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Modular Hybrid Powertrain with Jet Ignition

Mahle Powertrain has developed a hybrid drive for future global automotive markets, scalable across a wide range of vehicles, and intended to meet emissions and CO_2 targets for 2030 and beyond. The Mahle Modular Hybrid Powertrain is based around a high-voltage PHEV architecture, with a dedicated hybrid internal combustion engine, featuring Mahle's jet ignition system, integrated with a dual-mode hybrid electric drive.

INCREASING LEGISLATIVE PRESSURE

Vehicle manufacturers are facing increasing pressure by legislation and economics to reduce vehicle CO_2 emissions. Electric Vehicles (EVs) do not generate local pollutants during use and can potentially rely on energy provided by a selection of renewable sources, and are therefore drawing significant interest. However, limitations of battery technology concerning size, weight and cost constrain the overall range of such a vehicle.

Plug-in Hybrid Electric Vehicles (PHEVs) partly overcome the limitations of EVs by retaining an Internal Combustion Engine (ICE). The engine can directly provide drive power when the battery is depleted. Furthermore, once the vehicle has significant electric drive capability, it is possible to remove dynamic loading from the ICE to allow it to operate less transiently, simply maintaining the battery's State of Charge (SoC).

Gasoline engine downsizing is also a technology that can help to reduce CO_2 emissions. Mahle Powertrain has developed a heavily downsized, turbocharged in-line three-cylinder demonstrator engine with direct gasoline injection and 1.2 l displacement (Mahle Di3) [1, 2]. The Di3 engine achieves a peak Brake Mean Effective Pressure (BMEP) of 30 bar, and a peak power output of 120 kW (100 kW/l). It has been developed for industrialization, with two capacities of 1.2 and 1.5 l, with maximum commonality and benefiting from an advanced combustion system, combined with a low-friction base engine design and optimized thermal management, enabling a minimum Brake Specific Fuel Consumption (BSFC) of 233 g/kWh [3].

For over ten years, Mahle Powertrain has also been developing active and passive versions of the Mahle Jet Ignition (MJI) pre-chamber based combustion system that markedly increases combustion speed, giving improved dilution tolerance [4]. The active system contains both a spark plug and a Direct Injection (DI) fuel injector within the pre-chamber, whereas the passive system is fueled indirectly by drawing charge from the main chamber during the compression stroke.

In this study the combination of passive MJI, together with a high geometric Compression Ratio (CR), externally cooled Exhaust Gas Recirculation (EGR) and aggressive Miller-cycle operation enable extremely low BSFC levels to be achieved, while operating with a stoichiometric air-to-fuel ratio.

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FUTURE POWERTRAIN REQUIREMENTS

This study draws on the experience gained through the development of both the downsizing and MJI research and examines the powertrain requirements to meet the needs of passenger cars in the 2030 timeframe, and beyond. The fleet average tailpipe CO_2 target for the EU is currently 95 g/km. However, by 2030 the limit is reduced to 59 g/km, and will require a significant degree of plug-in hybridization, or electrification, within the fleet mix [5].

Beyond 2030, plug-in hybridization with a significant electric driving range capability to achieve a favorable tailpipe weighting factor will be a key technology enabler for achieving fleet CO_2 targets. Once the vehicle has significant electric drive capability, there are other benefits that also help to improve the ICE efficiency and to reduce emissions. Firstly, removal of dynamic loading from the engine, enabling it to operate in a more steady-load manner, approaching the operation seen for range extender units, where the target is to regain the battery SoC once the battery has become depleted [6]. Once the electric drive system is capable enough to remove the entire dynamic load requirement from the engine; the engine needs only to be sized to simply maintain SoC during use. If the engine no longer needs to respond instantaneously to load changes, as dynamic response can be handled via the electric drive unit, that means that the engine can be optimized for a narrower operating range, removing much of the complexity encountered on standard ICEs. A final benefit of this type of architecture is that the ICE does not need to be subjected to any significant loading until the exhaust aftertreatment has attained operating temperature. This is especially beneficial when considering RDE testing, where the vehicle could be under full-load within seconds of the key-on event.

