Annex XXXVIII Phase 2

A Report from the IEA Advanced Motor Fuels Implementing Agreement

Evaluation of Environmental Impact of Biodiesel Vehicles in Real Traffic Conditions

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About the Cover:

Feedstock, Biodiesel (BTL), Test vehicle, Test engine

Preface and Acknowledgement

This report focuses on the comparison of the real-world emissions between the case of using diesel fuel and biodiesel. For this purpose, the on-road driving tests were made, by applying biodiesel, with the latest diesel vehicles complying with the latest emission regulations while avoiding any particular modification to them. For measurement, a PEMS (Portable Emission Measurement System) was used.

Note that the heavy-duty diesel vehicles complying with the latest emission gas regulations of Japan also meet the heavy-duty vehicle fuel economy regulations introduced by Japan ahead of other countries of the world. Since application of biodiesel not only presents problems for the emission gas, but also has non-negligible influence on the fuel economy, the survey was also made for the real-world fuel economy.

This report has been produced as the final version deliverable from the International Energy Agency's (IEA's) Advanced Motor Fuels (AMF) Implementing Agreement (Annex XXXVIII - Evaluation of Environmental Impact of Biodiesel Vehicle in Real Traffic Conditions).

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Acronyms and Abbreviations

AMF	Advanced Motor Fuels
ATDC	After Top Dead Center
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVS	Constant Volume Sampler
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
FAME	Fatty Acid Methyl Esther
GPS	Global Positioning System
GVW	Gross Vehicle Weight
HVO	Hydrotreated Vegetable Oil
IBP	Initial Boiling Point
IEA	International Energy Agency
LEVO	Organization for the Promotion of Low Emission Vehicles
NOx	Nitrogen Oxide
NMHC	Non Methane Hydro Carbon
NTSEL	National Traffic Safety and Environment Laboratory
PEMS	Portable Emission Measurement System
PM	Particulate Matter
R. H. R.	Rate of Heat Release
RME	Rape-seed Methyl Esther
HC	Hydro Carbon

Executive Summary

Biodiesel has received much attention recently as a fuel greatly contributing to global environmental conservation, due to its capability of reducing CO_2 emissions and resource recycling. In fact, activities for expanding the production and utilization of biodiesel are positively being pushed forward throughout the world. For diesel vehicles complying with the latest emission gas regulations, on the other hand, efforts are being made to enhance the engine performance and to reduce hazardous emission contents by means of advanced elementary technologies and precise electronic control.

This study intends to compare real-world emissions between the case of using conventional diesel fuel and biodiesel such as Fatty Acid Methyl Ester (FAME), Hydrotreated Vegetable Oil (HVO) and Biomass to Liquid (BTL). For this purpose, an on-road driving test was performed by applying biodiesel, with the latest diesel vehicles complying with the Japanese 2009 emission regulations while avoiding any particular modification to them. For measurement, Portable Emission Measurement System (PEMS) was used. Before the comparison, an exhaust gas emission test using a chassis dynamometer was conducted so as to examine the basic performance of emission gas and fuel economy. In addition, an engine bench test was also done to assess the basic characteristics of combustion and emission characteristics in BTL.

Test fuels

The fuels tested in this study were ultra-low-sulfur diesel (ULSD) as conventional diesel fuel, FAME, HVO, BTL, mixed fuel of ULSD and FAME, mixed fuels of ULSD and HVO, and mixed fuel of ULSD and BTL. Table ES-1 shows the properties of test fuels.

Table ES-1 Properties of test fuels

Fuel		ULSD	FAME	HVO	BTL (Lot 1)	BTL (Lot 2)
Density (15 deg.C) [g/cm^3]		0.8295	0.8853	0.7798	0.7973	0.8142
Kinematic viscosity [mm^2/s]		3.655 (@30 deg.C)	4.605 (@40 deg.C)	3.708 (@30 deg.C)	3.180 (@ 30 deg.C)	5.258 (@ 30 deg.C)
Flash point [deg.C]		68.0	176.0	91.0	<2.0	10.0
Sulfur content [ppm]		8	2	<1	<1	<1
Cetane number		57.2	55.3	85.8	65.7	67.7
Pour point [deg.C]		-22.5	-2.5	-15.0	-10.0	-10.0
Distillation temp. [deg.C]	IBP	168.0	207.0	153.5	72.0	82.5
	10%	210.0	353.0	267.5	142.0	219.0
	50%	279.5	353.0	281.5	299.5	313.0
	90%	337.5	358.0	294.0	330.0	340.0
	EP	358.5	486.0	303.5	353.5	357.0
CHO [wt.%]	C	86.3	77.1	84.8	85.5	85.4
	H	13.7	12.1	15.1	14.5	14.6
	O	<0.1	10.8	<0.1	<0.1	<0.1
Lower heating value [kJ/kg]		43 170	37 340	44 110	43 270	43 440

Test vehicle

Table ES-2 indicates the specification of testing vehicle and Figure ES-1 shows its appearance. This test vehicle complied with the Japanese 2009 emission regulation.

Table ES-2 Specifications of the test vehicle

Vehicle type	Cargo truck
Vehicle model	Isuzu ELF
Vehicle mass	3 530 kg
Maximum pay load	3 000 kg
GVW	6 585 kg
Length x width x height	6 600 mm x 2 220 mm x 2 450 mm
Transmission	6MT
Engine type	Inline 4-cylinder turbo diesel
Engine model	4JJ1-TCH
Displacement	2 999 cm^3
Maximum power	110 kW / 2 800 rpm
Maximum torque	375 Nm / 1 400 ~ 2 800 rpm
Aftertreatment	DOC, DPF
Emission regulation	Japanese 2009 regulation

Figure ES-1 Broad overview of the test vehicle

Emission Evaluation with the Chassis Dynamometer

Before conducting the emission gas tests under on-road driving conditions, it is necessary to obtain the basic data of emission gas and fuel economy performance in using each biodiesel under the predetermined test cycle and condition.

Figure ES-2 shows the results of the measurement for the emissions [g/kWh] and energy consumption [MJ/km] of NOx, PM, CO, NMHC and CO_2, when the mixing ratio of FAME to ULSD was changed from 100:0 to 0:100. For reference, the results for the vehicle complying with the Japanese 2005 emission regulation reported in the Phase 1 in this Annex are also shown in this figure. In both vehicles and all mixing ratios, every emission gas except for NOx was recorded appreciably below the upper limit of each regulation. The NOx emissions showed a higher level than the limit of each regulation even in operation with FAME 0%, that is, ULSD 100%. Moreover, the NOx emissions increased with an increase in the FAME ratio. The CO_2 emissions from the vehicle complying with the Japanese 2009 regulation slightly increased with the increase in the mixing ratio of FAME, due to the difference in H/C ratio in the fuel. However, the energy consumption maintained almost the same level regardless of the FAME ratio, and the vehicle even in using FAME achieved the equivalent energy efficiency to that of ULSD.

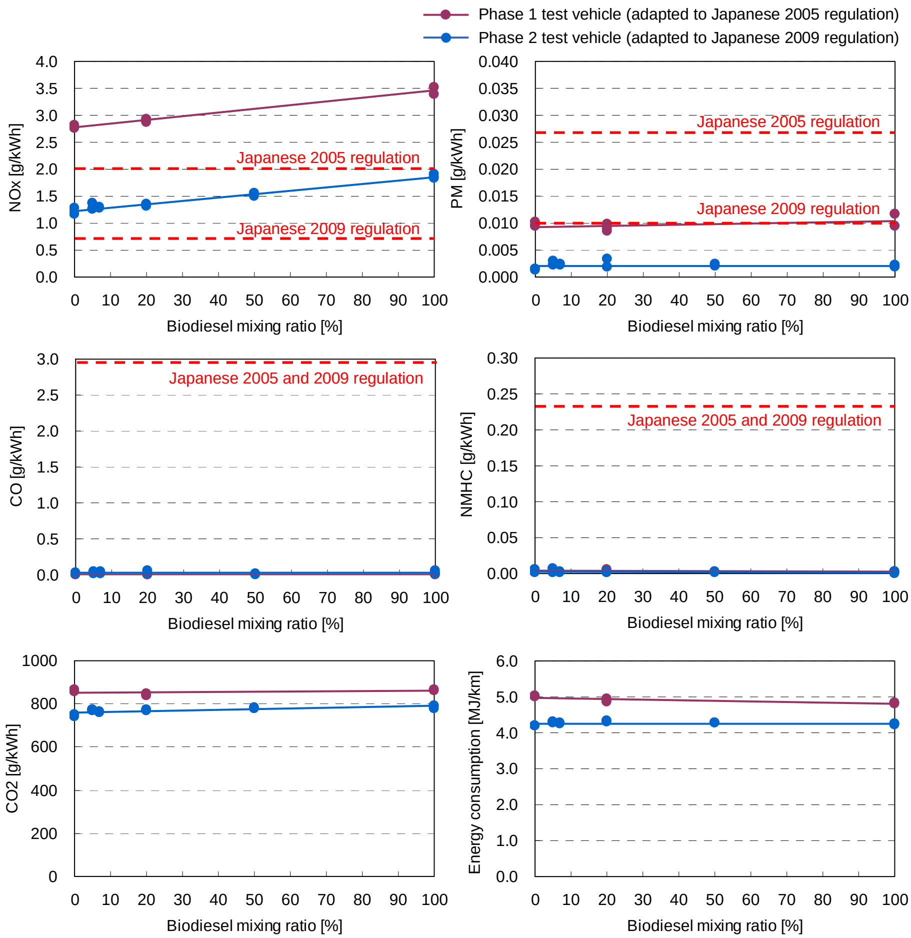


Figure ES-2 Emission and energy consumption characteristics of the JE05 driving cycle using FAME as fuel

Figure ES-3 shows the results of measurement for the emissions [g/kWh] of NOx, PM, CO, NMHC and CO_2 and energy consumption [MJ/km], when the mixing ratio of HVO to ULSD was changed from 100:0 to 0:100. The emissions of PM, CO and NMHC did not depend on the mixing ratio of HVO. The NOx emissions in both vehicles exceeded the limit of each regulation, but unlike the case of FAME, the emissions were hardly affected by a change in the mixing ratio of HVO. The CO_2 emissions slightly decreased with the increase in the mixing ratio of HVO. It was due to the difference in H/C ratio in the fuel. However, the energy consumption maintained almost the same level regardless of the HVO ratio and even in using HVO the vehicle achieved the equivalent energy efficiency to that of ULSD.

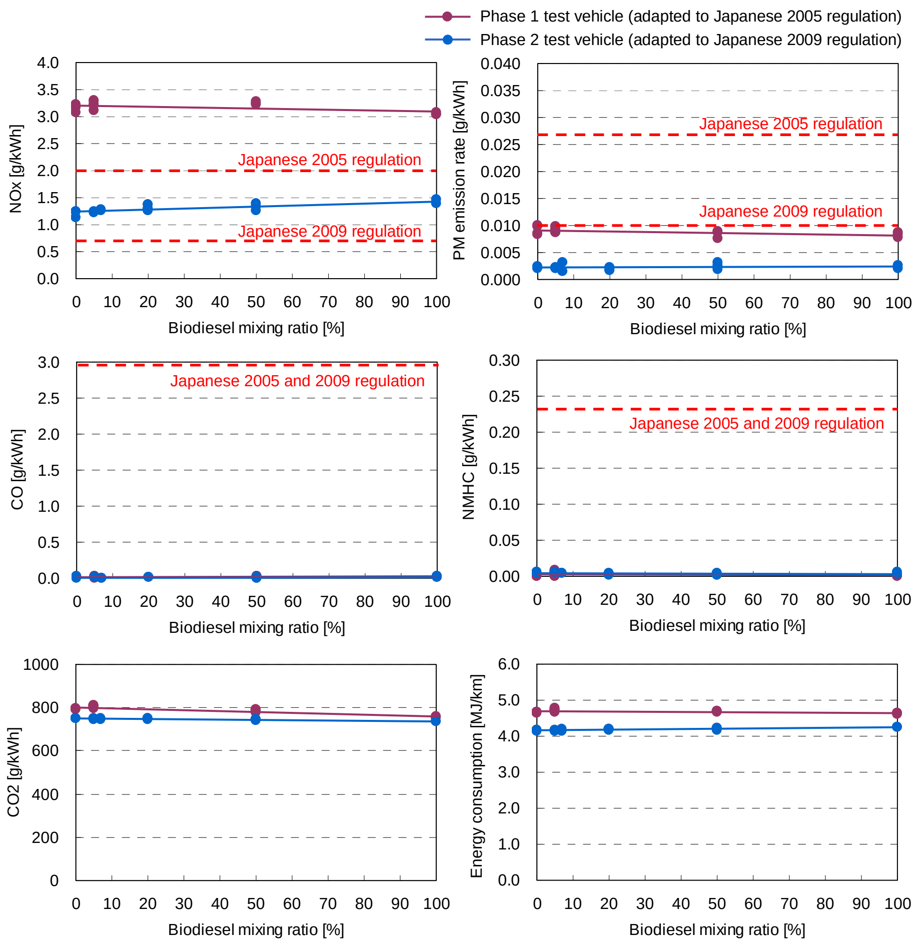


Figure ES-3 Emission and energy consumption characteristics of the JE05 driving cycle using HVO as fuel

Figure ES-4 indicates the results of measurement for the emissions [g/kWh] of NOx, PM, CO, NMHC and CO_2 and energy consumption [MJ/km], when the mixing ratio of BTL to ULSD was changed at 0:100, 20:80 and 100:0. As with the case of FAME and HVO, the emissions of PM, CO and NMHC were appreciably below the upper limit of the regulation in both production lots and all mixture ratios of BTL. However, the NMHC emissions in BTL (Lot 1) slightly increased with the increase in the mixing ratio of BTL, although it was not seen in BTL (Lot 2). Along with the case of FAME and HVO, the NOx emissions exceeded the regulatory limit in any mixing ratio. The effects of the BTL mixing ratio on the NOx emissions had the same tendency as NMHC, namely, in BTL (Lot 1) the emissions increased with the increase in the mixture ratio, but in BTL (Lot 2) it was controlled. The CO_2 emissions showed the same tendency as the case of HVO, namely, due to the difference in H/C ratio, the emissions slightly decreased with the increase in the mixture ratio of BTL, but the energy consumption maintained almost the same level regardless of the BTL ratio. It can be said that even in using BTL the vehicle achieved the equivalent energy efficiency to that of ULSD.

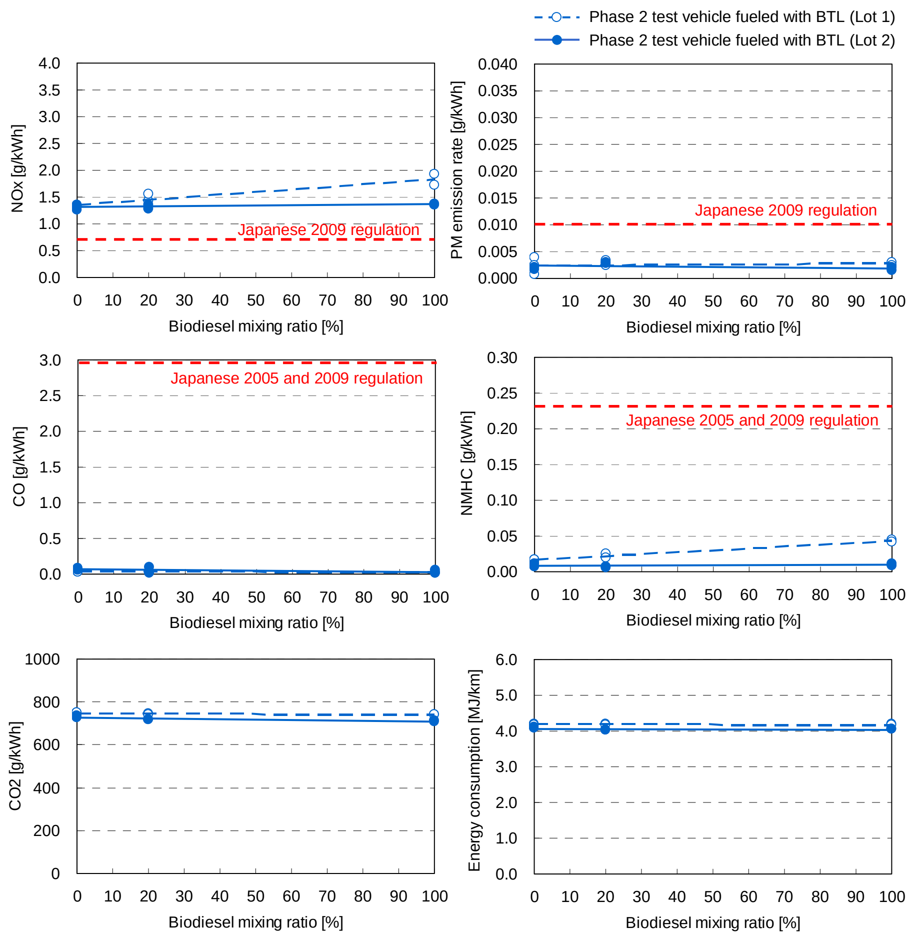


Figure ES-4 Emission and energy consumption characteristics of the JE05 driving cycle using BTL as fuel

Analysis of Combustion Characteristics of BTL with the Engine Test Cell

The exhaust gas emission tests with the chassis dynamometer resulted in the different NOx emission characteristics in using two types of BTL of different properties. In order to conduct a more detailed examination of the factors in this difference, the engine bench tests were conducted using the same type of engine as the testing vehicle.

The comparison of cylinder pressure and rate of heat release under high speed condition in JE05 test cycle is shown in Figure ES-5. The combustion by pilot injection was apparently varied even in BTL (Lot 1) and BTL (Lot 2), and thus it was considered that BTL (Lot 1) with activated combustion had the highest NOx emissions. The factor was inferred that, as represented by the difference in flash point, hydrocarbon components with low boiling point evaporated at the early stage and stimulated the ignition.

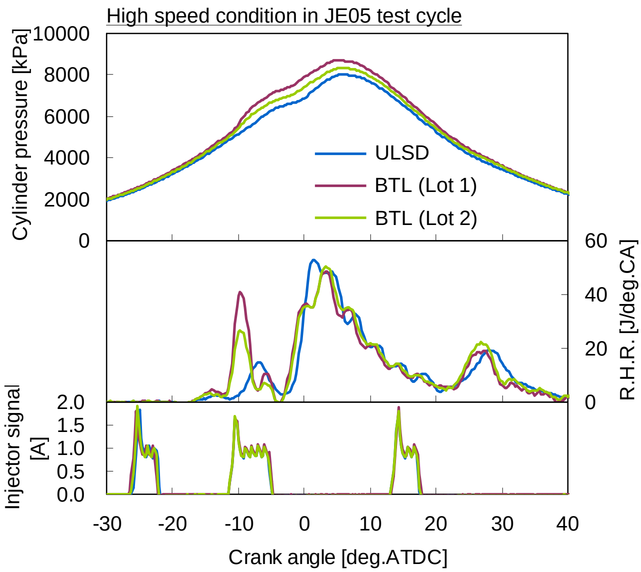


Figure ES-5 Comparisons of cylinder pressure and rate of heat release between ULSD, BTL (Lot 1) and BTL (Lot 2) under the high speed condition in JE05 test cycle

Evaluation of Real-world Emission in the On-road Driving Test

The multiple regression analyses were conducted to all the test results in using all the fuels, concretely, ULSD, FAME 5%, FAME 100%, HVO 5%, HVO 7%, HVO 20%, HVO 50%, HVO 100%, BTL 20% and BTL 100%, and then a mutual estimation formula which could be applied to all the fuels tested in this study was developed. Formula (ES-1) shows the estimation formula of NOx emissions.

$$\begin{aligned} NOx[g/kWh] = & -1.466\times10^{-6}\cdot\overline{N_e}^2 + 6.768\times10^{-3}\cdot\overline{N_e} \\ & + 3.520\times10^{-4}\cdot\overline{T_e}^2 - 8.109\times10^{-2}\cdot\overline{T_e} \\ & - 7.476\times10^{-3}\cdot\overline{V}^2 + 2.183\times10^{-1}\cdot\overline{V} \\ & + 3.292\times10^{-4}\cdot\overline{T_a}^2 - 5.699\times10^{-4}\cdot\overline{T_a} \\ & + 1.247\times10^{-1}\cdot\overline{P_w}^2 - 6.784\times10^{-1}\cdot\overline{P_w} \\ & - 1.536\times10^{-4}\cdot H_f - 9.043\times10^{-1}\cdot H/C \\ & + 5.361\times10^{0} \end{aligned} \quad \text{(ES-1)}$$

Hence, as for the vehicle driving, the average engine speed, N_e[rpm] and the average engine torque, T_e[N·m] during a positive value of the engine torque were used as the variables. Additionally, as the factors explaining road conditions, the average vehicle speed, V[km/h] during tests was used. As for the environmental conditions, both the average temperature, T_a[deg.C] and the average water vapor partial pressure, P_w[kPa] during tests were used as the variables. As for the fuel properties, the lower heating value per unit volume, H_f[kJ/L] and the H/C ratio were added to the explanatory variables.

Figure ES-6 shows the relation between the NOx emission estimation values calculated by the formula (ES-1) and the actual measurement values obtained by the on-road driving tests. It was ensured by this figure that there was a high correlation between them even when the multiple regression analyses were conducted to all the test fuels used in this study. Therefore, the validity of this method for comparing NOx emissions in fuels under real-world conditions was regarded as being generally secured.

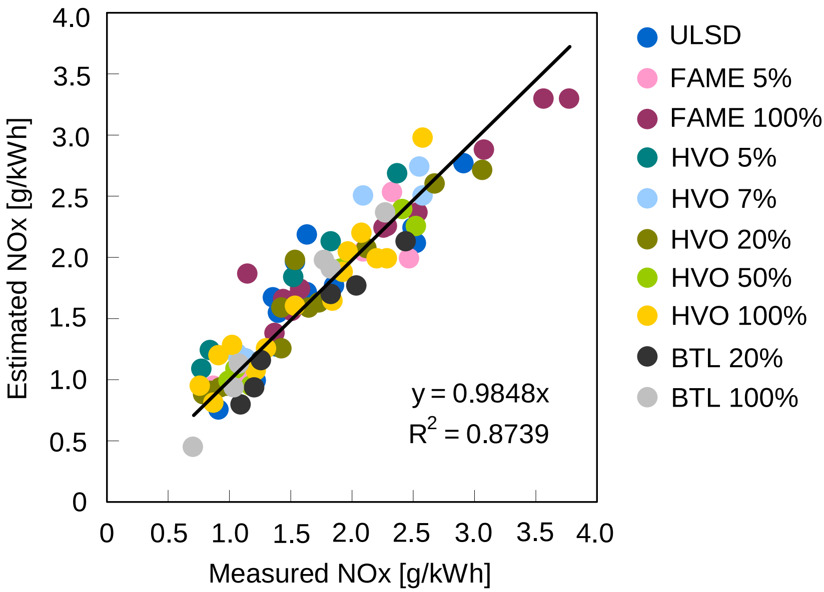


Figure ES-6 Comparisons between measured NOx emission and estimated NOx emission calculated by the results of multiple linear regression analysis using the results of ULSD, FAME 5%, FAME 100%, HVO 5%, HVO 7%, HVO 20%, HVO 50%, HVO 100%, BTL 20% and BTL 100%

Figure ES-7 shows the estimation results of the NOx emissions under the same conditions shown in Table ES-3 in using the four fuels of ULSD, FAME 100 %, HVO 100% and BTL 100%. As a result, it was concluded that FAME 100% especially increased the NOx emissions. In using HVO, on the other hand, it was inferred that the NOx emissions could be maintained at the equivalent level to those of ULSD. The case of BTL 100% showed that the NOx emissions were equivalent of those of ULSD.

