

Research on Engine Control to Make Effective Use of Bioethanol-Blend Fuels

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ABSTRACT

Research was carried out on engine systems and control that increase both thermal efficiency and maximum torque by making effective use of the limited ethanol content in E10 gasoline, which contains ethanol. Control that separates E10 gasoline into high octane number fuel (high-concentration ethanol) and low octane number fuel (low-concentration ethanol), using the ethanol effectively under conditions that tend to cause knocking during high-load operation and using mainly gasoline during low-load operation, was applied to a high-compression-ratio engine. A fuel management control logic was created so that, under this system, the basic characteristics of ignition timing and octane number (ethanol fraction) inside the cylinder are determined in accordance with the residual percentage of the fuel, and the gear ratio is cooperatively adjusted to yield an optimal engine speed and load matched to the engine's thermal efficiency at that time. Confirmation of this result in vehicle simulation indicated that in US06 mode, known to be an operating mode that generally is frequently under high load, the system is capable of operating without running short of ethanol. It also indicated that in a low-load operating mode such as the US combined mode, the system was capable of a maximum 26.8% increase in fuel economy through the effective use of separated ethanol.

1. Introduction

The use of renewable energy as a solution for environmental issues has been growing increasingly widespread. One such solution has been the manufacture of bio-ethanol from corn, sugar cane, or other such raw materials, for mixture in small quantities with gasoline to use as fuel for motor vehicles. This method is known to yield approximately the same performance as conventional gasoline engines^{(1), (2)}. The use of E10 gasoline comprising a 10% mixture of bio-ethanol in gasoline is in widespread use in the United States. Flexible Fuel Vehicles (FFV) that support the use of fuels containing high concentrations of bio-ethanol have also been developed and are in widespread use⁽³⁾.

Ethanol is a fuel with greater anti-knocking properties than gasoline, and it is known that this characteristic can be used to obtain greater thermal efficiency by raising the compression ratio⁽⁴⁾. It has also been demonstrated that gasoline containing bio-ethanol can be used effectively and has potential for high efficiency and high torque in an engine that can separate E10 gasoline into high octane number fuel (high-concentration ethanol) and low octane number fuel (low-concentration ethanol)⁽⁵⁾. It has further been reported that fuel that has actually been separated in

a fuel separation system has properties making it usable as motor vehicle fuel, and that separation can also yield sufficient quantities of the high octane number fuel that is needed in US06 mode, which calls for frequent high-load operation⁽⁶⁾.

One issue in the application of vehicles equipped with this system for actual users is that various operating conditions need to be considered. Operating conditions differ with the way drivers use the system, and driving conditions are also variable, so there may be unevenness in the amounts of high-concentration ethanol or low-concentration ethanol consumed. When the residual amount of high-concentration ethanol becomes low, for example, the system cannot ensure that a sufficient percentage of ethanol is injected, and it may become necessary to limit torque due to the occurrence of knocking. It is therefore necessary to configure the system so that no shortage of ethanol will occur even in driving modes such as US06 mode, in which high loads are frequent. With such a configuration alone, however, it may happen instead that the reduced use of high-concentration ethanol in low-load driving modes results in a surplus of ethanol. The surplus ethanol will not be used effectively to limit knocking, and the advantages of fuel separation will not come into play. In order to make effective use of the separated high-

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concentration ethanol, therefore, what is needed is a control method that limits the unevenness in the residual amounts of the two kinds of fuel and that will not degrade fuel economy even when unevenness occurs.

In addition to engine control, therefore, the present research has considered a system of fuel management control that incorporates cooperative control of the transmission. The effectiveness of this approach was confirmed with simulation of vehicle operation.

2. Concept and System Overview

2.1. In-Cylinder Octane Number Control

With ordinary high-compression-ratio engines, the octane number envisioned as necessary to set ignition timing at minimum spark advance for best torque (MBT) will have the engine speed and engine torque (engine load) in the relationship shown in Fig. 1. A high octane number is required only during operation at high load, and ignition at MBT timing can be achieved during low-load operation even with a low octane number. In accordance with this characteristic, ethanol with a high octane number is effectively supplied only when demanded during high-load operation, and in this way the limited amount of ethanol in E10 gasoline can be used effectively to limit knocking. In-cylinder octane number control with the capability to vary the octane number of the fuel that is supplied can, in this way, achieve a balance between the increase in torque obtained by limiting knocking and the enhancement of efficiency obtained by using a high-compression-ratio engine.

