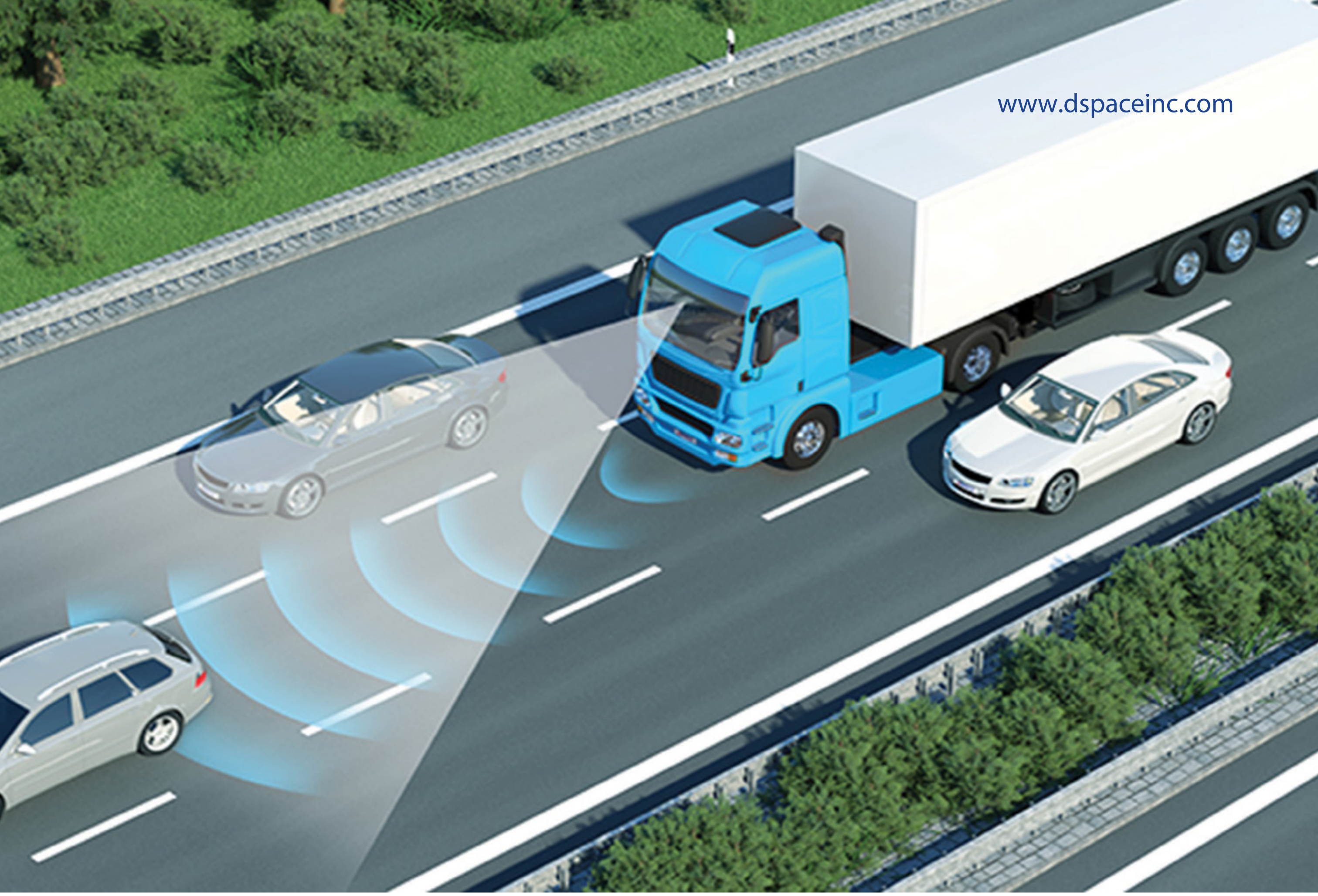
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EDITORIAL

Bright lights, brighter outlook

I'm writing this editorial from a hotel overlooking the brilliantly lit and bustling Las Vegas strip. This description also is apropos for the Las Vegas Convention Center this particular week in March, where bright lights shine on hulking metal machines and nearly 128,000 attendees bustle about the 2.8 million-plus ft^2 of exhibit space to check out the latest and greatest the equipment makers and their suppliers have to offer.

ConExpo/Con-Agg and the collocated IFPE (International Fluid Power Exposition) did not disappoint. Walking the expansive halls and sizable outdoor lots, and chatting with many exhibitors over the course of the week, I sensed a mostly positive outlook for the business being conducted on site, as well as a general good feeling for the economy and industry moving forward.

This sense was echoed in a press release posted to the event website just prior to the doors closing, which proclaimed "Optimism fuels brisk sales activity at ConExpo-Con/Agg and IFPE 2017."

"There was an element of confidence and pent-up demand at the show," Dave Foster, Vice President for Marketing & Corporate Communications at **Volvo CE**, said in the statement. "These are not tire-kickers. These are people willing to buy multiple machines for work they have now and anticipated growth based on a renewed confidence in the market."

U.S. buyer attendance was up 16% compared to the 2014 show, and total buyer attendance improved by almost 8%, according to an event spokesperson. Overall contractor and producer attendance grew by 10%.

Technology-wise, there was also plenty to be optimistic about. Countless new machines were revealed by major players such as **Komatsu America**. Among the three machines it introduced was the new 36-ton-class HB365OLC-3 hybrid excavator that sees a fuel-consumption reduction of up to 20% compared to non-hybrid 36-ton excavators.

Komatsu's fully-electric hybrid system uses an electric swing motor that captures swing deceleration energy which normally would go unused, and makes it available to do work. The energy captured during each swing cycle is stored in an ultracapacitor, which provides energy for the swing system.

Engine makers revealed a number of new offerings as well. For example, **JCB** debuted its new entry-level 3.0-L DieselMax, which will find OEM application in the U.S. later in 2017.

Alan Tolley, group director—engines at JCB Power Systems, said engines with a max output of 55 kW now play a significant role in the market because of the latest emissions standards in the U.S. and Europe. "55-kW is getting very popular," he said. "Above that, you need SCR (for Tier 4 and Euro Stage IIIB compliance)."

Isuzu Motors also made news by announcing a heavy-duty natural gas engine for off-highway application (see page 8 of this issue). Read more ConExpo coverage in these pages and on our website at http://offhighway.sae.org/.

And not surprisingly, connectivity was a major theme, touched on by many exhibiting companies. **Caterpillar**, for example, launched new Cat Connect hardware and software to enable equipment managers to connect all of their assets—from large earthmovers to small generators, and including both light- and heavy-duty trucks and utility vehicles.

Cat refers to these digital technologies as "beyond the iron" solutions, and executives believe these will account for a majority of productivity and efficiency gains made in the future.

"We can improve productivity just through the iron [i.e., technologies on machine] roughly 3-5% a year," George Taylor, Vice President for Marketing & Digital Division, said at a ConExpo briefing. "But what we're finding as we leverage digital technologies, it's growing even faster than that—10-15% improvements in productivity, improvements in fuel efficiency."

By the look of things in Las Vegas, growing optimism is not unwarranted.

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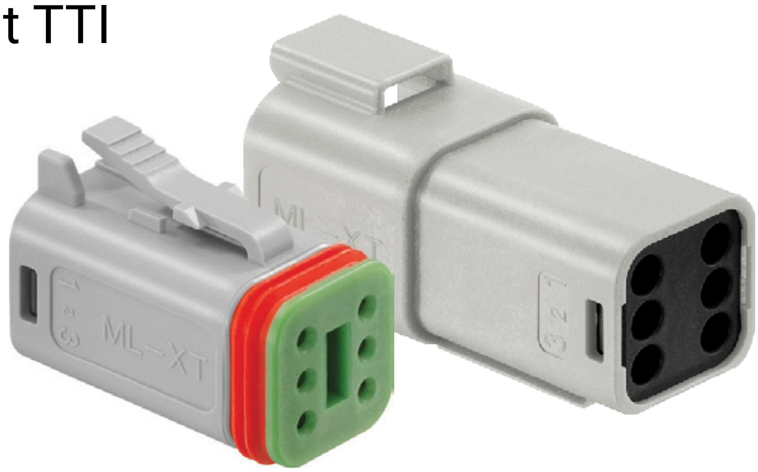

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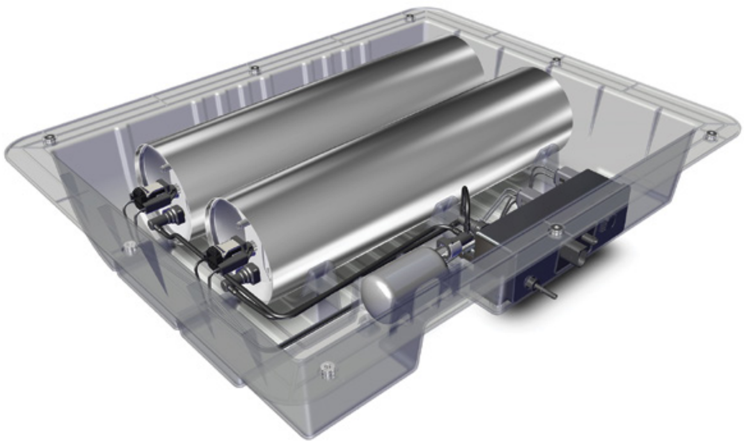
EMISSIONS

Faurecia targets NOx reduction at lower exhaust temps with lightweight cartridges



ASDS NOx-reduction technology is designed to replace conventional DEF or AdBlue tanks with lighter, high-efficiency cartridges containing a solid material called AdAmmine.

The Ammonia Storage and Delivery System (ASDS), developed by **Amminex**, has demonstrated an ability to nearly eliminate nitrogen oxide (NOx) pollutants from diesel engines. Called a "new generation" of NOx reduction technology, ASDS is designed ultimately to replace conventional tanks containing a diesel exhaust fluid (DEF) or AdBlue with lighter, high-efficiency cartridges containing a solid material called AdAmmine, also developed by the Danish company.

In December, **Faurecia** acquired a 91.5% share of Amminex, to intensify the development of ASDS technology for both commercial vehicles and passenger cars. Faurecia has worked with Amminex since mid-2009 and previously owned 42% of the company.

"ASDS functions at lower exhaust temperatures, even in winter driving conditions. Moreover, for equivalent quantities of ammonia, ASDS requires only half the volume of that required for AdBlue," said Christophe Bouly, CTO of Faurecia Emissions Control Technologies.

One 11-L ASDS cartridge is comparable to 20 L of AdBlue/DEF.

Selective catalytic reduction (SCR) using liquid reductant is the most widely-used method to reduce NOx emissions. Bouly said ASDS has the potential to become "the new world standard for NOx reduction."

AdAmmine consists of ammonia adsorbed in strontium chloride salt in a solid form. AdBlue, currently the most widely-used NOx-reduction fluid, can be injected into the exhaust stream only at exhaust temperatures above 180°C (356°F), while ASDS has the ability to optimize SCR in lower exhaust temperature ranges—from 140-180°C (284-356°F), according to Faurecia.

The ASDS cartridges can be stored or transported safely at temperatures ranging from -40 to +80°C (-40 to +176°F).

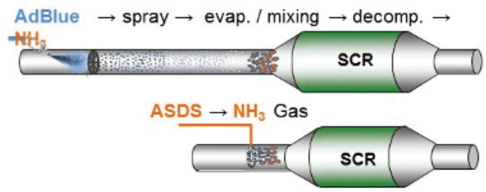
How it works

The ASDS system begins releasing pure ammonia in gaseous form into the exhaust line within a few minutes after engine start-up. Faurecia describes how the system works: At ignition of the engine, the start-up unit is electrically heated. In less than 2 minutes, the temperature reaches 60°C (140°F) and the salt releases pure ammonia on demand. The ammonia is routed under low pressure to the control unit, then an electrical valve pilots the distribution of ammonia directed to the exhaust stream.

While the start-up unit is operating, one of the main cartridges that is larger in size is heated. When the main cartridge reaches its operating temperature, it takes over the release of pure ammonia from the start-up unit. When the engine is turned off, the distribution of the ammonia is stopped. As the temperature drops, the pure ammonia returns to its solid form and is again stored in the salt.

ASDS has been proven to reduce NOx emissions by up to 85-99% on more than 15 million km (9.3 million mi) of real-world use with buses. This compares to an average 32% NOx reduction with AdBlue in the same city-driving conditions. These findings are the result of monitoring hundreds of ASDS-equipped buses

For equivalent quantities of ammonia, ASDS requires only half the quantity required for AdBlue, according to Faurecia.



ASDS reportedly achieves three to five times better NOx reduction in city driving with no CO_2 increase (cold engines) and 20% better NOx reduction on highways (hot engines).

in Copenhagen and London, and comparing them with buses using AdBlue on the same streets.

Demonstration vehicles also are running in Germany, China and Korea. In total an estimated 400 vehicles are in operation today, with the total fleet exceeding 25 million km (15.5 million mi). Faurecia has supplied more than 25,000 refilled cartridges, roughly equivalent to 500 ton of DEF/AdBlue.

System cost on the vehicle is comparable to a DEF system, Dave DeGraaf, President of Faurecia Clean Mobility North America, told *Truck & Off-Highway Engineering*.

"ASDS has no injector and uses a simple steel nozzle. The ammonia flows in through a non-heated tube," he explained. "Unlike the deposits left in the exhaust system from the liquid urea used in AdBlue/DEF systems, ASDS uses gas that does not leave deposits. This ultimately will allow a fleet owner to stay with diesel technology longer and reduces the need to refresh the fleet frequently."

Potential off-highway application

Faurecia showed the Amminex solution for commercial vehicles at the 2016 Paris Motor Show, as well as an ASDS system in a new format for diesel passenger vehicles. The company also is investigating other applications of ASDS, including for off-highway vehicles and high horsepower (HHP) engines used on ships and vessels.

"This is something that is still in development," DeGraaf said. "We believe the same commercial-vehicle ASDS system that is used on buses and trucks today can be used for off-highway and marine when the engines are comparable in size. We are still exploring specific solutions for larger engines using the same core technology."

For passenger cars, engineers have created a smaller package for ASDS that fits in the trunk or any other available space. Faurecia proposes offering a full line-up of cartridge sizes, from 1L to 11 L. The smaller cartridges can be changed by the driver in plug-and-play fashion.

What kind of weight savings are possible? "Light duty [vehicles] that currently use the 17-L AdBlue system would see a 30-40% weight reduction," said DeGraaf. "In commercial vehicles that currently use the 40-L AdBlue system, the weight reduction is slightly lower at approximately 20%. Preliminary results also indicate that ASDS could potentially optimize fuel consumption in the range of 2%."

Faurecia says the compact ASDS cartridges will be available for post-2020 passenger vehicles.

Ultra-low NOx regulations

Ultra-low NOx regulations are likely coming in the U.S. for heavy-duty on-highway engines beginning in model year 2024, lowering the allowable limit from 0.2 g/bhp-hr to 0.02 g/bhp-hr. DeGraaf believes ASDS can help achieve these targets with reduced impact on fuel economy.

"In-use performance in city driving is of high interest for the next step in U.S. legislation, in particular **CARB**," he said. "ASDS can help enable high performance in real driving conditions—particularly in cities—without the use of exhaust heating strategies that are needed in DEF injection."

In Copenhagen, for example, estimates indicate that buses have contributed to as much as 10% of the NOx pollution, DeGraaf noted. Faurecia's data suggests that the 261 ASDS-retrofitted buses there have already collectively removed more than 45 tons of NOx from the air.

"It has a positive impact on both fuel economy and CO_2," he added. "Exhaust heat management typically consumes 3-5% of extra fuel/CO_2 during light to medium load conditions. Since ASDS is not a liquid, it does not need catalyst heat management to function properly, which saves that fuel/CO_2 consumption."

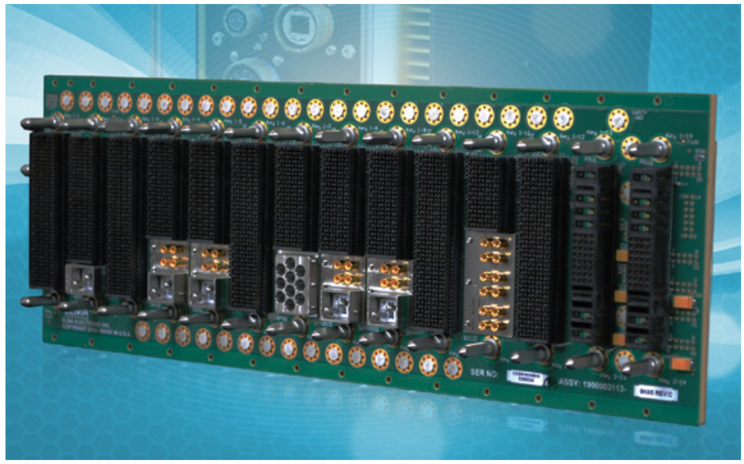
Amminex employs 50 people at its headquarters in Søborg, near Copenhagen, and its 6500-m^2 production facility in Nyborg. Annika Isaksson, Amminex CEO, and Tue Johannsen, CTO and inventor of the ASDS technology, have remained in their positions following the Faurecia acquisition, to help lead the technology's new stage of development.

Johannsen and other Amminex experts wrote an **SAE** Technical Paper (2008-01-1027) in 2008, in which they offer an initial look at the storage concept, including system design, performance data and implications for vehicle integration.

Ryan Gehm

ELECTRONICS

Military system designers aren't resting on COTS deployment



Elma's VPX backplane helps military designers utilize commercial products instead of designing custom boards.

As ground vehicles employ more electronic sensing, control and communication systems, design engineers are increasingly utilizing more commercial off-the-shelf (COTS) modules. Though COTS slashes development time and cost, it's still difficult for many military users to find COTS boards that meet their low-volume demands for ruggedization and redundancy.

Sensing and computing systems in vehicles get more complex, so there's increased interest in modules based on the VME and Open VPX, a successor to the venerable VME bus, created by the **VITA** Trade Association, according to several speakers at the recent Embedded Tech Trends conference. More military projects are adopting open architectures that offer a number of production-ready computing and sensing boards.

"Customers don't even want to look at solutions that aren't COTS," said Bill Ripley, Senior Designer at **Alligator Designs** Pvt Ltd. "They don't want to pay for development. Suppliers need to start designing products, not starting projects."

Using COTS products can also help military system designers meet their need for fault tolerance. Standard architectures can make it easier to find modules that can work together to provide fault tolerance while still shrinking overall system size. That's often accomplished by using elements like multicore processors that can be used for more than one task.

"They want redundancy, but they're also trying to come up with a converged architecture where resources that can be shared are shared," said Greg Rocco, **MIT Lincoln Laboratory**.

While VME and VPX provide standards that simplify design projects and foster competition among competing companies, many military design teams still find it difficult to transition away from customizing their requirements. Vehicles and user requirements vary widely, which can make it difficult to buy from a pre-designed product lineup.

"In the mil/aero market, people come in and tell us they need COTS, then they spend 20 minutes telling us why they're not able to use it," said Kenneth Brown, Program Manager at **LCR Embedded Systems** Inc. "We're seeing growing demand for VPX, which offers infinite possibilities. With VME, there's often not enough bandwidth or I/O capability."

VPX is gaining popularity largely because it increases overall performance compared to its predecessor, VME. VPX also provides a number of different options created to provide enough flexibility to meet nearly any customer requirements.

"There are 81 slot profiles for 3U and 6U boards," said Michael Munroe, **Elma Electronic** Inc. "If companies can describe their backplane requirements, they can use one of these templates."

However, having flexibility can reduce the benefits of open standards, since connector positions and pinouts can be incompatible. There's a push within VITA to reduce the number of user-defined pins in connectors. Engineers also need to consider their position and alignment.

"System designers want to ensure that connectors are in the same spot with the same configuration so when they get boards from different vendors they are truly compatible," said Patrick Collier of **NAVAIR**.

The move to COTS comes as ground vehicles not only use more sensors but also employ higher-resolution devices. It's becoming a challenge for microprocessors to handle all that data, which may prompt a change from conventional microcontrollers to graphic processing units (GPUs) or other parallel computing architectures. Parallel processors are well-suited to processing imagery and other sensor input.

"The next growth area is an increase in the number of pixels in cameras and use of more sensors like Lidar and gamma detection," said Douglas Patterson, Sales and Marketing Vice President at **Aitech Defense Systems** Inc. "There's so much data that CPUs aren't keeping up. Some companies are going to **Nvidia**'s graphic-processing units, which use many hundreds of simple cores to process images."

There may be solid market growth even in vehicle systems that don't require the latest technologies. Many military vehicles are aging, so replacements will help drive market growth for boards and systems that fit common platforms.

"There are 30,000 unmanned ground vehicles that need to be replaced in the next few years," said Brian Arbuckle, Senior Market Analyst at **IHS Markit**. "That creates a need for systems with new sensors."

Terry Costlow

HYDRAULICS | SIMULATION

Real-time manipulator position sensing for automation of hydraulic excavators

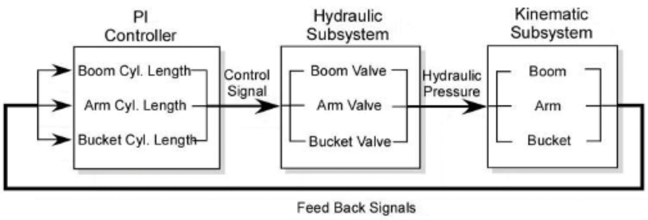


Figure 1. Excavator manipulator simulation model configuration.

Figure 2. Example of the manipulator sample image created using webcam.

Automation of hydraulic excavators is valuable due to their potential applications in hazardous environments or remote locations, such as radioactive-contaminated areas. Manipulator position sensing is a key issue in the study of hydraulic excavator automation.

A neural network-based computer vision system was designed using **MathWorks**' MATLAB neural network toolbox and used to estimate the boom, arm, and bucket cylinder displacements of an excavator manipulator during a grading operation simulation. A computer ran the excavator simulation and a webcam connected to the computer took snapshots of the excavator manipulator animation displayed on a secondary screen. The webcam took screenshots of the manipulator at different positions during a grading operation. Those images were then down-sampled and used to train the neural network. The researchers from **Volvo Construction Equipment** and **The University of Alabama** then compared the manipulator positions estimated by the neural network-based computer vision system with the actual values.

The neural network-based computer vision system consists of three main subsystems: excavator manipulator simulation model, image acquisition subsystem, and neural network subsystem. The excavator manipulator simulation model was developed in Simulink. The simulation model consists of three main subsystems: hydraulic subsystem, kinematic subsystem, and a proportional integral (PI) controller, as shown in Figure 1.

The hydraulic subsystem and the kinematic subsystem were modeled using SimHydraulics and SimMechanics toolboxes in Simulink, respectively. Three independent PI controllers were applied to control the excavator manipulator during the grading process.

The image-acquisition subsystem consists of four main hardware components: a computer that runs the grading operation simulation, a secondary monitor that visualizes the manipulator grading operation, a webcam to take snapshots of the manipulator animation, and an aluminum frame to support the webcam and the secondary screen.

For control of the webcam, the MATLAB image acquisition toolbox was used. The screenshots were down-sampled using a code developed in MATLAB to reduce the image resolution.

The grading operation simulation was visualized using the SimMechanics visualization function. The viewpoint for the manipulator animation was chosen to simulate the real situation in which a camera is installed on the excavator cab moving together with the cab such that the relative position between the manipulator anchor and the camera is always fixed. An exact image is shown in Figure 2.

In the experiment, the manipulator model simulated a 10-second grading operation in which the bucket tip moved inward along a level path. To create sample images, a snapshot was taken at every 0.01 second during the grading cycle simulation, and 80 images were taken for each position by repeating the process 80 times. A total of 80,080 sample images were created using the sample image creation program in MATLAB.

The neural network subsystem consists of three independent neural networks developed using the neural network toolbox in MATLAB. Each neural network was used to estimate displacement of one of the hydraulic cylinders: boom, arm, and bucket, independently.

Following the training process, the trained neural networks were used to estimate the displacements of the hydraulic cylinders in the manipulator during the simulation of a grading operation. The results of the cylinder displacement estimation during the simulation were compared with the actual values.

The simulation results were obtained for three different illumination conditions. The estimation errors for the three cylinders were small compared to the dimension of the excavator manipulator. The relatively low estimation errors show the capability of the neural networks to estimate the position of the excavator manipulator for feedback control applications.