As a result, under on-road driving conditions in the suburbs of Tokyo, it was verified that the highest NOx emission value was recorded in the condition of cold and low humid winter time without consciousness of eco-driving, concretely ca. 2.5 g/kWh in using ULSD and ca. 3.0 g/kWh in FAME 100%. In using HVO 100% and BTL 100%, the NOx emissions were almost the same or slightly larger compared to those of ULSD. These exhaust gas levels in the real-world far exceeded the limit of the Japanese 2009 regulation, 0.7 g/kWh with which the test vehicle used in this study had complied. It means that the emission level could be even worse depending on fuels. Therefore, it is deemed appropriate to apply a paraffinic hydrocarbon biofuel such as HVO or BTL to the latest heavy-duty diesel vehicles so as to prevent the exhaust gas from worsening in the real-world.

Table ES-3 Common evaluation conditions of real-world NOx emission based on the real-world driving test for each fuel

Condition	A	B	C	D
Assumed season	Summer (Tokyo)	Summer (Tokyo)	Winter (Tokyo)	Winter (Tokyo)
Eco-drive	Not considered	Considered	Not considered	Considered
Average engine speed [rpm]	1670	1330	1670	1330
Average engine torque [Nm]	146	133	146	133
Average vehicle speed [km/h]	19	19	19	19
Average ambient temperature [deg.C]	35	35	10	10
Average water vapor partial pressure [kPa]	2.7	2.7	0.2	0.2

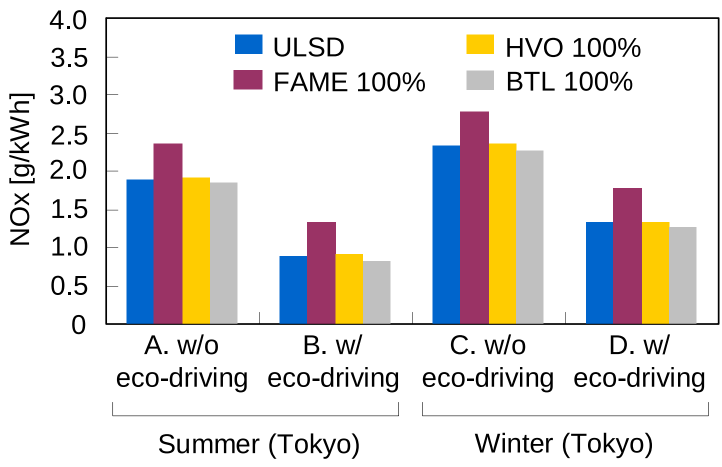


Figure ES-7 Evaluation results of real-world NOx emission characteristics estimated by equation (ES-1) in using ULSD, FAME 100%, HVO 100% and BTL 100% under common conditions in Table ES-3.

As with the case of the evaluation of NOx emissions, the multiple regression analyses were conducted to all data of energy consumption and CO_2 emissions. The explanatory variables used in this analysis were as follows; as for the vehicle driving, the average engine speed N_e[rpm] and engine torque T_e[N·m] during a positive value of the engine torque and the average vehicle speed during tests, and as for the fuel property, the Lower heating value H_f [kJ/kg], H/C ratio and O/C ratio. The formulae (ES-2) and (ES-3) show the estimated formulae of energy consumption EC[MJ/km] and CO_2 emissions [g/km] obtained by the multiple regression analyses.

$$\begin{aligned} EC[MJ/km] = {} & 3.075\times10^{-3}\cdot\overline{N_e} + 1.059\times10^{-2}\cdot\overline{T_e} \\ & -1.063\times10^{-1}\cdot\overline{V} + 4.686\times10^{-4}\cdot H_f \\ & -2.193\times10^{0}\cdot H/C + 2.257\times10^{1}\cdot O/C \\ & -1.482\times10^{1} \end{aligned} \tag{ES-2}$$

$$\begin{aligned} CO_2[g/km] = {} & 2.249\times10^{-1}\cdot\overline{N_e} + 7.698\times10^{-1}\cdot\overline{T_e} \\ & -7.927\times10^{0}\cdot\overline{V} + 2.542\times10^{-2}\cdot H_f \\ & -1.887\times10^{2}\cdot H/C + 1.269\times10^{3}\cdot O/C \\ & -6.431\times10^{2} \end{aligned} \tag{ES-3}$$

Figure ES-8 shows the relation between the estimated energy consumption values calculated by formula (ES-2) and the measurement values obtained by tests, and the relation between estimated CO_2 emission values calculated by formula (ES-3) and the measurement values. From this figure, it can be verified that both of the estimated results of energy consumption and CO_2 emissions showed a high correlation with the actual measurement results. Thus, it can be said that this method can estimate the energy consumption and CO_2 emissions and compare these values in the real-world among fuels.

Accordingly, this study focused on the driving conditions, in particular the condition with non-consciousness of eco-driving (the average engine speed of 1670 rpm and the average engine torque of 146 Nm) identical to the condition A and C in Table ES-3, and the condition with consciousness of eco-driving (the average engine speed of 1330 rpm and the average engine torque of 133 Nm) identical to the condition B and D. Under these conditions, the energy consumption and CO_2 emissions in each fuel were estimated by using formulae (ES-2) and (ES-3). The comparison results are shown in Figure ES-9. This figure indicates that every biofuel did not aggravate the energy consumption compared to ULSD but maintained the equivalent level. The CO_2 emissions in each biofuel were the same level or slightly decreased compared to ULSD. Moreover, it was clear that the eco-driving in every fuel decreased the energy consumption and CO_2 emissions by ca. 20 percent.

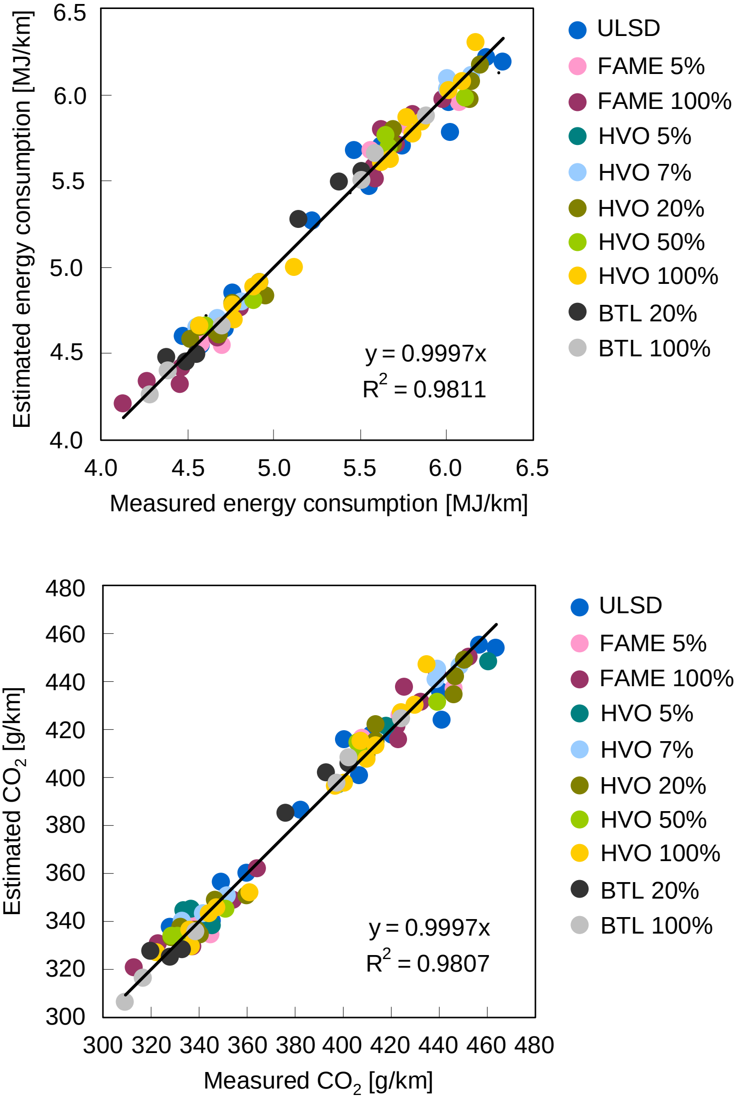
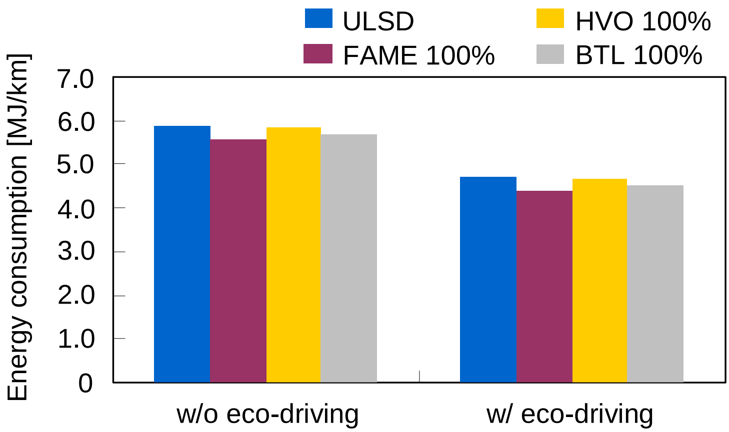


Figure ES-8 Comparisons between measured energy consumption and CO_2 emission and estimated energy consumption and CO_2 emission calculated by the results of multiple linear regression analysis using the results of ULSD, FAME 5%, FAME 100%, HVO 5%, HVO 7%, HVO 20%, HVO 50%, HVO 100%, BTL 20% and BTL 100%



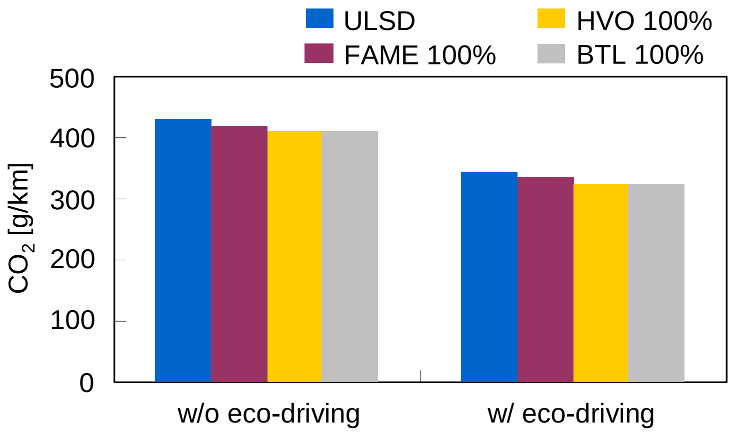


Figure ES-9 Evaluation results of real-world energy consumption and CO_2 emission characteristics estimated by equation (ES-2) and (ES-3) in using ULSD, FAME 100%, HVO 100% and BTL 100% under common conditions

Conclusions

This Annex introduced the performance evaluations for the emission gas and fuel economy to the heavy-duty diesel vehicle fueled with biodiesels of FAME, HVO and BTL under on-road driving conditions. The vehicle used in this study complied with the latest emission regulations and was equipped with PEMS (Portable Emission Measurement System). Before the on-road driving tests, the exhaust gas emission tests were performed using the chassis dynamometer so as to verify the basic performance of emission gas and fuel economy. Moreover, the evaluation for the characteristics of combustion and exhaust gas in BTL was conducted using the engine test cell, in order to consider the results of exhaust gas tests with the chassis dynamometer in using BTL as fuel. The findings obtained by the above evaluation are described below.

The vehicle used in this Annex had the DOC and DPF as aftertreatment system, and then the emissions of CO and NMHC by the chassis dynamometer emission measurement were sufficiently below the upper limit of Japanese 2009 regulation even in using each biodiesel. From the both results of chassis dynamometer emission test and on-road driving test, on the other hand, the NOx emissions varied depending on the biodiesel, to be specific, in using FAME the NOx emissions significantly increased with the increase in the mixing ratio of FAME to ULSD. The same phenomenon was seen in using BTL especially with an extremely low flash point. This type of BTL may contain large amounts of hydrocarbon components with low boiling point, and thus the tendency that the NOx emissions increased with the increase in the mixing ratio of BTL to ULSD was observed. On the other hand, in using HVO and BTL with a relatively high flash point, the NOx emissions maintained almost the same level as those of ULSD. The fuel consumption was not influenced by the change in fuel when it was evaluated by using an energy consumption index. In addition, the driving operation with consciousness of eco-driving could decrease the energy consumption and CO_2 emissions by ca. 20 percent compared to the non-consciousness of eco-driving in using every fuel.

1. Background

Biodiesel has been highlighted recently as a fuel greatly contributing to global environmental conservation, because of its capability of reducing CO_2 emissions and resource recycling. Actually, activities for expanding the production and utilization of biodiesel are positively being pushed forward throughout the world. First-generation biodiesels, for example, Fatty Acid Methyl Ester (FAME) such as RME, SME and PME have recently been followed by the development of second-generation biodiesels with more stable characteristics. In Japan, the first-generation oil, that is, FAME based on waste cooking oil, is used in diesel vehicles [1].

For diesel vehicles complying with the latest emission gas regulations, on the other hand, efforts are being made to enhance the engine performance and to reduce hazardous emission contents by means of advanced elementary technologies and precise electronic control. It should be noted however that, in general, these technologies prove the most appropriate when a conventional diesel fuel is used as fuel except for vehicles complying with EURO VI emission regulation with biodiesel in addition to conventional diesel fuel. If biodiesel such as FAME, differing greatly in fuel characteristics from conventional diesel fuels, is used for this type of vehicle, the emission gas characteristics will be deteriorated, which in turn may hinder wide application of biodiesel. Practically, it was reported that, when these vehicles were run in certification test mode such as JE05 mode without any particular modification of the engine and the fuel was simply changed from conventional diesel fuel to biodiesel, the consequence was an increase in NOx emission rate [2]-[10].

Namely, wide application of biodiesel proves highly effective in terms of CO_2

emission reduction, while raising concern about adverse effect on the atmospheric environment in urban areas. If factors hindering such wide application are to be eliminated, it will be essential to establish the characteristic standards of biodiesel compatible with the latest emission gas regulations. For this purpose, the actual emission gas state when biodiesel is applied to the latest vehicles has to be identified as the basic data needed for the above standards.

2. Objectives of the Study

In Japan, for example, in Kyoto city, vehicles (buses, refuse collecting trucks) are practically run on FAME biodiesel made from waste cooking oil. Needless to way, countries other than Japan are doing similar activities. In order to apply biodiesel to the latest diesel vehicles, therefore, it is critical to figure out the characteristics of not only the emission gas in the certification test mode, but also that during driving in the real world.

In this context, this study intends to compare real-world emissions between the case of using conventional diesel fuel and biodiesel. For this purpose, an on-road driving test was performed by applying biodiesel, with the latest diesel vehicles complying with the latest emission regulations while avoiding any particular modification to them. For measurement, Portable Emission Measurement System (PEMS) was used [11]-[13].

Note that the heavy-duty diesel vehicles complying with the latest emission gas regulations of Japan also meet the heavy-duty vehicle fuel consumption regulations introduced by Japan ahead of other countries of the world. Since application of biodiesel presents not only problems for the emission gas, but also non-negligible influence on the fuel consumption, a survey was also made of the real-world fuel consumption.

The assessment of real-world emissions in using a conventional diesel fuel, FAME as the first generation biodiesel and Hydrotreated Vegetable Oil (HVO) [14]-[17] as the second generation to the Heady-duty diesel vehicle complying with the Japanese 2005 regulation was already performed and the results can be founded in the Phase 1 in this Annex 38. Then, the phase 2 aimed to assess the real-world emissions and fuel consumption of a Heavy-duty vehicle complying with the Japanese 2009 regulation fueled with the three fuels used in the Phase 1 and additionally Biomass to Liquid (BTL).

3. Overview of the Annex

3.1. Test matrix

In this Annex, the real-world emissions from the latest diesel vehicles fueled with biodiesel will be evaluated. The test matrix is shown in Table 3-1. The test target is a vehicle complying with the Japanese 2009 emission regulation.

Table 3-1 Test matrix

Vehicle	Fuel	Test			Test period
		Chassis dynamometer test (JE05 mode)	Real-world driving test (Hot)	Engine bench test (Steady state)	
The vehicle complied with Japanese 2009 emission regulation	Conventional diesel fuel (ULSD)	x	x	x	2.5 years January 2012 ~ June 2014
	FAME (WME)	x	x		
	HVO	x	x		
	BTL	x	x	x	

In addition to the vehicle tests, an engine bench test was carried out in order to evaluate the basic combustion and emission characteristics of BTL.

3.2. Expected results

By implementing the plan described in this Annex, it can be verified whether biodiesel such as FAME, HVO and BTL adapts to the latest diesel vehicles as typified by Japanese vehicles, which have met the strict regulations. In this regards, there are two important points; vehicles should not be given special customization in providing these fuels in vehicles, and an on-road driving test should be conducted as well as a chassis dynamometer test for compliance confirmation, and then the emission gas performance in the real world should be evaluated. In this way, the environmental impact by biodiesel-fueled vehicles can be comprehensively assessed.

3.3. Period

2.5 years (January 2012 ~ June 2014)

3.4. Schedule

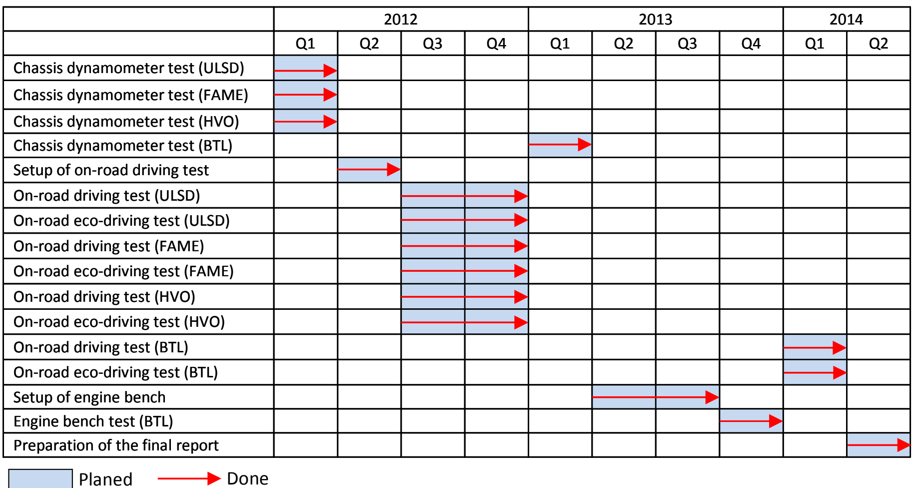


Figure 3-1 Test schedule

3.5. Participants of this annex

Participating countries are Finland, Germany, Japan (LEVO), Sweden and the United States

Cost share: Finland, Germany, Sweden and the United States

Task share: Japan (LEVO)

3.6. Management

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(2) Test provision

Neste Oil Oyj. in Finland provides HVO (NExBTL®) and Micro Energy Co. in Japan provides BTL to NTSEL in kind.

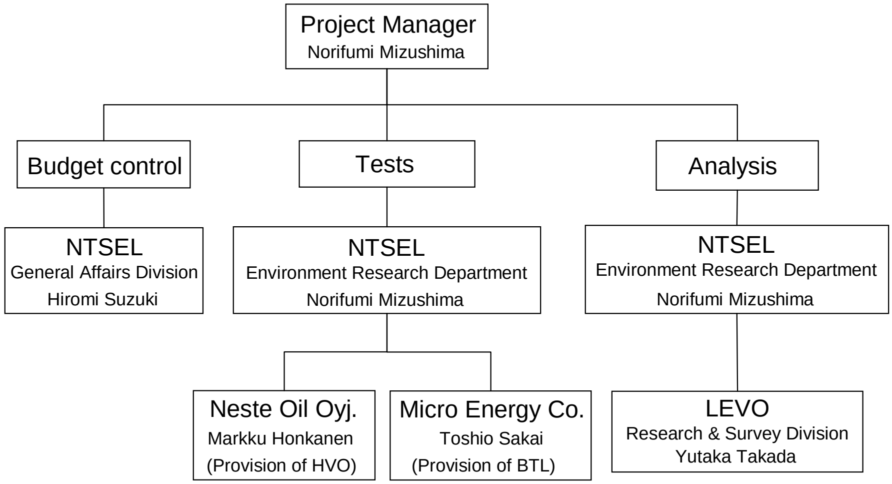


Figure 3-2 Annex management flow

4. Emission Evaluation with the Chassis Dynamometer

4.1. Objective

Before conducting the emission gas tests under on-road driving conditions, it is necessary to obtain the basic data of emission gas and fuel economy performance in using each biodiesel under the predetermined test cycle and condition. Then, the emission gas tests with a chassis dynamometer were performed to the same vehicle as used in the on-road driving tests.

4.2. Test fuels

The fuels tested in this study were ultra-low-sulfur diesel (ULSD) as conventional diesel fuel, FAME, HVO, BTL, mixed fuel of ULSD and FAME (FAME content of 5%, 7%, 20%, 50%), mixed fuels of ULSD and HVO (of 5%, 7%, 20% and 50%), and mixed fuel of ULSD and BTL (of 20%). Note that the mixing ratio of ULSD to each biodiesel was described here as the mass ratio of biodiesel to the mass after mixing. Table 4-1 shows the properties of test fuels. FAME used in this study was made from waste cooking oil. HVO delivered from palm oil was a hydrocarbon fuel obtained by hydrogenation, deoxidation and isomerization processes. HVO can be the alternative fuel to conventional diesel fuel, since the cetane number is sufficiently high, while the density is slightly lower than that of ULSD. BTL was a hydrocarbon fuel obtained by the process that thinned woods were shattered, dried, carbonated and gasified, and then they were synthesized by Fischer-Tropsch process. BTL can also be the alternative fuel to conventional diesel fuel due to its high cetane number, but unlike HVO, the flash point and initial boiling point (IBP) in BTL are lower than those of ULSD, and it can be inferred that BTL may contain some hydrocarbon components with low flash point. In this study, the tests used two types of BTL of different lot numbers; Lot 1 was the fuel with an extremely low flash point, and Lot 2 was the fuel whose flash point was set higher than that of Lot 1. At the time when the tests were performed, BTL was still under the pilot phase and the stable conditions of temperature or pressure, etc. in the Fischer-Tropsch process were not yet determined. Hence, it could be said that the different lot numbers changed the fuel properties. In this study, the effects of the difference in fuel properties of BTL on the emission gas were also assessed. However, due to the limit in supply, the mixed fuel of ULSD and BTL was prepared only one type of BTL content of 20%.

