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July 15, 2019

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Assessment and Standards Division
Environmental Protection Agency
2000 Traverwood Drive
Ann Arbor, MI 48105

Mr. James Tamm
Office of Rulemaking
Fuel Economy Division
National Highway Traffic Safety Administration
1200 New Jersey Avenue, SE
Washington, DC 20590

Subject: The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021–2026 Passenger Cars and Light Trucks [Docket Nos. NHTSA-2018-0067 and EPA-HQ-OAR-2018-0283]

Dear Mr. Lieske and Mr. Tamm:

Toyota Motor North America, Inc. (Toyota) is submitting additional supplemental comments on the above-referenced Notice of Proposed Rulemaking (NPRM). The comments provide additional details and clarification on Atkinson-cycle engines in Toyota products and are organized as follows:

For the sake of brevity throughout the document, the term "agency" or "agencies" refer collectively to NHTSA and EPA. When referring to a specific entity, we do so by name, e.g. EPA and NHTSA.

We trust you will find these comments helpful in developing the final rule. Please feel free to contact me at (202) 775-1700 if you have any questions.

Sincerely,

Richard Gezelle, Jr.
Senior Program Manager
Product Regulatory Affairs
Toyota Motor North America, Inc.

Atkinson-Cycle Technology Definitions

The SAFE Final Rule needs to clarify the definition of Atkinson technology. The current definitions have been inconsistent which has created stakeholder confusion as evidenced by recent comments on the SAFE proposal. Starting with the draft Technical Assessment Report (TAR), the agencies have defined the two phases of Atkinson technology (HCR1/HCR2; ATK1/ATK2) both by whether the internal combustion engine is the sole source of motive power (versus being assisted by a hybrid electric architecture) and by the sophistication or effectiveness of the technology. The SAFE proposal takes the latter approach where:

- HCR1 is defined by the effectiveness of the 2014 Mazda 2.0L SKYACTIV engine with 13:1 compression ratio (CR), and
- HCR2 is defined by the simulated effectiveness of the 2014 2.0L SKYACTIV engine with the addition of cooled Exhaust Gas Recirculation (cEGR), 14:1 CR, and cylinder deactivation.[1]

The TAR also describes a "future non-HEV Atkinson cycle, referred to as Atkinson-level 2" which entails 14:1 CR, cEGR and a dual-coil offset (DCO) ignition.[2] The cost effectiveness for the combination of the Atkinson cycle, cEGR, and cylinder deactivation developed in the TAR is used to support both the Proposed Determination and original Final Determination.[3,4] The SAFE proposal does not consider these HCR2-level technologies.[5]

The 2018 Camry 2.5L Atkinson-cycle engine includes cEGR and therefore resides between the SAFE proposal's definitions for the HCR1 and HCR2 technology packages. The Final Rule should evaluate the cost effectiveness of proven and available technologies such as those on the 2018 Camry, as well as the ability of manufacturers to deploy them.

Engine Technologies Contributing to Camry Efficiency

Past Toyota comments on Atkinson-cycle benefits have addressed only those derived from variable valve timing (VVT) with late intake valve closing (LIVC) that enables a 13:1 compression ratio. The total 18.6 percent improvement of the 2018 Camry 2.5L over the

[1] Preliminary Regulatory Impact Analysis (PRIA) The Safer Affordable Fuel-Efficient Vehicles Rule for Model Year 2021 – 2026 Passenger Cars and Light Trucks; Pgs. 302-303.
[2] Draft Technical Assessment Report (TAR), Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025; Pg. 5-282.
[3] Final Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation, Response to Comments; Pgs. 29 & 52.
[4] Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation; Pgs. 22 & A-7.
[5] The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021–2026 Passenger Cars and Light Trucks; Pg. 43038.

previous generation also includes benefits from cEGR and internal engine design changes such as to the block, cylinder head, pistons, valvetrain, as well as drivetrain and body/chassis enhancements.

Atkinson-cycle operation is just one of several measures responsible for the 2.5L Dynamic Force engine achieving a world-best 40 percent thermal efficiency. The Late Intake Valve Closing (LIVC) of the Atkinson cycle reduces low-load pumping losses and supports the 13:1 CR by suppressing engine knock. However, the engine's increased stroke-to-bore ratio (S/B ratio) and improved cooling, engine warmup, friction reduction, and exhaust system play an equally important role. For example, the 1.18 S/B ratio preserves stable combustion under high EGR flow rates which improves thermal efficiency as much as the longer effective expansion ratio from the Atkinson cycle. The increased S/B ratio also compliments intake port, valve timing (VVT-iE) and piston enhancements resulting in greater tumble intensity of the charge-air intake, higher speed combustion, and increased thermal efficiency. Greater detail on factors contributing to the thermal efficiency of the 2018 Camry 2.5L engine can be found in Toyota SAE paper 2017-01-1021 contained in Appendix 1 of this submission.

Toyota supports the agencies informing the Final Rule with the latest credible data. Final rule analyses should consider not only the much-discussed Atkinson architecture, but also the basic internal design advancements that contribute to the 2018 Camry's significant improvement. The Final Rule should identify as much as possible the costs and benefits for these technologies individually and as packages.

Comparing Camry and Tacoma Atkinson Performance

Toyota reiterates it is currently not possible for the 2016-2018 Tacoma pick-up truck to approach either the level of Atkinson-cycle operation or the fuel economy and CO_2 performance of the 2018 Camry. ICCT asserts that Atkinson-cycle operation for Tacoma and Camry should be similar because the normal operating load experienced by the Tacoma 3.5L engine should be similar to the Camry 2.5L engine.[6]

Tacoma and Camry require different basic engine designs which have different emissions and fuel economy characteristics. The Atkinson-cycle in Toyota products operates continuously at various levels of LIVC depending on conditions. Toyota uses the achieved geometric CR to loosely describe the level of Atkinson operation for a given engine application and design. To achieve the proper balance between engine efficiency and power, the level of Atkinson

[6] Supplemental Comment of the International Council on Clean Transportation (ICCT) on the National Highway Traffic Safety Administration's and Environmental Protection Agency's Proposed Rule: The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021–2026 Passenger Cars and Light Trucks, 83 Fed. Reg. 42,986; Pg. 4.

operation, i.e. CR, declines as a vehicle's Power-to-GCWR (Gross Combined Weight Rating) ratio increases as seen in Table 1 below.

Table 1 – Power-to-GCWR Ratio Impact on Atkinson Design Level (CR)

Model	Displ.	CR	HP	GCWR (lbs)	HP to GCWR
2018 Camry	2.5L	13:1	203	4,475	1:22.0
2018 Tacoma	3.5L	11.8:1	278	11,360	1:40.9

Note: Toyota Camry is not designed for trailer towing or for the use of tow hitch mounted carriers. Therefore the Gross Combined Weight Rating (GCWR) for Camry is the Gross Vehicle Weight Rating (GVWR).

While increased S/B ratio and the Atkinson cycle are key to 2018 Camry 2.5L efficiency, both reduce power density. The reserve power required for Tacoma's 11,360 lb. GCWR and 6.700 lb. maximum towing dictate a lower S/B ratio (0.88) and CR (11.8:1). Atkinson behavior for Camry and Tacoma may be similar over the FTP, but Tacoma's lower design level of Atkinson operation (11.8 CR versus 13 :1 CR for Camry 2.5L) results in lower efficiency compared to Camry. That said, Tacoma 3.5L is a highly efficient engine as explained in previous Toyota comments.[7]

Camry Performance Against GHG/CAFE Targets

Toyota agrees that the 2.5L Camry L configuration can technically reach its 2025 model year CAFE targets with a theoretical maximum application of off-cycle credits. Toyota's March 25, 2019 supplemental comments focus on the GHG standards because they are typically more stringent than the CAFE standards even with the addition of GHG-only credits. Toyota's off-cycle credits accounted for the upper limit of menu technologies (10.0 g/mi), air conditioning (AC) refrigerant/leakage (13.8 g/mi), and AC efficiency (5.0 g/mi) but did not include the on-cycle benefit from Start-Stop technology.[8] Based on Toyota's certification data, ICCT's suggested 3% on-cycle benefit combined with 28.8 g/mi of credits reduces Camry L CO2 from 188.6 g/mi to 154.1 g/mi which is 1.5 g/mi below the 155.6 g/mi target for the 2025 model year. (See Figure 1 below).

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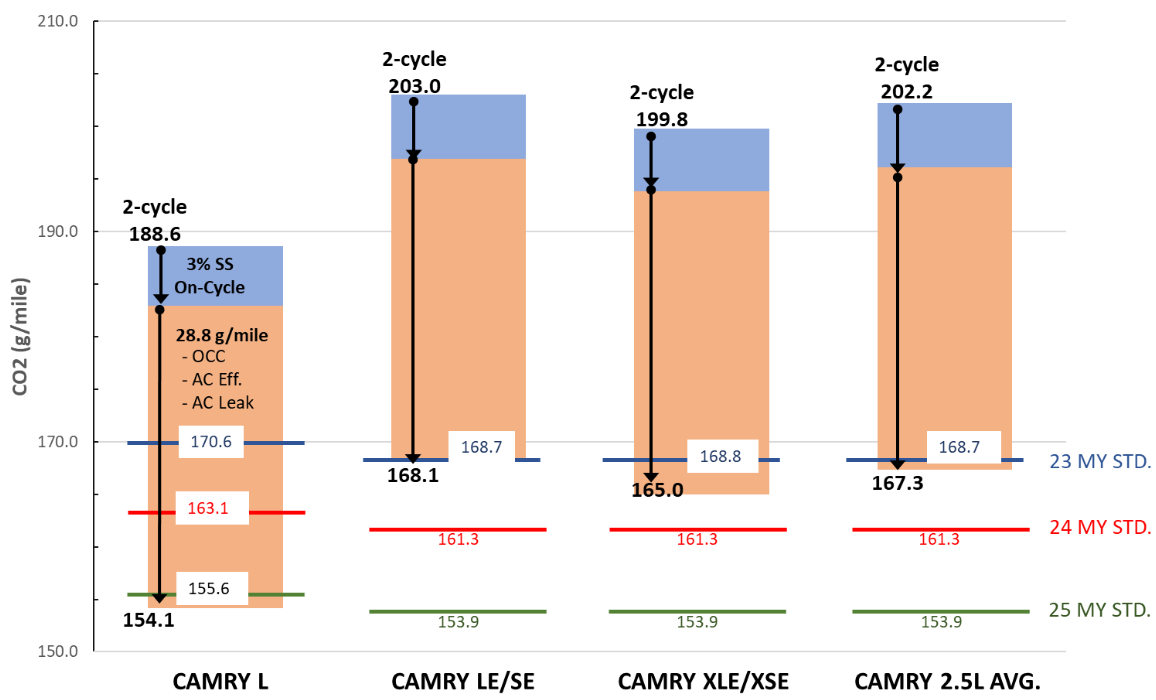
[7] Supplemental Comments of Toyota Motor North America, Inc., Notice of Proposed Rulemaking: Safer Affordable Fuel-Efficient Vehicles Rule, Docket ID Numbers: NHTSA-2018-0067 and EPA-HQ-OAR-2018-0283; Pgs. 7 & 8.