Although the proposed methodology was demonstrated with a single manipulator system, the same principle and algorithm can be applied to other excavator models with different shapes and dimensions. Future work will involve the creation of a larger set of sample images under various illumination conditions with different backgrounds for training the neural networks. Then the estimated manipulator cylinder displacement values will be used for feedback control of the hydraulic cylinders to automate the grading operations.

This article is based on SAE technical paper 2016-01-8122 authored by Jiaqi Xu and Hwan-Sik Yoon of The University of Alabama; and Jae Y. Lee and Seonggon Kim of Volvo Construction Equipment.

ALTERNATIVE FUELS | POWERTRAIN

At ConExpo, Isuzu Motors announces heavy-duty natural gas engine for off-highway

Isuzu Motors America used the ConExpo-Con/Agg 2017 stage to announce its intention to produce a dual-fuel capable (natural gas and propane) off-highway engine by mid-2018, leveraging its already-in-production on-highway CNG truck engine.

The 4.6-L 4HV1 engine, on display for the first time at the Las Vegas event, will have an expected maximum rated output of 81 hp (60.5 kW) at 1800 rpm and torque rating of 247 lb·ft (335 N·m) at 1400 rpm when operating in natural gas mode.

"We've studied the market for about two and a half years now and felt that it'd be a good fit for us to expand into the gas market [for off-highway]," Ken Martin, director of sales & service for the Powertrain Division of Isuzu Motors America, told *Truck & Off-Highway Engineering*. "We feel this engine is going to fill a hole that's out there. And we have a lot of experience and field usage already with the gas engine because the base engine model that we're using has been running since 2012 in our CNG truck market."

The truck version is used in the U.S. and some Asian markets. "That's one of the reasons why we'll be able to come to the market competitively priced: a lot of the R&D has already been completed," he said.

Since it's a "gasified" diesel engine design, the company is confident in the engine's durability and reliability, compared to some competitors that base their gas variants on gasoline engines, Martin said.

Some changes were necessary compared to the base diesel engine. "With gas there isn't any lubrication in the fuel, so you have to look at hardened seats, hardened valves. You have to lower compression ratio and change the piston rings, to name a few things. But again, we've already experienced that in real life on the truck side."

4HV1 employs a fuel system from IMPCO, which also supplies the system for the on-highway model. Durability testing of the fuel system on the new engine is currently under way. (Photo by Ryan Gehm)

The 4.6-L 4HV1 natural gas engine, on display for the first time at ConExpo in March, is suitable for various industrial and mobile applications including water pumps, generators, and forklifts. (Photo by Ryan Gehm)

4HV1 employs a fuel system from **IMPCO**, which also supplies the system for the on-highway model. Durability testing of the fuel system on the new engine is currently under way.

"We're programming the ECU to run off of natural gas and LPG, so with the flick of a switch you can switch back and forth," he said.

Isuzu Motors believes the new gas engine will find a fit in various industrial and mobile applications including pump markets, generators, and forklifts.

Additional specs for the 4-cylinder vertical inline engine include:

- Bore x stroke: 115 x 110 mm
- Length: 35.4 in (900 mm)
- Width: 22.9 in (580 mm)
- Height: 38.2 in (970 mm)
- Dry weight: approx. 815 lb (370 kg).

"After we launch the 4HV1 we'll see how it goes," Martin said, referring to possible next steps for a natural-gas product range. "We're looking at launching a 6-cylinder version, a higher kW rating, as well."

The engine was well-received at ConExpo, Martin said. Field testing with interested customers will begin this April.

Ryan Gehm

POWERTRAIN

International develops new, lighter A26 engine to replace N13

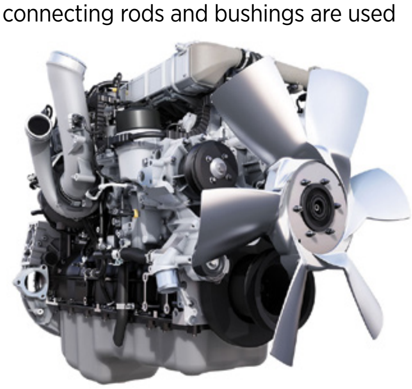
Any time a new engine is announced, it is major news. Pairing a new engine with a new approach to engine development is even bigger news. **International Truck** recently unveiled its all-new engine for the Class 8 market: the International A26. Along with that came news of an initiative called Project Alpha, which brought together a small team of powertrain engineers dedicated to a new perspective on engine development.

"The A26 was designed from the ground up to deliver industry-leading uptime, durability and reliability," said Darren Gosbee, vice president of advanced engineering. The 12.4-L A26 sources a **MAN** D26 inline 6-cylinder crankcase from their partnership with the **Volkswagen** Group and surrounds it with numerous all-new components to optimize four key criteria: uptime, fuel efficiency, weight and NVH (noise, vibration and harshness).

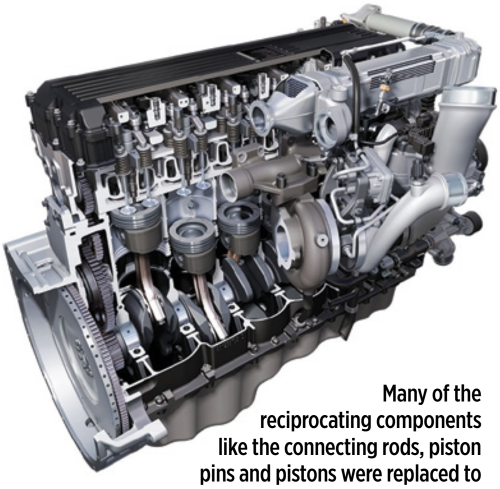
The engine weighs only 2299 lb (1043 kg), which is 55 lb (25 kg) less than the **Navistar** N13 engine it replaces and 600-700 lb (272-318 kg) lighter than traditional 15-L big bore engines. Despite the reduction in weight, the engine can still produce up to 475 hp (354 kW) and 1750 lb·ft (2373 N·m).

Simplicity was one of the focal points of the engine design to deliver maximum uptime. "The A26 is as simple as a modern engine can be, and we've built uptime into every part of the development process, from design to calibration to testing," said Gosbee. Larger piston pins, connecting rods and bushings are used for better load distribution. Smaller piston cooling jets have increased oil pressure and help extend oil change service intervals up to 70,000 mi (112,654 km).

Other improvements across engine systems have helped deliver up to a 5% increase in fuel economy. The new **BorgWarner** single-stage variable-



A six-blade fan was decided over the previous eleven-blade, which allows for quieter operation in addition to reducing power consumption.



Many of the reciprocating components like the connecting rods, piston pins and pistons were replaced to increase the compression ratio up to 18.5:1.

geometry turbocharger (VGT) leads off a simplified air management system. The **Bosch** 2500-bar (36,259-psi) high pressure common rail fuel system and new cylinder head with coolant passages that are 50% less restrictive help reduce both fuel consumption and emissions.

Simplification also helped lead to keeping the International A26 lightweight, in addition to component material choices. A titanium compressor wheel was used instead of aluminum for improved fatigue life while continuing to reduce weight. Composite valve covers and an aluminum flywheel housing provided additional weight savings.

To improve NVH, the A26 has a new sculpted crankcase with an isolated oil pan and rubber gasket designed to absorb vibrations. A six-blade fan was specified over the previous eleven-blade, which allows for quieter operation in addition to reducing power consumption. The engine calibration also is programmed for reduced engine noise.

Jacobs Vehicle Systems collaborated with Navistar engineers to provide a factory-installed compression-release engine brake for the A26 engine. "By leveraging the benefits of the new variable-geometry turbo, the A26 engine brake performance increased up to 67% at lower engine speeds and higher altitudes," according to Jacobs. Other stated benefits include a reduction in the need for downshifting and improved NVH.

Project Alpha initiative speeds development

All of these improvements were the goal of Project Alpha, a brand-new initiative by International for this engine's development. "Project Alpha has fundamentally changed how we design diesel engines," says Bill Kozek, president of Truck and Parts. The group was formed using fewer members to speed up and focus engine design decisions. They were also given more autonomy in their decision making to not only meet the 2017 emissions regulations but improve the overall product performance in those four key areas.

One of the mandates Project Alpha decided on was to leverage proven industry technologies over testing new ones on customers. "Keep the best and improve the rest," was a mantra for Jim Nachtman, marketing manager of Heavy-Duty Product Line. The crankshaft, main and rod bearings, EGR cooler and valves, oil and fuel filters, air compressors and flywheel housing along with several other components were carried over from the Navistar N13 engine. However, many of the reciprocating components like the connecting rods, piston pins and pistons were replaced to increase the compression ratio up to 18.5:1. A slower, single-speed water pump was chosen over a variable speed pump to improve the fuel economy and reduce complexity.

The Project Alpha team put the A26 engine through hundreds of thousands of hours of dynamometer testing at severe engine speeds and loads. "It's been tested to extremes and meets a demanding B10 design life standard for an unprecedented 1.2 million miles," said Kozek. The engine was temperature tested as low as -40°F (-40°C), which was aided by a switch to Compact Graphite Iron (CGI) for the crankcase; CGI has better thermal fatigue than traditional gray iron.

The A26 now will be available in the International LT Series trucks. International is backing the engine with a two-year, unlimited mile warranty. It is the first of a new wave of engines for International trucks. The Project Alpha team and A26 engine are a new beginning for the brand.

Matthew Borst

CYBERSECURITY

Sharpening the focus on OBD-II security

In Fall 2016, the U.S. House Committee on Energy and Commerce reached out to the **National Highway Traffic Safety Administration** (NHTSA) in regards to addressing OBD-II security. The letter requested NHSTA to "convene an industry-wide effort to develop a plan of action for addressing the risk posed by the existence of the OBD-II port in the modern vehicle ecosystem."

Enter SAE.

"**SAE International**, at NHTSA's urging, has started a working group that is 'looking to explore ways to harden the OBD-II port'—that was their [NHTSA's] language," said Tim Weisenberger, SAE's Project Manager, Technical Programs, Ground Vehicle Standards.

"SAE International, at NHTSA's urging, has started a working group that is 'looking to explore ways to harden the OBD-II port,'" said Tim Weisenberger of SAE's Ground Vehicle Standards. (PSA image)

SAE set to work by reaching out to a wide range of the industry. A working group of experts was assembled to examine the issue with the goal of developing a set of recommendations.

"The OBD-II port has moved beyond its originally designed intent as a port to check emissions by regulators like the **EPA** and **CARB**," Weisenberger explained.

There are vehicle data access vs. vehicle security issues at hand. Many entities are requesting both legitimate and non-legitimate access to the port.

The "legit" side include inspection and maintenance, workshop/service, insurance/other plug-in telematics and prognostics apps and performance tuners.

On the malicious side are the hackers.

Triggering the industry

The group of approximately 40 gathered for the first workshops on December 1, 2016 and January 30, 2017 to identify common issues, needs and an approach to secure the OBD.

"The group included a couple of our experts that run various committees—Bob Gruszczynski from **Volkswagen** and Mark Zachos from **DG Technologies** were really the lead experts," Weisenberger explained.

SAE staff were also present to facilitate and help to examine how the organization could rapidly move forward. They considered either standards development or expedited standards development that uses what SAE calls a Cooperative Research Project approach. This is a pathway for joint-venture research projects where two or more organizations pool their resources to study a pre-competitive technical area and share in the results.

"It was interesting that this was kind of a trigger for the industry to get together to create something that's a little more open for the entire industry," he said, "not just specific to company."

The new OBD working group SAE has assembled is broad. It is comprised of eight automotive OEMs (**BMW**, **Ford**, **General Motors**, **Honda**, **Hyundai**, **Isuzu**, **Toyota**, VW), a few heavy-truck OEMs and suppliers (including **Volvo Trucks** and **Cummins**), various associations (**MEMA** and **ETI**), as well as representation from government and regulators including the California Air Resources Board, NHTSA and the **National Institute of Standards and Technology**.

Get to know the TEVDS20

Through this effort, a new SAE committee was born: the Data Link Connector Vehicle Security Committee (TEVDS20). It is important to note that "data link connector" is the technical term for the OBD-II port (which really is more of an industry slang term, Weisenberger told *TOHE*). With the committee's naming as a trigger, members will begin to use the technical term moving forward.

As this issue of *Truck & Off-Highway Engineering* was assembled, the group was set to meet again to define the scope of work and engage a new Task Force under the committee to develop the technical work item (J3138). From there, the committee will continue to meet periodically to examine the issue and begin new work items as needed, Weisenberger explained.

"This new work item is a very specific use case," he said. "It is a deep dive."

The potential is there for other work down the road, but for now the group has its very specific goal to meet the U.S. House Committee's and NHTSA's requirements for "hardening" the OBD-II port squarely in sight.

Jennifer Shuttleworth

CONNECTIVITY continues its advance

VisionLink integrates Cat's connected capabilities.

More OEMs and Tier 1 suppliers are focusing on embedded telematic systems, hoping to displace aftermarket hardware.

by Terry Costlow

Fleet owners have been deploying telematic solutions for some time, but connectivity still is just beginning to move from early adopters to the mass market. Connectivity is providing more owners and operators a broad range of benefits, prompting a surge of developments by suppliers.

Connections using cellular and other wireless links are transforming design plans, running the gamut from axles and infotainment systems to leveraging cloud computing. Connectivity even is beginning to impact developments at companies that traditionally focus more on mechanical designs than electronics, according to some contract designers.

"Many of our programs are no longer looking just at transmissions or other systems, they're including connectivity," said Lee Barnes, Jr., Director of Connected and Autonomous Vehicle Business at **Ricardo**. "Companies that make axles that switch from two- to four-wheel drive want to use vehicle-to-vehicle (V2V) communications so that when the first vehicle in a convoy hits an icy patch, it can tell following vehicles that they should switch to deal with ice."

Analysts at **Berg Insight** predict that fleet-management system deployments in North America and Europe will exceed 17 million by 2019, up from barely eight million in 2014. To date, aftermarket devices have played a major role. But the benefits of integration by OEMs may drive a shift to factory installations.

"There's a trend for more people to go to embedded telematic solutions, but we still see a lot of companies using aftermarket solutions," said Stephan Tarnutzer, Vice President of Electronics, **FEV** North America. "For OEMs, embedded systems can be a differentiator; they can provide more value-added features. They can combine telematics with things like prognostics and diagnostics. Embedded solutions work with all features and functions of the vehicle, unlike aftermarket solutions."

Offerings multiply

Product offerings are exploding. In March **Caterpillar** unveiled Cat Connect and Cat Product Link technologies that connect any brand and type of equipment using a single reporting system, VisionLink. Cellular, satellite and Bluetooth links can be used to access data ranging from machine hours and location through machine health parameters and production data.

Parker Hannifin rolled out IQAN Connect, which integrates Parker's intelligent hydraulic components with electronic control hardware and software using **SAE** J1939 links. Data is stored in the cloud for access by fleet owners, giving them real-time diagnostics to help reduce downtime and improve productivity. **Cummins** is touting its Connected Advisor system for monitoring engines and aftertreatment systems.

Deere and **LHP Telematics** recently teamed up to expand the role of John Deere WorkSight and JDLink, combining platforms into one application and simplifying operations. These products follow a trend of making it easier to understand what's happening with vehicles.

Parker's IQAN Connect provides insight into hydraulics and other systems on J1939 buses.

"It's not good enough to just provide data any more," said Jeffrey Cohen, Vice President of **Telogis**. "A fleet manager's job is to run the fleet, not look at technology. They want something that's easy to understand and easy to use."

Ease of use always is a critical factor when new technologies emerge. For example, a fleet with an idling problem can create incentives for those who reduce idling the most. Conserving fuel then becomes a game for operators—and telematic data shows managers which operators need training.

Clouds rise

While some fleet owners will use their own information technology (IT) departments to collect data, many will turn to the Cloud. The volume of data transmitted by a system that monitors data available on vehicle networks will be huge. Third-party providers can help managers access data without becoming IT experts.

"Cloud computing is essential for the connected off-highway vehicle environment," said Jose Ogara, Product Manager at **TTControl**. "The cost and effort required to host machine data and to run applications for the analysis of the data is often too big for many customers, so cloud computing allows you to start small and scale."

Managers who want to schedule maintenance and monitor vehicle productivity for fleets soon may be clamoring for more bandwidth. Product developers are already making preparations to provide that as soon as

Hardware provides foundation for connectivity

The move to connectivity will alter the electronic architectures on vehicles, following the trend to perform more tasks using software. But making this transition requires a number of hardware changes.

Connected vehicles collect more data from vehicle systems, sending it to fleet managers. Vehicles will also be receiving more information, so more processing power and networking bandwidth will be needed. CAN networks will no longer suffice.

"Ethernet-based technology will become prevalent and flexibility in terms of local storage and computational power will play a key role in future-proofing your machines," said Jose Ogara, Product Manager at **TTControl**. "We are seeing interest in BroadR-Reach Ethernet gateways and ECUs as the amount of data transmitted in the vehicle increases."

Handling all this data will require more processing power. As more bandwidth and more-powerful microcontrollers become common, design teams may start consolidating functions. Combining telematic controllers and infotainment systems is an obvious move, but it isn't one that will be made universally.

"There's some interest in putting it in the head unit, but some companies like stand-alone systems," said Stephan Tarnutzer, Vice President of Electronics at **FEV** North America. "It depends on how modular they want to be. In general, telematics will probably be integrated into the head unit."

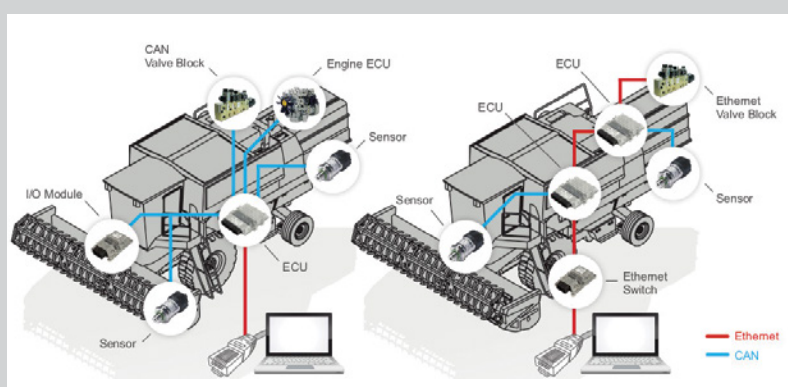
As this evolution occurs, infotainment systems are likely to handle a wide range of tasks. Apps may well run on both phones and vehicles, permitting tight integration between vehicles and services. For example, when the vehicle senses it's time for maintenance, the system could direct the driver to a suitable site and handle payments upon completion.

"Ultimately, everything will merge into the radio head unit; it will be the place to find parking, exchange money for services and so on," said Lee Barnes, Jr., Director of Connected and Autonomous Vehicle Business at **Ricardo**. "As more things move to the Cloud, more things can be driven by apps that are loaded onto the infotainment system."

Many suppliers feel that cloud services will eventually impact vehicle design. Some functions may be handled in the Cloud, so vehicle systems won't need the memory and processing power now used to process these functions.

"You will have a flexible platform where you can dynamically allocate CPU resources to applications that the machine owner will be able to download from the Cloud via the telematics interface without affecting safety-critical applications running on the same hardware," Ogara said. "This approach will lower overall machine cost and tremendously improve machine flexibility."

Terry Costlow



Today's architectures use Ethernet only to connect to outside systems (left), but TTControl foresees Ethernet serving as a backbone for connected vehicles.

CONNECTIVITY continues its advance

cellular providers start shifting from 4G to faster 5G technologies.

"Companies will move quickly to 5G when it's available because of the sheer volume of data being transferred," FEV's Tarnutzer said.

Platoon ready

There's a fair chance that within a few years, vehicle-to-vehicle/infrastructure (V2X) communications will be added to the connectivity mix. In the U.S., **NHTSA** (National Highway Traffic Safety Administration) has long promised to mandate its use in passenger cars. But fleet owners may leverage the concept more rapidly than automakers.

Commercial trucks can save fuel and reduce congestion by platooning. Several vehicles can travel closely together, setting a steady pace and even adjusting traffic lights so they can smoothly pass traffic lights as a convoy. As connectivity and cloud computing expand in transportation, interest is growing.

"We're seeing a lot of activity in the platooning space," Tarnutzer said. "In platooning, you need a lot of communication to the back end."

Some programs rely on communications sent between vehicles in a fleet, communicating speeds, potential braking needs and other information. Other projects use the Cloud to collect data from all connected vehicles on the road and sharing relevant information.

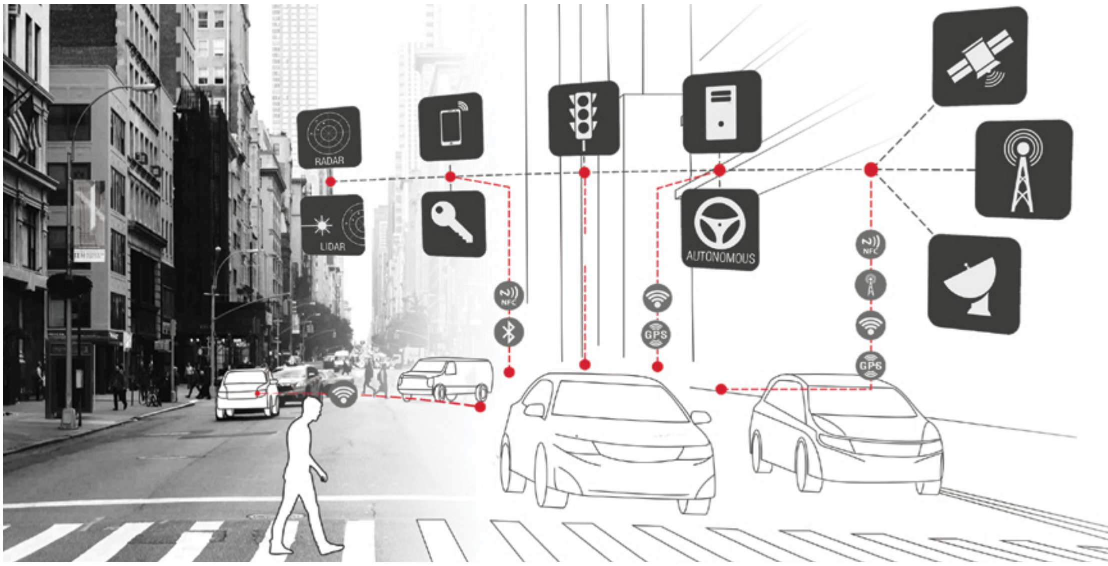
"If you have a smart infrastructure, data sent to the Cloud can be accessed by any vehicle," Ricardo's Barnes said. "Data can be held in the Cloud and can be parsed to vehicles that need it. For vehicle convoys, this data can tell them things like speed and distance and whether they need to shift because they're going up a hill."

Whether these communication systems will use cellular links or the dedicated short range communications (DSRC) promoted by NHTSA remains an open question. DSRC offers many benefits like high speed, but it won't make an impact until a fair number of vehicles have compatible

Connected Vehicles webinar

The discussion about connectivity and its promise for safer, more efficient and productive vehicles and worksites will continue in a free SAE Technical Webinar this June. Three experts will explain the trends and latest technologies in this quickly evolving area, along with the technical challenges that remain with development and testing of V2X communication, cybersecurity, and how to best utilize Big Data. Go to www.sae.org/magazines/webcasts/ for more information and to register.

Sponsored by dSPACE



FEV is helping heavy-vehicle developers to integrate the most suitable technologies developed for the automotive industry.