Cooperative control of the transmission is also used with respect to the demanded vehicle driving force, enabling variation of the engine speed and engine torque along the engine's constant output curve. In other words, the engine's demand octane number is controlled by the transmission, and the octane number for supply in the cylinder is controlled in accordance with that demand octane number. This enables control of the amount of ethanol consumed.

2.2. System Overview and Fuel Injection Configuration

Figure 2 shows the system configuration for achieving

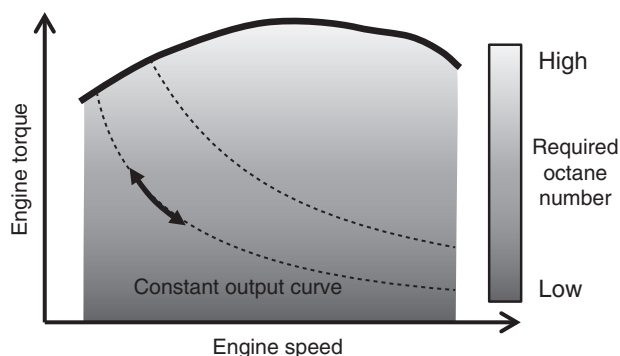


Fig. 1 Image of required octane number at MBT timing

in-cylinder octane number control. A fuel separation system was created to separate gasoline containing high-concentration ethanol from gasoline containing ethanol by means of a membrane using the principle of pervaporation (PV)⁽⁶⁾. The separated high-concentration ethanol (Fuel 1) and low-concentration ethanol (Fuel 2) are variously held in two tanks and then supplied to each engine cylinder in the desired injection ratio. In order to freely control the octane number in the cylinder in accordance with the required driving conditions, fuel injectors of two systems are used for each cylinder. This configuration allows the ethanol fraction in the cylinder to be changed instantaneously. The automatic transmission is interlocked with this system so as to control engine speed and engine torque to produce the demanded vehicle driving force.

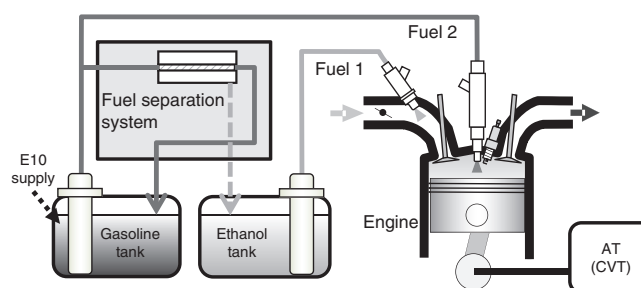


Fig. 2 System configuration

3. Experimental Device

A four-cylinder supercharged engine was used for the experiments in order to provide engine performance and to estimate the ethanol fraction required in the cylinder to obtain that performance. Table 1 shows the specifications for the two types of fuel used in the experiment, Table 2 shows the engine specifications, and Fig. 3 shows the set-up of the engine system. For the fuel, it is envisioned that ethanol and gasoline are separated from E10 gasoline. The system specification calls for the regular gasoline and ethanol to be held separately in independent tanks from which they are then supplied to each engine cylinder in the injection ratio desired. Each cylinder is configured with two fuel injection systems so that the ratio of the two types of fuel can be freely controlled to match driving conditions and the ratio of the total amount of fuel to the amount of intake air will be stoichiometric. Two injector patterns were verified. One was a basic configuration in which ethanol is supplied to the port injector and gasoline to the direct injector. The other, for comparison, was a configuration in which gasoline is supplied to the port injector and ethanol to the direct injector. The engine was equipped with a turbocharger, and the timing for opening and closing the intake valves could be controlled by variable valve timing and lift electronic control (VTEC) and continuous variable valve timing control (VTC). A specification was

Table 1 Fuel specifications

Fuels	Gasoline	Ethanol
Density [g/cm ³]	0.72	0.79
Boiling point [deg C]	-	78
Calorific value [J/g]	43.3	26.8
Octane number	91	115

Table 2 Engine specifications

Number of cylinders	4
Displacement [cm ³]	1755
Compression ratio	12.5
Combustion chamber	Pent roof
Valve control systems	VTEC, VTC
Fuel systems of each cylinder	Port injector Direct injector

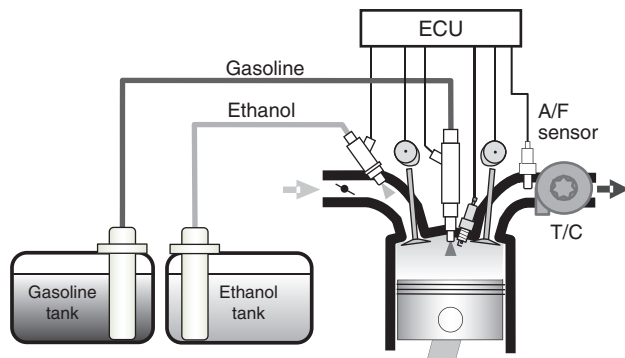


Fig. 3 Experimental engine system set-up

adopted that enables the timing for opening and closing the intake valves to be changed according to driving conditions, changing the intake air volume and the effective compression ratio and enabling supercharged Atkinson cycle operation.