[8] It appears ICCT adjusted the fuel economy value for start-stop (SS) technology after applying credits whereas the adjustment should be applied directly to the two-cycle results. The result is an overestimated on-cycle SS benefit.

Figure 1 – 2018 Camry 2.5L Theoretical Performance



The Camry L just attaining its 2025 model year targets with the maximum deployment of off-cycle technologies does not represent overall Camry performance which only meets its 2023 target after the application of maximum off-cycle credits.

ICCT justifies selection of the Camry L as being the only 2018 model year configuration that matches the 3,500 lb. Equivalent Test Weight (ETW) of the 2015 Camry 2.5L serving as the study's baseline vehicle. ICCT contends that the 2015 Camry 2.5L consists of a single configuration and that Toyota introduced the heavier, less efficient (LE/SE and XLE/XSE) configurations for 2018 model year.[9]

The 2015 Camry 2.5L comprised only the LE with a 3,500 lb. ETW. As standard features for all Camry configurations (LE, SE, XLE, XSE) have increased, so have curb weight and ETW. The 2018 LE increased to a 3,625 lb. ETW. The only new 2018 Camry configuration is the L which foregoes certain standard features found on the other configurations to further reduce road load and improve fuel economy and CO2 performance.

[9] Supplemental Comment of ICCT; Pg. 5.

Camry L de-contenting includes a Prius-like 14.5-gallon fuel tank, non-folding rear seats, manual seat adjustments, and smaller wheels with more narrow tires as seen in Table 2.

Table 2 – Comparison of Camry L and LE

Model Year	2015 LE	2018 LE	2018 L
Fuel Economy (cty/hwy/cmb)	**25/35/28**	**28/39/32**	**29/41/34**
	Weight and Capacity		
Curb Weight (lb)	3240	3296	3241
Estimated Test Weight	3500	3625	3500
Fuel Capacity (gal)	17	16	14.5
	Chassis and Body		
Tire Size	P205/65 R16	P215/55 R17	P205/65R16
Wheel Size	7.0 x 16 in	7.5x17in.	6.5x16 in.
Wheel Material	Steel	Alloy	Steel
Footprint	47.5	48.5	48.7
	Interior		
Front Seat	8 way power driver seat	8 way power driver seat	6-way manual driver's seat
Rear seat	60/40 fold down	60/40 fold down	No folding rear seat

While these measures preserve the 3,500 lb. ETW rating for the L configuration, there are tradeoffs affecting the customer driving experience. For example, moving from a 16 to 14.5-gallon fuel tank reduces vehicle refueling range from 512 to 493 miles. The loss of the 60/40 folding rear seat sacrifices one cubic foot of expanded cargo carrying capability and the ability to store long items into the main cabin both of which could push some customers to an SUV or pick-up truck. This less expensive eco-configuration allows us to gauge customer willingness to tradeoff certain features for improved fuel economy. Table 3 shows Camry L sales comprise just over one percent of total Camry sales and only 16 percent of Camry hybrids sales providing insight into factors that contribute to the overall value proposition for our Camry customers.

Table 3 – 2018 Camry Sales by Configuration

	LE/SE	XLE/XSE	Hybrid LE/SE/LXE	L
MSRP (2019)	$24,600/$25,800	$29,175/$29,725	$28,400/$30,100/$32,975	$24,095
Sales (2018)	300,703	71,687	27,513	4,442
% Total Sales	74.4%	17.7%	6.8%	1.1%

Additional Camry Improvement

Regarding the LE/SE and XLE/XSE configurations, ICCT believes that because Toyota improved the fuel efficiency of the 2018 Camry by almost 19 percent over the prior generation model, we should easily be able to close their estimated remaining 7 percent gap to the 2025 model year standards.[10]

The completely redesigned 2018 Camry embodies a package of technologies the agencies have identified as one general path toward 2025 model year compliance. Using Toyota GHG certification data, actual 2-cycle performance falls short of the 2025 model year targets by about 24 percent for the LE/SE and 23 percent for the XLE/XSE. If additional investment is made in off-cycle technologies, the shortfalls can be reduced to 8 percent for the XE/LE and 7 percent for the XLE/XSE.

The deployment of off-cycle technologies as well as additional road load reductions and cylinder deactivation are being characterized by some as low hanging fruit that should have been implemented with the 2018 Camry redesign and can easily be implemented now. The path to 2025 MY is much more constrained by the reality of design cycles, product cadence (especially involving global platforms), and available resources.

As we have explained in our past comments, bringing a new or redesigned vehicle to market is typically a several-year, capital-intensive undertaking. Technology costs, engineering resources and experience, manufacturing capabilities, as well as customer preferences dictate the level of improvement a manufacturer can achieve in any one redesign and still have an affordable product that customers want. These aspects vary by manufacturer and product. No manufacturer has the resources to be the expert or leader for every technology. Once new designs are introduced, a period of stability is required so investments can be amortized. Vehicle and technology introductions are staggered over time to manage limited resources. Technology sharing and inheritance between vehicle models tend to limit the rate of improvement in a manufacturer's fleet. Agency modeling now better recognizes these realities.

Applying a typical 5-year design cycle would result in a potential full redesign of the 2018 Camry no sooner than model year 2023. Similarly, vehicle platform and powertrain redesigns typically cycle about 10 years or more which means substantive mass reduction and engine/transmission improvements for the 2018 Camry are not likely happen before the 2025 model year.

Less substantive improvements can continue during a design cycle. Reduced rolling resistance, minor lightweighting, and aerodynamic improvements are possible, but are unlikely to warrant further engine downsizing which must be performed judiciously to manage the number of engine configurations within a vehicle platform. As explained in the section below, cylinder deactivation provides insufficient benefit to the 2018 Camry 2.5L Atkinson engine considering the cost of the technology.

[10] Supplemental Comment of ICCT; Pgs. 7 & 8.

Given, every vehicle cannot be improved at the same time, there is greater benefit to the manufacturer, its customers, and the environment in improving lower performing vehicles in the fleet rather than chase diminishing returns from fuel economy leaders like the current Camry.

Modeling of Camry Atkinson Technology

ICCT Study

ICCT has commented that because Toyota did not question their study's conclusion about the Lump Parameter Model (LPM) and OMEGA model our "silence affirms the ICCT's conclusion, and reinforces that OMEGA is a reliable framework to assess the impacts of the regulation."[11] Toyota's March 25, 2019 supplemental comments were only intended to inform the appropriate representation of Atkinson-cycle fuel economy and emissions performance in Toyota products.

Toyota comment on the efficacy of the OMEGA and LPM models is unnecessary. First, Toyota's position has been clearly represented by comments previously submitted by the Alliance of Automobile Manufacturers, Global Automakers, and Novation Analytics. Those comments identify the LPM and OMEGA models as sources of inaccuracy in EPA technology evaluations and provide suggested improvements. Neither model is transparent, intuitive, or user friendly. To improve modeling accuracy, EPA is replacing the LPM with the Response Surface Model.

Second, a study limited to one modeling run of one vehicle configuration that required post-run adjustments offers no statistically valid insight or conclusions. In contrast, the Novation fleet analyses encompass the entirety of the 1,543 vehicles representing all light-duty vehicles sold in the U.S. market for the 2018 model year (this includes all models/configurations/powertrains) and require no post simulation adjustments. Adjustments in the ICCT study were necessary because the modeling run applied to a 2025 powertrain comprising technology optimization and improvements beyond those incorporated in the actual 2018 Camry. We have already commented that ICCT's adjustment of the CO2 results for increased vehicle performance is unwarranted because the 2015 and 2018 Camry 2.5L engines have nearly equivalent performance using EPA's metrics (30-50 mph, 0-60 mph, 50-70 mph passing, and ¼ mile). It's not clear whether an adjustment for a cold start strategy is necessary because the 2018 Camry employs a new strategy for faster engine warmup. We have not closely evaluated ICCT's adjustment for engine compression ratio.

Finally, simulation of Atkinson technology effectiveness for the Final Rule seems less necessary if cylinder deactivation, 14:1 CR, and DCO are not included in the Atkinson technology packages. Compliance modeling for the Final Rule should emphasize the cost effectiveness of

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[11] Supplemental Comment of ICCT; Pg. 2.

all proven and available technologies, and the ability of manufacturers to deploy them. As mentioned previously, technologies embodying the 2018 Camry should be included.

EPA Benchmarking

EPA recently published an SAE paper benchmarking the 2018 Camry with the 2.5L Atkinson-cycle engine. We look forward to discussing details with EPA to better understand the benchmarking activity. For now, the laboratory-based testing methods appear appropriate. We have not fully evaluated the details of how EPA acquired data such as for cEGR and valve timing during the testing. The resulting Atkinson Ratio (AR) as a utilization metric is interesting and potentially insightful. We caution that a higher (AR) does not necessarily correlate to higher efficiency performance because the Atkinson cycle is just one contributor. For example, the paper correctly notes the Camry 2.5L uses less Atkinson (or more advanced LIVC) compared to a non-EGR Atkinson-cycle engine because cEGR reduces pumping losses like the Atkinson-cycle and because there are times when a trade-off between cEGR flow rate and Atkinson LIVC may be necessary.[12]

We need more information on the "futuring" of midsize exemplar vehicles that were constructed from the Camry 2.5L engine map generated during the benchmarking. As EPA acknowledges, neither the 2018 nor 2025 exemplar vehicles represent actual Camry performance. Alpha simulations intended to represent the 2018 Camry include start-stop technology which is not equipped on Camry. Holding the performance of a 2013 2.5L baseline engine constant through the 2025 model year may help isolate the contribution of individual technologies to overall exemplar vehicle emissions but taken from a compliance perspective runs counter to market viability as Toyota has explained in past comments.[13]

In the SAE paper, EPA adds cylinder deactivation to the hypothetical 2025 exemplar vehicle as a potential enhancement. Toyota acknowledges adding cylinder deactivation to Atkinson-cycle engines is technically possible and would provide some fuel economy and CO2 benefit. However, the primary function of cylinder deactivation is to reduce engine pumping losses which the Atkinson cycle and EGR already accomplish on the 2018 Camry. The overlapping and redundant measures to reduce engine pumping losses would add costs with diminishing efficiency returns.