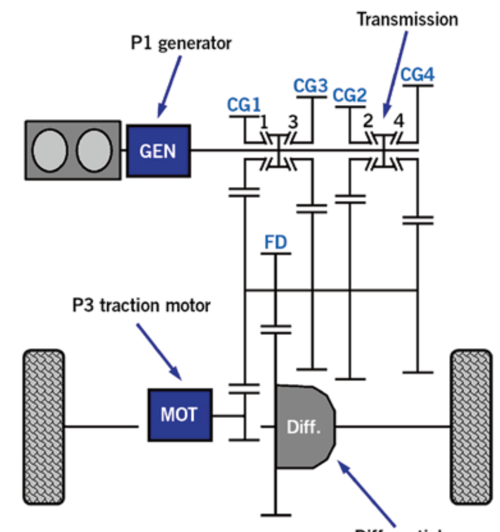

FIGURE 1 Dual-mode hybrid drive-line architecture of the MMHP (© Mahle)

MODULAR HYBRID POWERTRAIN

The MMHP has been developed to meet future legislative requirements for passenger cars. The dual mode hybrid arrangement of the MMHP combines the best features of the series and parallel arrangements. A schematic of the architecture selected is shown in **FIGURE 1**.

The Mahle Modular Hybrid Powertrain (MMHP) has been based around a high-voltage PHEV architecture, with a Dedicated Hybrid internal combustion Engine (DHE) integrated with a dual-mode hybrid electric drive, which features two electric machines. The traction motor is capable of providing full vehicle dynamic performance and vehicle maximum speed

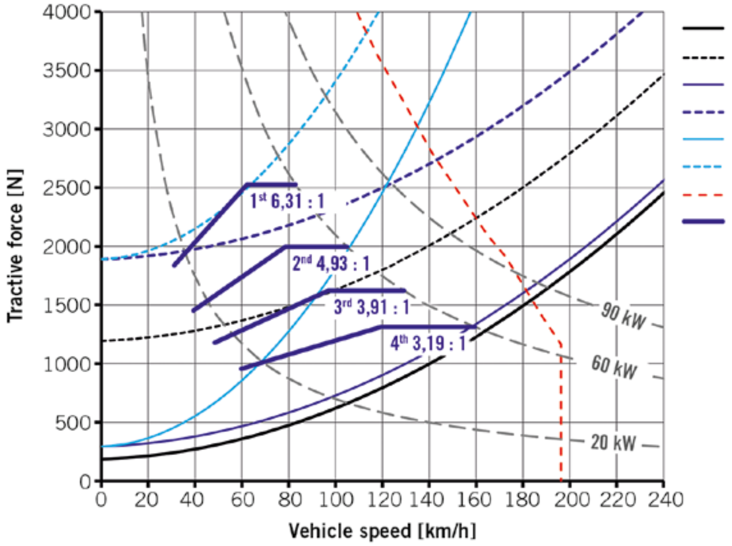

FIGURE 2 Road load and cascade diagram for the 1400 kg compact cross-over SUV with the MMHP fitted with a four-speed transmission and two-cylinder DHE with 60 kW (© Mahle)

capability without assistance from the DHE. This enables improved emissions and reduced aftertreatment complexity by avoiding DHE cold start at high power demand, which can be a challenge with PHEV systems that rely on ICE power for full vehicle dynamic performance capability. The design of the unit offers reduced cost, complexity, package size and weight compared to current hybrid powertrains. The system is also specified to deliver very low drive cycle CO_2 figures.

When battery SoC is high, the vehicle can operate as a pure BEV. Once the battery is depleted, the system operates as a series hybrid at low vehicle speeds, having the NVH and operating flexibility that this arrangement offers. At higher vehicle speeds the engine can be connected directly to the drive via the dedicated hybrid transmission that offers a number of ratios enabling some flexibility in engine operating speed. The traction motor is directly connected to the drive shaft, thus there is seamless torque delivery, even during a gear-shift event, enabling the use of a simple automated manual transmission.

SYSTEM POWER REQUIREMENTS

The target vehicle application considered is a compact cross-over SUV. To determine the power requirements of the components within the MMHP (DHE, generator and traction motor) vehicle performance targets have been defined. The vehicle dynamic performance determines the traction motor power (P3 location). The generator (P1 location) power is determined by the DHE minimum operating speed and the transmission ratios selected. The generator must maintain battery SoC until the vehicle is traveling fast enough to enable the switch into parallel hybrid mode. Finally, the engine maximum power and the transmission ratios required can be determined by the maximum cruising speed for maintaining battery SoC. Hill-climbing and towing scenarios need to also be considered.

