Annex XXXVIII Phase 1

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, Test vehicle, Test engine

Preface and Acknowledgement

This report focuses on the comparison of the real-world emissions between the case of using diesel oil and BDF for fuel. For this purpose, the on-road driving tests were made, by applying BDF, 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 diesel vehicles complying with the latest emission gas regulations of Japan also meet the heavy vehicle fuel economy regulations introduced by Japan ahead of other countries of the world. Since application of BDF presents problems not only 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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Contents

List of Tables

List of Figures

Acronyms and Abbreviations

AMF	Advanced Motor Fuels
ATDC	After Top Dead Center
BDF	Bio Diesel Fuel
BSEC	Brake Specific Energy Consumption
CA	Crank Angle
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVS	Constant Volume Sampler
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EMS	Eco-driving Management System
FAME	Fatty Acid Methyl Esther
GPS	Global Positioning System
GVW	Gross Vehicle Weight
HVO	Hydro-treated Vegetable Oil
IBP	Initial Boiling Point
IEA	International Energy Agency
IMEP	Indicated Mean Effective Pressure
JIS	Japanese Industrial Standards
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
THC	Total Hydro Carbon
VST	Average Vehicle Speed in a Short Trip

Executive Summary

Widespread use of biodiesel fuel (BDF) vehicles would greatly reduce CO_2 emissions and increase resource recycling, contributing to global environmental conservation. In fact, activities for expanding the production and utilization of BDF are already proceeding throughout the world. For diesel fuel vehicles, efforts are well underway to enhance the engine performance and to reduce hazardous gas emissions by means of advanced technology and precise electronic control. Because BDF differs greatly in fuel characteristics from diesel fuel, its use for this type of vehicle could increase hazardous gas emissions.

This report compares the real-world emissions between the diesel fuel and BDF vehicle. For this purpose, on-road driving tests were conducted with both types of fuel in the latest diesel vehicles complying with the latest emission regulations. The same vehicles were tested for both fuel types, with the emissions being determined by a Portable Emission Measurement System (PEMS). In addition, a test was also performed to determine the effect of BDF vehicles on the real - world fuel economy.

Emission Evaluation by Means of the Chassis Dynamometer Test

Prior to the road test on the road, chassis dynamometer tests were performed to gain an understanding of the basis emission gas characteristics of BDF vehicles. Table ES-1 shows the characteristics of the fuels used in this test: normal diesel, BDF, and a renewable diesel fuel. For diesel oil, JIS No.2 diesel oil available on the market was used. For biofuels, two types were used: BDF originating from waste food oil of Kyoto City and NExBTL® of Neste Oil. Note that testing of BDF and NExBTL were conducted with the fuel mixed with diesel oil and 100% BDF (NEAT).

Table ES-1 Test fuels

Fuel		Diesel	BDF (Kyoto)	NExBTL
Density (15 deg.C) g/cm^3		0.8275	0.8849	0.7797
Kinematic viscosity mm^2/s		3.777 (@30 deg.C)	4.689 (@40 deg.C)	2.985 (@30 deg.C)
Flash point deg.C		66.0	115.0	88.0
Cetane number		57.2	52.6	88.2
Distillation temp. deg.C	IBP	170.0	284.0	-
	10%	212.0	345.0	-
	50%	282.5	354.0	-
	90%	332.0	359.0	293.4
CHO wt.%	C	85.9	76.7	84.4
	H	13.9	12.2	15.3
	O	0.2	11.1	0
Pour point deg.C		-22.5	-15.0	-15.0
Sulfur content ppm		4.8	3.3	-
Lower heating value kJ/kg		42850	37000	44070

The test vehicle was a diesel truck applied to the new long-term emission regulations (2005) of Japan (Hino Dutro). The maximum pay-load capacity was 3 tons, and the vehicle was equipped with oxidation catalyst and a diesel particulate filter (DPF) for the after-treatment system. The JE05 driving cycle was employed, as introduced in the 2005 regulations.

BDF originating from waste cooking oil of Kyoto City was mixed with diesel fuel. The mixing ratios of BDF into diesel fuel were 0%, 20%, and 100%. Figure ES-1 shows the test result of CO_2, NOx, particulate matter (PM) emissions, as well as fuel economy and brake-specific energy consumption (BSEC). Note that the PM emissions shown in the figure are the result of measurements in the latter stage of DPF, and CO and nonmethane hydrocarbon (NMHC) emissions were almost zero. The data in Fig. ES-1 indicate that an increase in the BDF mixing ratio increases the NOx and PM emissions. However, the amount of PM emissions remains at a very low level. Also, when the BDF mixing ratio is changed, the amount of CO_2 emissions does not change, but the fuel economy and BSEC decline somewhat.

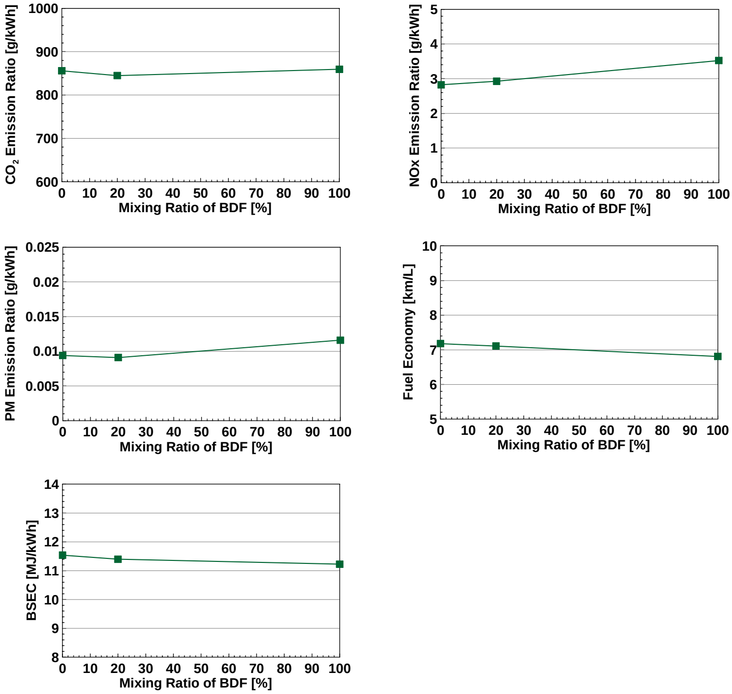


Figure ES-1 Emission and fuel economy characteristics of the JE05 driving cycle using BDF as fuel

Also for the chassis dynamometer tests NExBTL made by Neste Oil was mixed with diesel fuel in ratios of 0%, 5%, 50%, and 100% NExBTL. Figure ES-2 shows the test results of CO_2, NOx, PM, fuel economy, and BSEC. Note that CO and NMHC emissions were almost zero. The results in Fig. ES-2 confirm that an increase in the NExBTL mixing ratio reduces the amount of CO_2 and PM emissions and improve the BSEC. An increase in the mixing ratio does not increase the NOx emissions. The NMHC emissions are almost zero due to the oxidation catalyst in all the tests.

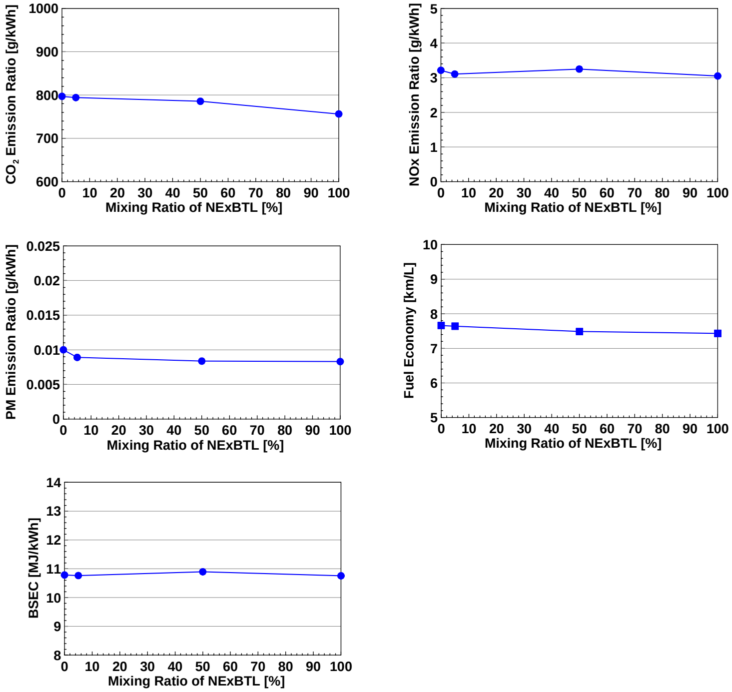


Figure ES-2 Emission and fuel economy characteristics of the JE05 driving cycle using NExBTL as fuel

In general, the chassis dynamometer test results show that the amount of PM emissions and the fuel economy are not significantly affected by the changes in the mixing ratio of BDF or NExBTL. For NOx, however, when BDF is mixed with diesel fuel, the amount of emissions increases with an increase in the mixing ratio. On the other hand, when NExBTL is mixed with diesel fuel, the amount of NOx emissions is not changed.

Analysis of Combustion and Emission Characteristics of BDF and NExBTL

To determine the basic combustion and emission characteristics of BDF and NExBTL, a single-cylinder diesel engine test was performed. The test was conducted by applying indicated mean effective pressures (IMEP) of 250, 500, and 750 kPa under single-and two-stage injection with the diesel, BDF, and NExBTL fuels. In either injection condition, the type of fuel is an important test parameter. Figures ES-3 and ES-4 indicate the NOx and soot emission under the single-stage injection condition for the three fuel types, respectively. As evident from the data, the NOx emission rate for BDF increased by 2.6-4.7% relative to diesel fuel. By contrast, the rate for NExBTL declined relative to both BDF and diesel fuel. In particular, it was reduced 7% relative to diesel fuel at a load of IMEP = 250 kPa. As evident from Fig. ES-4, the soot emission rate decreased about 50 to 80% for BDF and about 20 to 40% for NExBTL relative to diesel fuel. The large reduction of soot emission as compared with diesel fuel is attributed to both biofuels not containing any aromatic component. In addition, BDF contains oxygen atoms, which contributed to further reduction of the soot emission.

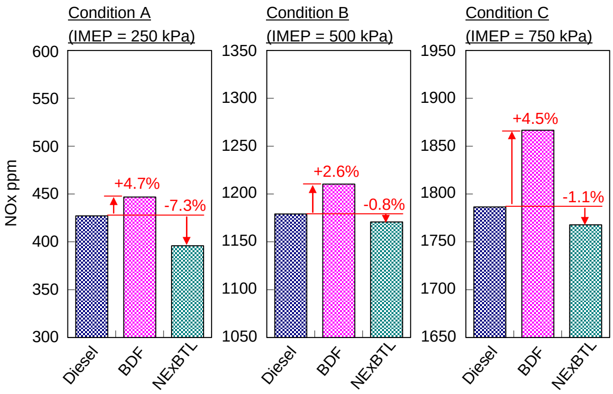


Figure ES-3 NOx emission characteristics of single-stage injection conditions

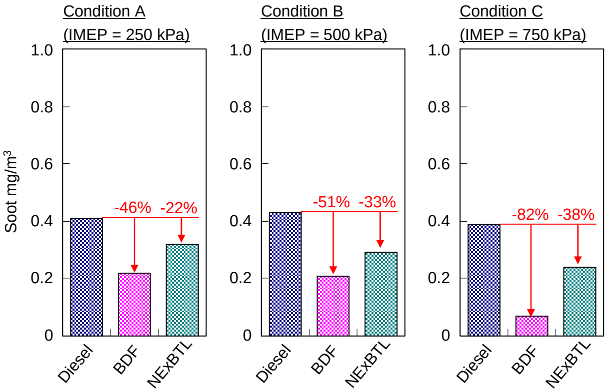


Figure ES-4 Soot emission characteristics of single-stage injection conditions

This study also determined the combustion and emission characteristics of BDF and NExBTL under two-stage injection conditions. Figures ES-5 and ES-6 show NOx and soot emissions under two-stage injection conditions. As a result of the test, NExBTL exhibited lower NOx emissions than BDF, except for Condition D in which the load was low (IMEP = 250 kPa). Also, the emission for NExBTL was nearly equivalent relative to diesel, that is, within about ±2%. Soot emission for NExBTL and BDF appears to have been reduced by 50-70% from the case of running with diesel fuel, because NExBTL does not contain any amorphous component.

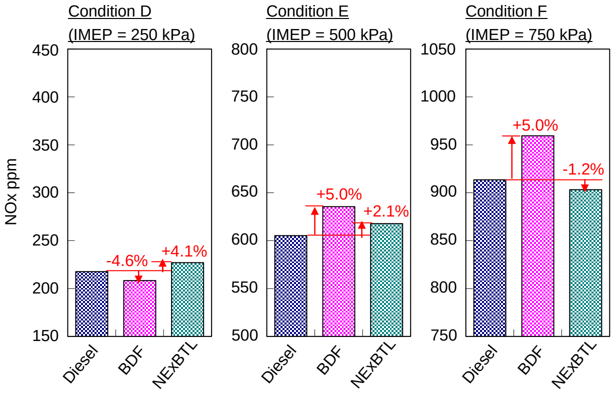


Figure ES-5 NOx emission characteristics of two-stage injection conditions

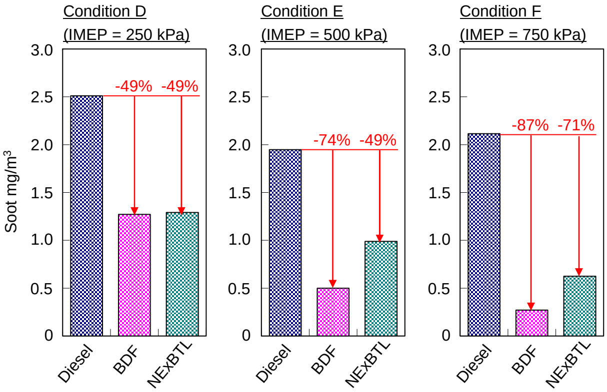


Figure ES-6 Soot emission characteristics of two-stage injection conditions

In sum, NExBTL is capable of suppressing NOx emission when compared with BDF and can maintain the emission level equivalent to the case of running with diesel fuel. One of the reasons for this finding is that NExBTL has a higher cetane value, causing shorter ignition delay and thus small ratio of premixed combustion during the initial period where NOx is readily generated.

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

The vehicle in the above test running with biofuel mixed with neat or diesel fuel and the vehicle running with diesel fuel were equipped with an on-board measurement system, including PEMS. Then, they were run on the road to evaluate emission characteristics. The on-board measurement system, which is used in the on-road driving test, is shown in Fig. ES-7. The test route, approximately 22.2 km in full circle, was set using local roads around the National Traffic Safety and Environment Laboratory (NTSEL). The vehicles were tested with each of the fuel mixing conditions, twice for normal driving and twice for eco-driving. Note that, for BDF B50 and BDF B75, the test was run within the yard of NTSEL because the vehicles could not be used on public roads due to legal constraints of Japan, “Act on the Quality Control of Gasoline and Other Fuels”. The on-road test evaluated the emission rate of NOx, CO, CO_2, and total hydrocarbon (THC), as well as the fuel economy.

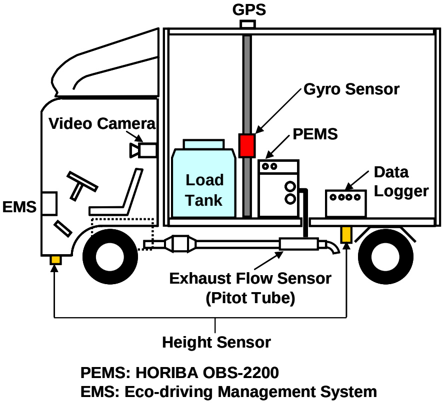


Figure ES-7 On-board measurement system

Figure ES-8 shows the fuel economy, CO_2 emission, and NOx emission in various mixing ratios of waste-cooking-oil BDF and diesel fuel. Note that under these conditions, the results of runs B50 and B75, as mentioned above, are the result of driving inside the NTSEL yard. These data indicate that fuel economy and CO_2 emissions did not appreciably change with an increase in the mixture ratio of BDF, while NOx emissions clearly increased. The same result was seen in the chassis dynamometer test. In particular, over 50% of mixing ratio of BDF led to a large increase in NOx emissions.

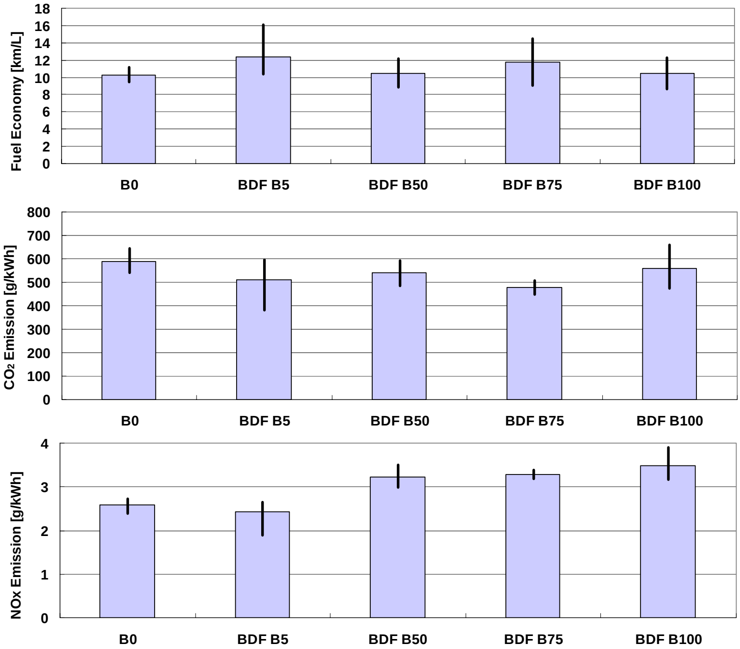


Figure ES-8 Route total results for fuel economy, CO_2 emissions, and NOx emissions at BDF ratios of 0, 5%, 50%, 75%, and 100% relative to diesel fuel

Figure ES-9 shows the fuel economy, CO_2 emissions, and NOx emissions in various mixing ratios of NExBTL and diesel fuel. Unlike the results for BDF, all results were obtained by driving tests in urban areas. These figures indicate that the fuel economy, CO_2 emissions, and NOx emissions did not appreciably change with an increase in the mixture ratio of NExBTL. In the chassis dynamometer tests, the results indicated that CO_2 emissions decreased with an increase in the mixture ratio of NExBTL. The on-road driving tests include the variations caused by traffic conditions, and the result of this test with NExBTL is within the range of these variations. From the results of each mixing ratio, it can be concluded that the fuel economy, CO_2 emissions, and NOx emissions are equivalent to those for operation using only diesel fuel.

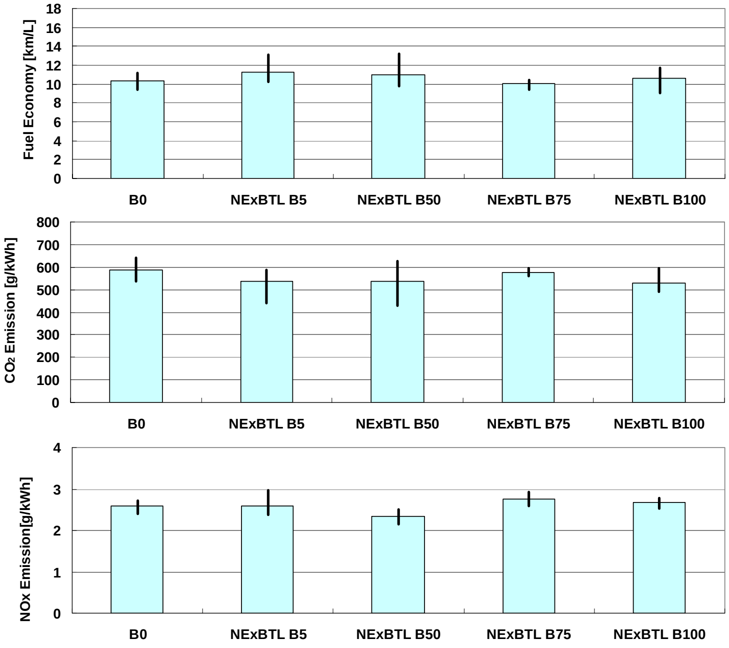


Figure ES-9 Route total results for fuel economy, CO_2 emissions, and NOx emissions at NExBTL ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

In operating the vehicle with the mixed fuel of BDF and diesel fuel in the on-road driving tests, NOx emissions increased with an increase of BDF ratio. On the other hand, when the mixed fuel of NExBTL and diesel fuel was used, NOx emissions did not increase. Fuel consumption performance was not affected by either fuel.

Effects of Eco-driving of a Bio-fuel Vehicle during Road Driving

The on-road eco-driving test was performed with the stress placed mainly on shifting up at lower engine speed because it is considered effective for reduction of CO_2 emissions. Specifically, an Eco-driving Management System (EMS) on the vehicle was set in such a manner that an alarm would be issued when the engine speed exceeded 2,000 rpm, and the driver was able to take care not to activate the alarm.

Table ES-2 outlines the results of the on-road driving test, which involved no particular change in the traffic condition among tests, with the average vehicle speed being the level for ordinary driving in urban areas, in the range of 16.3-21.5 km/h. The results of the average fuel economy, determined twice for each fuel and operation mode, were 5.53-6.62 km/L for normal driving and 6.41-8.89 km/L for eco-driving. For eco-driving, the fuel economy improvement was in the range 4.5 to 60.8%, and the CO_2 emissions reduction was 6.1-37.9%.