The 2.5L Camry engine map from benchmark testing is downsized to a 2.0L displacement based on assumed reductions in exemplar vehicle mass (7.5 percent), rolling resistance (10 percent), and aerodynamic drag (10 percent). The suggested level of mass reduction would need to occur during a platform redesign after the 2025 model year. Even if such aggressive road load

[12] Kargul, et al., Benchmarking A 2018 Toyota Camry 2.5-Liter Atkinson Cycle Engine with Cooled-EGR, SAE International, April 2, 2019; Pg. 11.
[13] Supplemental Comments of Toyota Motor North America, Inc., Pg. 5.

reductions were feasible, we see limited opportunities for successful deployment of cylinder deactivation in a midsize vehicle powered by a 2.0L engine already managing the power density limitations of the Atkinson-cycle, 13:1 CR, and 1.18 S/B ratio. We believe this is an example of simulated technology integration resulting in a vehicle that would be difficult to market to our customers.

Feasibility of the Standards

ICCT states the 2018 Camry configuration it studied "validates that existing technologies are sufficient to meet the current MY 2025 standards while maintaining constant (and in fact improving) vehicle performance" and that "EPA's existing standards are eminently feasible".[14]

Applying maximum off-cycle credits to the 2018 2.5L Camry L proves that as of today only the de-contented eco-configuration from one of the most efficient mid-size vehicle models on the market can theoretically reach its 2025 model year target. It provides no evidence of the entirety of the 2018 Camry model reaching its 2025 model year targets, much less the compliance of the Toyota or overall U.S. fleets.

Camry hybrid sales are six times greater than the Camry L. If market acceptance is not a component of feasibility, NHTSA and EPA could have pointed to hybrid vehicles and other electrified powertrains to demonstrate feasibility of the CAFE and GHG standards finalized in 2012. Neither the TAR, Proposed Determination, nor the original Final Determination have taken that approach.

Instead, all feasibility evaluations and determinations have assumed a predominate mix of conventional gasoline powertrains in the U.S. market recognizing the challenges electrified powertrains face. Up through the original FD, EPA insisted manufacturer compliance could be achieved through 2025 model year with minimal electrification. The SAFE rule now proposes the standards be adjusted because conventional gasoline technologies are not meeting expectations.

One indicator of conventional gasoline technologies not meeting earlier modeling projections is the current over-emphasis on off-cycle technologies for compliance. After applying 28.8 g/mi of off-cycle credits, the 2018 Camry 2.5L on average still falls 8 percent short of the 2025 model year targets. The 2012 Final Rule projected considerable less reliance on off-cycle flexibilities.[15]

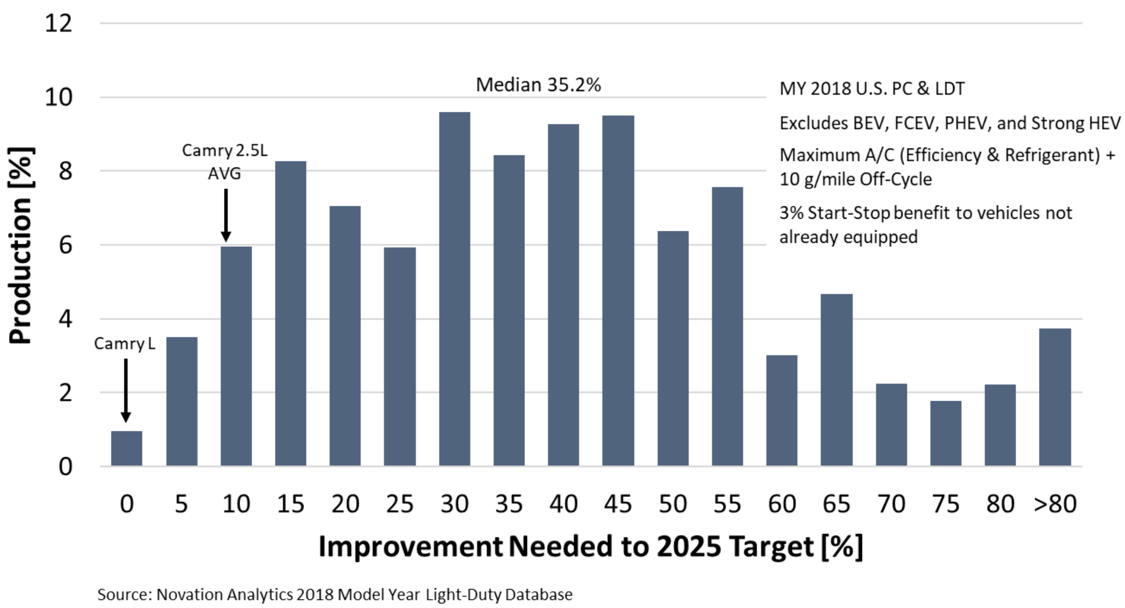
Off-cycle technologies are an important path to real environmental benefits; however, manufacturers generally would prefer not to rely so heavily upon the intended flexibility for compliance because most of the technologies provide little tangible value proposition for

[14] Supplemental Comment of ICCT; Pgs. 5 & 8.
[15] 77 Fed. Reg. at 62771 (TABLE III–1) estimates passenger cars fleetwide generating 20.2 g/mi of credits by the 2025 model year.

customers. It's a compliance investment necessitated by conventional gasoline engine technologies failing to meet previous agency modeling expectations.

Ultimately, feasibility will be determined by the performance of the US fleet, and not one configuration of one vehicle model. Figure 2 below illustrates that the GHG performance of the 2018 Camry L is in the top one percent of the U.S. fleet and the average of all 2.5L Camry configurations is in the top six percent. While the Camry's remaining compliance path will be challenging, it's relative proximity to the 2025 model year targets provides limited value in assessing feasibility of the standards across the entire U.S. vehicle fleet.

Figure 2 – MY 2018 Model Type GHG Improvement Needed to Meet 2025 Targets



Summary and Conclusion

Toyota recommends the definitions describing Atkinson-related technologies be clarified and include technologies such as VVT-iE and cEGR recently introduced with the 2018 Camry 2.5L. There is more to Camry's performance than the Atkinson-related technologies. Supporting agency analyses should also consider enhancements to the basic engine design (cylinder head, valves, S/B ratio, etc.) that are responsible for most of the fuel economy and GHG improvement over the previous generation Camry.

Atkinson technology is sufficiently represented in today's U.S. fleet so that appropriate standards over the next several years can be informed by actual vehicle technology performance rather than extensive projections from simulation.

Feasibility comprises more than a given set of technologies attaining CAFE and GHG targets under unrealistic conditions. The 2012 Final Rule standards warrant adjustment not because of a lack of technology, but because the technologies capable of meeting the standards are not being purchased by consumers in the volumes required for compliance especially with continued low fuel prices and a preference for light-duty trucks. Conventional gasoline engines have not met the performance expectations from earlier modeling particularly when considering customer requirements (cost, power, weight-adding options, etc.) that erode optimal fuel economy and normal business considerations that govern the pace of technology deployment.

Toyota supports standards that achieve annual fuel economy improvements midway between the existing standards and the preferred path in the SAFE proposal along with flexibilities that promote advanced technology for the sake of long-term environmental gains.

SAE INTERNATIONAL®

The New Toyota Inline 4-Cylinder 2.5L Gasoline Engine

2017-01-1021
Published 03/28/2017

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CITATION: hakariya, M., Toda, T., and Sakai, M., "The New Toyota Inline 4-Cylinder 2.5L Gasoline Engine," SAE Technical Paper 2017-01-1021, 2017, doi:10.4271/2017-01-1021.

Abstract

In order to adapt to energy security and the changes of global-scale environment, further improvement of fuel economy and adaptation to each country's severer exhaust gas emission regulation are required in an automotive engine.

To achieve higher power performance with lower fuel consumption, the engine's basic internal design such as an engine block and cylinder head were changed and the combustion speed was dramatically increased. Consequently, stroke-bore ratio and valve layout were optimized. Also, both flow coefficient and intake tumble ratio port were improved by adopting a laser cladded valve seat.

In addition, several new technologies were adopted. The Atkinson cycle using a new Electrical VVT (Variable Valve Timing) and new combustion technology adopting new multi-hole type Direct fuel Injector (DI) improved engine power and fuel economy and reduced exhaust emissions. Variable cooling system with an electric water pump and Flow Shut Valve (FSV) improved fuel economy by reducing warm-up time and mechanical losses. Also, a newly developed variable oil pump has significantly reduced friction losses.

By implementing these new technologies, the new naturally aspirated 2.5L gasoline engine achieved over 40% thermal efficiency and over 150kW engine power. In combination with a new 8 speed Automatic Transmission, fuel consumption was reduced by over 16%.

Introduction

For future energy and environmental issues, it becomes more and more important to realize a sustainable society. CO2 must be reduced and additional fuel economy improvement is needed for all engines.

In addition, future engines need clean exhaust gas emissions to meet not only the more severe regulation of various countries, but also European PN (Number of Particulate) regulations.

On the other hand, it is a universal fact that the importance of high performance and superior drivability is needed to realize "fun-to-drive" that exceeds the customers' expectation.

To meet this challenge, incremental improvements to the engine are not enough. So, it is necessary to redesign of the basics such as stroke-bore ratio and valve layout. The new engine based on new TNGA (Toyota New Global Architecture) architecture was developed [1,2,3].

In recent years, we made efforts in Thermal Efficiency improvement and achieved 40% of Thermal Efficiency of the world TOP in the engine for the hybrid vehicle.

However, in order to achieve the higher target of Thermal Efficiency, we paid our attention to a particularly high-speed combustion technology for various loss reduction. We must achieve not only the improvement of fuel economy but also the performance at a higher level.

Figure 1 shows the trend and new engine's target of the specific power and thermal efficiency. The performance target of maximum thermal efficiency of HEV (hybrid vehicle) was set at 41%. Even though this is a conventional engine, the target was set at 40%. This is the same as the one achieved by 2ZR-FXE (New Prius [4]), and the target of the specific power is set at 60kW/L and higher in order to bring customers more joy from driving.