Table 4-1 Properties of test fuels

Fuel		ULSD	FAME	HVO	BTL (Lot 1)	BTL (Lot 2)
Density (15 deg.C) [g/cm^3]		0.8295	0.8853	0.7798	0.7973	0.8142
Kinematic viscosity [mm^2/s]		3.655 (@30 deg.C)	4.605 (@40 deg.C)	3.708 (@30 deg.C)	3.180 (@ 30 deg.C)	5.258 (@ 30 deg.C)
Flash point [deg.C]		68.0	176.0	91.0	<2.0	10.0
Sulfur content [ppm]		8	2	<1	<1	<1
Cetane number		57.2	55.3	85.8	65.7	67.7
Pour point [deg.C]		-22.5	-2.5	-15.0	-10.0	-10.0
Distillation temp. [deg.C]	IBP	168.0	207.0	153.5	72.0	82.5
	10%	210.0	353.0	267.5	142.0	219.0
	50%	279.5	353.0	281.5	299.5	313.0
	90%	337.5	358.0	294.0	330.0	340.0
	EP	358.5	486.0	303.5	353.5	357.0
CHO [wt.%]	C	86.3	77.1	84.8	85.5	85.4
	H	13.7	12.1	15.1	14.5	14.6
	O	<0.1	10.8	<0.1	<0.1	<0.1
Lower heating value [kJ/kg]		43 170	37 340	44 110	43 270	43 440

4.3. Test vehicle

Table 4-2 indicates the specification of testing vehicle and Figure 4-1 shows its appearance. The vehicle was a heavy duty cargo truck with maximum pay load of 3 tons, and a diesel engine of 2999 cm^3 displacement was installed without any modification. An oxidation catalyst and a diesel particulate filter (DPF) were employed as aftertreatment device. This test vehicle complied with the Japanese 2009 emission regulation.

Table 4-2 Specifications of the test vehicle

Vehicle type	Cargo truck
Vehicle model	Isuzu ELF
Vehicle mass	3 530 kg
Maximum pay load	3 000 kg
GVW	6 585 kg
Length x width x height	6 600 mm x 2 220 mm x 2 450 mm
Transmission	6MT
Engine type	Inline 4-cylinder turbo diesel
Engine model	4JJ1-TCH
Displacement	2 999 cm^3
Maximum power	110 kW / 2 800 rpm
Maximum torque	375 Nm / 1 400 ~ 2 800 rpm
Aftertreatment	DOC, DPF
Emission regulation	Japanese 2009 regulation

Figure 4-1 Broad overview of the test vehicle

4.4. Test apparatus

The test was performed on a chassis dynamometer for a heavy-duty vehicle in NTSEL. Figure 4-2 shows the condition of placing the vehicle on the chassis dynamometer. Figure 4-3 shows a system diagram of the test apparatus. Exhaust gas emitted from the exhaust pipe of the vehicle is directed into various emission gas analyzers, while being directed at the same time to the full dilution tunnel via CVS (Constant Volume Sampler) for analysis.

Figure 4-2 Test vehicle set on the chassis dynamometer

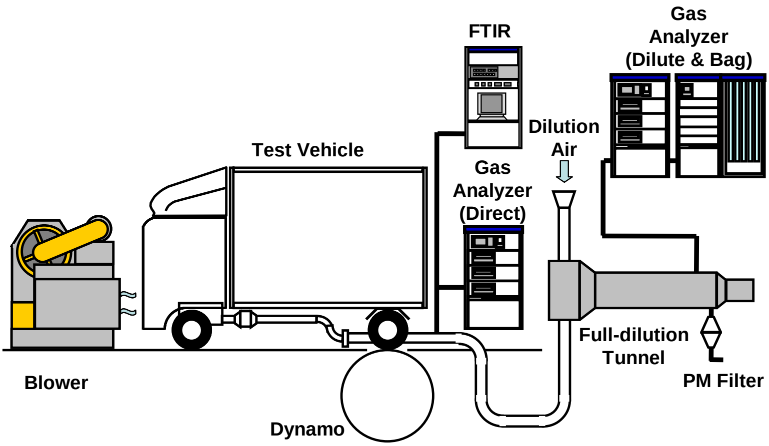


Figure 4-3 Chassis dynamometer test system

4.5. Test conditions and evaluation items

The chassis dynamometer test was performed in the JE05 driving cycle as introduced in the 2005 regulations. Figure 4-4 shows the speed pattern of the JE05 test cycle. In this test, the mass emissions of NOx, CO, CO_2, NMHC and PM, as well as the fuel consumption, were evaluated. Regarding the fuel consumption, the values of ULSD, FAME, HVO and BTL could not be compared directly, as they were different in the density and lower heating value, so energy consumption [MJ/km] was used.

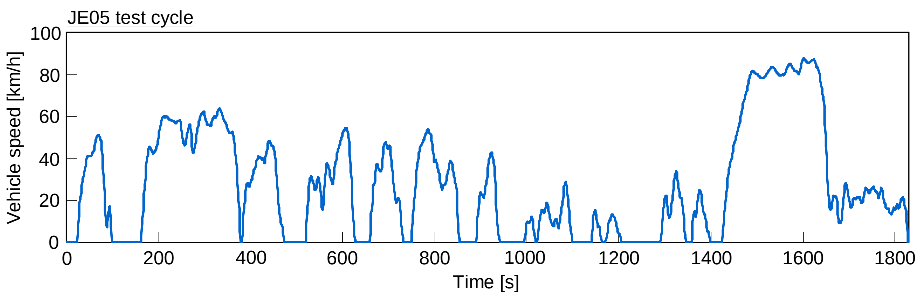


Figure 4-4 Vehicle velocity profile of the JE05 driving cycle

4.6. Test Results

(1) Emission characteristics of the JE05 driving cycle when FAME was used

Figure 4-5 shows the results of the measurement for the emissions [g/kWh] and energy consumption [MJ/km] of NOx, PM, CO, NMHC and CO_2, when the mixing ratio of FAME to ULSD was changed from 100:0 to 0:100. For reference, the results for the vehicle complying with the Japanese 2005 emission regulation reported in the Phase 1 in this Annex are also shown in this figure. In both vehicles and all mixing ratios, every emission gas except for NOx was recorded appreciably below the upper limit of each regulation. The reason of the low PM emissions was that PM was fully removed by the DPF installed in the exhaust pipe. It means that PM emissions did not depend on the mixing ratio of FAME. The emissions of CO and

NMHC indicated almost zero, since they were sufficiently oxidized by a diesel oxidation catalyst (DOC).

The NOx emissions, on the other hand, showed a higher level than the limit of each regulation even in operation with FAME 0%, that is, ULSD 100%. Moreover, the NOx emissions increased with an increase in the FAME ratio. This phenomenon was shown in each vehicle used in the Phase 1 and Phase 2. The exhaust gas emissions tests at type approval are performed on an engine bench and the engine operating conditions are determined based on the defined vehicle specifications. Hence, there is a possibility that the amount of exhaust gas emissions obtained by the chassis dynamometer tests using actual vehicles will be different from that of the type approval tests. Due to this phenomenon, it was considered that in the vehicles used in this study the NOx emissions exceeded the upper limit of the regulations.

The CO_2 emissions from the vehicle complying with the Japanese 2009 regulation slightly increased with the increase in the mixing ratio of FAME, due to the difference in H/C ratio in the fuel. However, the energy consumption maintained almost the same level regardless of the FAME ratio, and the vehicle even in using FAME achieved the equivalent energy efficiency to that of ULSD.

Figure 4-6 shows the comparison of NOx emissions between ULSD and FAME 100% in JE05 test cycle. The NOx emissions were recorded by instantaneous measurement and this figure focuses on the time from 1,000 seconds to 1,830 seconds in the cycle. The result indicates that the NOx emissions in using FAME 100 % increased compared to ULSD under the conditions of during idling operation, at starting and at acceleration. Meanwhile, the NOx emissions in both fuels maintained almost the same level during cruising conditions. As can be seen from Table 4-1, FAME is the oxygenated fuel and its lower heating value is lower than ULSD. The lower heating value per unit volume is also lower. These fuel properties leaded to the increase in the fuel injection volume compared to ULSD in order that the engine could have the same torque, and the combustion control state became higher fuel injection pressure and lower EGR ratio, and therefore the NOx emissions increased. In addition, the oxygenated fuel leads to a decrease in a stoichiometric air fuel ratio and the air-fuel mixture is shifted to more lean side. By these processes, it could be considered that the NOx emissions increased in this study.

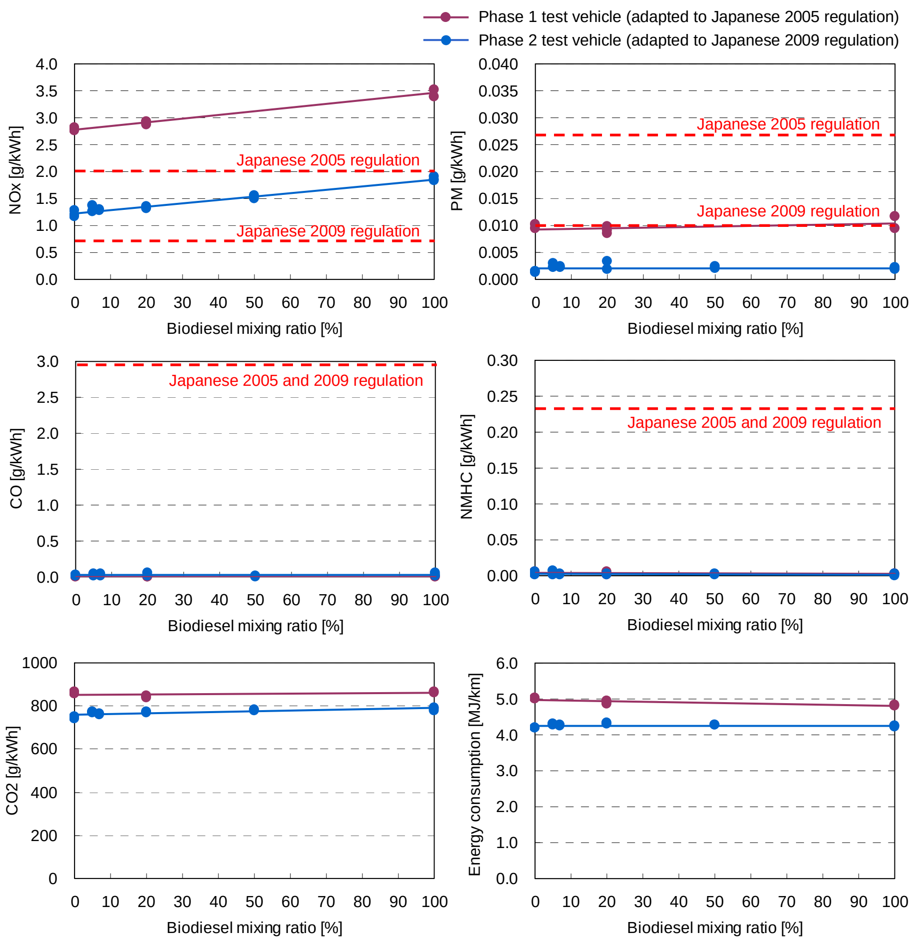


Figure 4-5 Emission and energy consumption characteristics of the JE05 driving cycle using FAME as fuel

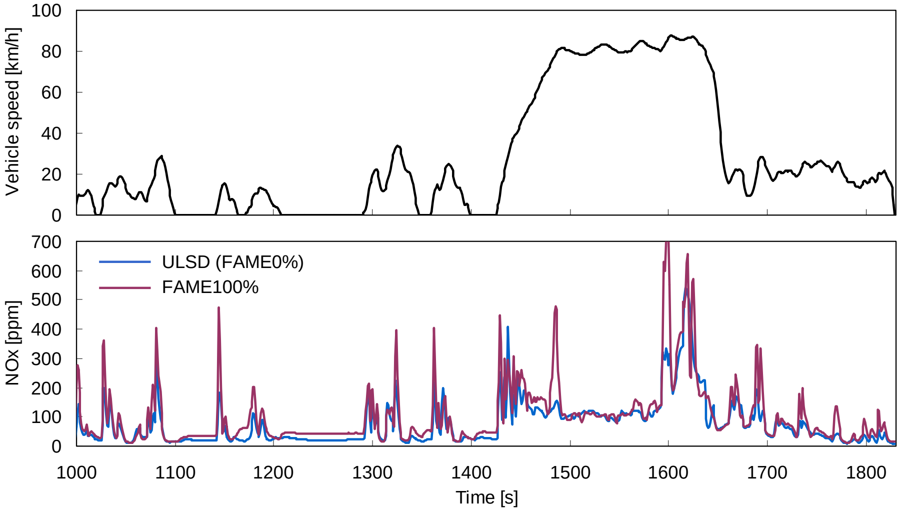


Figure 4-6 Comparison between the instantaneous emission concentration of NOx emission under the condition of FAME mixing ratio 0% and 100%

(2) Emission characteristics of the JE05 driving cycle when HVO was used as fuel

Figure 4-7 shows the results of measurement for the emissions [g/kWh] of NOx, PM, CO, NMHC and CO_2 and energy consumption [MJ/km], when the mixing ratio of HVO to ULSD was changed from 100:0 to 0:100. Along with the case in FAME, the results for the vehicle complying with the Japanese 2005 emission regulation described in the Phase 1 in this Annex are also shown in this figure. The emissions of PM, CO and NMHC indicated the similar levels as the case of FAME. In both vehicles and all mixing ratios, every emission gas was recorded appreciably below the upper limit of each regulation. In addition, each emission did not depend on the mixing ratio of HVO. Even in using HVO, the results ensured the equivalent exhaust gas performance to that of ULSD.

The NOx emissions in both vehicles exceeded the limit of each regulation, but unlike the case of FAME, the emissions were hardly affected by a change in the mixing ratio of HVO. It means that almost the same exhaust gas level as ULSD was maintained even in using HVO. This phenomenon was seen in both vehicles complying with each Japanese regulation of 2005 and 2009. The factor contributing to the increase in the NOx emissions beyond the regulatory limits is the difference in testing methods and it is the same as described in the case of FAME.

The CO_2 emissions slightly decreased with the increase in the mixing ratio of HVO. It was due to the difference in H/C ratio in the fuel. However, the energy consumption maintained almost the same level regardless of the HVO ratio and even in using HVO the vehicle achieved the equivalent energy efficiency to that of ULSD.

Figure 4-8 shows the comparison of NOx emissions between ULSD and HVO 100% in JE05 test cycle. The conditions are the same as Figure 4-6, that is, the instantaneous measurement and focusing on the time from 1,000 seconds to 1,830 seconds in the cycle. From the result, it was clear that the NOx emissions in using HVO 100% were almost the same level as those of ULSD and the effects of the difference in fuels on the NOx emissions hardly emerged.

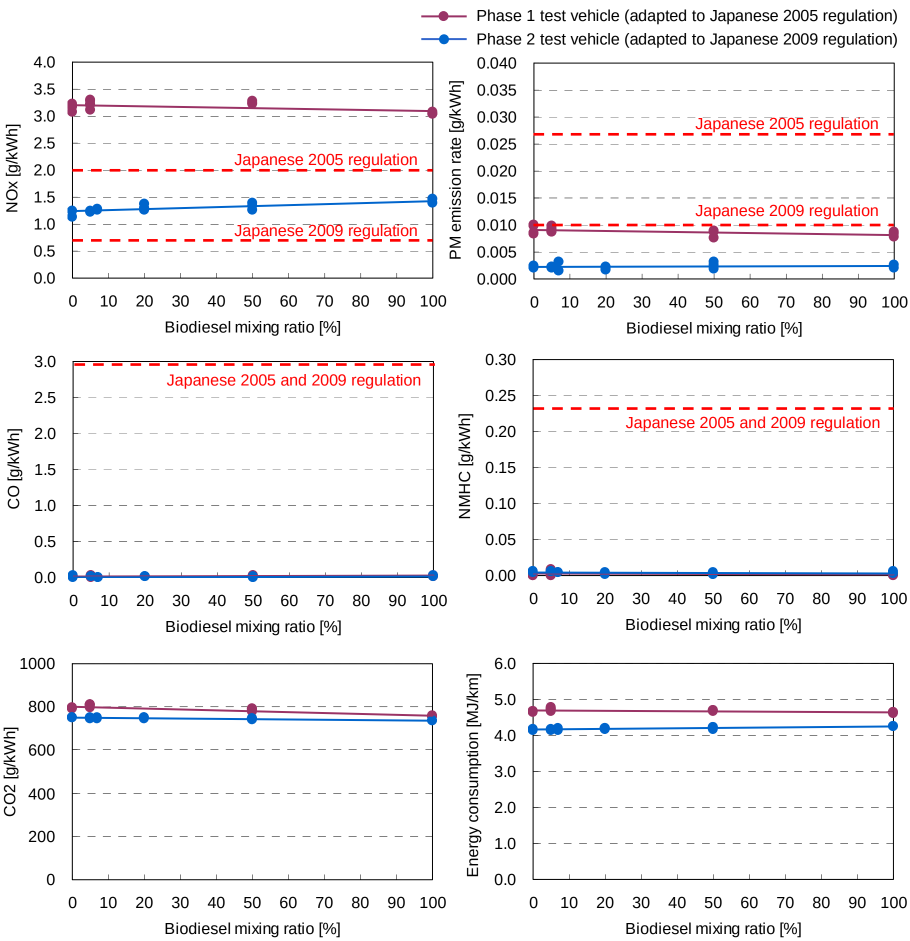


Figure 4-7 Emission and energy consumption characteristics of the JE05 driving cycle using HVO as fuel

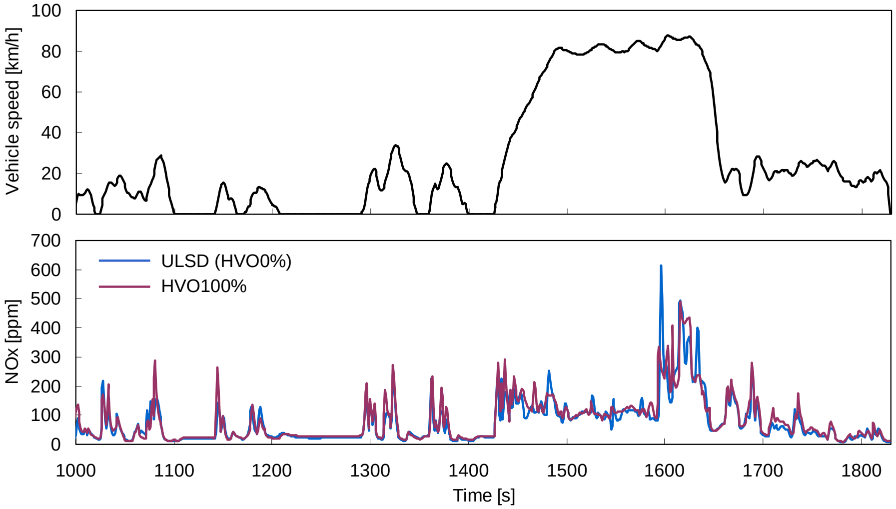


Figure 4-8 Comparison between the instantaneous emission concentration of NOx emission under the condition of HVO mixing ratio 0% and 100%

(3) Emission characteristics of the JE05 driving cycle when BTL was used as fuel

Figure 4-9 indicates the results of measurement for the emissions [g/kWh] of NOx, PM, CO, NMHC and CO_2 and energy consumption [MJ/km], when the mixing ratio of BTL to ULSD was changed at 0:100, 20:80 and 100:0. Since BTL was added to the evaluation from Phase 2 in this Annex, the measurement was performed only to the vehicle meeting the Japanese 2009 emission regulation. Moreover, as mentioned above, the BTL production was in the pilot phase at the time of this investigation, and the properties of BTL slightly varied according to the production lot. This study conducted the evaluation using two types of BTL of different lot numbers.

As with the case of FAME and HVO, the emissions of PM, CO and NMHC were appreciably below the upper limit of the regulation in both production lots and all mixture ratios of BTL. In particular, the PM and CO emissions were not increased by changes in the mixture ratio of BTL, and the results ensured even in using BTL the equivalent exhaust gas performance to that of ULSD. However, the NMHC emissions in BTL (Lot 1) slightly increased with the increase in the mixing ratio of BTL, although it was not seen in BTL (Lot 2). As shown in Table 4-1, BTL (Lot 1) has the extremely low flash point compared with other fuels. It means it may contain large amounts of hydrocarbon components with low boiling point. Hence, when BTL (Lot 1) was injected into the cylinder of the diesel engine, it was considered BTL evaporated faster than ULSD and then the air-fuel mixture became over lean. When this phenomenon occurred, the air-fuel mixture neither ignited nor burned and fuel components were emitted as unburned hydrocarbon to the atmosphere. The NMHC emissions, therefore, increased with the increase in the mixture ratio of BTL. On the other hand, BTL (Lot 2) also has lower flash point than ULSD, but it has higher flash point and distillation temperature than BTL (Lot 1). These fuel properties can suppress the phenomenon of the over lean air-fuel mixture. Hence, it was considered the NMHC emissions in using BTL (Lot 2) were equivalent to those of ULSD, even though the mixing ratio of BTL was increased.

Along with the case of FAME and HVO, the NOx emissions exceeded the regulatory limit in any mixing ratio. The effects of the BTL mixing ratio on the NOx emissions had the same tendency as NMHC, namely, in BTL (Lot 1) the emissions increased with the increase in the mixture ratio, but in BTL (Lot 2) it was controlled.

The CO_2 emissions showed the same tendency as the case of HVO, namely, due to the difference in H/C ratio, the emissions slightly decreased with the increase in the mixture ratio of BTL, but the energy consumption maintained almost the same level regardless of the BTL ratio. It can be said that even in using BTL the vehicle achieved the equivalent energy efficiency to that of ULSD.

Figure 4-10 shows the comparison of NOx emissions between ULSD and BTL (Lot 1)

100% in JE05 test cycle and Figure 4-11 shows the same comparison between ULSD and BTL (Lot 2) 100%. The conditions are the same as Figure 4-6 and Figure 4-8, that is, the instantaneous measurement and focusing on the time from 1,000 seconds to 1,830 seconds in the cycle. In using BTL (Lot 1), the NOx emission concentrations drastically increased under the high-speed running condition compared to ULSD. Meanwhile, under the idling and the low speed running conditions the concentrations were the equivalent to those of ULSD. In other words, in the case of BTL along with FAME, the NOx emissions increased throughout the JE05 test cycle, but the factors in the increase seemed to be different from those of FAME. In using BTL (Lot 2), it was seen that the NOx emission concentrations were the equivalent to those of ULSD under any of the running conditions.

It was inferred that the difference in the flash point influenced to the NOx emissions, but it was also considered that the influence varied according to the engine operating conditions. Then, engine bench tests were conducted to an engine fueled with ULSD, BTL (Lot 1) and BTL (Lot 2) so as to assess the effects of the difference in the fuel property on combustion and emission characteristics. The elaborate examination of the NOx emission characteristics obtained by the above tests will be described in the chapter 5.

