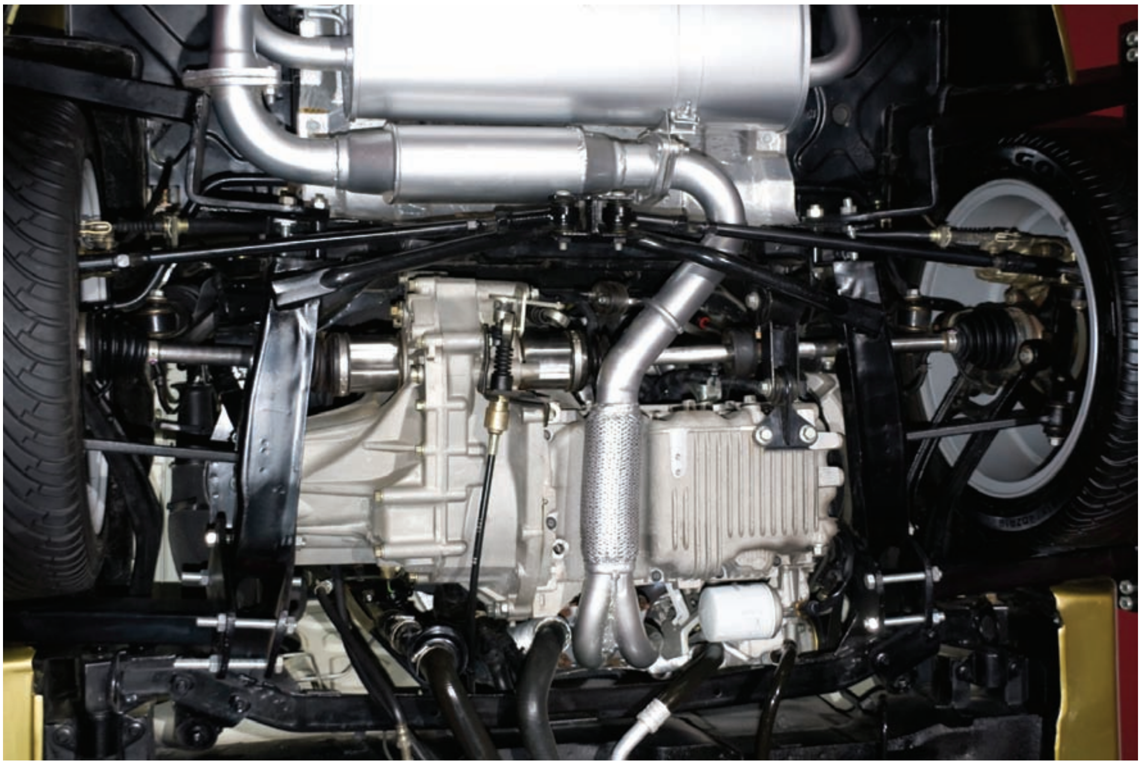
TRW Automotive GmbH
Tech Center Düsseldorf
Tel: +49 2115840;
Web: www.trw.com
Quote ref VDI 001

LEFT: **TRW'S BELT DRIVE EPS SYSTEM CAN BE PROGRAMMED THROUGH THE SOFTWARE TO INTEGRATE SEVERAL ADVANCED STEERING FUNCTIONS TO IMPROVE SAFETY AND ASSIST THE DRIVER**

BELOW LEFT: **INTEGRATION OF THE EPS WITH TRW'S ESC SYSTEM IS ALSO POSSIBLE, PROVIDING STEERING RECOMMENDATION IN SPLIT-MU BRAKING CONDITIONS**

Sensor range expansion

IMAGES THIS PAGE: **SENSORS ARE BECOMING INCREASINGLY IMPORTANT TO TODAY'S COMPLEX VEHICLE CHASSIS SYSTEMS**



For more than 30 years, Dytran Instruments has been a leading industry manufacturer of piezoelectric sensors and supporting electronics for vehicle dynamics measurements, such as stability control, ABS and power steering assessments, suspension system characterizations, automotive and off-highway NVH, emergency acceleration/deceleration, and road-load data acquisition.

These precision sensors have become a popular choice among OEMs and automotive testing facilities for use in the study of vehicle dynamics, due to their low-noise, robust designs, and reliable performance over wide measurement, frequency, and temperature ranges, as well as optional TEDS capabilities for use within larger channel-count applications.

In response to a growing number of customer requests for expanded technology offerings to support lower-frequency vehicle dynamics measurement parameters, Dytran has recently expanded its sensor technology portfolio to include new

ranges of single and triaxial MEMS DC response and variable capacitance (VC) accelerometers. Just as can be found among the company's piezoelectric models, MEMS DC response sensors offer a choice of sensitivities with lightweight designs and the incorporation of high-quality sensing elements.

MEMS DC response accelerometers are used in the study of vehicle dynamics to make high-sensitivity, low-frequency vibration measurements of acceleration and deceleration and long-duration transient motion events within low-to-medium frequency instrumentation applications, extending down to DC (steady state). These types of sensors are known for their reliable performance over temperature, and their ability to withstand higher levels of shock and vibration inputs, with fast response times and great accuracy over temperature. By adding this sensing type to its already expansive product line offering, Dytran has allowed its customers to benefit from the added capabilities for facilitating lower-frequency vehicle dynamics measurements, as well as enhanced precision measurement capabilities within crash testing, airbag safety testing, and other legislative and safety applications.

Included among the new models now available from Dytran is the 7500A series, a family of ultra-low-noise, single-axis MEMS DC accelerometers. Offered with a choice of eight different sensitivities and in available measurement ranges

IMAGES THIS PAGE: **WHETHER FOR ACTIVE OR PASSIVE SAFETY APPLICATIONS, DYTRAN PRODUCTS ARE ALL TESTED AGAINST RIGOROUS IN-HOUSE STANDARDS**

between 2*g* and 400*g*, these high-precision variable-capacitance (VC) sensors combine an integrated VC chip with high-drive, low-impedance buffering for low-level acceleration measurements. The sensors also offer a low-end frequency response down to DC, with an upper frequency range between 400 and 2,500Hz with differential output. Units are rugged to 5,000*g* shock and operate from +9 to +32 VDC power. These accelerometers are often specified for tilt measurements, crash test, and other low-frequency vibration measurements. A just-launched triaxial version, the Dytran 7503A series, adds further test capabilities.

Another popular series, the Dytran 7600B, is a family of single-axis, high-performance VC accelerometers, designed for use as a drop-in placement for piezoresistive units in new or existing zero-to-medium-frequency instrumentation applications. Available in six different models, with ranges from 5 to 200*g*, the Dytran 7600B series incorporates a MEMS capacitive sensing element and an advanced ASIC to simulate piezoresistive bridge operation, as well as an integrated VC accelerometer chip with high-drive, low-impedance buffering. Units respond equally well to both DC and AC acceleration.

Onboard regulation minimizes supply voltage variation effects, making them relatively insensitive to temperature changes and thermal gradients. The sensors are also hermetically sealed for reliable operation in high-humidity or dirty environments, and feature a custom integrated circuit amplifier and differential output stages, with an M4.5 x 0.35, four-pin radial connector, with easy mounting via two 4-40 screws.

Dytran 7600B series accelerometers use the same power supply as traditional piezoresistive and strain gauge sensors, allowing them to operate as standalone differential output accelerometers or in place of piezoresistive bridge-type accelerometers. These sensors are ideal for crash test, ride quality, and measurements of longitudinal vehicle acceleration and deceleration.