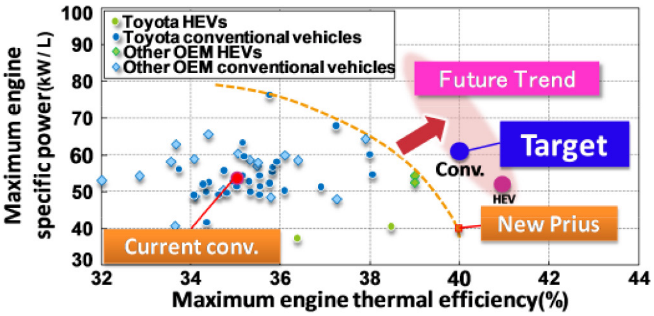


Figure 1. Trend and new engine's Target of Specific Power and Thermal Efficiency

This new naturally aspirated inline 4 cylinder 2.5L gasoline engine is the first mass produced TNGA engine to realize these targets.

Engine Overview

In order to achieve 40% of Maximum Thermal Efficiency and 60kW/L of Specific Power, High-Speed combustion package that can achieve high tumble ratio and flow coefficient has been developed.

Furthermore, we implemented new devices such as Motor-Driven VVT-iE (Variable Valve Timing) that uses an Atkinson cycle, a new D-4S system (Direct Injection & Port Fuel Injection) with a new multi hole fuel injector, cooled EGR (Exhaust Gas Recirculation) system, cooling system with heat management, electronic variable capacity oil pump and high energy ignition coil.

Table 1 shows the comparison of the main specification between the current 2AR-FE engine and the new 2.5L engine.

Table 1. Specification of new 2.5L engine

Engine	for conventional	
	New	2AR-FE
Engine Type	Inline-4cyl	←
Displacement [ml]	2487	2494
Bore×Stroke [mm]	Φ87.5×103.4	Φ90×98
Compression ratio	13	10.4
Max. power(kW/rpm)	151/6600	132.7/6000
Max. torque(Nm/rpm)	250/5000	230.5/4100
Valve system	DOHC 4 valves per cylinder HLA+Roller rocker	←
	IN:VVT-iE (Motor-Driven) EX:VVT-i	Dual VVT-i
Lubrication system	Variable controlled oil pump	Conventional
Cooling system	Motor-Driven W/P	Belt-Driven W/P
EGR system	Cooled EGR	-
Fuel injection system	D-4S (multi hole DI +PFI)	PFI
Emission ctrl. system	2CAT × 2A/F	2CAT × A/F+O2

High-Speed Combustion Technologies and Engine Basic Structure

Combustion Concept and Target

The most suitable base specification of the compression ratio (ε), the stroke and bore ratio (S/B ratio) were studied at the beginning of the engine development to achieve higher thermal efficiency and specific power.

Figure 2 shows computational fluid dynamics (CFD) analysis regarding the effect of S/B ratio for a constant displacement. It shows Effect of S/B ratio on combustion characteristics and engine specifications.

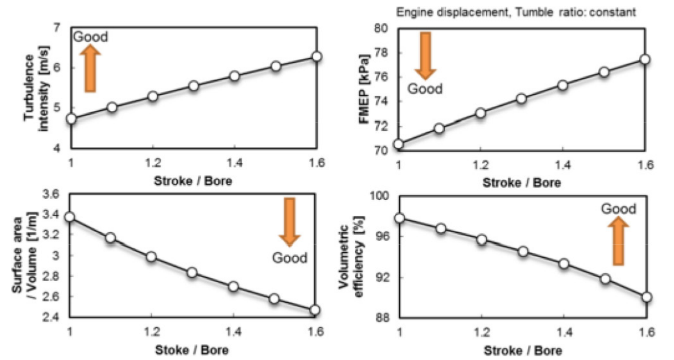


Figure 2. Effect of stroke / bore on combustion characteristics and engine specifications

Turbulence intensity which is significant for high speed combustion is higher with increasing S/B ratio (upper left graph on Figure 2). The reason is that a stroke of a piston becomes longer under the same displacement, so incoming flow gets higher speed under high piston speed.

But friction deteriorates with increased piston speed and so the thermal efficiency reduces. In addition volumetric efficiency is important especially for NA engine in terms of maximum specific power and it deteriorates by increasing S/B ratio due to smaller bore diameter leading to smaller valve diameter.

For these reasons, it is important to select an appropriate S/B ratio to achieve a good balance of thermal efficiency and specific power.

Figure 3 shows the analysis results for the effect of S/B ratio and compression ratio on thermal efficiency and specific power using a 1D model that is validated with experimental data.

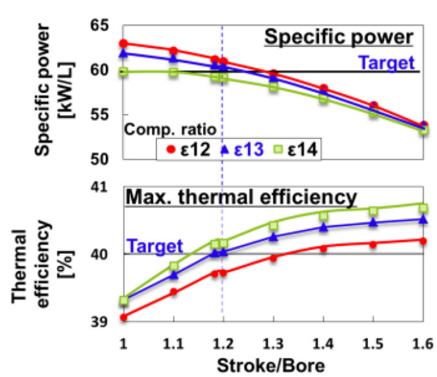


Figure 3. Effect of S/B ratio on engine performance

At S/B ratio of 1.0, maximum thermal efficiency saturates at around ε13.0 (lower on Figure 3). This is because the amount of EGR is limited by combustion instability, so knocking becomes a limiting factor to improve efficiency by increasing compression ratio. By increasing S/B ratio, EGR limit is extended due to enhanced combustion stability, so thermal efficiency improves, and the optimal compression ratio for maximum thermal efficiency also changes.

Specific power shows different trend for each compression ratio due to mutual effect of specific power and volumetric efficiency. If compression ratio is increased, power reduces even for smaller S/B ratio with larger valves (upper on Figure 3).

S/B ratio of roughly 1.2 is optimal, and ε13.0 is estimated to achieve the target maximum thermal efficiency of 40% and specific power of 60kW/L.

Figure 4 is the calculation result of turbulence intensity needed for 40% thermal efficiency. Requirement for turbulence intensity is 5.6m/s, and this can expand EGR limit up to 25%.

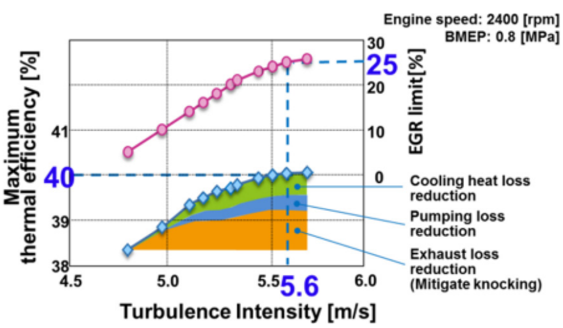


Figure 4. Estimated necessary turbulence intensity (estimated by CFD)

Combustion Design

Firstly, in order to realize the basic concept of high speed combustion, the factors affecting in-cylinder turbulence intensity were studied. Figure 5 shows the time-history of transient tumble ratio and turbulence intensity and the combustion specifications using the CFD results.

Transient tumble ratio has the peak A, caused by the incoming flow from the port during intake stroke. After that, it leads to peak B during compression stroke while forming tumble flow, and then starts to decay toward TDC. On the other hand, after transient tumble reached the peak B, turbulence intensity reaches peak C, caused by the conversion of tumble flow into turbulence due to compression, and then reaches D toward TDC.

Based on the past experiments and CFD results, it is known that the values of A~C are determined by the engine specifications shown in the boxes in Figure 5.

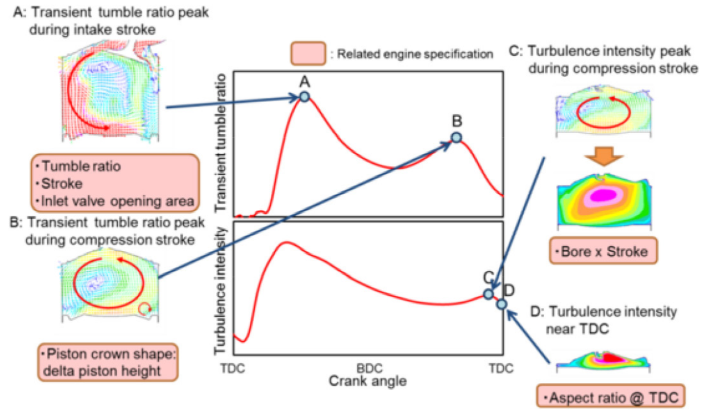


Figure 5. In-cylinder flow characteristic and related engine specification

It is apparent that tumble ratio alone has strong correlation with turbulence intensity, but its prediction accuracy is roughly ±0.23 [m/s] under the same tumble ratio (upper on Figure 6). It is necessary to make it clear by what kind of specification it can be achieved.

When the new method with additional parameter in Table 2 is used, prediction accuracy improves to ±0.06 [m/s] significantly (lower on Figure 6).

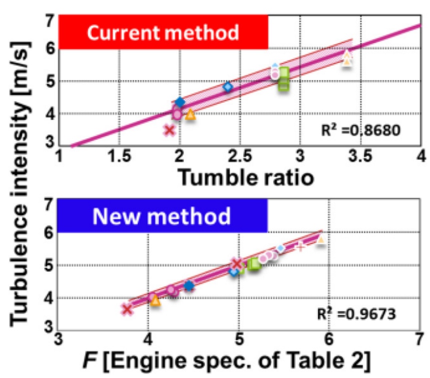


Figure 6. Prediction accuracy comparison of turbulence intensity

Values in Table 2 show each specification required to achieve 5.6m/s turbulence intensity using the new method for the conventional in-line 4cyl. 2.5L engine.

Table 2. Parameters in formula prediction and optimal results

Stroke/ Bore	1.18
Tumble ratio	2.8
Intake valve opening area [mm^2*CA]	1720
Aspect ratio @ TDC	0.18
Delta piston high [mm]	3.7

Cylinder Head (Intake port) Design

As mentioned previously, tumble ratio of 2.8 is required. On the other hand, based on the specific power requirement 60kW/L, volumetric efficiency at the maximum power condition need 92% and flow coefficient of 0.48 is required to achieve. Figure 7 shows target of port performance.

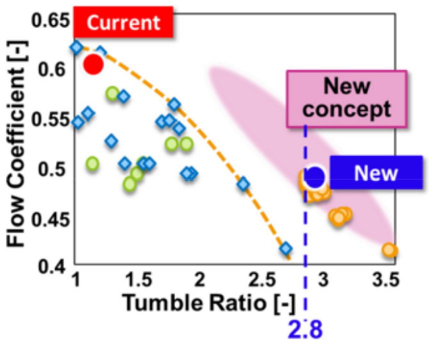


Figure 7. Target of port performance for 2.5L conventional engine

The high tumble ratio and the high flow coefficient are contradicting demands. Intake port design such as valve layout was completely changed in order to meet these demands.