Table ES-2 Fuel economy and emission results for on-road driving tests

Fuel	Operation	Date	Distance [m]	Average vehicle speed [km/h]	Fuel economy [km/L]	Average Fuel economy [km/L]	Improvement rate of Fuel economy	CO_2 emissions [g/km]	Average CO_2 emissions [g/km]	Improvement rate of CO_2 emissions
B0	Normal driving	09/09/10	21,487	20.6	9.39	9.43	18.1%	279	278	-15.2%
		09/10/10	21,469	18.9	9.48			277		
	Eco-driving	09/09/10	21,479	17.8	11.13	11.14		236	236	
		09/10/10	21,454	21.5	11.15			236		
BDF B5	Normal driving	10/13/10	21,465	18.6	11.22	10.79	29.1%	235	244	-21.2%
		10/14/10	21,475	20.7	10.35			253		
	Eco-driving	10/13/10	21,472	16.3	16.04	13.93		163	192	
		10/14/10	21,473	19.5	11.81			221		
BDF B50	Normal driving	10/18/10	3,590	17.0	8.88	9.13	29.1%	288	278	-22.1%
		10/18/10	3,599	19.8	9.39			269		
	Eco-driving	10/18/10	3,593	16.8	11.43	11.79		223	217	
		10/18/10	3,590	17.7	12.15			210		
BDF B75	Normal driving	10/18/10	7,157	21.3	9.01	9.01	60.8%	279	279	-37.9%
	Eco-driving	10/18/10	7,159	16.7	14.49	14.49		174	174	
BDF B100	Normal driving	10/19/10	21,508	18.1	8.60	9.15	28.1%	287	271	-21.4%
		10/19/10	21,484	19.1	9.69			256		
	Eco-driving	10/19/10	21,494	19.8	12.26	11.71		204	213	
		10/19/10	21,490	17.4	11.16			223		
NExBTL B5	Normal driving	10/08/10	21,455	16.3	10.44	10.35	17.4%	250	253	-14.6%
		10/12/10	21,493	19.9	10.26			255		
	Eco-driving	10/08/10	21,458	16.9	13.10	12.15		199	216	
		10/12/10	21,483	19.4	11.21			232		
NExBTL B50	Normal driving	10/12/10	21,470	19.4	10.47	10.13	17.2%	241	249	-14.0%
		10/13/10	21,473	20.1	9.80			257		
	Eco-driving	10/12/10	21,475	18.3	13.17	11.87		191	214	
		10/13/10	21,005	18.7	10.57			238		
NExBTL B75	Normal driving	10/05/10	21,504	19.9	9.44	9.84	6.1%	262	251	-6.9%
		10/06/10	21,481	19.3	10.25			241		
	Eco-driving	10/05/10	21,494	17.6	10.45	10.45		234	234	
		10/06/10	N.A.	N.A.	N.A.			N.A.		
NExBTL B100	Normal driving	10/07/10	21,470	20.2	9.32	10.69	4.5%	266	236	-6.1%
		10/07/10	21,468	19.6	12.06			206		
	Eco-driving	10/07/10	21,476	17.7	11.35	11.17		219	222	
		10/08/10	21,468	17.5	10.99			225		

Fuel economy is plotted in Fig. ES-10 for BDF-diesel mixtures and in Fig. ES-11 for NExBTL-diesel mixtures. The average fuel economy with diesel fuel (B0) was 5.79 km/L for normal driving and 6.84 km/L for eco-driving, with the fuel economy improvement being 18.1%. The average fuel economy with BDF was 5.53-6.62 km/L for normal driving and 7.19-8.89 km/L for eco-driving, with the fuel economy improvement being 28.1-60.8%. The average fuel economy with NExBTL was 6.04-6.56 km/L for normal driving and 6.41-7.46 km/L for eco-driving, with the fuel economy improvement being 4.5-17.4%. The fuel economy improvements by means of eco-driving vs. normal driving were equivalent to or lower than that of diesel fuel in the case of NExBTL, but higher than that of diesel fuel in the case of BDF.

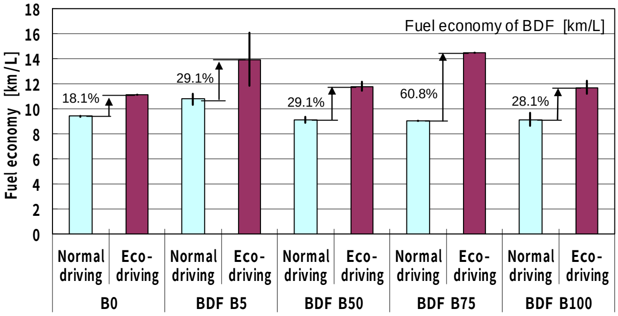


Figure ES-10 Fuel economy for normal driving and eco-driving fueled at BDF ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

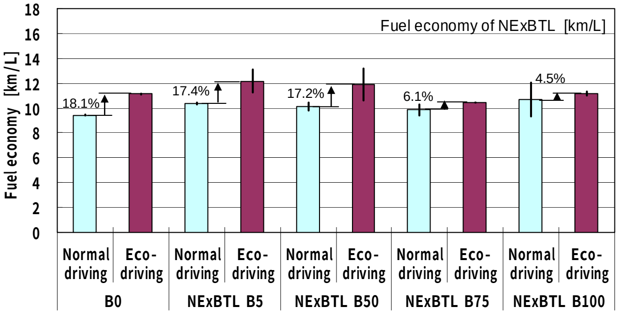


Figure ES-11 Fuel economy for normal driving and eco-driving fueled at NExBTL ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

Figure ES-12 plots the CO_2 emissions for BDF-diesel mixtures while Fig. ES-13 plots those with NExBTL-diesel mixtures. The average CO_2 emission level with diesel fuel (B0) was 453 g/km for normal driving and 384 g/km for eco-driving, with the CO_2 reduction ratio being 15.2%. The average CO_2 emission level with BDF was 397-455 g/km for normal driving and 283-353 g/km for eco-driving, with the CO_2 reduction being 21.2-37.9%. The average CO_2 emission level with NExBTL was 384-411 g/km for normal driving and 349-382 g/km for eco-driving, with the CO_2 reduction being 6.1-14.6%. The CO_2 reduction with eco-driving was equivalent to or less than that of diesel fuel in the case of NExBTL, but higher than both of them in the case of BDF.

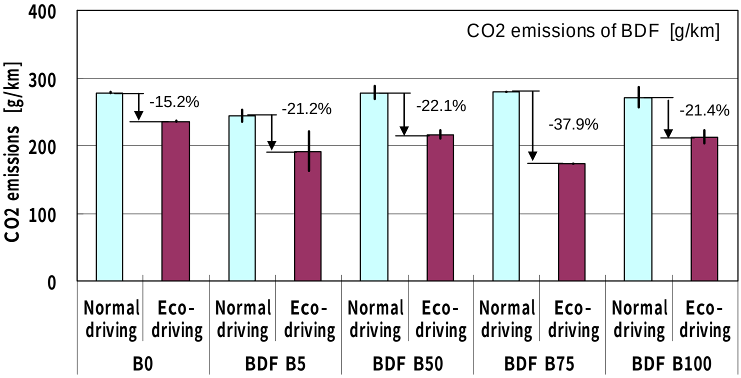


Figure ES-12 CO_2 emissions for normal driving and eco-driving fueled at BDF ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

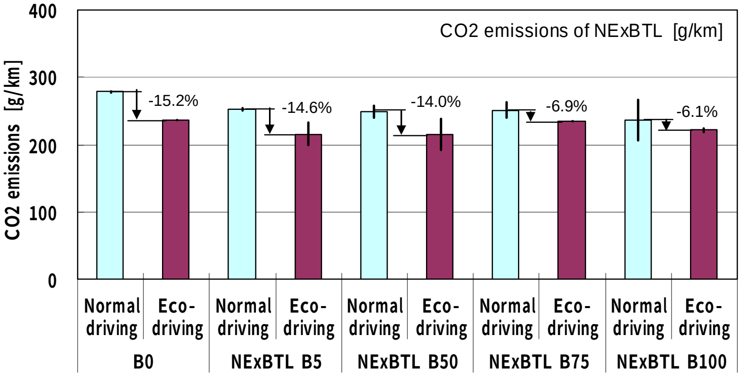


Figure ES-13 CO_2 emissions for normal driving and eco-driving fueled at NExBTL ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

Both BDF and NExBTL achieve CO_2 emission reductions approximately similar to those of diesel fuel when eco-driving is performed. Specifically, around 20% CO_2 emission reduction could be achieved during driving at an average speed of 20 km/h in urban areas.

Cold Start Driving Test Analysis

With some bio-fuels, the fuel supply to the engine depends on the temperature where the fuel is used. Namely, when the engine is not supplied with enough fuel due to the temperature, the starting or driving performance of a vehicle may be reduced. This section reports the results from tests of exhaust gas performance and fuel consumption at cold start with NExBTL, which is a hydrotreated vegetable oil (HVO). In addition, an on-road driving test was conducted in a cold climate to assess the cold-start performance of a vehicle with this fuel. The test vehicle was the same as the one previously used for the chassis dynamometer test and the on-road driving test. The on-board measurement system, including PEMS, was also the same as that used for the on-road driving test. The fuel is NExBTL only, not BDF. The cold climate test was performed at the end of March 2011, and the route was in a mountain area in Minakami-city, Gunma Prefecture. Minakami-city is approximately 450 meters above sea level, and the test was conducted at a temperature of -5 degrees Celsius in cloudy weather. After the test vehicle was started with a cold-start (no warming-up period), a distance of 29.5 km was logged in the mountain area. Figure ES-14 shows the history of the engine speed and coolant temperature at the time of engine start. At the cold start, the coolant temperature was almost -0.7 degree C. The cranking time of the test vehicle was less than 2 seconds. This cold-start performance, fueled with, was the same as that of normal diesel fuel under the hot start condition.

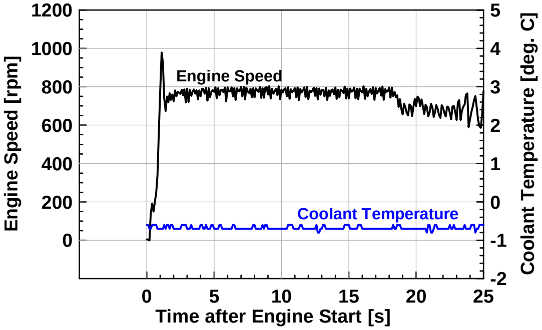


Figure ES-14 History of engine speed and coolant temperature at the time of engine start

Figure ES-15 shows the vehicle speed, engine speed, engine torque, coolant temperature, and CO, CO_2, and NOx emissions per unit time at the beginning of the driving test. CO emissions achieved a peak at the starting time, because the coolant temperature was low, and the after treatment system was not sufficiently warmed up. However, even in the condition where the coolant temperature did not fully increase, CO emissions decreased from around 100 s. In actual operation, the engine started smoothly even in an ambient temperature of -5 degrees Celsius, and the driving performance was not affected by this temperature.

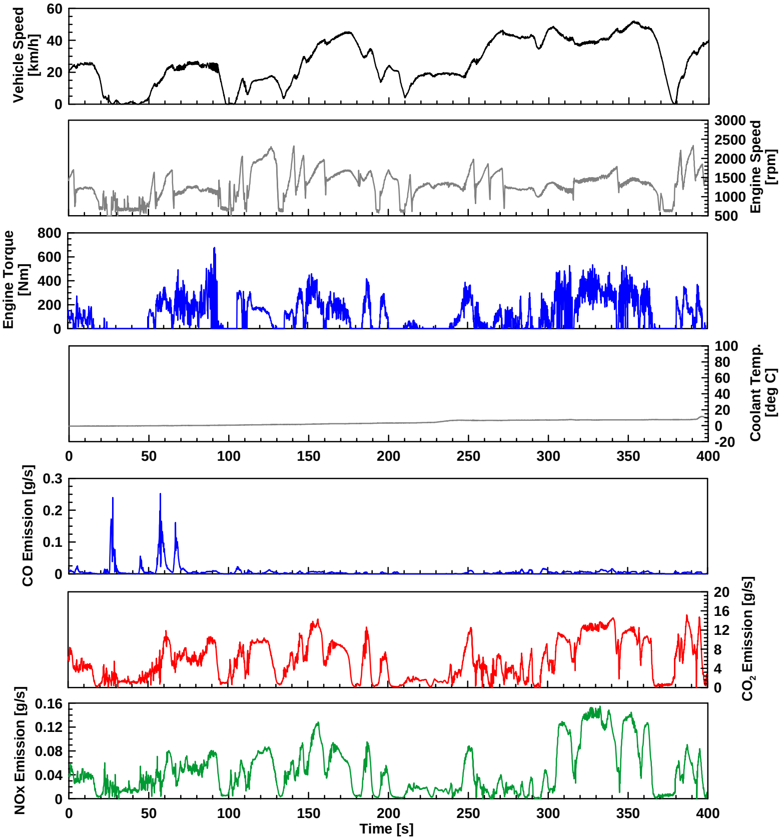


Figure ES-15 Vehicle speed, engine speed, engine torque, coolant temperature, and CO, CO_2, and NOx emissions at the beginning of the cold-start driving test

When NExBTL was used for the diesel freight vehicle meeting the 2005 regulation, the low ambient temperature did not affect the engine starting performance and the driving performance. Moreover, the result of exhaust gas performance had the equivalent results to that of the operation in the urban area.

Conclusions

This report focuses on the latest diesel vehicles that meet the latest emission regulation. Diesel vehicles are not given any special customization, but adopted BDF and HVO as fuel, and the influence of these diesel vehicles on their exhaust gas performance and fuel consumption under actual use condition was examined. The diesel vehicle was set on a chassis dynamometer, and then both the performance of exhaust gas and fuel economy were investigated by operating a Japanese driving cycle. At the same time, an on-road driving test was also conducted using PEMS in order to investigate the influence of the use of BDF and HVO on both exhaust gas emissions and fuel consumption. In addition to these vehicle tests, engine tests were also conducted, so that the change of fuel characteristics in using BDF and HVO was examined.

When the engine was operated using waste edible oil-based BDF (FAME), NOx emissions increased compared with the operation using only light oil. On the other hand, NExBTL as one of the HVOs can control NOx emissions more easily than BDF, and thus it maintained almost the same emission level with light oil. It is believed that a high cetane number would shorten the ignition delay of the fuel and reduce the rate of premixed combustion in the early stage of combustion, which is prone to produce NOx. In operating the vehicle with the mixed fuel of BDF and diesel fuel, as shown in the results of the test on the chassis dynamometer, NOx emissions increased in accordance with an increase of BDF rate. On the other hand, when the mixed fuel of NExBTL and diesel fuel was used, an increase of NOx emissions was not seen.

Fuel economy performance was not affected by either of the fuels. Even the on-road driving tests following the route that starts and finishes at NTSEL had the same tendency. Namely, the mixed fuel of BDF increased NOx emissions, while that of NExBTL inhibited the increase of NOx emissions. Moreover, eco-driving was conducted for each fuel during on-road driving, and the CO_2 emissions reduction effect was examined. The result indicated that both BDF and NExBTL had an equivalent CO_2 reduction effect on diesel fuel by eco-driving. The CO_2 reduction by eco-driving is assumed to be due to the area and frequency of use of the engine.

In addition, a cold climate test, that is, cold start test, using NExBTL was also conducted at a temperature of -5 degrees Celsius. It was clear that the vehicle operated smoothly during the period of engine starting to increase in engine coolant temperature, and NExBTL had the equivalent cold startability to diesel fuel.

1. Background

Because of its capability of reducing the CO_2 emission and resource recycling, biodiesel fuel (BDF) has been highlighted recently as a fuel greatly contributing to global environmental conservation. Actually, activities for expanding the production and utilization of BDF are positively being pushed forward throughout the world. For example, first-generation BDFs (RME, etc.) have recently been followed by the development of second-generation BDFs with more stable characteristics. In Japan, for example, first-generation oil, that is, BDF based on waste food oil, is in use.

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 technology and precise electronic control. It should be noted however that these technologies prove the most appropriate when conventional diesel fuel is used as fuel. If BDF, differing greatly in fuel characteristics from diesel fuel, is used for this type of vehicle, the emission gas characteristics will be deteriorated, which in turn may hinder wide application of BDF. Practically, it was reported that, when these vehicles were run in the authentication test mode without any particular modification and the fuel was simply shifted from diesel fuel to BDF, the consequence was an increase in NOx emission rate.

Namely, wide application of BDF proves highly effective in terms of CO_2 emission reduction and resource recycling in the region, while raising concern about adverse effect on the atmospheric environment in urban areas. If factors hindering such wide application are to be eliminated, it is essential to establish the characteristic standards of BDF compatible with the latest emission gas regulations. For this purpose, the actual emission gas state when BDF is applied to the latest vehicles has to be identified as data basically needed for the above standards.

2. Objectives of the Study

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

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

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

3. Overview of the Annex

3.1. Test matrix

In this Annex, the real-world emissions of the latest diesel vehicles fueled with BDF will be estimated. The test matrix is shown in Table 3-1. The test target is a vehicle adapted to the Japanese new-long term regulations (started in 2005).

Table 3-1 Test matrix

Vehicle	**Fuel**	**Test**				**Test Period**
		Chassis Dynamometer Test (JE05mode)	**Real-World Driving Test (Hot)**	**Real-World Eco-Driving Test (Hot)**	**Real-World Driving Test (Cold)**	
The Vehicle Adapted to the new-long Term Regulation	**Light Oil**	✓	✓	✓	-	**2 Years June, 2009 ~ May, 2011**
	Waste-Cooking Oil BDF	✓	✓	✓	-	
	2nd Generation BDF	✓	✓	✓	✓	

In addition to the vehicle tests, a single-cylinder engine test was carried out in order to investigate basic combustion characteristics of BDF.

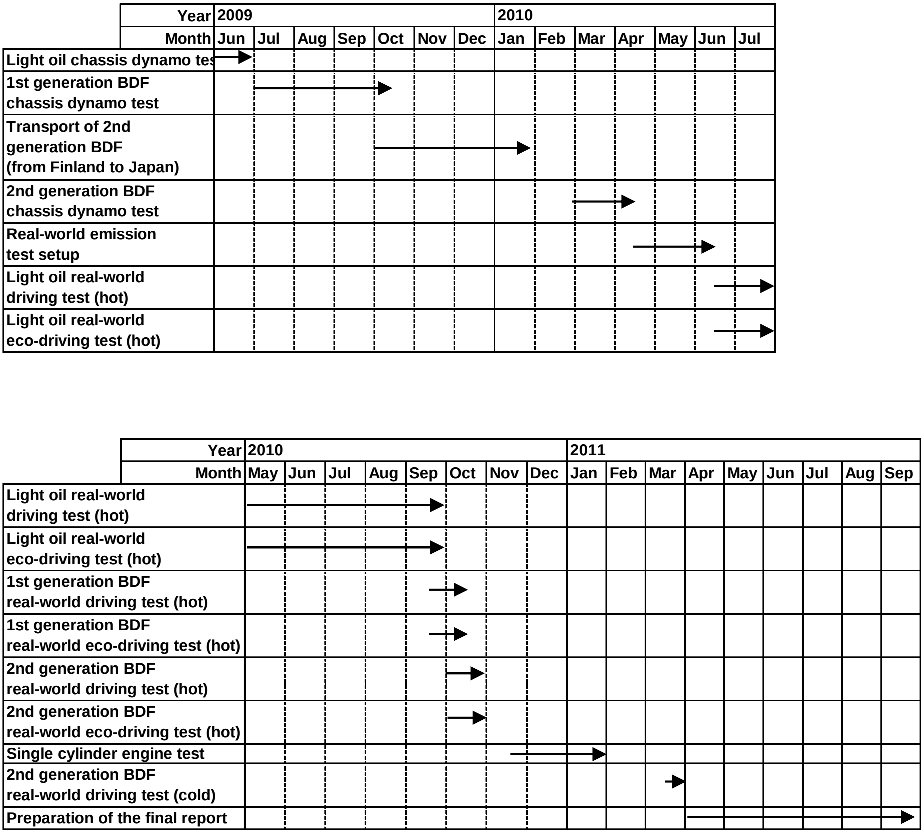
3.2. Expected results

By implementing the plan described in this Annex, it can be confirmed whether fuel such as BDF or HVO 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 environment load by BDF-fueled vehicles can be comprehensively assessed.

3.3. Period

2 years

3.4. Schedule



Year	2009							2010						
Month	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Light oil chassis dynamo tes	→													
1st generation BDF chassis dynamo test		→	→	→	→									
Transport of 2nd generation BDF (from Finland to Japan)					→	→	→	→						
2nd generation BDF chassis dynamo test										→	→			
Real-world emission test setup											→	→	→	
Light oil real-world driving test (hot)													→	→
Light oil real-world eco-driving test (hot)													→	→

Year	2010								2011								
Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Light oil real-world driving test (hot)	→	→	→	→	→												
Light oil real-world eco-driving test (hot)	→	→	→	→	→												
1st generation BDF real-world driving test (hot)					→	→											
1st generation BDF real-world eco-driving test (hot)					→	→											
2nd generation BDF real-world driving test (hot)						→											
2nd generation BDF real-world eco-driving test (hot)						→											
Single cylinder engine test							→	→	→								
2nd generation BDF real-world driving test (cold)											→						
Preparation of the final report												→	→	→	→	→	→

Figure 3-1 Test schedule

3.5. Participants of this annex

Participating countries are Finland, Japan, Sweden, Thailand and the United States

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

Task share: Thailand

Neste Oil© in Finland provides the NExBTL® (one of HVO) to NTSEL in kind.

3.6. Management

(1) Project leadership

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National Traffic Safety and Environment Laboratory (NTSEL)
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(2) Test provision

Neste Oil in Finland provides HVO (NExBTL®) to NTSEL in kind.

NTSEL will send progress reports of HVO tests to Neste Oil.