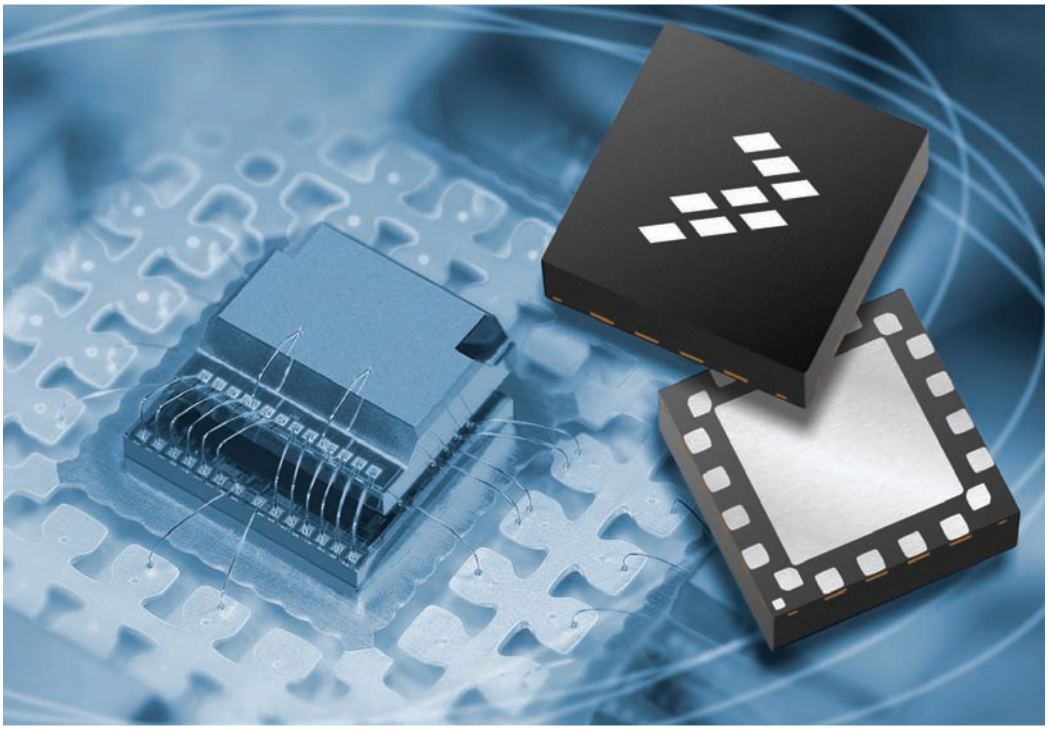
As a lower-cost alternative, Dytran also offers the 7521A series of single-axis DC response accelerometers, also designed for low-level, low-frequency vibration measurements, with stable operation over a broad temperature range. The sensors offer a low-end frequency response of 0Hz and an upper frequency range between 400 and 1,500Hz, with availability in a variety of sensitivities to support various application types. Units occupy a small footprint and feature a lightweight aluminum housing, with an integral cable and total weight of just 3.7g. They are supplied ready-to-operate and require only a 5V regulated supply voltage for power. A triaxial version, the 7523A series, offers additional low-frequency vibration measurement across three orthogonal axes.

In addition to its standard product line offering, Dytran has the necessary in-house capabilities to custom design and package nearly any sensor, connector, or cable to precise customer or vehicle dynamics test program specifications, with highly competitive pricing and lead times. Calibration services are also A2LA accredited to the ISO 17025 standard, ensuring product quality and uniformity.

CONTACT

Dytran Instruments, Inc
Tel: +1 818 700 7818;
Fax: +1 818 700 7880;
Email: info@dytran.com;
Web: www.dytran.com
Quote ref VDI 002

MEMS accelerometers



STACKED DIE CONFIGURATION OF THE MMA6900Q LOW-*g* SENSOR IN A QFN 6 x 6MM PACKAGE

Many governments are now introducing vehicle safety legislation programs that shift the focus from passive to active safety. For example, all new vehicles up to 4.5 tons sold in the USA will have to be equipped with ESC by 2012. And the European Commission has adopted legislation on ESC for new cars by November 2014, following major countries like Brazil, Japan, and South Korea, which have already announced their own ESC mandates for 2012 and beyond.

All these mandates create a huge demand and so it is no surprise that Strategy Analytics recently announced that safety systems will provide one of the highest growth applications over the 2009 to 2014 period. In turn, this is creating new opportunities for MEMS sensor manufacturers like Freescale Semiconductor, which was ranked by iSuppli as the number one supplier of automotive MEMS accelerometers in 2009.

The demand is mainly driven by the implementation of several active systems including ESC, which goes from 26 million today up to 44 million systems in 2014. iSuppli estimates that this would represent a market of 47.7 million MEMS accelerometers at that time, 66% being standalone, dual-axis, low-*g* sensors.

The use of two-axis, low-*g* sensors gives also the possibility to integrate new functionalities such as hill start assist and electric parking brake (EPB) by measuring accurately the tilt of the vehicle while on a slope. The addition of such functions, together with the already tight performance required by the ESC, is a challenge for the accelerometer.

In an ESC system, the various MEMS sensors are usually installed very close to the vehicle's center of gravity and their task is to continuously watch for the vehicle's chassis movements. Together with a yaw rate sensor, which measures the angular acceleration along the vertical axis, a low-*g* inertial sensor is used to detect the vehicle's lateral acceleration and thus provide additional information to the system. During a loss of control when the vehicle starts to slide, this acceleration is less than 1*g*. So the inertial sensor must have a high sensitivity to sense the low-*g* motion together with a high accuracy. This translates into a device's output need with very low noise and a small zero-*g* acceleration shift in temperature.

Furthermore, the accelerometer needs to be immune to the parasitic, high-frequency content present in the car at the chassis level. Low energy signals with large frequency bandwidth can be found, from a few hundred Hz during normal driving conditions to a few kHz due to shocks coming from the road. Frequencies above 1kHz must be filtered to avoid corrupting the sensor response.

By definition, an inertial sensor is highly sensitive to acceleration of any origin, since the micromachined sensing element is based on a seismic mass moving relative to a fixed plate. The sensor output signal is typically cleaned of parasitic high frequencies via electronic low pass filtering. A sensor with an overdamped transducer, which can eliminate this unwanted higher frequency acceleration content, mechanically provides additional benefit.

Freescale recently released the MMA6900Q, an advanced XY low-*g* accelerometer that tackles all these challenges. It brings interesting characteristics and features making it perfectly suitable for ESC systems. It offers a robust design with very good immunity to parasitic vibrations and a wide full scale range (±3.5*g*), thus enabling the ESC application to remain operational above ±1.7*g* in case of vehicle roll-over conditions. It also provides low noise output with a ±50mg offset stability over the entire automotive range, from -40°C to 105°C.

Like most Freescale accelerometers, the MMA6900Q includes a surface micromachined capacitive sensing element and a control ASIC for the signal conditioning (conversion, amplification, and filtering) assembled in a small QFN 6 x 6mm plastic package.

One of the key elements in the device's performances is obtained due to the proven automotive High Aspect Ratio MEMS transducer (HARMEMS). The term 'high aspect ratio' refers to the width of the key mechanical features in the transducer such as the spring portion of the mass-spring system or the gap between movable and fixed capacitor plates.