Press-fitting valve seat type needs thickness valve seat to water jacket. Therefore, valve diameter and side flow are restricted from free design. Laser-cladded valve seat can increase intake valve diameter, widen angle between intake and exhaust valve. As a result, we can linearize the intake flow to cylinder inside of intake port.

Laser-cladded valve seat is molded with the cylinder head directly by laser using cladding powder based on copper (Figure 8). In order to meet the various world-wide markets, a new material that has high wear resistance has been developed for alternative fuel.

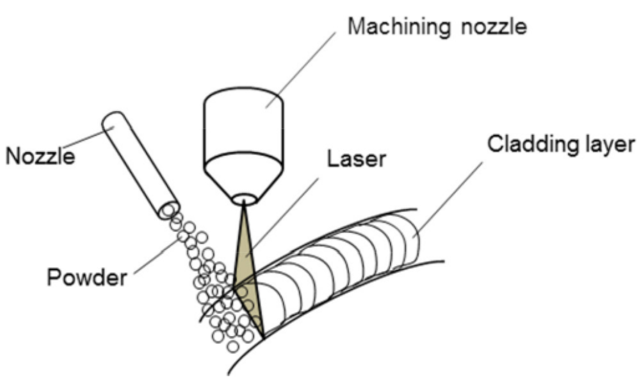


Figure 8. Laser cladded valve seat

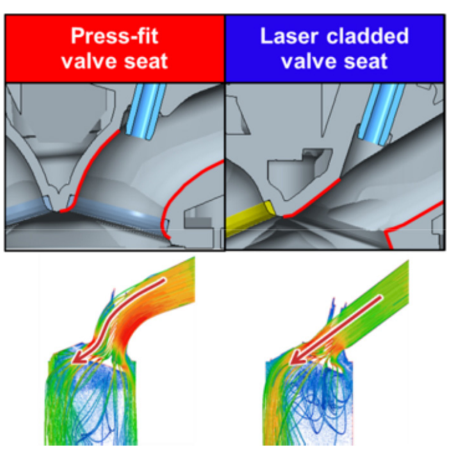


Figure 9. Comparison of intake port

Figure 9 shows the comparison of cross section of intake port between current type and new one. The separation air flow from cylinder was reduced. As a result of this optimization, the tumble ratio of 2.89 and flow coefficient of 0.487 were achieved.

Combustion Chamber design

New D-4S system was developed in order to improve thermal efficiency and confirm specific performance by knock mitigation under high compression ratio.

In consideration of the future PN (Number of Particulate) regulation, new multi-hole injector with low penetration was developed to reduce fuel wet to piston and wall surface.

The new piston was redesigned to keep a high tumble flow. Figure 10 shows the comparison of the current D-4S piston crown and the new D-4S piston. For spray design using high tumble air from high efficient port, spherical-shaped combustion chamber shape was implemented to keep a high tumble flow.

And Figure 10 also shows the CFD results of these two pistons. It is apparent that the new D-4S piston shape allows incoming flow into cylinder during intake stroke without obstruction and reaches high tumble peak. As a result of this, it contributed to the stability of combustion.

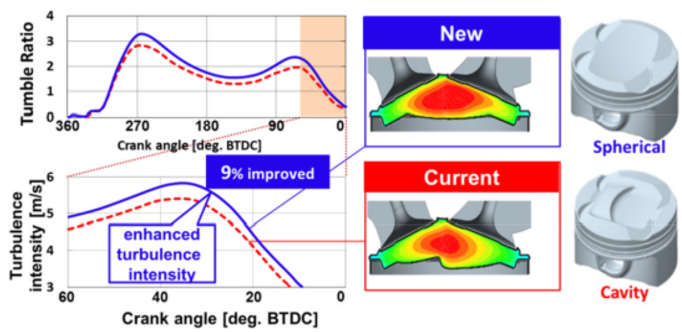


Figure 10. Comparison of tumble ratio between old and new piston

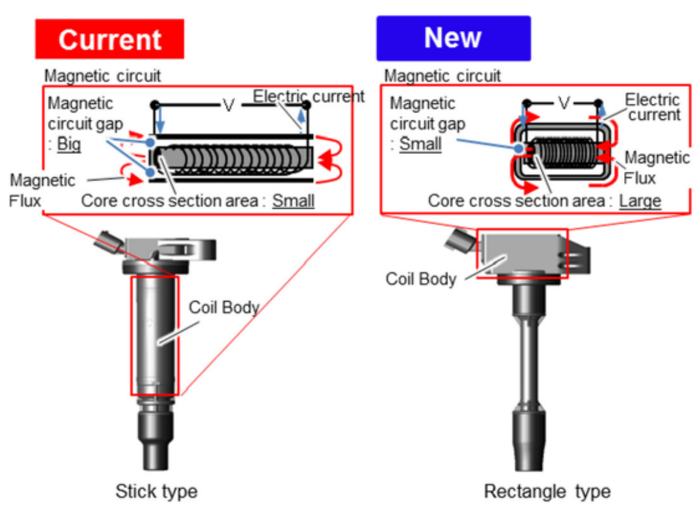


Figure 11. High energy ignition coil

Furthermore, in order to confirm the combustion stability under a high EGR (Exhaust Gas Recirculation) rate and tumble ratio, a high energy ignition coil was implemented. It is made by reducing the Magnetic Circuit gap and by enlarging the cross section area of the core (Figure 11).

By implementing these items, stable combustion could be achieved under 23% EGR ratio and the target Maximum Thermal Efficiency 40% with an actual engine.

Optimization of gas exchange (Valve train system)

As well as performance, appropriate valve timing is important to plan fuel efficiency improvement in the whole driving condition. This section describes the air volume control including valve timing.

It is important to decide intake-side work angle on the balance of fuel economy and performance. Cam profile cannot be enlarged because of decreasing of volumetric efficiency from returning gas flow to intake port especially at the range from low to middle engine speed.

Like as current model, roller follower with Hydraulic Lush Adjuster (HLA) was implemented. In order to increase the time-area of intake side, machining of the cam extended cam lift profile. Figure 12 shows the comparison of valve timing and lift. It can enlarge the work angle from the current model.

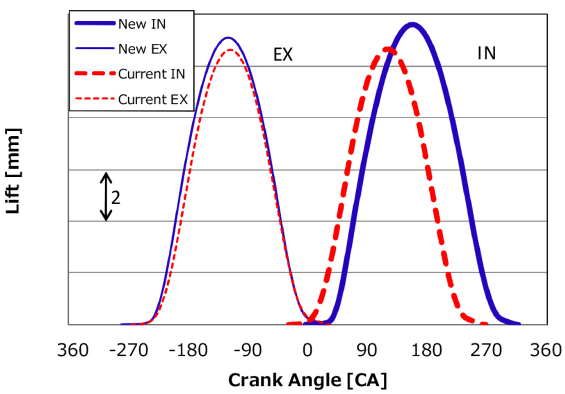


Figure 12. Comparison of valve timing

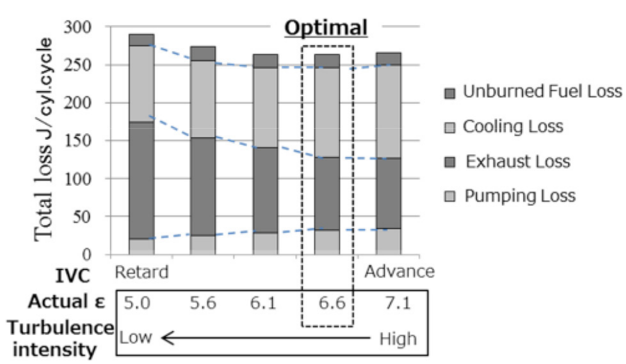


Figure 13. Sensitivity of various losses according to IVC

In addition, the Atkinson cycle improves a fuel economy in the low load engine condition. Figure 13 shows the relationship between Intake Valve Closing timing (IVC) and each loss such as pumping loss. As a valve close timing is retarded, pumping loss decreases. But actual compression ratio and tumble intensity are down. As a result of this, combustion gets worse and the total losses are increased. So, these parameters are a trade-off relationship and indicate the optimal valve timing for the minimum loss.

In recent years, Mid-Position Lock VVT (Variable Valve Timing) system (VVT-iW) has been implemented on the intake side to ensure both good engine startability and Atkinson cycle during driving. However, the motor-driven VVT (VVT-iE) was adopted for this engine in order to instantly achieve optimal valve timing even at low speeds with low oil temperature and pressure, which is difficult to control with the conventional VVT-iW (intermediate-lock).

A Center-spooled VVT oil control valve was adopted on the exhaust side to improve a response speed by shortening of the oil passage and operation characteristics at low temperature.

Furthermore, in order to contribute superior drivability, the demand torque from driver is controlled to an optimal throttle valve and EGR valve position at the same time so that a fuel economy becomes more suitable.

Moving parts

To achieve 40% of Maximum Thermal Efficiency, long stroke spec. and high compression ratio were selected. Furthermore, the maximum speed of 6600rpm is required to achieve the specific power of 60kw/L. Maximum piston speed reaches 22.8[m/s], so a weight reduction of moving parts was thoroughly carried out to reduce an inertia load. This section describes Piston and Connecting-rod, Crankshaft design.

Firstly, the piston mass was significantly reduced by removing unnecessary material through redesigning of the die and optimization of casting. The crown top wall thickness, skirt thickness and backside of the piston ring groove could be thinner. Figure 14 shows relations between Piston mass including Piston-Pin and the torque per cylinder of natural aspiration (NA) engine. The piston weight reduced more than 14% compared to the current 2.5L engine and the world top level weight was achieved.

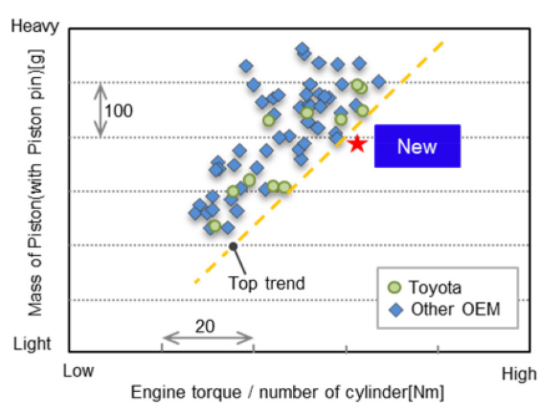


Figure 14. Relations between piston mass and the torque per cylinder

Under high piston speeds, it is difficult to balance between oil consumption and low friction performance. To realize that balance, several new technologies such as narrower contact width piston ring for reducing oil shear resistance, thinner side rail oil ring for improving sealing performance against bore deformation and DLC (Diamond-Like Carbon) coating for reducing friction coefficient were implemented.