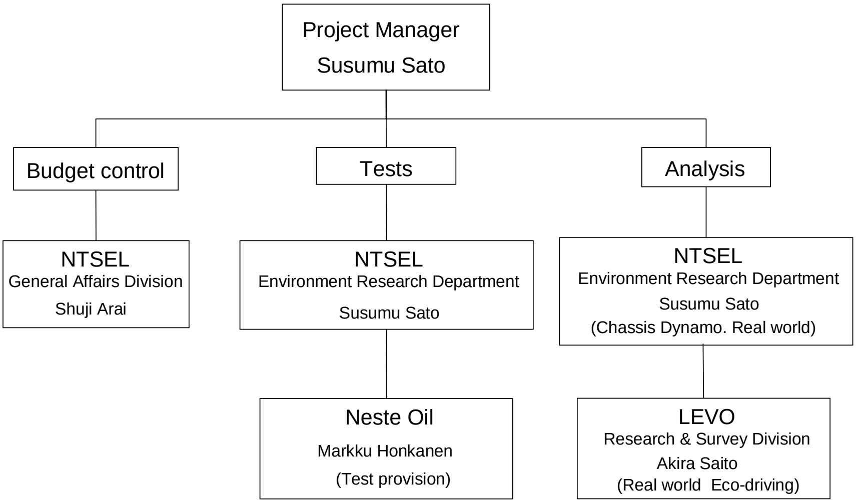


Figure 3-2 Annex management flow

4. Emission Evaluation by Means of the Chassis Dynamometer Test

4.1. Objective

This study has a major objective of studying the emission gas characteristics of BDF vehicles during road driving. Prior to the test on the road, however, a chassis dynamometer test was performed to gain understanding of the basic emission gas characteristics of BDF vehicles.

4.2. Test fuels

Table 4-1 shows the characteristics of fuels used in this test. For diesel fuel, JIS No.2 diesel fuel available on the market was used. For biofuels, two types were used; BDF originating from waste food oil of Kyoto City and NExBTL® of Neste Oil. Note that testing of BDF and NExBTL were conducted with the fuel mixed with diesel oil and 100% BDF (NEAT).

Table 4-1 Test fuels

Fuel		Diesel	BDF (Kyoto)	NExBTL
Density (15 deg.C) g/cm^3		0.8275	0.8849	0.7797
Kinematic viscosity mm^2/s		3.777 (@30 deg.C)	4.689 (@40 deg.C)	2.985 (@30 deg.C)
Flash point deg.C		66.0	115.0	88.0
Cetane number		57.2	52.6	88.2
Distillation temp. deg.C	IBP	170.0	284.0	-
	10%	212.0	345.0	-
	50%	282.5	354.0	-
	90%	332.0	359.0	293.4
CHO wt.%	C	85.9	76.7	84.4
	H	13.9	12.2	15.3
	O	0.2	11.1	0
Pour point deg.C		-22.5	-15.0	-15.0
Sulfur content ppm		4.8	3.3	-
Lower heating value kJ/kg		42850	37000	44070

4.3. Test vehicle

Fig. 4-1 outlines the vehicles used in this test while Table 4-2 shows parameters. The vehicle was a diesel truck applied to the new long-term regulations (2005 regulations) of Japan (Hino Motors, Ltd., “Dutro”). The maximum payload capacity is 3 t, and the vehicle is equipped with an oxidation catalyst and DPF for an after treatment system.

Figure 4-1 Broad overview of the test vehicle

Table 4-2 Specifications of the test vehicle

Vehicle type	Cargo truck
Max. load	3,000 kg
GVW	6,260 kg
Length	6,510 mm
Width	2,185 mm
Height	3,045 mm
Engine type	N04C-UE
Emission regulation	2005
Displacement	4,009 L
Max. power	100 kW / 2,500 rpm
Max. torque	392 Nm / 1,600 rpm
Transmission	6MT
Aftertreatment	DOC, DPF

4.4. Test apparatus

The test was performed on a chassis dynamometer for heavy vehicles in NTSEL. Fig. 4-2 shows the condition of placing the vehicle on the chassis dynamometer. Fig. 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

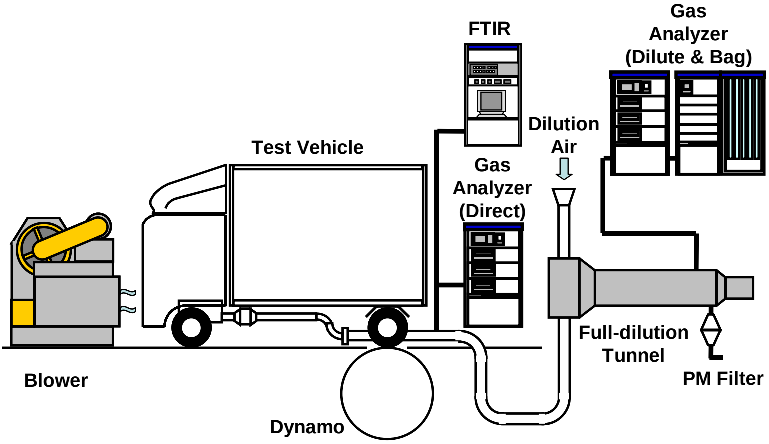


Figure 4-3 Chassis dynamometer test system

4.5. Test conditions and evaluation items

The chassis dynamometer test was performed in the JE05 driving cycle as introduced in the 2005 regulations. Fig. 4-4 shows the speed pattern of the JE05 driving cycle. In this test, the mass emissions of NOx, CO, CO_2, NMHC and PM, as well as the fuel economy, were evaluated. Regarding the fuel economy, the values of diesel fuel, BDF, and NExBTL could not be compared, as they were on an equal basis because of difference in the density and calorific power, so BSEC (Brake Specific Energy Consumption) was also used.

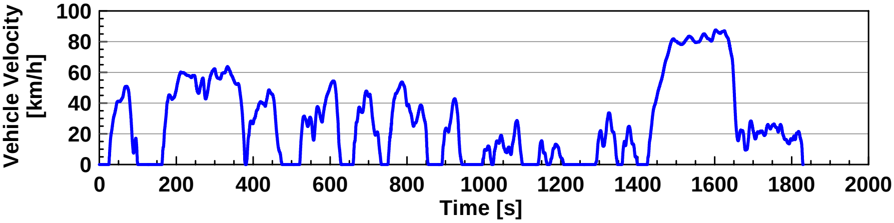


Figure 4-4 Vehicle velocity profile of the JE05 driving cycle

4.6. Test Results

(1) Emission characteristics of the JE05 driving cycle when BDF was used as fuel

BDF originating from waste cooking oil of Kyoto City was mixed with diesel fuel, with the mixture supplied to the vehicles that were run in the JE05 driving cycle. The mixing ratios of BDF into diesel fuel were 0%, 20%, and 100%. Fig. 4-5 shows the test results of NOx, CO, PM, NMHC, CO_2, fuel economy and BSEC. Note that the PM emissions shown in the figure indicate the result of measurement in the latter stage of DPF. From Fig. 4-5, it is found that an increase in the BDF mixing ratio results in an increase in the amount of NOx emissions and PM emissions. However, the amount of PM emissions remains at a very low level. The amount of CO emissions and NMHC emission is almost zero. When the BDF mixing ratio is changed, the amount of CO_2 emissions does not change, but the fuel economy becomes worse. This trend of worsening fuel efficiency with the change in the BDF mixing ratio is also observed in the case of BSEC.

Fig. 4-6 shows a comparison between the historical emission concentration of NOx and that of CO_2 under the condition of the BDF mixing ratio 0% and 100%. The data during the period from 1000 to 1800 seconds in the JE05 driving cycle is shown in the figure. From this figure, it is found that the history of BDF 100% causes a higher NOx emission concentration than that of BDF 0%. In addition to the higher concentration during the idling period, the concentration is high in the peak area when a vehicle accelerates. Because the amount of exhaust gas flow increases during acceleration, such a difference in the emission concentration at the peaks results in the same difference also in the emission mass at the peaks.

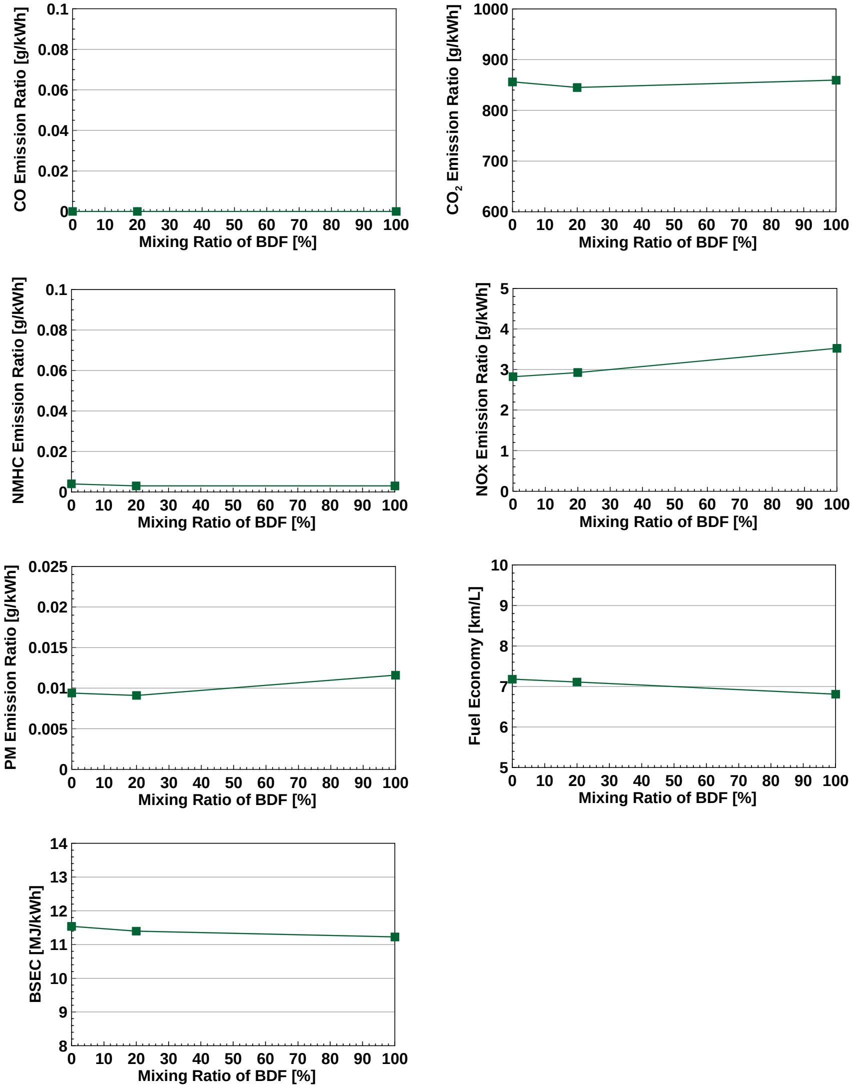


Figure 4-5 Emission and fuel economy characteristics of the JE05 driving cycle using BDF as fuel

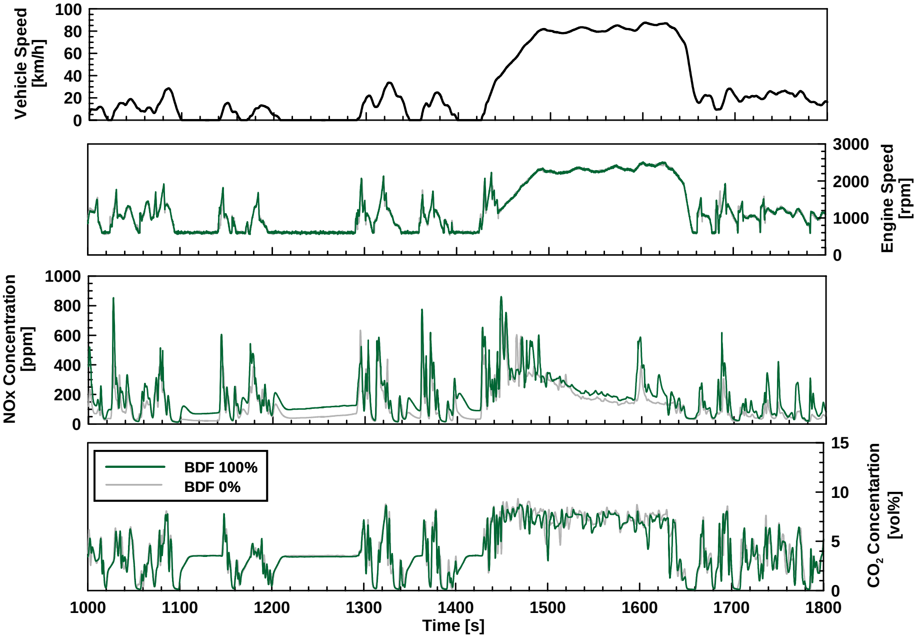


Figure 4-6 Comparison between the historical emission concentration of NOx and that of CO_2 under the condition of BDF mixing ratio 0% and 100%

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

NExBTL, made by Neste Oil, was mixed with diesel fuel, with the mixture supplied to the vehicles that were run in the JE05 driving cycle. The mixing ratios of NExBTL into diesel fuel were 0%, 5%, 50% and 100%. Fig. 4-7 shows the test result of NOx, CO, PM, NMHC, CO_2, fuel economy and BSEC.

From the results shown in Fig. 4-7, it is confirmed that an increase in the NExBTL mixing ratio reduces the amount of CO_2 emissions and of PM emissions, and improves the BSEC. Despite the increase in the amount of CO emissions, its value is very small. Increase in the mixing ratio does not increase the amount of NOx emission. The amount of NMHC emission is almost zero.

Fig. 4-8 shows a comparison between the historical emission concentration of

NOx and CO_2 under the conditions of the NExBTL mixing ratio 0% and 100%. The data during the period from 1000 to 1800 seconds in the JE05 driving cycle is shown in the figure. From this figure, it is found from the comparison between the NExBTL 100% history and the 0% history that NOx emission concentration of 0% becomes slightly higher during the idling period. However, there is almost no change in the amount of emissions during acceleration between 0% and 100%. The same result is obtained in the total amount of emissions in the JE05 driving cycle.

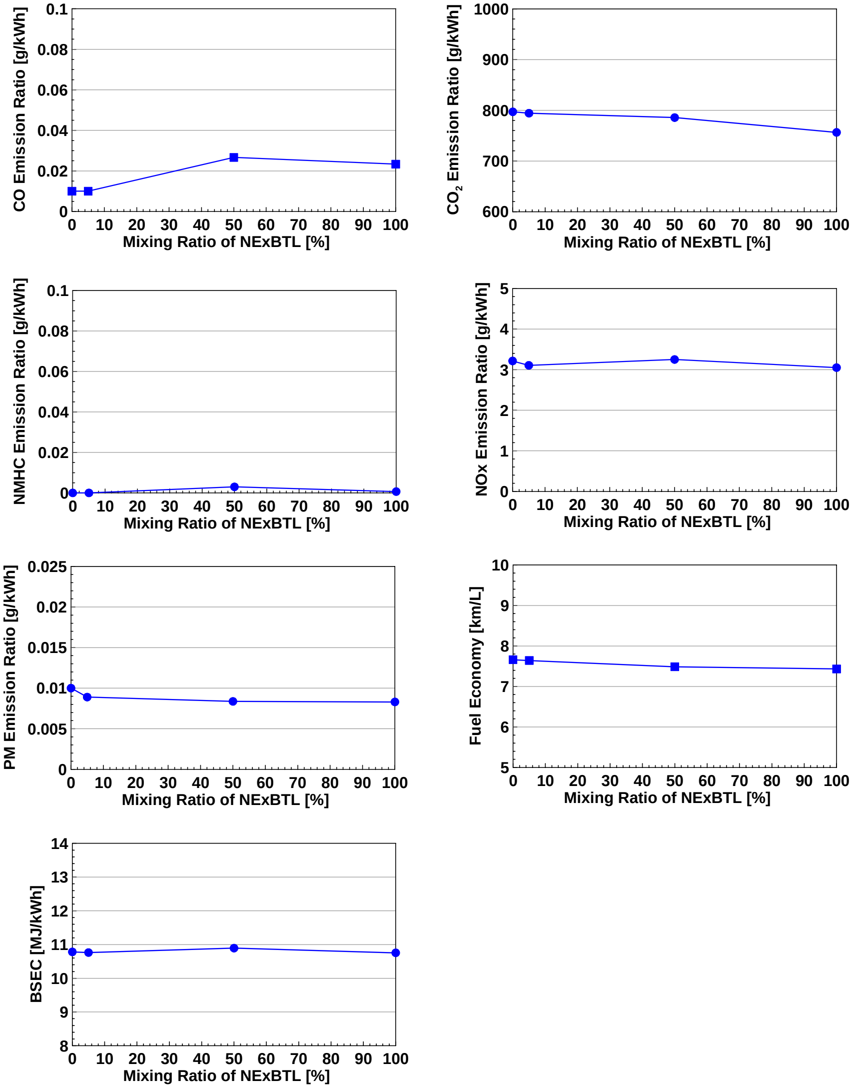


Figure 4-7 Emission and fuel economy characteristics of the JE05 driving cycle using NExBTL as fuel

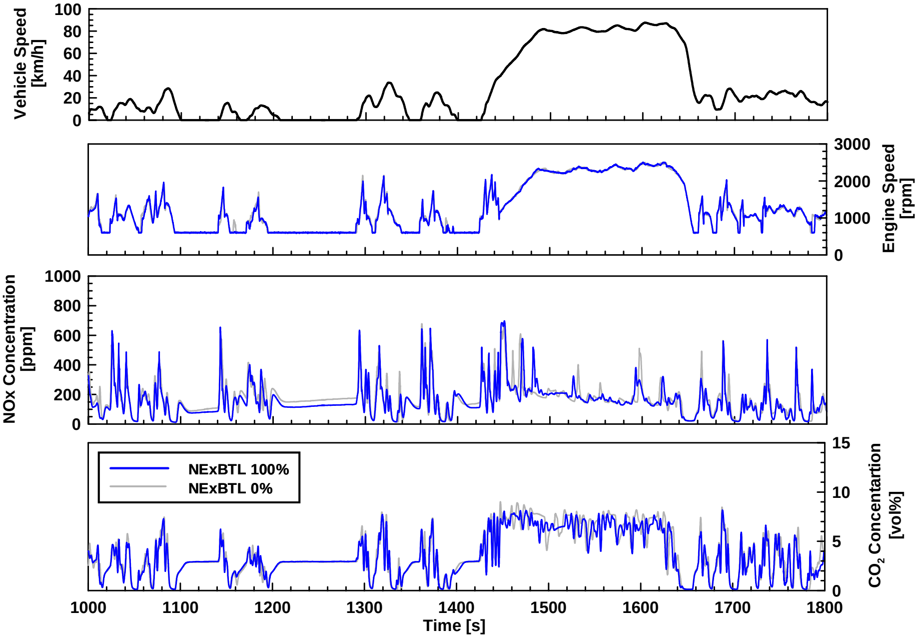


Figure 4-8 Comparison between the historical emission concentration of NOx and that of CO_2 under the condition of NExBTL mixing ratio 0% and 100%

4.7. Summary of this chapter

Result of the chassis dynamometer test shows that the amount of CO emission and NMHC emission is nearly zero in either case of mixing the BDF or NExBTL fuel with diesel fuel. At the same time, the amount of PM emission and the fuel economy are not significantly affected by changes in the mixing ratio. For NOx, however, when BDF is mixed with diesel fuel, the amount of emissions increases with an increase in the mixing ratio. On the other hand, when NExBTL is mixed with diesel fuel, an increase or decrease in the amount of NOx emissions is not found.

Many problems have been pointed out in the amount of NOx emission with regards to the BDF mixing ratio. The study on this problem from the test results of stand-alone engines is described in the next chapter.

5. Analysis of Combustion and Emission Characteristics of BDF and NExBTL

5.1. Objective

In order to confirm the basic combustion and emission characteristics of BDF of Kyoto city and NExBTL made by Neste Oil, a single-cylinder diesel engine test was performed. The results were compared with the combustion and emission characteristics determined from driving with diesel fuel and BDF (FAME) originating from waste cooking oil.

5.2. Single-cylinder diesel engine test arrangement

Fig. 5-1 shows the overall view and Fig. 5-2 shows the test system apparatus of the single-cylinder diesel engine used in the test. The parameters are shown in Table 5-1. This engine, displacement-2147 cm^3, is a common-rail type single-cylinder diesel engine, which is provided with a supercharger and intercooler for external supercharging, and with an exhaust gas recirculation (EGR) system for EGR. The injection controller was also provided to enable free setting of the fuel injection time, timing, and pressure. In addition, an emission gas analyzer (Horiba: MEXA-7100D) was provided for measurement of emission gas, a smoke meter (AVL: 415S) for soot measurement, and a pressure sensor (Kistler: 6052C) and charge amplifier (Kistler: 5018A1010) were installed on the cylinder head so as to measure the cylinder internal pressure.

Figure 5-1 Overall view of the single-cylinder diesel engine

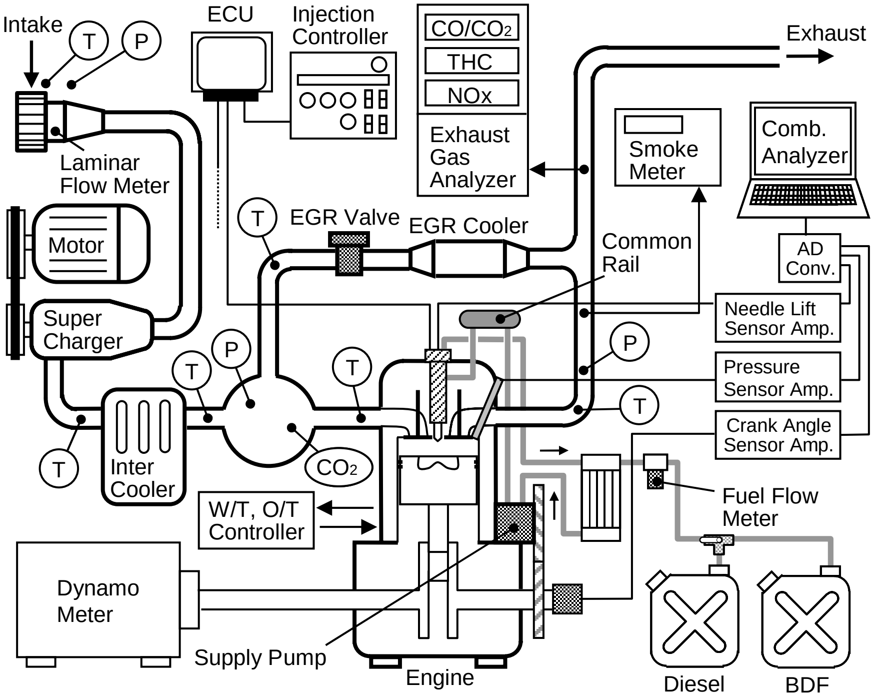


Figure 5-2 Test system apparatus of the single-cylinder diesel engine

Table 5-1 Specifications of the single-cylinder diesel engine

Engine type	Water cooled, single-cylinder, 4-stroke cycle
Intake system	Supercharger with intercooler
Fuel supply system	DI Common-rail (Max.: 160 MPa) (ϕ0.22 mm x 6 holes)
Displacement cm^3	2147
Compression ratio	16.0
Bore x Stroke mm	135 x 150
Max. power kW/rpm	25 / 2000
Max. torque Nm/rpm	120 / 1000

5.3. Test fuels

Table 5-2 shows the characteristics of fuels used in this test. For diesel fuel, the JIS No.2 diesel fuel available on the market was used. For biofuels, two types were used; BDF originating from waste cooking oil of Kyoto City and NExBTL of Neste Oil. It is known that NExBTL is featured by an extremely high cetane number. None of these fuels was mixed with the other and used fully in the NEAT mode. In this way, the combustion and emission characteristics of NExBTL were identified through comparison with diesel fuel and BDF.