4. Experimental Results

4.1. Comparison of Fuel Injection Configurations

Figure 4 shows the results from comparison of two injection system patterns, Injection System 1, in which ethanol is supplied to the port injector and gasoline to the direct injector, and Injection System 2, in which gasoline is supplied to the port injector and ethanol to the direct injector. The ethanol fraction required to obtain the same engine load (indicated mean effective pressure: IMEP) and the indicated thermal efficiency with Injection System 1 could be reduced to approximately 10 points lower than with Injection System 2. This is thought to be mainly because the influence of vaporization heat from gasoline injected directly into the cylinder was able to limit knocking even with small amounts of ethanol. Given the limited amount of usable ethanol made available in this system by separating

ethanol from E10 gasoline, it was considered advantageous to use smaller amounts of ethanol, and Injection System 1 was therefore adopted as the basic configuration.

4.2. Influence of the Ethanol Fraction

Figure 5 shows the influence on the basic configuration when the ethanol fraction in the cylinder is varied. The horizontal axis shows the IMEP, in relation to which are shown the ethanol fraction, the point at which the mass fraction burned (MFB) is 50% as an indicator of combustion timing, the indicated thermal efficiency, and the indicated specific fuel consumption (ISFC). In supercharged Atkinson cycle operation fueled only by gasoline, retarded ignition timing becomes necessary due to knocking when the IMEP exceeds 900 kPa, and the indicated thermal efficiency diminishes. The IMEP then reached the maximum load of 1600 kPa, and the engine could not operate at that high a load or higher. Under Case 1 conditions, by contrast, the use of ethanol in a high concentration enabled ignition at MBT timing up to high load (IMEP of 1800 kPa), and the indicated thermal efficiency increased. Furthermore, taking the influence of ethanol's lower calorific value into consideration, trial operation was conducted using an ethanol fraction adjusted to a lower level so that the engine would have about the same ISFC as during MBT operation under Case 2 conditions. The result was that the required ethanol fraction could be kept down to a level approximately 17 points lower. It was confirmed in this way that stoichiometric operation could be achieved by limiting the amount of ethanol used while also operating under high load (IMEP of 2100 kPa).

Comparison of Case 1 and Case 2 shows that when the driving mode is assumed to be the same because the ISFC is the same, the fuel consumption per mass is equal. Looking now at the amount of ethanol consumed from driving

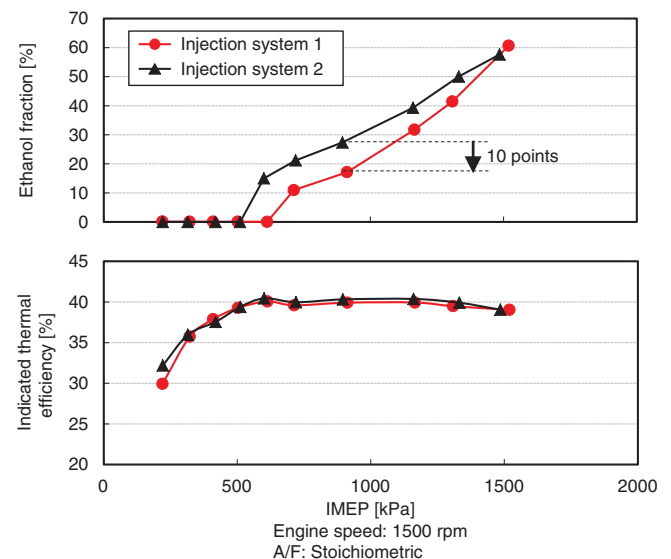


Fig. 4 Comparison of injection system

one time, Case 2 enables driving with a smaller amount of ethanol. By applying optimal ethanol injection control in this way so that thermal efficiency is reduced slightly but fuel economy is not reduced, the effects of ethanol (increased fuel economy and acceleration performance) can be provided with the limited amount of usable ethanol in E10 gasoline even to users who engage in relatively greater degrees of high-load operation. Taking Case 2 as the basic configuration, the amount of ethanol consumed can be adjusted within the margins of engine control by switching over to Case 1 when there is a surplus of ethanol or by other such means.