A high-strength material for the connecting rod was used and strength was improved by 30% compared to the current model. Furthermore, in order to achieve both the reliability of connecting rod bearing and weight reduction, for example, big end upper part (Figure 15) was thinned so that the surface pressure of the bearing was dispersed, avoiding localized high surface pressure. As a result of this, more than 20% weight was reduced compared to the current.

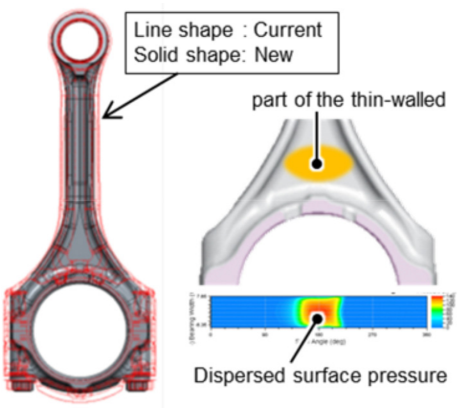


Figure 15. Optimized connecting rod

The crankshaft design is very important for reliability under high speed revolution. To design smaller crank pin diameter, the optimization of arm rigidity of the crankshaft reduced the inertial mass of #3 Journal. As a result of this, the impact load to the block was reduced. Full Counter Weight structure was adopted in other Journals and improving balance rate, each arm reduced the impact load, too.

Even in long stroke specification and a high maximum engine speed, the block size was equal with current model.

Cooling System

Overview

It is important to reduce cooling loss in order to improve the thermal efficiency. In addition, for the performance, knock mitigation is also needed.

Not only a cooling circuit optimization, but also a cooling control system with electric water pump according to the driving condition was implemented. Furthermore, to improve a fuel economy for cold engine condition, the heat management system was implemented to improve the warm-up process.

This section focuses on the cooling system and the heat management system.

Knock Mitigation and Reduction of Losses

To mitigate knocking, an electric water pump that operates free from crank rotation has been implemented on not only HV but also used on the conventional engine.

The water jacket flow system is redesigned from longitudinal flow to side flow in order to achieve an optimal balance between cooling performance and pump size of conventional engine (Figure 16). This system reduces pressure loss of water flow, and water pump size can be smaller even for a conventional engine, confirming enough cooling performance of inner cylinder head.

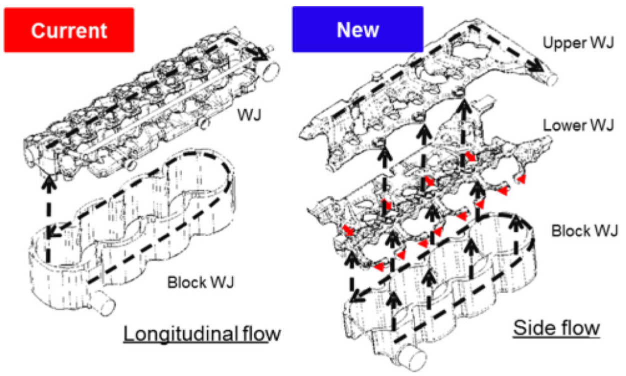


Figure 16. Structure of water jackets

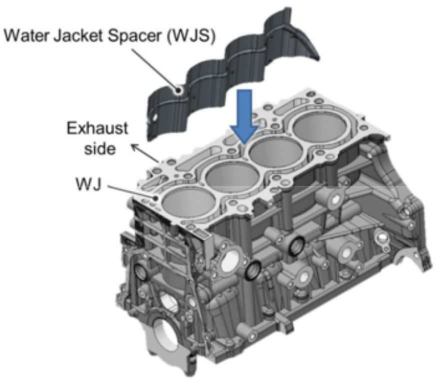


Figure 17. Water jacket spacer

A water jacket spacer (WJS) was placed in the cylinder block water jacket on only the exhaust side to optimize cylinder bore temperature distribution (Figure 17). The WJS controls and concentrates the flow to prevent knocking by cooling the upper range of the exhaust side of cylinder bore. This is the most effective means to cool the tumble flows.

This system achieves better cooling performance by high flux even at low engine speed and increases engine torque by knock mitigation. In addition, heater assisted thermostat contributes to high performance by driving down the water temperature at knocking limit area (Figure 18).

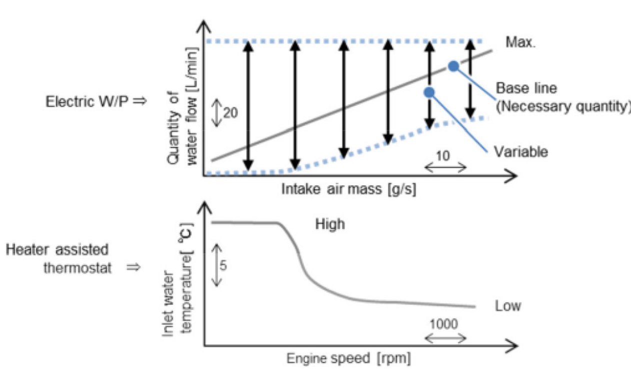
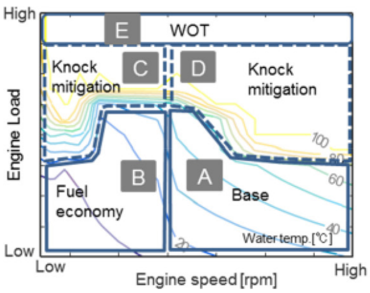


Figure 18. Control of electric W/P and heater assisted thermostat

A new logic to control high water temperature has been implemented to reduce cooling heat loss and friction loss in the Minimum advance for Best Torque (MBT) driving condition such as at low engine load.

Figure 19 shows strategy for water temperature control with these devices.



Zone	Water temp.	Flow quantity
A	Low	Base
B	High	Decrease
C	High	Increase
D	Low	Increase
E	Low	Max.

Figure 19. Strategy of water flow and temperature control

Improvement for Warm-up Process

To improve fuel economy, it is important to improve warm-up speed and reduce the time. In order to increase water temperature more quickly from a cold start condition, a new heat-management system has been implemented. The system controls not only the water flow by Electric water pump but also water path opening or closing by FSV (Flow Shut Valve).

Figure 20 shows cooling system circuit for conventional engine and it has two FSV units. One is for flow of Heater Core and the other is Warmer-core for Automatic Transmission Fluid.

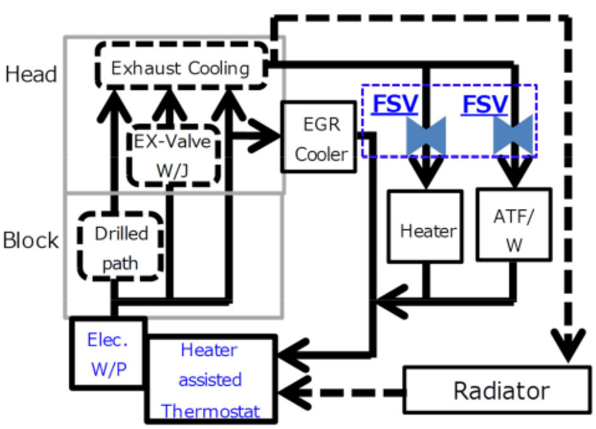


Figure 20. Cooling system circuit (FSV)

Fuel economy in the warm-up process was improved without imparing comfort by securing the warm-up performance through opening and closing the FSV according to the outside temperature and driving conditions (Figure 21).

In addition, the best flow control that held the heat distribution in the engine body was carried out and this control prevents a degradation of Noise and Vibration during the warm-up process.

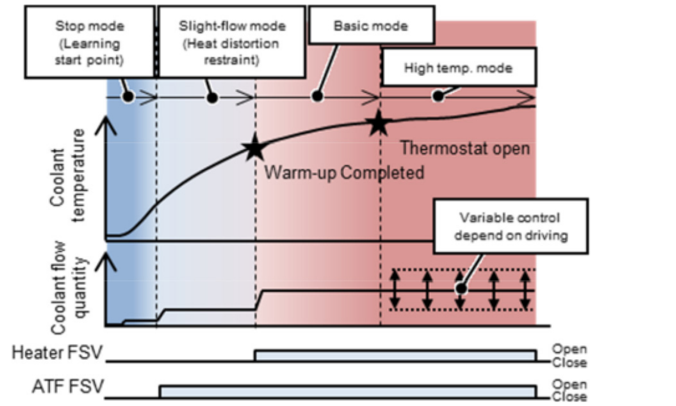


Figure 21. Example of control with FSV and coolant flow quantity in warm up process

Lubrication System

It is the important factor for improvement of fuel economy to reduce friction loss also.

Electronic control-type Variable Capacity Oil Pump (Figure 22) was implemented and can control the oil flow rate with "electrical oil control valve". The rotor is "Trochoid Type" for less friction than one of the previous variable type oil pumps.

The system can supply the appropriate oil and confirm the required oil pressures to several parts of engine, according to the main oil channel pressure. In addition, the friction loss was reduced for fuel economy.

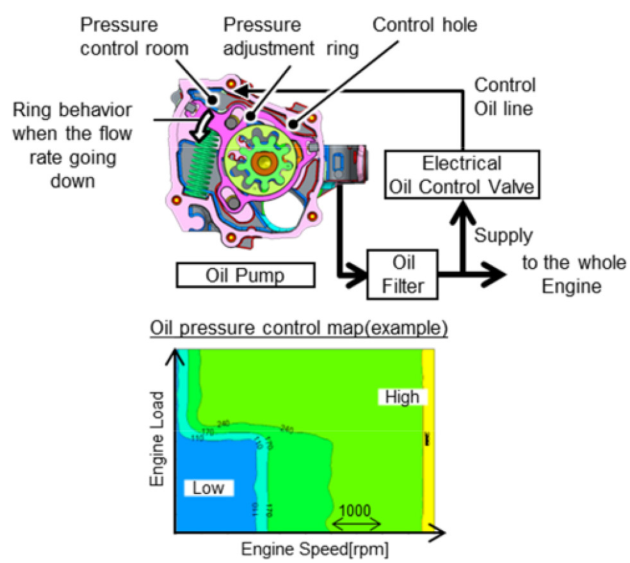


Figure 22. Electric control-type variable capacity oil pump

On the other hand, oil pressure control can stop the oil jet flow to the piston with pressure control. So the temperature of the piston increases more quickly in warm-up process and PN (Number of Particulate) emission is reduced. Furthermore, friction loss of piston is got down.

The engine oil circuit is supplied by the trochoid oil pump fitted on the front section of the crankcase, driven by the chain. The oil circuit is divided into 2 ways, the oil jet channel and the main oil channel (to Cam shaft, VVT, HLA channel and vacuum pump), by doing so, the oil jet flow can be easily controlled (Figure 23).

