The new General Motors 3.0 ℓ Duramax Diesel engine:  
A technology milestone combining state-of-art efficiency, emissions, performance and refinement

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Abstract

General Motors just introduced, for the first time in the Light-Duty Pickup Truck market, a new Duramax 3.0 ℓ 6-cylinder inline diesel engine. This engine has been designed from “clean sheet” paper and specifically developed for the new GM Full-Size Truck platform: it will equip the next generation of Chevrolet Silverado and GMC Sierra as well other vehicles in the future.

In order to ensure the best possible in-vehicle integration of the propulsion system in the new platform, a modern “state of the art”, very efficient, all-aluminum diesel engine architecture has been selected, breaking through the paradigm of V engines for pickups and adopting the “inline” configuration, very challenging to package but essential to get the highest fuel economy combined with excellent NVH.

The paper describes how the engine has been developed to meet the high expectations of North American Pickup customers, including rated power performance and towing capacity as well noise refinement, tougher emissions standards combined with excellent fuel economy. The key technical features of the base engine thermodynamics and mechanical sub-systems, boosting and EGR, controls, and emission reduction technology are described in the paper.

Main results

Introduction

In 2017, the penetration of diesel engines in the NAFTA region (USA, Canada and Mexico) has been roughly 4% of the overall light-duty market, which includes passenger cars, light- and medium-duty pickup trucks and SUVs, as well as light commercial vehicles. While 4% is a relatively low share (especially by European standards, where diesel market share in 2018 achieved ~35%), given the magnitude of the overall NAFTA region the actual number of diesel vehicles sold was about 650,000, representing a considerable opportunity. This is one of the main considerations behind the strategic decision taken by General Motors back in 2014 to start the development of a brand-new inline 6-cylinder diesel engine (with the huge related investments in engineering and manufacturing) specifically conceived and designed for that market.

In addition, two powerful trends are at work that will make this commercial opportunity even more attractive in the next decade:

- CAFE standards are increasing the fuel economy requirements significantly, and this challenge is even greater for the full-size pickup trucks and LCVs. Diesel, with a 20-25% better fuel economy versus gasoline, is a very effective compliancy option on par or even better than best gasoline-hybrids.
- Consumer studies are showing that in the two vehicle categories above there is already an established demand for diesel engines, that is expected to grow even more in the future decade thanks also to the positive ownership experience of the many current drivers from medium-duty market (Figure 1).
The new 3.0 ℓ Duramax has been specifically addressed to such customers, and the choice by General Motors of the inline 6-cylinder configuration is a direct result of no compromise in the performance, refinement and durability that these segments expect.

**Targets, Engine Architecture and Technical Data**

As described in the introduction, the choice between ‘Inline’ and ‘Vee’ configurations for the new 6-cylinder engine was one of the first milestones in the development. In order to achieve this in a solid and rational way, an initial architectural study has been carried out, comparing the two options in regard to several attributes: packaging, weight, fuel economy, performance, NVH and cost.

The overall Pugh selection matrix is reported in Figure 2. Inline 6 configuration showed appreciable advantages in the fuel economy, performance, NVH and cost (including modularity with 3-and 4-cylinder derivatives) that eventually made it a winner.

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**Table 1: Engine Base Specifications**

The authors would like to stress again that the overall engine design has been organized around the objective of the maximum efficiency and reliability, therefore the sophisticated manufacturing technologies for aluminium casting have been joined to a relatively low Peak Firing Pressure PFP target and Compression ratio CR, leading to a benchmark friction.
The combination of high-performance combustion system with a state-of-art turbocharging system allowed the achievement of a compelling power and torque curves (measured according to SAE J1349), reported in Figure 3. On the same figure are also reported the specifications of main competitors in the 3.0 ℓ full-size pickup truck market, highlighting the excellent shape of both low-end torque (for towing and elasticity) and high-end power (acceleration and fun-to-drive).