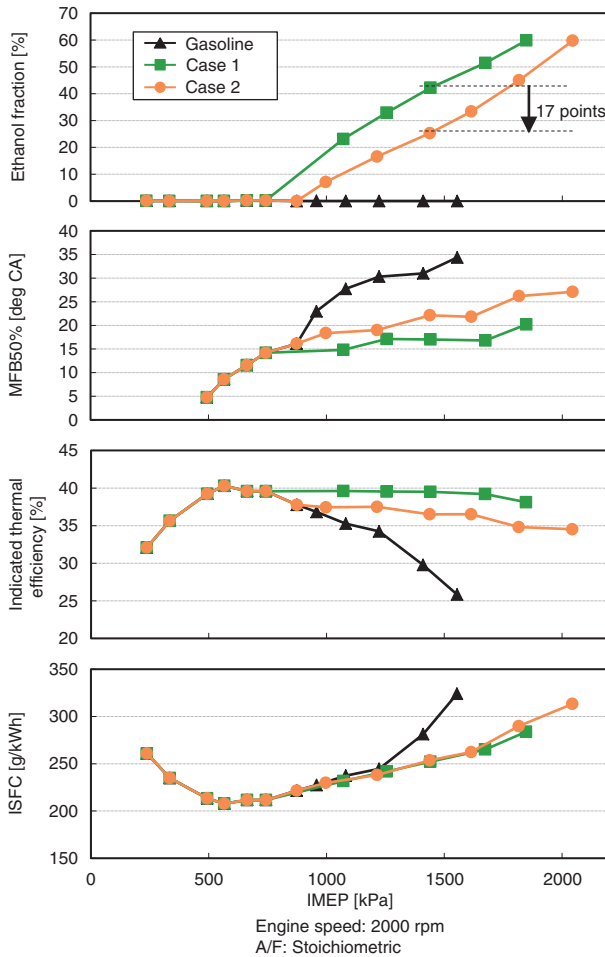


Fig. 5 Effect of altering ethanol fraction

5. Fuel Management Control Verification

5.1. Engine Speed and Load Control According to Residual Amount of Fuel

In light of the properties obtained through the experiments in chapter 4, a fuel management control logic that achieves effective use of ethanol in accordance with the residual amount of fuel was created. Figure 6 shows the concept of control by varying the engine operating points

(engine speed and load) according to the ethanol retention rate. The configuration that yields MBT operation when the engine speed is 1500 rpm is shown as Case 1. Similarly, the configuration that yields ISFC at about the same level as in MBT operation is shown as Case 2. Envisioning that the residual quantity of ethanol is small, the configuration that has the engine speed at 2000 rpm to conserve on ethanol use is shown as Case 3. For the purpose of comparison, the configuration that keeps the engine speed at 1500 rpm to conserve on ethanol use is shown as Case 4. Taking, for example, the case of an engine output of 30 kW, when the engine speed is 1500 rpm, the IMEP is approximately 1400 kPa, and when the engine speed is 2000 rpm, the IMEP is approximately 1100 kPa (envisioning the engine specifications in Table 2). When ethanol is in surplus, the engine operates at Point A of Case 1 where a high indicated thermal efficiency can be obtained. When the residual quantity of ethanol begins to diminish, operation at Point B of Case 2 can reduce the ethanol fraction to a level approximately 13 points lower than at Point A. The indicated thermal efficiency is lowered approximately two points, but the ISFC remains virtually unchanged. When the residual quantity of ethanol is further diminished, the configuration that limits the ethanol fraction is combined with cooperative control with the transmission for operation at Point C of Case 3. At this time, the indicated thermal efficiency drops approximately three points lower than

