A High-Expansion-Ratio Gasoline Engine for the TOYOTA Hybrid System

Toshifumi Takaoka**
Katsuhiko Hirose*
Tatehito Ueda*
Yasushi Nouno**
Hiroshi Tada**
Hiroshi Kanai*

Abstract

A 50% reduction in CO_2 and fuel consumption in comparison with a vehicle with the same engine displacement has been achieved by the newly developed gasoline engine for the Toyota Hybrid System. This is achieved by a combination of an electric motor and an internal-combustion engine that is optimized in terms of its displacement and heat cycle. Delaying the closing of the intake valve effectively separates the compression ratio and expansion ratio, so that the expansion ratio, which is normally set to 9:1 to 10:1 to suppress knocking, can be set to 13.5:1. Motor-assisted quick start, improved catalyst warm-up, and the elimination of light-load firing allow the system to achieve emissions levels that are only one-tenth of the current Japanese standard values.

Keywords: *hybrid, low fuel consumption, low emissions, low friction, variable valve timing*

1. Introduction

The earth's remaining reserves of fossil fuels are said to total approximately two-trillion barrels, or about a 50-year supply. The electric vehicle, because of its zero emissions level and the diversity of sources to supply electrical energy, is regarded as a promising automobile for the future. On the other hand, the energy limitations of on-board batteries, which is to say, their inferior energy density in comparison with fossil fuels, has meant that the electric vehicle has remained no more than just one future technology. The internal-combustion/electric hybrid system is promoted as a technology that compensates for this shortcoming of the electric vehicle, but it is also the object of attention as a system that eliminates the problems of the internal-combustion engine.

Because the drive energy of the hybrid system comes either from electrical generation by the internal-combustion engine or from the engine's direct drive of the axle, the efficiency of the engine, the primary power source, strongly influences the efficiency of the entire system. In the development of the Toyota Hybrid System, a new gasoline engine was developed with more emphasis on thermal efficiency than on specific output. Because priority was given to the total efficiency of the entire system, it was decided that a high-expansion-ratio cycle would be used, and the engine displacement and maximum output were chosen to reduce friction loss. This paper describes the investigative process and the results that were obtained.

2. Hybrid System and Engine Specifications

2.1 Hybrid System

The configuration of THS is shown in **Fig. 1**. The system links the engine output and the motor output by means of a planetary gear system to control the power split. One notable feature is that because the drive power is the combined power of the engine and the motor, the engine output can be set to a relatively low value without reducing vehicle performance.

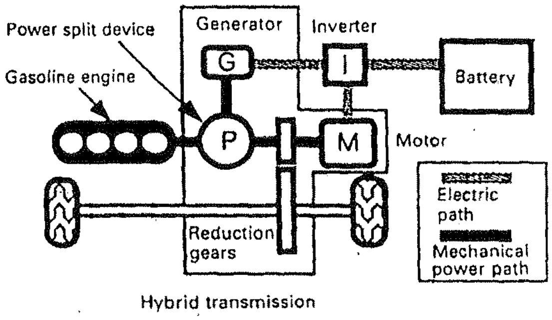

Fig. 1 Toyota Hybrid System Configuration

Fig. 2 shows the relationship between output and efficiency. One issue for the engine was how to raise the net thermal efficiency from point A to point B.

2.2 Engine Specifications

In order to achieve the thermal efficiency objective, the engine for the hybrid vehicle was planned with the following three points in mind:

(1) The only restriction to be placed on the choice of engine displacement would be that it be within a range that satisfies the engine output and installability requirements. This makes it possible to use a high-expansion-ratio cycle with delayed intake valve clos-

---

* Engine Engineering Div. II
** Power Train Engineering Div. II

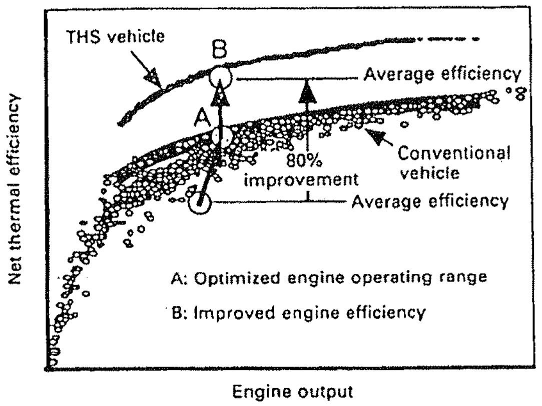

Fig. 2 Relationship of Engine Output and Efficiency

ing, as well as to reduce friction loss by lowering the engine speed.