The technology delivers this high aspect ratio by a combination of a 25µm thick SOI layer and narrow trenches defined by deep reactive ion etching (DRIE). The HARMEMS silicon on insulator (SOI) process uses a deposited polysilicon layer, with air bridges, to form the electrical interconnects for the MEMS die. The poly air bridges are formed on a sacrificial oxide layer after the DRIE is used to form the MEMS structures. A timed chemical etch is then used to release the MEMS structures.

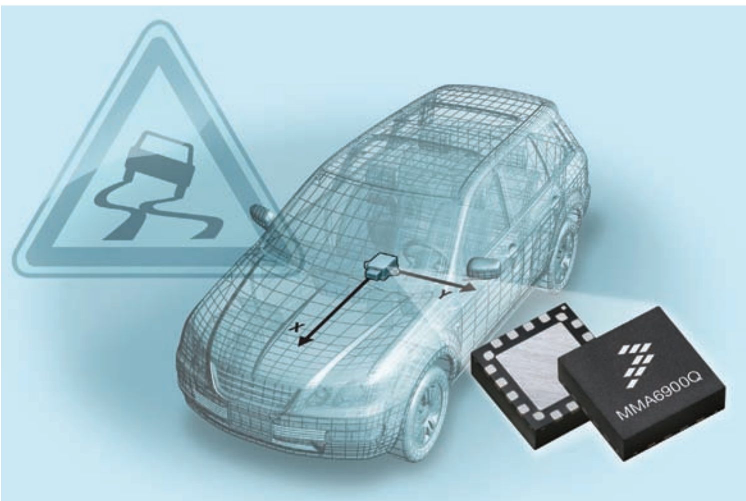
Single crystal SOI enables better control of the DRIE process, thus giving better consistency in the mechanical properties of the device. The thick SOI layer provides increased stiffness and greater mass for the moving mechanical element, plus increased electrical capacitance. Benefits are an increased sensitivity with an enhanced noise performance compared to standard surface micromachined processes, together with improved reliability since it better mitigates possible in-use stiction. Combined with higher-than-vacuum hermetic sealing made possible with glass frit wafer bonding, the transducer experiences considerable air resistance as it moves, providing an overdamped mechanical response with a natural cut-off frequency below 1kHz.

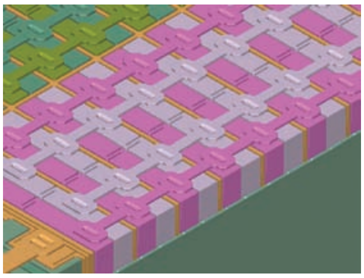
Finally, small error tolerance of the system is enabled, again by the high aspect ratio of the MEMS process. Thicker capacitor plates mean less out of plane deformation of the sensor structure due to package stress over temperature variation. And, the improved signal-to-noise ratios available in HARMEMS translate to lower gain of the transducer signal in the sensor system. Errors in transducer, ASIC, or package are reduced, making for a tighter total error from the product system.

For signal conditioning, an automotive proven 0.25µm analog mixed signal technology is used combining precision analog blocks and high-speed CMOS logic. Its high density of 25K gates/mm^2 enables the integration of complex digital signal processing blocks (DSP) with many parametric trimming options.

Two independent 16-bit sigma delta converters for the X and Y channels provide the interface between the sensing element and DSP. Their detection resolution has been improved, due to a high over-sampling frequency of the ΣΔ conversion, increasing the signal/noise ratio and dynamic range.

The device has a 4ms maximum recovery time following acceleration overload. A full digital signal conditioning is implemented bringing advantages such as programmability (filters; acceleration range) and auto diagnostics. Data integrity features improve the system's fail-safe strategy like a continuous parity determination of programmed data array and SPI commands, capable of detecting potential 'bit flips' during operation. Should any of these integrity checks fail, the device will respond with an error message, avoiding that communications faults could be misinterpreted for valid acceleration measurements.





LEFT: **A HARMEMS TRANSDUCER, WITH THICK SOI LAYERS, NARROW TRENCHES, AND POLY BRIDGES**

BELOW LEFT: **MMA6900Q, DUAL-AXIS XY LOW-*g* SENSOR TARGETING ESC APPLICATIONS**

The device temperature and all critical internal voltages are continuously monitored, improving the accuracy of acceleration measurements. The device resets if any voltage exceeds acceptable limits or sends an error message when temperature exceeds a certain threshold. It provides an 11-noise-free-bit data output, thus reducing susceptibility to PCB routing effect. Furthermore, it offers flexibility to the system designer by proposing a dual power supply 3.3V or 5V capability.

For packaging, MMA6900Q comes in a 16-leads 6 x 6 x 1.98mm QFN. This industry standard package enables smaller PCB designs and better immunity to parasitic frequency vibrations. Indeed, its first package drum mode resonance frequency is at around 160kHz (per FEA results), far above any potential parasitic frequencies found in a vehicle.

CONTACT

Matthieu Reze
Freescale Halbleiter Deutschland GmbH
Tel: +49 89 92 103 875;
Email: Matthieu.reze@freescale.com;
Web: www.freescale.com
Quote ref VDI 003

Simulator reality check

RIGHT: **THE GRAPHICS BLUR THE DIVIDE BETWEEN THE PHYSICAL AND VIRTUAL ENVIRONMENTS**

Since its launch three years ago rFactor Pro has fast become the 'must-have' simulation development tool for any serious professional motorsport or performance car organization.

Initially developed for an F1 team in 2008 under the leadership of technical director Chris Hoyle, rFactor Pro 'driver-in-the-loop' (DIL) simulation technology has become a top development tool for vehicle dynamicists and race engineers in all categories of the sport.

Simulator technology in motorsport is nothing new of course, but the fact that rFactor Pro is now established within five F1 teams, as well as in NASCAR and feeder series, has grabbed the attention of many team owners. Faced with increasing restrictions on testing and expenditure, teams have seen that this particular technology is very different in the way it offers more potential in the quest for laptime improvement per dollar spent.

Hoyle himself reveals why an F1 team would abandon many man-years of in-house development, not to mention the possible millions in financial investment, and then swap over to rFactor Pro.

"rFactor Pro has been designed to meet the needs of all participants in the high-performance car and motorsport industries," he says. "It incorporates a number of unique features, which allow a human driver-in-the-loop to truly contribute to engineering development."

Most people used to think of a simulator purely as a driver training tool but this use is perhaps the least relevant to overall performance improvement.

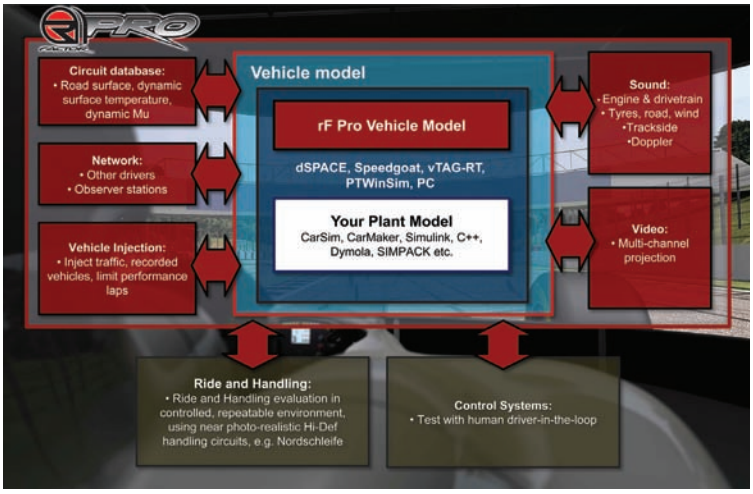
"You're not going to make an F1 driver a better driver with a simulator – even though it can be helpful for an established driver to learn a new circuit or maybe for a team to test how good a rookie might be," Hoyle continues.