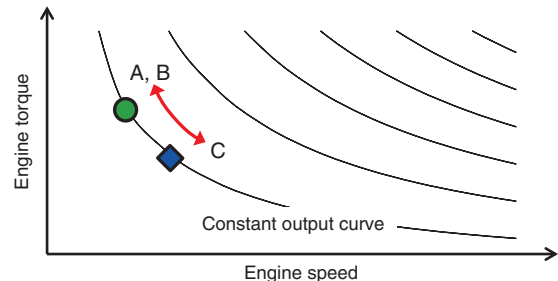
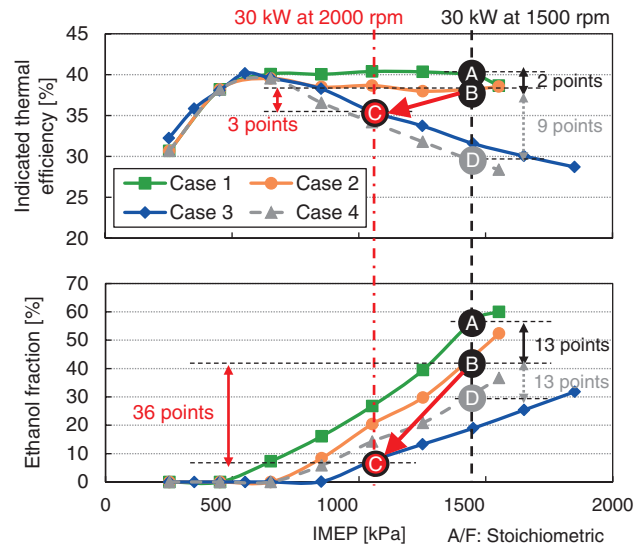


Fig. 6 Fuel management concept

at Point B, but the ethanol fraction can be held down by approximately 36 points. Operation at Point C can limit the amount of decrease in the indicated thermal efficiency by comparison with operation at Point D of Case 4, and can hold down the ethanol fraction by approximately 23 points. This combined use not only of engine control according to the residual amount of fuel, but also of transmission control, can limit the reduction in fuel economy while limiting the amount of ethanol consumed. In the case of a continuously variable transmission (CVT) that demands a constant vehicle driving force, the engine speed and engine torque trace a virtually constant output curve from Points A and B to Point C.

5.2. Fuel Management Control Logic

Figure 7 shows an overview of fuel management control and the control flow. First, the system calculates the vehicle driving force required due to driver operation. Next, the fuel concentration estimator calculates the ethanol concentration in the two types of fuel. The retained fuel amount estimator then uses equation (1) with those concentration values and the amounts of the two kinds of fuel remaining in the vehicle's tanks to calculate the percentage of ethanol present in the vehicle's fuel.

$$ER = (EC_1 \times RQ_1 + EC_2 \times RQ_2) / (RQ_1 + RQ_2) \quad (1)$$

ER: Total ethanol residual rate [%]

EC₁: Ethanol concentration of fuel 1 [%]

EC₂: Ethanol concentration of fuel 2 [%]

RQ₁: Ethanol residual quantity of fuel 1 [L]

RQ₂: Ethanol residual quantity of fuel 2 [L]

In the distributor, the optimal case is selected from the instances given, including those shown in Fig. 6.

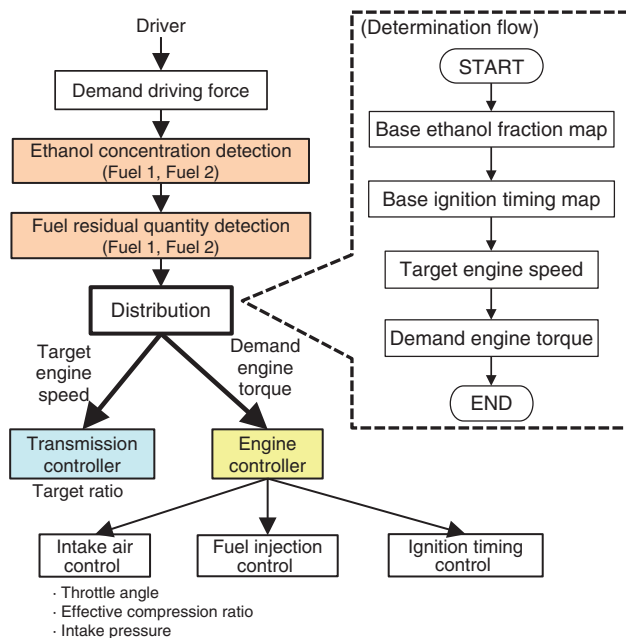


Fig. 7 Overview of fuel management control logic

Specifically, it determines the in-cylinder octane number demanded according to the ethanol retention rate, or in other words, the target value for the in-cylinder ethanol fraction (base map), and it decides the base ignition timing characteristic to match that value. The system then decides the transmission map (shifting schedule) so that the engine speed and load will produce optimal fuel consumption matched to the changing thermal efficiency characteristic. The driving force demanded from the driver is distributed as a target engine speed to the transmission and demand torque to the engine. In the transmission, the gear ratio is controlled so that the engine speed matches the target engine speed (target ratio, target gear). In order to make the engine generate the demand torque, the system controls the intake air volume as well as the fuel injection volume and ignition timing.