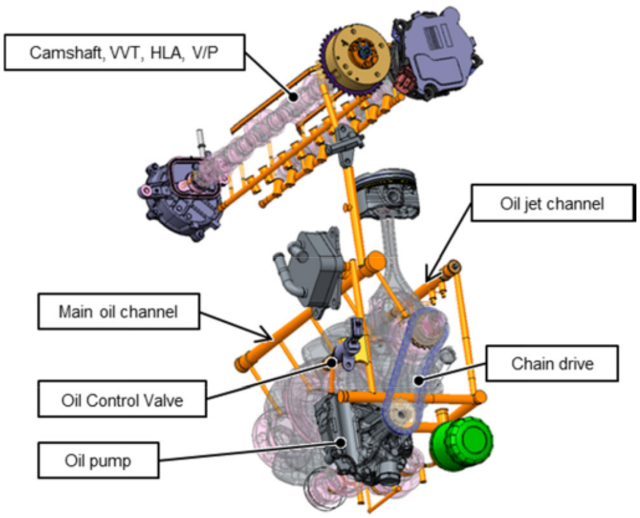


Figure 23. Lubrication system

Exhaust System

Overview

Catalyst temperature control gets more and more important to meet more severe regulations such as SULEV30 in North America, European Euro6 and so on.

Catalyst position was decided with warm-up characteristics from a cold start and stoichiometric driving area especially on a high load. However, these requirements are contrary to each other. The exhaust port layout in the cylinder head, surface area to the catalyst and position of catalyst were redesigned to achieve both simultaneously at a high level.

Furthermore, not only improvement in performance through reduction of back pressure and optimization of the branch length but also arranging the under-floor catalyst close to the engine are necessary, so it is important to secure the degree of freedom in catalyst arrangement. In order to realize the requirement above, the rear exhaust system was adopted with a plan to rollout to the engine series (Figure 24).

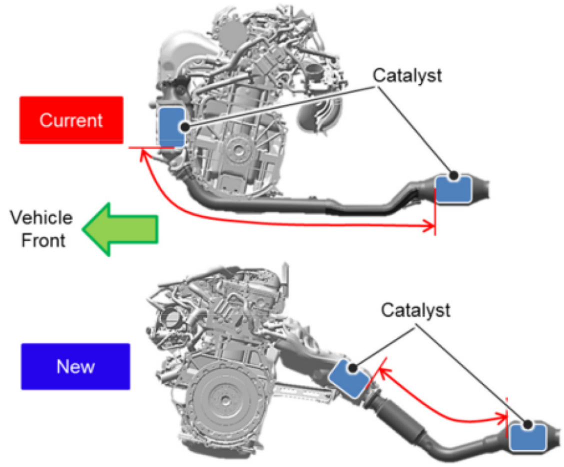


Figure 24. Exhaust system layout on vehicle

Furthermore, the 2A/F sensor control system is implemented. This system has two A/F sensors located in front and behind start-up catalyst. Therefore, gas detectability can be higher catalyst performance. As a result of this system, catalyst size will be smaller and reduce precious metals for the high environmental performance.

Exhaust Cooling System (Cylinder Head)

Concentrated lateral flow between exhaust valves in cylinder head was implemented. In addition, the water jacket section area was decreased 20% to improve the heat transfer coefficient.

These items can reduce temperature between exhaust valves about 10°C from current model, and water pressure loss and amount of flow were reduced. Figure 25 shows the layout of the port and water jackets. This configuration allows us to expand the surface area and to lower the temperature by double the current model. But the above-mentioned electric water pump cooling system controls coolant flow rate in the warm-up process and reduces the heat loss of exhaust gases. On the one hand, as Figure 26 shows, stoichiometric area(λ=1 area: red) is greatly enlarged from current model.

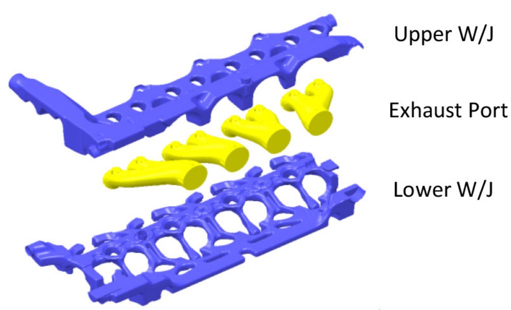


Figure 25. Exhaust port and water jackets structure in cylinder head

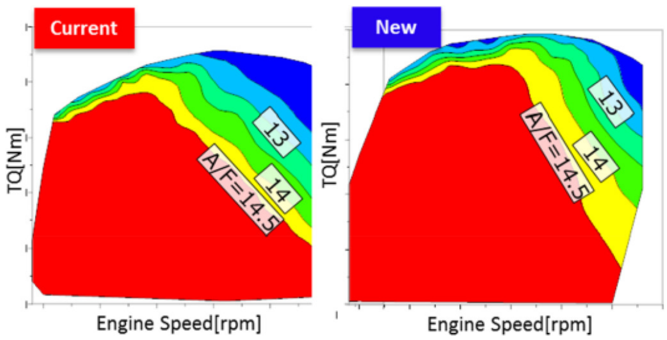


Figure 26. Comparison of stoichiometric area

Design of Exhaust Manifold

Figure 27 shows general view of Exhaust manifolds. As mentioned previously, exhaust direction has been move to the back side because of the reduction of back pressure for performance. Furthermore, scavenging rate has been improved by the optimization of valve timing and the improvement of isometric length adopting 4-1 branch pipe. As a result, performance has been improved by mitigating knocking. In addition, the improvement of gas flow deflection toward catalyst and exhaust sensor contributes to the reduction of quantity of precious metal in catalyst.

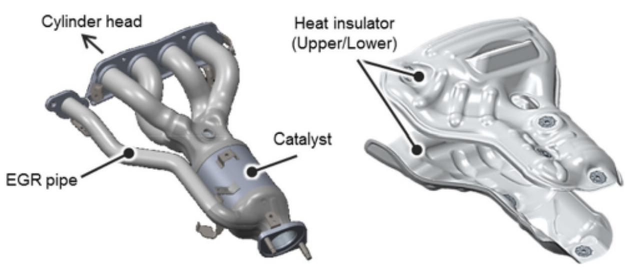


Figure 27. Exhaust manifold

The optimization of the branch pipe length and the exhaust surface area gives not only high torque performance but also higher exhaust purification performance by quicker warm-up process. The optimization could be balanced with the breakthrough of production technology by the minimization of branch pipe bend.

Catalyst Warm-Up

A reduction of the emission in the cold catalyst warm-up process is very important to meet stricter emission regulation. Figure 28 shows the relation and balance between energy needed for catalyst warm up and gas quantity from the engine before warm up. A specific target was set for the balance of this relation.

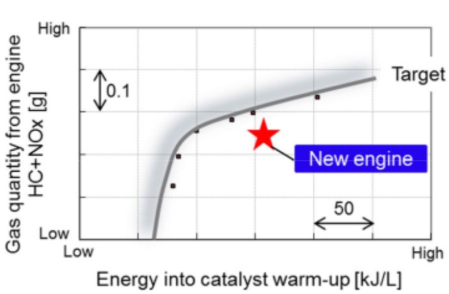


Figure 28. Target for necessary energy to catalyst in warm-up process

On the other hand, for PN (Number of Particulate) reduction during the cold condition, it is significant technology to reduce fuel wall wetting. Current fan spray's nozzle is an enlarged taper shape, and it has high capability of atomization and coking robustness. However, fan spray lacks degree of freedom in the spray layout and injection timing, so is needed to reduce the in-cylinder wall wetting.

As mentioned previously, direct injection system with low spray penetration and spherical-shaped piston are implemented. Furthermore, partial lift control is developed in order to realize a multi split injection of small quantity (Figure 29).

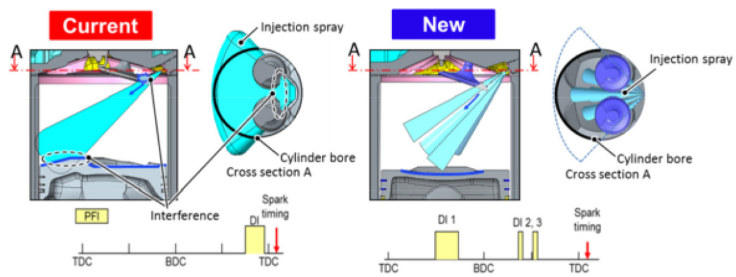


Figure 29. Comparison of injection timing and number in catalyst warm-up process

Because of optimization for multi injections and timing, PN (Number of Particulate) reduction and stratified charge combustion with proper air by fuel ratio around spark plug are done. Clean combustion is not dependent on post-processing exhaust system.

These items confirm the combustion stability under the ignition retard condition in order to get thermal energy for a catalyst warm-up, and target is satisfied. As a result of this, each country's emission regulation, for example, SULEV30 regulation in North America was met.

Cooled EGR System

The quality of EGR gas which means temperature, passage pressure loss and distribution variation is very important for the cooled EGR system. Turbulence intensity is significant for high speed combustion and stability of combustion, leads to the wide EGR limit about 25% in maximum.

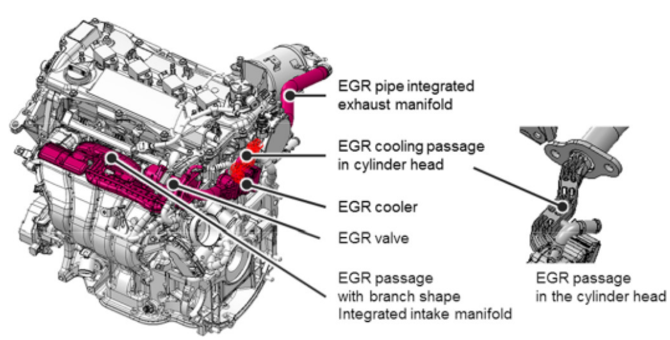


Figure 30. EGR system layout

The shape of intake manifold was tuned by CFD to achieve this highest EGR ratio under good combustion and to reduce the variation of EGR distribution between cylinders to less than 3%. EGR gas ratio of each cylinder was equalized by tuning EGR gas passage. And cooling capacity of gas was increased by not only EGR cooler but also EGR cooling passage in the cylinder head (Figure 30).

Low Friction Technology

This engine implemented low friction technology as following and greatly reduced the friction.

For improvement of the cylinder system, we adopted not only the off-set crank which was used for the previous engine, but also the resin coating that is subjected to smoothing processing is applied to the surface of the piston skirt for the purpose of reducing the friction at the time of application of combustion pressure. As mentioned previously, a DLC coating was applied to the top ring and the oil ring sliding surfaces.