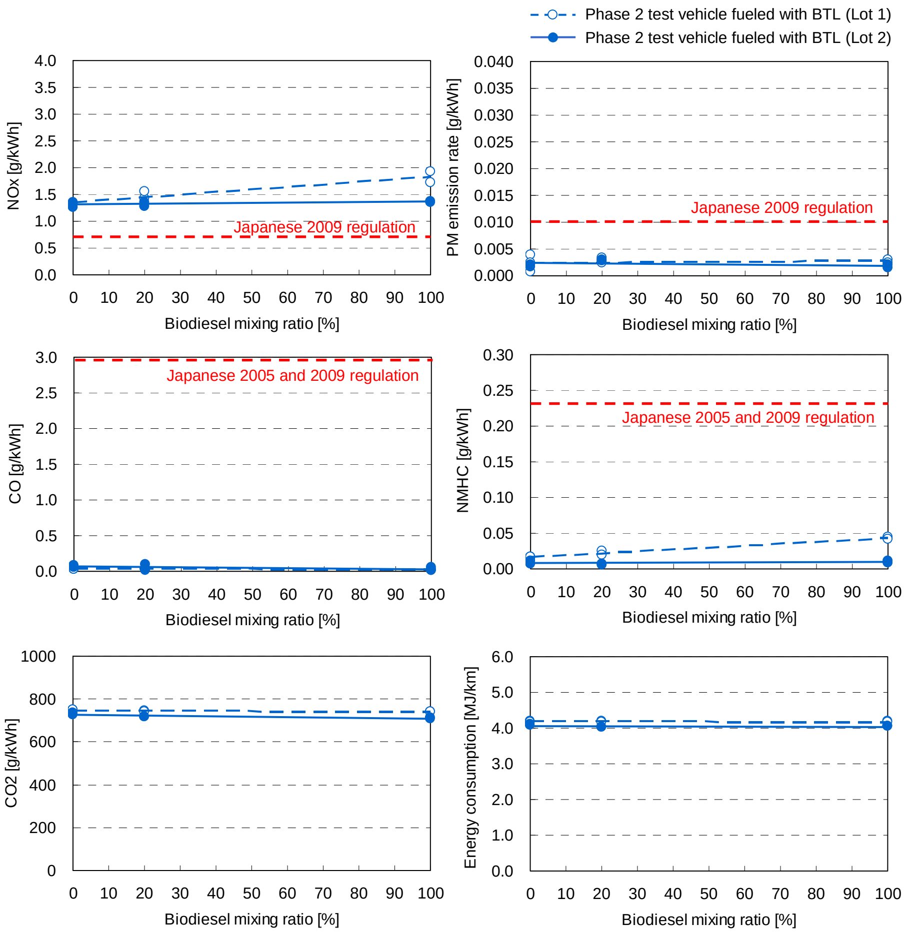


Figure 4-9 Emission and energy consumption characteristics of the JE05 driving cycle using BTL as fuel

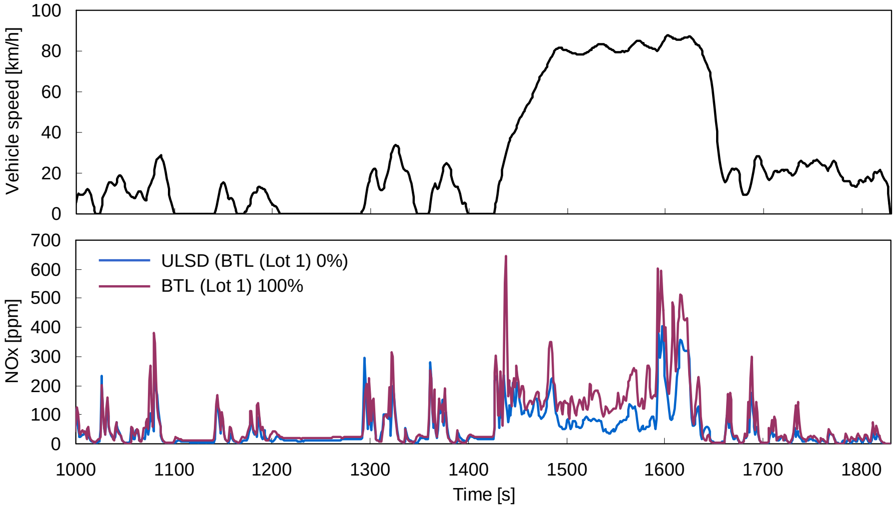


Figure 4-10 Comparison between the instantaneous emission concentration of NOx emission under the condition of BTL (Lot 1) mixing ratio 0% and 100%

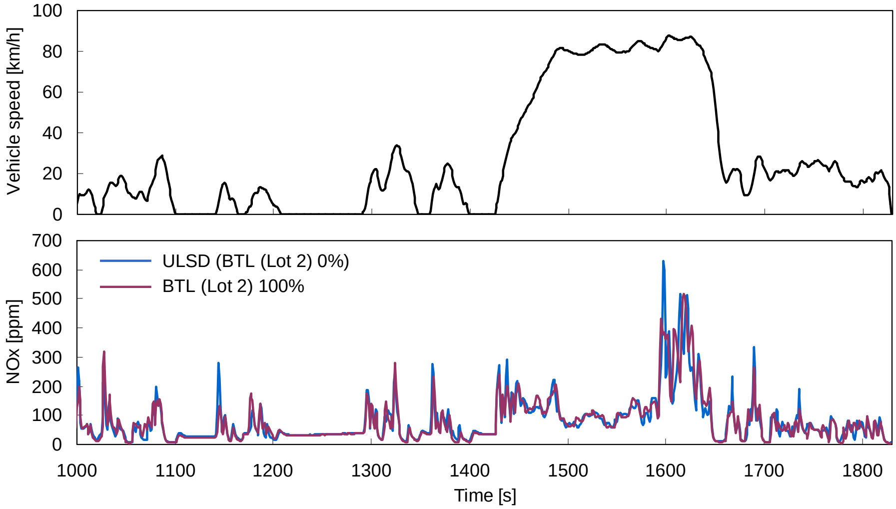


Figure 4-11 Comparison between the instantaneous emission concentration of NOx emission under the condition of BTL (Lot 2) mixing ratio 0% and 100%

4.7. Summary of this chapter

The result of the chassis dynamometer test showed that the amount of CO emission and NMHC emission was nearly zero in either case of mixing the FAME, HVO or BTL with ULSD except for BTL (Lot 1). At the same time, the amount of PM emission and the energy consumption was not significantly affected by changes in the mixing ratio for each biodiesel. For the NOx emissions, however, when FAME or BTL (Lot 1) was mixed with ULSD, the amount of emissions increased with an increase in the mixing ratio. On the other hand, when HVO or BTL (Lot 2) was mixed with ULSD, an increase or decrease in the amount of NOx emissions was not found.

In using FAME, the factors in the NOx emissions increase were already cleared as previously described. In using BTL, however, the factors in the increase by the fuel properties could be largely inferred, but it is necessary to assess the combustion characteristics and then the factors should be rigorously investigated. Hence, the both characteristics of combustion and emission gas were evaluated by conducting engine bench tests. The details will be described in the next chapter.

5. Analysis of Combustion and Emission Characteristics of BTL with the Engine Test Cell

5.1. Objective

The exhaust gas emission tests with the chassis dynamometer resulted in the different NOx emission characteristics in using two types of BTL of different properties. In order to conduct a more detailed examination of the factors in this difference, the engine bench tests were conducted using the same type of engine as the testing vehicle previously mentioned and the combustion and emission characteristics in using BTL were assessed by comparison to the case of ULSD.

5.2. Test apparatus

Figure 5-1 shows the overall view of the engine test cell and Figure 5-2 describes the experimental setup of the test engine. Table 5-1 is the specifications of the engine. The engine tested in this investigation was a turbocharging diesel engine of 2999cm^3 displacement and was the same type as the engine mounted on the test vehicle used in the chassis dynamometer tests and on-road driving tests, and to be specific it was installed in the light duty truck, ISUZU ELF. The engine placed at the engine test cell only had an oxidation catalyst and a DPF as the aftertreatment system without any NOx purification devices like urea SCR (Selective Catalyst Reduction) catalyst. Instead, an ultra-high EGR (Exhaust Gas Recirculation) was adopted as the technology making the NOx emissions comply with the Japanese 2009 regulation. In addition, a two-stage turbocharging system for securing enough intake air flow due to high boost pressure and a cooled EGR system for cooling down the EGR gas were also adopted to the engine.

For the evaluation of the combustion characteristics, a cylinder pressure sensor (Kistler: 6056A) was installed at a first cylinder in the engine and voltage signals obtained by this sensor were passed to a combustion analyzer (Onosokki: DS-2000) via a charge amp (Kistler: 5011). Moreover, for the evaluation of the exhaust gas characteristics at the engine out, exhaust gases sampling from an exhaust pipe were delivered into an exhaust gas analyzer (Horiba: MEXA-7400DEGR).

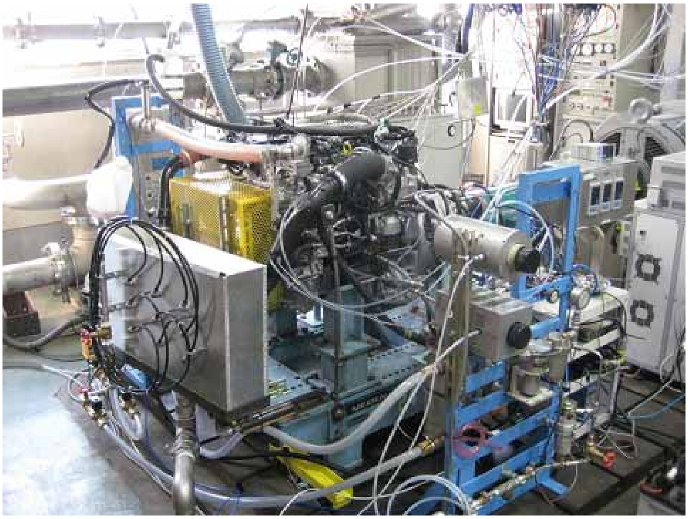


Figure 5-1 Overall view of the engine test cell

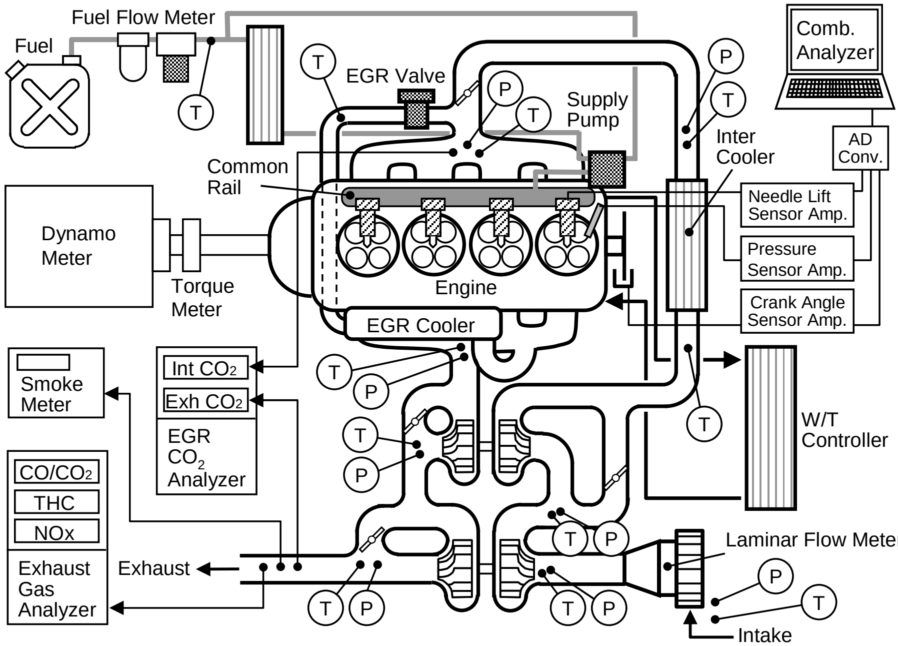


Figure 5-2 Experimental setup of test diesel engine

Table 5-1 Specifications of the test engine

Engine type	Inline 4-cylinder turbo diesel
Engine model	4JJ1-TCH
Displacement	2 999 cm^3
Maximum power	110 kW / 2 800 rpm
Maximum torque	375 Nm / 1 400 ~ 2 800 rpm
Intake system	2-stage turbocharger
EGR sysrem	Cooled EGR
Fuel supply system	Common rail
Aftertreatment	DOC, DPF
Emission regulation	Japanese 2009 regulation

5.3. Test conditions

In this investigation, seven types of steady state driving conditions were prepared and they represented the typical driving conditions in JE05 test cycle as the exhaust gas emission test. Both characteristics of combustion and exhaust gas were assessed under each condition. Table 5-2 shows these seven conditions for the engine bench test. The testing fuels were ULSD, BTL (Lot1) and BTL (Lot2) as described in Table 4-1.

Table 5-2 Experimental conditions in the engine bench test

Conditions	No.1	No.2	No.3	No.4	No.5	No.6	No.7
Engine speed [rpm]	1200	1200	1400	1400	1400	1800	2400
Engine torque [Nm]	40	100	20	120	180	60	80

5.4. Test results and considerations

5.4.1. Basic emission characteristics of BTL

Firstly, it was verified whether there was any difference in the combustion control state under the seven steady state driving conditions described in Table 5-2. Figure 5-3 shows the comparisons of accelerator position and EGR ratio among ULSD, BTL (Lot1) and BTL (Lot2). The accelerator positions were almost the same level in all three fuels, and it means the EGR ratios were also controlled as equivalent in all fuels. Based on this verification, the comparison of the emission gas of NOx, CO and HC at the engine out was conducted among the three fuels and the result is shown in Figure 5-4. From this figure, the effects of the difference in fuel type on the NOx emissions in every condition except for condition No. 7 were not so large as those in the chassis dynamometer tests. However, under condition No. 7, the NOx emissions were largely influenced by the difference in fuel type, in particular the highest emission was recorded in BTL (Lot 1). The condition No.7 corresponded to the high-speed running condition that emerged after 1400 seconds in JE05 test cycle, and under this condition the phenomenon of the highest NOx emission in using BTL (Lot1) agreed with the result of the chassis dynamometer test as previously mentioned.

The emissions of CO and HC, on the other hand, were clearly influenced by the difference in fuels. It was expected that some of the combustion characteristics varied. However, these emission tendencies were not the same as the result of the chassis dynamometer test. The main factors are considered that the evaluation in the engine bench tests were conducted by the steady state conditions and the vehicle used for the chassis dynamometer tests was equipped with the oxidation catalyst.

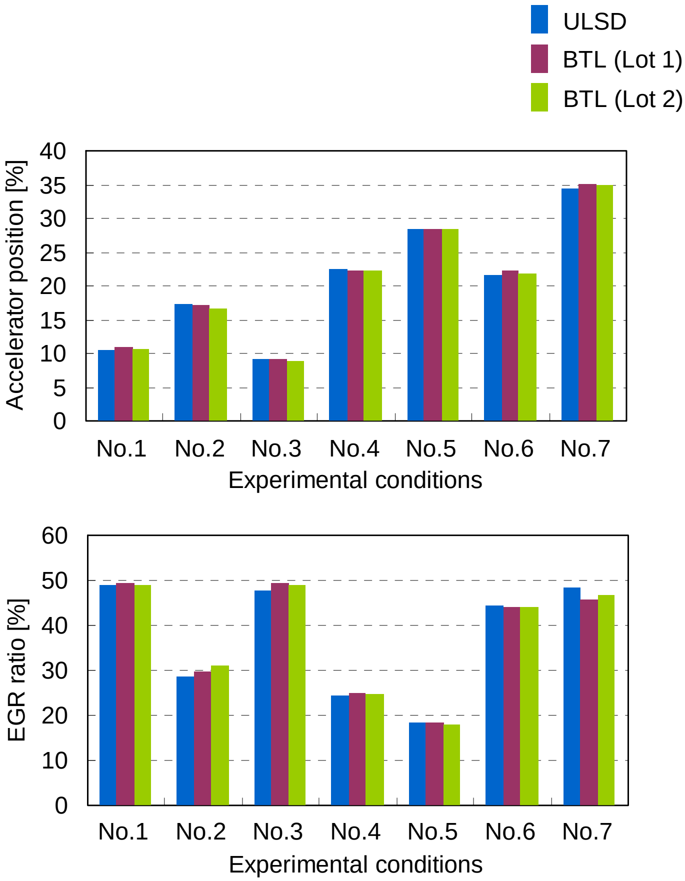


Figure 5-3 Comparisons of accelerator position and EGR ratio between ULSD, BTL (Lot 1) and BTL (Lot 2) for each condition

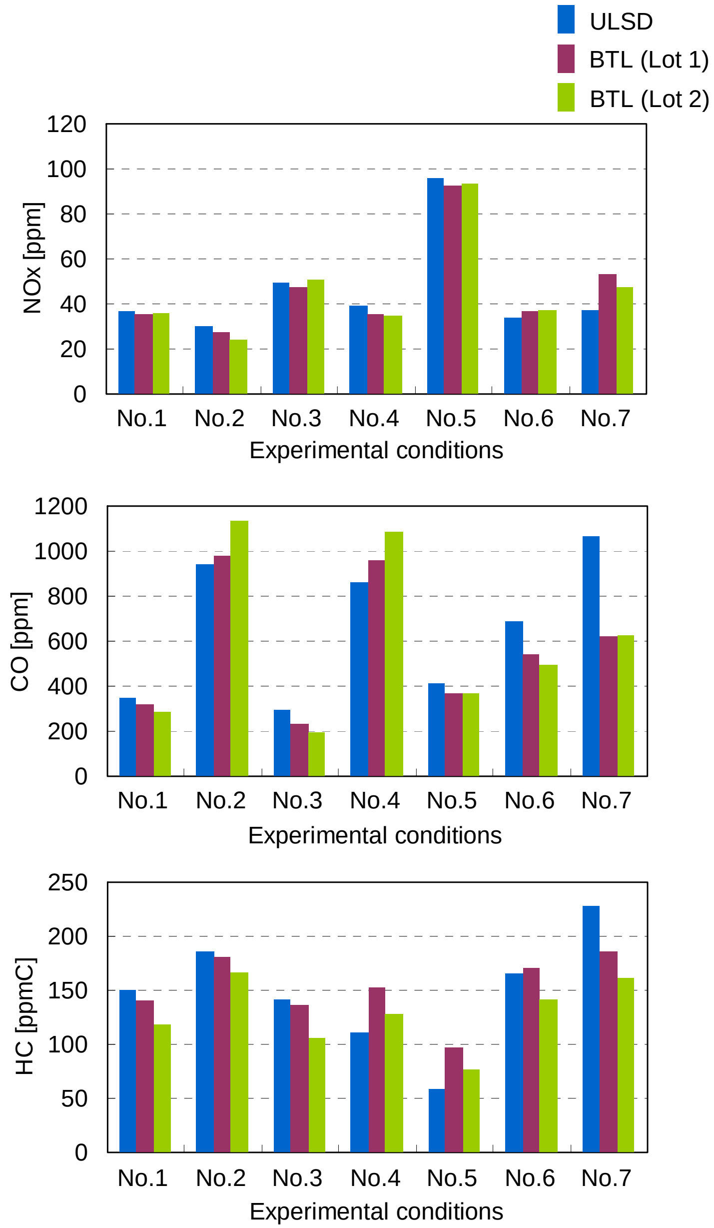


Figure 5-4 Comparisons of NOx, CO and HC emissions between ULSD, BTL (Lot 1) and BTL (Lot 2) for each condition

5.4.2. Basic combustion characteristics of BTL

The comparison of cylinder pressure and rate of heat release under each condition is shown in from Figure 5-5 to Figure 5-11. It was verified that, in these figures, there were no differences in the fuel injection timing among three fuels by simultaneous measurement of the drive current in the injector. Each figure indicates that, at the early stage of combustion, the rate of heat release was influenced by the difference under every condition. In particular, under condition No. 4, No.6 and No.7 the notable differences were demonstrated. As described in Table 4-1, due to the high cetane number in BTL compared with ULSD, the timing of combustion initiation by the pilot-injected fuel was hastened and activated. Accordingly, the maximum value of the rate of heat release by the main combustion was decreased. Under condition No. 7, especially, the combustion by pilot injection was apparently varied even in BTL (Lot 1) and BTL (Lot 2), and thus it was considered that BTL (Lot 1) with activated combustion had the highest NOx emissions. The factor was inferred that, as represented by the difference in flash point, hydrocarbon components with low boiling point evaporated at the early stage and stimulated the ignition. Meanwhile, there was the condition like condition No. 6, without any difference between BTL fuels. Since the effects on the characteristics of combustion or exhaust gas varied depending on the conditions, it was considered BTL (Lot 1) had the mixed conditions of increase in NOx and not-increase in NOx.

In the engine bench tests, the comparison was conducted only in the steady state condition, and hence it was quite difficult to exactly represent the results of the chassis dynamometer tests. However, the tests provided the data showing the relation between the different flash point in each fuel and the NOx emissions. From these data, it was indicated that, in some conditions, BTL with low flash point caused to increase in the NOx emissions.