Figure 8 shows an overview of engine and transmission control. Following the base map previously determined from the present engine speed, intake air volume, and ethanol retention rate, the system decides the ethanol fraction and base fuel flow rate. The air-fuel ratio feedback coefficient from the exhaust gas together with knocking detection value, ethanol concentration sensor value, and other such information are used as the basis for calculating the estimated ethanol concentration, the fuel adhesion quantity, and other environmental correction values to factor in to determination of the injection volume and injection timing for the port injector and the direct injector. The base ignition timing is similarly calculated from the base map, corrections are factored in to the estimated octane number value estimated from knocking and other characteristics, and the ignition timing is decided. The transmission controller uses the demand driving force, the target engine speed, and the vehicle speed to decide the target ratio (target gear).

5.3. Fuel Economy and Ethanol Consumption Rate Verification Results

The fuel economy and ethanol consumption rate were verified by vehicle simulation. The engine performance obtained above was used, taking a mass-production vehicle equipped with a naturally aspirated engine (NA) as the base, and envisioning it equipped with a fuel separation system and supercharged engine. The vehicle conditions used in the simulation are shown in Table 3. In order to make effective use of this technology, which yields high efficiency characteristics up to high-load conditions, the engine was envisioned as a downsized supercharged engine with the engine displacement reduced. Case 1 was defined as using the ethanol fraction of Condition A, operating at MBT when there is a surplus of ethanol. Case 2 was defined as using the ethanol fraction of Condition B, operating with about the same ISFC as at MBT. Case 3 was defined as Condition C, using the injection ratio map configured to conserve ethanol when the ethanol retention rate has become low, and adding cooperative control with the transmission.

Envisioning that the available ethanol is separated from

E10 gasoline, it becomes necessary to limit the quantity of ethanol used to no more than 10% of the total fuel quantity. Here it is assumed that all the ethanol in E10 gasoline has been extracted by separation, and when all of this has been used, the ethanol consumption rate is defined as 100%. The calculations for this simulation use US06 mode as the driving mode with a high frequency of high-load operation, and US combined mode as the low-load fuel consumption reference mode. Figure 9 shows the characteristic of net

Table 3 Vehicle simulation conditions

	Ethanol fraction	Displacement [cm ³]	Weight [kg]	Compression ratio	Fuels
Mass-production vehicle 5AT (NA, Base)	—	1799	1361	10.5	E10
Case 1	A	1496	1423	12.5	Separated
Case 2	B				
Case 3	C				