In the crank system, a resin surface coating was applied on all connecting rod bearings and main bearings in order to reduce friction under loaded conditions.

In the lubricating system, the electronically controlled variable displacement trochoid oil pump was adapted along with low viscosity engine oil at SAE 0W-16. The combination between the low viscosity engine oil and the variable displacement oil pump enabled the optimal oil supply to the system. It resulted in the significant reduction of oil pump driving workload and realized the reduction of overall engine friction.

In the valve-train system, a low friction resin material was adapted on the sliding surface of chain guide. A beehive valve spring was adapted for the moving mass reduction and the spring load reduction.

As the accessory system, the water pump was motorized and the water pump pulley was removed to reduce the driving workload of accessories. The efficiency of vacuum pump was improved to reduce the friction.

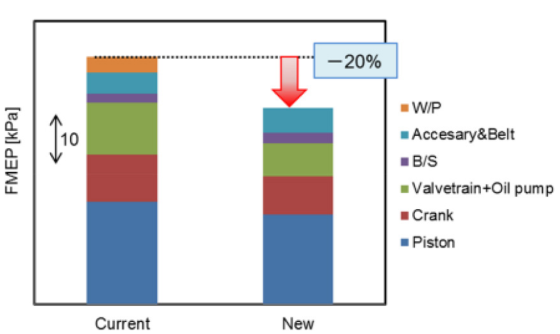


Figure 31. FMEP comparison (at 2000rpm motoring)

The combination of all of the above improvements realized the friction reduction more than 20% compared to current model (Figure 31).

Measures to Reduce Noise and Vibration

The engine Noise and Vibration (NV) performance as the whole vehicle has been improved by developing the new vehicle platform and the new transmission at the same time.

First of all, regarding the NV performance of low frequency area, the powertrain (coupled with the engine and the transmission) in the engine compartment was placed ideally by the highly precise prediction of inertial specification of each component. Placing a mount on the torque roll axis makes lower level of vibration at the idle speed condition. And placing the center of gravity of the power train to the elastic main axis makes lower level in the engine starting also.

Next, regarding the middle frequency area, the power plant rigidity was improved by CAE optimizing the combination point with the new transmission. As a result, the mount vibration has been reduced approximately 4[dB] from the current engine (Figure 32).

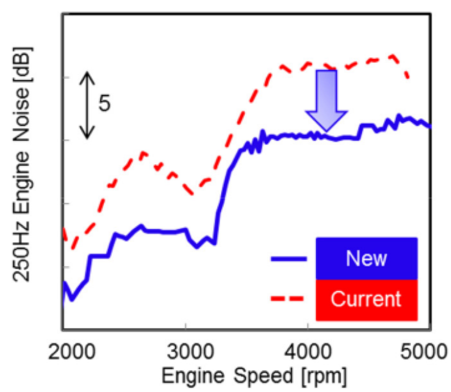


Figure 32. Comparison of engine noise

Figure 33 shows comparison of contact surface shape between engine and transmission. This surface was enlarged to improve power plant rigidity. As a result of this, the engine noise was reduced and a comfortable driving environment is provided to customers.

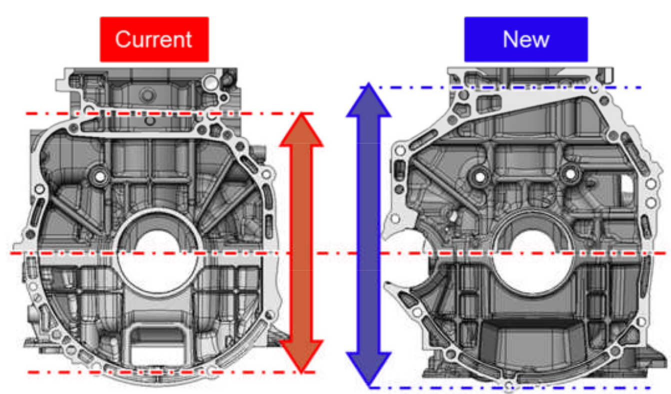


Figure 33. Comparison of engine contact surface shape

In the current engine, balancer which is cassette type and driven directly by crankshaft gear (Figure 34) has been implemented for the customer comfortable driving. Some gears are made by resin with aramid fiber reinforcement for preventing from gear noise as same as current technology.

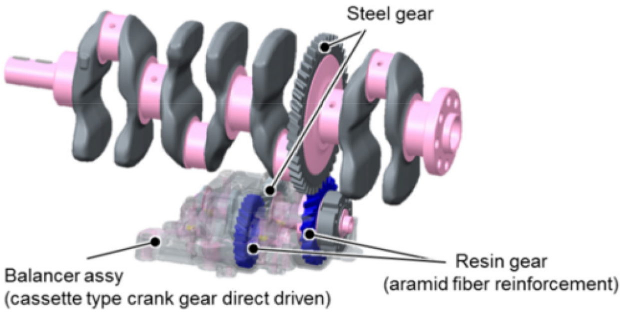


Figure 34. Balancer

Generally, high-speed combustion increases the high-frequency noise. The noise insulations made of polyurethane were provided in the proper places by selecting parts with more noise among parts and components after controlling the combustion speed properly at the development phase (Figure 35).

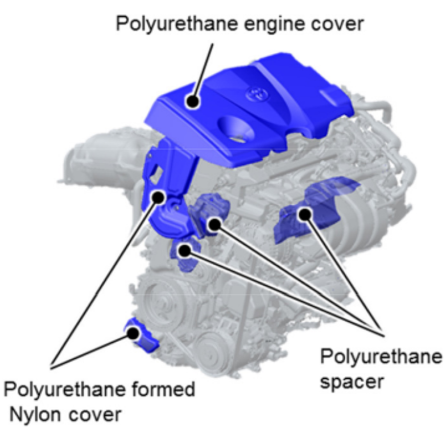


Figure 35. NV insulation items

Summary

Full Load Performance

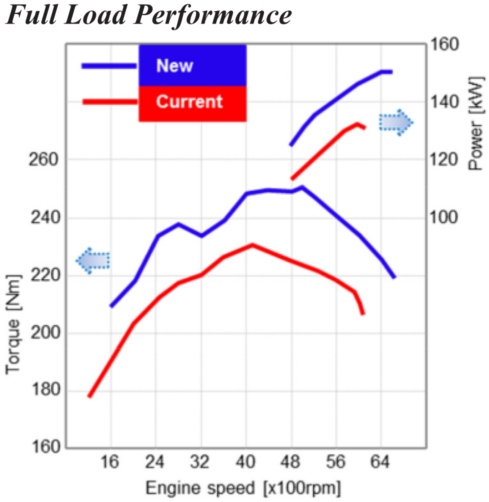


Figure 36. The engine power and torque curve

Figure 36 shows the comparison of the engine power and torque curve between current and new.

Maximum power is 151kW, so 60kW/L specific power has been achieved. In addition, torque is improved over all engine speeds.

Fuel consumption (Thermal efficiency)

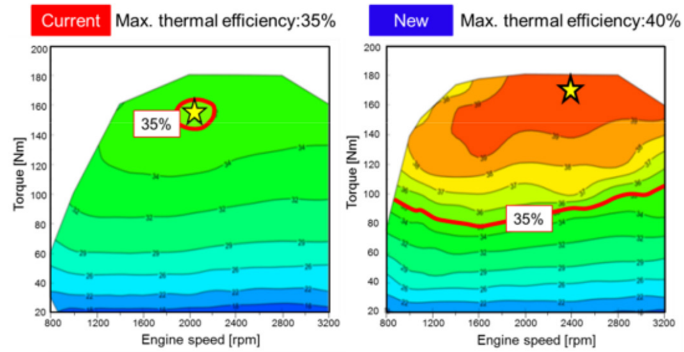


Figure 37. Comparison of thermal efficiency map

Figure 37 shows the thermal efficiency map of the 2.5L current engine and new engine. Not only was maximum thermal efficiency achieved 40%, but also 35% was realized in wide range of operating conditions. By combining with new TNGA 8 speed Automatic Transmission, over 16% lower fuel consumption is achieved.

Conclusions

This paper has described the hardware and system characteristics of new Toyota inline 4-cylinder 2.5L Gasoline Engine, based on “Toyota New Global Architecture (TNGA) concept”. The main points of this engine can be summarized as follows.

1. High-Speed combustion package with long stroke, high tumble ratio and flow coefficient was developed and 40% of Maximum Thermal Efficiency and 60kW/L of Specific Power were achieved.
2. As a devise to realize high-speed combustion, Laser-cladded valve seat, and spherical-shaped piston to keep a high tumble flow, D-4S system with multi-hole injector and optimization of balance rate and weight reduction of moving parts were implemented.
3. The cooling system with electric water pump has been implemented. High engine performance and low fuel consumption was balanced with the control of the pump and FSV (Flow Shut Valve) optimized the most suitable water temperature in each driving condition.
4. Electronic control-type variable Capacity Oil Pump is implemented and the combination of other items reduced the friction by more than 20%.
5. Low emissions were achieved using catalyst warm-up control with a new direct multi injection system with low spray penetration and spherical-shaped piston. In addition, stoichiometric area (λ=1 area) was greatly enlarged by exhaust cooling system and the design optimization of the exhaust manifold.

These techniques, especially the high-speed combustion package that can be applied to engines with other displacements will be used for the following engine series.

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Definitions/Acronyms

SULEV - Super Ultra-Low Emission Vehicle

PN - Number of Particulate

NA - Naturall Aspiration

HV - Hybrid Vehicle

CFD - Computational Fluid Dynamics

FMEP - Friction Mean Effective Pressure

BMEP - Brake Mean Effective Pressure

S/B ratio - Stroke and Bore ratio

TDC - Top Dead Center

MBT - the Minimum advance for Best Torque

NV - Noise and Vibration

CAE - Computer-Aided Engineering

DI - Direct fuel Injection

PFI - Port Fuel Injection

D-4S - Direct injection 4-stroke gasoline engine Superior version (DI&PFI system)

EGR - Exhaust Gas Recirculation

HLA - Hydraulic Lash Adjuster

DLC - Diamond-Like Carbon

IVC - Intake Valve Closing timing

VVT - Variable Valve Timing

VVT-iW - Mid-Position Lock VVT

VVT-iE - Motor-Driven VVT

W/P - Water Pump

WJS - Water Jacket Spacer

FSV - Flow Shut Valve

TNGA - Toyota New Global Architecture

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE’s peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

http://papers.sae.org/2017-01-1021