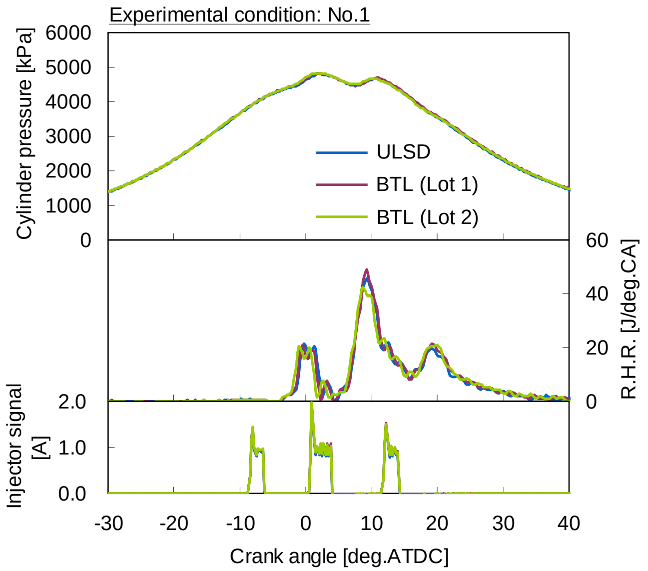


Figure 5-5 Comparisons of cylinder pressure and rate of heat release between ULSD, BTL (Lot 1) and BTL (Lot 2) under the condition No.1

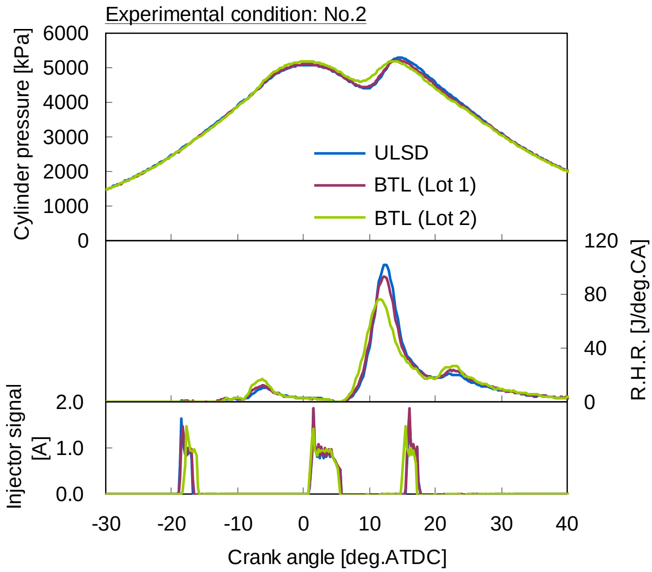


Figure 5-6 Comparisons of cylinder pressure and rate of heat release between ULSD, BTL (Lot 1) and BTL (Lot 2) under the condition No.2

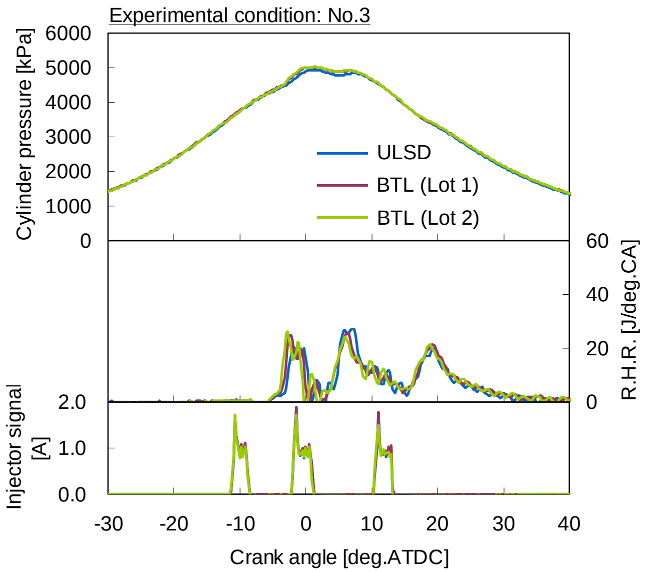


Figure 5-7 Comparisons of cylinder pressure and rate of heat release between ULSD, BTL (Lot 1) and BTL (Lot 2) under the condition No.3

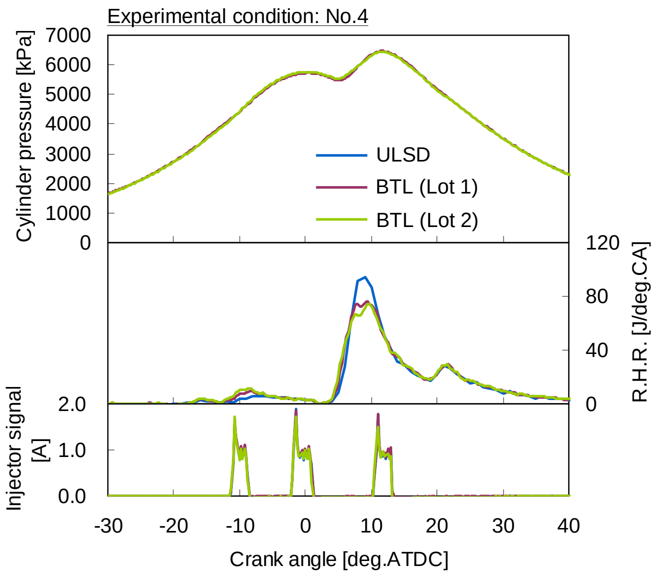


Figure 5-8 Comparisons of cylinder pressure and rate of heat release between ULSD, BTL (Lot 1) and BTL (Lot 2) under the condition No.4

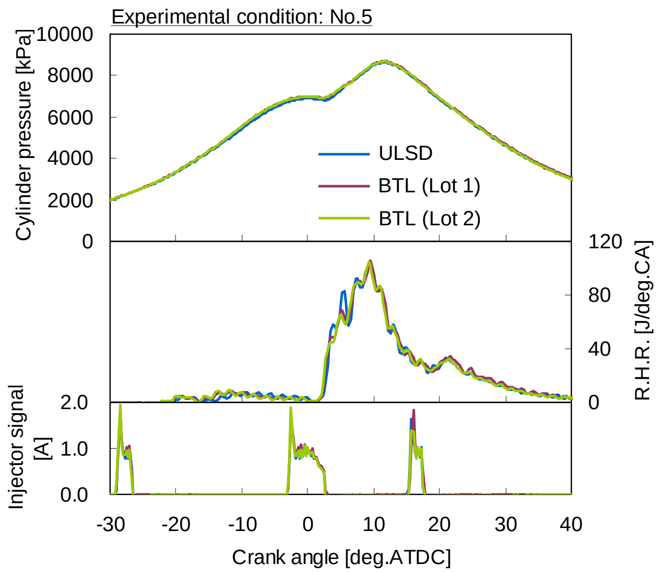


Figure 5-9 Comparisons of cylinder pressure and rate of heat release between ULSD, BTL (Lot 1) and BTL (Lot 2) under the condition No.5

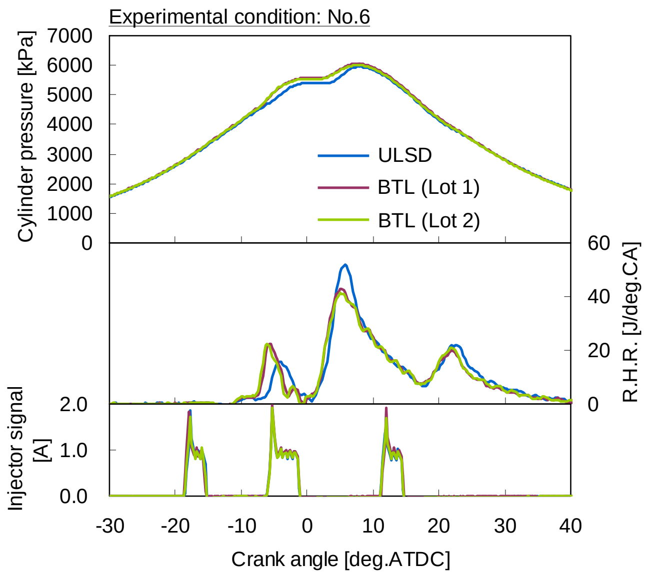


Figure 5-10 Comparisons of cylinder pressure and rate of heat release between ULSD, BTL (Lot 1) and BTL (Lot 2) under the condition No.6

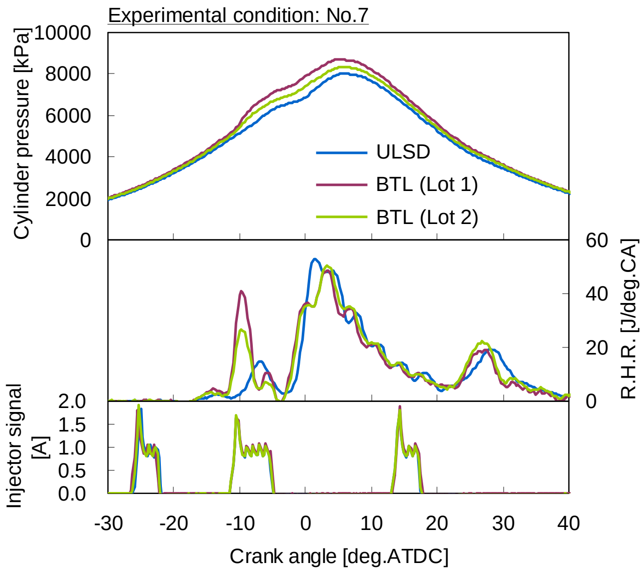


Figure 5-11 Comparisons of cylinder pressure and rate of heat release between ULSD, BTL (Lot 1) and BTL (Lot 2) under the condition No.7

5.5. Summary of this chapter

In the emission tests with the chassis dynamometer, the difference in NOx emission characteristics was seen in using two types of BTL of different properties. In order to examine the factors in this difference in more detail, the engine bench tests were conducted, and the evaluation for the characteristics of combustion and exhaust gas in using BTL was conducted by comparison to those of ULSD. In consequence, when BTL (Lot 1) with low flash point was used, the combustion was more activated by pilot injection than that of BTL (Lot 2) under the condition of the engine speed and torque equivalent to the high speed running. Since BTL (Lot 1) has lower flash point than BTL (Lot 2), it was considered that BTL (Lot 1) contained large amounts of hydrocarbon components with low boiling point, and these components evaporated in the early stage and stimulated the ignition, and then this phenomenon occurred. It was concluded by this consideration that in using BTL (Lot 1) the NOx emissions were particularly increased when running at high speed.

Therefore, it can be said that BTL with high enough flash point should be used, since the NOx emissions were increased in using BTL with low flash point.

6. Evaluation of Real-world Emission in the On-road Driving Test

6.1. Objective

In order to evaluate the real value of emission characteristic from a diesel engine fueled with biodiesel and disseminate information about environmental impact of biodiesel, it will be necessary to conduct not only evaluation in a test cell but also measurement by on-road driving tests. In this research, real-world emissions and fuel consumption from a heavy-duty diesel vehicle fueled with biodiesel such as FAME, HVO and BTL were evaluated by the on-road emission measurement using a portable emission measurement system (PEMS).

6.2. Test fuels

The test fuels were ULSD, FAME, HVO, and BTL (Lot 2) as indicated in Table 4-1. Each biofuel was mixed with ULSD and these mixed fuels were also used as test fuel. The mixing ratio of each biofuel to ULSD was FAME 5%, HVO 7%, HVO 20%, HVO 50% and BTL 20%, respectively. For safety concerns, BTL (Lot 1) was not used in this investigation, since it has the extremely low flash point. Note that the mixing ratio of FAME which can be used on a public road is limited by the regulation, “Act on the Quality Control of Gasoline and Other Fuels” [18], so more than 5% of mixing ratios of FAME cannot be used for on-road driving test. HVO and BTL meet the quality standards of diesel fuel, so that the test vehicle fueled with any mixing ratios could be operated on a public road. As with the case of the chassis dynamometer test, BTL was limited in supply, and hence the mixture ratio of BTL to ULSD was only 20%.

6.3. On-board measurement system

The PEMS was mounted in the cargo room in the vehicle so as to measure the exhaust gas emissions in the on-road driving. The schematic of PEMS is shown in Figure 6-1 and the appearance of experimental setup is in Figure 6-2. The measurement of CO, CO_2, THC and NOx was conducted by the on-board exhaust gas analyzer, OBS-2200 (HORIBA, Ltd.). The exhaust gas flow rate was measured by a pitot tube set in the exhaust pipe. In order to evaluate the exhaust gas in the unit of [g/kWh], it was necessary to obtain the exhaust gas weight per unit of work produced by the engine. To obtain this data, the running resistance of a vehicle had to be calculated and the engine torque and workload had to be estimated. Hence, the vehicle speed and the engine speed signal by ECU were loaded into the data logger. In addition to the carbon balance method, the signal of fuel injection quantity was also loaded from ECU in order to evaluate CO_2 emission and fuel consumption.

Two 500-liter tanks filled with water were installed to realize the half-loaded condition in the cargo room. The road gradient should be measured in order to know accurately the driving resistance that the vehicle experiences during the real road driving. NTSEL developed a highly accurate measurement method for calculating the road gradient by combining the pitch angle measurement using a gyro sensor with the measurement of the vehicle tilt angle against the road surface using two height sensors. The road gradient was measured by installing these sensors in the test vehicle. The engine torque could be analyzed based on the calculated driving resistance.

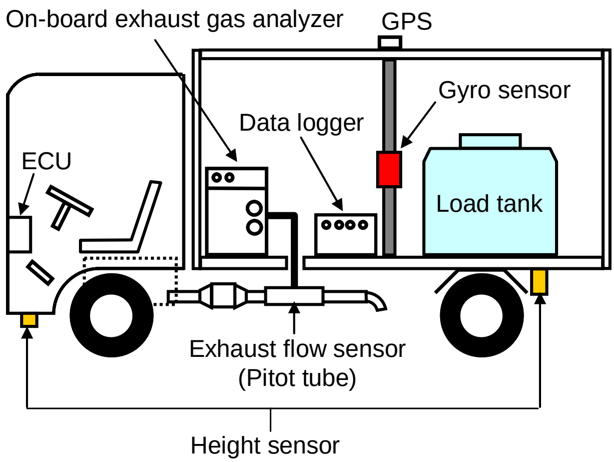


Figure 6-1 On-board measurement system

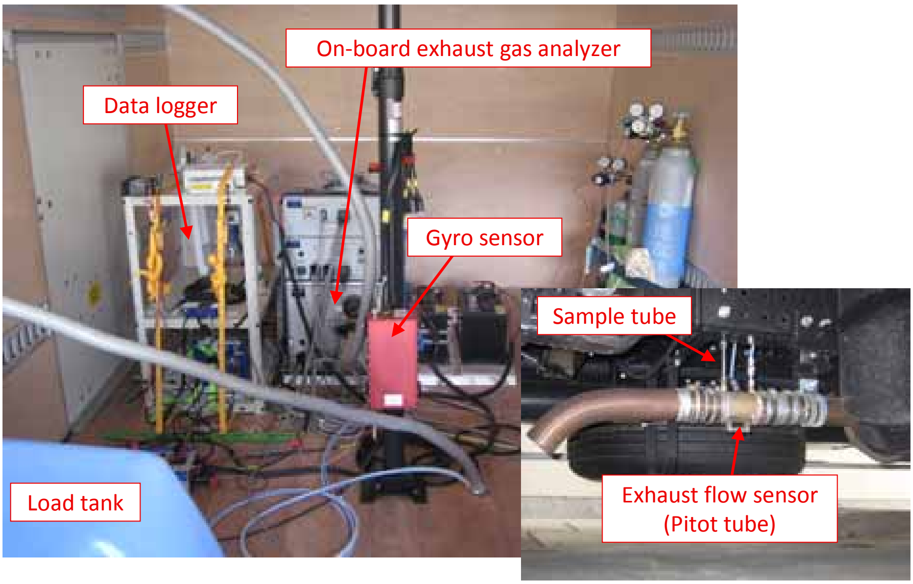


Figure 6-2 Overview inside the trunk of the test vehicle

6.4. Experimental method

Figure 6-3 shows the driving test route. It was a circle route with a distance of about 22 km where the vehicle started and ended at NTSEL located in the suburbs of Tokyo. The route consisted of various road types such as an arterial road with wider than four-lane, a narrow road with no center line and a pitched road. The testing vehicle ran the route many times in daytime under various temperature and humidity conditions. Two types of operation patterns were prepared; one was eco-driving [19]-[22] that the driver consciously drove the route with early shift up and smooth acceleration so as to maintain the engine speed not exceeding 2000 rpm, the other was normal driving that the driver did not bear eco-driving in mind and drove normally along with the traffic flow. The driving tests were conducted in these various acceleration conditions. The three types of test fuels were used at least three times in each driving pattern, that is, each fuel was tested at least six times, with intent to understand the effects of the difference in road environment and weather conditions on the exhaust gas.

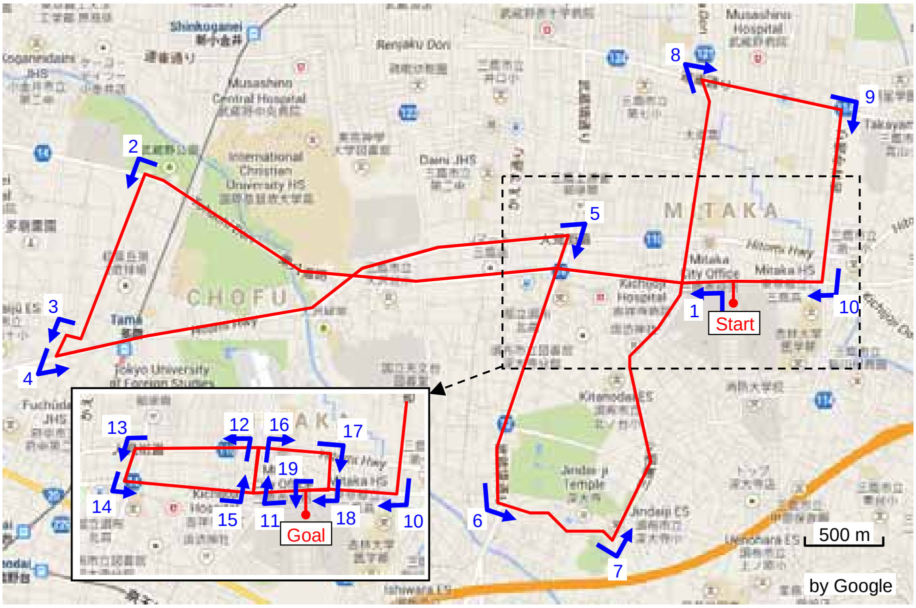


Figure 6-3 Map of the test route

6.5. Method of engine torque estimation

It is necessary for the evaluation of exhaust gas in the unit of [g/kWh] to estimate the engine power [kW], but before that, the engine torque firstly needs to be estimated. Thus, the running resistance of a vehicle was measured and then the engine torque, T_e was estimated by the formula (1)-(5) below. This calculation is based on a method of JE05 driving cycle procedure for heavy-duty vehicle emission test in Japanese type approval [23]. JE05 test has a process to convert a vehicle speed profile to an engine speed profile and an engine torque profile by inputting vehicle specifications, such as vehicle weight, transmission gear ratio and transmission efficiency, and so on. Based on this process, this study applied to a calculation method of engine torque. However, this study aims to analyze the effect in a real-world emission, and thus the value of gradient resistance R_s was added to this method.

$$T_e = \frac{r}{\eta_m \cdot \eta_f \cdot i_m \cdot i_f}\left(R_r + R_l + R_s + R_a\right) \tag{1}$$

$$R_r = \mu_r \cdot m \cdot g \cdot \cos\theta \tag{2}$$

$$R_l = \mu_a \cdot A \cdot V^2 \tag{3}$$

$$R_s = m \cdot g \cdot \sin\theta \tag{4}$$

$$R_a = \left(m + \Delta m\right) \cdot \alpha \tag{5}$$

where,

A: frontal projected area [m^2], g: gravitational acceleration [m/s^2], i_f: final gear ratio [-], i_m: transmission gear ratio [-], m: vehicle weight [kg], r: tire dynamic load radius [m], R_a: acceleration resistance [N], R_l: air resistance [N], R_r: rolling resistance [N], R_s: gradient resistance [N], T_e: engine torque [N·m], V: vehicle speed [km/h], α: vehicle acceleration [m/s^2], Δm: equivalent weight of rotating part [kg], η_f: efficiency of final gear [-], η_m: efficiency of transmission [-], μ_a: coefficient of air resistance [N/(m^2·(km/h)^2)], μ_r: coefficient of rolling resistance [N/kg], θ: road gradient [deg.]

The road gradient, θ was able to be estimated by the gyro sensor mounted in the cargo room which measured the pitch angle of the vehicle. This estimation, however, included the ups and downs at front and back of the vehicle. Hence, the ups and downs were corrected with the data obtained by the height sensor installed at front and back of the vehicle, and this correction allowed for the highly accurate measurement of road gradient. Moreover, the road gradient data obtained by the above method was corrected by using the elevation data at the starting and ending point extracted from an elevation database in a map. A detailed description can be found in the previous paper.

By use of the estimated engine torque and the measured engine speed obtained by the above mentioned method, the workload produced by the engine while the vehicle was running was calculated, and then the exhaust gas was evaluated in the unit of [g/kWh].

6.6. Test results and consideration

6.6.1. Understanding of real-world emission characteristics

In general, an actual on-road driving test is conducted under various weather conditions depending on the date and time or route. Moreover, the timing or degrees of acceleration/deceleration and the vehicle speed differ from test to test, according to road conditions such as traffic congestion or traffic light. Hence, it is quite difficult to evaluate the exhaust gas data obtained by measurement tests due to the changing conditions. This study therefore examined the emission characteristics in the actual on-road driving with conventional diesel fuel, before comparing the emission characteristics of each test fuel, and focused on only NOx among the emission gas components.

Figure 6-4 shows the results of NOx emission measurements under the real-world condition in using ULSD. This figure indicates that NOx emissions obtained by this measurement fluctuated widely according to the test dates or operation of driving. In order to accurately assess the results of emission gas measurement tests, it is necessary to understand the effects of these differences in conditions on the NOx emissions and to identify the influencing factors. Hence, the major possible factors influencing on the NOx emissions were firstly extracted as follows; as for the factors of driving conditions, accelerator position, vehicle speed, acceleration, engine power, engine speed and engine torque, as for the factors of weather conditions, atmospheric pressure, ambient temperature and water vapor partial pressure (humidity). This study focused on the average accelerator position (excluding zero percent) and the average vehicle speed during tests, the average acceleration during accelerating, the average engine power, the average engine speed and the average engine torque during a positive value of the engine torque, and the average outside air temperature and water vapor partial pressure during tests.