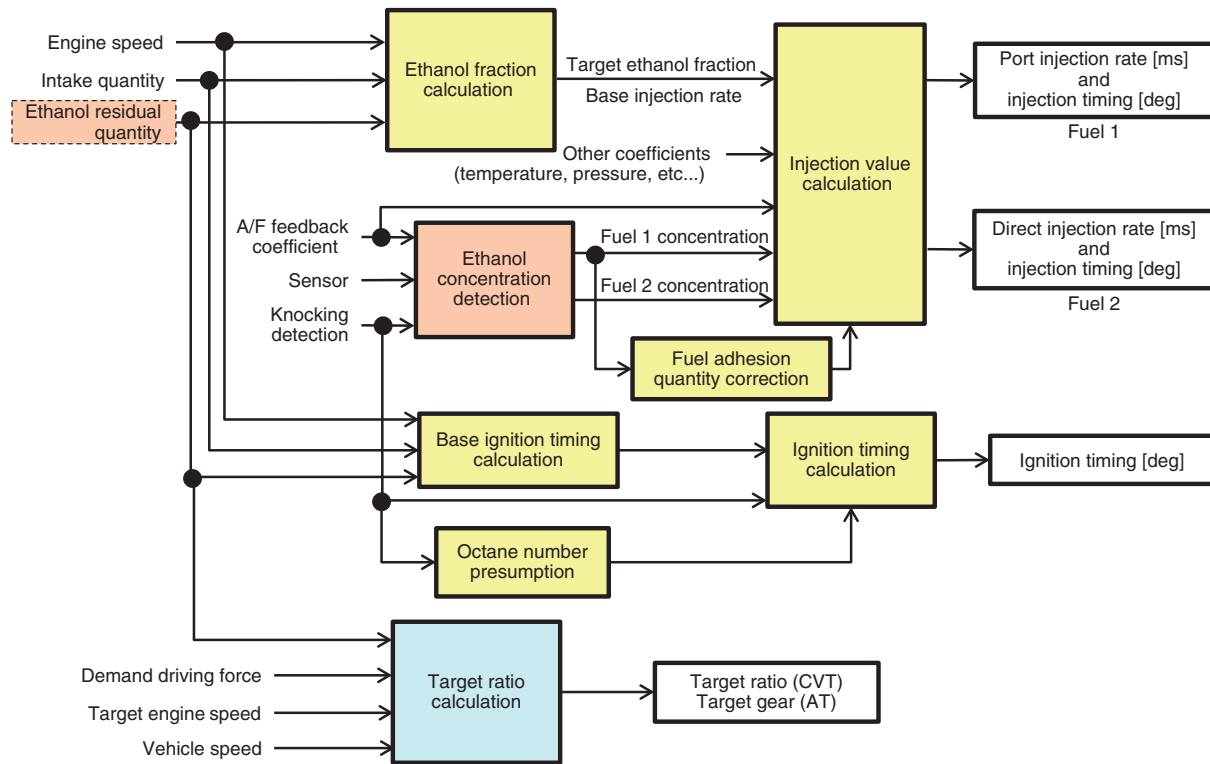


Fig. 8 Overview of engine and transmission control

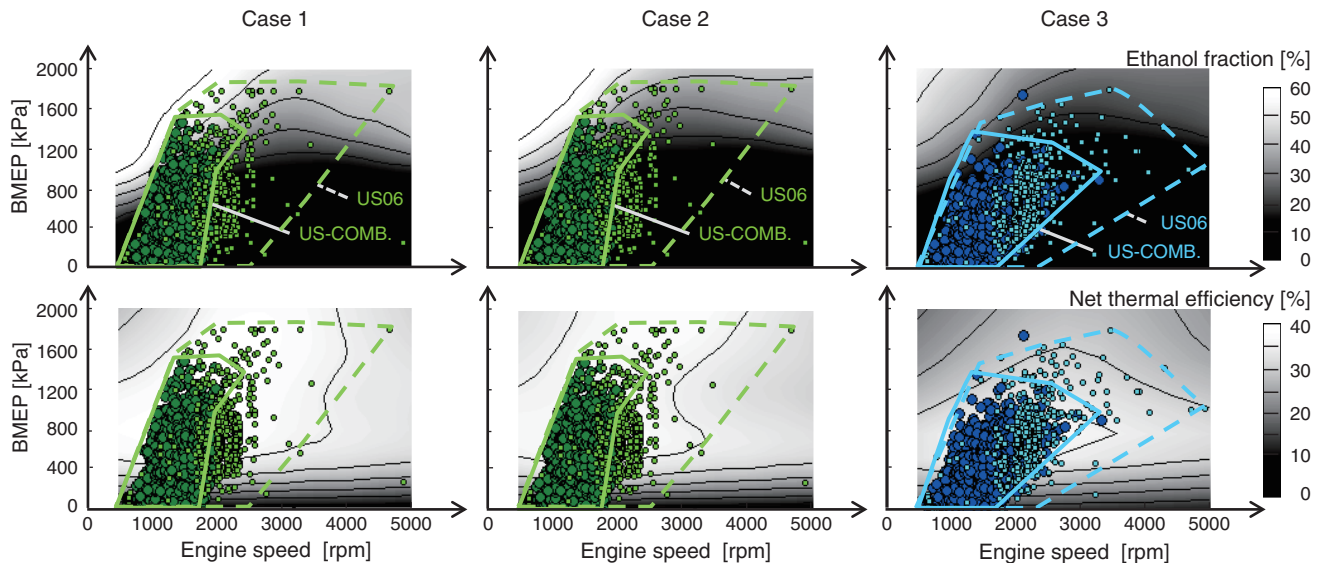


Fig. 9 Operating range with ethanol fraction and thermal efficiency

thermal efficiency when the ethanol fraction is taken as the variable, together with the driving plots (engine speed and brake mean effective pressure: BMEP) for the various driving modes in the simulation. Case 1 and Case 2 have the ethanol fraction set at a high level under high load, and it is apparent that the engine is operating at low speed and high load due to the shifting schedule matched to the high thermal efficiency found up to the high-load level. In Case 3, it is apparent how the operating range has shifted toward high speed and low load to match the change in the thermal efficiency characteristic.