(2) In order to achieve a major reduction in emissions, the engine would operate with λ = 1 over its entire range, and the exhaust system would use a 3-way catalyst.

(3) Active measures would be taken to reduce weight and increase efficiency.

Fig. 3 shows the relationship between the S/V ratio (the ratio of combustion chamber surface area to combustion chamber volume) and the indicated mean effective pressure. The smaller the S/V ratio, the less heat is dissipated into the coolant, raising the indicated mean effective pressure. Since the S/V ratio tends to decrease as the displacement per cylinder increases, this also raises the indicated mean effective pressure.

Fig. 4 shows the relationship between displacement and friction loss in two engines designed to have identical output. Because the maximum engine speed can be set lower as the displacement increases, it is possible to reduce friction loss by reducing both the load on the valve system springs and the tensile strength of the piston rings while maintaining the same output.

Based on these considerations, the relationship between displacement and fuel consumption was calculated. The results are shown in **Fig. 5** and **Fig. 6**. From **Fig. 5** it can be seen that in the high-output range, thermal efficiency rises as the displacement becomes larger, but in the low-output range, thermal efficiency is higher with a small-displacement engine. Both the indicated thermal efficiency and the mechanical efficiency (friction loss) improve as displacement becomes larger, but in the low-output range, because of the effect of the pumping loss that results from the shift to a partial load, thermal efficiency is better with a small-displacement engine.

Fig. 6 shows the relationship between displacement and fuel consumption. For the reasons cited above, 1500 cc was deemed the optimum engine displacement, given the curb weight of the THS vehicle.