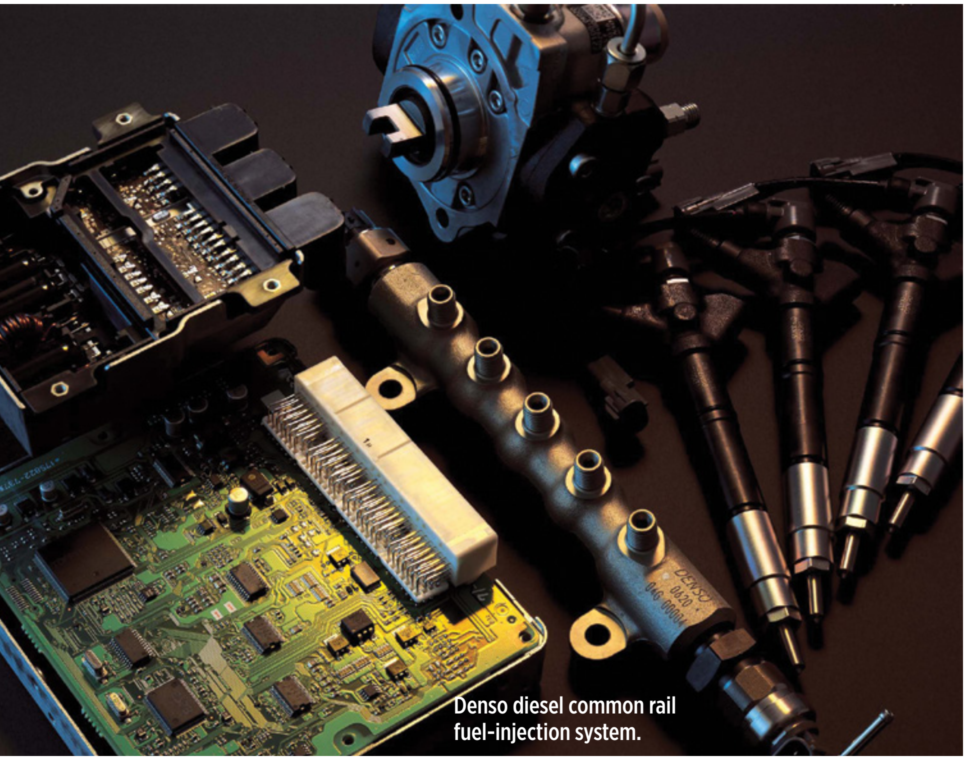
communications. Cellular is ubiquitous, but no one's yet spent much time figuring out how V2X data would be handled securely. Opinions vary.

"There's more interest in cellular communications than in DSRC," Tarnutzer said.

But that's not what Barnes is hearing. "It's not set in stone whether cellular or DSRC will be used, but every situation we're involved in now uses DSRC," he said. "As the industry goes to 5G, that could change." ■

WCX17 WORLD CONGRESS EXPERIENCE

Tailoring fuel injection to control NOx



Denso diesel common rail fuel-injection system.

The next big step to help heavy-duty diesel engines meet stricter emissions regulations involves adapting the fuel-injection system to the combustion needs.

Future diesel engine legislation, such as the EU's Stage V and possible Tier 5 in the U.S. for off-highway, demand further improvements to reduce CO_2 while keeping the already-low NOx emissions levels. For on-highway trucks in the U.S., a stricter limit of 0.2 g/bhp-hr NOx emissions needs to be achieved, with even tougher ultra-low NOx limits on the horizon. In this trade-off, system costs and complexity of the aftertreatment are defining the constraint in which the common-rail fuel injection system layout is defined.

In the past, the increase of rail pressure was the major step to control the soot emissions in view of low engine-out NOx emissions by applying massive EGR (exhaust gas recirculation). With the on-going development of NOx-aftertreatment by selective catalytic reduction (SCR), conversion efficiencies of up to 97% allow a reduction in the EGR and rail pressure usage. In that context, the steepness of injection rate, the nozzle flow rate and the injection pressure are remaining parameters to control the NOx emissions. A shallow injection rate in combination with larger nozzle flow rates is beneficial to reduce the NOx emissions thanks to a reduced premixing of fuel with air.

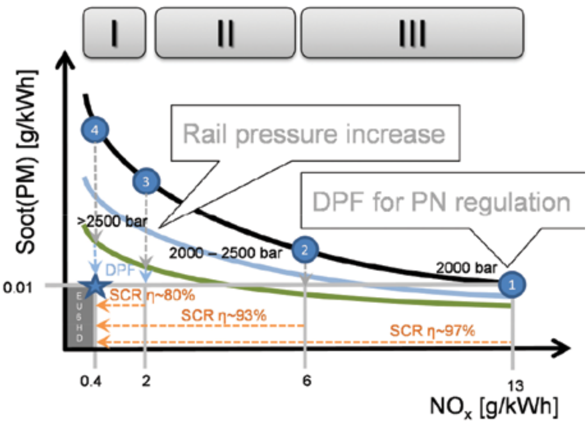
To study this effect, researchers from **Denso** utilized the latest solenoid injector with improved magnetic actuation. The influence of the steepness of injection rate is studied on a six-cylinder heavy-duty diesel engine on three representative part-load points of the WHSC (World Harmonized Steady state test Cycle). Depending on the engine-out NOx emissions requirements, two scenarios are considered. In case of a strong NOx aftertreatment, the shallow injection rate steepness is beneficial for the fuel consumption. In case of less NOx aftertreatment, high EGR rates are required and soot emissions can be controlled through the steepness of injection rate.

Denso experts presented this research as part of the "Combustion in Compression-Ignition Engines" technical session at April's WCX17: **SAE** World Congress Experience in Detroit.

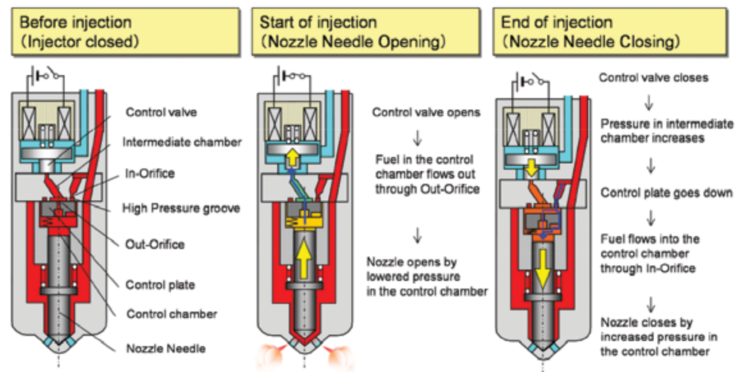
Diesel fuel injector technology

The combustion process of the diesel engine directly depends on the performance of the fuel-injection system, particularly on injector performance with regard to the steepness of the injection rate and minimum hydraulic interval, and the maximum rail pressure level. In the past, the increase of rail pressure was the key to control the air entrainment and the premixed combustion portion. This premixing combustion increases the combustion noise but also reduces the soot emissions as the air is entrained into the fuel rich zones.

The increase of injection rate steepness has a similar effect. Using a quick needle opening, pressure losses by the needle seat throttle are reduced, especially in the case of pilot injection events. The rail pressure is utilized more efficient for the spray momentum and enhances the air entrainment of the spray. Similar to the rail-pressure increase, this leads to the increase of a premixed combustion and reduces soot emissions by entraining the air into the rich fuel areas. Such quick injection opening and high rail pressure is required in engine concepts with high EGR usage to reduce NOx emissions—but combustion noise increases. To countermeasure the combustion noise,



Future emissions trade-off scenario.



Actuation principle of the solenoid servo valve of the G4S injector.

the premixed combustion therefore has to be limited, even in the presence of high rail pressures. This approach is realized by employing the flexibility of the injection system to increase the number of injection events and to achieve short hydraulic intervals.

Such a concept already was developed and tested by using piezo servo valve technology for passenger-car applications, and studied by trial samples for solenoid injectors for passenger car and heavy-duty diesel engine tests. Now this technology is further improved through the ongoing development of new solenoid actuators. The G4S injector functionality during start-of-injection and end-of-injection is pictured.

A small control plate separates the high- and low-pressure areas and has the function of a three-way valve. The switching is released through the movement of the control plate. The pressure decrease is defined by the flow-rate characteristics of the out-orifice, which is part of the control plate. It is therefore the flow characteristics of the out-orifice to define the needle opening speed. To improve the needle opening speed, this flow-rate characteristic of the out-orifice was increased while keeping the flow rate of the inlet orifice constant.

In addition, the intermediate chamber volume and sub-orifice diameter were increased to avoid a throttling downstream, but causes an increase of the pressure forces on the control valve. As a consequence, the spring set force is increased against which the magnetic force acts during actuation. Therefore, the magnetic force had to be increased by changing the solenoid material. As a result of these improvements, the injection rate steepness could be increased while the closing speed controlled through the inlet orifice flow rate and motion of the three-way valve were kept the same.

The increase of the out-orifice flow rate achieves a shorter hydraulic interval. The standard solenoid injector for passenger-car applications achieves in best case a hydraulic interval of 200 µs.

Hydraulic performance was investigated on a pump bench. For analyzing the minimum hydraulic interval, three consecutive pilot injections are applied followed by a main injection. Within the standard G4S specification, the min. hydraulic interval of 250 µs is achieved. With increased out-orifice diameters, a much shorter hydraulic interval of 100 µs is feasible. Overall, the injector's performance demonstrated that the 3-way valve allows the adaption of the out-orifice flow rate independent of the in-orifice throttle by utilizing a new solenoid actuator.

The performance of the improved solenoid injector was evaluated on a heavy-duty EU6 diesel engine (see table for details). The engine was equipped with a high-pressure fuel pump (HP6: 2 cylinders, 3 lobes) with a maximum rail pressure of 300 MPa. All cylinders are instrumented by pressure transducers (**Kistler** 6053CCsp) to analyze the combustion cycle individually. For engine testing, five operating points of the World Harmonized Steady state test Cycle (WHSC) were selected. These points cover the area of low part-load, mid part-load and full-load engine operating conditions. NOx emissions are controlled by utilizing the high-pressure exhaust gas recirculation (HP-EGR).

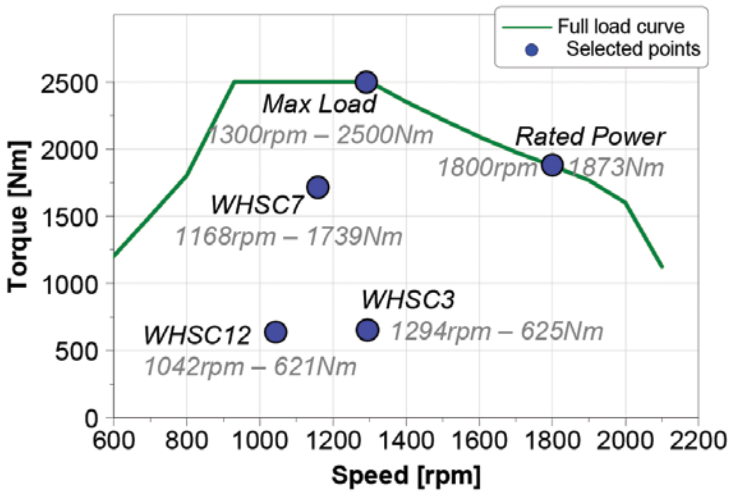
Displacement Volume	12L
No. of Cylinders	6
Related Power	353 kW
Max. Torque	2500 Nm
Peak Firing Pressure	190 bar
Compression Ratio	17
Turbo Charger	1 stage VNT
EGR	Cooled HP-EGR

Properties of the heavy-duty EU6 diesel engine.

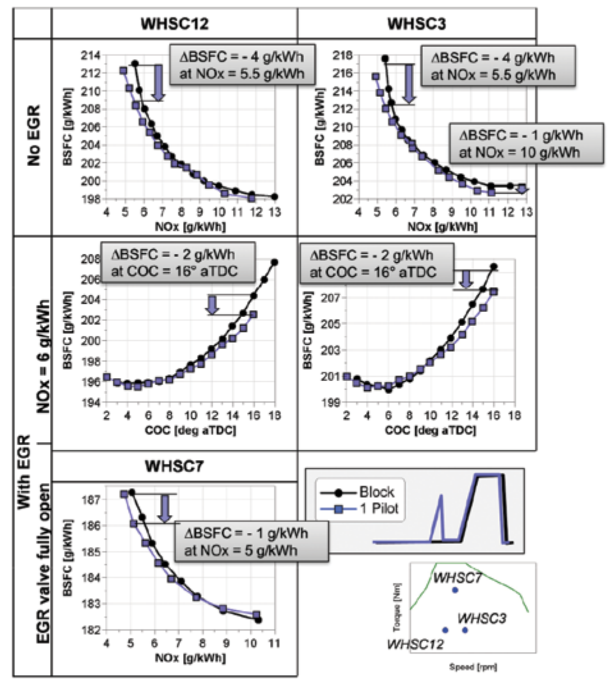
Multiple-injection strategy

Several injection strategies at short hydraulic intervals were evaluated at several load points. Because the optimized emission trade-off depends on many variables, a DoE (Design of Experiments) was performed for each injection strategy. As inputs for the DoE, the rail pressure, injection timing and pilot quantities were varied. From this data a Gaussian model was created. After confirming the model's accuracy, this model was used to find the best brake specific fuel consumption (BSFC)-NOx trade-off within a given soot constraint of 0.02 g/kWh. To evaluate the necessity of short interval, the hydraulic interval was varied as an additional input variable during the single pilot injection DoE.

Tailoring fuel injection to control NOx



Selected engine operating points from WHSC.



Potential of single pilot injection strategy.

Already from the optima, block and single pilot injection display a low rail pressure 60 MPa, whereas the double and triple pilot injection strategy uses higher rail pressure. The reason for this increased rail pressure is (1) to satisfy the given soot constraint and (2) to not extend the combustion duration too much by additional pilot injections. Subsequently, these optima were validated on the engine by a center-of-combustion (CoC) variation.

It turns out that the single pilot injection strategy achieved the best BSFC-NOx trade-off. The first pilot quantity triggers the combustion and enables the early ignition shortly before engine top dead center (TDC). At lower NOx emissions—achieved by retardation of injection timing—the single pilot injection shows even increased benefit in the BSFC-NOx emissions trade-off. At retarded injection, the single pilot ensures that the combustion occurs near TDC by a relatively large pilot quantity in combination with larger hydraulic interval.

The double pilot and triple pilot injection strategy do not really influence the heat release, and a single pilot injection strategy is sufficient for a smooth shape of the heat release rate.

At the higher speed, part-load operating point WHSC3, a similar DoE approach was conducted. The optimum at WHSC3 showed smaller pilot quantities for all injection strategies and a short interval in the case of single pilot injection compared to the WHSC12 engine load point.

The optima of this engine operating point WHSC3 again are evaluated on the engine through a CoC variation. Similar to the engine load point WHSC12, soot emissions are again below the DoE constraint of 0.02 g/kWh thanks to an overall air-fuel ratio of λ=2.17. Therefore, the optima from each injection strategy do not affect the soot emissions.

In this load point, block injection, single pilot injection and triple pilot injection strategies achieve a similar emissions trade-off. At this speed and load, the pressure trace is already shallow for the block injection. Therefore, the addition of the pilot injections cannot shape the heat release rate and the ignition occurs closely to engine TDC.

A similar result was achieved for part-load operating points with EGR and including the WHSC7 part load point. For the low load conditions (WHSC12 and WHSC3) the EGR rate was varied to obtain a constant NOx emission of 6 g/kWh. At WHSC7 the EGR valve was set fully open and NOx was varied by retardation of the combustion timing. Compared to the block injection, the single pilot injection strategy improves the fuel consumption by max. 2 g/kWh with EGR and max. 4 g/kWh without EGR.

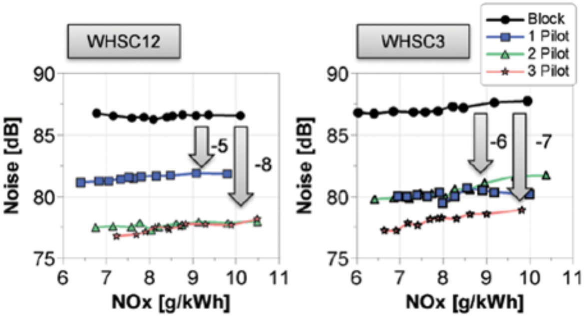
Whereas the single pilot injection leads to the best BSFC-NOx trade-off on this heavy-duty engine, additional injections become more interesting when engine noise might become limited—e.g., by future emissions legislation or hybrid application. Data shows a significant noise reduction by adding a single pilot injection. Adding additional pilot injections in combination with noise-optimization could further reduce the combustion noise.

Injection-rate steepness

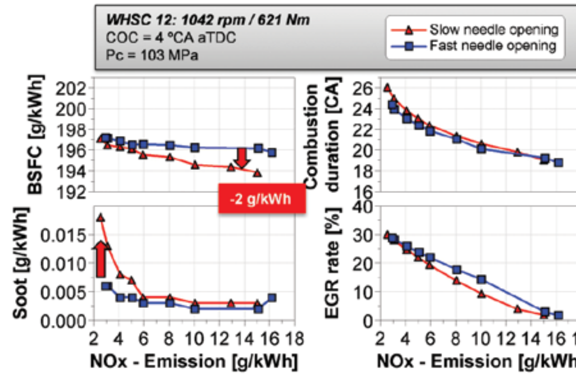
Three different types of injection-rate steepness—fast needle opening, standard needle opening and slow needle opening—were investigated at two different levels of raw engine-out NOx emissions. The NOx emission level is again controlled by the EGR rate.

At NOx=6 g/kWh, the optimum BSFC is between 4 and 6°CA aTDC. Still the engine has sufficient air remaining and the influence of the injection rate is minor. Increasing the EGR to NOx=2 g/kWh, the shallow injection rate cannot sufficiently entrain the air, and soot increases significantly. In this case, the countermeasure to increase the rail pressure by 40 MPa still exists.

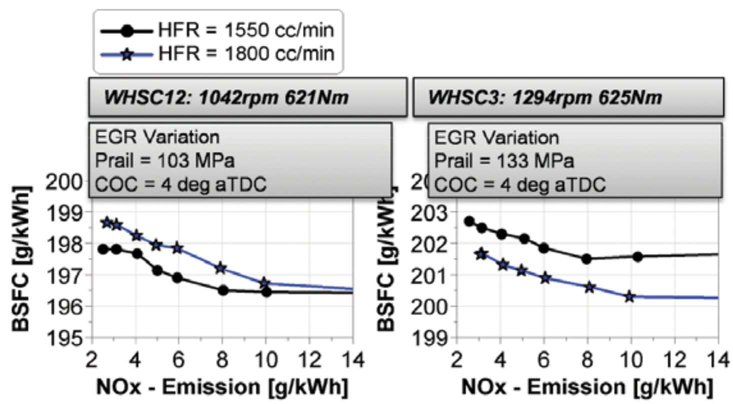
This is a common approach to balance the injection-



Influence of multiple injections on noise.



Injection rate influence at WHSC12, EGR variation, const. CoC = 4°CA.



Increase of nozzle flow rate at WHSC12 and WHSC3.

rate steepness by rail pressure. Both controls the amount of air entrainment and hence the local mixing from the charge into the fuel spray. On the other hand, the EGR could be reduced or omitted to have sufficient oxygen and reduce the soot emissions. Here the NOx engine-out raw emissions must be converted through the aftertreatment. NOx levels of 13 g/kWh require an SCR conversion efficiency of ~97%. In such a scenario, the BSFC is further improved when applying a slow needle opening rate.

Soot emissions are at the limit of detection. As EGR is decreasing the combustion duration is shortened regardless of the needle opening speed, and BSFC could be improved by 2 g/kWh.

Such improvement of a scenario with less EGR and reducing the needle opening speed does not necessarily deteriorate the rated power performance. BSFC could be enhanced by increasing the rail pressure for both fast and slow needle openings. It is interesting to note that although NOx emissions increase with the higher rail pressure, the shallow injection rate by the slow needle opening counters this effect and gives a small benefit in NOx of 1 g/kWh.

Nozzle flow rate

In the scenario that the EGR is reduced by the SCR and soot emissions becoming very low, the nozzle flow rate can be adapted to the raw engine-out NOx and soot emissions. Typically, the nozzle flow rate should be small to reduce the spray penetration and limit the soot formation but sufficiently large to supply the fuel to achieve the full load engine performance. Under the constraints of high NOx levels and sufficient oxygen, soot emissions are not limiting the increase of the nozzle flow rate and the demand of rail pressure is reduced. Then nozzle flow rate could be increased to reduce the combustion duration. Both the reduction of rail pressure and increased flow rate are mechanisms that shorten the combustion duration and improve the fuel consumption in terms of BSFC.

This approach was evaluated on the engine. Increasing the flow rate from 1550 to 1800 cc/min, the BSFC was improved by 0.5% at WHSC3. At lower engine speed conditions of WHSC12, the BSFC is similar at high NOx emissions but increases at low NOx emissions.

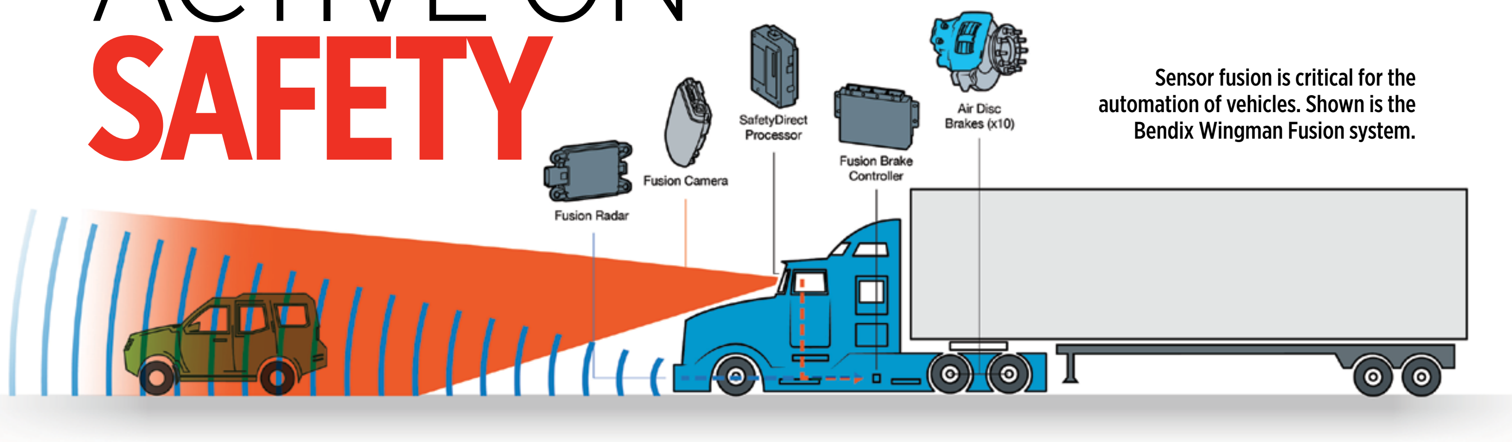
At the rated torque engine operation, the shorter combustion duration also improves the fuel consumption without a penalty in the soot emissions. Here the CoC is limited only by peak firing pressure (PFP) and an improvement of fuel consumption by 1% is achieved at similar soot emissions. A penalty results in the NOx emissions, which are increased by 1 g/kWh due to the increase of the spray penetration and premixed combustion amount.

However, this increase of NOx emissions only appears at 136-MPa rail pressure. Toward a rail pressure usage of 180 MPa, the BSFC is further improved and NOx increases by 2 g/kWh. This behavior could be explained by the increase of maximum heat release and a shorter combustion duration with respect to the increase of rail pressure and the increase of nozzle flow rate. A further increase to 250 MPa does not improve the air utilization for either nozzle.

For rated-power operation, fuel consumption also is improved by increasing the rail pressure from 180 MPa to 250 MPa; an increase to 300 MPa does not further reduce fuel consumption. At these conditions, the increase of nozzle flow rate does not demonstrate an additional positive effect on the fuel consumption, although the 1800 cc/min nozzle has a shorter combustion duration by 2°CA and an increase of maximum heat release rate, meaning the formation of increased NOx emissions. ■

This article is based on SAE Technical Paper 2017-01-0705 written by Jost Weber, Olaf Herrmann and Ron Puts of Denso Automotive Deutschland GmbH, and Jyun Kawamura, Yasufumi Tomida and Makoto Mashida of Denso Corp. http://papers.sae.org/2017-01-0705/

ACTIVE ON SAFETY



Sensor fusion is critical for the automation of vehicles. Shown is the Bendix Wingman Fusion system.

Crash-avoidance technologies are vital "building blocks" to automate commercial vehicles, implement truck platooning and ultimately achieve zero accidents.

by Bill Visnic and Ryan Gehm

Preco Electronics invented the vehicle backup alarm in 1962 and now seeks to set a similar safety milestone with the PreView Side Defender technology the company showcased at the ConExpo 2017 trade exposition in Las Vegas. The company calls the radar-based side-collision avoidance system "the industry's most-advanced side-object detection solution."

Targeted at over-the-road vehicles but also suitable for off-road applications, PreView Side Defender provides audible and visual alerts to avoid or mitigate collisions with pedestrians and objects in the side blindspots, an area in which the company said accident frequency is increasing. The range can be from 3 to 8 m (10 to 26 ft) from the vehicle sides and up to 6 m (20 ft) fore and aft.