"The true value in rFactor Pro is that it provides such a realistic and immersive experience for the driver that his own 'virtual' performance can truthfully mimic his 'real world' ability and, as a consequence, provide engineers with an accurate assessment of whether a new development is a quantifiable improvement."

The advantages of having a human DIL are becoming increasingly apparent to vehicle dynamicists and car designers. In reality, traditional methods of developing new parts derived from using Lap Sims, wind tunnels or CFD alone often do not result in an anticipated lap-time improvement. Once a car has taken to the track, a predicted aero gain may evaporate if a dynamic handling instability effect also occurs that only the driver can detect.

Adding increased realism to a DIL simulator is a major factor in what differentiates rFactor Pro from solutions the F1 teams used in the past.

"It is essential that the driver feels as if he is working in his real environment and not subconsciously thinking he is playing on a computer game," says Hoyle. "To achieve this we do a number of things to



LEFT: **SOME OF THE FEATURES AND BENEFITS OF rFACTOR PRO'S SIMULATION TECHNOLOGY**

maximize cueing. We have photo-realistic graphics with ambient occlusion, which creates very naturally lit scenes with hard and soft shadows.

"If a motion platform is used, we can maximize its performance by taking off as much of the payload weight as possible, projecting warped and blended images onto a fixed screen mounted to the ground – and not the motion platform – at an acceptable distance from the driver. By applying optically correct motion-compensation to the graphics, rFactor Pro helps you to get more performance from your existing motion hardware".

Supplying accurate tracks is another important factor.

"We have an ever-increasing library of high- and low-definition tracks to offer clients, with options on graphics quality and price," adds Hoyle. "Track surface detail is achieved by mapping survey photographs to a LiDAR point-cloud-generated road surface, and the results can be stunning. We can offer nearly all the F1 tracks, as well as La Sarthe, the Nordschleife, and many more."

If the drivers are more convinced about what they are experiencing with rFactor Pro it would seem that the vehicle dynamicists and team owners are too.

"The way rFactor Pro has been created means that engineers are able to develop and integrate their own vehicle model in a way that keeps it detached from the rest of the simulator software and functionality. This means one definitive vehicle model can be developed offline and used by all departments within the organization using a variety of tools such as CarSim, CarMaker, Dymola, Simulink, SIMPACK, and C++."

It also means that if a third-party simulator is used, a client can be assured of keeping their IP protected as rFactor Pro effectively 'wraps' around a vehicle model – enabling it to be 'plugged or unplugged' at the appropriate time.

Alternatively, clients without their own vehicle model can run with rFactor Pro's internal model. Crucially, this enables them to replace one component at a time for a lower-risk approach to developing a full-car vehicle model of their own.

Of particular importance to the automotive marketplace is the ability to support hardware-in-the-loop (HIL) with dSpace, vTAG-RT, and Speedgoat, or software-in-the-loop (SIL) on Win7-64 and vTAG-310 for the testing of control systems with a human DIL. rFactor Pro can be used as the plant model or by integrating with CarSim, CarMaker, Simulink, Dymola and SIMPACK.

Even in the automotive world, simulation is not all about control systems. There is still a need to simulate vehicle dynamics and rFactor Pro offers a very high-quality, controlled, repeatable environment in which to lap the Nürburgring or a preferred handling circuit, but with near photo-realistic visuals.

Another of the company's strengths is its independence as a consultancy to coordinate or propose complete turnkey solutions.

"We work with a number of partners with whom we integrate our respective technologies, and provide clients with complete turn-key solutions – at various levels of sophistication or budget," Hoyle explains. "We pride ourselves that we remain independent and are able to recommend complementary technologies and hardware that suit a client's needs precisely. We can even supply a static transportable and demountable simulator to take to events if required."

This philosophy is typified in the area of the selection of motion platform partners. Not all clients have the budget or desire to integrate a motion platform but for those who do, a number of options are available.

At one end of the scale, an rFactor Pro-integrated hexapod solution can be provided with a frequency response in the region of 15-20Hz, but with very large excursion capability. At the high end of the performance scale another partner supplies a motion platform that peaks at 250Hz, high enough not just to provide faithful motion cueing for handling and ride, but also to pass on NVH.

Now, with motorsport clients becoming well established, Hoyle is turning his attention to the general automotive market.

"From the results we have seen with motorsport clients, we have been left in no doubt that rFactor Pro DIL technology will soon have a direct impact on the way the automotive industry as a whole will be developing cars in the future. It will be in a virtual world with a human driver-in-the-loop."

CONTACT

rFactor Pro
Email: chris.hoyle@rfactor-pro.com;
Web: www.rfactor-pro.com
Quote ref VDI 004

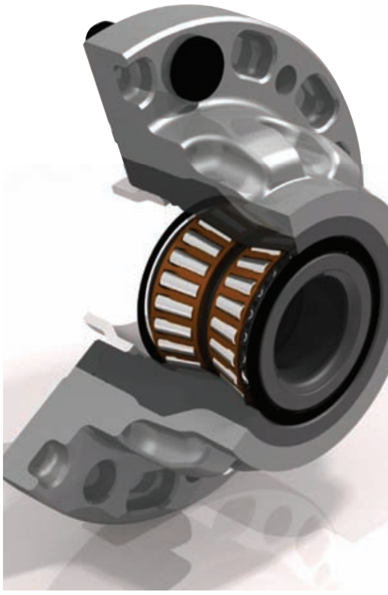
Lighter hub bearing unit

RIGHT: **SKF'S LATEST LOW WEIGHT HUB BEARING UNIT IS MADE OF ALUMINUM, BUT PERFORMS AS WELL AS A NORMAL STEEL UNIT**

The design of modern wheel hub units for cars requires an effective balance of several factors including weight, cost, durability, stiffness, and friction. Other requirements to be considered relate to the growing variety of models, including electric vehicles. Hub units must cope with high speeds and massive forces under precise environmental conditions, as they are the only structural link between the rotating wheels of the vehicle and its static body.

SKF has been working for many years to address these technical challenges. With its deep engineering knowledge, SKF has succeeded in finding ways to reduce the mass of wheel hub units. The latest results have made significant contributions to the unsprung mass and inertia reduction. This contributes directly to reduced fuel consumption and related CO_2 emissions, as well as being a positive influence on the overall vehicle dynamics.

In the near future, when every milligram of CO_2 reduction will count, engineers will need to think outside the box and develop innovative solutions. SKF engineers have used modeling tools to simulate various solutions, exploring new technologies, prototyping, and fully validating robust products.



The real challenge has been how to combine steel, which provides the expected performance, with another lighter material, which could reduce the overall weight.

Studies have focused on how to combine the use of new materials with a design that would maintain stiffness, endurance, and structural integrity, under corrosive and varying operating temperatures.

The result is a lighter wheel end solution, the SKF Low Weight Hub Bearing Unit. Despite the material change from steel to aluminum, the same performance and reliability levels have been maintained.