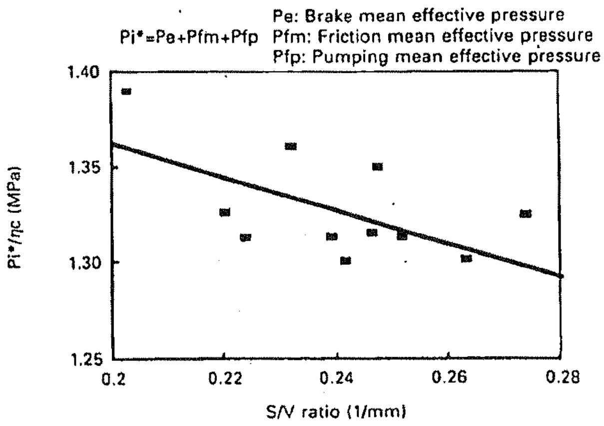

Fig. 3 Relationship of S/V Ratio and Indicated Mean Effective Pressure

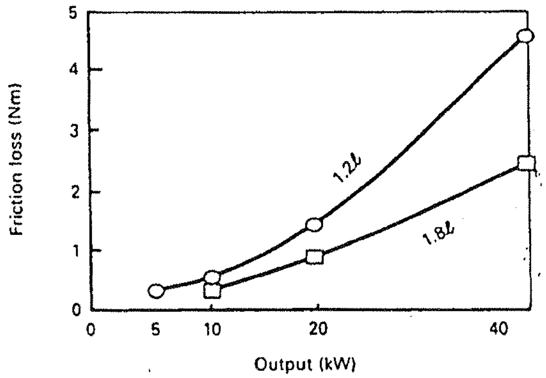

Fig. 4 Relationship of Displacement and Friction

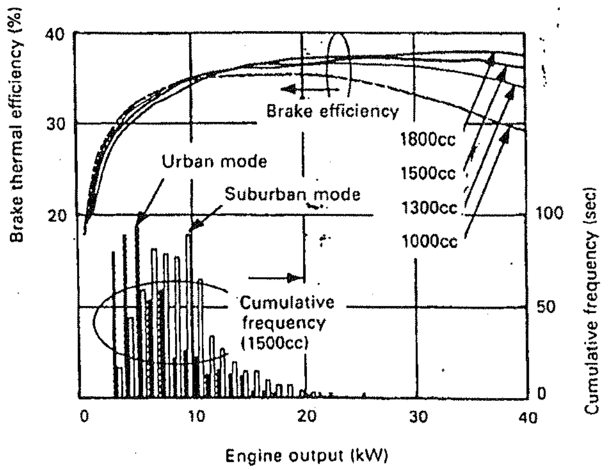

Fig. 5 Displacement and Engine Efficiency

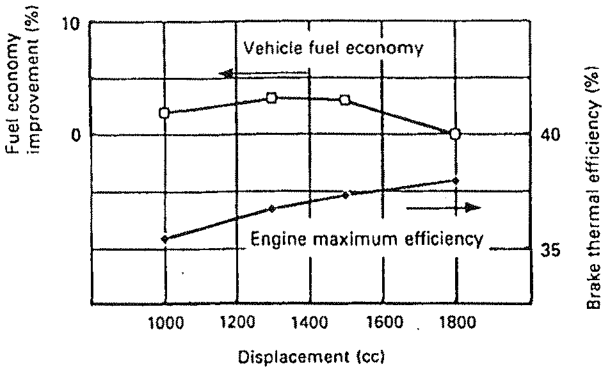

Fig. 6 Displacement and Fuel Economy

3. Improving Efficiency by Means of High Expansion Ratio

3.1 Principle

The theoretical thermal efficiency of an equivalent charge cycle is improved by raising the compression ratio. But if the compression ratio is raised in a gasoline engine, the compression end temperature rises, and knocking occurs. To prevent knocking in the high-expansion-ratio engine, the timing of intake valve closing was delayed considerably, thus lowering the effective compression ratio and raising the expansion ratio, which essentially controls the thermal efficiency. **Fig. 7** is a pressure-volume (p-V) diagram comparing the high-expansion-ratio cycle with the conventional cycle when the charging efficiencies of the two are equal. **Fig. 8** shows the same sort of comparison when the compression end pressures are equal. When the charging efficiency is identical, delaying the closing of the intake valve raises the maximum pressure and increases the positive work, and also reduces pumping loss. With identical compression end pressure, increasing the expansion ratio raises the theoretical efficiency.(1)(2)(3)(4)(5)(6)(7)(8)(9)

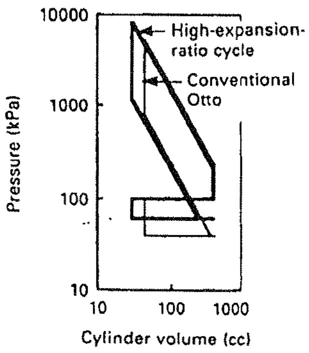

Fig. 7 p-V Diagrams with Equivalent Charging Efficiency

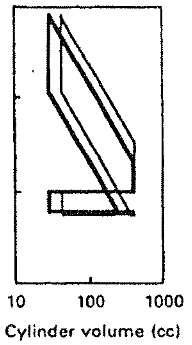

Fig. 8 p-V Diagrams with Equivalent Compression End Pressure

3.2 Relationship of Mechanical Compression Ratio, Valve Timing, and Brake Thermal Efficiency

Before a prototype of the high-expansion-ratio engine was built, the effects of the mechanical compression ratio and valve timing on brake thermal efficiency were studied. An in-line four-cylinder, 2164-cc Toyota 5S-FE engine was used in the experiments.

Fig. 9 shows the changes in thermal efficiency with different combinations of expansion ratio and valve timing. If the expansion ratio is increased and intake valve closing is delayed, brake thermal efficiency rises, but it reaches a limit at an expansion ratio of 14.7:1. Also, the maximum value of the brake mean effective pressure drops as the delay in intake valve closing increases.