Matt Wood, vice president of global sales for Boise, ID-based Preco, said light vehicles' increasing development of advanced driver-assistance systems (ADAS) has been instrumental in causing the commercial-vehicle sector to more intensively examine the possibilities for new collision-avoidance technology.

"Frankly, the auto industry has helped open the eyes of the construction and commercial-vehicle industry," Wood said.

He said Preco initially began with a reversing "solution" for avoiding collisions, but quickly realized that its long experience with radar could extend the idea to the side blindspots while traveling forward.

Object detection, side-turn assist to enhance safety

The PreView Side Defender system already is used by roughly a dozen OEMs, several of which displayed vehicles using Preco technology at the ConExpo 2017 event. The range included a cement mixer truck and concrete pump truck demonstrating the Side Defender technology and other commercial vehicles employing Preco's rear-object detection and even a telehandler with radar-based active braking operator assist.

Wood said the PreView Side Defender is designed to feed its 24-Ghz frequency-modulated continuous wave (FMCW) radar signal to the vehicle CAN bus via the **SAE** J1939 protocol, making the information available for several potential ADAS-related safety advances. He said that although the system is effective in recognizing objects in the side blindspots, it still is difficult to differentiate between pedestrians and solid objects. For now, the system is able to "ignore" stationary objects down to a speed of about 10 mph (16 km/h), but at slower speeds, "it's either on or off," in terms of providing a warning of an object or pedestrian in the blindspot areas.

The next step, he said, is to advance the technology to be able to distinguish, at slow speeds, between a person and a stationary object. The current PreView Side Defender setup operates in two modes: in highway mode, the system alerts to vehicles in the blind zones but ignores stationary objects to mitigate the instance of "nuisance" alerts. In slow-speed mode, the system seeks to provide side-turn assist "aimed specifically at reducing the incidence of collisions with pedestrians and cyclists in urban environments," the company said in a release.

PreView Side Defender was introduced last fall and is now showing up in various OEM applications. Wood said the system also is available for aftermarket fitment and can be combined with its Sentry radar-sensing technology, as well as camera-vision systems, to generate a 360-degree sensing environment.

Backbone for autonomous and platooning

Active safety technologies are the "building blocks" for commercial vehicle automation, Fred Andersky, director of government and industry affairs for **Bendix Commercial Vehicle Systems**, noted at the SAE Government/Industry Meeting in Washington, D.C., this January.

"Within the past few years, we've seen commercial-vehicle safety systems refine and incorporate full stability, collision warning and mitigation, and lane departure warning," said Andersky. "And the industry is on course to evolve and integrate these systems into even more advanced driver-assistance systems over the next few years, with expected driver-supported platooning and lane-keeping capabilities. Beyond

Fully integrated active steering is the next step for collision-avoidance systems—and ultimately autonomous driving capability. Shown is the ZF Innovation Truck 2016 performing an evasive maneuver with steering assistance. (Photo by Ryan Gehm)

those horizons lie automated applications like highway autopilot systems, leading to true autonomous technologies in the future."

The foundational technologies are in place, he said, but many advancements are still required for future generations of safety systems.

"To allow tomorrow's advanced driver-assistance systems to mitigate larger amounts of crash energy, we'll need to see further enhancements of camera and radar technologies, 'smarter' algorithms capable of increased object and situation recognition, vehicle-to-vehicle and vehicle-to-infrastructure communications, along with stronger deceleration and steering intervention," Andersky said. "In short, more information into the system to enable earlier and stronger acceleration and steering interventions to help mitigate more types of crash scenarios."

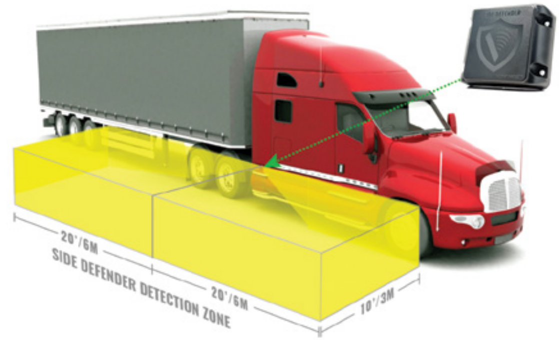
Sensor fusion is also critical on the path to automated vehicles, experts agreed at the SAE event. Collision-mitigation systems available today are already effectively combining radar, camera and brakes. For example, Bendix Wingman Fusion, available as a factory-installed option on various medium- and heavy-duty models including **Navistar**'s **International** ProStar trucks since the system's unveiling in 2015, cross-checks information from multiple sources to realize events sooner, alerting the driver and decreasing the vehicle's speed up to twice as much.

The system's camera is powered by **Mobileye**'s System-on-Chip EyeQ processor with state-of-the-art vision algorithms.

Fully integrated active steering is a critical next step for collision avoidance—and ultimately autonomous driving, Dr. Christian Wiehen, Chief Technology Officer for **WABCO**, told *Truck & Off-Highway Engineering*. (Read full interview at http://articles.sae.org/15228/.) The company is partnering with an Asian Tier 1 automotive supplier to develop, manufacture and sell electronically controlled active-steering systems for the global truck and bus market. Such integration will enable intelligent control of both the longitudinal and lateral movements of vehicles, Wiehen noted.

WABCO already has worked with **ZF** to develop Evasive Maneuver Assist, an active-steering system demonstrated on the ZF Innovation Truck 2016 prototype last summer.

"As the vehicle starts to warn the driver and initiates the braking phase, and if the driver initiates steering, the system takes over and helps him finish the maneuver," explained Ananda Pandy, lead system designer at WABCO North America. "The key part here is to balance between the brake and the steering capability [to maneuver around an obstacle].



Operational coverage area of Preco Electronics' PreView Side Defender side-object detection and collision-warning system. (Image: Preco Electronics)

"These are back-up, or redundant, technologies that might be available because you cannot just depend on one single braking maneuver as we work toward autonomous driving," Pandy added.

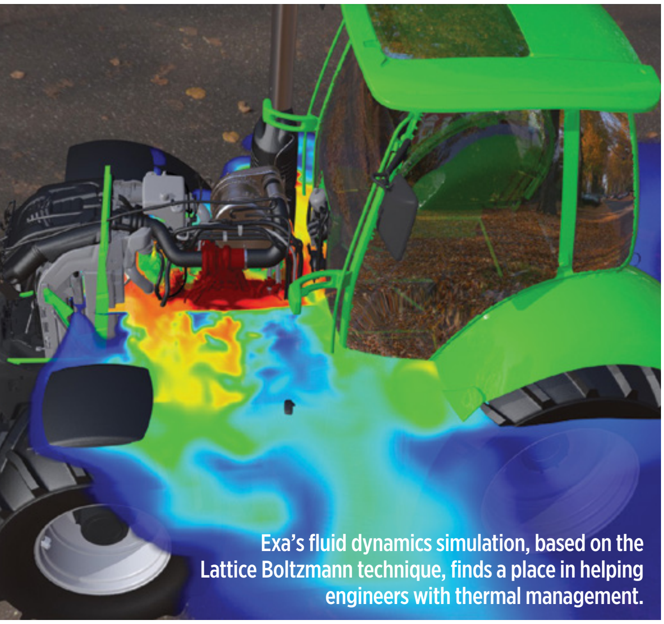
Collision mitigation acts as a redundant system in vehicle platooning, as well. Trucks communicate through DSRC (dedicated short-range communications), allowing the lead truck and following trucks to accelerate and brake in unison. But should the wireless communication fail, safety systems such as active braking and predictive cruise control are essential.

Peloton's V2V software communications, for example, allows for the following truck to brake within 0.1 seconds of the lead truck. This allows the vehicles to follow at distances as close as 40-50 ft (12-15 m) for aerodynamic efficiency gains.

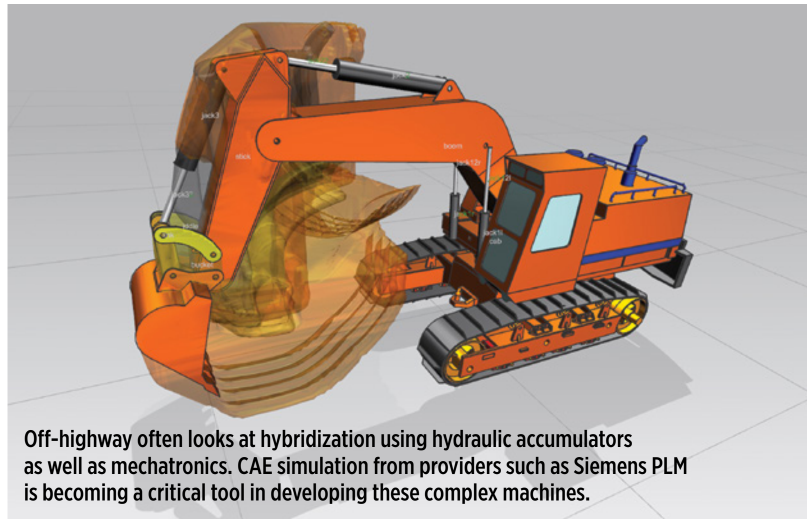
"In the future, we'll add more redundancy to the [Fusion] system, so we can get to the more semi-autonomous applications," said Andersky, such as **Daimler**'s Highway Pilot, **Tesla**'s Enhanced Autopilot, and platooning road trains where only the front vehicle has a driver.

"But that doesn't mean we duplicate systems on the vehicle," he said. For example, brake steer will back-up the primary steering control system. ■

ENGINEERING WITH SIMULATION AND DATA



Exa's fluid dynamics simulation, based on the Lattice Boltzmann technique, finds a place in helping engineers with thermal management.



Off-highway often looks at hybridization using hydraulic accumulators as well as mechatronics. CAE simulation from providers such as Siemens PLM is becoming a critical tool in developing these complex machines.

Companies are discovering new simulation techniques, especially optimization; the next step is to combine simulation with sensor data and predictive analytics to create even more robust off-highway equipment.

by Bruce Morey

Making off-highway equipment, such as construction or agriculture machines, more efficient continues to be a priority after the final phase-in of the U.S. **EPA** Tier 4 Final emissions regulations.

"Some of the companies we work with are running out of credits and unfortunately still struggling with Tier 4," explained Tristan Donley, Technical Director, Off-Highway Heavy Vehicles North American for **Exa**, a supplier of software for computational fluid dynamics (CFD). These companies continue to balance thermal and noise requirements due to their upgraded engines and aftertreatment devices, for example. "Others are now focusing on cutting the additional cost from components that enabled them to meet Tier 4 Final, but drove up the cost of their machines," she said.

A key element of this packaging is optimally managing thermal flows in systems that must be ever more efficient and smaller. That is where Exa's flagship software PowerFLOW enters the picture. PowerFLOW uses a relatively new technique in simulation, Lattice Boltzmann CFD. Without going into mathematical details, it claims advantages over the more common CFD based on continuous Navier-Stokes formulations, according to Donley. Using Lattice Boltzmann allows PowerFLOW to use a computational mesh with larger cells, or voxels as they term them.

"It is easier to resolve complex geometry and is inherently transient. Our voxels can be larger than the feature we are trying to predict the flow around," she said.

While the method is also useful for aerodynamic flows, off-highway engineers tend to use it mostly for aeroacoustics and thermal management. "The priority for our current customers is using optimization techniques for package layouts. They want to know space claims for different components such as heat exchangers, or how to orient the engine to protect electronics," she said. "They also want to know where to place grilles and louvers to make sure they get enough airflow through their engine compartment."

She notes that some of these companies had never used any type of CFD software prior to designing systems for Tier 4. There were so many challenges that their tried-and-true design techniques of the past—what she calls "tribal knowledge"—were not working, creating an opening for using advanced simulation like PowerFLOW's Lattice Boltzmann CFD. She also notes the increasing use of various optimization techniques, like multifunctional objectives and trade-off techniques that balance competing priorities for an optimum solution.

Integration and digital twins

At **PTC**, provider of CAD and simulation software as well as Internet of Things (IoT) solutions, "integration" is an important trend. The company's flagship CAD software, Creo, is tightly integrated with its finite-element simulation package, Creo Simulate, for performing structural, thermal and vibration analysis.

"There are many geometric design changes in the lifecycle of a design, and typically if you make that change you have to start the analysis process again," explained Jose Coronado, Product Manager for Creo Simulate. "With Creo Simulate, this is not the case. Whenever you change the geometry because you had to change the design requirement, the downstream settings are updated automatically."

He also touts the software as easy to use, with an interface designed for engineers without a deep background in advanced finite element analysis—no PhD required. "The user interface is common with Creo to make it consistent," he said.

While Creo Simulate adapts to design changes, Coronado points out that the use-case scenarios for setting initial conditions and loads often remain assumptions. How much weight will be in a bucket, how fast will the machine be driven, or how many hours a day will it be used are derived from spotty observations or educated guesses.

"Better is to establish a digital twin by integrating data from a physical product with a digital representation of that product. This will give us greater insight into the product's state, performance and behavior," he said. "We can use real loads in our simulations instead of assumptions."

Connected to embedded sensors, the company's ThingWorx product will facilitate transmitting real data to the designer of, say, a backhoe. The data will show if operators are lifting 2 tons or 5 tons, operating it 12 or 8 hours a day, and so on. This provides "performance based analysis" that can reproduce critical circumstances.

"Not only for a family of products, we can even get down to a particular serial number and determine how it is being used versus another individual product, continuously re-evaluating assumptions," explained Coronado. "Think of ThingWorx as the real-time aggregation engine of the real sensors to close the loop."

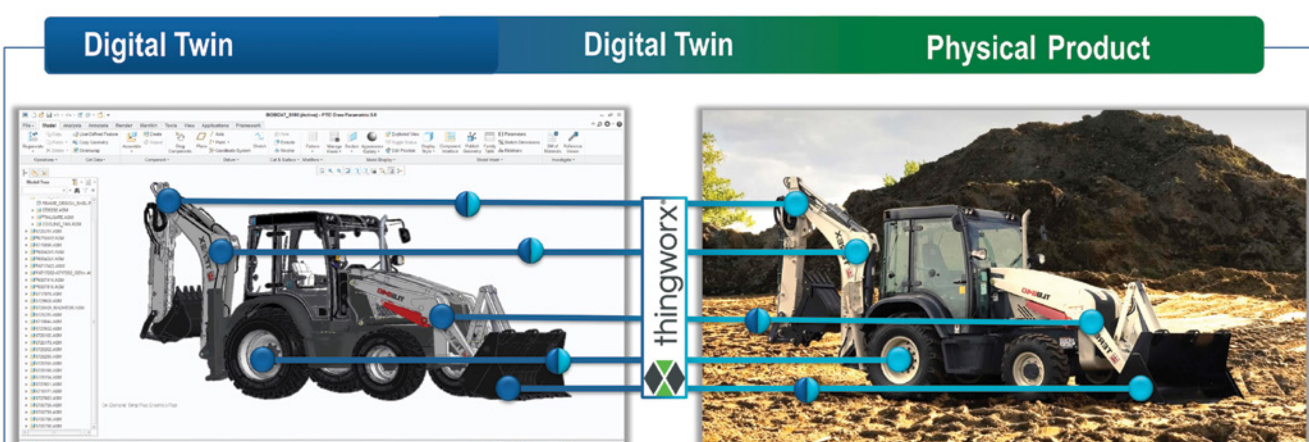
Siemens PLM believes the industry is in the early stages of seeing an impact of sensors, data collection and analytics on the design process beyond simple predictive maintenance. Here, a prototype is instrumented as part of a test campaign. (Siemens PLM)

Holistic solutions

Ravi Shankar from **Siemens PLM Software** offers a comprehensive view of the problems off-highway equipment manufacturers face. Machines need to increase their effectiveness in terms of greater loads, but they also need to improve durability and fuel economy. Operator comfort is equally important.

"They need to ensure their operators are not stressed too heavily to ensure smooth operation and efficiency," explained Shankar. "These requirements often work in conflict with each other, for example increasing load capacity means larger components that negatively affects emissions and fuel economy, as does air conditioning." These often force a look at different types of hybridization, including both electrical and hydraulic. These are more difficult to design than a pure mechanical system.

The solutions Siemens now offer are just as comprehensive and growing, expanding through acquisitions. To their existing tools in simulation and data management, they have added 1D and 3D systems simulations expertise through its acquisition of **LMS**, and CFD and design exploration through **CD-adapco**. Predictive analytics tools have come along with **Camstar** and its Omneo product.

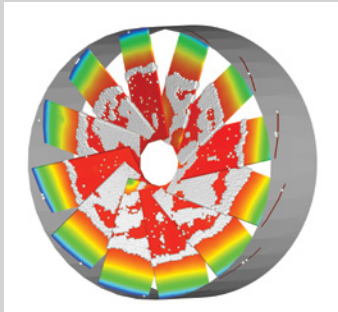


Establishing a digital twin through IoT communicators like ThingWorx brings even more reality to CAE simulations by incorporating actual test measurements into future analysis. (PTC)

ENGINEERING WITH SIMULATION AND DATA

Advances in urea deposit modeling

One of the key components for most off-highway engine makers to meet emissions regulations is selective catalytic reduction (SCR). These systems convert nitrous oxides, or NOx, into nitrogen and water. They require a separate fluid added to the exhaust gas. This is typically anhydrous ammonia, aqueous ammonia or urea, collectively referred to as diesel exhaust fluid (DEF). The conversion process requires a catalyst to complete.



Predicting where deposits will form in SCRs using the CONVERGE CFD package. (Convergent Science)

Long-term effectiveness and durability is greatly affected by unwanted formation of deposits. The systems work better if they remain clean and smooth. “Deposits are even more of a problem in the compact, low-temperature SCRs that are better overall at meeting requirements,” said Scott Drennan of **Convergent Science**. “Everyone who uses SCR aftertreatment says deposits are their biggest concern.”

Engineers would have valuable insight, and a cost-effective design tool, if they could use CAE simulation to predict where deposits might grow. It is a challenging problem, involving complex chemistry, phase change, and multi-phase CFD. Making modeling even trickier, according to Drennan, is that these deposits only form in a limited temperature range, above 433K or below 406K. “Most simulations to date will identify areas in the design where there is a risk that deposits will form,” he explained, making analysis after the fact.

“We are now modeling the actual chemistry and moving to predicting where actual deposits will form,” he said. The capability will be available in the next release of CONVERGE, the detailed chemistry and CFD code the company is known for. While predicting where they will form, it is still beyond the computational capability of any computer to predict how thick such deposits might be.

“However, it is a good tool to help people design more durable SCR,” he said.

Bruce Morey

Making sense of how simulation, IoT and predictive analytics all fit can seem confusing. “There are really three ways of thinking about Big Data and predictive analytics,” he said.

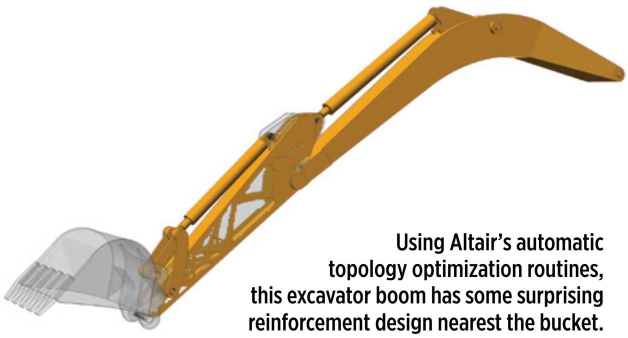
First is integrating sensor-based data with physics-based simulations, using the digital twin concept. This means augmenting test and test data protocols with virtual sensors and bringing that data back into the early stages of design and engineering.

A second way is in the postprocessing of data, for instance by using its LMS Test.Lab technology. “For example, to use data from multiple sensors that measures durability for critical types of off-highway equipment,” he said. Think of aftertreatment devices or critical joints. “There are reams and reams of such data, but you need to postprocess that data using math techniques and convert them to some key performance indicator useful in the design process.”

The third way is to view simulation optimization as another form of data analytics. Shankar believes Siemens’ HEEDS multi-domain optimization tool is really a form of Big Data analytics that uses hundreds of simulations—reams of data—to arrive at optimum solutions that meet given constraints. Multi-domain optimization, or MDO, combines the results of multiple simulation types, say engine, heat transfer, vehicle dynamics, into a single, results-oriented model. Sorting through the multiple, combined runs lets the software suggest the best solution that meets constraints.

“These are all valid ways of combining sensor data with physics-based simulations and test. Twenty years ago, some thought that CAE would replace test, but in some ways, test is just as important as CAE in the context of predictive analytics,” he said.

With Big Data analytics coupled with a vision of vast data collection, whole product populations can now be incorporated into digital prototypes or digital twins. (PTC)



Using Altair's automatic topology optimization routines, this excavator boom has some surprising reinforcement design nearest the bucket.

Simulation and results

Makers of off-highway equipment rely heavily on classical proven methods of design and the company's legacy knowledgebase. These are viewed as reliable and dependable.

"Currently CAE simulation is becoming a more useful tool in a world dominated by traditional methods of equipment design," said Venugopal Ravula, Program Manager of **Altair**. "Many of the success stories we have had with heavy equipment companies have been in reducing weight and costs, and developing the methods to manufacture the biomimicry designs—large fabricated components."

The key to success in reducing weight and cost is in using CAE for optimization, according to Ravula. Design and topology optimization tools are premier components of Altair's software offerings. Across all industries, educating engineers in the proper use of optimization is needed.

"Often, customers do not know what they want," he said. "They might come to us through our consulting service asking about shape optimization, but once we expose them to other tools, like multi-domain optimization, they can see the benefits." He also stated that the industry is moving towards increasing use of MDO.

Topology optimization, where the shape of a component is suggested through automatic means, is one of Altair's specialties. A recent case study the company shared in an interview points to some of the peculiarities and advantages that future engineers need to know. Using its OptiStruct tool, Altair helped **Liebherr** redesign a crane boom that resulted in a component that was 20% lighter yet could lift 400 kg (880 lb) more. The resulting shape is not one that "tribal knowledge" or design books might produce, looking more organic with odd spacing of reinforcements. Other examples he showed included castings of tractor transmissions that reduced mass by 10%.

Ravula also notes that IoT, Big Data and data analytics are becoming more important in predictive maintenance, a field in which Altair also is active. ■

Q&A

Alternative powertrain tech, connectivity hot topics at ICPC 2017

"The amount of CO_2 reduction [connectivity/ADAS] technologies will achieve cannot yet be estimated, but it will certainly be higher than technical measures on the powertrain alone will enable," said AVL's Marko Dekena.

Focusing on technologies and strategies impacting truck and bus, agricultural tractors, and construction machinery, the biennial **AVL** International Commercial Powertrain Conference (ICPC) organized in cooperation with **SAE International** will be held in Graz, Austria from May 10-11, 2017. Experts from each of these sectors will share their insights related to the 2017 event's overarching theme: CO_2 reduction and innovations to improve operating efficiency. Dr.-Ing. Marko Dekena, Executive Vice President, Global Business Development, Sales and International Operations Powertrain Systems, AVL List GmbH, recently spoke with Editor-in-Chief Ryan Gehm about some of the strategic and technical issues to be discussed at this year's event.

Electrification is a major topic of the event across all three segments. What is the outlook for electrification in each of them?
Let's first define "electrification" because it covers a huge field of technologies: hybridization (mild, full, plug-in), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). Most likely this is also the introduction sequence for eventual applications of these technologies. The extent to which these technologies will be applied depends on the kind of vehicle, application and the main operating conditions—so, you see, it is quite complicated.

Secondly, we need to be clear how "CO_2 emissions" is defined: tank-to-wheel, well-to-wheel or cradle-to-grave. The results are completely different. Personally, I would prefer the holistic view from cradle-to-grave, because it is the only correct way to reduce CO_2 emissions. However, it is the most difficult approach due to lack of data in the various areas at present. To make it a little easier, let's take tank-to-wheel—this is also the way most publications are dealing with this matter.