The high-voltage system components operate on a nominal system voltage of 400 V. The traction motor is water cooled and features a novel stator winding cooling system, which enables the motor to achieve a high continuous power rating of 127 kW (157 kW peak) from a compact package size. The serial hybrid generator unit is capable of operating at a continuous power of 20 kW. Finally, the DHE power requirement to meet the charge sustaining operation during cruising at 130 km/h is 60 kW.

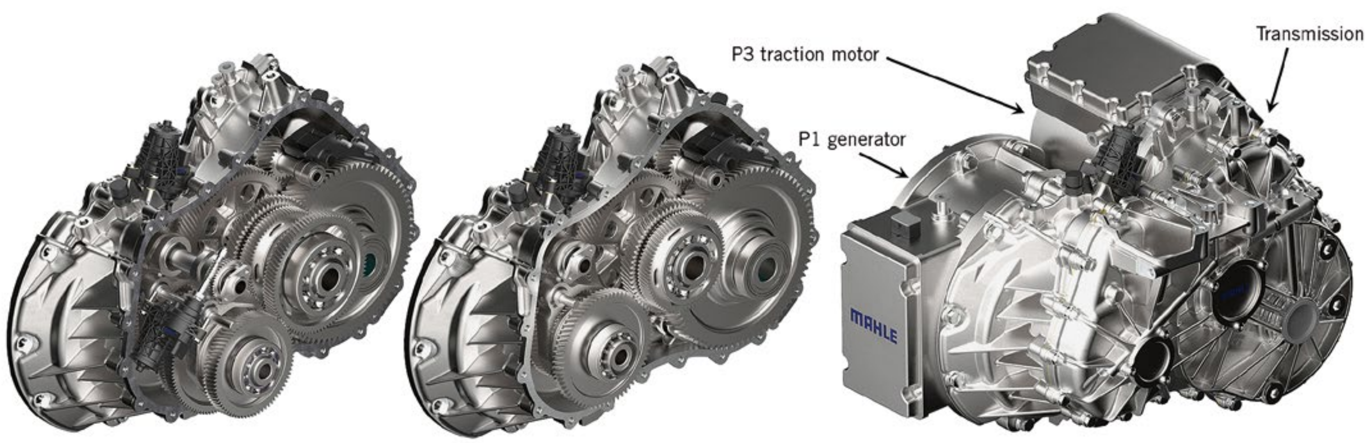

FIGURE 3 Four- (left) and two-speed versions (middle) of the MMHP transmission and integrated hybrid drive shown in the two-speed transmission (right) (© Mahle)

DEDICATED HYBRID TRANSMISSION

The traction motor drives the differential directly (P3 location). The generator is coupled directly to the engine crankshaft (P1 location). Both the traction motor and generator have their inverters integrated into their housings. The transmission input shaft is also directly engaged with the generator.

To save cost, weight and package space, there is no clutch within the system, as this is not required because the DHE is not used for vehicle launch. The engine is decoupled from the driveline, for pure-electric or hybrid operation, by selecting neutral in the transmission. During a gear shift event in parallel hybrid mode, wheel torque is seamlessly provided by the traction motor. The generator can quickly speed match the DHE for the next gear.

The transmission ratios enable the DHE to operate in direct drive mode over a wide range of vehicle speeds and enable charge sustaining operation to be achieved, even on steep inclines while towing a heavy trailer or caravan. **FIGURE 2** shows road load curves for the compact cross-over SUV, on both a level road and a 6 % grade, and the influence of a 1000 kg trailer and a caravan (1000 kg trailer with a large frontal area) on the road load of the vehicle are also included in the plot. The engine tractive wheel forces, for the DHE in each of the four transmission ratios, are also shown. The transmission design uses cylindrical helical gears to provide a cost optimized solution and can be tailored to have one, two or four ratios, using a common main casing, depending upon application requirements.

For some applications a single gear ratio could enable the majority of the vehicle performance targets to be met. However, to enable charge sustaining operation while towing on a gradient, additional ratios can be added. The transmission is configured as two sets of two ratios with a neutral position between each of the ratios. In the four-speed version, when the DHE is in direct drive mode, one set of gears will be in neutral, while the other is in the selected drive ratio. This layout means that even for the simple sequential layout used, the transmission is only one shift away from neutral in any condition. **FIGURE 3** shows the four- and two-speed versions of the transmission as well as the entire hybrid drive.