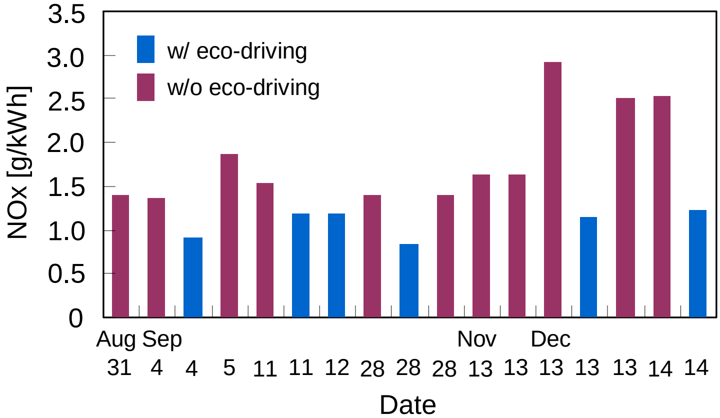


Figure 6-4 Results of NOx emission measurements under real-world conditions in each date

Figure 6-5 and Figure 6-6 show the relationship between these factors and the NOx emissions. The results suggest that each factor did not have clear correlation with the NOx emissions, and it is obvious that the only single factor could not explain the NOx emission characteristics. Nonetheless, it is indisputable that the NOx emissions vary according to driving or weather conditions. Understanding the NOx emission characteristics with these factors is still expected. Hence, a multiple regression analysis was conducted so as to comprehend the relation between these factors and the NOx emissions in a quantitative way. However, in the multiple regression analysis, it has to be noted that if there is high correlation among the explanatory variables, multicollinearity may arise, and thus the most important factor has to be used only as the explanatory variable. In this study, there were similar relations between average value of accelerator position and the NOx emissions, average value of acceleration and the NOx emissions, and average value of engine power and the NOx emissions, respectively, and these factors could be replaced with the average engine speed or the average engine torque. Hence, as for the vehicle driving, the average engine speed, N_e[rpm] and the average engine torque, T_e[N·m] were used as the variables. Additionally, as the factors explaining road conditions, the average vehicle speed, V[km/h] was used. As for the environmental conditions, both the average temperature, T_a[deg.C] and the average water vapor partial pressure, P_w[kPa] were used as the variables. Moreover, it was anticipated that the effect of each explanatory variable was not always shown in linear relation, and then the squared terms of each variable were added to the explanatory variables. Based on the variables selected by the above method, the results of NOx emission measurements were conducted in multiple regression analysis, and thus the formula (6) was obtained as follows.

$$
\begin{aligned}
NOx[g/kWh] = & -4.441\times10^{-6}\cdot\overline{N_e}^2 + 1.472\times10^{-2}\cdot\overline{N_e} \\
& + 9.793\times10^{-4}\cdot\overline{T_e}^2 - 2.358\times10^{-1}\cdot\overline{T_e} \\
& - 4.062\times10^{-2}\cdot\overline{V}^2 + 1.575\times10^{0}\cdot\overline{V} \\
& + 4.021\times10^{-3}\cdot\overline{T_a}^2 - 2.620\times10^{-1}\cdot\overline{T_a} \\
& - 9.576\times10^{-2}\cdot\overline{P_w}^2 + 7.333\times10^{-1}\cdot\overline{P_w} \\
& - 8.875\times10^{0} \qquad (6)
\end{aligned}
$$

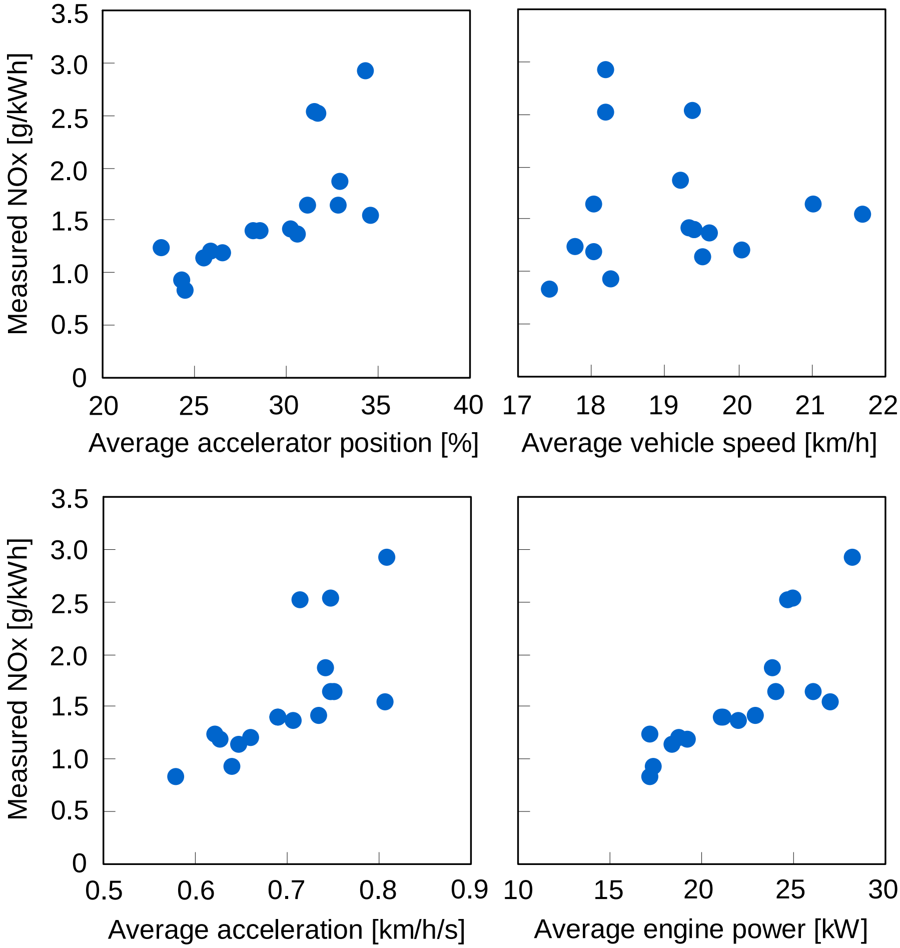


Figure 6-5 Relationship between average accelerator, vehicle speed, acceleration, engine power and NOx emission

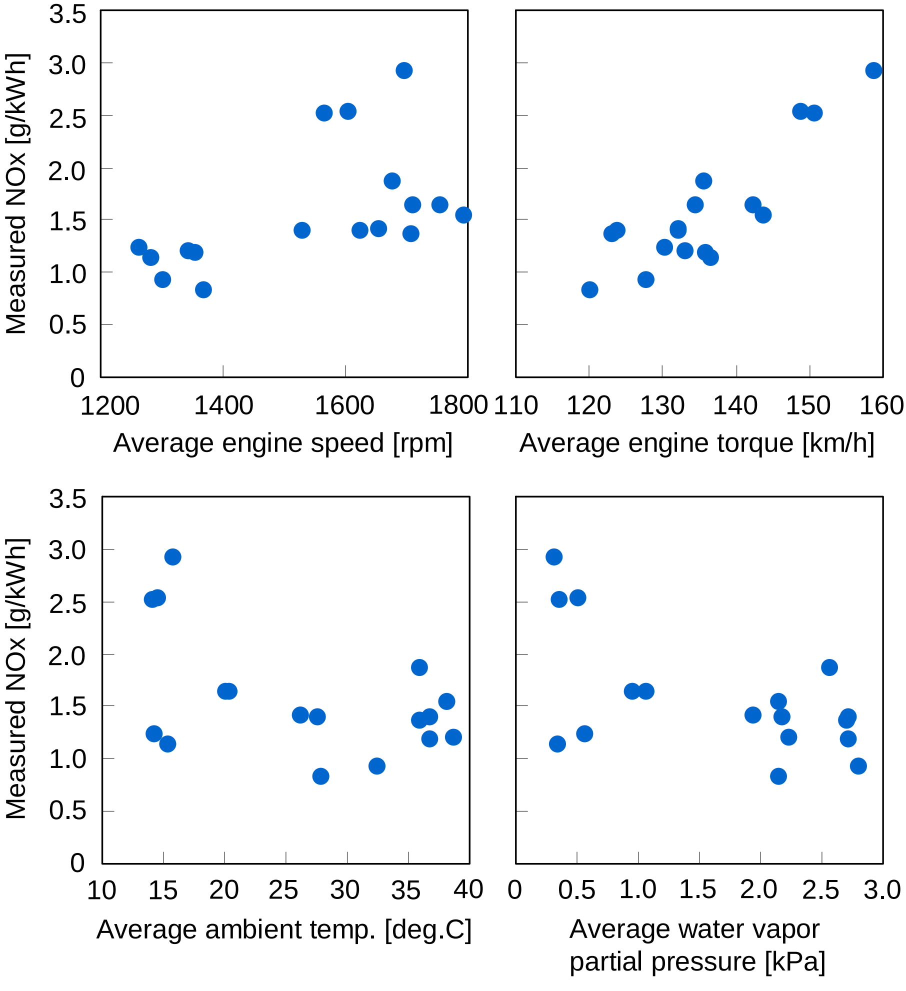


Figure 6-6 Relationship between average engine speed, engine torque, ambient temperature, water vapor partial pressure and NOx emission

Figure 6-7 shows the relationship between the estimated NOx emission values obtained by the formula (6) and the actual measurement values obtained by tests. For the purpose of reference, the results of multiple regression analyses in both cases including and excluding the squared terms in the explanatory variables are also shown in Figure 6-7. In the case of including the squared terms, the high accurate result of multiple regression analysis was obtained.

As described above, it was indicated that the changes in the NOx emissions in the actual on-road driving could be largely explained by the changes in the factors such as the average engine speed and the average engine torque during a positive value of the engine torque, and the average vehicle speed, ambient temperature and water vapor partial pressure during tests. Then, the NOx emission characteristics in the actual on-road driving were evaluated after understanding the effects of differences in the above factors with each change in tests on the NOx emissions by multiple regression analysis.

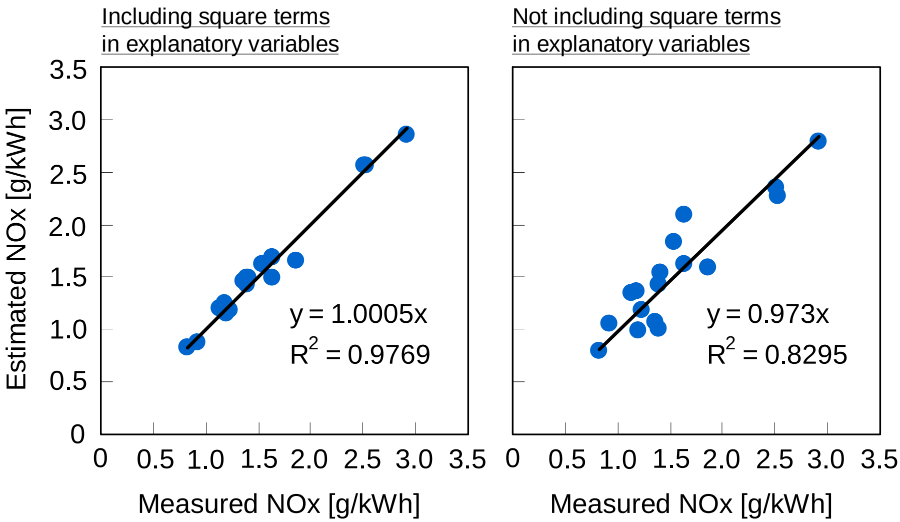


Figure 6-7 Comparisons between measured NOx emission and estimated NOx emission calculated by the results of multiple linear regression analysis

6.6.2. Real-world emission characteristics in using biofuels

The real-world emission characteristics in using FAME, HVO and BTL were evaluated by the method described above. For the evaluation in changing the conventional diesel fuel into each biofuel, factors arising from the fuel property were added to the explanatory variables for multiple regression analysis. Specifically, the lower heating value per unit volume, H_f[kJ/L] and the H/C ratio were added to the explanatory variables. In general, the former, H_f[kJ/L] is a factor influencing a combustion control state, and it has high density, with the tendency that the higher the oxygen content in the fuel, the lower the value. The latter, H/C ratio is a factor influencing a stoichiometric air fuel ratio and an adiabatic flame temperature, and it has the tendency that the higher the paraffinic hydrocarbon content, the higher the value. By the previous papers, it has been cleared that both factors were important factors influencing the NOx emissions, and thus it was considered appropriate that they were added to the explanatory variables for multiple regression analysis.

Through the estimated formula for NOx emissions obtained by the above method of multiple regression analysis, the same conditions as the real-world were assumed, and then the NOx emission characteristics were compared among fuels. The conditions for comparison were prepared the following four types; the condition A and B were assumed a hot and humid summer time in Tokyo and A was non-conscious of eco-driving and B was conscious of eco-driving, the condition C and D were assumed a cold and low humid winter time in Tokyo and C was non-conscious of eco-driving and D was conscious of eco-driving. Under these conditions, the comparison was performed, and Table 6-1 shows the average engine speed and engine torque during a positive value of the engine torque, and the average vehicle speed, the average ambient temperature and water vapor partial pressure during tests.

Table 6-1 Common evaluation conditions of real-world NOx emission based on the real-world driving test for each fuel

Condition	A	B	C	D
Assumed season	Summer (Tokyo)	Summer (Tokyo)	Winter (Tokyo)	Winter (Tokyo)
Eco-drive	Not considered	Considered	Not considered	Considered
Average engine speed [rpm]	1670	1330	1670	1330
Average engine torque [Nm]	146	133	146	133
Average vehicle speed [km/h]	19	19	19	19
Average ambient temperature [deg.C]	35	35	10	10
Average water vapor partial pressure [kPa]	2.7	2.7	0.2	0.2

(1) Real-world emission characteristics in using FAME

Figure 6-8 shows the each test result of the measurement of NOx emissions, [g/kWh] under the real-world conditions in using the mixed fuel of ULSD and FAME whose content of FAME was 5% and the fuel of FAME 100%. From this figure, it was seen that on the whole the NOx emissions in non-conscious of eco-driving tended to be higher than those of conscious of eco-driving. Compared with the mixed fuel of FAME 5%, the fuel of FAME 100% also showed the tendency of higher NOx emissions. However, each emission value fluctuated as well as the case in using ULSD. These variations were attributed to the different weather or road conditions. Hence, it was firstly necessary to comprehend the effects of each factor on the NOx emissions through the previously described method with multiple regression analysis, and then the comparison among each fuel had to be conducted.

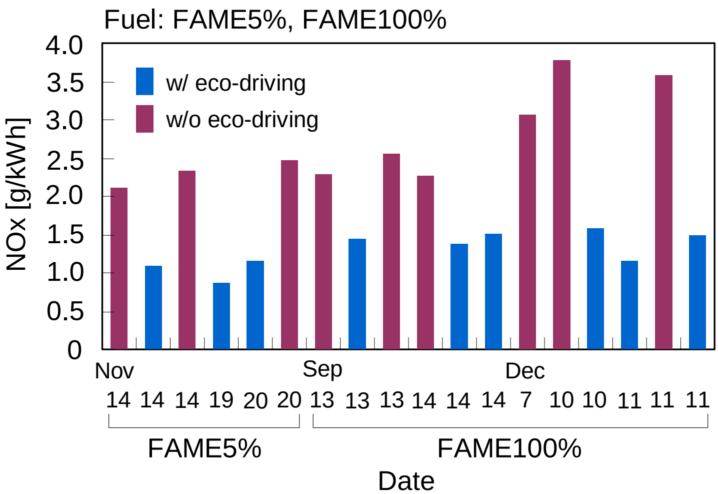


Figure 6-8 Results of NOx emission measurements under real-world conditions in each date in using FAME 5% and FAME 100%

Thus, the multiple regression analysis was conducted to the data in using ULSD and FAME, and then an estimated formula of NOx emissions, [g/kWh] was calculated. Formula (7) is the estimated formula of NOx emissions, [g/kWh] obtained by the multiple regression analysis.

$$
\begin{aligned}
NOx[g/kWh] = &-6.960\times10^{-6}\cdot\overline{N_e}^2 + 2.348\times10^{-2}\cdot\overline{N_e} \\
&+ 2.682\times10^{-4}\cdot\overline{T_e}^2 - 4.967\times10^{-2}\cdot\overline{T_e} \\
&- 1.790\times10^{-3}\cdot\overline{V}^2 - 1.917\times10^{-2}\cdot\overline{V} \\
&+ 8.494\times10^{-4}\cdot\overline{T_a}^2 - 3.549\times10^{-2}\cdot\overline{T_a} \\
&+ 1.847\times10^{-1}\cdot\overline{P_w}^2 - 7.396\times10^{-1}\cdot\overline{P_w} \\
&+ 1.253\times10^{-1}\cdot H_f - 1.321\times10^{4}\cdot H/C \\
&+ 2.073\times10^{4}
\end{aligned}
\quad (7)
$$

The relation between the estimated NOx emission values calculated by this formula and the actual measurement values obtained by on-road driving tests are shown in Figure 6-9. From this figure, it was ensured that the results of the estimation of NOx emissions in using FAME calculated by formula (7) had an adequate correlation with the results of actual measurements. Therefore, it could be said that this method was able to be adopted without any problems by adding the lower heating value per unit volume, H_f[kJ/L] and the H/C ratio to the explanatory variables, even though a vehicle was fueled by different fuels.

By using the estimation formula (7), the NOx emissions under the same conditions shown in Table 6-1 were compared between ULSD, FAME 5% and FAME 100%. The result is shown in Figure 6-10. From the result, it was clear that the NOx emissions were greatly influenced by the driving and weather conditions. In particular, in the condition B, that was assumed a hot and humid summer time in Tokyo with conscious of eco-driving, the NOx emissions indicated the lowest value, and in the condition C, that was assumed a cold and low humid winter time in Tokyo with non-conscious of eco-driving, they were the highest. In so far as this test route and the test vehicle were used, the NOx emissions in using ULSD indicated ca. 1.0 g/kWh in a minimum and ca.2.6 g/kWh in a maximum. However, it is quite possible that the results extend beyond the above values depending on the driving operation or weather conditions. On the other hand, when the fuel was changed from ULSD to FAME, in the case of FAME 5% the NOx emissions increased by ca. 0.2 g/kWh and in the case of FAME 100% they increased by ca. 0.4 g/kWh under each condition. Based on this, it was indicated that in using FAME 100%, the NOx emission value was ca. 3.0 g/kWh under the condition C.

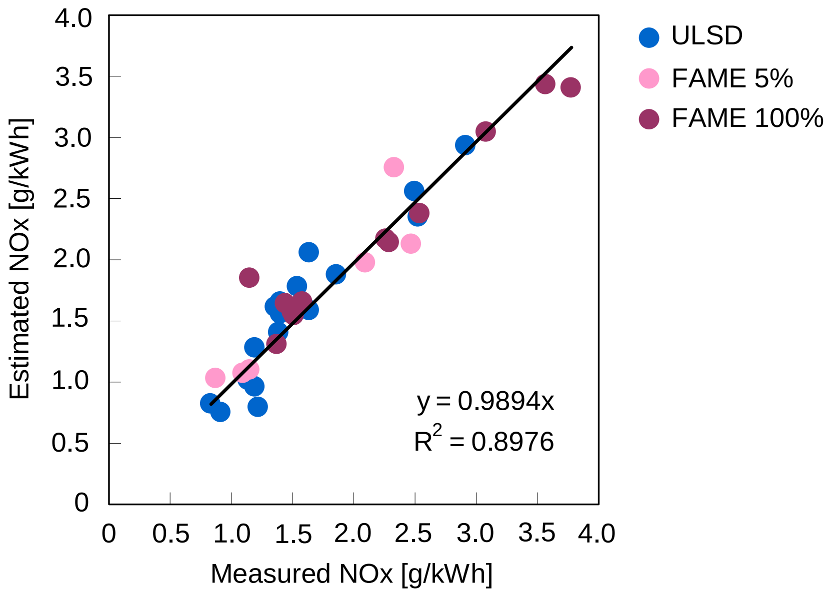


Figure 6-9 Comparisons between measured NOx emission and estimated NOx emission calculated by the results of multiple linear regression analysis in using ULSD, FAME 5% and FAME 100%

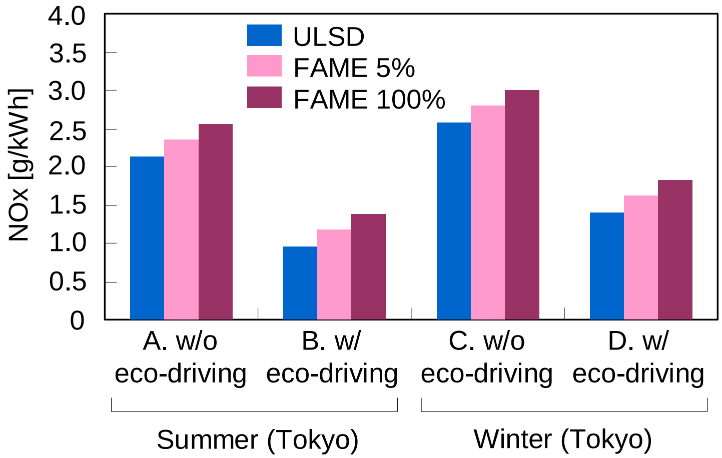


Figure 6-10 Evaluation results of real-world NOx emission characteristics estimated by equation (7) in using ULSD, FAME 5% and FAME 100% under common conditions

(2) Real-world emission characteristics in using HVO

Figure 6-11 shows the each test result of the measurement of NOx emissions, [g/kWh] under the real-world conditions in using the fuel of HVO. The results indicated there was obvious difference in the NOx emissions between with and without conscious of eco-deriving, nevertheless the NOx emissions fluctuated according to the tests even when the same test fuel was used. It was difficult to explain the differences among fuels. Thus, as is the case of FAME, the multiple regression analysis was conducted in order to understand the effects of each factor on the NOx emissions. Formula (8) is the estimated formula of NOx emissions, [g/kWh] obtained by the multiple regression analysis to the data in using ULSD and HVO.

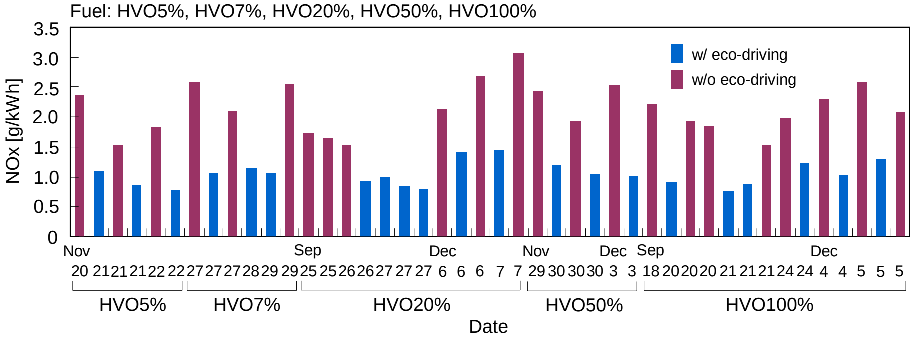


Figure 6-11 Results of NOx emission measurements under real-world conditions in each date in using HVO 5%, HVO 7%, HVO 10%, HVO 20%, HVO 50% and HVO 100%

$$
\begin{aligned}
NOx[g/kWh] = & -3.734\times10^{-6}\cdot\overline{N_e}^{2} + 1.356\times10^{-2}\cdot\overline{N_e} \\
& + 3.407\times10^{-4}\cdot\overline{T_e}^{2} - 7.774\times10^{-2}\cdot\overline{T_e} \\
& - 8.693\times10^{-3}\cdot\overline{V}^{2} + 2.632\times10^{-1}\cdot\overline{V} \\
& + 8.808\times10^{-4}\cdot\overline{T_a}^{2} - 2.993\times10^{-2}\cdot\overline{T_a} \\
& + 1.675\times10^{-1}\cdot\overline{P_w}^{2} - 7.705\times10^{-1}\cdot\overline{P_w} \\
& + 1.418\times10^{-2}\cdot H_f + 8.932\times10^{1}\cdot H/C \\
& - 6.854\times10^{2} \qquad (8)
\end{aligned}
$$

The relation between the estimated NOx emission values calculated by this formula and the actual measurement values obtained by on-road driving tests are shown in Figure 6-12. The coefficient of determination, R^2 in using HVO was slightly low compared to the case of FAME, but it was sufficiently high. Thus, it could be said that the results of the estimation of NOx emissions in using HVO had an adequate correlation with the results of actual measurements.

By using the estimation formula (8), the NOx emissions under the same conditions shown in Table 6-1 were compared among ULSD, the mixed fuels of ULSD and HVO whose content of HVO was 5%, 7%, 10%, 20% and 50%, respectively, and HVO 100%. The result is shown in Figure 6-13. Unlike the case of FAME, the NOx emissions in each mixing ratio of HVO to ULSD were almost equivalent to ULSD. Particularly, the NOx emissions indicated ca. 2.5 g/kWh in the condition C, which had the tendency of the highest NOx emissions. This value was obviously low compared with the case of FAME. These results were valid from the previous paper by the authors, and at the same time, it was considered that the properties of HVO such as non-oxygenated fuel and paraffinic hydrocarbon appeared.