Table 5-2 Characteristics of test fuels

Fuel		Diesel	BDF (Kyoto)	NExBTL
Density (15 deg.C) g/cm^3		0.8275	0.8849	0.7797
Kinematic viscosity mm^2/s		3.777 (@30 deg.C)	4.689 (@40 deg.C)	2.985 (@30 deg.C)
Flash point deg.C		66.0	115.0	88.0
Cetane number		57.2	52.6	88.2
Distillation temp. deg.C	IBP	170.0	284.0	-
	10%	212.0	345.0	-
	50%	282.5	354.0	-
	90%	332.0	359.0	293.4
CHO wt.%	C	85.9	76.7	84.4
	H	13.9	12.2	15.3
	O	0.2	11.1	0
Pour point deg.C		-22.5	-15.0	-15.0
Sulfur content ppm		4.8	3.3	-
Lower heating value kJ/kg		42850	37000	44070

5.4. Test conditions

The test conditions are shown in Table 5-3. In this study, the test was performed by applying three types of loads (IMEP) under two conditions; single-stage injection and two-stage injection. In either condition, the type of fuel becomes an important test parameter because the purpose of the test is to gain an understanding of the effects of the difference in the fuel characteristics on the combustion and emission characteristics. For this purpose, the fuel injection time and the EGR rate were kept constant under both conditions, while the fuel injection pressure and suction air pressure were also kept constant for each load. For the pilot injection in the case of two-stage injection, its injection time was determined by establishing, for each load, the ratio of the heat generation by pilot combustion relative to the total heat release amount.

Table 5-3 Test conditions

Condition	A	B	C	D	E	F
Engine speed rpm	1200					
IMEP kPa	250	500	750	250	500	750
Number of injection	Single			Double		
Pilot inj. timing deg.ATDC	-			-20		
Ratio of R.H.R. by pilot inj. %	-			14	7	5
Main inj. timing deg.ATDC	-12			-4		
Injection pressure MPa	80	100	120	80	100	120
Boost pressure kPa	0		20	0		20
EGR ratio %	0					

5.5 Test results and considerations

(1) Emission characteristics of the single-stage injection conditions

Evaluation was made of the emission characteristics under respective conditions. Figs. 5-3 and 5-4 indicate NOx emission and soot emission under single-stage injection conditions (Conditions A through C), respectively. Similar to the case of BDF, the NOx emission rate increased by 5% maximum relative to diesel fuel. In the case of NExBTL, the result showed a reduction relative to BDF and diesel fuel. In particular, about 7% reduction could be identified when compared with the fuel economy at a load of IMEP = 250 kPa. Though BDF is generally known to suffer an increase in the NOx emission rate, basic combustion and emission characteristics of hydrogenated vegetable oil, such as NExBTL, are not sufficiently understood. Therefore, factors responsible for reduction of NOx in NExBTL will be discussed in the next section by analyzing the combustion characteristics. In regards to the soot emission rate, the result shows a reduction of about 50 to 80% for BDF and a reduction of about 20 to 40% for NExBTL relative to diesel fuel. Such reduction of soot emission as compared with diesel fuel is considered due to the fact that both bio fuels do not contain any aromatic component. In addition, BDF contains oxygen atoms in the fuel, which contributed to further reduction of the soot emission.

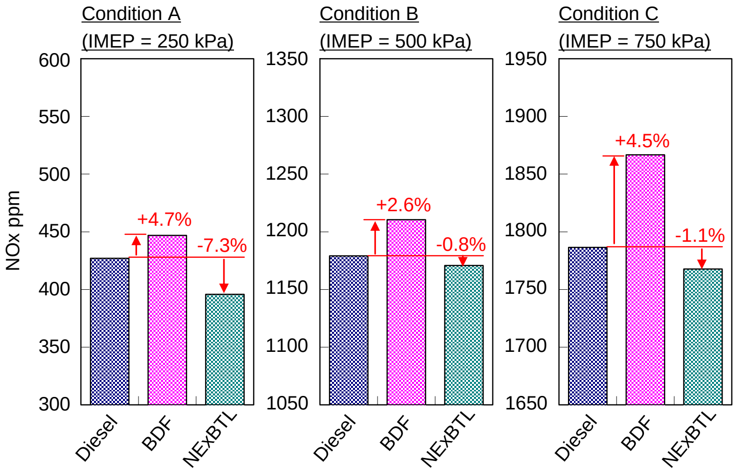


Figure 5-3 NOx emission characteristics of single-stage injection conditions

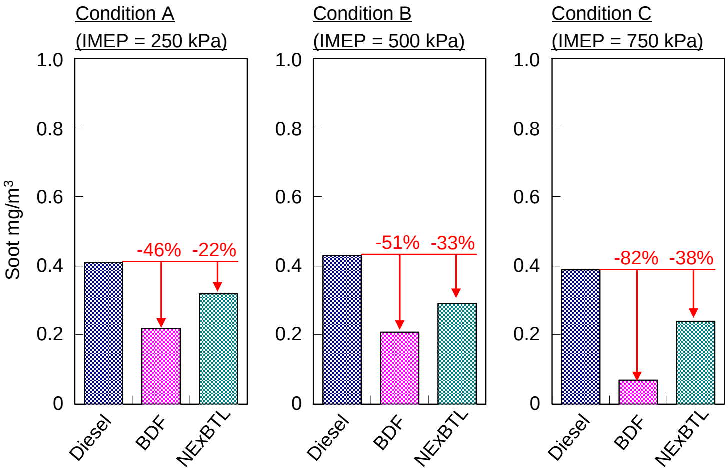


Figure 5-4 Soot emission characteristics of single-stage injection conditions

(2) Combustion characteristics of single-stage injection conditions

As described above, NExBTL could reduce the NOx emission rate when compared with the case of diesel fuel and BDF. To review the factors, three types of fuels were compared in terms of the cylinder pressure, rate of heat release, and needle rift under the respective conditions in Figs. 5-5 to 5-7. During ordinary diesel combustion, the initial portion of heat release rate is called the initial combustion or premixed combustion, and it is known that there exists a correlation among the ignitability and ignition delay of fuel and the premixed combustion ratio. Namely, the fuel has a higher ignitability with increasing cetane value, resulting in shorter ignition delay period and smaller premixed combustion ratio. Moreover, during premixed combustion, fuel spray and air are fully mixed in the course of ignition delay, resulting in an equivalence ratio distribution allowing generation of NOx with relative ease. In this context, it is known that the NOx emission increases in the combustion pattern with increased ratio of premixed combustion.

As is evident from Figs. 5-5 ~ 5-7, NExBTL has a higher cetane value than diesel fuel and BDF under all conditions. Namely, this confirms that the combustion start timing becomes earlier (i.e., the ignition delay time becomes shorter) and the ratio of premixed combustion becomes smaller. This in turn indicates that, for NExBTL, diffusion combustion is prevailing, resulting in less NOx emission when compared with other fuels, as described above. This is a particularly significant improvement relative to the widely-employed bio-fuel, that is, BDF. In single-stage injection, the effects attributable to the cetane value of NExBTL were remarkable.

On the other hand, soot emissions from diesel combustion are known to be formed in the diffusion combustion following premixed combustion. They also oxidize in the diffusion combustion process. If there are any soot emissions not oxidizing during the expansion stroke, they are emitted from the cylinder. This fundamental mechanism of conventional diesel fuel, BDF and NExBTL, is almost same. From the results of R.H.R. in Figs. 5-5 ~ 5-7, NExBTL, which has small ratio of premixed combustion, tends to have a large ratio of diffusion combustion. Nevertheless, soot emissions from NExBTL were lower than those of diesel fuel. This is because aromatic components, which can form precursor of soot emissions, are not included in NExBTL. Soot emissions from BDF were the lowest of the three, though combustion characteristics were almost same between diesel fuel and BDF. One reason of this result is not including aromatic components, and the other is including oxygen, which encourages soot oxidation in BDF.

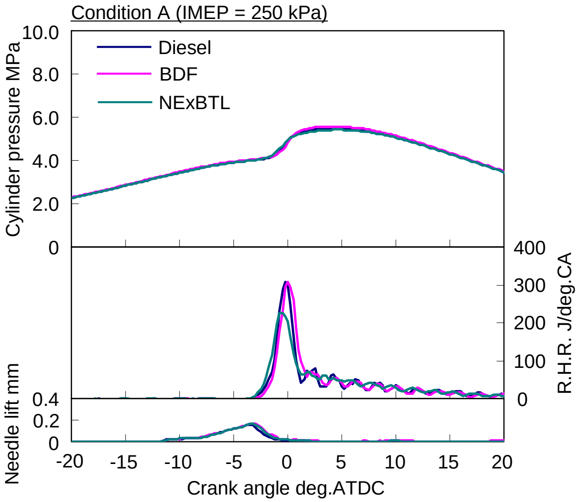


Figure 5-5 Cylinder pressure, rate of heat release and needle lift under single-stage injection condition A

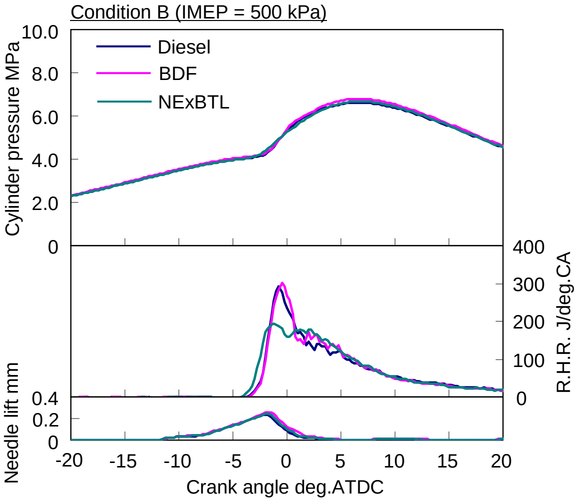


Figure 5-6 Cylinder pressure, rate of heat release and needle lift under single-stage injection condition B

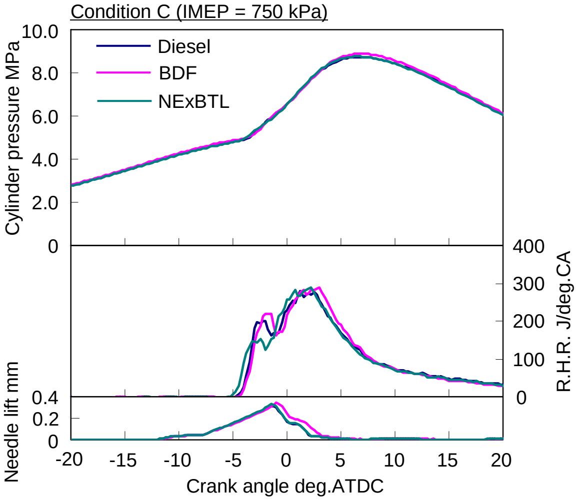


Figure 5-7 Cylinder pressure, rate of heat release and needle lift under single-stage injection condition C

(3) Emission characteristics of two-stage injection conditions

Most recent ordinary diesel engines have introduced two-stage or multiple-stage injection to reduce noise and emission. This study also conducted evaluation of combustion and emission characteristics of BDF and NExBTL under two-stage injection conditions. Figs. 5-8 and 5-9 show NOx emission and soot emission under two-stage injection conditions (Conditions D through F). As a result of the test, NExBTL proved to be smaller in NOx emission than the case of driving with BDF, except for Conditions D in which the load was low. This emission was nearly equivalent, that is, about ±2% in the case of driving with diesel fuel. Soot emission is considered to have been reduced by 50 to 70% successfully from the case of driving with diesel fuel because NExBTL does not contain any amorphous component.

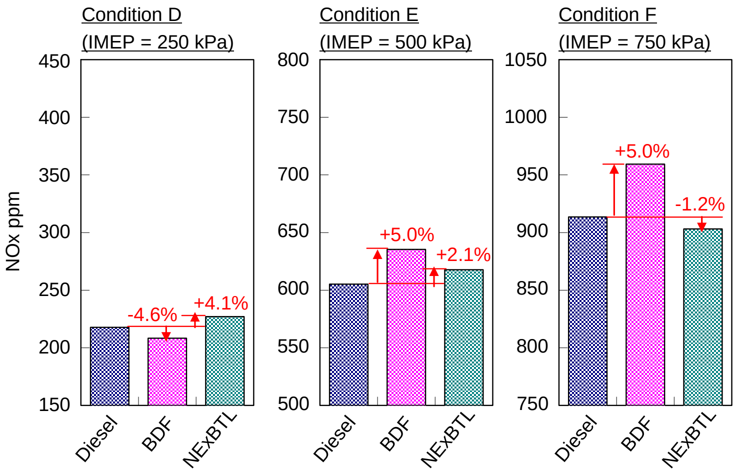


Figure 5-8 NOx emission characteristics of two-stage injection conditions

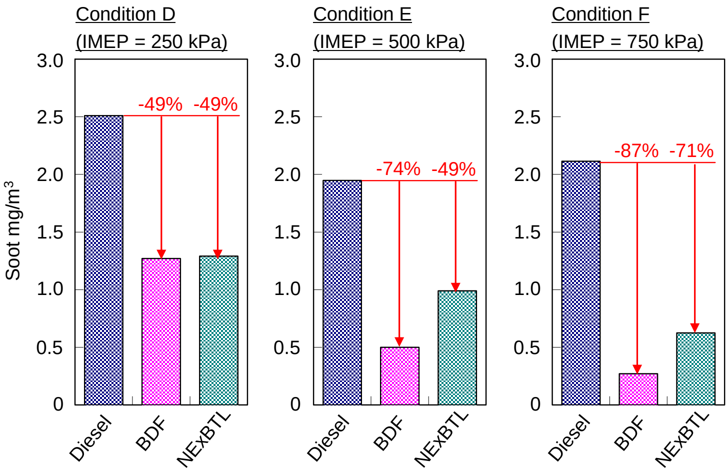


Figure 5-9 Soot emission characteristics of two-stage injection conditions

(4) Combustion gas characteristics of two-stage injection conditions

As described above, NExBTL was confirmed to be shorter in ignition delay and have a small ratio of premixed combustion because of its higher cetane value. This section analyzed the effects of cetane value on combustion characteristics for two-stage injection. Three types of fuels were compared in terms of the cylinder pressure, rate of heat release and needle lift under the respective conditions in Figs. 5-10 to 5-12. As the result shows, NExBTL with higher cetane value has a pilot combustion start time earlier than the other two fuels under all conditions. In particular, under conditions with relatively high load, that is, Conditions E and F, it may be confirmed that the ignition delay of main combustion was shorter in the case of NExBTL than diesel fuel and BDF, and that the startup of initial combustion in the portion of crank angle 3 ~ 6 deg. ATDC was slower. In this way, NExBTL is considered to have suppressed NOx generation during initial portion of main combustion, and have a lower level of NOx emission than the case of driving with BDF, but equivalent to that of the case of driving with diesel fuel.

The mechanism of soot emission formation is considered to be same as the single injection condition. From the results of Figs. 5-10 to 5-12, combustion characteristics of main combustion such as ignition delay, ratio of premixed combustion and diffusion combustion were almost the same between each fuel. These phenomena notably lead to the difference of soot emission characteristics due to the difference of fuel components. Therefore, soot emissions from BDF and NExBTL are much lower than those of diesel fuel.

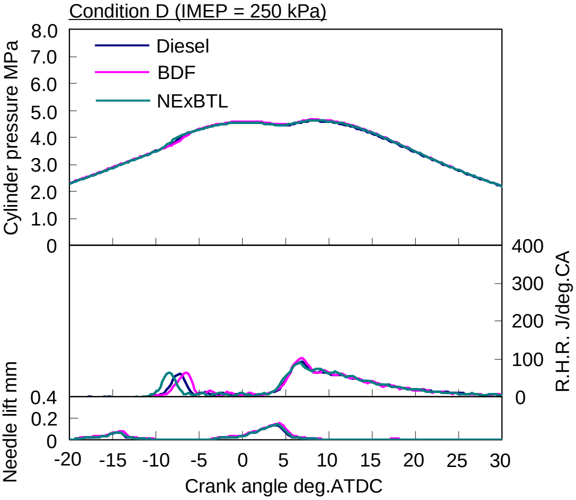


Figure 5-10 Cylinder pressure, rate of heat release and needle lift under two-stage injection condition D

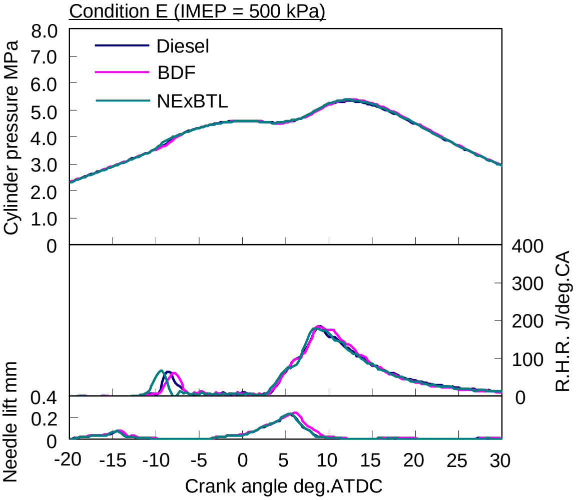


Figure 5-11 Cylinder pressure, rate of heat release and needle lift under two-stage injection condition E

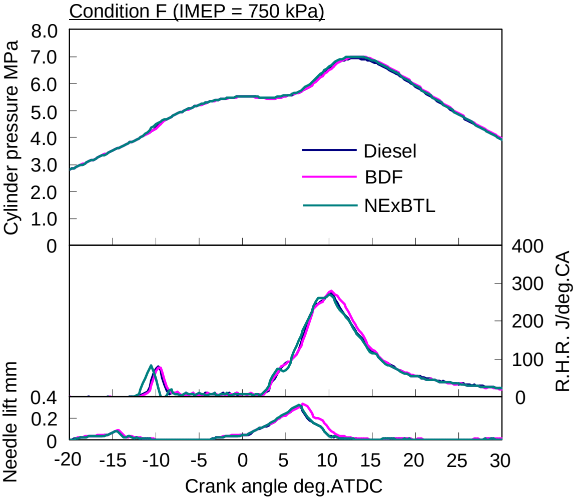


Figure 5-12 Cylinder pressure, rate of heat release and needle lift under two-stage injection condition F

5.6. Summary of this chapter

To confirm the basic combustion and emission characteristics of NExBTL made by Neste Oil, a single-cylinder diesel engine test was performed. The result of comparison of the test results thus obtained with those of driving with diesel fuel and BDF originating from waste cooking oil (FAME) is summarized below.

- NExBTL is capable of suppressing NOx emission when compared with BDF, and can maintain an emission level equivalent to the case of driving with diesel fuel. One of the factors for this is that NExBTL has a higher cetane value, causing shorter ignition delay and thus small ratio of premixed combustion during the initial period where NOx is readily generated. This in turn indicates that, for NExBTL, diffusion combustion is prevailing, resulting in less NOx emission. This is a particularly significant improvement relative to the widely-employed bio-fuel, that is, BDF.

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

6.1. Objective

The vehicle under test driving with biofuel mixed with neat or diesel fuel and that using diesel fuel were equipped with an on-board measurement system including PEMS (Portable Emission Measurement System). They were run on the actual road to evaluate emission characteristics in the real world.

6.2. Test fuels

Test fuels used in this test are shown in Table 6-1. For diesel fuel, the diesel fuel JIS NO.2 available on the market was used. For biofuels, two types were used; BDF originating from waste cooking oil of Kyoto City and NExBTL of Neste Oil.

Table6-1 Characteristics of test fuels

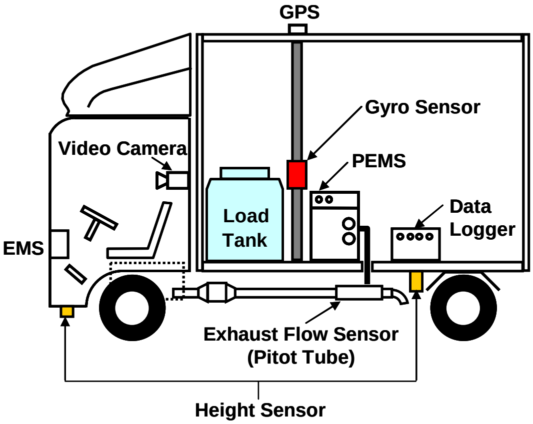
Fuel		Diesel	BDF (Kyoto)	NExBTL
Density (15 deg.C) g/cm^3		0.8275	0.8849	0.7797
Kinematic viscosity mm^2/s		3.777 (@30 deg.C)	4.689 (@40 deg.C)	2.985 (@30 deg.C)
Flash point deg.C		66.0	115.0	88.0
Cetane number		57.2	52.6	88.2
Distillation temp. deg.C	IBP	170.0	284.0	-
	10%	212.0	345.0	-
	50%	282.5	354.0	-
	90%	332.0	359.0	293.4
CHO wt.%	C	85.9	76.7	84.4
	H	13.9	12.2	15.3
	O	0.2	11.1	0
Pour point deg.C		-22.5	-15.0	-15.0
Sulfur content ppm		4.8	3.3	-
Lower heating value kJ/kg		42850	37000	44070

6.3. On-board measurement system

The on-board measurement system that is used in the on-road driving test is shown in Fig. 6-1, and an overview inside the trunk of the test vehicle is shown in Fig. 6-2. PEMS (Portable Emission Measurement System), HORIBA OBS-2200, is installed in the test vehicle that is used in the test described in Chapter 4. A pitot tube-type exhaust gas flowrate meter is installed in the midst of an exhaust pipe. The emission concentration of CO, CO_2, THC and NOx that is constantly measured by the analyzer is multiplied by the exhaust gas flowrate that is measured by the pitot tube to calculate the mass emission of the respective components. The fuel consumption per hour can also be calculated based on the mass emission with the carbon balance method.