Combustion System

The development of the new 3.0 ℓ Duramax diesel started from the core of the engine: the combustion system. As a result, the key architectural features and dimensions were defined pursuing improved performance, fuel economy, and combustion noise, while complying already with stringent U.S. Tier 3 emission standards.

The combustion system parameterization was included in the optimization process: bore and bore-to-stroke ratio (Figure 4), compression ratio, bowl profile, nozzle and intake port characteristics. In addition to this, the boundary conditions in terms of Manifold Absolute Pressure (MAP), Peak Firing Pressure (PFP) capability and exhaust temperature (T_exh) were taken into account as well, in order to define the most balanced set of these parameters ([2, 3]).

Fig. 3 – 3.0 ℓ Duramax engine torque and power vs main competitors in truck market

One of the objectives of new 3.0 ℓ Duramax combustion system was the capability to achieve high specific power (up to 100 hp/liter), while keeping high low-end torque and fast responsiveness to transients. The enablers were identified in the following sub-systems:

- Charging system (boost level, turbine inlet temperature)
- Base engine (peak firing pressure, compression ratio)
- Cylinder head (volumetric efficiency, swirl ratio)
- Fuel injection system (nozzle geometry, injection pressure)

The optimization of these parameters in view of maximizing power density is subjected to significant constraints in terms of emissions, fuel consumption, durability, real-world operation (including low-temperature startability) and packaging. On the other hand, certain enablers provide the opportunity to decouple emissions constraints from high specific power achievement. For example, the maximum fuel injection pressure allows decreasing nozzle flow number and thus hole diameter for optimized fuel atomization at part load, while keeping combustion duration at rated power at acceptable levels (CA10-90 is ~ 50 deg CA). Thanks to availability of 2,500 bar maximum fuel injection pressure, a nozzle flow number of 380 cc / 30 s was selected, with a 9-hole nozzle and 116 microns hole diameter (see Chapter 3.1 for details).

Since boost pressure exhibits the strongest link with the power density, a low compression ratio becomes a fundamental enabler for a lightweight yet high-power density engine, and at the same time contributes to the improvement of engine-out emissions. Therefore, a rather low value of 15.0:1 was selected as best balance
between rated power, emissions and cold startability requirements (excellent cold startability up to -30°C was achieved in conjunction with fast-response high-temperature ceramic glow plugs).

Concerning optimization of bore-to-stroke ratio (B/S), the balance to reach is between improved engine breathing as B/S increases, and thermodynamic efficiency, wall heat transfer and packaging as B/S decreases. Based on this trade-off, a B/S of ~0.93 was selected as the best balance.

The selected base swirl ratio was ~1.4, a relative low value, in order to increase port flowage at rated conditions, but provision has been made for turbulence increase at part load conditions with a Variable Swirl Actuator (VSA) capable to increase SR up to ~2.5 only where needed (Figure 5).

The combustion chamber profile plays an important role in the overall combustion system performance definition: various shapes have been evaluated via 3D-CFD analysis prior to being tested and refined on both single- and multi-cylinder engines. The optimization process was based on an integrated approach combining simulation and testing, as described in previous papers [4-6] and represents a GM patented design (Figure 6) internally called DP11r ([7]).

While the diesel CI combustion process is fundamentally heterogeneous, in order to develop high power density, it is necessary to achieve a high degree of air utilization by the combustion end, around 90° ATDC at rated power conditions (3,750 – 4,000 RPM).

In this regard, the DP11r profile has shown very good air utilization over a wide range of engine operating conditions, and high tolerance to EGR with the objective to reduce the engine-out NOx emissions while keeping low engine-out HC and PM emissions, as well as the BSFC. The authors attribute this advantageous behavior to the low re-entrant profile, which on one side is minimally sensitive to injection timing and hence spray targeting, and on the other side promotes direct and reverse squish motions that produce strong mixing of the central area of the chamber, thus leading to a complete air utilization and enhancing the late soot oxidation. Therefore, it is useful to track and represent the combustion process evolution over the crank-angle CA in terms of lambda, which allows to highlight the zones that are too lean (lambda > 2.0) and too rich (lambda < 1.0) as responsible of poor performance Fig. 7). This criterion enables the ranking of several nozzle types via 3D-CFD, well before any test is carried over.