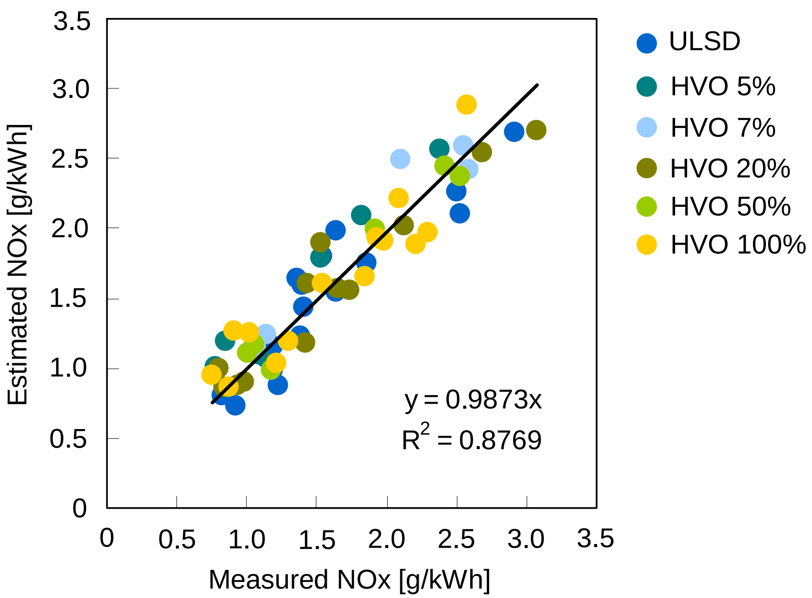


Figure 6-12 Comparisons between measured NOx emission and estimated NOx emission calculated by the results of multiple linear regression analysis in using ULSD, HVO 5%, HVO 7%, HVO 20%, HVO 50% and HVO 100%

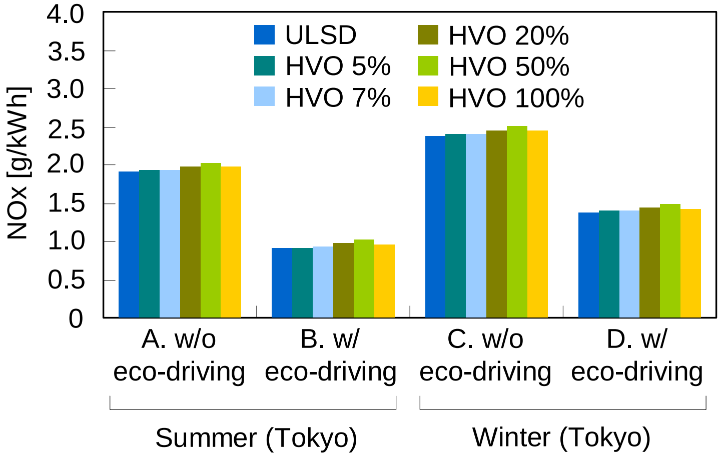


Figure 6-13 Evaluation results of real-world NOx emission characteristics estimated by equation (8) in using ULSD, HVO 5%, HVO 10%, HVO 20%, HVO 50% and HVO 100% under common conditions

(3) Real-world emission characteristics in using BTL

Figure 6-14 shows the each test result of the measurement of NOx emissions, [g/kWh] under the real-world conditions in using the fuel of BTL. In using BTL, once again, the NOx emission difference between the case with conscious of eco-driving and without conscious of eco-driving was clearly indicated, but the results of the measurement of NOx emissions in using the same fuel varied. It was suggested that the driving operation or weather conditions had influence on the NOx emissions. Then, along with the case of FAME and HVO, the multiple regression analysis to the data obtained in using ULSD and BTL was conducted so as to understand the effects of each factor on the NOx emissions. Formula (9) is the estimated formula of NOx emissions, [g/kWh] obtained by this process.

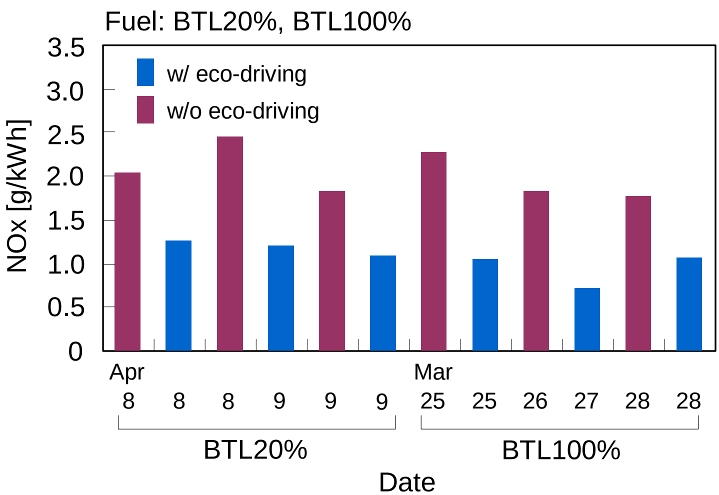


Figure 6-14 Results of NOx emission measurements under real-world conditions in each date in using BTL 20% and BTL 100%

$$\begin{aligned} NOx[g/kWh] = & -5.443\times10^{-6}\cdot\overline{N_e}^2 + 1.765\times10^{-2}\cdot\overline{N_e} \\ & + 7.122\times10^{-4}\cdot\overline{T_e}^2 - 1.669\times10^{-1}\cdot\overline{T_e} \\ & - 2.343\times10^{-2}\cdot\overline{V}^2 + 8.981\times10^{-1}\cdot\overline{V} \\ & + 7.013\times10^{-4}\cdot\overline{T_a}^2 - 3.068\times10^{-2}\cdot\overline{T_a} \\ & + 1.193\times10^{-1}\cdot\overline{P_w}^2 - 5.436\times10^{-1}\cdot\overline{P_w} \\ & - 3.238\times10^{-2}\cdot H_f - 9.908\times10^{1}\cdot H/C \\ & + 1.338\times10^{3} \end{aligned} \qquad (9)$$

Figure 6-15 shows the relation between the estimated NOx emission values calculated by this formula and the actual measurement values obtained by on-road driving tests. From this figure, it was ensured that the results of the estimation of NOx emissions in using BTL calculated by the formula (9) had an adequate correlation with the results of actual measurements.

By using the formula (9), the NOx emissions under the same conditions shown in Table 6-1 were compared among ULSD, the mixed fuel of ULSD and BTL, whose content of BTL was 20%, and BTL 100%. The results shown in Figure 6-16 indicated that in using BTL in the real-world, the NOx emissions were ca. 2.7 g/kWh in the condition C that was assumed a cold and low humid winter time in Tokyo with non-conscious of eco-driving. A tendency was seen that the NOx emissions slightly increased compared to ULSD.

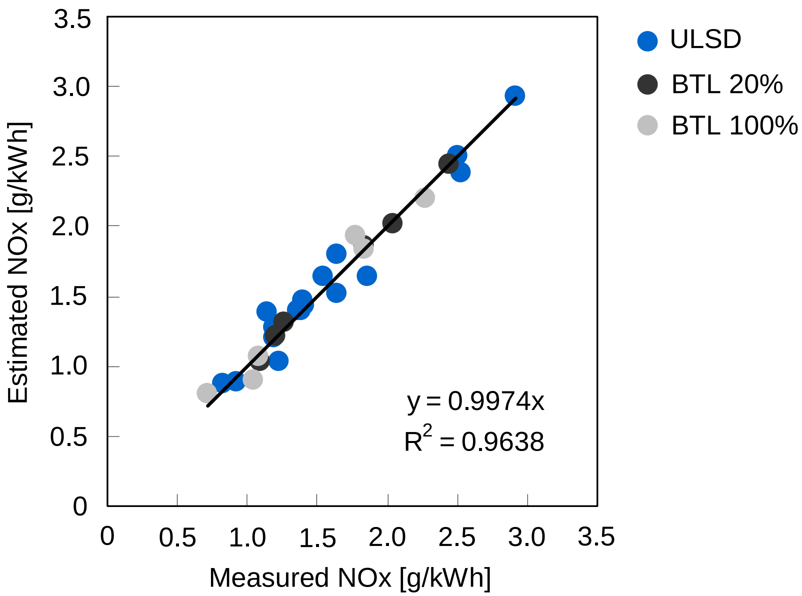


Figure 6-15 Comparisons between measured NOx emission and estimated NOx emission calculated by the results of multiple linear regression analysis in using ULSD, BTL 20% and BTL 100%

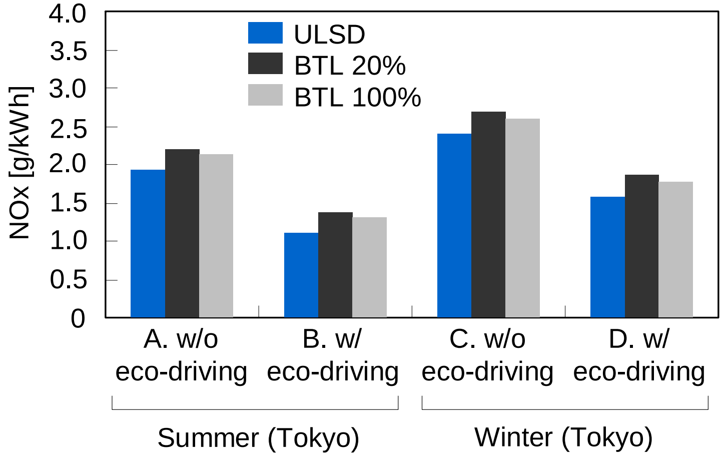


Figure 6-16 Evaluation results of real-world NOx emission characteristics estimated by equation (9) in using ULSD, BTL 20% and BTL 100% under common conditions

6.6.3. Evaluation of real-world emission characteristics for each biofuel

The explanation described above is the results of the evaluation conducted for each biofuel only by means of the measurement results in using ULSD and each biofuel. For this reason, the NOx emission estimation formulae shown in the formula (7), (8) and (9) are only applied to within the range of the data used for the multiple regression analysis. It means the reliability is not guaranteed under the conditions beyond the above range or using other types of fuel. Namely, an estimation formula of NOx emissions obtained by a multiple regression analysis to the data in using ULSD and a biodiesel cannot directly be applied to NOx emission estimation in using any other biofuels. Therefore, the multiple regression analyses were conducted to all the test results in using all the fuels, concretely, ULSD, FAME 5%, FAME 100%, HVO 5%, HVO 7%, HVO 20%, HVO 50%, HVO 100%, BTL 20% and BTL 100%, and then a mutual estimation formula which could be applied to all the fuels tested in this study was developed. Formula (10) shows the estimation formula of NOx emissions created by this process.

$$
\begin{aligned}
NOx[g/kWh] = & -1.466\times10^{-6}\cdot\overline{N_e}^{2} + 6.768\times10^{-3}\cdot\overline{N_e} \\
& + 3.520\times10^{-4}\cdot\overline{T_e}^{2} - 8.109\times10^{-2}\cdot\overline{T_e} \\
& - 7.476\times10^{-3}\cdot\overline{V}^{2} + 2.183\times10^{-1}\cdot\overline{V} \\
& + 3.292\times10^{-4}\cdot\overline{T_a}^{2} - 5.699\times10^{-4}\cdot\overline{T_a} \\
& + 1.247\times10^{-1}\cdot\overline{P_w}^{2} - 6.784\times10^{-1}\cdot\overline{P_w} \\
& - 1.536\times10^{-4}\cdot H_f - 9.043\times10^{-1}\cdot H/C \\
& + 5.361\times10^{0} \qquad (10)
\end{aligned}
$$

Figure 6-17 shows the relation between the NOx emission estimation values calculated by the formula (10) and the actual measurement values obtained by the on-road driving tests. It was ensured by this figure that there was a high correlation between them even when the multiple regression analyses were conducted to all the test fuels used in this study. Therefore, the validity of this method for comparing NOx emissions in fuels under real-world conditions was regarded as being generally secured.

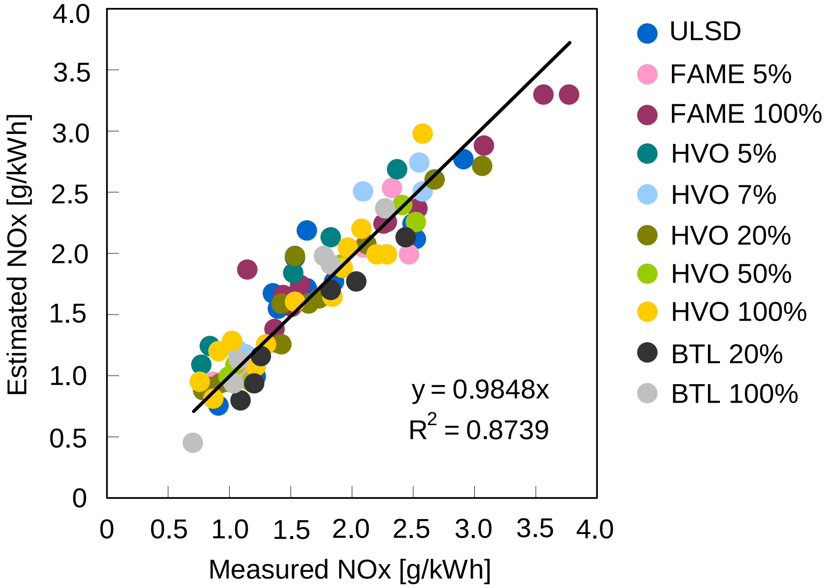


Figure 6-17 Comparisons between measured NOx emission and estimated NOx emission calculated by the results of multiple linear regression analysis using the results of ULSD, FAME 5%, FAME 100%, HVO 5%, HVO 7%, HVO 20%, HVO 50%, HVO 100%, BTL 20% and BTL 100%

Figure 6-18 shows the estimation results of the NOx emissions under the same conditions shown in Table 3 in using the four fuels of ULSD, FAME 100 %, HVO 100% and BTL 100%. As a result, the NOx emission characteristics under real-world conditions in using FAME and HVO largely agreed with the results indicated by Figure 6-10 and 6-13, and it was concluded that FAME 100% especially increased the NOx emissions. In using HVO, on the other hand, it was inferred that the NOx emissions could be maintained at the equivalent level to those of ULSD. The case of BTL 100% showed a slightly different result from Figure 6-16, that is, the NOx emissions were equivalent of those of ULSD. The reason was considered that the coefficient of determination, R^2 in Figure 6-17 was lower than that of the case in Figure 6-15, and thus the accuracy of NOx emission estimation was slightly reduced. The decrease in the accuracy was considered due to the lack of data in various weather conditions, which was caused by that the on-road driving tests were intensively conducted in the short-term, and small in number of tests compared to other fuels. However, in view of the results of Figure 6-16 and 6-18, the NOx emission characteristics under real-world conditions in using BTL 100% did not lead to the phenomenon of significant increase in NOx emissions like in the case of FAME 100%. It was inferred that there was a small increase or equivalent level of the NOx emissions compared with the case of ULSD.

As a result, under on-road driving conditions in the suburbs of Tokyo, it was verified that the highest NOx emission value was recorded in the condition of cold and low humid winter time without conscious of eco-driving, concretely ca. 2.5 g/kWh in using ULSD and ca. 3.0 g/kWh in FAME 100%. In using HVO 100% and BTL 100%, the NOx emissions were almost the same or slightly larger compared to those of ULSD. These exhaust gas levels in the real-world far exceeded the limit of the Japanese 2009 regulation, 0.7 g/kWh with which the test vehicle used in this study had complied. It means that the emission level could be even worse depending on fuels. Therefore, it is deemed appropriate to apply a paraffinic hydrocarbon biofuel such as HVO or BTL to the latest heavy-duty diesel vehicles so as to prevent the exhaust gas from worsening in the real-world.

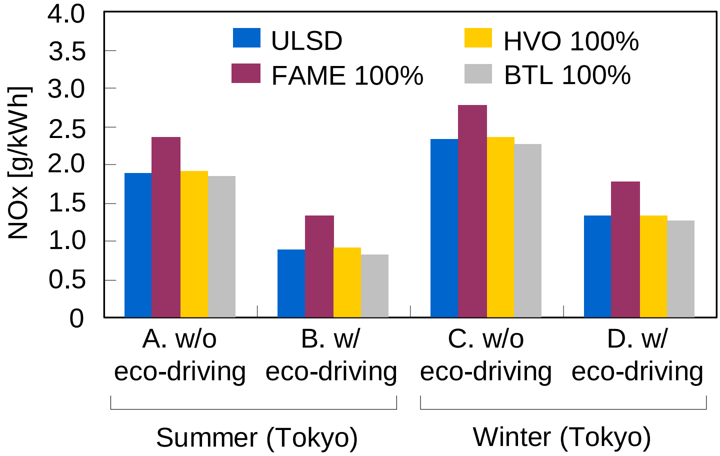


Figure 6-18 Evaluation results of real-world NOx emission characteristics estimated by equation (10) in using ULSD, FAME 100%, HVO 100% and BTL 100% under common conditions

6.6.4. Evaluation of real-world energy consumption and CO_2 emission characteristics for each biofuel

(1) Results of energy consumption and CO_2 emission measurements

This section will describe the results of the comparison of fuel consumption and CO_2 emissions during on-road driving among each fuel and the evaluation of the effects of the difference in fuels. The fuel consumption was calculated by two methods; one was a calculation using the carbon balance method with the emissions of CO, CO_2 and HC measured by PEMS, and the other was a calculation by the integrated values of the signal of fuel injection quantity loaded from ECU, and then the evaluation was conducted. In the same way, the CO_2 emissions were evaluated by the above mentioned methods. The fuel consumption, however, could not be simply compared by volume, since the density [kg/L] and the lower heating value [kJ/kg] varied when the fuel type was different. Hence, in this study, the energy consumption [MJ/km] was adopted to the evaluation index as an alternative to the fuel consumption.

The figures from Figure 6-19 to Figure 6-22 show the results of energy consumption [MJ/km] and CO_2 emissions [g/km] calculated by the two methods when ULSD, FAME, HVO and BTL were used as fuel. As with the case in the evaluation of NOx emissions, it is clear here that the values of energy consumption and CO_2 emissions varied by test, and a simple comparison among fuels could not be performed. Moreover, these values varied depending on the driving operation, namely, the energy consumption and the CO_2 emissions were generally decreased by the driving with conscious of eco-driving compared to the non-conscious of eco-driving. However, the measurement results of both values of energy consumption and CO_2 emissions by PEMS were underestimated by from 10 to 20 percent or more in some cases compared to the estimation results by the signal of fuel injection quantity loaded from ECU. This phenomenon was seen pronouncedly in the conscious of eco-driving. As mentioned previously, PEMS gives the calculation of emissions of exhaust gas components by weight, and the exhaust gas flow rate was measured by the pitot tube. In fact, using pitot tube has the disadvantage of low precision of measurement at low flow rate region. For this reason, the measurement accuracy was deteriorated under low exhaust gas flow rate conditions such as idling. The driving with conscious of eco-driving had a relatively high percentage of exhaust gas by idling, since the exhaust gas flow rate was totally controlled to be reduced. Moreover, the CO_2 emissions had a relatively high concentration even in the idling operation due to high EGR ratio. It is considered that the CO_2 emissions were significantly influenced by variations in the measurement results. This phenomenon was not seen in the NOx emissions, because the NOx emissions were low enough in the idling operation and they were emitted in large amounts in the starting and accelerating operations of high exhaust gas flow rate.

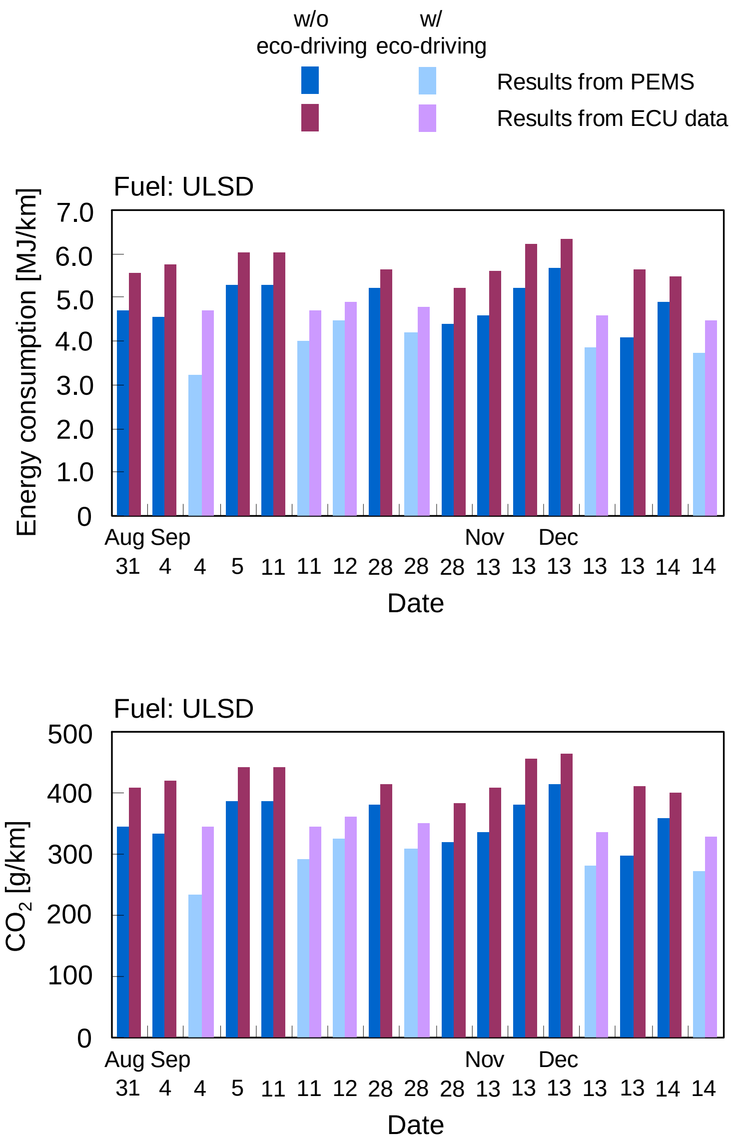


Figure 6-19 Results of energy consumption and CO_2 emission under real-world conditions in each date in using ULSD