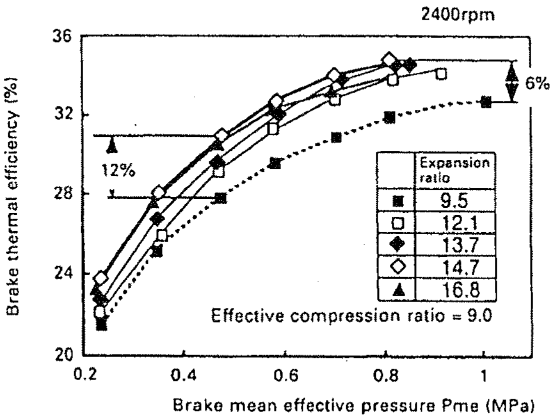

Fig. 9 Expansion Ratio and Thermal Efficiency

Fig. 10 shows the relationship between brake thermal efficiency and brake mean effective pressure under full load. As the expansion ratio increases, the timing advance becomes slower due to knocking, and the brake thermal efficiency drops, but if the intake valve closing

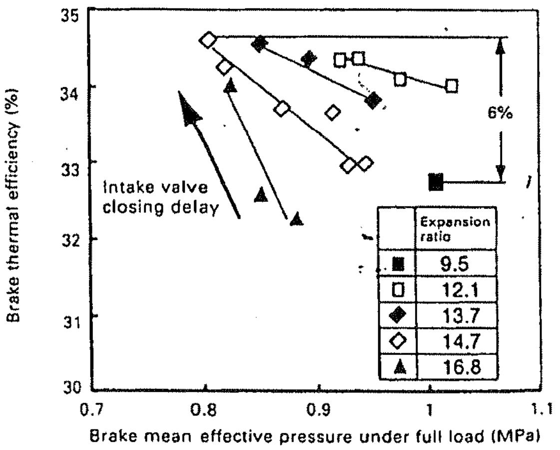

Fig. 10 Relationship of Brake Mean Effective Pressure and Thermal Efficiency as Expansion Ratio and Compression Ratio Change

is delayed at the same time, knocking gradually diminishes and efficiency improves. Therefore, if the brake mean effective pressure is allowed to fall, the combination of high expansion ratio and delayed intake valve closing achieves high efficiency. **Fig. 11** is an indicator diagram of actual measured results showing that the heat cycle illustrated in **Fig. 7** and **Fig. 8** was achieved.

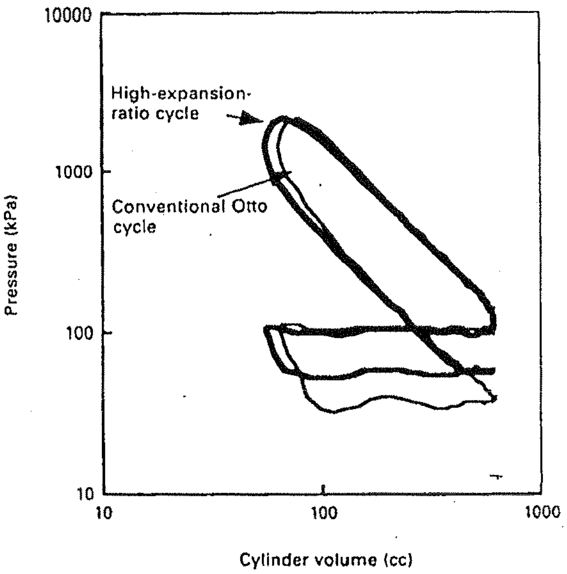

Fig. 11 Indicator Diagram of Actual Measurements

4. High-expansion-ratio THS Engine

4.1 Basic Specifications

Table 1 shows the main specifications for the high-expansion-ratio engine. The mechanical compression ratio is set to 13.5:1, but the effective compression ratio is suppressed to the range of 4.8:1 to 9.3:1 by using intelligent variable valve timing (VVT-i) to time the intake valve closing between 80° and 120° after bottom dead center (ABDC). The ratio of 4.8:1 is obtained by the maximum delay of VVT-i and is used to counter vibration during engine restart, as explained below.