Two tanks filled with water (two 500 L tanks) are installed to realize the half-loaded condition in the trunk. 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 two gyro sensors with the measurement of the vehicle tilt angle against the road surface using two height sensors. The road gradient is measured by installing these sensors in the test vehicle. The engine torque can be analyzed based on the calculated driving resistance.

At the same time, EMS (Eco-driving Management System) is installed in the test vehicle for the Eco-driving diagnosis.



PEMS: HORIBA OBS-2200
EMS: Eco-driving Management System

Figure 6-1 On-board measurement system

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

6.4. Test conditions and evaluation items

The test conditions of this study are summarized in Table 6-2. The test route of about 22.2 km in full circle was set using local roads around the National Traffic Safety and Environment Laboratory (NTSEL). Using each of the mixing conditions, vehicles were run; twice for each of normal driving and eco-driving. The test route in this test is shown in Fig. 6-3. Note that, for BDF B50 and BDF B75, the test run was made within the yard of NTSEL because they could not be used on public roads due to legal constraints of Japan, “Act on the Quality Control of Gasoline and Other Fuels”. This test was intended to evaluate the emission rate of NOx, CO, CO_2 and THC as well as the fuel economy.

Table 6-2 Test conditions

Name	Mixing ratio of fuel			Number of test		Route
	Diesel (JIS No.2)	BDF (Kyoto)	NExBTL	Normal driving	Eco-driving	Test route
B0	100%	0%	0%	2	2	Test route
BDF B5	95%	5%	0%	2	2	Test route
BDF B50	50%	50%	0%	2	2	Inside of NTSEL
BDF B75	25%	75%	0%	2	2	Inside of NTSEL
BDF B100	0%	100%	0%	2	2	Test route
NExBTL B5	95%	0%	5%	2	2	Test route
NExBTL B50	50%	0%	50%	2	2	Test route
NExBTL B75	25%	0%	75%	2	2	Test route
NExBTL B100	0%	0%	100%	2	2	Test route

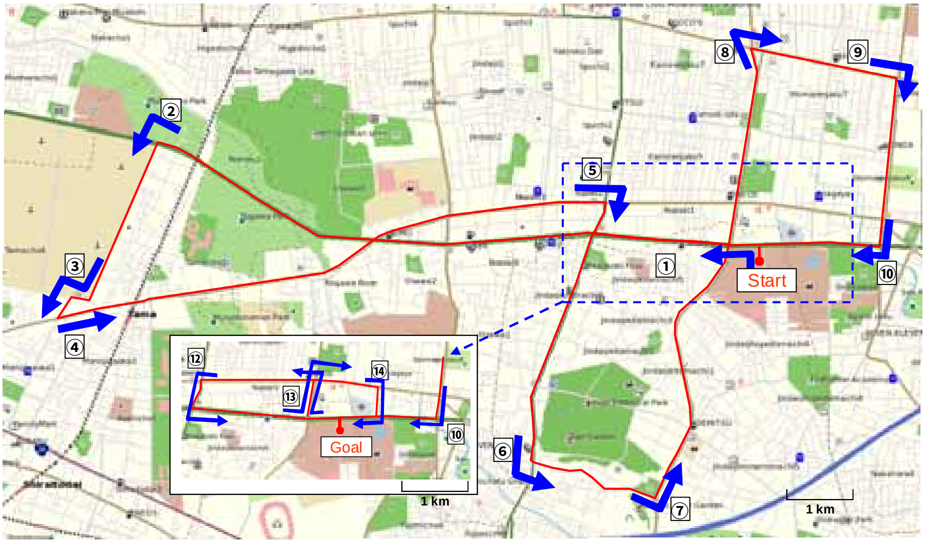


Figure 6-3 Map of the test route

6.5. Analysis methods

The important factor in this case is how the engine operating range varies depending on the difference in the driving method and kind of fuel. It was decided to calculate the engine torque from the driving resistance on the vehicle (Equation 1 - Equation 5). This calculation is based on a method of the JE05 driving cycle procedure for the heavy-duty vehicle emission test in Japanese type approval. The JE05 test has a process to convert a vehicle speed profile to an engine speed profile and 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 was applied to a calculation method of engine torque. However, this study aims to analyze the effect in real-world emission, and thus the value of gradient resistance R_e is added to this method. The reason for the adoption of this method is because that ECU (Engine Control Unit) protocol of heavy duty vehicles is not standardized among vehicle manufacturers in Japan, and it is quite difficult to get the engine torque value from ECU data.

$$T = \frac{r}{i_m i_f \eta_m \eta_f}\left(R_c + R_a + R_r + R_e\right) \qquad \text{(Eq. 1)}$$

$$R_c = \left(W + W_r\right)\alpha \qquad \text{(Eq. 2)}$$

$$R_a = \mu_a A v^2 \qquad \text{(Eq. 3)}$$

$$R_r = \mu_r W \qquad \text{(Eq. 4)}$$

$$R_e = W g \sin\theta_r \qquad \text{(Eq. 5)}$$

Here,

A: frontal projected area [m^2], g: gravitational acceleration [m/s^2], i_f: final gear ratio [-], i_m: transmission gear ratio [-], Ne: engine speed [rpm], r: tire dynamic load radius [m], R_a: air resistance [N], R_c: acceleration resistance [N], R_e: gradient resistance [N], R_r: rolling resistance [N], T: engine torque [N·m], W: vehicle weight [kg], W_r:

equivalent weight of rotating part [kg], α: vehicle acceleration [m/s^2], η_f: efficiency of transmission [-], η_m: efficiency of final gear [-], μ_a: coefficient of air resistance [N/(m^2·(km/h)^2)], μ_r: coefficient of rolling resistance [N/kg], θ_r: road gradient [deg]

The air resistance coefficient μ_a in Equation 3 and rolling resistance coefficient μ_r in Equation 4 were acquired from the result of a coast down test with the test vehicle. Note that the work W_{act} [kWh] shown here was calculated on the basis of the instantaneous engine torque T.

6.6 Test results and consideration

(1) Overall route results

Fig. 6-4 shows the fuel economy, CO_2 emission ratio and NOx emission ratio in various mixing ratios of waste cooking oil BDF and diesel fuel. Fig. 6-5 shows the route-averaged CO_2 emission and route-averaged NOx emission. The bar graphs in the figures indicate the averaged values of the results of driving 4 times for each under each condition, and the vertical lines in the graphs mean the width between maximum and minimum values in each 4-time driving. Note that under these conditions, the results of B50 and B75, as mentioned above, are the results of driving inside the yard of NTSEL. These figures indicate that fuel economy and CO_2 emission did not largely change relative to an increase in the mixture ratio of BDF, while NOx emissions clearly increased. The same result was seen in the chassis dynamometer test. In particular, a mixing ratio of BDF over 50% led to a large increase in NOx emission.

Next, the results depending on the driving methods will be shown. Fig. 6-6 shows the fuel economy, CO_2 emission ratio and NOx emission ratio for each mixing ratio in normal driving and eco-driving. Fig. 6-7 shows the route-averaged CO_2 and NOx emissions. Eco-driving significantly contributed to improve the fuel economy and CO_2 emission. The changes in the fuel economy and CO_2 emission due to the different operating methods will be analyzed in the next chapter. In the changes in NOx emission due to the different operating methods, eco-driving reduced NOx emission under most conditions except for the condition of B50, in which NOx emission increased. The reason is considered to be that the area of use in the engine was changed by eco-driving, and the area where EGR does not usually work was used.

Focusing on the results of normal driving, NOx emission increased under conditions of more than B50. Similarly, the results of eco-driving show that NOx emission largely increased under conditions of more than B50.

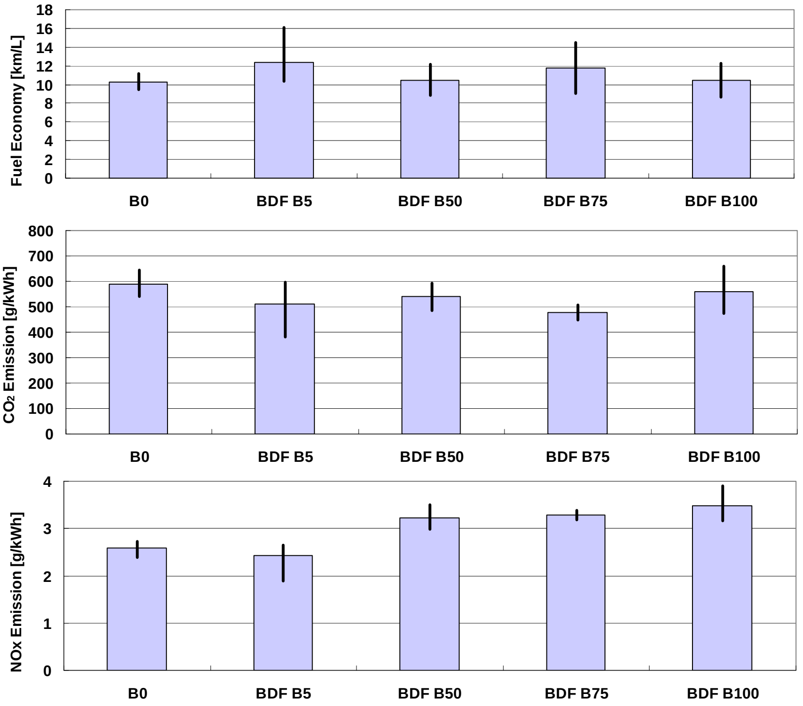


Figure 6-4 Route total results for fuel economy, CO_2 emissions, and NOx emissions at BDF ratios of 0, 5%, 50%, 75%, and 100% relative to diesel fuel

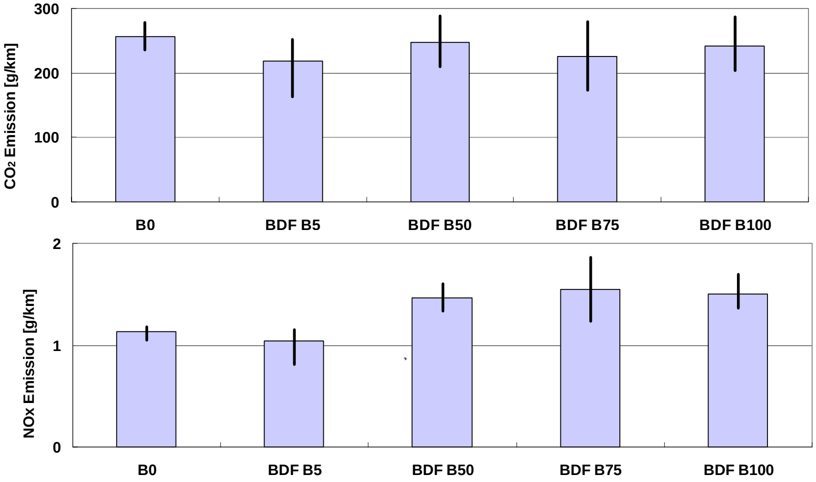


Figure 6-5 Route total results; Route-averaged CO_2 emissions and route-averaged NOx emissions at BDF ratios of 0, 5%, 50%, 75%, and 100% relative to diesel fuel

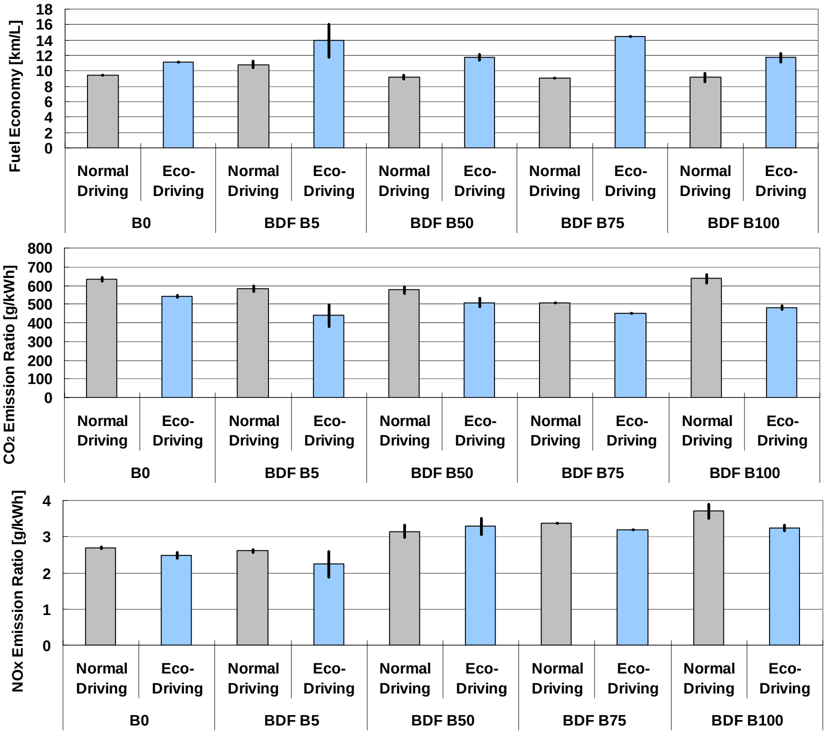


Figure 6-6 Route total results of each driving method;

Fuel economy, CO$_2$ emissions and NOx emissions at BDF ratios of 0, 5%, 50%, 75%, and 100% relative to diesel fuel

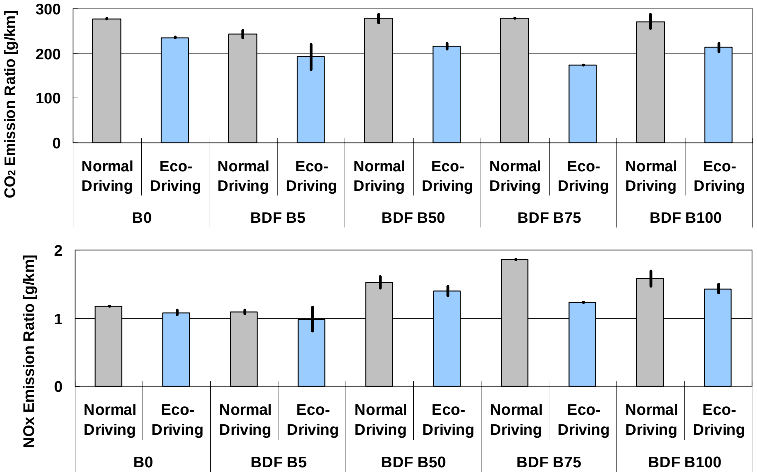


Figure 6-7 Route total results of each driving method;

Route-averaged CO_2 emissions and route-averaged NOx emissions at BDF ratios of 0, 5%, 50%, 75%, and 100% relative to diesel fuel

Fig. 6-8 shows the fuel economy, CO_2 emission ratio and NOx emission ratio in various mixing ratios of NExBTL and diesel fuel. Fig. 6-9 shows the route-averaged CO_2 emission and route-averaged NOx emission. The bar graphs in the figures indicate the averaged values of the results of driving 4 times for each under each condition, and the vertical lines in the bar graphs mean the width between maximum and minimum values in each 4-time driving. Unlike the results of BDF, all results are obtained by the driving tests in urban area. These figures indicate that the fuel economy, CO_2 emission and NOx emission did not largely change relative to increase in the mixture ratio of NExBTL.

In the chassis dynamometer tests, the results indicate that CO_2 emission decreased in accordance with an increase in the mixture ratio of NExBTL. The results of the on-road driving tests include the variations caused by traffic conditions, and the result of this test with NExBTL is within the range of these variations. From the results of each mixing ratio, it can be judged that the fuel economy, CO_2 emission and NOx emission are equivalent to those during operation using only diesel fuel.

Next, the results depending on the operating methods will be shown. Fig. 6-10 shows the fuel economy, CO_2 emission ratio and NOx emission ratio for each mixture ratio in normal driving and eco-driving. Fig. 6-11 shows the route-averaged CO_2 and NOx emissions. As is the case with the mixture of BDF, the significant contribution of eco-driving in improvement of the fuel economy and CO_2 emission is also seen. When NExBTL is used as fuel, the changes in the fuel economy and CO_2 emission due to the different operating methods will be analyzed in the next chapter. In the changes in NOx emission due to the different operating methods, eco-driving reduced NOx emission under most conditions except for the condition of B75, in which NOx emission increased. These changes in NOx emission were the same as in the case of using BDF.

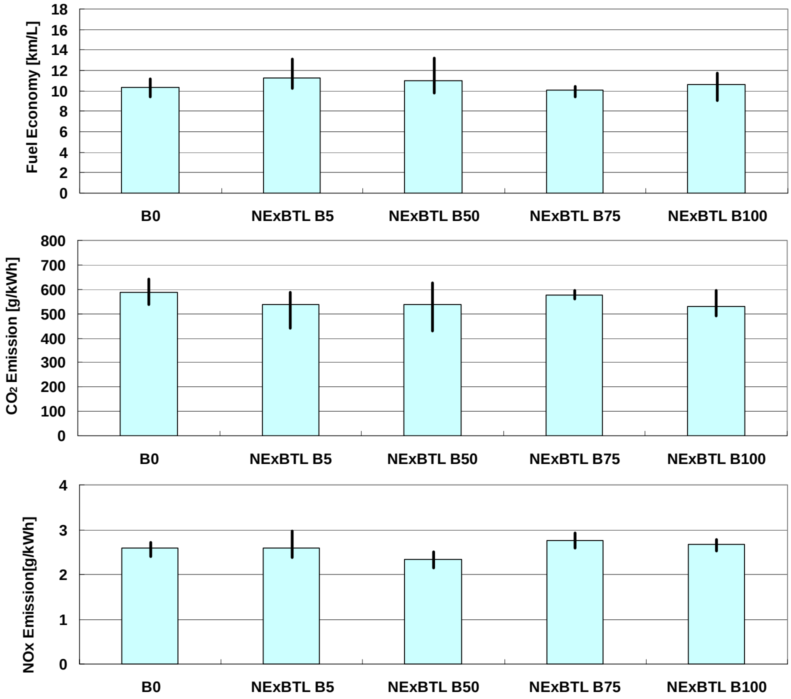


Figure 6-8 Route total results for fuel economy, CO2 emissions, and NOx emissions at NExBTL ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

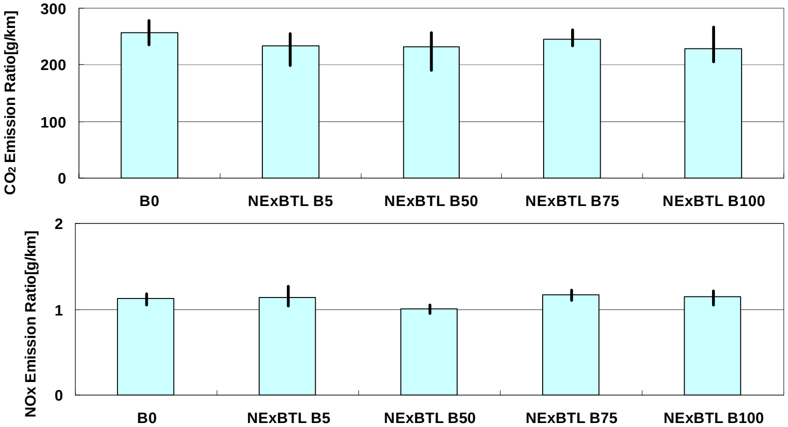


Figure 6-9 Route total results; Route-averaged CO_2 emissions and route-averaged NOx emissions at NExBTL ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

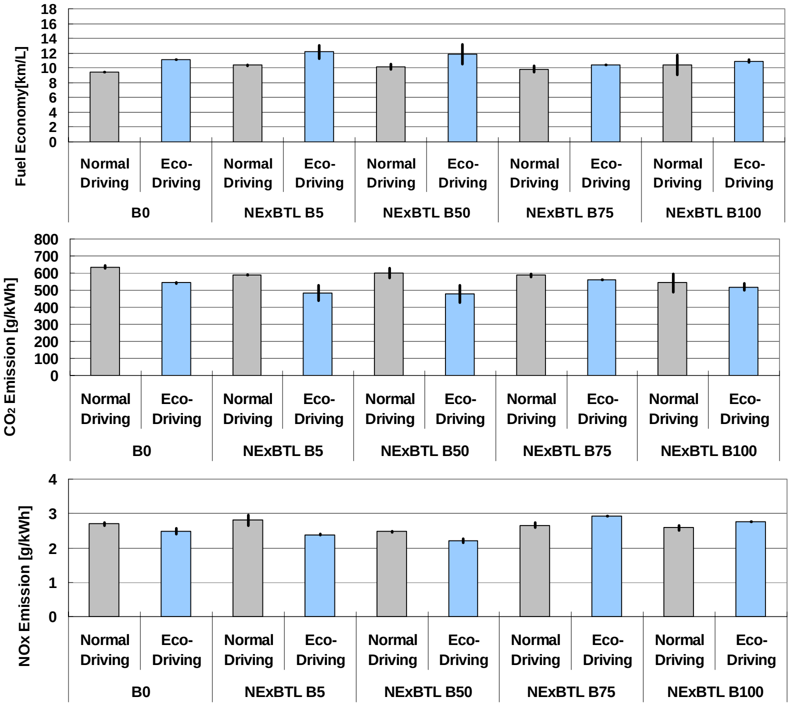


Figure 6-10 Route total results of each driving method;

Fuel economy, CO_2 emissions and NOx emissions at NExBTL ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

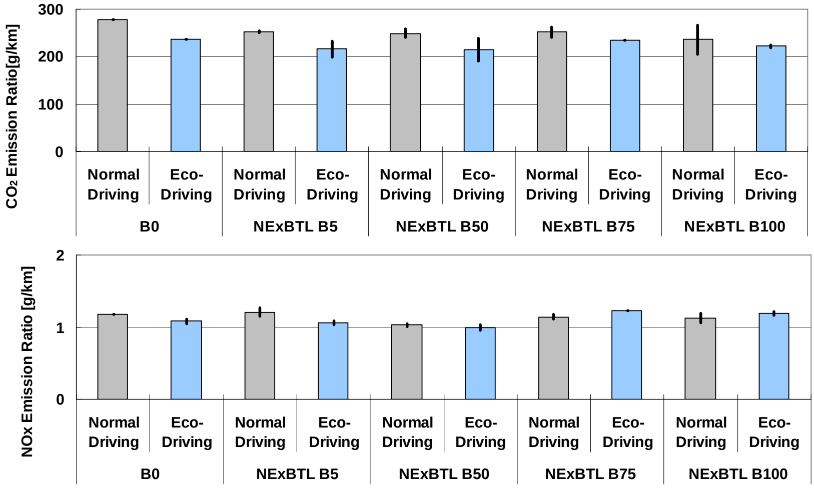


Figure 6-11 Route total results of each driving method;

Route-averaged CO_2 emissions and route-averaged NOx emissions at NExBTL ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

(2) Analysis of a short trip

This section will analyze each result mentioned in the previous section in terms of a short trip. A short trip is defined in Fig. 6-12 as the interval between start and re-start of a vehicle. Under the following three conditions, 100% diesel fuel-fueled, 100% BDF-fueled and 100% NExBTL-fueled, the NOx and CO_2 emissions per unit distance were analyzed in each short trip.