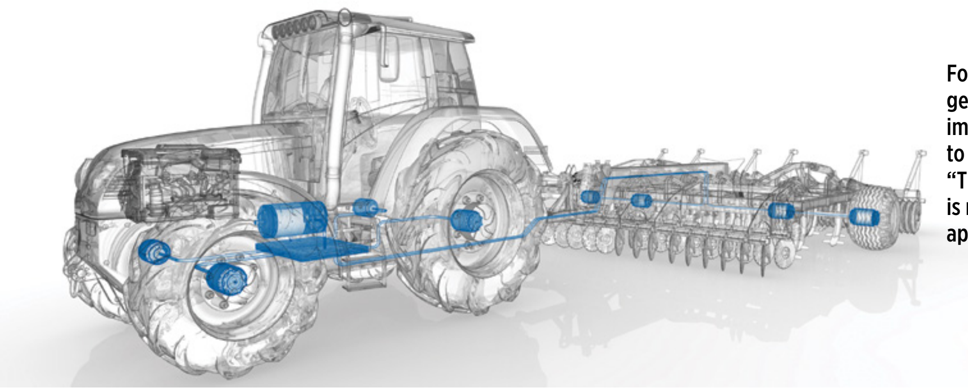
Light-duty and some **medium-duty trucks**, operating in urban traffic, are suitable both for hybridization and BEV operation, maybe in the long term also for fuel-cell operation. The CO_2 saving potential with city hybrids is in the range of up to 20%. But instead there seems to be a new trend towards BEVs. And here the amount of CO_2 reduction (tank-to-wheel) is much higher, but the reduction, when you regard well-to-wheel, depends very much on the electric power source—where does the power come from? If you take, for instance, today's power mix of China there could be no well-to-wheel reduction at all. If all electric power comes from renewable energy sources, the well-to-wheel CO_2 reduction will be much higher. Very much the same can be said for city buses.

Heavy-duty long-haul trucks are different. They run typically 150,000 to 200,000 km per year and therefore every percentage point of fuel / CO_2 savings makes a big difference. Hybridization in combination with downsized diesel engines makes a lot of sense and can achieve savings of 8 to 10% depending on the topography. Waste heat recovery can save another 3 to 5%. I can hardly imagine HD trucks as BEVs. Batteries are still—even in a theoretically very advanced status—by far too heavy and costly. Trucks need to earn money and so every kilogram of dead weight / lost payload reduces efficiency and profitability. If at all, in the longer term I could imagine a fuel-cell-powered long-haul truck.

Let's talk about **agricultural tractors**—I mean real farming tractors, not derivatives such as street sweepers, utility tractors for communities, etc. For the hard and sometimes extremely diverse work that tractors do, electrification can save a lot of CO_2 and consumables when applied to the various implements. The diesel drives a generator which supplies power to the PTO and/or to the implements which now have no mechanical connection to the engine anymore but are driven by electric motors. This makes a lot of sense—the whole system is much more efficient and flexible for different applications.

Finally, let's consider **construction equipment**. BEVs may be suitable for very small equipment for shorter operations, very much depending on the operation purpose. Hybridization is the choice for all vehicles operating under heavily changing load cycles and braking. Here the electric motors can assist transient behavior by boosting acceleration and acting as generators during braking, thus feeding power back to the battery, which can then be used for the next acceleration. Simulations we made in AVL, for example, for wheel loaders proved fuel / CO_2 savings in the order of 10-15%.

How much is shared technology?
I think quite a lot, both in hardware and control software. However, the huge amount of different vehicles, applications



For ag tractors, the diesel engine can drive a generator that supplies power to the PTO and/or the implements which have no mechanical connection to the engine but rather driven by electric motors. "This makes a lot of sense—the whole system is much more efficient and flexible for different applications," said Dekena.

and operation conditions makes it very difficult to find the best solution in every case. Finding the "right" combination of diesel engine, transmission, electric devices, storage system and control system is an enormous challenge in all the discussed application areas, even if the individual components are known or even the same. Here, full system simulation comes into the game, an area where AVL has collected significant experience in the last 10 years. All tools and procedures to simulate even very complex systems in any real operating condition have been developed, proven and are ready for use.

Likewise for operator efficiency, connectivity and ADAS appear to be major trends that cross the segments.

Basically, there is a huge potential to increase the efficiency of all kinds of commercial vehicles by applying connectivity, Big Data and autonomous driving. Although there currently seems to be a hype in all areas, it will take many years to make use of these technologies on a large scale. There are still too many open issues like standardization, legal issues, national and international rulemaking, safety and technical issues, insurance and liability questions and many more. You may know that larger agricultural tractors have for a number of years been operating autonomously or at least partially autonomously, enabling precision farming. The vehicle or several vehicles at once are controlled by GPS not only for precise tracking but also for soil detection and optimized fertilizer output control.

Trucks and buses will be the next category of vehicles to apply this technology, first in enclosed areas and later also on highways, in the simplest form of platooning. Also, logistics control will enable a major improvement of vehicle and operator efficiency by largely avoiding 'empty drives.' The ongoing intensive activities in the passenger car area will definitely also pave the way for commercial vehicles. But it is clear that every vehicle needs specific adaptations according to its operating conditions. I can hardly imagine driverless vehicles but I am sure that the tasks of the driver or operator will change and result in higher efficiency.

"To implement predictive functions into the control software is the consequential next step."

I see big advantages in the operation of construction machines, especially when it comes to larger construction sites with many different machines and vehicles involved—the so-called site management. By optimizing and linking the various and manifold operations, waiting times and inefficient travels can be avoided. Intelligent condition monitoring and preventive maintenance and service of the vehicles will help to further reduce unplanned downtime to a high extent.

The amount of CO_2 reduction these technologies will achieve cannot yet be estimated, but it will certainly be higher than technical measures on the powertrain alone will enable. The challenges mentioned initially have to be solved across all applications, but everyone will have their own specific solution. Thrilling times ahead of us!

Which upcoming emissions regulations are top of mind and pose the greatest challenges to engineering efforts?

It's still the well-known emission of NOx, hydrocarbons, and particulates. We have to envisage even tighter limitations beyond EU6 and Stage V together with changes of the measurement procedures—with the keywords Real Driving Emissions and In-Use Compliance. The real future challenge is the combination of tough CO_2 / fuel consumption limitations in nearly every part of the industrialized world with further drastically reduced NOx limits. Whatever we do to reduce the toxic emissions will basically contradict CO_2 and fuel consumption reduction. How to reduce emissions in general is well known in the meantime—the technologies to be applied are available and proven. They need to be refined for the various applications, which is a tremendous amount of work but the road map is rather clear. This applies for all vehicle segments from passenger cars to construction equipment within different time frames.

However, for the time being the recent new proposals or intentions of the U.S. Environmental Protection Agency (**EPA**) and the **California Air Resources Board** (CARB) create a lot of headaches for engineers. Fuel consumption of HD truck engines has to be reduced until 2027 by further 4% compared to model year 2017, according to EPA. CARB even wants to cut fuel consumption figures by 8% within the same time frame combined with a further NOx reduction of 90% compared to MY 2017! In addition, the new EPA proposal calls for a 20% reduction of fuel consumption of the complete truck—this is a quite new and extremely challenging situation. And it is very likely that similar restrictions will one day be transferred to the

Q&A

non-road sector. AVL is currently successfully working on solutions—how modern powertrain technologies can be combined in a cost-effective way to meet those tough regulations.

What other alternative powertrain technologies can make a big impact in this regard?

Certainly there is still improvement and refining potential in conventional powertrains including transmissions. This is ongoing and business 'as usual.' Fuel cells are back again after the hype in the late '90s. As said already earlier, I do see a good chance longer term for application in long-haul trucks. When it comes to fuel cells it is mandatory to make the view from cradle to grave. Although the fuel cell itself offers a rather high efficiency, there are significant losses to be taken into account which happen during production and transport of hydrogen—in the end there might not be an efficiency advantage for many applications. Of course, infrastructure issues will be a major hurdle, especially when it comes to agricultural tractors and/or construction machines. I cannot imagine a hydrogen filling station somewhere on a construction site in the middle of nowhere. And of course, the price question has to be answered.

I do see much more potential in alternative fuels, but not those discussed in the past. I see a thrilling potential in synthetic fuels or so-called e-fuels generated from renewable CO_2-neutral power, and hydrogen synthesis making use of CO_2 from power plants and other CO_2-generating factories—or even extracted from ambient air. The basic technologies and processes are known and according to recent publications even the costs could be reduced significantly. I do hope that all involved industries take this path seriously into account as it opens a much more effective way by which conventional diesel (and also gasoline) engines could be used further on. It would be a great achievement, because these kinds of alternative fuels would also have an immediate effect on the whole existing engine population.

What's your view of waste heat recovery? Many say it's not cost-effective and becomes less important as engine efficiency is optimized.

I do not agree at all! Even if engine efficiency is increased there will still be a waste of 20% of the fuel energy, so it is worth exploiting that potential. AVL and others have proven a fuel consumption reduction by WHR in the order of 3-5% in real long-haul trucking. These trucks run about 150,000 km/year and consume about 40,000-50,000 L of diesel. Depending on the actual fuel price, savings in the order of 2000-3000 €/year are realistic. This means that the payback period could be less than 2 years. Of course, it depends very much on the application, the topography the vehicle is driving and the fuel price. WHR is still under development and I expect further efficiency improvements to come. WHR makes a lot of sense for applications like long-haul trucks, coaches or marine applications in which no extra energy is needed for cooling fans to get rid of the heat during WHR operation.

Ryan Gehm

Read the complete transcript of this interview at http://articles.sae.org/15305/.

Case unveils compact dozer loader concept at ConExpo

Called "Project Minotaur," the **Case** DL450 compact dozer loader is a "first-of-its-kind" machine that combines the footprint and performance of a compact track loader (CTL) with the power and dozing characteristics of a bulldozer. The crossover concept was revealed at ConExpo-Con/Agg 2017, where Case Construction Equipment conducted extensive focus groups with contractors to help determine how the machine can be further refined for production. The company would not confirm a launch date.

"Unlike concept vehicles that you see from other OEMs, which are simply meant to create a reaction, Project Minotaur is very practical evolution of two product lines that will provide added machine flexibility to those in the residential and commercial construction industries," Scott Harris, vice president – North America, Case Construction Equipment, said at the machine's reveal in Las Vegas. "It could also be a transformational piece of equipment for landscapers and other small to midsize contractors looking to add greater earthmoving power and precision to their operations."

The Case DL450 machine concept marries the current TV380 compact tractor style frame with a radial-lift loader arm design similar to the Case legacy 465 skid steer.

The cab and controls inside the machine are similar to what's in current CTLs and skid steers—*and* dozers. Some of the pending patents involve the changeover from CTL operation to dozer.

The machine's platform runs all of the attachments a contractor might currently own for skid steers and CTLs.

"Contractors now have one machine on site that handles all of these items," Harris said.

C-Frame interface the core feature

How is this new machine different than a CTL matched with a dozer blade attachment? The answer is a new C-Frame dozer interface that pins directly into the chassis of the machine. This setup provides the stability and smooth operating plane of a CTL and ensures that operating power and stresses are channeled through the machine's chassis and not its loader arms.

The C-Frame, which is one of the more than 30 pending patents stemming from Case's Minotaur project, can be unpinned from the chassis and disconnected like any other attachment, allowing the machine to perform like a standard CTL.

"The problem with dozer attachments common with CTLs and skid steers—while effective in specific operations—is that they channel all operating stress through the coupler and the loader arms, and are really only suitable for groundline work," said John Dotto, brand marketing manager, Case Construction Equipment. "This affects performance and adds wear and stress to those components. The operator gets true dozing performance with this machine—no arm float, a consistent plane and true 6-way blade performance through the machine's new controls."

Counterweight has been added to the machine and the undercarriage features steel tracks and grousers "for added bite and pushing force," Harris said. Other enhancements include a fifth roller for better traction—compared to the standard four on a CTL—and greater ground clearance, at 13 in (33 cm), to reduce the likelihood of drag.

A rear ripper assembly increases functionality without sacrificing access to daily-service points.

Proven frame, with some tweaks

"Project Minotaur" was conceived between the Case skid steer manufacturing plant in Wichita, KS, and **CNH Industrial**'s research and development center in Burr Ridge, IL.

"It's a project that's more or less bridged the gap between last ConExpo [in 2014] and here. It's been in development for a couple years," Dotto told *Truck & Off-Highway Engineering*. "The task was given to the engineering group to find a solution for that contractor that's using a large track loader to do a lot of earthmoving and pushing. So it started as a brainstorming project in the Wichita design and engineering group."

The DL450 combines current and legacy technologies and designs to create a new product category, Harris said. The frame of the machine is similar to that of a current TV380 compact tractor, the largest and most powerful CTL in the Case family, but has been further increased in size to handle greater loads.

The frame is based on a vertical-lift machine, but "Case engineers wanted to build the pushing power and the frame strength of a radial-lift machine into the design, so the machine marries that TV380-style frame with a radial-lift loader arm design similar to the Case legacy 465 skid steer," Harris said.

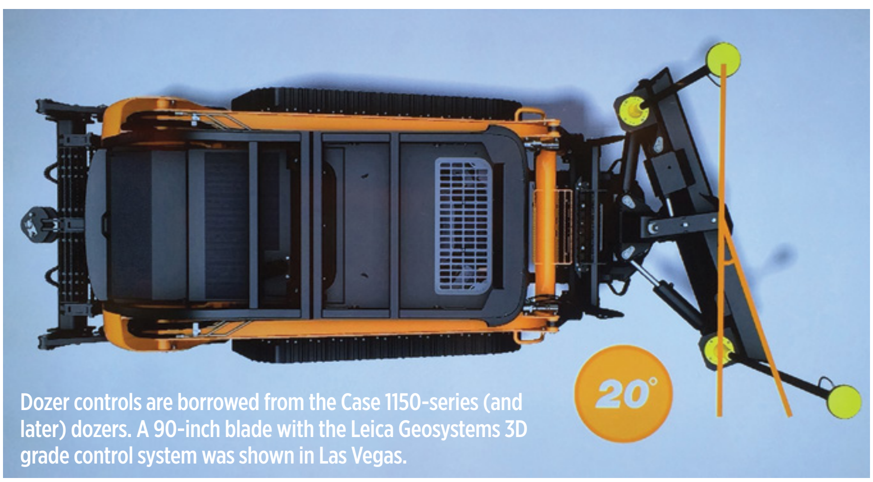
A rear ripper assembly increases functionality without sacrificing access to daily-service points. (Photo by Ryan Gehm)

Another inspiration for this concept machine was the 450 Series Case dozers, according to Dotto. "Our engineers focused on building performance and operating characteristics similar to that platform into this machine. Early indications show that they've accomplished this, with an anticipated drawbar pull of around 21,000 lb," he said.

Cab and controls

The cab and controls inside the machine are similar to what's in current CTLs and skid steers—and dozers.

The core feature is a new C-Frame dozer interface that pins directly into the chassis of the machine. This setup ensures that operating power and stresses are channeled through the machine's chassis and not its loader arms. (Photo by Ryan Gehm)



Dozer controls are borrowed from the Case 1150-series (and later) dozers. A 90-inch blade with the Leica Geosystems 3D grade control system was shown in Las Vegas.

Similar to ISO controls, forward and reverse travel and steering is controlled with the left hand. Boom and bucket controls are manipulated with the right. Those same controls in the right hand control the lift angle and tilt of the 6-way dozer blade.

At least one of the pending patents involves the changeover from CTL operation to dozer. "Where you'd normally see an ISO/H-pattern changeover switch in a CTL, you're going to see an ISO-to-dozer control switch on the DL450," Dotto said.

"If you have standard CTL sticks in there, you're not quite dozing because you don't have all the six-way ability," he continued. "So that's why we threw in the dozer-style controls. The dozer controls that we're using are from our 1150 and up series dozers, a 90-inch blade with the **Leica Geosystems** 3D grade control system."

Dozer control features such as blade shake and pitch adjustment will be incorporated. Focus groups also will help determine "what the future brings for Project Minotaur with grade-control options," Dotto said.

"We see this [new machine] as something that will help contractors achieve ideal utilization rates and simplify the footprint of equipment they deploy to a site," he said.

Ryan Gehm

Work trucks strive to curtail addiction to fuel

Reducing fuel consumption was a focal point of several trucks unveiled in March. Electric drivetrains and four-cylinder engines were among the tactics disclosed at The Work Truck Show in Indianapolis.

Mitsubishi Fuso Truck of America, Inc. rolled out an all-electric medium-duty work truck, the eCanter, which it says will be the first plug-in electric work truck produced by a major truck manufacturer. The Class 4 truck has a payload capacity of roughly 9380 lb (4255 kg).

It offers a range of up to 100 mi (160 km), one-hour quick charging, and standard eight-hour overnight charge. Compared to a two-year lease, the eCanter will carry a 15-20% premium over a comparable diesel engine, Fuso CEO Jecka Glasman said. She added that it weighs about 800 lb (363 kg) more than a similar diesel vehicle.

"There are six batteries developed by **Mercedes**, they output 360 V," said Otto Schmid, Fuso's Director, Product Management. "They provide 82 kW·h of energy to power a 129-kW asynchronous motor. These motors have high torque—compared to a V10 gasoline engine, they provide 34 foot-pounds more torque."

Ford took a different tack on electrification, expanding its Advanced Fuel Qualified Vehicle Modifier program to include three developers that install electrified and hydraulic hybrid powertrains on Ford trucks and vans. **XL Hybrids**, **Motiv Power Systems** and **Lightning Hybrids** offer solutions for a range of Ford vehicles popular with fleet and commercial customers, including F-150, F-250 to F-550 Super Duty, F-650 and F-750 medium-duty trucks, Transit and E-Series vans and chassis, and F-53/F-59 stripped chassis.

One supplier noted that fleets are now upfitted to hybrids solely to save money.

"The days of buying hybrids just to be green are over," said Clay Siegert, chief operating officer of XL Hybrids. "Every acquisition now is based on a

Fuso's fully electric eCanter is a Class 4 truck with a range of 100 miles.

financial payback."

A four-cylinder engine was the highlight of **Isuzu** Commercial Truck of America's 2018 FTR, a Class 6 medium-duty truck, which the company says is the first four-cylinder in this segment. It's powered by the Isuzu 4HK1-TC 5.2-L turbocharged diesel. Isuzu didn't provide mileage data, but said the turbocharged 4HK1-TC generates 520 lb·ft (705 N·m) of torque at 1650 rpm and 215 hp (160 kW) at 2500 rpm.

The FTR employs an **Allison** 2550 RDS six-speed automatic transmission with power take-off (PTO) capability. The front axle has a capacity of 12,000 lb (5445 kg), while the rear axle's capacity is 19,000 lb (8620 kg).

In another change, Fuso unveiled a gasoline powertrain for its FE Series medium-duty cabover trucks. A 297-hp (222-kW) V8, the 6-L PSI-GMPT Vortec, powers three Fuso models, the FE130, FE160 and FE180, spanning Class 3, 4 and 5. An Allison 1000 6-speed automatic transmission will offer a PTO capability. Fuso also focused on safety, teaming up with **Mobileye**, using its advanced collision-avoidance system, which is used on a number of passenger cars.

"We did a test, installing the systems and letting people drive for one month without turning them on," Glasman said. "When the Mobileye system was turned on, emergency braking and lane departure without warning were reduced by 50%."

Terry Costlow

Four-cylinder engines help Isuzu's FTR family conserve fuel.

PRODUCT BRIEFS

SPOTLIGHT: ENGINE COMPONENTS

One-piece fully molded fan

The Truflo SDS39 molded fan from **Phillips & Temro Industries** (Eden Prairie, MN) is a one-piece, fully-molded fan for engines in the off-road and power generation markets. With a diameter range of 500 mm to 990 mm (19.7 in to 38.9 in), the company claims the SDS39 is one of the world's largest one-piece, fully-molded fans for engines in those respective markets. In addition to being 26% more efficient than other molded fans, the Truflo SDS39 makes less noise, is lighter—and with lower power consumption, less need for attenuation materials and elimination of a clutch—is more affordable, according to the company. The Truflo SDS39 molded fan is available in any fan-mounting pattern, including fitment to viscous clutch. Other specifications include standard and reverse flow, glass-filled polyamide sickle-shaped blades, a steel center disk and optional shaft adaptors for direct, electrical or hydraulic drives.

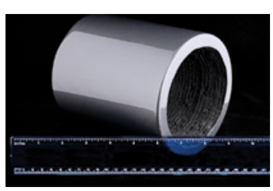
For more information, visit http://info.hotims.com/65850-450

High-temperature conduit and fittings

Harnessflex TempGuard conduit and fittings from **ABB Electrification Products** (Memphis, TN) are designed specifically to protect and route high-temperature cables, providing an integrated system for engine wiring in temperatures up to 392°F (200°C). The company claims the Harnessflex TempGuard conduit and fittings system increases the temperature rating by more than 60% over standard fittings in the range. According to ABB Electrification Products, the reliability of the new line and validity of the temperature ratings have been verified through long-term heat aging, as well as tensile and impact strength testing. A wide range of TempGuard fittings and conduits are available, made from specially formulated polyamide and co-polyester materials. The range includes HTC08-HTC20 conduit, with respective T- and Y-Piece fittings, straight and elbow joiners and back shells for **AMP**, **Bosch**, **Deutsch** and **FCI** connectors.

For more information, visit http://info.hotims.com/65850-451

Advancing 3D-printed NdFeB magnets



Magnet Applications, Inc. (DuBois, PA), a **Bunting Magnetics** Co., has made a technology advancement in 3D-printed neodymium iron boron (NdFeB) magnets. According to Magnet Applications, engineers from the company, working together with researchers at **Oak Ridge National Laboratory** (ORNL), have proven that permanent magnets produced by additive manufacturing outperform bonded magnets using traditional methods with less waste. The company claims it manufactured the starting composite pellets with 65 % (by volume) isotropic NdFeB powder and 35% polyamide nylon-12 binder in a precise ratio, blended to a consistent texture. The 3D printing was performed at ORNL with the Big Area Additive Manufacturing (BAAM) system. "Additive manufacturing in magnets provides multiple benefits," said Magnet Applications' Dr. John Ormerod, Senior Technical Advisor. "They have more design flexibility." NdFeB magnets are the most powerful on earth and are used in applications including robotics, wind turbines, electric vehicles, electric motors and other consumer and industrial equipment. The complete study is published in *Scientific Reports*.

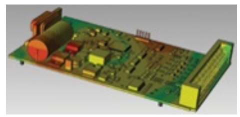
For more information, visit http://info.hotims.com/65850-456

Long-body LED indicators

Wilbrecht LEDCO, Inc. (St. Paul, MN), a **Microprecision Electronics** SA company, offers a long-body nickel-plated panel mount LED suitable for various applications, including industrial control panels, transportation dashboards, and aircraft/military instrumentation. The housing is designed to easily fit panel thicknesses of up to 9.0 mm (0.35 in) even with additional gasket. The front mounted prominent and recessed bezel shaped forms come with termination options leads or Faston-style quick connects. The fully-potted leads version with additional gasket offers front and backside IP67 sealing for water resistance and outdoor use. The rugged vibration- and water-resistant LED indicators are U.S.-made and can be modified to fit custom needs for special wires, connectors or marking. All versions are available in a range of colors and intensities, including daylight readable red, yellow, green, orange, as well as bicolor, blue, white, flashing, infrared and night vision compatible LEDs.

For more information, visit http://info.hotims.com/65850-452

Vibration and acceleration simulation



Mentor Graphics Corp.'s (Wilsonville, OR) Xpedition vibration and acceleration simulation product for printed circuit board (PCB) systems reliability and failure prediction addresses the challenges of harsh environments for today's electronics. Xpedition Design for Reliability (DfR) augments mechanical analysis and physical testing by introducing virtual accelerated lifecycle testing much earlier in the design process. According to Mentor Graphics, it is the industry's first PCB-design-specific vibration and acceleration simulation solution targeting products where harsh environments can compromise product performance and reliability, including automotive, military, aerospace and industrial markets. Bridging mechanical and electronic design disciplines, Mentor Graphics claims Xpedition DfR provides vibration simulation significantly faster than any existing method, which results in increased test coverage and shortened design cycles. Visit www.youtube.com/watch?v=Yna1jLnn4qw for a demonstration of DfR.

For more information, visit http://info.hotims.com/65850-453

3D printer

Methods 3D Inc. (Sudbury, MA) introduces the **3D Systems**' ProX SLS 500 Selective Laser Sintering production 3D printer featuring fast speeds, high print resolution and a range of engineered composite materials. According to the company, the printer delivers parts with high precision, durability and quality, all in a compact production-grade system. Created for the manufacturing floor, the ProX SLS 500 printer is designed to produce exceptionally smooth surfaces and high-resolution thermoplastic parts, claims Methods 3D. Ready-to-use functional parts and complete assemblies are suitable for automotive applications, among others. The ProX SLS 500 was developed in tandem with the DuraForm ProX materials line to produce smoother wall surfaces, high print resolution and edge definition, generating injection molding-like part quality. The ProX SLS 500 uses three DuraForm ProX materials—the DuraForm ProX PA, DuraForm ProX GF, and DuraForm ProX HST Composite.