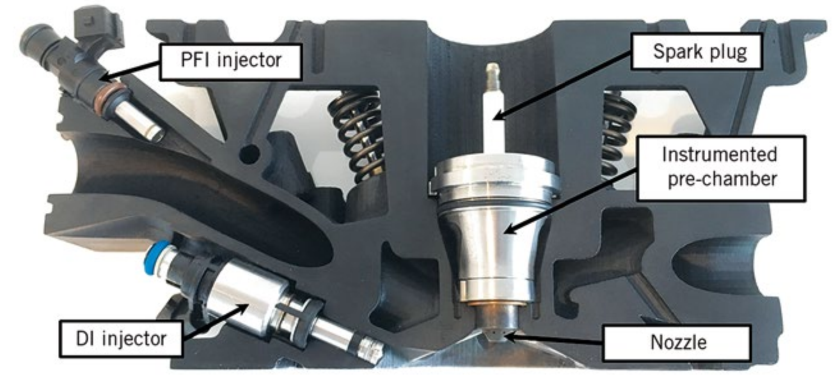

FIGURE 4 Cross-section through the prototype passive MJI development cylinder head showing the prototype pre-chamber (© Mahle)

DEDICATED HYBRID ENGINE

The DHE has been designed to achieve greatest efficiency, with a low cost architecture and compact package size. The 60 kW maximum power output is achieved at maximum operating speed, which has been limited to 4000 rpm for good NVH. The DHE has a parallel twin layout to reduce package volume, part count and weight. It has an even firing order, with a contra-rotating balancer shaft to minimize vibration and reduce the torque recoil about the crank center line arising due to cyclic speed fluctuations.

The engine features a passive MJI based combustion system with Port Fuel Injection (PFI), two valves per cylinder, a single camshaft and fixed valve timings. To maximize the operating efficiency, the engine has a high degree of Miller-cycle operation combined with a high geometric CR. The engine operates with a single, fixed geometry turbocharger, using an electrically controlled waste-gate actuator. To enable further efficiency gains an external cooled EGR system is also used. The 1.0 l engine achieves a peak BMEP of 18 bar between 2500 and 4000 rpm.

INITIAL DEDICATED HYBRID ENGINE TEST RESULTS

Initial validation of the combined use of passive MJI, high geometric CR and a high degree of Miller-cycle operation has been conducted using the Mahle Di3 with a revised cylinder head to enable assessment of a variety of pre-chamber geometries. The pre-chamber was instrumented to allow pressure to be measured within the pre-chamber. A cross-section of the prototype cylinder head is shown in **FIGURE 4**.

A comparison of the combustion events, at the target peak power operating point of 4000 rpm and 18 bar BMEP, between the passive MJI system and a conventional Central Spark Plug (CSP), is shown in **FIGURE 5**. The pre-chamber combustion event can be seen as the spike in pre-chamber pressure trace just prior to top dead center firing at 0 °CA. This initiates rapid combustion in the main chamber and, at this test condition, the 10 to 90 % Mass Fraction Burned (MFB) duration is reduced by 40 %, from 25.9 to 15.4 °CA, which then enables the combustion phasing to be advanced by almost 9 °CA before the onset of knock. Using the Mahle Di3 engine, adapted for passive MJI, operating with a high geometric CR, in conjunction with a PFI system, Miller-cycle intake camshaft, and a low-pressure EGR system, an Indicated Thermal Efficiency (ITE) map for the DHE was generated, **FIGURE 6**. It gives a promising indication of the potential of this combustion system to achieve very high ITE levels using cost effective technologies. A maximum ITE value of 43 % is achievable at an