Figure 10 shows the rate of increase in fuel economy relative to the base performance obtained in simulation together with calculated results for the ethanol consumption rate. In the US combined mode of Case 1, the rate of increase in fuel economy is the greatest, at approximately 26.8%, and the ethanol consumption rate comes out to approximately 98%. In the US06 mode, however, the ethanol consumption rate comes out to approximately 196%. This indicates that although there was no difficulty when the ethanol was in surplus, when driving conditions that involve repeatedly driving under frequent heavy load are envisioned, the ethanol retention rate begins to decline. In the configuration of Case 2, the increase in fuel economy in US combined mode is approximately 25.3% and that of the ethanol consumption rate is approximately 53%, showing that the quantity of ethanol consumed has successfully been limited by comparison with Case 1. Although the ethanol consumption rate was successfully limited to approximately 131% in US06 mode, however, when driving conditions that involve repeatedly driving under frequent heavy load are envisioned, the ethanol retention rate begins to decline. In the Case 3 configuration, by contrast, the ethanol consumption rate is approximately 65% in US06 mode, showing even greater limitation than in Case 2.

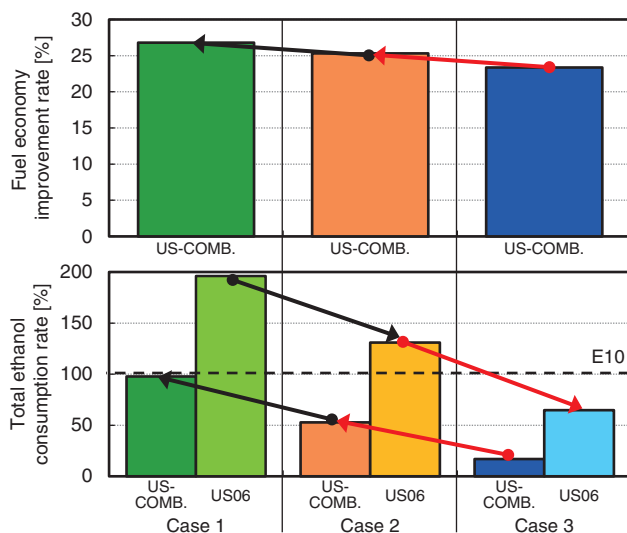


Fig. 10 Fuel economy improvement rate and ethanol consumption rate

The increase in fuel economy in US combined mode is approximately 23.4%, indicating that the decline in fuel economy has been successfully limited. The ethanol consumption rate then comes out to approximately 17%. When low-load operation continues, a surplus of ethanol occurs, at which point shifting to Case 2 and then to Case 1 will enable use of the surplus ethanol to increase fuel economy. Actual drivers will be able to respond to varying driving conditions, such as driving situation, residual amount of fuel and other such factors, by switching control configurations continuously from Case 1 to Case 3, in accordance with driver demand.

Given the above results, this system equipped with the fuel separation system and supercharged Atkinson cycle engine can be considered a technology capable of increasing fuel economy by making effective use of the ethanol separated from E10 gasoline in scenarios envisioning actual users. The implementation of fuel management control according to the ethanol retention rate enables driving without shortage of ethanol even under conditions when frequent high-load operation is required. The system is also able to increase fuel economy by making effective use of surplus ethanol under ordinary driving conditions.

6. Conclusion

The following findings were obtained from the results of verification of a supercharged Atkinson cycle engine combined with transmission control in order to make effective use of the separated fuels in engine systems that separate E10 gasoline containing ethanol into high-concentration ethanol and low-concentration ethanol:

- (1) Configuring the fuel injectors so that the port injector supplies ethanol and the direct injector supplies gasoline enables limitation of the quantity of ethanol used so that the limited quantity of ethanol contained in E10 gasoline can be used effectively.
- (2) Envisioning the separation of high concentration ethanol from E10 gasoline, the use of this fuel to effectively limit knocking enables high-load operation. The point is not just to inject large quantities of ethanol under every driving condition to increase the thermal efficiency, but rather to inject the optimal amount considering the indicated specific fuel consumption so that the reduction in fuel economy can be limited while limiting the quantity of ethanol used.
- (3) The fuel economy enhancement effect of this system, which makes optimal use of the two fuels obtained by fuel separation of E10 gasoline, was verified by vehicle simulation. The results indicate that, when applied in a downsized supercharged gasoline engine, this technology can increase the vehicle's fuel economy by up to a maximum of 26.8%.
- (4) When combined with fuel management control logic that implements cooperative control of the transmission according to the ethanol retention rate, this technology

enables driving without running short of ethanol even in the frequent high-load operation of US06 mode. Under low-load driving conditions such as found in US combined mode, the technology is also able to make effective use of surplus ethanol to increase fuel economy.

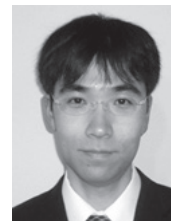
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