For more information, visit http://info.hotims.com/65850-457

Oil- and abrasion-resistant cable

ÖLFLEX 409 P PUR control cable from **Lapp Group USA** (Florham Park, NJ) is an oil- and abrasion-resistant cable for industrial machine tools and appliances. According to the company, a special interstice filling functional layer on a PVC base enables more efficient and reliable stripping and ensures improved stripping characteristics, reduction of damage to core insulation, less subsequent manual processing and reduced material waste—compared to common PUR jacketed cables. Due to a robust polyurethane outer sheath, the cable delivers increased durability under harsh conditions. ÖLFLEX 409 P is also resistant to contact with many mineral oil-based lubricants, diluted acids, aqueous alkaline solutions and other chemical media.

For more information, visit http://info.hotims.com/65850-458

Linear potentiometers

H.G. Schaevitz LLC **Alliance Sensors Group** (Moorestown, NJ) expanded its sensor product offering by adding resistive technology to its portfolio of linear position products. Environmentally sealed to IEC IP-64, the LP-22 series of linear potentiometers offers a cost-effective solution to sensing requirements in the factory automation market. The company claims LP-22 series potentiometers are constructed to satisfy applications like robotic control, X-Y table feedback, injection-molding machine slides, press or die arm position, control valve shaft position and mil/aero test stands. Features include full ranges from 25 to 300 mm (1 to 12 in), self-aligning swivel-rod eyes on both ends, and -40 to +150°C (-40 to +302°F) operating temperature.

For more information, visit http://info.hotims.com/65850-459

Compact pressure transducers

OMEGA Engineering (Norwalk, CT) offers a new series of low-cost, compact pressure transducers with an all stainless-steel body and rugged construction. The new PX119 Series is designed to provide reliable pressure measurement for material handling, industrial and mobile equipment applications where cost and space constraints requiring a small body are important. A high reliability piezoresistive ceramic sensor with a custom ASIC signal conditioner provide what the company claims is an excellent thermally-compensated output. With pressure ranges from 15 to 5000 psig and psia ranges (1 to 345 bar), a standard 4 to 20 mA and CE certification, the PX119 is suited to meet the most demanding applications.

For more information, visit http://info.hotims.com/65850-454

Power transfer coupling

The TSC8300 is a new power transfer coupling from startup-company **Twin Spring Coupling** (Pearl River, NY) that is warrantied to 300 lb·ft (407 N·m) of torque. Increased flexibility with the same torque curves allows the designer/engineer to achieve increased reliability with little to no modification, according to CEO Darren Finch. The constant maintenance of the internals of a universal joint is not a factor with the company's coupling since there are no internal components—i.e., no needle bearings to maintain or bearings to wear out. Suitable for use in automotive, mining, agriculture and industrial industries, TSC8300 applications include axle, PTO, driveshaft, steering and conveyor belts.

For more information, visit http://info.hotims.com/65850-455

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WHAT'S ONLINE

WHAT'S NEW
JCB's new 3L DieselMax: Tier 4 without SCR

Off-highway powertrain and driveline specialist **JCB** said at Conexpo 2017 the company is starting production of its new entry-level engine, the 3.0-L DieselMax, with its first applications in OEM machines coming in the U.S. market later in 2017.

Alan Tolley, group director—engines at **JCB Power Systems**, said DieselMax's key design feature is that it produces the industry-standard 74-hp (55-kW) rating while complying with U.S. **EPA** Tier 4 emissions standards without selective catalytic reduction (SCR) exhaust aftertreatment, a boon for reducing operating cost and maintenance complexity.

(Image: JCB)

The Dieselmax 4-cylinder is 25% smaller, physically, than JCB's 4.4-L EcoMax diesel, until now the company's smallest-displacement Tier 4-compliant engine. The new 3L also is roughly 30% lighter than the 4.4-L engine—and as much as 8% more fuel-efficient, Tolley told *Truck & Off-Highway Engineering* during an interview an Conexpo (additional coverage from the event is online at offhighway.sae.org/).

Read more at **articles.sae.org/15295/**.

WHAT'S NEW
Volvo Trucks tests hybrid powertrain for long-haul transport in Concept Truck

With improvements in aerodynamics, rolling resistance and reduced weight, **Volvo Trucks** has developed and enhanced the Volvo Concept Truck. First unveiled in 2016, the new version of the truck features a hybrid powertrain that the company claims is one of the first of its kind for heavy-duty trucks in long-haul applications. In combination with the vehicle's other improvements, the total reduction in fuel consumption and CO_2 is reported to be around 30%.

"We strive to be at the forefront of electromobility and to constantly push the limits when it comes to reducing fuel consumption and emissions," said Volvo Trucks' CEO Claes Nilsson, in a release statement."

Read more at **articles.sae.org/15330/**.

WHAT'S NEW
Alt fuels make inroads despite obstacles

Commercial vehicles are beginning to adopt alternative energy sources, but the transition remains slow. Batteries and an array of renewable fuels are seeing more usage, but costs and infrastructure remain hindrances for these fragmented technologies.

Alternative-fuel consumption was about 3% of the market in 2015, according to **NTEA** - The Association for the Work Truck Industry. Speakers at NTEA's Green Truck Summit in Indianapolis in March highlighted a number of advances that are occurring as global regulations tighten emissions levels.

Carlton Rose, President of Global Fleet Maintenance & Engineering at **UPS**, highlighted the company's expanding fleet of alternative vehicles, noting that vehicles using these fuels traveled over 1 billion miles since 2000.

In Eugene, OR, the Water & Electric Board is using renewable diesel to slash carbon output by 38%. Gary Lentsch, fleet supervisor, said renewable diesel can be used without changing engines or storage systems, bringing significant reductions in carbon.

Read more at **articles.sae.org/15323/**.

2017

HEAVY-DUTY DIESEL ENGINES

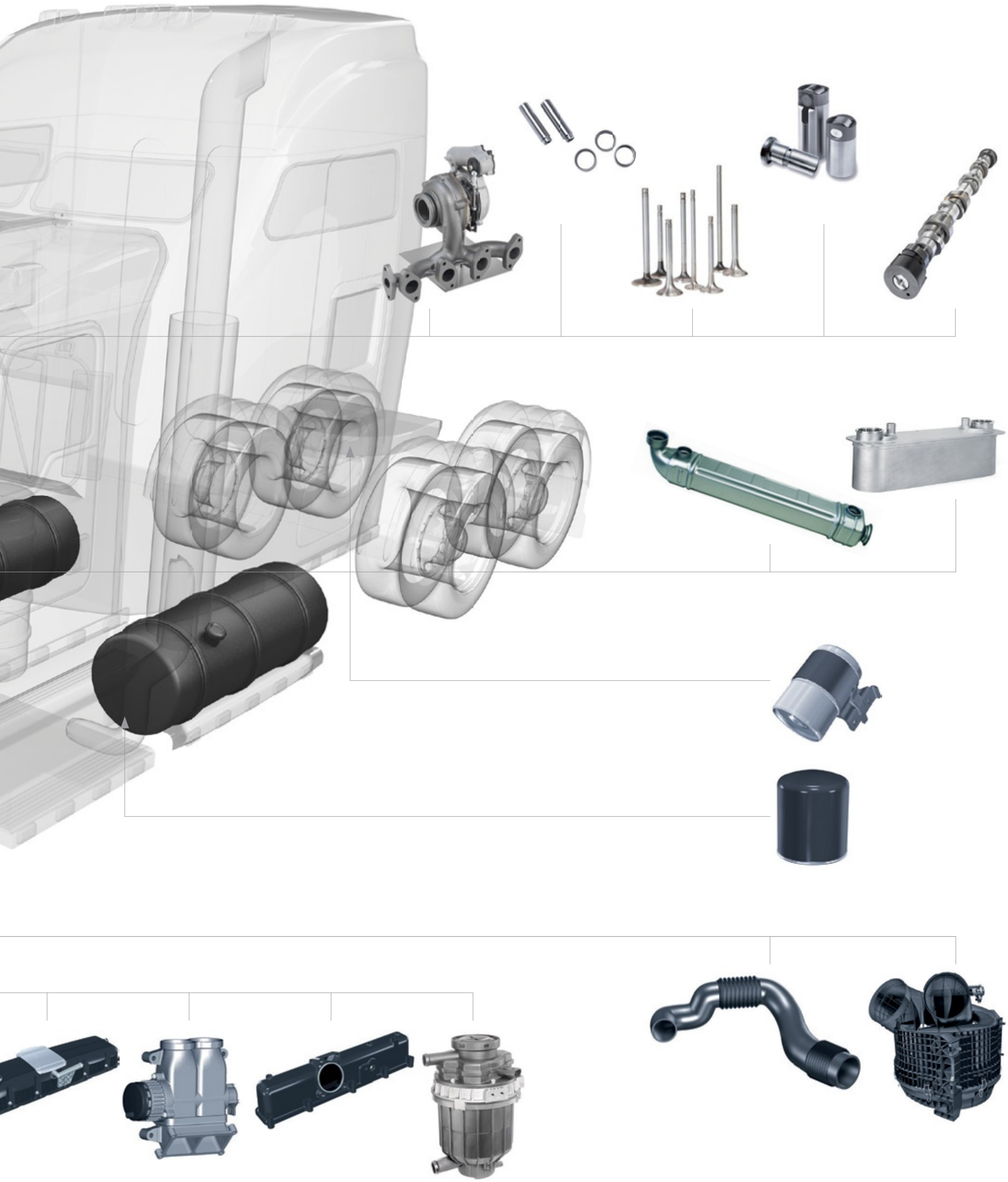
North American Availability & Specifications

SAE INTERNATIONAL TRUCK & OFF-HIGHWAY ENGINEERING

MAHLE

Driven by performance

MAHLE PRODUCT PORTFOLIO



NORTH AMERICA LOCATIONS

▪ Production Facilities and Offices
▪ Research & Development Centers/Headquarters

BUSINESS

ENGINE SYSTEMS

USA
- Atlantic, Iowa
- Farmington Hills, M
- Fletcher, North Car
- McConnelsville, Oh
- Morristown, Tenne
- Muskegon, Michig
- Russelville, Arkans
- St. John, Michigan

MEXICO
- Aguascalientes, M
- Lerma, Mexico
- Naucalpan, Mexico
- Ramos Arizpe, Mex

FILTRATION AND

USA
- Murfreesboro, Ten
- Troy, Michigan
- Winterset, Iowa

CANADA
- Tilbury, Ontario

MEXICO
- Celaya, Mexico
- Santa Catarina, Me

SERVICES

USA
- Farmington Hills, M
- Morristown, Tenne

UNITS

S AND COMPONENTS

Michigan
rolina
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an
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exico

o
xico

ENGINE PERIPHERALS

nessee

exico

Michigan
ssee

THERMAL MANAGEMENT

USA
- Charleston, South Carolina
- Dayton, Ohio
- Fort Worth, Texas
- Lockport, New York
- Troy, Michigan
- Vandalia, Ohio

MEXICO
- Juarez, Mexico
- Queretaro, Mexico
- Ramos Arizpe, Mexico
- Silao, Mexico

AFTERMARKET

USA
- Farmington Hills, Michigan
- Olive Branch, Mississippi
- York, Pennsylvania

CANADA
- Burlington, Ontario

MEXICO
- Lerma, Mexico

PROFIT CENTERS

MECHATRONICS

USA
- Rockford, Illinois

INDUSTRIAL THERMAL SYSTEMS

USA
- Belmont, Michigan

COMPRESSORS

USA
- Amherst, New York

MEXICO
- Juarez, Mexico

2017

HEAVY-DUTY DIESEL ENGINES

North American Availability & Specifications

37-1120 kW (50-1500 hp)

MAHLE PRODUCT PORTFOLIO

Brand (Maker)	Engine Family	Engine Model	Displacement (L)	Production Location	2016 Production Volume [1]	
AM General						
General Engine Products	Optimizer	3200	3.2	Franklin, OH	25	
General Engine Products	Optimizer	6500	6.5	Franklin, OH	2,200	
Caterpillar						
Cat	C	C2.2 (electronic)	2.2	Peterborough, UK; Griffin, GA	1,500	
Cat	C	C2.2	2.2	Peterborough, UK; Griffin, GA	4,500	* Availa
Cat	C	C3.4B	3.4	Turin, Italy	1,100	
Cat	C	C4.4 ACERT	4.4	Peterborough, UK	300	
Cat	C	C4.4 (LRC)	4.4	Peterborough, UK; Wuxi, China; Curitiba, Brazil	1,900	* Availa
Cat	C	C7.1 ACERT	7.0	Peterborough, UK	1,200	
Cat	C	C7.1 ACERT	7.0	Peterborough, UK	2,500	
Cat	C	C7.1 (LRC)	7.0	Peterborough, UK; Wuxi, China; Curitiba, Brazil	300	* Availa
Cat	C	C9.3 ACERT	9.3	Seguin, TX	1,000	
Cat	C	C9.3 ACERT	9.3	Seguin, TX	4,000	
Cat	C	C9 ACERT	8.8	Seguin, TX	2,000	* Availa
Cat	C	C11 ACERT	11.1	Seguin, TX	1,000	* Availa
Cat	C	C13 ACERT	12.5	Seguin, TX	300	
Cat	C	C13 ACERT	12.5	Seguin, TX	1,500	
Cat	C	C13 ACERT	12.5	Seguin, TX	4,500	* Availa
Cat	C	C15 ACERT	15.2	Seguin, TX	1,100	
Cat	C	C15 ACERT	15.2	Seguin, TX	4,100	* Availa
Cat	C	C18 ACERT	18.1	Seguin, TX	300	
Cat	C	C18 ACERT	18.1	Seguin, TX	1,000	
Cat	C	C18 ACERT	18.1	Seguin, TX	3,000	* Availa
Cat	C	C27 ACERT	27.0	Griffin, GA	100	
Cat	C	C27 ACERT	27.0	Griffin, GA	1,100	* Availa
Cat	C	C32 ACERT	32.1	Griffin, GA	300	
Cat	C	C32 ACERT	32.1	Griffin, GA	1,150	
Cat	3400	3406C	14.6	Hosur, India	50	* Availa
Cat	3500	3508B	34.5	Lafayette, IN	75	* Availa
Cat	3500	3512	51.8	Lafayette, IN	100	* Availa
Cat	3500	3512B	51.8	Lafayette, IN	800	* Availa
Cat	3500	3512C	51.8	Lafayette, IN	50	* Availa
Cat	3500	3516	69.0	Lafayette, IN	150	* Availa
Cat	3500	3516B	69.0	Lafayette, IN	650	* Availa
Perkins	400	404F-E22T	2.2	Griffin, GA	700	
Perkins	400	404F-E22TA	2.2	Griffin, GA	500	
Perkins	400	404D-22	2.2	Peterborough, UK; Griffin, GA; Wuxi, China	100	
Perkins	400	404D-22T	2.2	Peterborough, UK; Griffin, GA; Wuxi, China	100	
Perkins	400	404D-22TA	2.2	Peterborough, UK; Griffin, GA; Wuxi, China	220	
Perkins	850	854F-E34T	3.4	Turin, Italy	3,800	
Perkins	850	854F-E34TA	3.4	Turin, Italy	1,200	
Perkins	850	854E-E34TA	3.4	Turin, Italy	1,200	
Perkins	1200	1204F-E44TA	4.4	Peterborough, UK	11,500	
Perkins	1200	1204F-E44TTA	4.4	Peterborough, UK	24,000	
Perkins	1200	1204E-E44TA	4.4	Peterborough, UK	11,500	
Perkins	1200	1204E-E44TTA	4.4	Peterborough, UK	14,500	
Perkins	1100	1104D-E44T	4.4	Wuxi, China	1,700	* Availa
Perkins	1100	1104D-E44TA	4.4	Peterborough, UK; Wuxi, China	250	* Availa
Perkins	1100	1104C-44	4.4	Peterborough, UK; Curitiba, Brazil	500	* Availa
Perkins	1100	1104C-44T	4.4	Peterborough, UK; Curitiba, Brazil	500	* Availa
Perkins	1100	1104C-44TA	4.4	Peterborough, UK; Wuxi, China; Curitiba, Brazil	500	* Availa
Perkins	1100	1104D-44T	4.4	Peterborough, UK; Wuxi, China; Curitiba, Brazil	880	* Availa
Perkins	1100	1104D-44TA	4.4	Peterborough, UK; Wuxi, China; Curitiba, Brazil	2,800	* Availa
Perkins	1200	1206F-E70TA	7.0	Peterborough, UK	5,000	
Perkins	1200	1206F-E70TTA	7.0	Peterborough, UK	1,000	
Perkins	1200	1206E-E70TTA	7.0	Peterborough, UK	3,000	
Perkins	1100	1106D-E70TA	7.0	Peterborough, UK; Wuxi, China; Curitiba, Brazil	400	* Availa
Perkins	1100	1106C-70TA	7.0	Peterborough, UK; Wuxi, China	400	* Availa
Perkins	1100	1106D-70TA	7.0	Wuxi, China	100	* Availa
Cummins						
Cummins	F	QSF2.8	2.8	Beijing, China	650	
Cummins	F	QSF3.8	3.8	Beijing, China	5,500	
Cummins	B	QSB4.5	4.5	Rocky Mount, NC	1,600	
Cummins	V	V5.0	5.0	Columbus, IN	12,000	

SAE INTERNATIONAL TRUCK & OFF-HIGHWAY ENGINEERING

MAHLE
Driven by performance

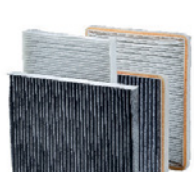
U.S./EU Emissions Level	Layout	Cylinder Head, VPC	Power, kW (hp) @ rpm	Torque, N•m (lb•ft) @ rpm	Bore x Stroke, mm (in)	Compression Ratio	Application	MAHLE Components
NA	6, inline	DI	224 (300) @ 4300	678 (500) @ 2200	85 x 94 (3.35 x 3.7)	16:1	GS, MI	
NA	V8	IDI, 2	119-187 (160-250) @ 3000-3400	393-746 (290-550) @ 1700-2000	103 x 97 (4.06 x 3.82)	20.2:1	GS, M, MI, TB	
Tier 4 Final / Stage IIIB	4, inline	DI	36.4-50 (48.8-67.1) @ 2800	165-208 (121.6-153.4) @ 1800	84 x 100 (3.3 x 3.9)	18.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	4, inline	IDI	31.4-36.4 (42.1-48.8) @ 2400-3000	142.7-208.4 (105.3-153.7) @ 1800	84 x 100 (3.3 x 3.9)	23.3:1	AG, IS, OH	✓
> 56 kW = * Tier 4	4, inline	DI	63-86 (84.5-115.3) @ 2200-2500	354-450 (261.1-331.9) @ 1400-1600	99 x 110 (3.9 x 4.3)	17.0:1	AG, IS, OH	✓
* Tier 4	4, inline	DI	61.5-129.4 (82.5-173.5) @ 2200	347-750 (256-553.2) @ 1400	105 x 127 (4.1 x 5.0)	16.5:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	4, inline	DI	56-83 (75-111) @ 2200-2300	265-418 (195-308) @ 1400	105 x 127 (4.1 x 5.0)	18.2:1	AG, IS, OH	✓
Tier 4 Final / Stage IV	6, inline	DI	116-225 (156-301.7) @ 2200	755-1274 (557-940) @ 1400	105 x 135 (4.1 x 5.3)	16.5:1	AG, IS, OH	✓
* Tier 4	6, inline	DI	140-225 (187.7-301.7) @ 2200	890-1257 (656.4-927.1) @ 1400	105 x 135 (4.1 x 5.3)	16.5:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	112-162 (150-220) @ 2000-2200	672-900 (495-664) @ 1100-1400	105 x 135 (4.1 x 5.3)	18.2:1	AG, IS, OH	✓
Tier 4 Final / Stage IV	6, inline	DI	224-298 (300-400) @ 1800-2200	1371-1726 (1011-1273) @ 1400	115 x 149 (4.53 x 5.87)	17.0:1	AG, IS, OH	✓
* Tier 4	6, inline	DI	224-261 (300-350) @ 1800-2200	1369-1596 (1010-1177) @ 1400	115 x 149 (4.53 x 5.87)	17.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	205-280 (275-375) @ 1800-2200	1225-1668 (904-1230) @ 1400	112 x 149 (4.41 x 5.87)	16.1:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	242-336 (325-450) @ 1800-2100	1487-2056 (1097-1516) @ 1400	130 x 140 (5.12 x 5.51)	17.2:1	AG, IS, OH	✓
Tier 4 Final / Stage IV	6, inline	DI	287-388 (385-520) @ 1800-2100	1760-2381 (1298-1756) @ 1400	130 x 157 (5.12 x 6.2)	17.0:1	AG, IS, OH	✓
* Tier 4	6, inline	DI	287-388 (385-520) @ 1800-2100	1760-2381 (1298-1756) @ 1400	130 x 157 (5.12 x 6.2)	17.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	287-388 (385-520) @ 1800-2100	1760-2215 (1298-1634) @ 1400	130 x 157 (5.12 x 6.2)	17.3:1	AG, IS, OH	✓
Tier 4 Final / Stage IV / * Tier 4	6, inline	DI	354-433 (475-580) @ 1800-2100	2176-2655 (1605-1959) @ 1400	137 x 171 (5.4 x 6.73)	17.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	328-444 (440-595) @ 1800-2100	2012-2717 (1484-2004) @ 1400	137.2 x 171.4 (5.4 x 6.75)	18.0:1	AG, IS, OH	✓
Tier 4 Final / Stage IV	6, inline	DI	429-597 (575-800) @ 1800-2000	2696-3710 (1988-2736) @ 1300	145 x 183 (5.71 x 7.2)	16.0:1	AG, IS, OH	✓
* Tier 4	6, inline	DI	447-563 (600-755) @ 1800-1900	2749-3501 (2072-2582.2) @ 1400	145 x 183 (5.71 x 7.2)	16.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	429-597 (575-800) @ 1800-2100	2628-3655 (1938-2696) @ 1400	145 x 183 (5.71 x 7.2)	16.3:1	AG, IS, OH	✓
Tier 4 Final	V12	DI	597-783 (800-1050) @ 1800	3635-4674 (2681-3447) @ 1200	137.2 x 152.4 (5.4 x 6.0)	16.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	V12	DI	597-858 (800-1150) @ 1800-2100	3657-5255 (2698-3876) @ 1400	137.2 x 152.4 (5.4 x 6.0)	16.5:1	AG, IS, OH	✓
Tier 4 Final	V12	DI	746-895 (1000-1200) @ 1800	5184-5861 (3824-4323) @ 1200	145 x 162 (5.71 x 6.38)	15.0:1	AG, IS, OH	✓
* Tier 4	V12	DI	839-895 (1125-1200) @ 1800	5054-5429 (3728-4005) @ 1400	145 x 162 (5.71 x 6.38)	15.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	298-347 (400-465) @ 1800-2100	1427-1841 (1053-1358) @ 1800	137.2 x 165.1 (5.4 x 6.5)	14.5:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	V8	DI	746-820 (1000-1100) @ 1800	Up to 4337 (3199) @ 1400	170 x 190 (6.7 x 7.5)	14.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	V12	DI	761-1119 (1020-1500) @ 1200-1800	Up to 6210 (4580) @ 1400	170 x 190 (6.7 x 7.5)	13.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	V12	DI	1119-1231 (1500-1650) @ 1800	Up to 7153 (5276) @ 1400	170 x 190 (6.7 x 7.5)	14.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	V12	DI	1120 (1500) @ 1800	Up to 7321 (5400) @ 1400	170 x 190 (6.7 x 7.5)	14.7:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	V16	DI	1011-1492 (1355-2000) @ 1200-1800	Up to 6763 (4988) @ 1400	170 x 190 (6.7 x 7.5)	13.0:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	V16	DI	1492-1640 (2000-2200) @ 1800	Up to 9536 (7034) @ 1400	170 x 190 (6.7 x 7.5)	14.0:1	AG, IS, OH	✓
Tier 4 Final / Stage IIIB	4, inline	DI	36 (49) @ 2800	165 (122) @ 1800	84 x 100 (3.3 x 3.9)	18.0:1	AG, IS, OH	✓
Tier 4 Final / Stage IIIB	4, inline	DI	50 (67) @ 2800	208 (153) @ 1800	84 x 100 (3.3 x 3.9)	18.0:1	AG, IS, OH	✓
* Tier 4	4, inline	IDI	31-38 (42-51) @ 2200-3000	143 (105) @ 1800	84 x 100 (3.3 x 3.9)	23.3:1	AG, GS, IS, OH	✓
* Tier 4	4, inline	IDI	36-46 (48-61) @ 2600-3000	154-189 (114-139) @ 1800	84 x 100 (3.3 x 3.9)	23.3:1	AG, GS, IS, OH	✓
* Tier 4	4, inline	IDI	49 (66) @ 2800	208 (154) @ 1800	84 x 100 (3.3 x 3.9)	23.3:1	AG, GS, IS, OH	✓
Tier 4 Final / Stage IIIB	4, inline	DI	45-55.4 (60.3-74.3) @ 2200-2500	243-318 (179.2-234.5) @ 1400-1600	99 x 110 (3.9 x 4.3)	17.0:1	AG, GS, IS, OH	✓
Tier 4 Final / Stage IV	4, inline	DI	63-90 (84-121) @ 2200-2500	354-490 (261-361) @ 1400	99 x 110 (3.9 x 4.3)	17.0:1	AG, GS, IS, OH	✓
* Tier 4	4, inline	DI	55-86 (74-115) @ 2200-2500	344-450 (254-332) @ 1200-1600	99 x 110 (3.9 x 4.3)	17.0:1	AG, GS, IS, OH	✓
Tier 4 Final / Stage IV	4, inline	DI	70-110 (94-148) @ 2200	450-560 (332-413) @ 1400	105 x 127 (4.1 x 5.0)	16.5:1	AG, IS, OH	✓
Tier 4 Final / Stage IV	4, inline	DI	105-129 (141-174) @ 2200	630-750 (465-553) @ 1400	105 x 127 (4.1 x 5.0)	16.5:1	AG, IS, OH	✓
* Tier 4	4, inline	DI	62-110 (83-148) @ 2200	347-560 (256-413) @ 1400	105 x 127 (4.1 x 5.0)	16.5:1	AG, IS, OH	✓
* Tier 4	4, inline	DI	105-129 (141-174) @ 2200	650-750 (479-553) @ 1400	105 x 127 (4.1 x 5.0)	16.5:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	4, inline	DI	75 (100) @ 2200	420 (310) @ 1400	105 x 127 (4.1 x 5.0)	16.2:1	AG, GS, IS, OH	✓
ble in other regulated or non-regulated areas	4, inline	DI	75-106 (100-142) @ 2200	441-558 (325-412) @ 1400	105 x 127 (4.1 x 5.0)	16.2:1	AG, GS, IS, OH	✓
ble in other regulated or non-regulated areas	4, inline	DI	64 (86) @ 2400	302 (226) @ 1400	105 x 127 (4.1 x 5.0)	19.3:1	AG, GS, IS, OH	✓
ble in other regulated or non-regulated areas	4, inline	DI	75 (100) @ 2300	415 (306) @ 1350	105 x 127 (4.1 x 5.0)	18.2:1	AG, GS, IS, OH	✓
ble in other regulated or non-regulated areas	4, inline	DI	97 (130) @ 2200	500 (369) @ 1400	105 x 127 (4.1 x 5.0)	18.2:1	AG, GS, IS, OH	✓
ble in other regulated or non-regulated areas	4, inline	DI	75 (100) @ 2200	392 (289) @ 1400	105 x 127 (4.1 x 5.0)	18.2:1	AG, GS, IS, OH	✓
ble in other regulated or non-regulated areas	4, inline	DI	83 (111) @ 2200	418 (308) @ 1400	105 x 127 (4.1 x 5.0)	18.2:1	AG, GS, IS, OH	✓
Tier 4 Final / Stage IV	6, inline	DI	116-151 (156-202) @ 2200	755-870 (557-642) @ 1400	105 x 135 (4.1 x 5.3)	16.5:1	AG, IS, OH	✓
Tier 4 Final / Stage IV	6, inline	DI	151-225 (202-302) @ 2200	983-1274 (725-940) @ 1400	105 x 135 (4.1 x 5.3)	16.5:1	AG, IS, OH	✓
* Tier 4	6, inline	DI	140-225 (188-302) @ 2200	890-1257 (656-927) @ 1400	105 x 135 (4.1 x 5.3)	16.5:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	116-205 (156-275) @ 2200-2500	706-1050 (520-774) @ 1400	105 x 135 (4.1 x 5.3)	16.8:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	112-162 (150-217) @ 1200-1400	687-900 (507-664) @ 1200-1400	105 x 135 (4.1 x 5.3)	18.2:1	AG, IS, OH	✓
ble in other regulated or non-regulated areas	6, inline	DI	112-129 (150-172) @ 2000-2200	672-750 (495-552) @ 1100-1300	105 x 135 (4.1 x 5.3)	18.5:1	AG, IS, OH	✓
Tier 4 Final	4, inline	DI, 4	37-55 (49-74) @ 2200-2500	190-300 (140-221) @ 1600	94 x 100 (3.7 x 3.94)	NA	AG, GS, IS, OH	✓
Tier 4 Final	4, inline	DI, 4	55-99 (74-132) @ 2000-2500	400-488 (295-360) @ 1300-1600	102 x 115 (4.02 x 4.53)	NA	AG, GS, IS, OH	✓
Tier 4 Final	4, inline	DI, 4	90-130 (121-173) @ 1700-2500	470-705 (347-520) @ 1500	107 x 124 (4.21 x 4.88)	NA	AG, GS, IS, OH	✓
EPA 2017	V8	DI, 4	149-205 (200-275) @ 3200	705-759 (520-560) @ 1600	94 x 90 (3.7 x 3.54)	NA	TB	✓