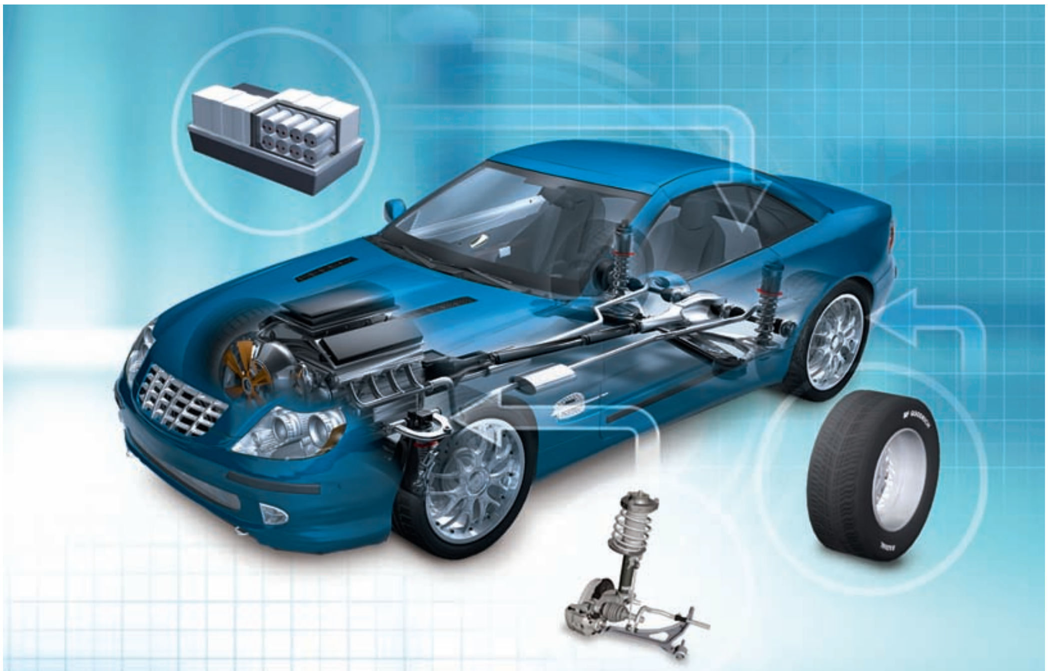
For example, in premium cars the unit is able to reduce the weight by 1kg per axle, reducing CO_2 emissions by approximately 0.1g/km.

For light commercial vehicles the unit can reduce the weight by 3.5kg per axle, reducing CO_2 emissions by approximately 0.3g/km.

In a time when environmental regulations worldwide are getting tougher, SKF can offer a low weight wheel end solution that offers a combined effect of friction and mass reduction, together with reduced CO_2 emissions.

CONTACT
Katia Girini
Tel: +39 02 48327207;
Email: katia.girini@skf.com;
Web: www.skf.com
Quote ref VDI 005

Simulation central



Today's development process for automotive control algorithms is highly complex. Modern control algorithms require intensive interaction between distributed functions on different electronic control units (ECUs).

A typical development process starts with the PC-based simulation of single control functions and ends with a full-blown ECU network test on a hardware-in-the-loop simulator (HIL). During each development step, functions have to be verified by simulating them together with a model of the device under control (e.g., combustion engine, brake hydraulics, electric motor).

dSPACE Automotive Simulation Models (ASM) are the ideal toolkit for this. They are MATLAB/Simulink-based models for simulating essential automotive components and properties, such as combustion engines, electric motors, vehicle dynamics, electrical systems, and traffic for passenger vehicles as well as commercial vehicles.

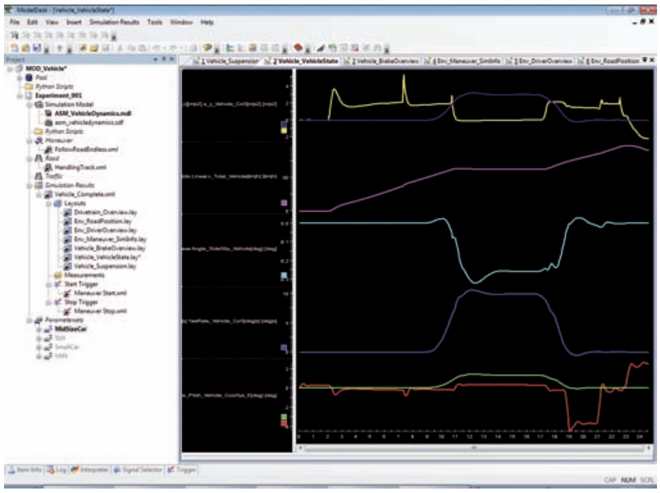
The models are open down to Simulink block level so that users can view the functions and modify them in any way they want. This is especially useful since in practice, developers often create their own models of the controlled system or components to cover specific aspects. Indeed, creating such models is regarded as the user's core competence. Users supplement the ASMs or replace parts of them with self-defined models, such as a specific tire model or one for brake hydraulics.

The ASMs plus the custom extensions can be handled as one model if both are integrated into ModelDesk, the central graphical front end for configuration, parameterization and simulation. ModelDesk takes care of the parameters and simulation results of both kinds of models – a prerequisite for seamless process integration.

The new version of ModelDesk includes powerful functions for directly executing and displaying simulations, and managing their results. Users can start and stop simulations on the PC and on the HIL system; save, compare, and manage simulation and measurement data; and save simulation experiments such as driving maneuvers, roads, traffic, etc. There are ready-made plotters that provide the signals of individual models, for example, for direct access to vehicle dynamics characteristics. Further stimulus signals can be included or displayed in additional plotters. The ASM signal bus's clear design makes it easy to select signals.

With its integrated simulation functions, ModelDesk is the main user interface, bringing together all the tasks that are essential before, during, and after simulation. ModelDesk and the ASMs are equally well suited to model-in-the-loop (MIL) simulations or Simulink simulations (offline) and hardware-in-the-loop (HIL) simulations (online), so they support an integrated process from function development to ECU testing.

During simulation experiments, ModelDesk stores parameters such as roads, driving maneuvers, traffic, and vehicle configurations together with the simulation results and any measurement data to ensure that simulations are easy to reproduce. Offline and online simulations can also be compared just as easily.



All the simulation and graphical parameterization features can also be applied to custom models. Together, the ASMs and ModelDesk form a framework that brings together all the models required so they can be run from one user interface.

TOP: **CUSTOM MODELS CAN BE EASILY INCLUDED IN THE OPEN AUTOMOTIVE SIMULATION MODELS**

ABOVE: **SIMULATION RESULTS VISUALIZED IN MODELDESK**

CONTACT
dSPACE GmbH
Tel: +49 5251 1638 0;
Email: info@dspace.com;
Web: www.dspace.com
Quote ref VDI 006

Inertial measuring

RIGHT: **MANY AUTOMOTIVE SENSOR APPLICATIONS ARE AIMED AT IMPROVING ROAD SAFETY**

INSET: **THE VTI SCC1300 IS A COMBINED X-AXIS GYROSCOPE AND THREE-AXIS ACCELEROMETER**

Electronic stability control (ESC) is currently the main automotive sensor application, but new uses – especially for gyros – are emerging all the time. Safety remains the focus for now, but in future we could see user-interface applications taking advantage of high-performance inertial sensors.

Featuring yaw, lateral accelerometer, and steering angle sensors, ESC is the most widely spread automotive sensor application and the one that is most familiar to drivers and engineers. Recent sensor developments have led from a separate sensor cluster to integration in the brake ECU under the hood. This has been enabled by more robust gyro sensors such as the SCC1300 from VTI, which withstands the vibration and temperatures under the hood. More on this later.