Unused Air (λ>2)
Ideal Mixture (1<λ<2)
Slightly Rich (0.5<λ<1)
Very Rich (λ<0.5)
In Figure 8, results of such a screening are reported. Air utilization parameters are plotted at end of combustion (90 deg ATDC) for rated power conditions, varying:
- 8, 9, 10 nozzle hole types;
- 340, 380, 420 cc / 30 s Hydraulic Flow Rate (HFR);
- 1.0, 1.5, 2.0, 2.5 Nozzle Tip Protrusion (NTP);
- 150, 155, 160 Nozzle Cone Angle (NCA).

Over-lean volume fraction with lambda > 2.0 is plotted on X-axis, while Y-axis reports over-rich lambda < 1.0 charge fraction: of course, the axes origin represents the ideal target. As can be noticed, the 9-hole nozzle is the best option, with many configurations falling close to the ideal target, and small sensitivity to NTP and NCA. Certain 8-hole nozzle variants are promising, while 10-hole nozzles do not seem feasible.

The 8- and 9-hole variants that have been found more capable via 3D-CFD have then undergone experimental assessment at both Full Load and Part Load, in order to validate their suitability. For all nozzle variants, the availability of rail pressure up to 2,500 bar has been extremely beneficial in shortening the combustion duration around rated power conditions, improving its completeness and efficiency, therefore contributing to enhanced air utilization and consequently enabling engine operation at lower lambda. The 9-hole, 380 cc / 30 s HFR and 155 deg COA with 2.0 mm NTP has been confirmed the one showing best compromise, with overall lower soot, HC, CO and BSFC at part load, as well as lower soot, BSFC combined with higher performance at full load. Therefore, it has been selected for new 3.0 ℓ Duramax.

Eventually, it’s also worth plotting the nozzle specs as function of hole diameter and HFR (Figure 9). The region below 115 microns (0.15 mm) is shaded in grey because it is not considered safe to coking for engine power density close to 100 hp/l and the long-term durability expected from pickup truck engines. No 10-hole variant respects this specification, whereas the 7-, 8- and 9-hole options do. Therefore, the 9-hole selection can be considered fully acceptable also from this standpoint.

**Lubrication System, Cooling System and Active Thermal Management**

The LM2 lubrication circuit is designed to optimize the friction loss and to get the best cooling and lubrication at the same time. For this purpose, it has been implemented a continuous Variable Displacement Oil Pump (cVDOP) in the circuit design. The cVDOP can supply the exact amount of oil demanded and it minimizes the torque absorption in non-critical operating points. Using calibrated maps, the Engine Control Unit drives a solenoid valve that in turn controls the mode of the cVDOP by providing continuous control on displacement so to reduce fuel consumption and CO₂ emissions. The engine is fitted with active thermal management in order to
rapidly achieve an optimal operating temperature in all conditions, from warm-up to light-load operation. This includes keeping the combustion chamber temperature as warm as possible to reduce heat losses and oil viscosity.

The cooling circuit is characterized by a Split Cooling layout having a mechanical water pump and a coolant control valve placed at engine outlet. The water enters in the circuit through a rail integrated in the block casting. The rail distributes the flow to cylinder head and block. Water circulation is transversal cross flow in both cylinder head and cylinder block. Another rail on the block cold side collect the water and conveys it to coolant control valve (Figure 10).

The circuit is also equipped with a cold bypass branch that allows an amount of flow to be directed from the inlet rail to rotary valve without transiting through block and head. The system control is based on the feedback of water temperature sensors on cylinder head outlet, block outlet, cooling system inlet, metal temperature sensor, oil temperature sensor.