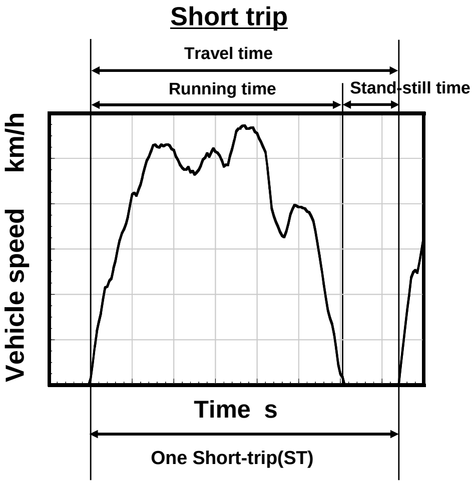


Figure 6-12 Definition of a short trip

Figures from 6-13 to 6-16 show the analysis results in the above three conditions. Fig. 6-13 shows the relationship between CO_2 emission per work of a short trip and average speed of a short trip in the results of the B0 (diesel fuel) condition and BDF B100 condition. Fig. 6-14 shows the relationship between CO_2 emission per work of a short trip and average speed of a short trip in the results of the B0 (diesel fuel) condition and NExBTL B100 condition. Both figures indicate that there are no significant differences in the CO_2 emission ratio of a short trip between the diesel fuel condition, BDF B100 condition and NExBTL B100 condition. These results of CO_2 emission of a short trip lead to the total results of urban route driving. The point distribution of CO_2 emission varied significantly depending on the degree of the improvement of fuel economy by operating methods. This point distribution due to the different operating methods will be described in the next chapter.

Fig. 6-15 shows the relationship between NOx emission per work of a short trip and the average speed of a short trip in the results of the B0 (diesel fuel) condition and BDF B100 condition. Fig. 6-16 shows the relationship between NOx emission per work of a short trip and average speed of a short trip in the results of the B0 (diesel fuel) condition and NExBTL. In Fig. 6-15, the point distribution in the greater than 7 km/h speed region was compared, in the condition of 100% BDF-fueled, points were seen in a region of higher NOx emission than that under the B0 condition. On the other hand, in Fig. 6-16, there was no great distinction between the condition of 100% diesel fuel-fueled and 100 % NExBTL-fueled.

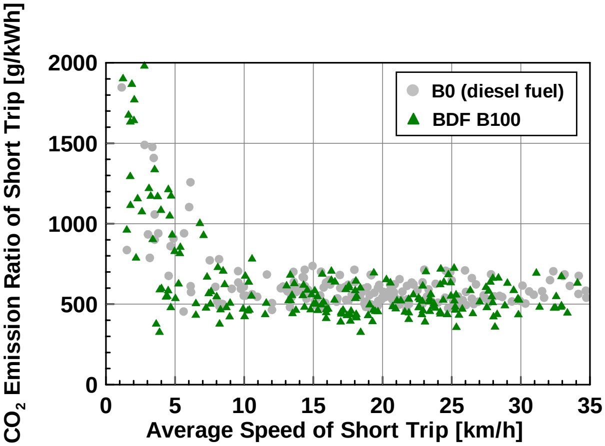


Figure 6-13 Relationship between CO$_2$ emission per work of a short trip and average speed of a short trip in the results of the B0 (diesel fuel) condition and BDF B100 condition

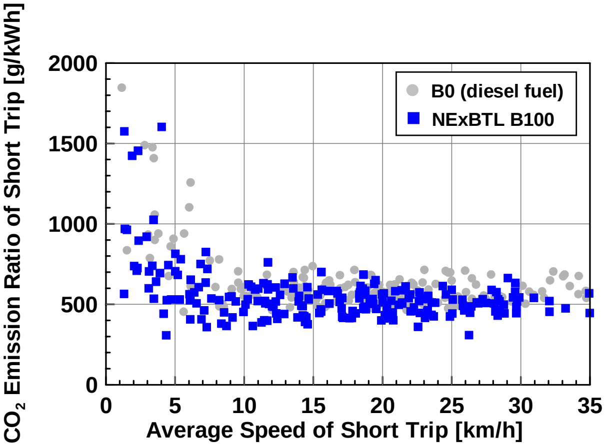


Figure 6-14 Relationship between CO$_2$ emission per work of a short trip and average speed of a short trip in the results of the B0 (diesel fuel) condition and NExBTL B100 condition

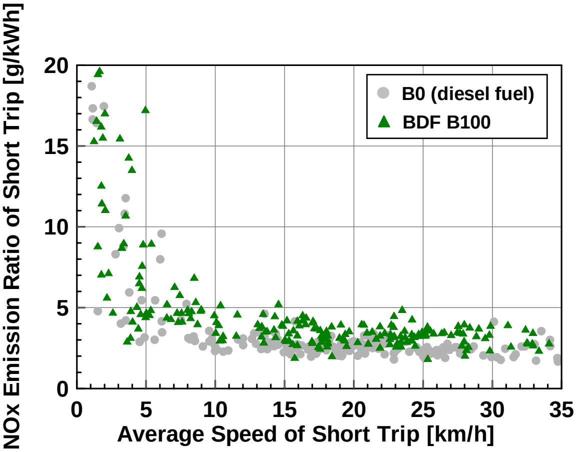


Figure 6-15 Relationship between NOx emission per work of a short trip and average speed of a short trip in the results of the B0 (diesel fuel) condition and BDF B100 condition

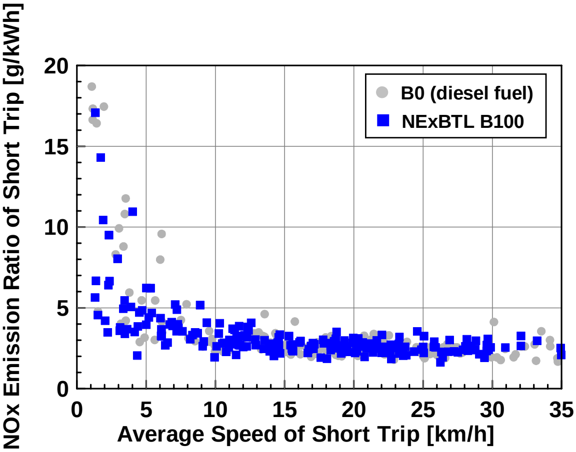


Figure 6-16 Relationship between NOx emission per work of a short trip and average speed of a short trip in the results of the B0 (diesel fuel) condition and NExBTL B100 condition

6.7. Summary of this chapter

In operating the vehicle with the mixed fuel of BDF and diesel fuel in the on-road driving tests, NOx emissions increased in accordance with an increase of BDF ratio. On the other hand, when the mixed fuel of NExBTL and diesel fuel was used, an increase of NOx emissions was not seen. Fuel consumption performance was not affected by either fuels.

7. Effects of Eco-driving of a Bio-fuel Vehicle during Road Driving

7.1. Eco-driving practice method

Typical eco-driving practice methods are shown in Table 7-1. Seven parameters are shown; preventing sudden acceleration and deceleration, shifting-up at lower engine speed, driving at an economical speed, driving at constant speed, preventing wasted racing of the engine, using engine brake sufficiently for deceleration, and avoiding excessive idling. This on-road driving test was performed with the stress placed mainly on shifting-up at lower engine speed among these parameters because it is considered highly effective for reduction of CO_2 emission. Specifically, EMS (Eco-driving Management System) was set in such a manner that the alarm is issued when the engine speed exceeds 2,000 rpm and the driver was to drive while taking care not to activate the alarm.

Note that every o.5 seconds, EMS measured and recorded the vehicle speed, engine speed, and vehicle position information from GPS, in addition to activated the alarm at engine speeds exceeding the upper limit of set value. The data thus obtained was used in analysis.

Table 7-1 Typical eco-driving practice methods

No.	Practical measures for Eco-Driving
1	Preventing sudden acceleration and deceleration
2	Shifting-up at lower engine speed
3	Driving at economical speed
4	Driving at constant speed
5	Preventing from wasted racing of engine
6	Using engine brake sufficiently for deceleration
7	Avoiding excessive idling

7.2. Test results

Table 7-2 outlines the results of the on-road driving test. The on-road driving tests involved no particular change in the traffic condition among tests, with the average vehicle speed being the level for ordinary driving in urban areas, ranging 16.3 ~ 21.5 km/h. The average fuel cost of tests done twice for each fuel and operation mode was 5.53 ~ 6.62 km/L for normal driving, and 6.41 ~ 8.89 km/L for eco-driving. The fuel economy improvement ratio by eco-driving ranged 4.5 ~ 60.8%. For all of the kinds of fuel, eco-driving proved effective for improvement of fuel economy. Similarly, the CO_2 reduction ratio by Eco-driving was 6.1 ~ 37.9%.

Table 7-2 Fuel economy and emission results for on-road driving tests

Fuel	Operation	Date	Distance [m]	Average vehicle speed [km/h]	Fuel economy [km/L]	Average Fuel economy [km/L]	Improvement rate of Fuel economy	CO_2 emissions [g/km]	Average CO_2 emissions [g/km]	Improvement rate of CO_2 emissions
B0	Normal driving	09/09/10	21,487	20.6	9.39	9.43	18.1%	279	278	-15.2%
		09/10/10	21,469	18.9	9.48			277		
	Eco-driving	09/09/10	21,479	17.8	11.13	11.14		236	236	
		09/10/10	21,454	21.5	11.15			236		
BDF B5	Normal driving	10/13/10	21,465	18.6	11.22	10.79	29.1%	235	244	-21.2%
		10/14/10	21,475	20.7	10.35			253		
	Eco-driving	10/13/10	21,472	16.3	16.04	13.93		163	192	
		10/14/10	21,473	19.5	11.81			221		
BDF B50	Normal driving	10/18/10	3,590	17.0	8.88	9.13	29.1%	288	278	-22.1%
		10/18/10	3,599	19.8	9.39			269		
	Eco-driving	10/18/10	3,593	16.8	11.43	11.79		223	217	
		10/18/10	3,590	17.7	12.15			210		
BDF B75	Normal driving	10/18/10	7,157	21.3	9.01	9.01	60.8%	279	279	-37.9%
	Eco-driving	10/18/10	7,159	16.7	14.49	14.49		174	174	
BDF B100	Normal driving	10/19/10	21,508	18.1	8.60	9.15	28.1%	287	271	-21.4%
		10/19/10	21,484	19.1	9.69			256		
	Eco-driving	10/19/10	21,494	19.8	12.26	11.71		204	213	
		10/19/10	21,490	17.4	11.16			223		
NExBTL B5	Normal driving	10/08/10	21,455	16.3	10.44	10.35	17.4%	250	253	-14.6%
		10/12/10	21,493	19.9	10.26			255		
	Eco-driving	10/08/10	21,458	16.9	13.10	12.15		199	216	
		10/12/10	21,483	19.4	11.21			232		
NExBTL B50	Normal driving	10/12/10	21,470	19.4	10.47	10.13	17.2%	241	249	-14.0%
		10/13/10	21,473	20.1	9.80			257		
	Eco-driving	10/12/10	21,475	18.3	13.17	11.87		191	214	
		10/13/10	21,005	18.7	10.57			238		
NExBTL B75	Normal driving	10/05/10	21,504	19.9	9.44	9.84	6.1%	262	251	-6.9%
		10/06/10	21,481	19.3	10.25			241		
	Eco-driving	10/05/10	21,494	17.6	10.45	10.45		234	234	
		10/06/10	N.A.	N.A.	N.A.			N.A.		
NExBTL B100	Normal driving	10/07/10	21,470	20.2	9.32	10.69	4.5%	266	236	-6.1%
		10/07/10	21,468	19.6	12.06			206		
	Eco-driving	10/07/10	21,476	17.7	11.35	11.17		219	222	
		10/08/10	21,468	17.5	10.99			225		

Comparison of fuel economy with BDF among operation patterns is shown in Fig. 7-1 while that with NExBTL is shown in Fig. 7-2. The average fuel economy with diesel fuel (B0) was 5.79 km/L for normal driving, and 6.84km/L for eco-driving, with the fuel economy improvement ratio being 18.1%. The average fuel economy with BDF was 5.53 ~ 6.62 km/L for normal driving, and 7.19 ~ 8.89 km/L for eco-driving, with the fuel economy improvement ratio being 28.1 ~ 60.8%. The average fuel economy with NExBTL was 6.04 ~ 6.56 km/L for normal driving, and 6.41 ~ 7.46 km/L for eco-driving, with the fuel economy improvement ratio being 4.5 ~ 17.4%. The fuel economy improvement ratios by means of eco-driving were equivalent to or lower than those of diesel fuel in the case of NExBTL, but higher than those of diesel fuel in the case of BDF.

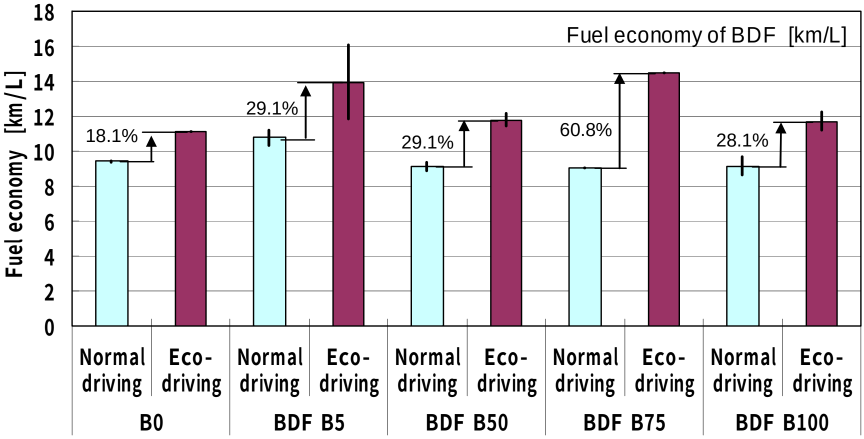


Figure 7-1 Fuel economy for normal driving and eco-driving fueled at BDF ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

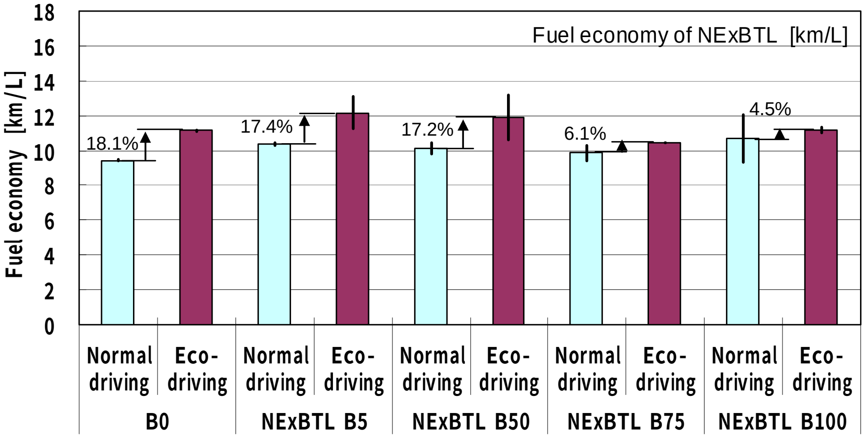


Figure 7-2 Fuel economy for normal driving and eco-driving fueled at NExBTL ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

Comparison of fuel economy with BDF among operation patterns is shown in Fig. 7-3, while that with NExBTL is shown in Fig. 7-4. The average CO_2 emission with diesel fuel (B0) was 453 g/km for normal driving, and 384 g/km for eco-driving, with the CO_2 reduction ratio being 15.2%. The average CO_2 emission with BDF was 397 ~ 455 g/km for normal driving, and 283 ~ 353 g/km for eco-driving, with the CO_2 reduction ratio being 21.2 ~ 37.9%. The average CO_2 emission with NExBTL was 384 ~ 411 g/km for normal driving, and 349 ~ 382 g/km for eco-driving, with the CO_2 reduction ratio being 6.1 ~ 14.6%. The CO_2 reduction effect by eco-driving was equivalent to or less than that of diesel fuel in the case of NExBTL, but higher than both of them in the case of BDF.

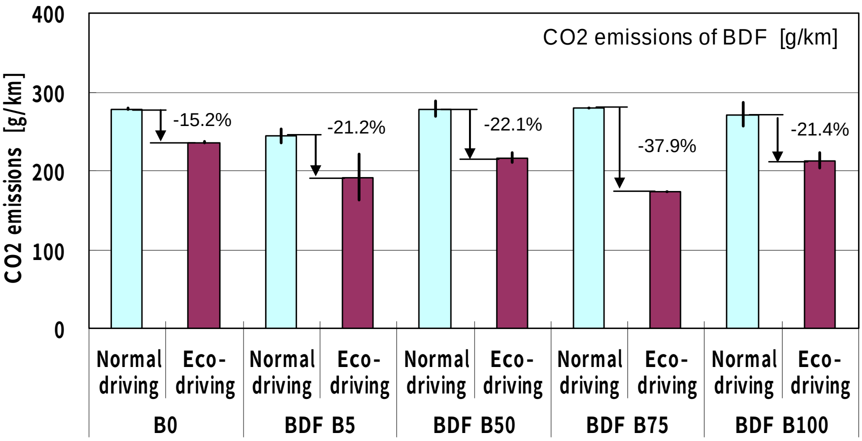


Figure 7-3 CO_2 emissions for normal driving and eco-driving fueled at BDF ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

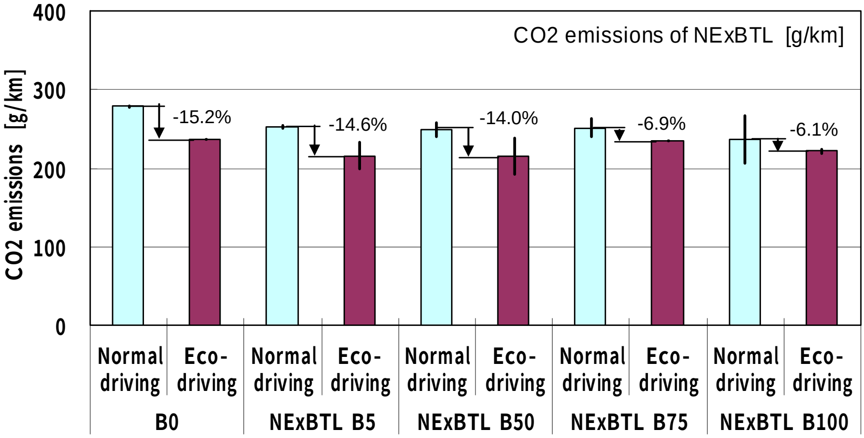


Figure 7-4 CO_2 emissions for normal driving and eco-driving fueled at NExBTL ratios of 0%, 5%, 50%, 75%, and 100% relative to diesel fuel

7.3. Analysis of the CO_2 emission

(1) Analysis of the CO_2 emission during a short trip

The results shown above are the average values when the vehicle runs the test route once. It is difficult to compare the CO_2 emission correctly among tests because of more or less variance in the average vehicle speed depending on the traffic conditions in the course of the test. Therefore, this section is intended to perform a short-trip analysis and to compare the CO_2 emissions at average vehicle speeds during a short trip. The definition of a short trip was shown in Fig. 6-12. One short trip was defined as a period from departure of a vehicle, through driving and stopping, to the next departure.

From the vehicle speed data recorded on the EMS and the CO_2 emission data of the analyzer, the short trip analysis was made for each fuel of diesel fuel (B0), BDF B100 and NExBTL B100. The result is shown in Figs. 7-5 ~ 7-7. In these figures, the average vehicle speed, VST [km/h] of a short trip is taken on the horizontal axis while the CO_2 emission [g/km] of a short trip is taken on the vertical axis. These figures show the approximate curve plotted according to the least square method, in addition to the average vehicle speed and CO_2 emission rate of a short trip.

As is known from Figs. 7-5 ~ 7-7, the CO_2 emission increases suddenly when the short-trip vehicle speed drops below 10 km/h. The CO_2 emission does not change much in the range of the short-trip average velocity speed above 10 km/h. It is also known that, with any fuel, eco-driving produces less CO_2 emission than normal driving within the range of the short-trip average vehicle speed of 10 km/h or more.