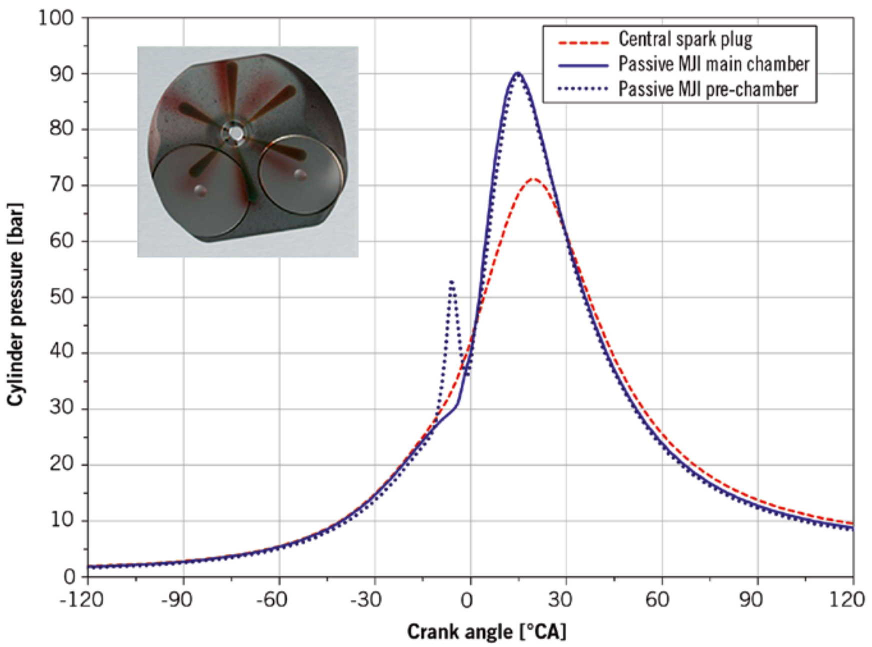

FIGURE 5 Comparison of passive MJI combustion to a conventional central spark plug at 4000 rpm and 18 bar BMEP (© Mahle)

engine speed of 3000 rpm and a load of 12 bar BMEP as well as a very large area of operation above an ITE of 40 %.

Achieving stable operation over a wide operating range is a known challenge for pre-chamber based combustion systems, especially under low load conditions, or with delayed combustion phasing as employed during the cold start catalyst heating phase of operation. Testing has demonstrated that with the MJI pre-chamber combustion phasing can be retarded a similar amount to that achieved for the CSP and with comparable catalyst heat flux levels. Furthermore, the engine out gaseous and particulate emissions measured for the MJI equipped engine are comparable to those measured with the CSP across the whole engine operating range.

FULLY INTEGRATED MODULAR HYBRID UNIT

The complete MMHP has been designed to be as compact as possible. **FIGURE 7** shows views of the MMHP unit with the two-speed transmission, and includes the transmission, engine, generator, traction motor and the inverters for motor and generator. Due to the compact DHE layout, the width of the unit (excluding exhaust) is only 721.5 mm, and 762.2 mm for the four-speed variant. Similarly the total mass has been kept low and is 180 kg for the two-speed and 191 kg for the four-speed variant.

The MMHP has been designed to be scalable across a broad range of vehicles. The DHE can be produced as either a two-cylinder with up to 60 kW or a three-cylinder unit with up to 90 kW, both variants achieving peak power at 4000 rpm and 18 bar BMEP. Likewise, the transmission can be configured with one, two or four gear ratios using common ratios and main transmission casing. The traction motor can be sized to achieve the desired dynamic performance of the vehicle.

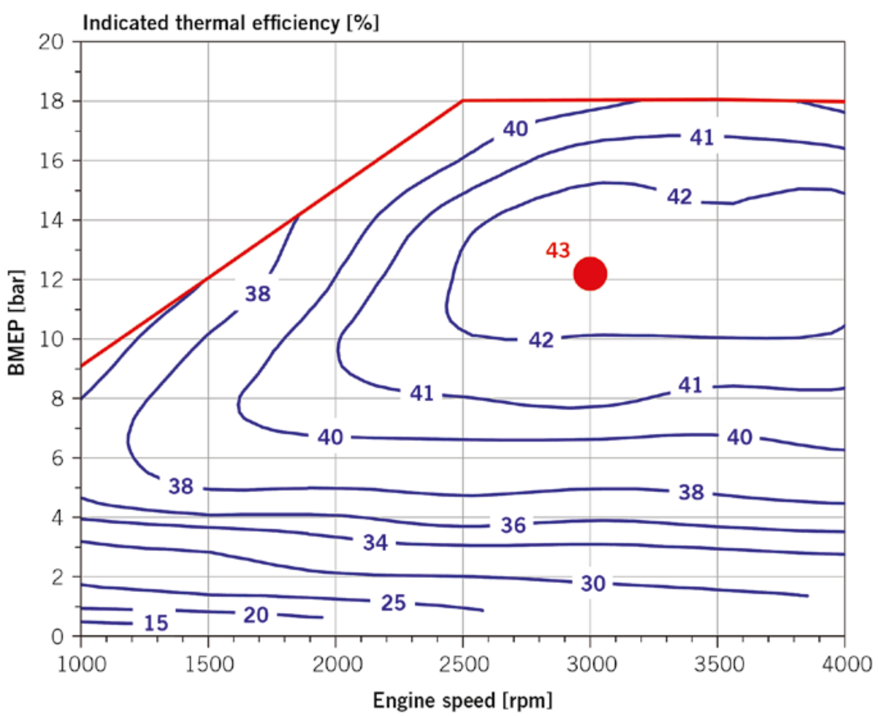

FIGURE 6 DHE ITE map from initial testing of the concept (© Mahle)