Table 1 Design Specifications

Engine model	1NZ-FXE
Displacement (cc)	1497
Bore×stroke	ø75×84.7
Maximum output	43kW/4,000rpm
Combustion chamber volume	30cc
Mechanical compression ratio	13.5
Effective compression ratio	4.8~9.3
Intake valve closing timing	80~120° ABDC
Exhaust valve opening timing	32° BBDC

4.2 Engine Structure

Fig. 12 is a transverse sectional view of the high-expansion-r engine. An aluminum-alloy cylinder block, offset crankshaft,(10) ladder-frame structure are used. The crankshaft has been made th ner and lighter, and the load on the valve system springs has been duced, as has the tensile strength of the piston rings. The connect rod/stroke ratio has been increased, and the intake inertia effect been reduced by using a small intake manifold. The engine also u a slant squish combustion chamber. All of these features combin achieve lighter weight, lower friction, and improved combustion.

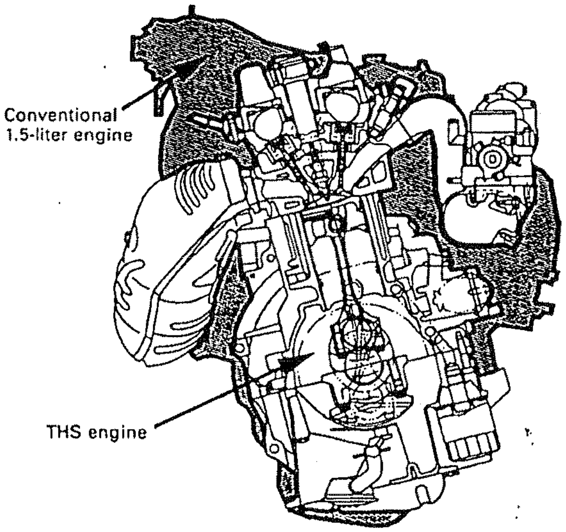

Fig. 12 Transverse Section of High-expansion-ratio Eng

5. Experimental Results and Considerations

This section summarizes the results of experiments conducte the 1.5-liter high-expansion-ratio engine and some considerations cerning them.

5.1 Relationship of Expansion Ratio and Brake Ther Efficiency

Fig. 13 shows the relationship of ignition timing to torque ar brake specific fuel consumption (BSFC). Expansion ratios of 14:1, and 15:1 were compared, and it can be seen that as the ex sion ratio increases, the trace knock ignition timing is delayed. W 15:1 expansion ratio, the efficiency improves at the point of mini spark advance for best torque (MBT), but the expansion ratio i stricted by the knocking that occurs due to the high effective com sion ratio. The best results in terms of torque and BSFC wer tained with an expansion ratio of 14:1.

Fig. 14 shows the results of a study of thermal efficiency v engine output. A 14:1 expansion ratio showed the best results the entire output range. Ultimately, an expansion ratio of 13.5: chosen, taking into account such factors as the allowable variati combustion chamber volume and the adhesion of deposits in the combustion chamber, in order to leave a margin for pre-ignition.