Besides ESC, a number of new applications featuring inertial sensing are emerging, and it seems that we are only seeing the tip of the iceberg in terms of new applications. For example, Jaguar makes its diesel engines quieter and more refined by actively measuring and damping engine vibration.

With the pressure to downsize engines, including the adoption of three- and two-cylinder engines as well as cylinder shut-off systems, noise, vibration, and harshness (NVH) properties are becoming more complex. As a result, more intelligent mounting systems are required. Volvo is using the same type of sensor used for detecting heartbeats for its Volvo Heartbeat system. And, if you can detect a heartbeat, you will be able to detect if and how the seats are occupied and then use that data for various safety systems.

The VTI sensing elements with different measurement axes, ranges, and frequency responses are combined with analog or digital electronics, depending on system requirements and capabilities to suit any vehicle measurement need.

The same sensors with slightly different tuning are also being used to refine the ride of the Porsche Cayenne, Mercedes S-Class, and many others. An interesting note is that although most vehicles only require a body sensor and a suspension position sensor, those in the supercar league occupied by the likes of Ferrari require another accelerometer in the wheel hub, as the suspension travel in a sports car is so short.

So far we have not seen inertia-based user interfaces in the automotive environment, but as they are becoming more popular in gaming and mobile devices, it is only a matter of time before we begin to see these kinds of applications as well.

Meanwhile, new sensor applications emerge, and to satisfy the growing demand, VTI, the market-leading manufacturer and supplier of sensitive (low-*g*) acceleration sensors to the global automotive industry, has recently expanded its product range to gyros and combined sensors.

VTI's sensors are based on the company's proprietary 3D MEMS technology that enables high robustness, extremely accurate measuring, and excellent offset temperature. The SCC1300, combining an X-axis gyroscope and a three-axis accelerometer, is exceptionally insensitive to mechanical shocks and vibrations, and presents a superior angular rate bias stability over temperature and time.

Indeed, SCC1300 is so accurate that according to a research study implemented by the University of Tampere in Finland, it is possible to measure the Earth's rotation with it. This leaves some room for car designers' imaginations!

CONTACT
Contact Tommi Vilenius, product manager, VTI Technologies Oy
Web: www.vtitechnologies.com
Quote ref VDI 007

automotive EXHIBITOR testing expo 2011 europe

Robotic driving systems

ABOVE: **LONG-RANGE RADIO SYSTEM**

LEFT: **CUTAWAY OF THE SCTV TO SHOW CENTRAL DRIVE BOX AND INFLATABLE CUSHIONS**

BELOW LEFT: **SR15 STEERING AND CBAR (DRIVERLESS) PEDAL ACTUATOR IN A FORD FOCUS**

BOTTOM LEFT: **(DELIBERATE) REAR IMPACT BETWEEN FOCUS AND SCTV**

Most major automotive manufacturers already use driving robot systems designed and manufactured by Anthony Best Dynamics Ltd (ABD), predominantly for on-track vehicle dynamics development work. New products developed by ABD extend the range of applications to include vehicle durability testing and the evaluation of vehicle advanced driver assistance systems (ADAS).

The soft crash target vehicle (SCTV) is a new ADAS specific product from ABD, developed in conjunction with Daimler, for the testing of vehicle collision detection and crash avoidance systems. It enables precise and repeatable low-speed collision scenarios to be performed without causing damage to the test vehicle.

The SCTV comprises a central drive box surrounded by inflatable cushions. The central drive box is physically compatible with inflatable cushions specified by the European ASSESS project (http://www.assess-project.eu). The SCTV accurately follows a specified path at speeds up to 70km/h, and its robust design can withstand impacts of 50*g*. The SCTV can be used in conjunction with vehicles fitted with ABD driving robot systems to create synchronized and highly repeatable collision scenarios. A typical scenario is a vehicle driving into the side of the SCTV at a road intersection, or a rear collision as shown below.

The SR15 steering robot and the combined brake and accelerator robot (CBAR) are new ABD products particularly suited to ADAS and durability test applications, where the peak steering torque and pedal forces are lower than those required for vehicle dynamics testing.

James Holloway, design engineer, comments, "The entry-level lightweight geared SR15 steering robot can be quickly and easily installed onto the steering wheel in a few minutes. Although the SR15 has lower torque capability than ABD's direct-drive steering robots such as the SR-60 Torus, it is more than adequate for most ADAS and durability test applications."

CBAR is a more compact, lighter and cost-effective alternative to ABD's proven brake and accelerator robots. It can be easily installed in most vehicles, with or without a driver, and has sufficient force/speed performance for most typical ADAS and durability test scenarios. For driverless applications the CBAR is fitted with an integral redundant braking system for increased safety. The CBAR actuator can be upgraded to include a clutch actuator for vehicles with manual gearshift.

Another product innovation from ABD is the use of long-range, license-free radios for data communication between multiple vehicles. The system was primarily designed for driverless system base-station to vehicle communications, but is also suited to ADAS applications.

Mat Hubbard, technical director explains, "There is a requirement during ADAS testing to reliably pass real-time data between vehicles. Our product uses high-quality, military-grade antennae and a customized, programmable router to achieve excellent working range without signal dropouts."

ABD has now supplied more than 200 robot systems to customers around the world, working closely with users to produce timely solutions to ever-evolving vehicle test requirements.

CONTACT
Jeremy Ash, senior engineer, Anthony Best Dynamics
Tel: +44 1225 860200;
Email: info@abd.uk.com;
Web: www.abd.uk.com
Quote ref VDI 008

OxTS

Cone placement tool

OxTS has released a cone placement tool for RT measurement systems to ensure the highest accuracy and repeatability for vehicle dynamics tests. The tool makes it simple to lay out cones accurately on a proving ground – a task that can be very hard without the correct tools.

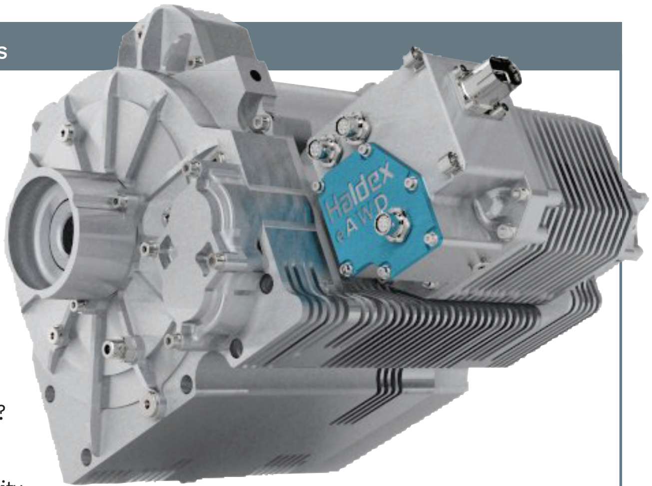
With the RT inertial and GPS navigation system installed correctly in the vehicle, the tester chooses a location on the outside of the vehicle where the cones will be dropped and measures their position accurately. A CSV file is loaded, containing the locations of the cones and the software guides the driver to the location where the cone can be dropped. Using a tape measure, small offsets from the car's position to the correct cone location can be compensated before moving on to the next cone.

The tool transforms the cone coordinates in the CSV file from meters to latitude and longitude so that the same cone locations can be placed at different proving grounds. An export to Google Earth can be used to check the cone locations are correct before driving begins. By using the line survey tool of the RT-Range, the position of cones can be surveyed at one location and then laid out at another location or at another time.