For the case of using diesel fuel (B0), the short-trip average vehicle speed VST and the CO_2 emission rate were compared between normal driving and eco-driving. The result indicates that the CO_2 emission rate at the average vehicle speed of 20 km/h was lower by 22.0% in the case of eco-driving than in normal driving.

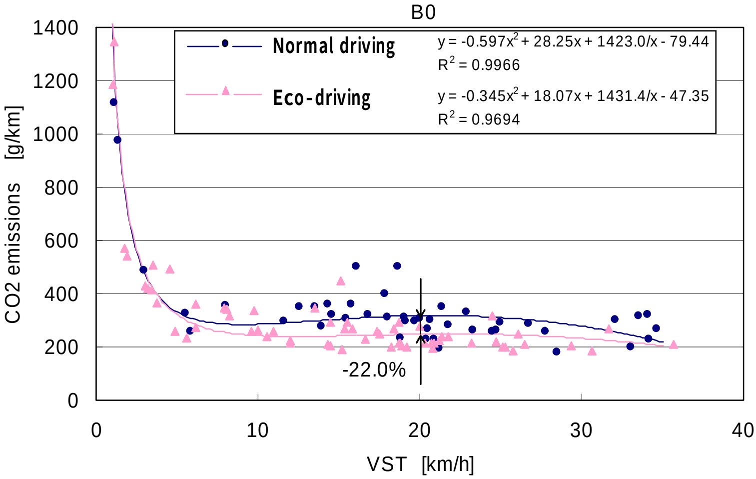


Figure 7-5 Relationship between the averaged vehicle speed of each short trip and CO_2 emission when fueled with diesel fuel (B0)

For the case of using BDF B100 fuel, the short-trip average vehicle speed VST and the CO_2 emission rate were compared between normal driving and eco-driving. The result indicates that the CO_2 emission rate at the average vehicle speed of 20 km/h was lower by 17.2% in the case of eco-driving than in normal driving.

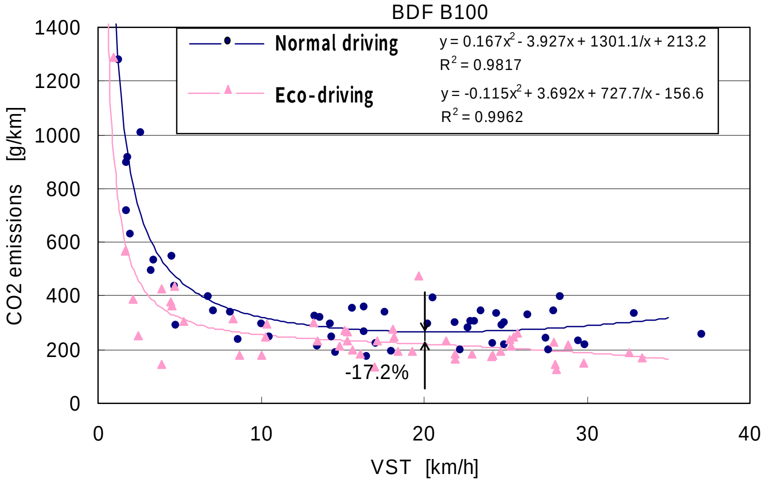


Figure 7-6 Relationship between the averaged vehicle speed of each short trip and CO_2 emission when fueled with BDF B100

For the case of using NExBTL B100 fuel, the short-trip average vehicle speed VST and the CO_2 emission rate were compared between normal driving and eco-driving. The result indicates that the CO_2 emission rate at the average vehicle speed of 20 km/h was lower by 17.9% in the case of eco-driving than in normal driving.

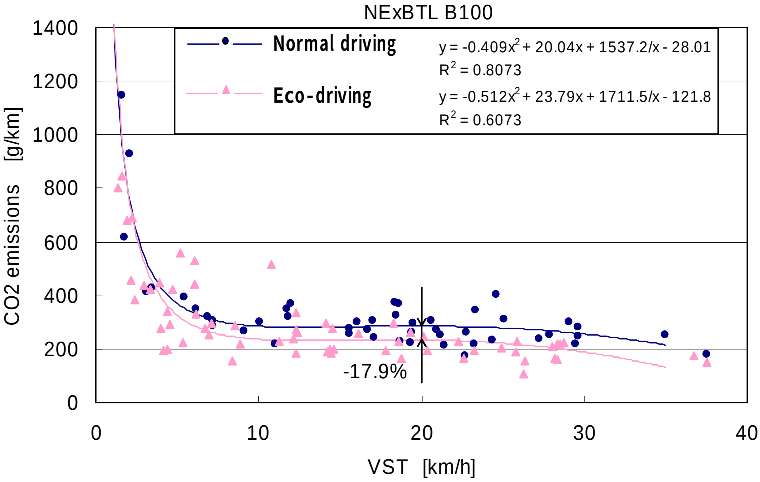


Figure 7-7 Relationship between the averaged vehicle speed of each short trip and CO_2 emission when fueled with NExBTL B100

As is evident from the above result, with the short-trip average vehicle speed fixed at 20 km/h for comparison, the effect of CO_2 emission reduction during eco-driving was around 20%, meaning that there is not much difference among fuels. In other words, regardless of the type of bio-fuels used, the CO_2 emission reduction effect of eco-driving is expected to be equivalent in the real world.

(2) Analysis of the CO_2 emission reduction mechanism by eco-driving

Analysis was made on the mechanism of reducing the CO_2 emission by Eco-driving.

Fig. 7-8 plots the transition of the vehicle speed, engine speed, and CO_2 emission for 300 seconds after the start of data measurement; the upper stage shows the case of normal driving with diesel fuel (B0), and the lower stage shows the case of eco-driving. The engine speed during acceleration (shaded portion) exceeds 2000 rpm in normal driving, but remains 2000 rpm or less in the case of eco-driving.

The latter case means that the driving is done as set with EMS. CO_2 is mostly emitted at departure and during acceleration, with the peak CO_2 emission point agreeing approximately with the point of peak engine speed. The peak value of CO_2 emission exceeds 12 g/s in normal driving, but is lower at about 10 g/s in eco-driving.

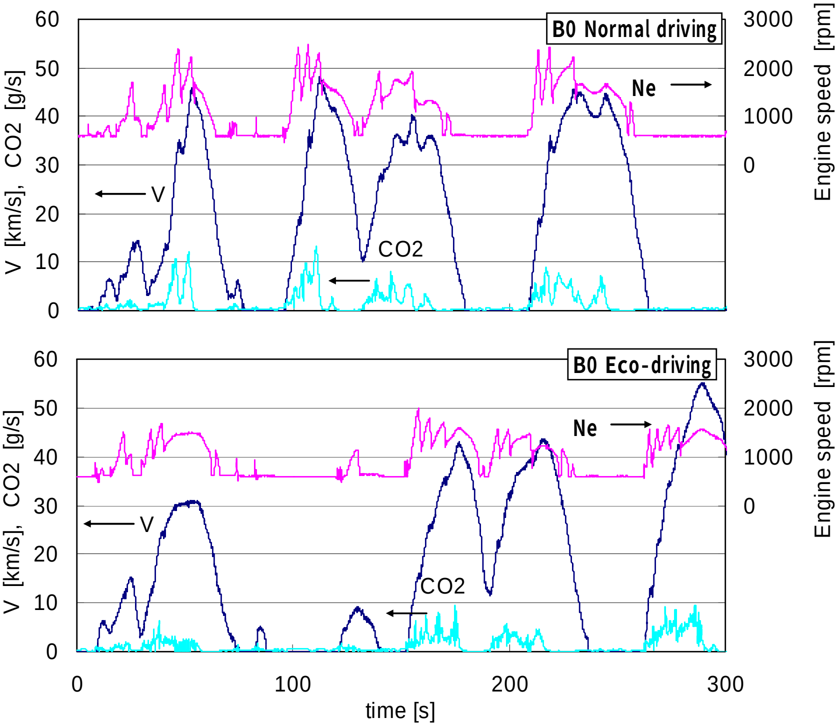


Figure 7-8 Example of vehicle speed, engine speed and CO_2 emission when fueled with diesel fuel (B0)

Fig. 7-9 plots the transition of the vehicle speed, engine speed, and CO_2 emission for 300 seconds after the start of data measurement; the upper stage shows the case of normal driving with BDF B100, and the lower stage shows the case of Eco-driving. Similar to the case of using diesel fuel and B100 fuel, the engine speed during acceleration (shaded portion) exceeds 2000 rpm in normal driving, but remains 2000 rpm or less in the case of eco-driving. The latter case means that the driving is done as set with EMS. CO_2 is mostly emitted at departure and during acceleration, with the peak CO_2 emission point agreeing approximately with the point of peak engine speed. The peak value of CO_2 emission exceeds 12 g/s in normal driving, but is lower at about 10 g/s in eco-driving.

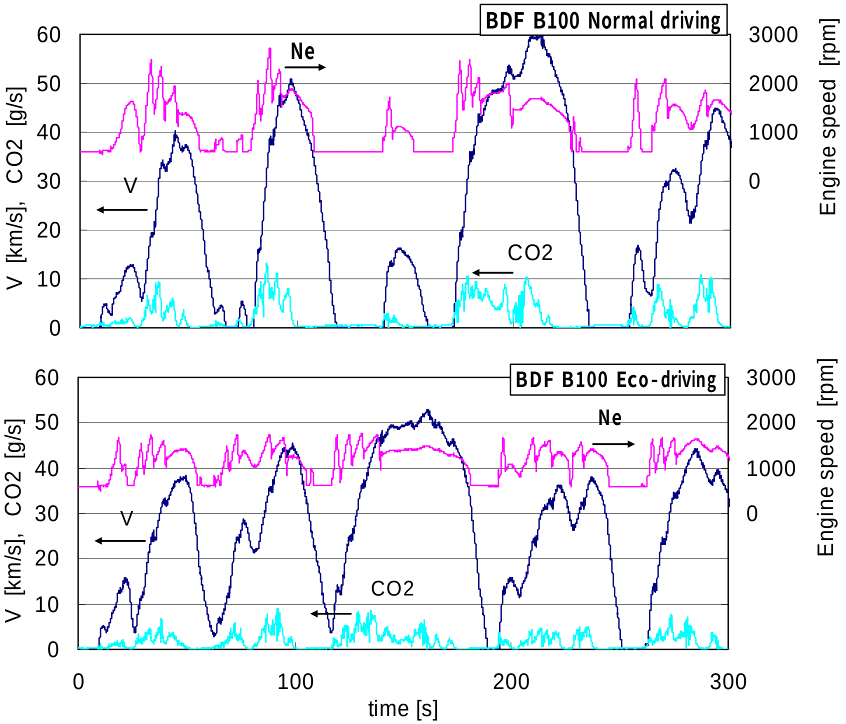


Figure 7-9 Example of vehicle speed, engine speed and CO_2 emission when fueled with BDF B100

Fig. 7-10 plots the transition of the vehicle speed, engine speed, and CO_2 emission for 300 seconds after the start of data measurement; the upper stage shows the case of normal driving with NExBTL B100, and the lower stage shows the case of Eco-driving. Similarly to the case of using diesel fuel, the engine speed during acceleration (shaded portion) exceeds 2000 rpm in normal driving, but remains 2000 rpm or less in the case of eco-driving. The latter case means that the driving is done as set with EMS. CO_2 is mostly emitted at departure and during acceleration, with the peak CO_2 emission point agreeing approximately with the point of peak engine speed. The peak value of CO_2 emission is around 11 g/s in the normal driving, but is lower at about 8 g/s in eco-driving.

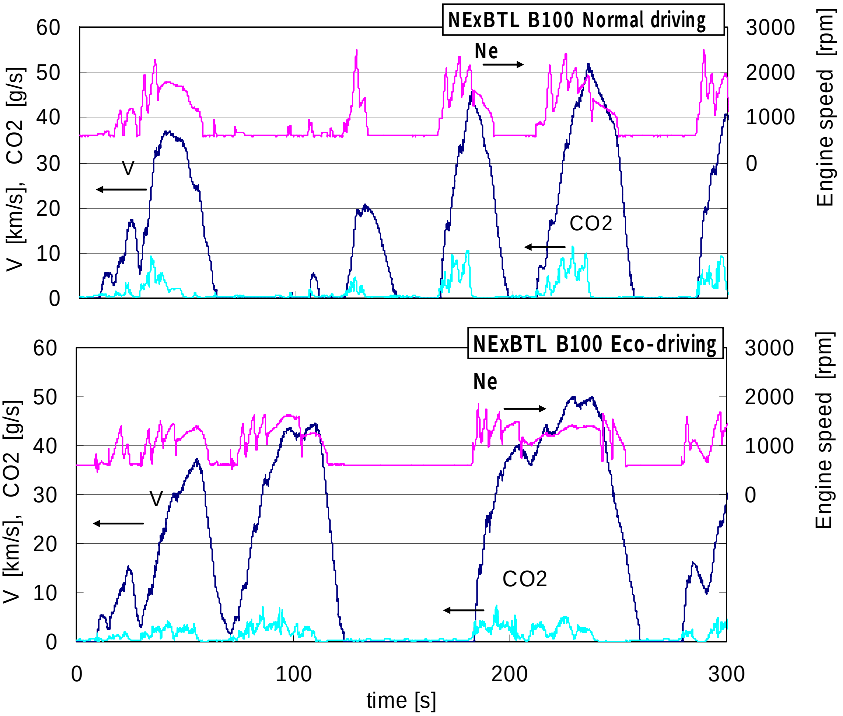


Figure 7-10 Example of vehicle speed, engine speed and CO_2 emission when fueled with NExBTL B100

It is considered now that reduction of the CO_2 emission through eco-driving is not due to the type of fuel, but due to the engine operation range at departure and during acceleration.

As is known from the above results, CO_2 is mostly emitted at departure and during acceleration. In this context, further analysis was made mainly on the acceleration state. Using the on-board measurement system, the vehicle behavior including the driving resistance on the vehicle was measured every 0.1 seconds, and the engine torque was calculated from the driving resistance thus obtained. Data corresponding to the acceleration period only was extracted and plotted on the engine map, in which the engine speed is taken along the horizontal axis and the engine torque along the vertical axis. Acceleration was assumed to be 0.25 m/s^2 or more. Fig. 7-11 shows the engine operation range during acceleration when diesel fuel (B0) is used. It is known from Fig. 7-11 that, in normal driving, acceleration covers from low-rpm to high-rpm ranges. On the other hand, acceleration in eco-driving is made within the low to medium rpm range of 2000 rpm or less.

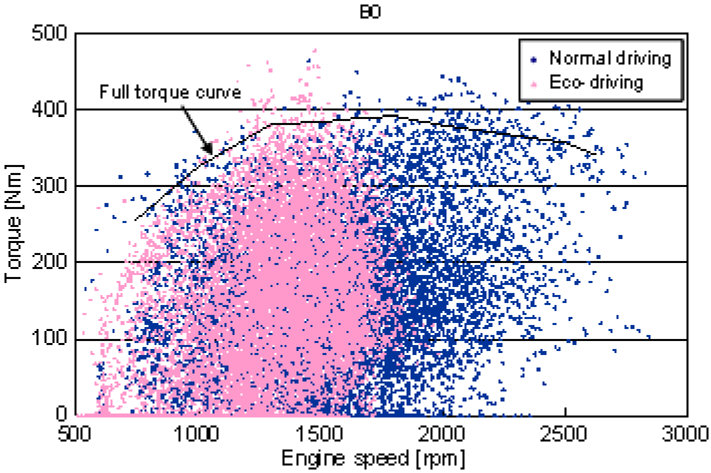


Figure 7-11 Engine operating map during acceleration when fueled with diesel fuel (B0)

Fig. 7-12 shows the engine operation range during acceleration when BDF B100 is used. Similar to the case of diesel fuel and B100 fuel, it is known from this figure that, in normal driving, acceleration covers from the low-rpm to high-rpm range. On the other hand, acceleration in eco-driving is made within the low to medium rpm range of 2000 rpm or less.

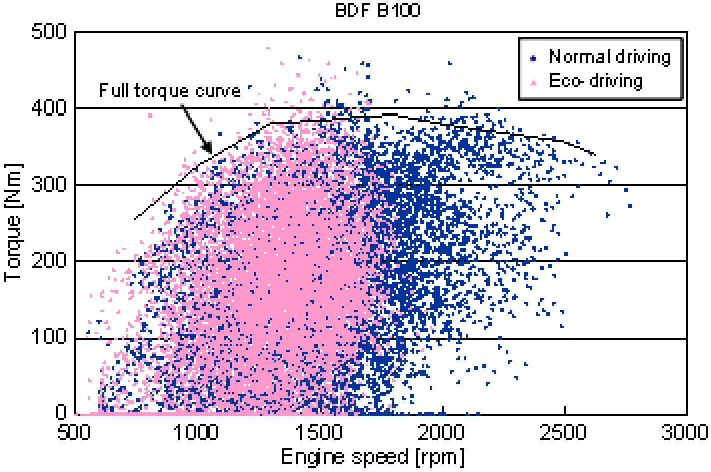


Figure 7-12 Engine operating map during acceleration when fueled with BDF B100

Fig. 7-13 shows the engine operation range during acceleration when NExBTL B100 is used. Similar to the case of diesel fuel, it is known from this figure that, in normal driving, acceleration covers from the low-rpm to high-rpm range. On the other hand, acceleration in eco-driving is made within the low to medium rpm range of 2000 rpm or less.

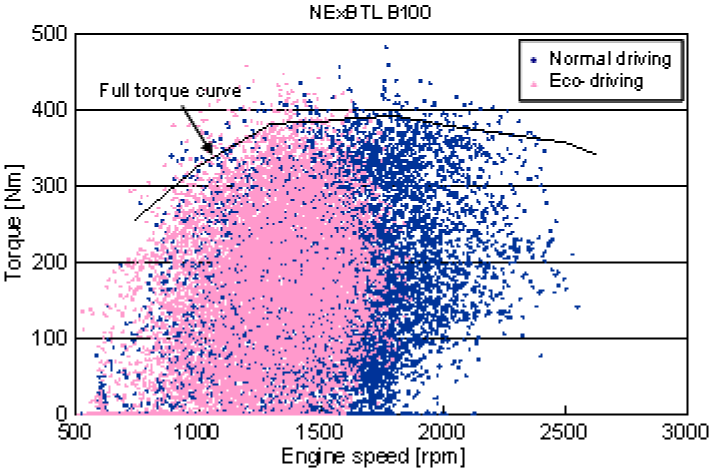


Figure 7-13 Engine operating map during acceleration when fueled with NExBTL B100

Data plotted in Figs. 7-11 ~ 7-13 was divided into nine ranges and the time-based operation frequency of each range was analyzed. Division into ranges was as follows: less than 1250 rpm (low speed range), 1250 rpm or more, less than 2000 rpm (medium speed range), and 2000 rpm or more (high speed range) in terms of the engine speed. Regarding the torque, ranges included less than 125 Nm (low load range), 125 Nm or more, less than 250 Nm (medium load range), and 250 Nm or more (high load range).

Fig. 7-14 shows the result of operation frequency by ranges during acceleration when diesel fuel (B0) is used. In either operation pattern, the medium-speed and medium-load range of 1250 ~ 2000 rpm is operated most frequently. For eco-driving, it is known that the operation frequency of the low-speed high-load range is higher than in normal driving. The low-speed medium-load range is also operated more frequently in eco-driving than in normal driving.

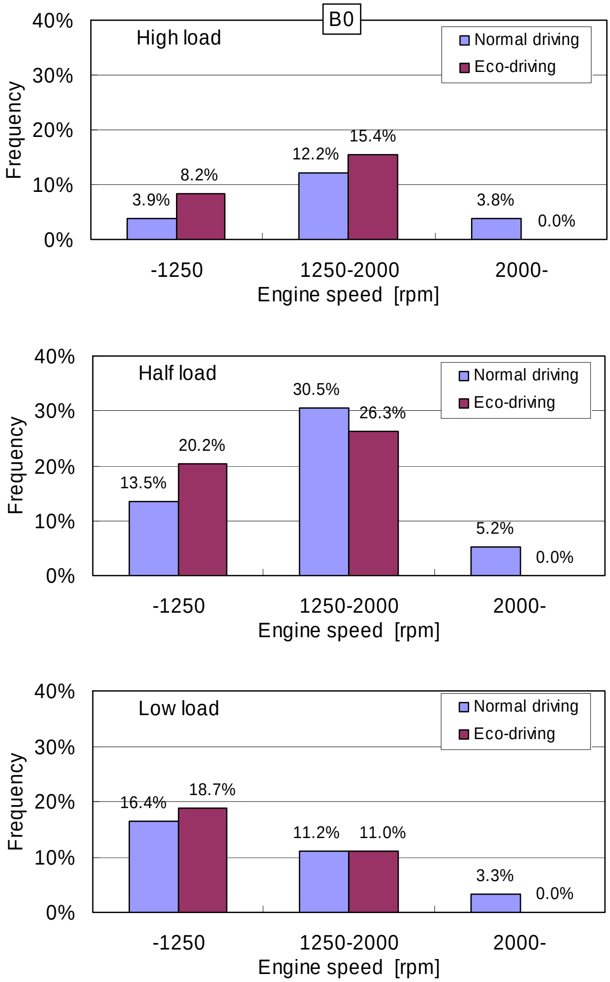


Figure 7-14 Operation frequency by ranges during acceleration when fueled with diesel fuel (B0)

Fig. 7-15 shows the result of operation frequency by ranges during acceleration when BDF B100 is used. Similar to the case of diesel fuel and B100 fuel, in either operation pattern, the medium-speed and medium-load range of 1250 ~ 2000 rpm is operated most frequently. For eco-driving, it is known that the operation frequency of the low-speed high-load range is higher than in normal driving. The low-speed medium-load range is also operated more frequently in eco-driving than in normal driving.