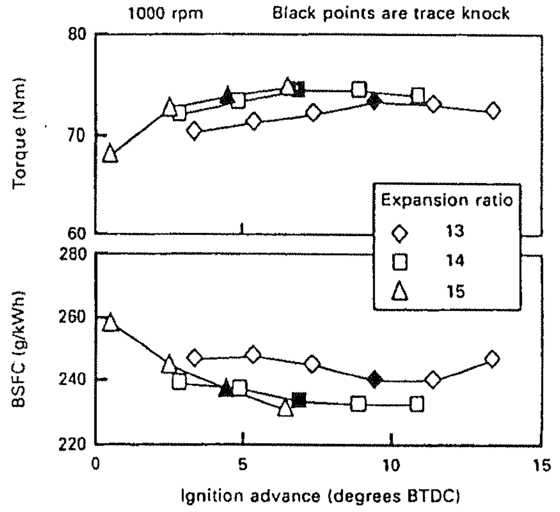

Fig. 13 Relationship of Ignition Timing and BSFC

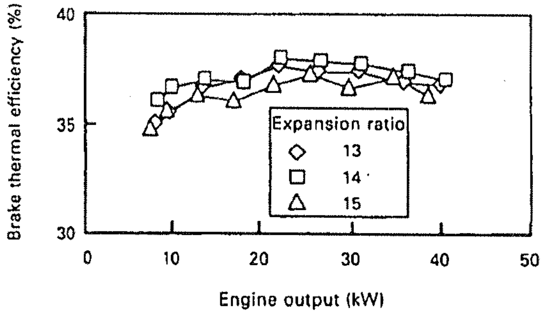

Fig. 14 Expansion Ratio and Brake Thermal Efficiency

5.2 Torque Improvement by VVT-i

Full-load torque was adjusted using VVT-i. The results are shown in **Fig. 15**. An improvement in torque of 10% or more was made possible by advancing the intake valve closing by 10°. In THS, the engine is controlled so that intake valve closing is advanced when the load requirements are high.

5.3 Friction Loss

As stated previously, the engine speed was lowered in an attempt to reduce friction loss. The measured results are shown in **Fig. 16**. It can be seen that the friction loss for the high-expansion-ratio engine is at a consistently lower level than the cluster of points plotted for conventional engines and that the objective of reducing friction loss was achieved.

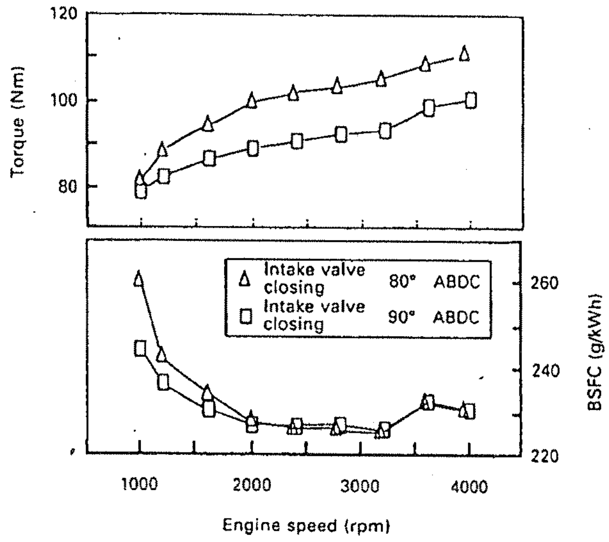

Fig. 15 Torque Improvement Effect of VVT-i

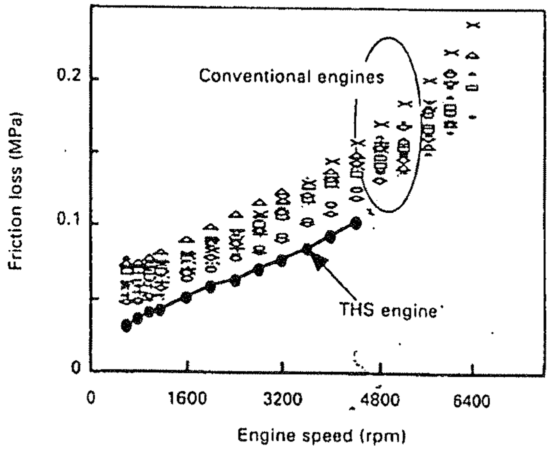

Fig. 16 Comparison of Friction Loss

5.4 Reduction of Exhaust Emissions

The advantages and disadvantages of the hybrid vehicle with respect to cleaner exhaust emissions are summarized below.

Advantages

(1) By using the supplementary drive power of the electric motor, the system eliminates the light-load range, where concentrations of hydrocarbons in the emissions are high and the exhaust temperature is low.

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**