For more information go to www.oxts.com
or visit www.ukipme.com/recard/vdmcard.html
quoting reference VDI 009

BorgWarner Drivetrain Systems

New eAWD system



THE HALDEX EAWD SYSTEM COMBINES ELECTRIC AWD WITH BUILT-IN TORQUE VECTORING TO IMPROVE STABILITY, TRACTION AND ECONOMY, AND LOWER EMISSIONS

The Haldex eAWD system from BorgWarner Drivetrain Systems solves a dilemma facing electric and hybrid vehicle manufacturers of how to provide all-wheel drive traction and stability without adding the weight and driveline losses that increase emissions and reduce fuel economy?

The solution is an electrically driven all-wheel drive system with built-in torque vectoring functionality.

The eAWD system consists of an electric traction motor that provides both propulsion and regenerative torque to the rear wheels through a planetary gear arrangement on each side. The traction motor can be dimensioned for the required torque from the eAWD system (working in conjunction with the front powertrain) up to pure electrical drive. For improved lateral dynamics, a smaller electric torque vectoring motor adjusts the differential torque left to right between the rear wheels on a balance shaft. This enables vectoring torque independent of vehicle speed, and delivering more stability with the fun-to-drive experience drivers crave. The controllable system continuously calculates and adjusts torque transfer to provide superior handling and traction, even at different speeds and vehicle states. Because the eAWD system is always active, no driver intervention is needed, making the combination of exciting performance and improved safety effortless.

Further details are available from corpmktg@borgwarner.com.

For more information go to www.borgwarner.com
or visit www.ukipme.com/recard/vdmcard.html
quoting reference VDI 010

GeneSys Elektronik

Altitude and position

THE BAROMETRIC ALTITUDE SENSOR AND ADMA SYSTEM TOGETHER SUPPLY ACCURATE HEIGHT DATA

One prerequisite of driving tests as part of vehicle development is to precisely determine the vehicle's position. In such applications, the ADMA (Automotive Dynamic Motion Analyzer) from GeneSys Elektronik delivers optimized and highly precise data.

Developed originally for vehicle dynamics testing, developers use the ADMA with increasing frequency for validating driver assistance systems, such as lane departure-warning systems. Another important function of ADMA is to provide road data including realistic height profiles. This information is needed, in particular, to optimize powertrain design.

To ensure precise positioning even under difficult GPS reception conditions, GeneSys Elektronik now presents the new ADMA-PP post-processing software which enables optimization of ADMA data recordings and inclusion of GPS correction data after the test drive. The software's core is a Kalman filter which perfectly combines GPS and inertial data.

Although the real-time option continues to be provided by the ADMA system, offline calculation has two decisive advantages. Firstly, GPS correction data can be downloaded easily from the Internet for the required test run. This facilitates installation work for the measurement process compared to the real-time mode, where GPS correction data must be supplied via a radio or GSM link from a private base station or an RTK network provider. Secondly, ADMA-PP is able to calculate position solutions forward and backward along the time axis, which improves positioning accuracy.

The package is rounded off by an auxiliary module with a barometric altitude sensor enabling accurate measurements of critical height-related data.

For more information
go to www.genesys-offenburg.de
or visit www.ukipme.com/recard/vdmcard.html
quoting reference VDI 011

Mechanical Simulation Corporation

ESC compliance testing

CARSIM RT RUNNING ON A DSPACE HIL SYSTEM CONNECTED TO AN OPERATING FORD F-150 ESC CONTROLLER. DEMONSTRATED AT THE 2010 SEMA SHOW

Assuring compliance with government safety regulations is normally carried out by vehicle manufacturers, but when vehicles are modified with aftermarket products an alternative means to ensure compliance is needed. This became a particular problem for members of the Specialty Equipment Market Association, SEMA, in the USA with the promulgation of ESC regulations. Consequently the Association sought outside help to develop a "best practices" solution to offer their membership.

Drawing on the experience of Advanced Controls Engineering Consultants LLC, the CarSim vehicle dynamics simulation from Mechanical Simulation Corporation, and the HIL technology of dSPACE GmbH, a virtual test method was demonstrated at the 2010 SEMA Show in Las Vegas. A modified Ford F-150 pickup supplied by Superlift Suspensions, was used as the testbed.

In the demonstration a virtual model of the pickup truck in CarSim was connected to the ESC controller and brake system of the actual truck via the dSPACE hardware. CarSim software provided a dynamic model of the pickup, a proving ground on which to conduct the tests, and the steering and throttle inputs required to execute the ESC sine with dwell test. This demonstration, held in the SEMA Vehicle Technology Lab, gave SEMA show attendees a first hand look at the effect of various vehicle modifications on ESC performance.

For more information go to www.carsim.com
or visit www.ukipme.com/recard/vdmcard.html
quoting reference VDI 012

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Sacred ground?

JOHN HEIDER REFLECTS ON THE IMPLICATIONS OF PROVING GROUND SALES

"Replicating a preferred ride or handling circuit of 2km in length is a much more palatable task than doing the same for a 20km durability loop"

The changing landscape of the North American automotive market in recent years has had a considerable impact on what most OEMs used to consider their 'crown jewels' – the massive, infrastructure-laden proving grounds where vehicles are developed and proven out.

Ford, GM, Chrysler and others all sold major proving ground facilities over the past 10 years – a strategic decision that rarely would have been considered in prior decades. As this issue of *VDI* goes to press, in the USA there are at least three ex-OEM proving grounds on the market: the former Honda facility in California, the former Ford/Harley-Davidson facility in Florida, and the former Chrysler facility in Arizona (now entombed as Chrysler left it with an uncertain future). Who would have guessed there would ever be a buyer's market for proving grounds?

OEMs and suppliers have different perspectives on their proving grounds. Some view their facilities, road surfaces, and capabilities as a competitive advantage not to be shared; others look at them as capital investments that can be used to generate cash flow for the company. There is, of course, no right answer. Companies such as Ford, Chrysler, and Nissan, which have invested money in attracting brokering customers, reap large, real-time cash flow; others keeping their gates closed have a less well-defined and longer-term payback equation.

But will these facilities be missed by their former owners? Despite the increased use of CAE simulation for every attribute of a vehicle, proving grounds continue to be the ultimate tool used in the development of modern vehicles. From a vehicle dynamics perspective, CAE simulations have produced tremendous advances by improving the function of early prototypes, reducing the number of tuning iterations and improving a vehicle's sensitivity to error states.

Having said that, the major deficiencies in vehicle dynamics CAE capability requiring on-road development work at proving grounds fall into three major categories: tire limit handling, enveloping, and overall non-linear characteristics; chassis system friction, compliance and overall hysteresis, and mid- to high-frequency transmissibility from road and powertrain inputs to the driver. To evaluate these attributes, a prototype vehicle, a comprehensive set of controlled road surfaces, a skilled engineer, and/or objective test equipment is required.

When an OEM closes a major proving ground facility, the implication is that the work will be contained at an alternative facility. For vehicle dynamics engineers, with some advanced planning and capital expenditures the risks of changing proving grounds can be managed and can even result in enhanced capabilities. For other attributes – durability being a prime example – losing historical surfaces for which there exists a tremendous amount of data that correlates proving ground events to real-world customer events, can be problematic. Replicating a preferred ride or handling circuit of 2km in length is a much more palatable task than trying to do the same for a 20km durability loop.