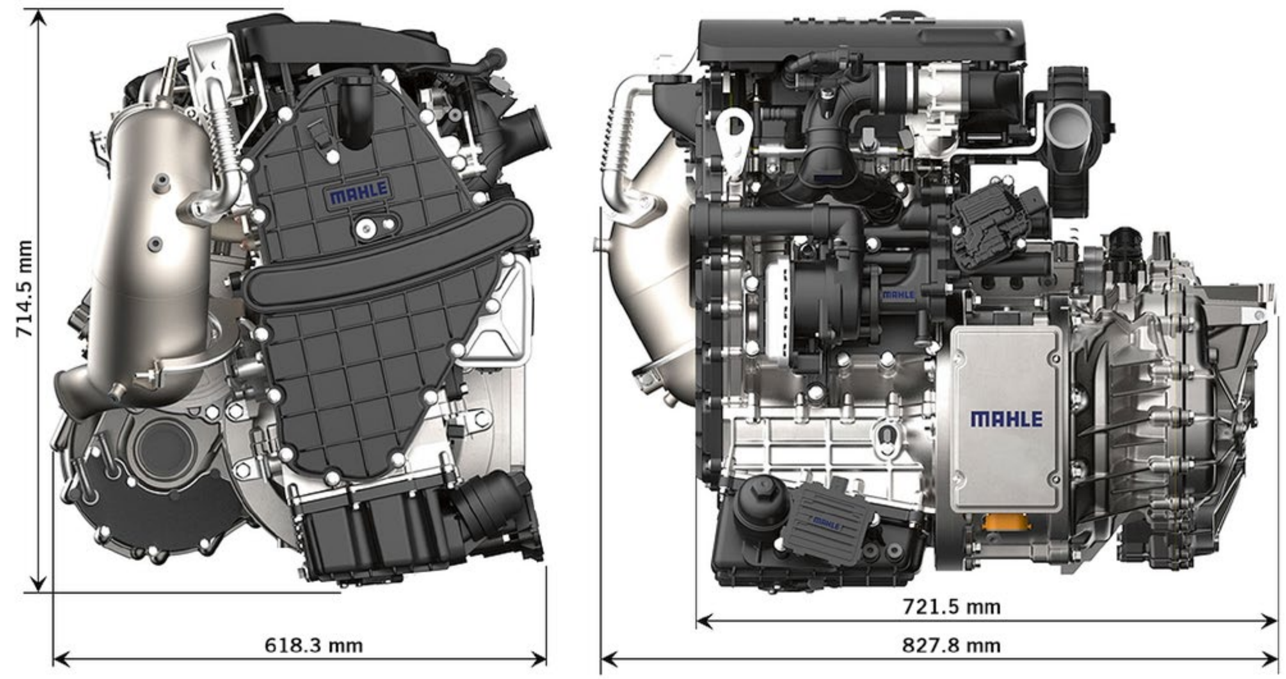

FIGURE 7 Overall dimensions of the two-speed version of the MMHP (© Mahle)

CONCLUSIONS

The MMHP is based around a high-voltage PHEV architecture, with a DHE integrated with a dual-mode hybrid electric drive. The traction motor provides full vehicle dynamic performance without assistance from the DHE. This enables improved emissions and reduced after treatment complexity. Additionally, the direct drive arrangement enables seamless torque delivery, enabling the use of a simple automated manual transmission. The design of the unit has targeted reduced cost, complexity, package size and weight compared to current hybrid powertrains. The concept is scalable across multiple vehicle applications with a variety of traction motor powers, two and three cylinder DHE variants and one-, two- or four-speed transmission options available.

Careful selection of the combustion system technologies allows the engine efficiency to be maximized over the reduced speed/load operating map. Initial testing has yielded very positive results showing that the combination of the pre-chamber based combustion layout, together with high geometric CR, externally cooled EGR and aggressive Miller-cycle operation enable an ITE of 43 % to be achieved with a very modest technology package.

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