Brand (Maker)	Engine Family	Engine Model	Displacement (L)	Production Location	2016 Production Volume [1]
Cummins	B	QSB6.7	6.7	Rocky Mount, NC	25,000
Cummins	B	B6.7	6.7	Rocky Mount, NC	200,000
Cummins	L	QSL9	8.9	Rocky Mount, NC	14,000
Cummins	L	L9	8.9	Rocky Mount, NC	33,000
Cummins	G	QSG12	11.8	Beijing, China	500
Cummins	X	ISX12	11.9	Jamestown, NY	5,500
Cummins	X	X15	14.9	Jamestown, NY	65,000
Cummins	X	QSX15	14.9	Jamestown, NY	450
Cummins	K	QSK19-R	19.0	Seymour, IN	3,200
Cummins	K	QSK23	23.0	Oyama, Japan	1,500
Cummins	T	QST30	30.5	Seymour, IN	800
Cummins	K	QSK38	37.7	Daventry, UK	50
Cummins	K	QSK50	50.3	Daventry, UK	170
Cummins	K	QSK60	60.0	Daventry, UK	160
Daimler					
Detroit Diesel	DD Platform	DD13	12.8	Detroit, MI; Mannheim, Germany	100,000
Detroit Diesel	DD Platform	DD15	14.8	Detroit, MI; Mannheim, Germany	43,000
Detroit Diesel	DD Platform	DD16	15.6	Detroit, MI; Mannheim, Germany	9,500
Deutz					
Deutz	G 2.2 L3	-	2.19	Germany	500
Deutz	D 2.2 L3	-	2.2	Germany	1,000
Deutz	D 2.9	-	2.9	Germany	10,000
Deutz	TD 2.9	-	2.9	Germany	5,000
Deutz	TCD 2.9 / TCD 2.9 (High Torque)	-	2.9	Germany	7,000
Deutz	G 2.9 L4	-	2.92	Germany	400
Deutz	TD 3.6 L4	-	3.6	Germany	8,000
Deutz	TCD 3.6 L4 (High Torque)	-	3.6	Germany	8,000
Deutz	TCD 3.6 L4	-	3.6	Germany	3,500
Deutz	TCD 3.6 L4 (High Power)	-	3.6	Germany	500
Deutz	TCD 4.1	-	4.1	Germany	25,000
Deutz	TCD 5.0	-	5.0	Germany	7,600
Deutz	TCD 6.1	-	6.1	Germany	17,500
Deutz	TCD 7.8	-	7.8	Germany	6,500
Deutz	TCD 9.0 L4	-	9.0	Germany	200
Deutz	TCD 12.0 V6	-	11.9	Germany	4,000
Deutz	TCD 16.0 V8	-	15.9	Germany	250
FPT Industrial					
FPT Industrial	F1 Series	F23	2.3	Foggia, Italy	30,000
FPT Industrial	F1 Series	F30	3	Foggia, Italy	47,000
FPT Industrial	F5 Series	F32	3.2	Pregnana,Italy	9,500
FPT Industrial	F5 Series	F34	3.4	Torino, Italy	14,000
FPT Industrial	F5 Series	F34	3.4	Torino, Italy	5,000
FPT Industrial	NEF Series	N45	4.5	Pregnana, Italy	50,000
FPT Industrial	NEF Series	N45	4.5	Torino, Italy	16,000
FPT Industrial	NEF Series	N45	4.5	Torino, Italy	15,000
FPT Industrial	NEF Series	N67	6.7	Pregnana, Italy	10,000
FPT Industrial	NEF Series	N67	6.7	Torino, Italy	18,000
FPT Industrial	NEF Series	N67	6.7	Torino, Italy	10,000
FPT Industrial	Cursor Series	Cursor 9	8.7	Pregnana, Italy	4,000
FPT Industrial	Cursor Series	Cursor 9	8.7	Chongqing, China	14,000
FPT Industrial	Cursor Series	Cursor 9	8.7	Chongqing, China	500
FPT Industrial	Cursor Series	Cursor 10	10.3	Pregnana, Italy	20
FPT Industrial	Cursor Series	Cursor 11	11.1	Bourbon-Lancy, France	14,000
FPT Industrial	Cursor Series	Cursor 11	11.1	Bourbon-Lancy, France	50
FPT Industrial	Cursor Series	Cursor 13	12.9	Bourbon-Lancy, France	10,000
FPT Industrial	Cursor Series	Cursor 13	12.9	Bourbon-Lancy, France	1,700
FPT Industrial	Cursor Series	Cursor 16	15.9	Bourbon-Lancy, France	10
Ford					
Ford	Power Stroke	6.7L	6.7	Chihuahua, Mexico	150,000
General Motors					
GM/Isuzu	Duramax	6.6L	6.6	Moraine, OH	75,000
John Deere					
John Deere	PowerTech EWX	3029H	2.9	Saran, France; Torreon, Mexico	55,000
John Deere	PowerTech	4045HF285	4.5	Saran, France; Torreon, Mexico	1,000
John Deere	PowerTech	4045TF285	4.5	Saran, France; Torreon, Mexico	2,200
John Deere	PowerTech E	4045T/H	4.5	Saran, France; Torreon, Mexico	2,400
John Deere	PowerTech EWX	4045T	4.5	Saran, France; Torreon, Mexico	3,000
John Deere	PowerTech PSL	4045H	4.5	Torreon, Mexico	2,000
John Deere	PowerTech PSL	4045H	4.5	Torreon, Mexico	500
John Deere	PowerTech PSS	4045H	4.5	Saran, France; Torreon, Mexico	4,000
John Deere	PowerTech PWL	4045H	4.5	Saran, France; Torreon, Mexico	7,500
John Deere	PowerTech M	4045T	4.5	Saran, France; Torreon, Mexico	18,000
John Deere	PowerTech PWX	4045H	4.5	Saran, France; Torreon, Mexico	5,000
John Deere	PowerTech Marine	4045TFM	4.5	Saran, France; Torreon, Mexico	200
John Deere	PowerTech M	4045T/H	4.5	Saran, France; Torreon, Mexico	1,200
John Deere	PowerTech Plus	4045H	4.5	Saran, France; Torreon, Mexico	2,000
John Deere	PowerTech E	6068H	6.8	Saran, France; Torreon, Mexico	3,500
John Deere	PowerTech PSL	6068H	6.8	Torreon, Mexico	200

U.S./EU Emissions Level	Layout	Cylinder Head, VPC	Power, kW (hp) @ rpm	Torque, N•m (lb•ft) @ rpm	Bore x Stroke, mm (in)	Compression Ratio	Application	MAHLE Components
Tier 4 Final	6, inline	DI, 4	109-231 (146-310) @ 1500-2500	672-1044 (496-770) @ 1500	107 x 124 (4.21 x 4.88)	NA	AG, GS, IS, OH, M	✓
EPA 2017	6, inline	DI, 4	149-242 (200-325) @ 2400	705-1017 (520-750) @ 1600-1800	107 x 124 (4.21 x 4.88)	NA	TB	✓
Tier 4 Final	6, inline	DI, 4	186-298 (250-400) @ 1600-2100	1085-1627 (800-1200) @ 1400-1500	114 x 145 (4.49 x 5.69)	NA	AG, GS, IS, OH	✓
EPA 2017	6, inline	DI, 4	194-283 (260-380) @ 1900-2100	976-1695 (720-1250) @ 1300-1400	114 x 145 (4.49 x 5.69)	NA	TB	✓
Tier 4 Final	6, inline	DI, 3	250-383 (335-513) @ 1700-2100	1695-2299 (1250-1696) @ 1400	132 x 144 (5.2 x 5.67)	NA	AG, GS, IS, OH	
EPA 2017	6, inline	DI, 4	231-335 (310-450) @ 1800-2100	1559-2237 (1150-1650) @ 1100	130 x 150 (5.11 x 5.91)	NA	TB	✓
EPA 2017	6, inline	DI, 4	298-451 (400-605) @ 1800-2000	1966-2778 (1450-2050) @ 1000-1200	137 x 169 (5.39 x 6.65)	NA	TB	✓
Tier 4 Final	6, inline	DI, 4	336-503 (450-675) @ 1800-2100	2237-2778 (1650-2050) @ 1400	137 x 169 (5.39 x 6.65)	NA	AG, GS, IS, OH	✓
Tier 4 Final	6, inline	DI, 4	567 (760) @ 1800-2000	3084 (2275) @ 1500	159 x 159 (6.26 x 6.26)	NA	OH	✓
Tier 4 Final*	6, inline	DI, 4	567-708 (760-950) @ 1800-2100	3468-3928 (2558-2897) @ 1350-1400	170 x 170 (6.69 x 6.69)	NA	GS, IS, M, OH	✓
Tier 4 Final*	V12	DI, 4	746-1119 (1000-1500) @ 1800-2100	3806-5951 (2807-4389) @ 1300-1400	140 x 165 (5.51 x 6.5)	NA	GS, IS, M, OH	✓
Tier 4 Final*	V12	DI, 4	810-1193 (1086-1600) @ 1800-1900	4869-6242 (3591-4604) @ 1350-1500	159 x 159 (6.26 x 6.26)	NA	GS, IS, M, OH	✓
Tier 4 Final	V16	DI, 4	1119-1864 (1500-2500) @ 1800-1900	6570-9599 (4846-7080) @ 1300-1500	159 x 159 (6.26 x 6.26)	NA	GS, IS, M, OH	✓
Tier 4 Final	V16	DI, 4	1398-2237 (1875-3000) @ 1800-1900	8364-11,440 (6169-8438) @ 1500	159 x 190 (6.26 x 7.48)	NA	GS, IS, M, OH	✓
GHG 2017	6, inline	DI, 4	260-350 (350-470) @ 1625	1695-2240 (1250-1650) @ 975	132 x 156 (5.20 x 6.15)	18.4:1	OH, TB	✓
GHG 2017	6, inline	DI, 4	340-377 (455-505) @ 1625	2100-2373 (1550-1750) @ 975	139 x 163 (5.47 x 6.42)	18.5:1	OH, TB	✓
GHG 2017	6, inline	DI, 4	373-447 (500-600) @ 1800	2508-2780 (1850-2050) @ 975	139 x 171 (5.47 x 6.73)	17:1	OH, TB	✓
Stage V / Tier 4 Final	3, inline	-	42 (56) @ 2600	163 (120) @ 1400-1600	92 x 110 (3.6 x 4.3)	NA	OH	✓
Stage V / Tier 4 Final	3, inline	DI	26 (35) @ 2600	110 (81) @ 1600	92 x 110 (3.6 x 4.3)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	DI	36.4 (50) @ 2600	147 (108) @ 1600	92 x 110 (3.6 x 4.3)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	DI	55.4 (75) @ 2600	260 (192) @ 1600-1800	92 x 110 (3.6 x 4.3)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	DI	55.4 (75) @ 2600	300 (221) @ 1600	92 x 110 (3.6 x 4.3)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	-	54.4 (73) @ 2600	215 (159) @ 1400-1600	92 x 110 (3.6 x 4.3)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	DI	55.4 (74) @ 2300	330 (243) @ 1600	98 x 120 (3.9 x 4.7)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	DI	55.4 (74) @ 2300	500 (369) @ 1600	98 x 120 (3.9 x 4.7)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	DI	100 (136) @ 2300	500 (369) @ 1600	98 x 120 (3.9 x 4.7)	NA	OH	✓
Stage V	4, inline	DI	105 (141) @ 2300	550 (406) @ 1600	98 x 120 (3.9 x 4.7)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	DI	115 (154) @ 2300	610 (450) @ 1600	101 x 126 (4.0 x 5.0)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	DI	150 (200) @ 1800-2300	890 (656) @ 1500	109 x 134 (4.29 x 5.28)	NA	OH	✓
Stage V / Tier 4 Final	6, inline	DI	180 (241) @ 2300	1000 (738) @ 1450	101 x 126 (4.0 x 5.0)	NA	OH	✓
Stage V / Tier 4 Final	6, inline	DI	260 (348) @ 2200	1400 (1033) @ 1450	110 x 136 (4.3 x 5.4)	NA	OH	✓
Stage V / Tier 4 Final	4, inline	DI	300 (402) @ 1900	1700 (1254) @ 1200	135 x 157 (5.3 x 6.2)	NA	OH	✓
Stage V / Tier 4 Final	V6	DI	390 (524) @ 2100	2130 (1571) @ 1400	132 x 145 (5.2 x 5.7)	NA	OH	✓
Stage V / Tier 4 Final	V8	DI	520 (697) @ 2100	2890 (2132) @ 1400	132 x 145 (5.2 x 5.7)	NA	OH	✓
Euro 6	4, inline	DI, 4	78-107 (104-143) @ 3900-3600	270-350 (199-258) @ 1500-1800	88 x 94 (3.46 x 3.7)	16.2:1	TB	✓
EPA 2010 / ULEV 340 / Euro VI / Euro 6	4, inline	DI, 4	81-150 (109-205) @ 3500	260-470 (192-347) @ 1250-1600	95.8 x 104 (3.77 x 4.09)	17.5:1	TB	✓
Tier 3	4, inline	DI, 2	47-57 (63-76) @ 1800	NA	99 x 104 (3.90 x 4.09)	17:1	GS	✓
Tier 4 Final	4, inline	DI, 2	43-55 (58-74) @ 1800-2500	243-318 (179-234) @ 1400-1600	99 x 110 (3.90 x 4.33)	17:1	AG, IS, OH	✓
Tier 4 Final	4, inline	DI, 4	61-90 (82-121) @ 2000-2500	334-506 (246-373) @ 1500	99 x 110 (3.90 x 4.33)	17:1	AG, IS, OH	✓
Tier 3	4, inline	DI, 2/4	57-95 (76-127) @ 1800	NA	104 x 132 (4.09 x 5.2)	17.5:1	GS	✓
Euro VI	4, inline	DI, 4	118-152 (158-204) @ 2500	580-750 (428-553) @ 1250-1400	104 x 132 (4.09 x 5.2)	17:1	TB	✓
Tier 4 Final	4, inline	DI, 4	66-129 (89-173) @ 1800-2200	405-719 (299-530) @ 1200-1600	104 x 132 (4.09 x 5.2)	17:1	AG, OH	✓
Tier 3	6, inline	DI, 2/4	141-200 (189-268) @ 1800	NA	104 x 132 (4.09 x 5.2)	17.5:1	GS	✓
Euro VI	6, inline	DI, 4	162-235 (217-315) @ 2500	800-1100 (590-811) @ 1250-1400	104 x 132 (4.09 x 5.2)	17:1	TB	✓
Tier 4 Final	6, inline	DI, 4	110-221 (147-296) @ 2000-2550	700-1300 (516-959) @ 1300-1800	104 x 132 (4.09 x 5.2)	17:1	AG, OH	✓
Tier 3	6, inline	DI, 4	280 (380) @ 1800	NA	117 x 135 (4.60 x 5.31)	16.5:1	GS	✓
Euro VI	6, inline	DI, 4	228-294 (306-394) @ 2200	1300-1700 (959-1254) @ 1200	117 x 135 (4.60 x 5.31)	16:1	TB	✓
Tier 4 Final	6, inline	DI, 4	210-313 (281-419) @ 2000-2200	1349-1850 (995-1364) @ 1300-1500	117 x 135 (4.60 x 5.31)	16:1	AG, OH	✓
Tier 3	6, inline	DI, 4	317 (425) @ 1800	NA	125 x 140 (4.92 x 5.51)	16.5:1	GS	✓
Euro VI	6, inline	DI, 4	309-353 (414-473) @ 1900	1900-2250 (1401-1660) @ 1050	128 x 144 (5.04 x 5.67)	16.5:1	TB	✓
Tier 4 Final	6, inline	DI, 4	345-365 (462-489) @ 2100	2000-2082 (1475-1536) @ 1500	128 x 144 (5.04 x 5.67)	16.5:1	AG	✓
Euro VI	6, inline	DI, 4	302-412 (405-553) @ 1900	2100-2500 (1549-1844) @ 1000	135 x 150 (5.31 x 5.91)	16.5:1	TB	✓
Tier 4 Final	6, inline	DI, 4	320-500 (429-670) @ 2100	2003-2980 (1477-2197) @ 1400-1500	135 x 150 (5.31 x 5.91)	16.5:1	AG, OH	✓
Tier 4 Final	6, inline	DI, 4	480-570 (634-764) @ 2100	2751-3323 (2029-2450) @ 1500	141 x 170 (5.55 x 6.69)	16.5:1	AG	✓
EPA 2010	V8	DI, 4	328 (440) @ 2800	1254 (925) @ 1800	99.1 x 108 (3.90 x 4.25)	16.2:1	TB	✓
EPA 2010	V8	DI, 4	332 (445) @ 2800	1234 (910) @ 1600	103 x 99 (4.06 x 3.9)	16.0:1	TB	✓
Final Tier 4 / Stage IIIB	4, inline	DI, 3	36-55 (48-74) @ 2200-2400	190-304 (140-224) @ 1600	106 x 127 (4.2 x 5.0)	16.9:1	AG, GS, IS, OH	✓
Marine Tier 3	4, inline	DI, 2	129 (173) @ 1800	621 (504) @ 1800	106 x 127 (4.2 x 5.0)	19.0:1	IS	✓
Marine Tier 3	4, inline	DI, 2	74-78 (99-105) @ 1800-2200	321-376 (237-305) @ 1800-2200	106 x 127 (4.2 x 5.0)	19.0:1	IS	✓
Tier 3 / Stage IIIA	4, inline	DI, 2	63-104 (85-140) @ 2200-2400	313-525 (231-387) @ 1500-1600	106 x 127 (4.2 x 5.0)	19.0:1	AG, GS, IS, OH	✓
Final Tier 4 / Stage IIIB	4, Inline	DI, 4	55 (74) @ 2200-2400	292-304 (215-224) @ 1600	106 x 127 (4.2 x 5.0)	19.0:1	AG, GS, IS, OH	✓
Final Tier 4 / Stage IV	4, Inline	DI, 4	93-129 (125-173) @ 2200-2400	616 (454) @ 1600	106 x 127 (4.2 x 5.0)	17.2:1	AG, IS, OH	✓
Final Tier 4 / Stage IV	4, Inline	DI, 4	172 (128) @ 1800	616 (454) @ 1600	106 x 127 (4.2 x 5.0)	17.2:1	GS	✓
Final Tier 4 / Stage IV	4, Inline	DI, 4	93-129 (125-173) @ 2200-2400	494-667 (364-492) @ 1600	106 x 127 (4.2 x 5.0)	16.1:1	AG, GS, IS, OH	✓
Final Tier 4 / Stage IV	4, Inline	DI, 4	63-104 (85-140) @ 2200-2400	333-540 (246-398) @ 1600	106 x 127 (4.2 x 5.0)	16.1:1	AG, GS, IS, OH	✓
Interim Tier 4	4, inline	DI, 2	55 (74) @ 2400	265 (195) @ 1700	106 x 127 (4.2 x 5.0)	19.0:1	AG, GS, IS, OH	✓
Interim Tier 4 / Stage IIIB	4, inline	DI, 4	63-91 (85-122) @ 2200-2400	333-480 (245-354) @ 1600	106 x 127 (4.2 x 5.0)	17.0:1	AG, GS, IS, OH	✓
Marine Tier 3	4, inline	DI, 2	74 (99) @ 1800	391 (288) @ 1800	106 x 127 (4.2 x 5.0)	19.0:1	GS	✓
Tier 3 / Stage IIIA	4, inline	DI, 2	56-74 (75-99) @ 2200-2400	275-383 (203-282) @ 1600-1700	106 x 127 (4.2 x 5.0)	19.0:1	AG, GS, IS, OH	✓
Tier 3 / Stage IIIA	4, inline	DI, 4	111-129 (149-173) @ 2000-2400	574-645 (424-476) @ 1400	106 x 127 (4.2 x 5.0)	17.0:1	AG, GS, IS, OH	✓
Tier 3 / Stage IIIA	6, inline	DI, 2	104-149 (139-200) @ 2200-2400	598-785 (441-579) @ 1500	106 x 127 (4.2 x 5.0)	19.0:1	AG, GS, IS, OH	✓
Final Tier 4 / Stage IV	6, inline	DI, 4	216-241 (290-323) @ 1800	1146-1280 (843-941) @ 1800	106 x 127 (4.2 x 5.0)	17.2:1	GS	✓