Only time will reveal the full effect of abandoning these facilities. A mass-production vehicle is created from the toolbox of engineering and facility resources deployed by an OEM. When the decision comes whether to run a CAE simulation or physical test, one thing will be assured: that the OEMs with the best tools will produce the most successful products.

John Heider is from Cayman Dynamics LLC, providing vehicle dynamics expertise to the transportation industry: www.caymandynamics.com

FIRST-GENERATION MINIVAN AT THE FORMER CHRYSLER PROVING GROUND IN WITTMANN, ARIZONA IN 1986. THE FACILITY IS ONE OF SEVERAL NOW FOR SALE

ON THE WEB
Further comments from Heider at vehicledynamicsinternational.com

Is this a setup?

CARS WE DROVE RECENTLY THAT DIDN'T BEHAVE AS THEY SHOULD

CASE 23: FIAT 500, BY JOHN MILES

SPECIFICATIONS

Fiat 500 Lounge

Suspension: Independent MacPherson front with lower wishbones anchored to a subsidiary cross-member and anti-roll bar connected to the dampers; twist-beam rear

Steering: Nexteer EPS, turning circle 10.6m

Brakes: Discs, vented 257mm (F), 240mm (R). ABS, EBD

Wheels/tires: 185/55 R15

This example of the re-engineered classic had a 100bhp, 1.4-liter I4 with 185/55-15 tires, six speeds, two-setting EPS and AC, topped off by that familiar Fiat 500-style sunroof. Inside there is a 1950s coffee bar feel, with a heavy dose of shiny cream and gray check panels – all very jukebox and Californian.

Fiat was an early user of EPS. Steering is literally finger light for parking, and at speed efforts are also ladylike. Response gain is quite high until Sport is selected, when the weight gain and consequent response reduction cuts the roll gain a lot.

It's a nippy car like it should be, and stable enough flat out, but response and grip are rather numb, so understeer when it comes in the damp is sudden – more of an outward slip than a steady build-up. On the dual carriageway the twist-beam lateral "shuffle" can be felt with small excitations – a forgivable trait, because in general Fiat has done well enough on the handling front.

But oh dear, that ride. On the first drain cover we encounter there is a thump (fine) then tremble (not fine) from the front and some shaking from the rear. Ten minutes down the road and it is the lumpy ride, especially from the front axle, that is beginning to grate. On we go over Norfolk's rough aggregate surfaces, and on goes the excitable response. Oh how we wish motor manufacturers would do their ride work in the UK. We don't expect a very small car to ride like a Mk 6 Golf, but an hour of this and even our passenger is worn down by the continuous heavy shuddering from the front axle and higher-frequency shaking from the rear. This is sad because the body structural feel is rather good, and primary body control OK too.

Back at base the car goes on the four-post rig for the standard swept sine input test. Lo and behold, the whole powertrain starts leaping about on its mounts at around 8Hz (a frequency spectrum close to human body cavity modes), and as the input frequencies build up, the rear wheels become a blur at 15Hz, the critical wheel-hop mode. A powertrain hydramount would do wonders for the front axle ride (the Ford Ka doesn't have one either), and the extremely soft, voided rear damper top mounts are clearly unable to transfer damping to the body at hub frequencies, therefore smaller inputs, and certainly not worth the downside in axle control if they were fitted for rough surface noise attenuation.

Never mind. Customers are wowed by the little 500's funky looks and overlook the discomfort, probably assuming that all micro cars ride like this. Maybe they do, but at least try one on the optional 175/65-14 tires, or perhaps the twin-cylinder version, whose lighter powertrain probably has less offensive vibration modes.

Looks like the bean counters have struck again.

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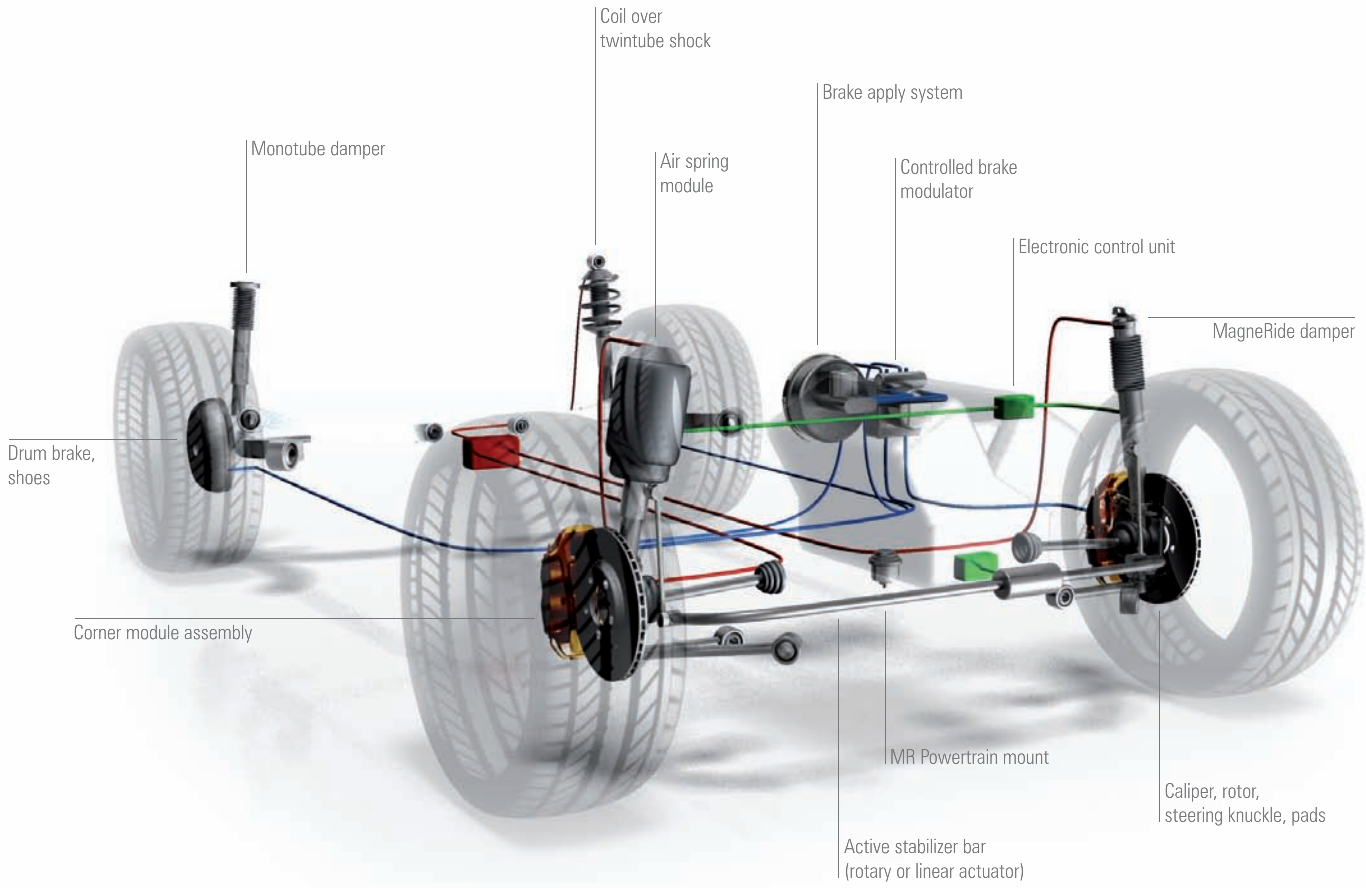

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