Figure 10 – Cooling circuit with Main Rotary Valve (top) and details of the MRV itself (bottom)

**Turbocharger and Exhaust Gas Recirculation Systems**

The turbocharger and the exhaust gas recirculation system were developed as a unique macro-system. One of the key goals was to balance the low-end torque, the peak power and the EGR capability. To this extent, in addition to the standard analysis for the full load and the transient maneuvers, a strong focus was put on the part load simulations. Different turbocharger sizes and EGR circuit design combinations were evaluated. As a result, by means of combined 1-D and 3-D CFD simulations, the detailed design of the EGR circuit was defined in order to optimize the overall permeability ([2]). This optimization of all the subsystems and components allowed to meet several apparently conflicting requirements.

The VGT turbocharger, supplied by Garrett, is electrically actuated and features ball-bearing technology for maximum responsiveness under transient and cold temperature operation (Fig. 11). For robustness and durability, it is water cooled to withstand the most demanding driving cycles. Finally, to optimize the NVH behavior, precise balancing and resonators at the compressor inlet and outlet were adopted.

Figure 11 – Variable geometry turbocharger with ball-bearing technology

In order to extend EGR usage to all engine and ambient conditions, EGR system features both a High-Pressure (HP) route and a Low-Pressure (LP) route. A water-cooled and compact valve (DC-motor) manages the HP pressure system, used mainly during engine and aftertreatment fast warm-up strategies (Figure 12).

Due to the compact layout of the intake system featuring Water-Charge-Air-Cooler (WCAC), a particular attention was given to the HP-EGR distribution among the 6 cylinders, necessary to achieve the extremely low emissions for Bin160.

Figure 12 – HP-EGR (highlighted in red color) and LP-EGR (blue) circuits
Exhaust Aftertreatment System

The diesel aftertreatment system for the 3.0 ℓ Duramax engine is based on an innovative architecture which has a plethora of patented components ([8, 9]). The first element in this system is a close coupled diesel catalyst (DOC) which oxidizes hydrocarbon emissions, and converts some of the NOx emissions into a form that is easier for the SCR to reduce. Following the DOC is the mixer section, where exhaust gases are mixed with injected Diesel Exhaust Fuel (DEF), and where DEF vaporizes and decomposes into ammonia.

The new 3.0 ℓ Duramax diesel engine features the first application of a selective catalytic reduction on particulate filter (SCRF) in a GM vehicle. Combining these two functions in one close-coupled component reduces the number of aftertreatment parts in the exhaust system, and results in lower back-pressure.

There is a second SCR following the close coupled SCRF. This underfloor SCR ensures that conversion of NOx emissions into harmless byproducts is maximized, especially under high load conditions typical of towing. Following the underfloor SCR is a further catalyst which is meant to oxidize any ammonia that may slip past the SCR without reacting with NOx. This Ammonia Slip Catalyst (ASC) is the last after treatment system component in the exhaust system.

The overall layout of the system is visualized in Figure 13, both as it appears from the outside and in cross section. The catalysts are represented in red color, while the Ad-blue injector is represented in yellow color in the zoomed part which also shows more details of the Ad-blue mixer.

Figure 13 – 3.0 ℓ Duramax aftertreatment system with cross-section of major components. DOC: Diesel Oxidation Catalyst; SCRF: Selective Catalyst Reduction on Diesel Particulate Filter; SCR: Selective Catalyst Reduction; ASC: Ammonia Slip Catalyst

Friction and Fuel Consumption

The new 3.0 ℓ Duramax diesel engine has been designed with efficiency as a main target. Therefore, both the thermodynamics (as seen in Chapter 3) and the mechanics received a great deal of effort. As a consequence of very lean sizing of all components (especially the rotating and reciprocating ones that have been described in detail in Chapter 4), and of usage of electronically-controlled accessories (like the continuous variable displacement oil pump, the active piston cooling jets and the coolant control valve – Chapter 7), a very low level of friction has been achieved, especially considering the high specific power and torque of the engine.

In the Figure 14, a comparison of the 3.0 ℓ Duramax Friction Mean Effective Pressure (FMEP) with the FEV scatter band of recent production diesel engines for passenger cars and light-duty trucks is reported.