Brand (Maker)	Engine Family	Engine Model	Displacement (L)	Production Location	2016 Production Volume [1]
John Deere	PowerTech PSS	6068H	6.8	Saran, France; Torreon, Mexico	2,000
John Deere	PowerTech PVL	6068H	6.8	Torreon, Mexico	100
John Deere	PowerTech PVS	6068H	6.8	Saran, France; Torreon, Mexico	10,000
John Deere	PowerTech PSX	6068H	6.8	Saran, France; Torreon, Mexico	500
John Deere	PowerTech PVX	6068H	6.8	Saran, France; Torreon, Mexico	5,000
John Deere	PowerTech Marine	6068AFM	6.8	Saran, France; Torreon, Mexico	100
John Deere	PowerTech Marine	6068SFM	6.8	Saran, France; Torreon, Mexico	100
John Deere	PowerTech Plus	6068H	6.8	Saran, France; Torreon, Mexico	3,200
John Deere	PowerTech PSL	6090H	9.0	Waterloo, IA	100
John Deere	PowerTech PSS	6090H	9.0	Waterloo, IA	6,500
John Deere	PowerTech PSX	6090H	9.0	Waterloo, IA	3,500
John Deere	PowerTech PVX	6090H	9.0	Waterloo, IA	1,200
John Deere	PowerTech Marine	6090AFM	9.0	Waterloo, IA	20
John Deere	PowerTech Marine	6090SFM	9.0	Waterloo, IA	25
John Deere	PowerTech Plus	6090H	9.0	Waterloo, IA	7,000
John Deere	PowerTech PSL	6135H	13.5	Waterloo, IA	50
John Deere	PowerTech PSS	6135H	13.5	Waterloo, IA	500
John Deere	PowerTech PSX	6135H	13.5	Waterloo, IA	2,500
John Deere	PowerTech Plus	6135H	13.5	Waterloo, IA	1,500
Kubota					
Kubota	03 Series	D1803-CR-T-E4B	1.8	Japan	9,500
Kubota	03 Series	V2403-CR-E4B	2.4	Japan	30,000
Kubota	03 Series	V2403-CR-T-E4B	2.4	Japan	13,000
Kubota	07 Series	V2607-CR-T-E4B	2.6	Japan	4,400
Kubota	07 Series	V3307-CR-T-E4B	3.3	Japan	23,000
Kubota	V3 Series	V3800-TI-EF4B	3.8	Japan	37,000
MTU America					
MTU/Mercedes-Benz	Series 900	924	4.8	Mannheim, Germany	9,000
MTU/Mercedes-Benz	Series 900	924	4.8	Mannheim, Germany	6,000
MTU	Series 1000	4R1000	5.1	Mannheim, Germany	800
MTU/Mercedes-Benz	Series 900	906	6.4	Mannheim, Germany	130
MTU/Mercedes-Benz	Series 900	926	7.2	Mannheim, Germany	3,000
MTU/Mercedes-Benz	Series 900	926	7.2	Mannheim, Germany	22,000
MTU	Series 1000	6R1000	7.7	Mannheim, Germany	3,200
MTU	Series 1100	6R1100	10.7	Mannheim, Germany	300
MTU/Mercedes-Benz	Series 460	460	12.8	Mannheim, Germany	9,000
MTU/Mercedes-Benz	Series 460	460	12.8	Mannheim, Germany	54,000
MTU	Series 1300	6R1300	12.8	Mannheim, Germany	300
MTU/Mercedes-Benz	Series 500	501	12.0	Mannheim, Germany	1,450
MTU/Mercedes-Benz	Series 500	501	12.0	Mannheim, Germany	150
MTU	Series 1500	6R1500	15.6	Mannheim, Germany	50
MTU/Mercedes-Benz	Series 500	502	15.9	Mannheim, Germany	700
MTU/Mercedes-Benz	Series 500	502	15.9	Mannheim, Germany	50
MTU/Detroit Diesel	Series 60	S60	14.0	Tooele, UT	1,500
MTU/Detroit Diesel	Series 60	S60	14.0	Tooele, UT	200
MTU	Series 1600	6R/8V/10V/ 12V1600	10.5-21.0	Friedrichshafen, Germany	100
MTU	Series 1600	10V1600	17.5	Friedrichshafen, Germany	600
MTU	Series 1600	12V1600	21.0	Friedrichshafen, Germany	200
MTU	Series 2000	12V2000C02/ S02	23.9	Aiken, SC	100
MTU	Series 2000	12V/16V/ 18V2000G05	23.9-35.8	Friedrichshafen, Germany; Aiken, SC	400
MTU	Series 2000	12V/16V/ 18V2000G06	26.8-40.2	Friedrichshafen, Germany	120
MTU	Series 2000	12V2000S06	26.8	Aiken, SC	50
MTU	Series 2000	12V2000C06	26.8	Aiken, SC	100
MTU	Series 2000	12V2000M06	26.8	Friedrichshafen, Germany	140
MTU	Series 2000	16V2000C02	31.9	Aiken, SC	100
MTU	Series 2000	16V2000C06	35.7	Aiken, SC	80
MTU	Series 4000	8V4000M04	38.1	Friedrichshafen, Germany	40
MTU	Series 4000	8V4000M04	38.1	Friedrichshafen, Germany	40
MTU	Series 4000	12V4000C05	57.2	Aiken, SC	20
Navistar					
Navistar	Navistar	N9	9.3	Melrose Park, IL	3,100
Navistar	Navistar	N10	9.3	Melrose Park, IL	700
Navistar	Navistar	N13	12.4	Huntsville, AL	6,500
PACCAR					
PACCAR	PX	PX-7	6.7	Rocky Mount, NC	9,500
PACCAR	PX	PX-9	8.9	Rocky Mount, NC	13,000
PACCAR	MX	MX-11	10.8	Columbus, MS	1,500
PACCAR	MX	MX-13	12.9	Columbus, MS	25,000
Volvo					
Mack	MP7	MP7	11.0	Hagerstown, MD	6,900
Mack	MP8	MP8	13.0	Hagerstown, MD	9,900
Volvo	D11	D11	11.0	Hagerstown, MD	1,400
Volvo	D13	D13	13.0	Hagerstown, MD	18,400
Yanmar					
Yanmar	TNV	4TNV84T	2.0	Japan	28,000
Yanmar	TNV	4TNV98	3.3	Japan	40,000
Yanmar	TNV	4TNV98T	3.3	Japan	20,000

LEGEND FOR NORTH AMERICAN HEAVY-DUTY DIESEL ENGINES 2017

AG: Agriculture
GS: Generator Set
IS: Industrial/Stationary
M: Marine
MI: Military
NA: Not Available
O&G: Oil and Gas
OH: Off-Highway Mobile
TB: Truck/Bus/Coach
VPC: Valves per Cylinder

* Meet Tier 4 Interim regulations using Transitional Program for Equipment Manufacturers (TPEM). Available in other regulated areas.

[1] North American engine production estimates provided by Rhein Associates, Inc.

U.S./EU Emissions Level	Layout	Cylinder Head, VPC	Power, kW (hp) @ rpm	Torque, N•m (lb•ft) @ rpm	Bore x Stroke, mm (in)	Compression Ratio	Application	MAHLE Components
Final Tier 4 / Stage IV	6, Inline	DI, 4	168-224 (225-300) @ 2200-2400	1000-1057 (738-780) @ 1600-1700	106 x 127 (4.2 x 5.0)	16.7:1	AG, GS, IS, OH	✓
Final Tier 4 / Stage IV	6, inline	DI, 4	160-192 (215-257) @ 1800	849-1020 (624-750) @ 1800	106 x 127 (4.2 x 5.0)	17.2:1	GS	✓
Final Tier 4 / Stage IV	6, Inline	DI, 4	104-187 (140-250) @ 2000-2400	552-1000 (407-738) @ 1600	106 x 127 (4.2 x 5.0)	17.2:1	AG, GS, IS, OH	✓
Interim Tier 4 / Stage IIIB	6, inline	DI, 4	168-187 (225-250) @ 2200	1000-1025 (738-756) @ 1600	106 x 127 (4.2 x 5.0)	17.2:1	AG, GS, IS, OH	✓
Interim Tier 4 / Stage IIIB	6, inline	DI, 4	104-187 (140-250) @ 2000-2400	549-1025 (405-756) @ 1600	106 x 127 (4.2 x 5.0)	17.2:1	AG, GS, IS, OH	✓
Marine Tier 3	6, inline	DI, 4	166 (223) @ 1800	883 (651) @ 1800	107 x 127 (4.21 x 5.0)	16.7:1	GS	✓
Marine Tier 3	6, inline	DI, 4	186-298 (249-400) @ 2400-2800	742-1016 (547-750) @ 2400-2800	106 x 127 (4.2 x 5.0)	16.3:1	OH	✓
Tier 3 / Stage IIIA	6, inline	DI, 4	134-205 (180-275) @ 2000-2400	690-1025 (509-756) @ 1400	106 x 127 (4.2 x 5.0)	17.0:1	AG, GS, IS, OH	✓
Final Tier 4 / Stage IV	6, inline	DI, 4	273-345 (366-462) @ 1800	1443-1730 (1061-1272) @ 1800	118 x 136 (4.6 x 5.4)	16.0:1	GS	✓
Final Tier 4 / Stage IV	6, Inline	DI, 4	187-317 (250-425) @ 2000-2200	1120-1685 (826-1243) @ 1600	118 x 136 (4.6 x 5.4)	16.0:1	AG, GS, IS, OH	✓
Interim Tier 4 / Stage IIIB	6, inline	DI, 4	242-317 (325-425) @ 2000-2200	1444-1685 (1065-1243) @ 1600	118 x 136 (4.6 x 5.4)	16.0:1	AG, GS, IS, OH	✓
Interim Tier 4 / Stage IIIB	6, inline	DI, 4	187-224 (250-300) @ 2000-2200	1120-1305 (826-963) @ 1600	118 x 136 (4.6 x 5.4)	16.0:1	AG, GS, IS, OH	✓
Marine Tier 3	6, inline	DI, 4	213-317 (285-425) @ 2100-2400	967-1262 (713-931) @ 2100-2400	118 x 136 (4.6 x 5.4)	16.3:1	OH	✓
Marine Tier 3	6, inline	DI, 4	242-410 (325-550) @ 2100-2500	1100-1966 (812-1450) @ 2100-2500	118.4 x 136 (4.66 x 5.35)	16.3:1	OH	✓
Tier 3 / Stage IIIA	6, inline	DI, 4	168-298 (225-400) @ 2000-2200	984-1554 (726-1146) @ 1500	118 x 136 (4.6 x 5.4)	16.0:1	AG, GS, IS, OH	✓
Final Tier 4 / Stage IV	6, Inline	DI, 4	473 (634) @ 1800	2510 (1846) @ 1800	132 x 165 (5.2 x 6.5)	15.3:1	GS	✓
Final Tier 4 / Stage IV	6, Inline	DI, 4	309-448 (414-600) @ 2100	1986-2750 (1465-2028) @ 1550	132 x 165 (5.2 x 6.5)	15.3:1	AG, GS, IS, OH	✓
Interim Tier 4 / Stage IIIB	6, inline	DI, 4	298-448 (400-600) @ 1900-2100	1870-2660 (1379-1962) @ 1500-1600	132 x 165 (5.2 x 6.5)	15.3:1	AG, GS, IS, OH	✓
Tier 3 / Stage IIIA	6, inline	DI, 4	261-448 (350-600) @ 1900-2100	1602-2550 (1182-1881) @ 1400	132 x 165 (5.2 x 6.5)	16.0:1	AG, GS, IS, OH	✓
Tier 4	3, inline	DI	37.0 (49.6) @ 2700	150.5 (111.0) @ 1600	87 x 102.4 (3.43 x 4.03)	18.1:1	AG, IS, M, OH	✓
Tier 4	4, inline	DI	37.4 (50.2) @ 2700	159.8 (117.9) @ 1600	87 x 102.4 (3.43 x 4.03)	18.1:1	AG, IS, M, OH	✓
Tier 4	4, inline	DI	48.6 (65.1) @ 2700	198.5 (146.4) @ 1600	87 x 102.4 (3.43 x 4.03)	18.1:1	AG, IS, M, OH	✓
Tier 4	4, inline	DI	53.0 (71.1) @ 2700	225.0 (165.9) @ 1600	87 x 110.0 (3.43 x 4.33)	16.8:1	AG, IS, M, OH	✓
Tier 4	4, inline	DI	55.4 (74.3) @ 2600	265.0 (195.5) @ 1500	94 x 120.0 (3.70 x 4.72)	17.5:1	AG, IS, M, OH	✓
Tier 4	4, inline	DI	86.4 (115.8) @ 2600	379.0 (279.5) @ 1500	100 x 120.0 (3.94 x 4.72)	17.0:1	AG, IS, M, OH	✓
Stage IIIA / Tier 3	4, inline	DI, 4	145 (195) @ 2200	750 (555) @ 1200-1600	106 x 136 (4.2 x 5.4)	18.0:1	AG, IS, OH	✓
Stage IIIB / Tier 4 Interim	4, inline	DI, 4	95-150 (127-201) @ 2200	500-800 (370-590) @ 1200-1600	106 x 136 (4.2 x 5.4)	18.0:1	AG, IS, OH	✓
Stage IV / Tier 4 Final	4, inline	DI, 4	100-170 (134-228) @ 2200	600-900 (443-664) @ 1200-1600	110 x 135 (4.3 x 5.3)	17.6:1	AG, IS, OH, O&G	✓
Stage IIIA / Tier 3	6, inline	DI, 4	130-205 (174-275) @ 2200	675-1100 (500-810) @ 1200-1600	102 x 130 (4.02 x 5.12)	18.0:1	AG, IS, OH, O&G	✓
Stage IIIA / Tier 3	6, inline	DI, 4	220-240 (295-322) @ 2200	1200-1300 (885-960) @ 1200-1600	106 x 136 (4.2 x 5.4)	18.0:1	AG, IS, OH, O&G	✓
Stage IIIB / Tier 4 Interim	6, inline	DI, 4	175-240 (234-322) @ 2200	850-1300 (625-960) @ 1200-1600	106 x 136 (4.2 x 5.4)	18.0:1	AG, IS, OH	✓
Stage IV / Tier 4 Final	6, inline	DI, 4	180-260 (241-349) @ 2200	1000-1400 (738-1033) @ 1200-1600	110 x 135 (4.3 x 5.3)	17.6:1	AG, IS, OH, O&G	✓
Stage IV / Tier 4 Final	6, inline	DI, 4	280-320 (375-429) @ 1700	1900-2100 (1401-1549) @ 1300	125 x 145 (4.9 x 5.7)	17.6:1	AG, IS, OH, O&G	✓
Stage IIIA / Tier 3	6, inline	DI, 4	220-375 (295-503) @ 1800	1300-2200 (960-1620) @ 1300	128 x 166 (5.0 x 6.5)	18.0:1	AG, IS, OH, O&G	✓
Stage IIIB / Tier 4 Interim	6, inline	DI, 4	265-375 (355-503) @ 1800	1750-2200 (1290-1620) @ 1300	128 x 166 (5.0 x 6.5)	18.0:1	AG, IS, OH	✓
Stage IV / Tier 4 Final	6, inline	DI, 4	320-390 (429-523) @ 1700	2100-2450 (1549-1807) @ 1300	132 x 156 (5.2 x 6.1)	17.3:1	AG, IS, OH, O&G	✓
Stage IIIA / Tier 3	V6	DI, 4	260-315 (349-422) @ 1800	1730-2000 (1275-1475) @ 1080-1300	130 x 150 (5.1 x 5.9)	18.0:1	AG, IS, OH, O&G	✓
Stage IIIB / Tier 4 Interim	V6	DI, 4	265-350 (355-469) @ 1800	1850-2300 (1365-1695) @ 1300	130 x 150 (5.1 x 5.9)	18.0:1	AG, IS, OH	✓
Stage IV / Tier 4 Final	6, inline	DI, 4	400-460 (536-617) @ 1700	2600-2900 (1918-2139) @ 1300	139 x 171 (5.5 x 6.7)	17.3:1	AG, IS, OH, O&G	✓
Stage IIIA / Tier 3	V8	DI, 4	330-480 (442-644) @ 1800	2150-2800 (1585-2065) @ 1300	130 x 150 (5.1 x 5.9)	18.0:1	AG, IS, OH, O&G	✓
Stage IIIB / Tier 4 Interim	V8	DI, 4	375-480 (503-644) @ 1800	2400-3000 (1770-2210) @ 1300	130 x 150 (5.1 x 5.9)	18.0:1	AG, IS, OH	✓
Stage II / Tier 2	6, inline	DI, 4	336-496 (450-665) @ 2000-2300	2237-2576 (1650-1900) @ 1350	133 x 168 (5.2 x 6.6)	16.0:1	AG, IS, OH, O&G	✓
Stage IIIA / Tier 3	6, inline	DI, 4	242-496 (325-665) @ 1800-2300	1559-2576 (1150-1900) @ 1350	133 x 168 (5.2 x 6.6)	16.0:1	AG, IS, OH, O&G	✓
Stage IIIA / Tier 2 / Tier 3	6, inline; V8; V10; V12	DI, 4	200-668 (268-896) @ 1500-1800	NA	122 x 150 (4.8 x 5.9)	17.5:1	GS	✓
Tier 4 Final	V10	DI, 4	567-613 (760-822) @ 1900-2100	3385-3517 (2497-2594) @ 1200-1300	122 x 150 (4.8 x 5.9)	17.5:1	AG, IS, OH, O&G	✓
Tier 4 Final	V12	DI, 4	636-736 (853-987) @ 1900-2100	4020-4220 (2965-3113) @ 1300	122 x 150 (4.8 x 5.9)	17.5:1	AG, IS, OH, O&G	✓
Tier 2	V12	DI, 4	567-750 (760-1005) @ 2100	3098-4204 (2280-3100) @ 1350-1500	130 x 150 (5.1 x 5.9)	16.0:1	AG, IS, OH, O&G	✓
Tier 2	V12; V16; V18	DI, 4	515-1310 (691-1757) @ 1500-1800	NA	130 x 150 (5.1 x 5.9)	16.0:1	GS	✓
Tier 4 Interim	V12; V16; V18	DI, 4	665-1371 (892-1839) @ 1500-1800	NA	135 x 156 (5.3 x 6.1)	16.5:1, 17.5:1	GS	✓
Tier 4 Interim	V12	DI, 4	783-858 (1050-1150) @ 2100	4640-4911 (3423-3622) @ 1300-1600	135 x 156 (5.3 x 6.1)	16.5:1	O&G	✓
Tier 4 Interim	V12	DI, 4	783 (1050) @ 1800-2100	4636 (3419) @ 1100	135 x 156 (5.3 x 6.1)	16.5:1	AG, IS, OH	✓
EPA T3 Recreational	V12	DI, 4	1268-1432 (1700-1920) @ 2450	NA	135 x 156 (5.3 x 6.1)	16.1:1	M	✓
Tier 2	V16	DI, 4	783-1120 (1050-1500) @ 1800-2100	4450-6005 (3288-34429) @ 1350-1500	130 x 150 (5.1 x 5.9)	16.0:1	AG, IS, OH, O&G	✓
Tier 4 Interim	V16	DI, 4	970 (1301) @ 2100	5286 (3899) @ 1400	135 x 156 (5.3 x 6.1)	16.5:1	AG, IS, OH	✓
EPA T3 Commercial	V8	DI, 4	746-895 (1000-1200) @ 1600-1800	NA	170 x 210 (6.7 x 8.3)	19.8:1	M	✓
EPA T3 Commercial	V8	DI, 4	746-895 (1000-1200) @ 1600-1800	NA	170 x 210 (6.7 x 8.3)	19.8:1	M	✓
Tier 4 Final	V16	DI, 4	1150-1500 (1542-2012) @ 1800	7351-9588 (5422-7072) @ 1494-1500	170 x 210 (6.7 x 8.3)	15.5:1	AG, IS, OH	✓
EPA 2010	6, inline	DI, 4	223-246 (300-330) @ 2200	1166-1288 (860-950) @ 1200	117 x 146.1 (4.59 x 5.75)	17.2:1	TB	✓
EPA 2010	6, inline	DI, 4	230-276 (310-370) @ 2200	1425-1695 (1050-1250) @ 1200	117 x 146.1 (4.59 x 5.75)	17.2:1	TB	✓
EPA 2010	6, inline	DI, 4	272-354 (365-475) @ 1700	1695-2305 (1250-1700) @ 1000	126 x 166 (4.96 x 6.54)	17.0:1	TB	✓
Euro 6 / EPA 2013	6, inline	DI, 4	149-268 (200-360) @ 1600-2400	705-1085 (520-800) @ 1600-1800	107 x 124 (4.21 x 4.88)	17.3:1	TB	✓
Euro 6 / EPA 2013	6, inline	DI, 4	194-335 (260-450) @ 1400-2100	976-1695 (720-1250) @ 1300-1400	114 x 145 (4.49 x 5.69)	16.6:1	TB	✓
Euro 6 / EPA 2013	6, inline	DI, 4	250-320 (335-430) @ 1600	1560-2237 (1150-1650) @ 900-1700	123 x 152 (4.84 x 5.98)	18.5:1	TB	✓
Euro 6 / EPA 2013	6, inline	DI, 4	303-380 (405-510) @ 1600	1966-2500 (1450-1850) @ 900/1000-1700	130 x 162 (5.12 x 6.38)	18.5:1	TB	✓
GHG 2017 / EPA 2017	6, inline	DI, 4	242-317 (325-425) @ 1500-1900	1708-2115 (1260-1560) @ 1200	123 x 152 (4.84 x 5.98)	17:1	TB	✓
GHG 2017 / EPA 2017	6, inline	DI, 4	309-362 (415-505) @ 1500-1800	1979-2522 (1460-1860) @ 1200	131 x 158 (5.16 x 6.22)	17:1	TB	✓
GHG 2017 / EPA 2017	6, inline	DI, 4	242-317 (325-425) @ 1400-1900	1627-2102 (1250-1550) @ 1200	123 x 152 (4.84 x 5.98)	17:1	TB	✓
GHG 2017 / EPA 2017	6, inline	DI, 4	250-361 (375-500) @ 1400-1800	1830-2508 (1450-1850) @ 1100	131 x 158 (5.16 x 6.22)	17:1	TB	✓
Tier 4 / Stage IIIA	4, inline	DI, 4	42.7 (57.3) @ 3000	131 (96) @ 3000	84 x 90 (3.30 x 3.54)	18.9:1	AG, GS, IS, OH	✓
Tier 4 / Stage IIIA	4, inline	DI, 4	52.1 (69.9) @ 2500	193 (142) @ 2500	98 x 110 (3.85 x 4.33)	18.5:1	AG, GS, IS, OH	✓
Tier 4 / Stage IIIA	4, inline	DI, 4	64.1 (86.0) @ 2500	238 (175) @ 2500	98 x 110 (3.85 x 4.33)	18.1:1	AG, GS, IS, OH	✓