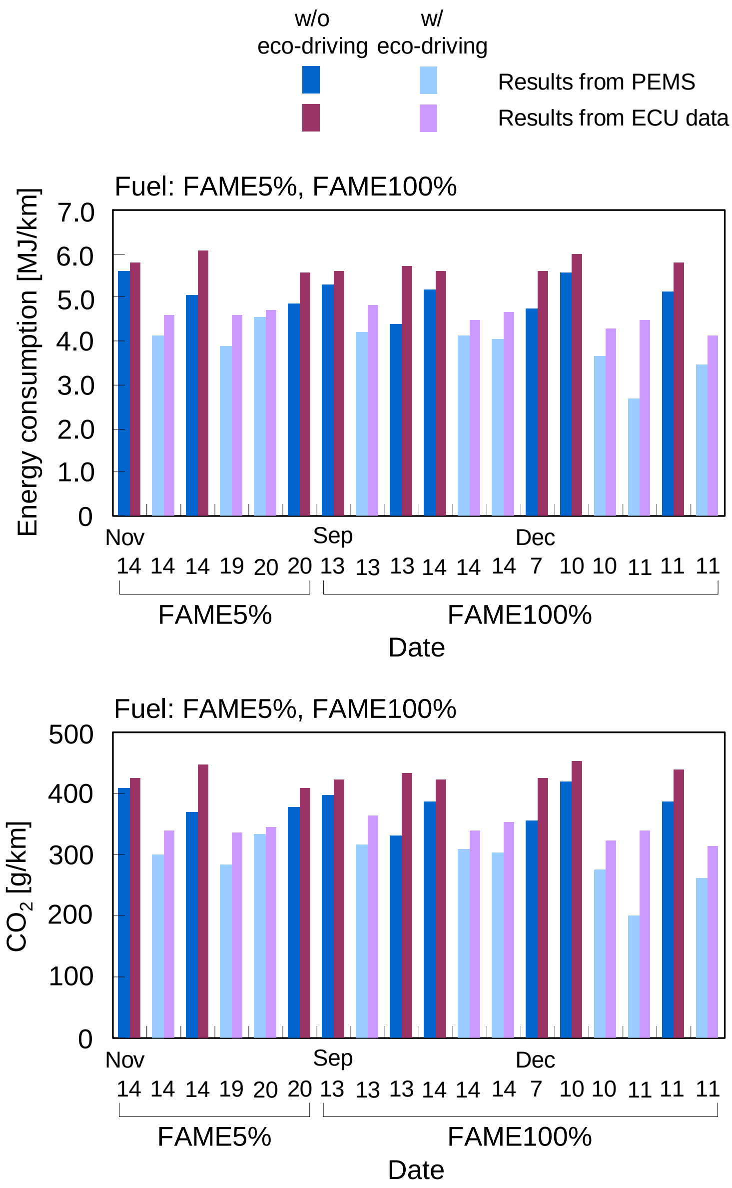


Figure 6-20 Results of energy consumption and CO_2 emission under real-world conditions in each date in using FAME 5% and FAME 100%

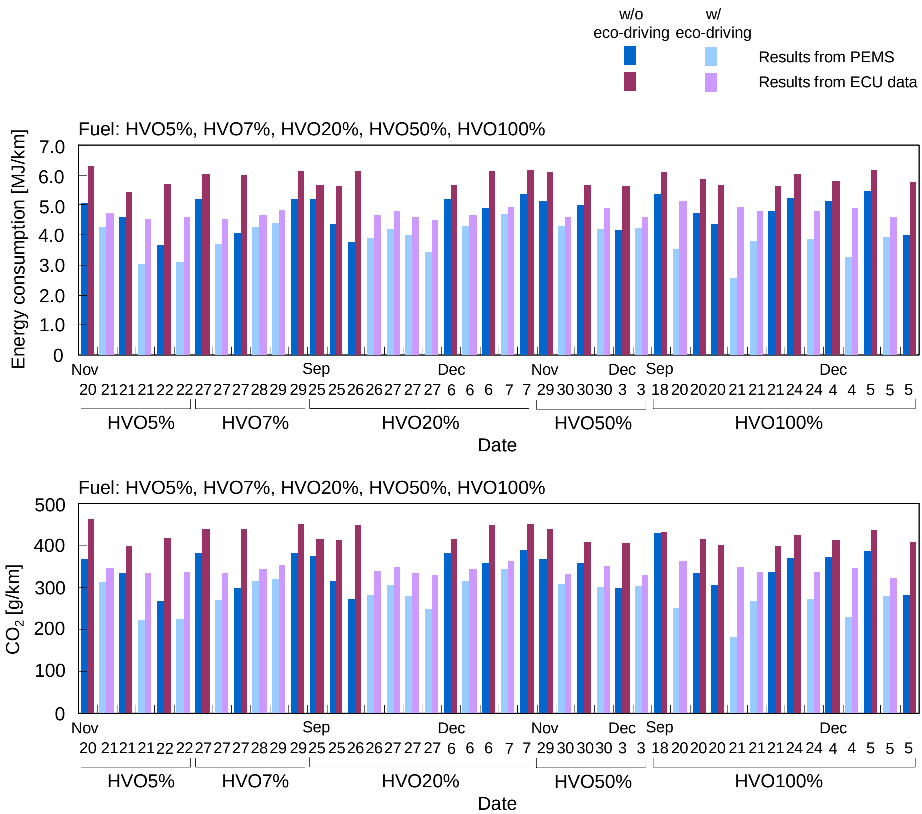


Figure 6-21 Results of energy consumption and CO_2 emission under real-world conditions in each date in using HVO 5%, HVO 7%, HVO 10%, HVO 20%, HVO 50% and HVO 100%

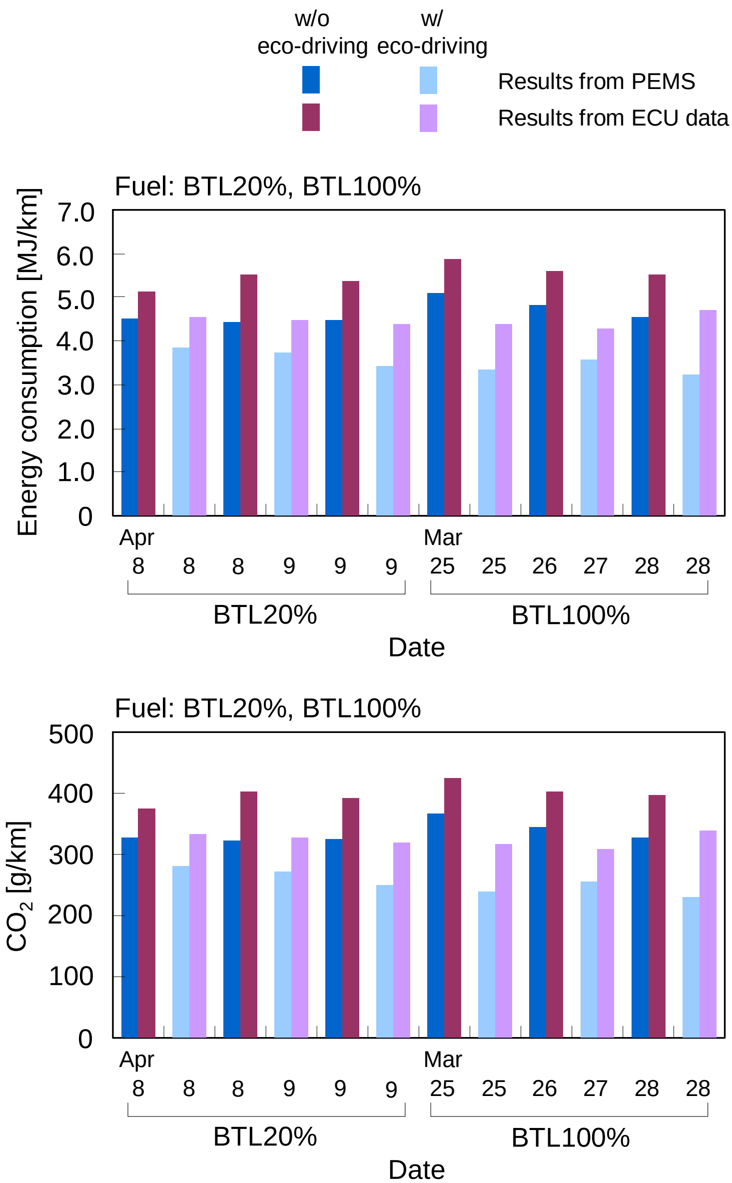


Figure 6-22 Results of energy consumption and CO_2 emission under real-world conditions in each date in using BTL 20% and BTL 100%

(2) Comparisons of energy consumption and CO_2 emission for each fuel

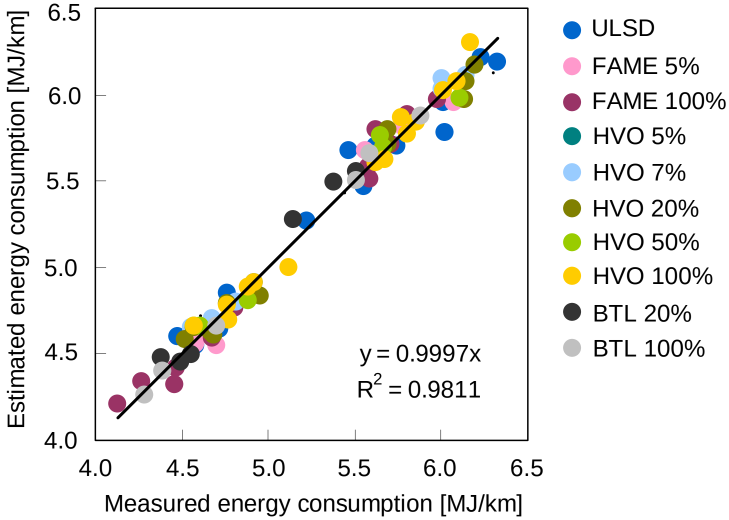
As with the case of the evaluation of NOx emissions, possible factors influencing on the energy consumption and CO_2 emissions were extracted, and then by using these factors as explanatory variables, the multiple regression analyses were conducted to all data shown in from Figure 6-19 to Figure 6-22. By these analyses, the effect of each factor on the energy consumption and CO_2 emissions was analyzed quantitatively. It should be noted, however, that the results of energy consumption and CO_2 emissions used here were the estimation results of the signal of fuel injection quantity loaded from ECU. The explanatory variables used in this analysis were as follows; as for the vehicle driving, the average engine speed N_e[rpm] and engine torque T_e[N·m] during a positive value of the engine torque, and the average vehicle speed V during tests, and as for the fuel property, the lower heating value H_f [kJ/kg], H/C ratio and O/C ratio. The formulae (11) and (12) show the estimated formulae of energy consumption EC[MJ/km] and CO_2 emissions [g/km] obtained by the multiple regression analyses.

$$\begin{aligned} EC[MJ/km] = {} & 3.075\times10^{-3}\cdot\overline{N_e} + 1.059\times10^{-2}\cdot\overline{T_e} \\ & -1.063\times10^{-1}\cdot\overline{V} + 4.686\times10^{-4}\cdot H_f \\ & -2.193\times10^{0}\cdot H/C + 2.257\times10^{1}\cdot O/C \\ & -1.482\times10^{1} \end{aligned} \tag{11}$$

$$\begin{aligned} CO_2[g/km] = {} & 2.249\times10^{-1}\cdot\overline{N_e} + 7.698\times10^{-1}\cdot\overline{T_e} \\ & -7.927\times10^{0}\cdot\overline{V} + 2.542\times10^{-2}\cdot H_f \\ & -1.887\times10^{2}\cdot H/C + 1.269\times10^{3}\cdot O/C \\ & -6.431\times10^{2} \end{aligned} \tag{12}$$

Figure 6-23 shows the relation between the estimated energy consumption values calculated by formula (11) and the measurement values obtained by tests, and the relation between estimated CO_2 emission values calculated by formula (12) and the measurement values. From this figure, it can be verified that both of the estimated results of energy consumption and CO_2 emissions showed a high correlation with the actual measurement results. Thus, it can be said that this method can estimate the energy consumption and CO_2 emissions and compare these values in the real-world among fuels.

Accordingly, this study focused on the driving condition, in particular the condition with non-conscious of eco-driving (the average engine speed of 1670 rpm and the average engine torque of 146 Nm), which are identical to the condition A and C in Table 6-1, and the condition with conscious of eco-driving (the average engine speed of 1330 rpm and the average engine torque of 133 Nm) identical to the condition B and D. Under these conditions, the energy consumption and CO_2 emissions in each fuel were estimated by using formulae (11) and (12). The comparison results are shown in Figure 6-24. This figure indicates that every biofuel did not aggravate the energy consumption compared to ULSD but maintained the equivalent level. The CO_2 emissions in each biofuel were the same level or slightly decreased compared to ULSD. Moreover, it was clear that the eco-driving in every fuel decreased the energy consumption and CO_2 emissions by ca. 20 percent. In fact, the evaluation by this method was the result from the statistical analysis of the on-road driving tests under various conditions, and thus in some condition, the estimated results were slightly different from the actual measurement values. Nevertheless, the similar tendency as the results of the emission tests using the chassis dynamometer was verified by this method.



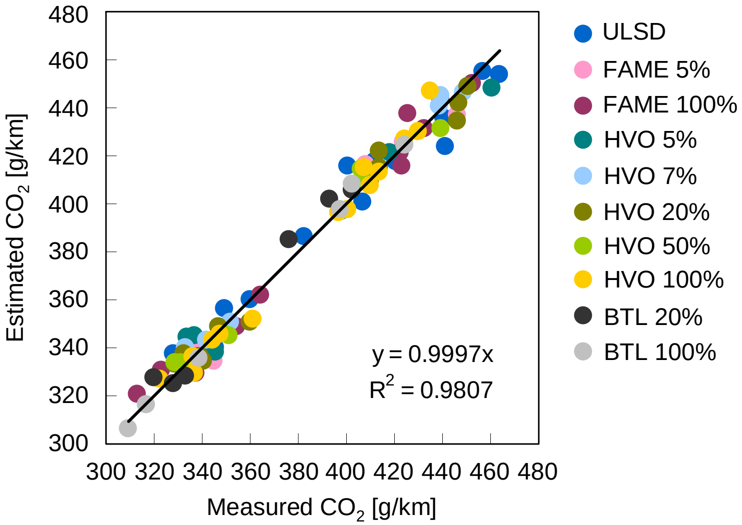


Figure 6-23 Comparisons between measured energy consumption and CO_2 emission and estimated energy consumption and CO_2 emission calculated by the results of multiple linear regression analysis using the results of ULSD, FAME 5%, FAME 100%, HVO 5%, HVO 7%, HVO 20%, HVO 50%, HVO 100%, BTL 20% and BTL 100%

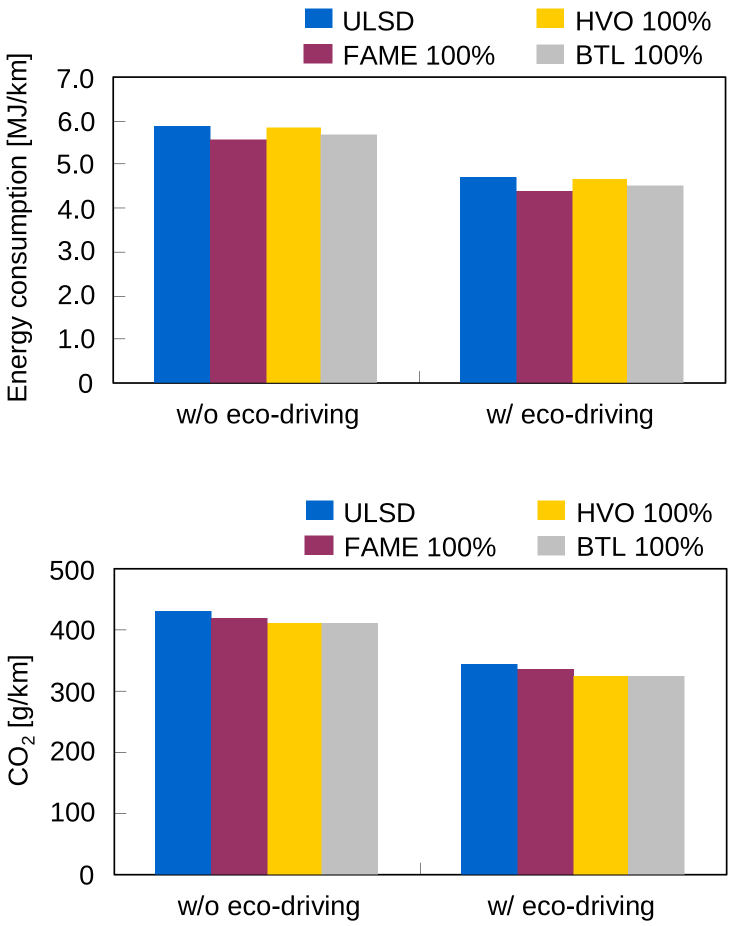


Figure 6-24 Evaluation results of real-world energy consumption and CO_2 emission characteristics estimated by equation (11) and (12) in using ULSD, FAME 100%, HVO 100% and BTL 100% under common conditions

6.7. Summary of this chapter

This study performed the on-road driving tests for the evaluation of the real-world exhaust gas in using biofuels of FAME, HVO and BTL, and considered the future direction of biofuels applicable to heavy-duty diesel vehicles. As a result, some knowledge was obtained as follows;

In the case where the same test vehicle and driving route were used for every on-road driving test, the NOx emissions, [g/kWh] were able to be estimated by the multiple regression analysis with the explanatory variables of the average vehicle speed during tests, the average engine speed and engine torque during a positive value of the engine torque, the average ambient temperature and water vapor partial pressure during tests.

In addition to the above, in the case where the fuels different from ULSD were used, the NOx emissions under the real-world conditions were also able to be estimated by adding the factors arising from the fuel property, that is, the lower heating value per unit volume, H_f[kJ/L] and the H/C ratio to the explanatory variables.

It was clear that the NOx emission characteristics under the real-world conditions were influenced by weather conditions, such as ambient temperature or water vapor partial pressure, and driving operation, concretely the low NOx emissions were indicated in the hot and humid condition, and high emissions in the cold and low humid condition. Moreover, in the driving operation without conscious of eco-driving, the high NOx emissions were recorded and in the operation with conscious of eco-driving, the low emissions. Therefore, when the vehicle was operated under the cold and low humid condition, like winter time in Tokyo, without conscious of eco-driving, the NOx emissions resulted in the highest amount. This highest amount of NOx emission was several times higher than the limit of the

Japanese 2009 regulation with which the test vehicle used in this study had complied.

In using FAME in particular among every biofuel, the NOx emission amount significantly increased under the real-world conditions. On the other hand, in using HVO, the NOx emission characteristics were equivalent to those of ULSD and in the case of BTL they were almost the same or slightly increased.

The energy consumption and CO_2 emissions were able to be estimated by developing formulae. The formulae were constructed by the multiple regression analyses conducted to all the test results with the following explanatory variables; the average vehicle speed during tests, the average engine speed and engine torque during a positive value of the engine torque, and the lower heating value H_f [kJ/kg], H/C ratio and O/C ratio in the fuels.

It was clear that all fuels of FAME, HVO and BTL did not show the deterioration in energy consumption and CO_2 emissions compared to ULSD but maintained the equivalent level. In addition, in every fuel, the eco-driving could decrease the energy consumption and CO_2 emissions could be decreased by ca. 20 percent.

7. Conclusions

This Annex introduced the performance evaluations for the emission gas and fuel economy to the heavy-duty diesel vehicle fueled with biodiesels of FAME, HVO and BTL under on-road driving conditions. The vehicle used in this study complied with the latest emission regulations and was equipped with PEMS (Portable Emission Measurement System). Before the on-road driving tests, the exhaust gas emission tests were performed using the chassis dynamometer so as to verify the basic performance of emission gas and fuel economy. Moreover, the evaluation for the characteristics of combustion and exhaust gas in BTL was conducted using the engine test cell, in order to consider the results of exhaust gas tests with the chassis dynamometer in using BTL as fuel. The findings obtained by the above evaluation are described below.

7.1. Results of chassis dynamometer emission tests

The vehicle used in this Annex had the DOC and DPF as an aftertreatment system, and then the emissions of CO and NMHC were sufficiently below the upper limit of Japanese 2009 regulation even in using each biodiesel. The NOx emissions, on the other hand, varied depending on the biodiesel, to be specific, in using FAME the NOx emissions significantly increased with the increase in the mixing ratio of FAME to ULSD. The same phenomenon was seen in using BTL especially with an extremely low flash point. This type of BTL may contain large amounts of hydrocarbon components with low boiling point, and thus the tendency that the NOx emissions increased with the increase in the mixing ratio of BTL to ULSD was observed. However, the conditions of the increase in NOx emissions were different, namely, in the case of FAME, the emissions were increased under the starting and accelerating conditions and in the case of BTL with an extremely low flash point, they were increased under the high speed running condition. On the other hand, in using HVO and BTL with a relatively high flash point, the NOx emissions maintained almost the same level as those of ULSD. The fuel consumption was not influenced by the change in fuel when it was evaluated by using an energy consumption index.

7.2. Results of engine tests with the engine test cell

The effects of the difference in the flash point on the characteristics of combustion and exhaust gas varied depending on conditions. Along with the results of the exhaust gas emission tests using the chassis dynamometer, in the case of BTL with a low flash point, the combustion by pilot injection was more activated than that of BTL with a relatively high flash point under the condition of the engine speed and torque identical with those of high speed running. At the same time, BTL with an extremely low flash point had a low distillation temperature, and thus it was considered it contained large amounts of hydrocarbon components with low boiling point. In these BTL properties, the effect of the low flash point was obviously observed under the high speed running condition. The combustion associated with the increase in the NOx emissions was considered to be caused by that the pilot-injected fuel evaporated at the early stage and was mixed with air.

7.3. Results of real-world emission tests with PEMS

The characteristics of NOx emission in real-world were largely influenced by weather conditions, road environment and driving operations. For this reason, the evaluation of the effects of the difference in fuel type on the NOx emission characteristics is performed effectively by through the following procedures; an estimated formula of NOx emissions was constructed by the statistical method with the test results, and the formula was given to the same conditions as real-world, and then the comparison among fuels was conducted. Using this method, the NOx emission characteristics in real-world were evaluated and the results indicated that the NOx emissions increased compared to ULSD only in using FAME, along with the results of the exhaust gas emission tests with chassis dynamometer. On the other hand, in using HVO and BTL with a relatively high flash point, the NOx emissions were the similar level as those of ULSD. Moreover, the NOx emission values became the highest under the cold and low humid condition without conscious of eco-driving, and the values were three to four times higher than the upper limit of the emission regulations. However, the NOx emission levels could be controlled by the driving operation with conscious of eco-driving.

The energy consumption and the CO_2 emissions could be evaluated in the same method as the case of the NOx emissions, namely, developing an estimated formula by the statistical method and then comparing among fuels. The results of the evaluation indicated that every biofuel did not aggravate the energy consumption and the CO_2 emissions compared to ULSD. In addition, the driving operation with consciousness of eco-driving could decrease the energy consumption and CO_2 emissions by ca. 20 percent compared to the non-consciousness of eco-driving in using every fuel.

The pour point of FAME and BTL used in this Annex, however, were 10 degree C higher than that of ULSD. Therefore, it is very difficult to use these biofuels without mixing with ULSD in cold regions under -20 degree C of ambient temperature. In order to use these biofuels in such cold regions, the isomerization or the utilization of pour-point depressant for the decrease of pour point should be applied. Needless to say, low-concentration mixing a small amount of biofuel with a large amount of ULSD is also useful way to use these biofuels in such regions. In case that paraffinic-hydrocarbon biofuels are isomerized, fuel properties other than the pour point such as the cetane number also change. For this reason, it is necessary for the usage of such isomerized biofuels to investigate more including their combustion characteristics in the future.

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