The top diagram in Figure 14 reports FMEP as function of engine RPM, whereas in the bottom one FMEP @ 2,000 RPM is plotted against engine displacement. As can been seen, the new 3.0 ℓ Duramax is setting a new benchmark level in both regards.

Figure 14 – Scatter band for FMEP as function of engine speed (top) and engine displacement (bottom)
Finally, as a direct result of the above-described characteristics, i.e. the very high thermodynamics and mechanical efficiencies, the 3.0 ℓ Duramax BSFC map results in a flat and low distribution as pictured in the Figure 15. The flatness of the map is highlighted by the relative BSFC iso-lines, with the majority of the FTP-75 and US-06 operating points falling within just 10% of peak BSFC point (assumed as 100%).

**Fig. 15 – Normalized BSFC map for 3.0 ℓ Duramax.**

In particular, looking at the 2,000 RPM x 2 bar BMEP point – widely used in the literature as benchmark for engine efficiency at part load – the 3.0 ℓ Duramax engine achieves an outstanding value of just 256 g/kWh, far exceeding the closest efficient competitor and thus becoming, by far, the best-in-class engine on the market (Figure 16, left).

The exceptional results achieved can be also visualized in historical perspective, by looking at the trend over time of the diesel engine efficiencies for light-duty application (Figure 16, right). This diagram reports both the peak efficiency as well as the efficiency at 2,000 RPM – 2 bar BMEP (left axis), together with the typical average engine-out NOx specific emissions (right axis). As can be noticed, while the emissionization has become progressively much tighter over the years to comply with criteria pollutant legislation, thanks to the technology advancements the efficiencies have improved as well, even if they are on a well-known trade-off with NOx emissions. This is particularly true for the 2,000 RPM – 2 bar BMEP point, and is reflecting a massive reduction of diesel engine friction over the last 20 years. This is a strong indicator of how the engine BSFC map has flattened-out, and delivers real world fuel economy also at light loads typical of everyday life.

**Fig. 16 – Scatter band for BSFC @ 2,000 RPM x 2 bar BMEP as function of engine displacement (left). Historical data series of engine peak efficiency and efficiency at 2,000 RPM x 2bar BMEP, with average engine-out NOx emissions on NEDC for diesel engines (right).**

**NVH Design**

As mentioned in the introduction paragraph, since the very beginning of the design process GM team clearly identified the 6-cylinder inline architecture as main driver to achieve an outstanding NVH feeling. In fact, secondary inertia forces are indeed purely balanced in an inline 6-cylinder engine (thanks to the 120 CA° offset of crank throws) with respect to a Vee 6 where unbalanced components are present, and the crankshaft speed fluctuations are low due to the small firing interval. This resulted in a superbly smooth operation even without balance shafts, with a benefit in terms of mass and cost.

On the top end a high-density foam cam cover insulator provided an optimal encapsulation of valve-train and injectors and, being the cover fully isolated from the cylinder head, the combustion energy transfer was much reduced (up to 2.5 dB sound pressure reduction with top engine side microphone measurement). In regards of the air path acoustic treatment an integral foam solution was used for a compact lightweight intake manifold noise barrier (delivering 1 to 1.5 dB sound power reduction at part load), while a fully encapsulated after-treatment...
system design was selected to further mitigate the noise emission and improve the engine sound quality. Furthermore, a high-pressure resonator was adopted to reduce the turbocharger hiss noise (air pressure insertion loss up to 12 dB in 2.5 kHz 3rd octave band), being a low pressure one already in place to keep the air induction noise under control (Figure 17).

Fig. 17 – High-density foam cam cover insulator, integral foam intake manifold shield and high-pressure T/C resonator

Additionally, the combustion noise requirements were properly set and controlled to deliver a balanced traded-off calibration in terms of emissions, fuel consumption and noise.