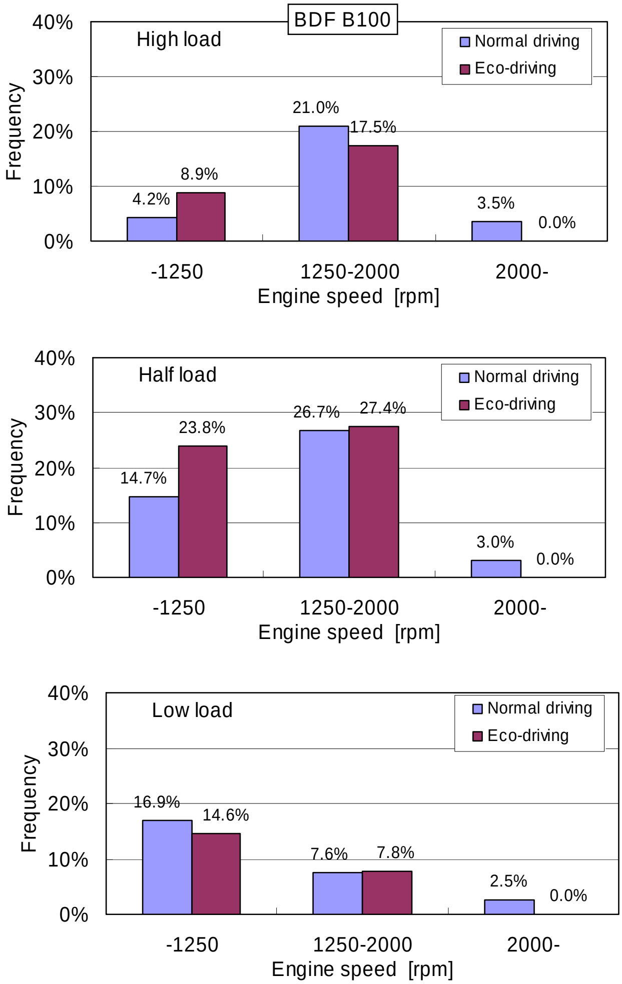


Figure 7-15 Operation frequency by ranges during acceleration when fueled with BDF B100

Fig. 7-16 shows the result of operation frequency by ranges during acceleration when NExBTL B100 is used. Similar to the case of diesel fuel, in either operation pattern, the medium-speed and medium-load range of 1250 ~ 2000 rpm is operated most frequently. For eco-driving, it is known the operation frequency of the low-speed high-load range is higher than in normal driving. The low-speed medium-load range is also operated more frequently in Eco-driving than in normal driving.

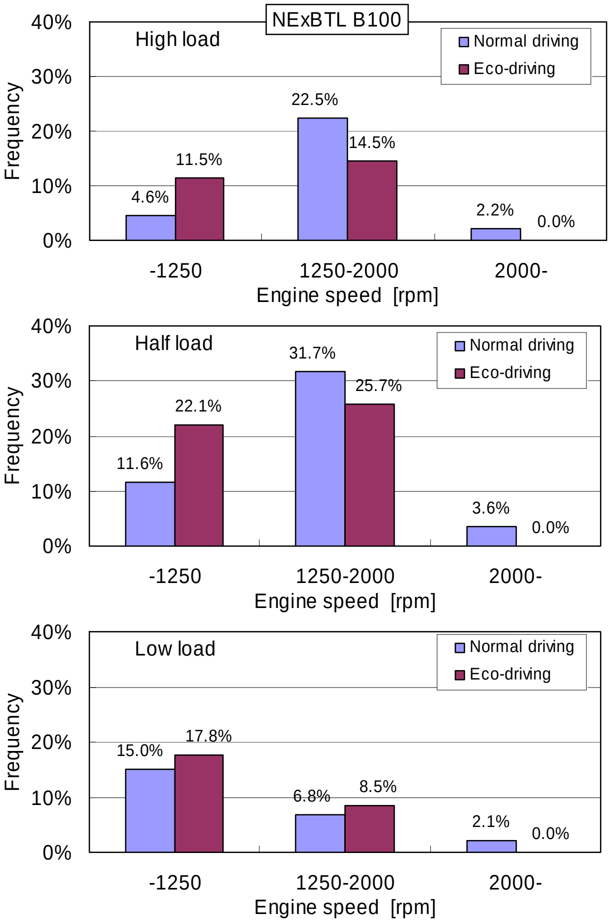


Figure 7-16 Operation frequency by ranges during acceleration when fueled with NExBTL B100

The thermal efficiency of ordinary diesel engines is the highest in the low-speed and high-load range and tends to decrease with increasing engine speed and load reduction. From this viewpoint and the results shown in Figs. 7-14 through 7-16, eco-driving could have reduced the CO_2 emission because eco-driving operates more frequently in the engine operation range ensuring high heat efficiency.

7.4. Summary of this chapter

Using the test vehicle using NEAT, bio fuel mixed with diesel fuel, and diesel fuel, the eco-driving driving test was performed in the real world, investigating the effects of eco-driving on the CO_2 reduction effect. For eco-driving, shift-up was made consciously earlier. The results of the eco-driving driving test may be summarized as follows:

- Both BDF and NExBTL achieve the CO_2 emission reduction effect approximately similar to diesel fuel when Eco-driving is performed. Specifically, around 20% CO_2 emission reduction could be achieved during driving at an average speed of 20 km/h in the urban area.
- The CO_2 emission reduction mechanism of eco-driving is considered due to the engine operation range and the frequency of operation in the range concerned. Generally, the diesel engine has the highest heat efficiency, with the least CO_2 emission, in the low-speed high-torque range. As a result of eco-driving by shifting up earlier, the frequency of operation in the lower-speed and higher-load range increased more than the case of normal driving, leading to CO_2 emission reduction.

8. Cold Start Driving Test Analysis

8.1. Objective

When some kind of bio fuel is used, the fuel supply to the engine depends on the temperature environment where the fuel is used. Namely, when the engine is not supplied with enough fuel due to the temperature environment, starting performance or driving performance in a vehicle may be deteriorated. This chapter will report the results of the examination of exhaust gas performance and fuel consumption performance during a cold-start with NExBTL, which is one of the HVOs. At the same time, the results of an on-road driving test in a cold climate, which was conducted in order to assess cold-start performance of a vehicle will also reported.

8.2. Test method

The test vehicle used for this test is the same vehicle as the one previously used for the chassis dynamometer test and the on-road driving test. The on-board measurement system including PEMS (Potable Emission Measurement System) installed in the vehicle is also the same equipment as that used for the on-road driving test.

NExBTL is used as fuel, but waste cooking oil BDF is not used this time in the cold-start driving test.

The test was going to be conducted in the middle of Mach, 2011. The route was designed to pass through a mountain area in Nikko-city, Tochigi Prefecture. However, the Great East Japan Earthquake in March 11th destroyed a large part of the major roads in the northern areas. The Tohoku Expressway was also cut off, and thus it was impossible to reach Nikko-city from downtown Tokyo. To make matters worse, the quake and tsunami caused a serious nuclear accident at Fukushima No. 1 nuclear power plant, and thus Japan faced power shortages and Tokyo Electric Power rationed electricity with rolling blackouts in parts of Tokyo.

For this reason, the cold climate test was postponed until the end of March and the route was changed to pass through a mountain area in Minakami-city, Gunma Prefecture.

The driving route was located in Minakami-city, around 450 meters above sea level, and the test was conducted in a temperature of -5 degree Celsius in cloudy weather. The test vehicle was not warmed up and driving was started with a cold-start, and then logged 29.5 km in the mountain area. Fig. 8-1 shows the map of the cold start driving test route.

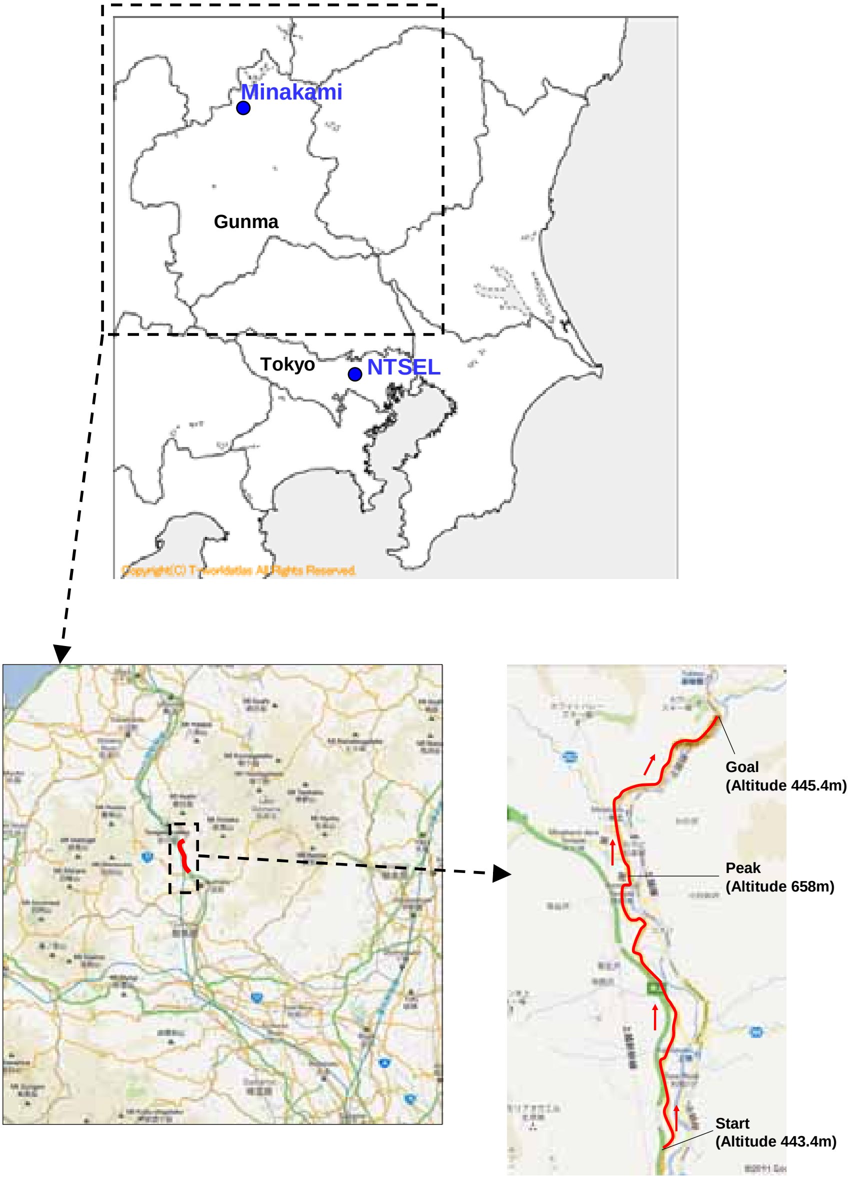


Figure 8-1 Map of the cold start driving test route (red line: test route)

8.3. Test results

(1) Engine start performance

Fig. 8-2 shows the history of engine speed and coolant temperature at the timing of engine start. Coolant temperature was measured in the middle of the hose connecting the radiator and the engine. At the start of the cold start engine test, coolant temperature is almost -0.7 degree C. Cranking time of the test vehicle is less than 2 seconds. This engine start performance fueled with NExBTL under the cold start condition was same as that when using normal diesel fuel under the hot start condition.

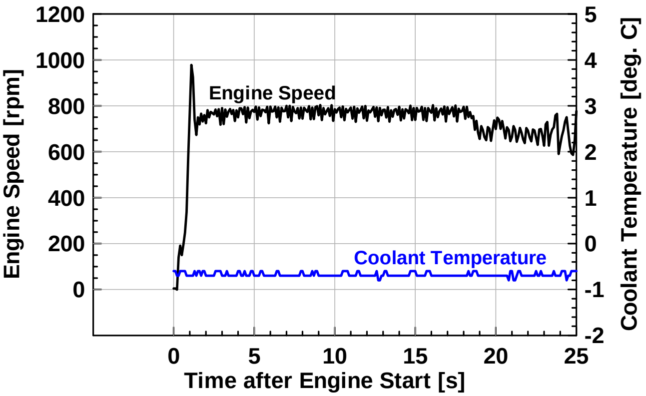


Figure 8-2 History of engine speed and coolant temperature at the time of engine start

(2) Emission performance in the cold start driving test

Fig. 8-3 shows the vehicle speed, engine speed, engine torque, coolant temperature, CO, CO_2 and NOx emissions per unit time at the beginning of the driving test. CO emissions achieved a peak at the starting time, because the coolant temperature was low and the after treatment system was not warmed up enough. However, even in the condition that the coolant temperature did not fully increase, CO emissions decreased from around 100 s.

Fig. 8-4 shows the history of before and after warm-up was completed and coolant temperature increased. It was clear that the CO, CO_2 and NOx emission characteristics did not largely change before and after the increase in coolant temperature. In summing up the results, the characteristic of exhaust gas after 100s is linked to the change of engine speed and engine torque. It does not depend on the conditions of vehicle and engine warm-up.

In actual operation, the engine started smoothly even in an ambient temperature of -5 degree Celsius, and the driving performance was not affected by this temperature.

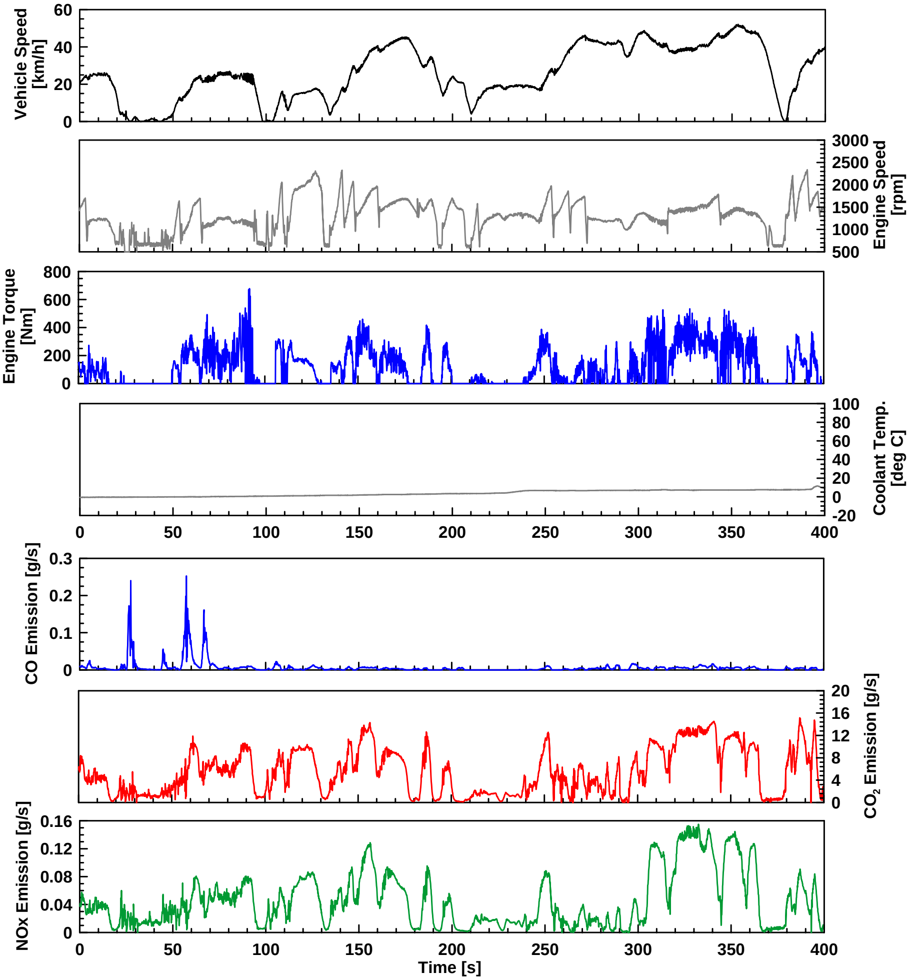


Figure 8-3 Vehicle speed, engine speed, engine torque, coolant temperature, and CO, CO_2, and NOx emissions at the beginning of the cold-start driving test

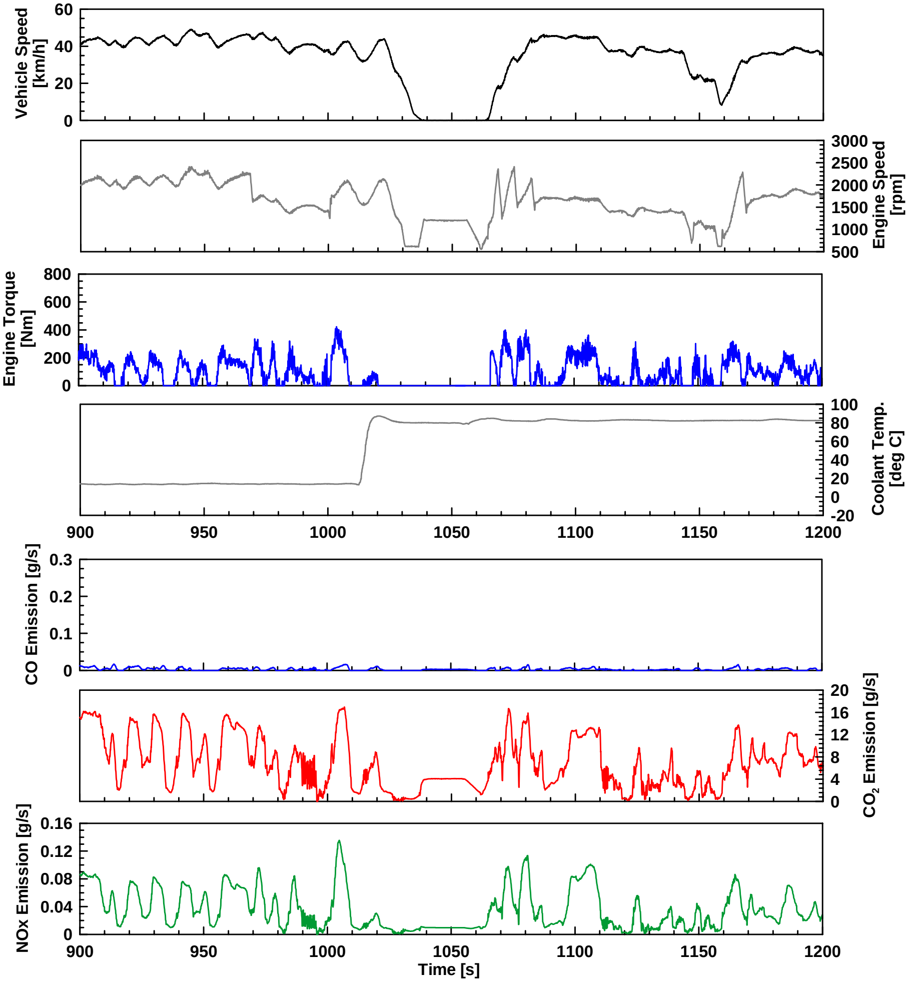


Figure 8-4 Histories of vehicle speed, engine speed, engine torque, coolant temperature, CO emission, CO_2 emission and NOx emission before and after warm-up was completed

Table 8-1 shows the overall route results. THC was almost zero emission, while it was not indicated in this table. From these results, it is clear that the exhaust gas level is almost the same as that of operation in urban areas as mentioned in previous chapters.

Table 8-1 Overall results of cold start driving test

CO emission ratio [g/kWh]	0.012
CO_2 emission ratio [g/kWh]	758.66
NOx emission ratio [g/kWh]	4.52
Route-averaged CO emission [g/km]	0.0074
Route-averaged CO_2 emission [g/km]	463.11
Route-averaged NOx emission [g/km]	2.76
Fuel economy [km/L]	5.22

8.4. Summary of this chapter

The following results were obtained by conducting the on-road driving test in a cold climate. When NExBTL was used for the diesel freight vehicle meeting the 2005 regulations, the low ambient temperature did not affect the engine starting performance and the driving performance. Moreover, the result of exhaust gas performance had results equivalent to those of the operation in the urban area.

This study shows that HVO Fuel such as NExBTL can be used as an alternative to diesel fuel even under severe environmental conditions.

9. Conclusions

This Annex focuses on the latest diesel vehicles that meet the latest emission regulations. Diesel vehicles in this Annex are not given any special customization, but adopted BDF and HVO as fuel, and the influence of these fuels on the exhaust gas performance and fuel consumption of these diesel vehicles under actual use conditions was examined.

The diesel vehicle was set on a chassis dynamometer, and then both performance of exhaust gas and fuel economy were investigated by operating a Japanese driving cycle. At the same time, an on-road driving test was also conducted using PEMS (Portable Emission Measurement System) in order to investigate the influence of the use of BDF and HVO on both performances of exhaust gas and fuel consumption.

In addition to these vehicle tests, engine tests were also conducted, so that the change of fuel characteristics in using BDF and HVO was examined.

9.1. Results of engine tests

When the engine was operated using waste edible oil-based BDF (FAME), NOx emissions increased compared with the operation when using only light oil. On the other hand, NExBTL as one of the HVOs can control NOx emissions more easily than BDF, and thus it maintained almost the same emission level with light oil. It is considered that one of the factors of this result is that a high cetane number would shorten the ignition delay of the fuel and reduce the rate of premixed combustion in the early stage of combustion, which is prone to produce NOx.

9.2. Results of vehicle tests

In operating the vehicle with the mixed fuel of BDF and diesel fuel, as shown in the results of the test on a chassis dynamometer, NOx emissions increased in accordance with an increase of BDF rate. On the other hand, when the mixed fuel of NExBTL and diesel fuel was used, an increase of NOx emissions was not seen. Fuel economy performance was not affected by either fuels.

Even the on-road driving tests following the route that starts and finishes at NTSEL had the same tendency. Namely, the mixed fuel of BDF increased NOx emissions, while that of NExBTL could inhibit an increase of NOx emissions.

Moreover, eco-driving was conducted for each fuel during on-road driving, and the CO_2 emissions reduction effect was examined. The result indicated that both BDF and NExBTL had an equivalent CO_2 reduction effect on diesel fuel by eco-driving. The mechanism of CO_2 reduction by eco-driving is assumed to be due to the area and frequency of use of the engine.

In addition, a cold climate test, that is, a cold start test, using NExBTL was also conducted in a temperature of -5 degrees Celsius. It was clear that the vehicle was operated smoothly during the period of engine starting to an increase in engine coolant temperature, and NExBTL had the equivalent cold startability as diesel fuel.

10. References

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