The intrinsic advantages of 6-cylinder inline architecture, together with the optimization above-described, allowed the new Duramax 3.0 ℓ diesel engine to achieve a remarkable mechanical noise (Figure 18).

Figure 18 – 4-sides averaged mechanical noise of new Duramax 3.0 ℓ diesel

In-vehicle Performance and Driving Characteristic

The combustion calibration concept developed for new 3.0 ℓ diesel Duramax includes two distinct modes:

1) Predominant combustion mode:
   • “Normal Mode”, active for ~80% of the life time;
2) Not Predominant combustion mode:
   • “Particle Filter regeneration”;
   • “Soft Warm-up” and “Strong Warm-up” for aftertreatment system.

The switching logic between them was optimized in order to enhance the performance of the aftertreatment system, for all driving and environmental conditions, as well as customer comfort.

The Normal mode combustion calibration setpoints are the output of an extensive DoE campaign on 18 key points, selected to cover all the engine operating points, with particular regard to the homologation cycles (Figure 19).

Figure 19 – Engine operating points on FTP75, Highway FET and SFTP US-06 cycles

Key combustion parameters (injection pattern, start of main injection, rail pressure, swirl, boost, EGR rate and swirl ratio) combinations have been experimentally tested to create model surfaces and optimize for fuel consumption, NVH, emission targets. The low engine-out soot emissions allow to achieve SCRF regeneration
interval of more than 500 miles in extra-urban driving. Particle filter regeneration is very effective in all driving and environment condition thanks also to the multi-after concept that make use of up to nine pulses allowed by ECM ([10]). The low oil dilution rate, optimized during calibration, together with low soot production and high regeneration efficiency permitted to reach high oil life, above the actual standard for customer expectation (7,500 miles).

An innovative after-treatment system warm-up strategy is used in order to increase after-treatment temperature almost independently from engine operating condition and maintain the system in its optimal temperature range, thus minimizing tailpipe emissions. After a cold start, the ‘Strong Warm up’ combustion mode is used to achieve rapidly DOC light off temperature, mainly thanks to the usage of multi-after injections. ‘Soft Warm-up’ combustion mode is then activated to achieve SCR optimal temperature range; the ‘Soft Warm-up’ combustion concept is very similar to that of Normal combustion mode. Thanks to the high heat rejection of the ‘Strong Warm-up’ mode in combination with the flexibility of the Active Thermal Management (ATM), it has been possible to meet another customer requirement, i.e. the cabin heater comfort, also in extreme environment condition.

It is important to highlight that without the contribution of ATM it would not have been possible to reach the high combustion efficiency and low pollutant emissions required by the severe US certification. The DoE were integrated with additional parameters like coolant temperature and minimum coolant flow, defined for each component in a dedicate development activity. The integration between ATM and calibration setpoint were optimized during cold start emission cycle performed run at high dynamic test bench before moving the final validation on vehicle. A representation of the achieved results with such a strategy is represented in the following Figure 20 related to the FTP75.

![Figure 20 – Selected engine and emissions parameters on ‘FTP-75’ cycle](image)

The figure can be divided into two main parts: the lower one reports a set of engine control and working parameters, whereas the upper one is focused on HC and NOx emissions that are most relevant for US certification.

It is very interesting to notice, under each operating condition, the capability of ATM circuit to control the engine warm-up at a fast rate and stabilize it at optimal levels. The same is true of the afttreatment system, with HC and NOx conversion efficiencies very close to 100% already after just ~180 s from a cold start. The high effectiveness of the active cooling and aftertreatment systems has enabled, in turn, an optimal combustion cycle, with MFB50 setting always in the best interval centered around 8 CA ATDC.
Conclusions and Summary

The new Duramax 3.0 ℓ diesel engine developed by General Motors represents a state-of-art propulsion system specifically tailored for the new generation of pickup trucks, combining performance, fun-to-drive, very low emissions and high fuel economy requirements of the next decade.

References

[1] IHS VPaC vehicles US 2018 H1 Database, IHS Markit Autoinsight, 2019