FY2003 Fact-Finding Survey concerning Exhaust Gases of New Fuels

Report on Results of Testing

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National Traffic Safety and Environment Laboratory
(Independent Administrative Institution)

Contents

Exhaust gas tests using biodiesel fuel in conventional vehicles

1. Purpose of tests

There has been a serious problem with atmospheric pollution for several years, and countermeasures are required. One urgent topic is preventing global warming by suppressing emissions by the transportation sector, particularly emissions of carbon dioxide (hereinafter referred to as "CO2") by automobiles. One of the potential ways to achieve this is for automobiles to use biomass fuels, which are carbon-neutral fuels derived from plants, and this approach is being tried around the world. However, it is still not clear what the influence and effects on the environment will be when these sorts of new fuels are used in automobiles, and the practicability and applicability of bio-ester fuels to diesel vehicles is also unclear.

Given these circumstances, these tests have been conducted for the purpose of quantitatively and systematically identifying the effects on automobile exhaust gases of biofuel in comparison with ordinary diesel fuel, examining the issue from the viewpoint of evaluating the impact on the environment envisaged if biofuels were to be utilized for diesel vehicles, which are particularly subject to the need for urgent action to prevent urban atmospheric pollution.

Since biodiesel fuel is expected to become a practicable proposition and capture a certain share of the market, there is a need for fact-finding surveys to be conducted in advance to analyze the effects on exhaust gas if this sort of fuel is used without change in existing diesel-powered automobiles in the context of fuel properties, and to further examine motive power performance, fuel economy, and other issues affecting practicality as an automobile fuel.

Biodiesel fuel (BDF) is a generic term for many different types of fuels under investigation around the world, and the properties of such fuels are expected to vary greatly in accordance with the feedstock selected and the method of manufacture. For the purposes of the current survey, it was decided to use a fatty acid methyl ester fuel based on vegetable oil, which has a good probability of coming into general use at some point in the future. The specific fuel selected was one type of rapeseed oil methyl ester (RME) fuel that meets EU standards, and the tests were conducted with three different diesel trucks on a chassis dynamometer, conducting an overall evaluation of the effects on exhaust gases etc. with the objective of obtaining data for use as reference when planning the introduction and widespread utilization of such fuels.

2. Testing methods

2.1 Fuel used in testing

For the biodiesel fuel exhaust gas testing, three types of diesel truck were supplied with RME fuel compliant with EU standards and subjected to exhaust gas testing on a chassis dynamometer. Tests were conducted with blends of biodiesel fuel and diesel fuel mixed in a range of different proportions. Blends of 0%, 5%, 20%, 50% and 100% were tested, and the diesel fuel used for blending was specially ordered for the purposes of these tests, having a sulfur content not exceeding 10 ppm. The results of analyzing the properties of the biodiesel fuel and diesel fuel used in the test are shown in Table 1-1. The diesel fuel specifications were chosen because Japan plans to introduce low-sulfur diesel fuel with sulfur content not exceeding 10 ppm in 2005, making it available nationwide by 2007.

The RME used was a fatty acid methyl ester (FAME), a type of vegetable oil methyl ester (VOME), and a batch of the fuel manufactured in France to EU standards was purchased for the purposes of testing with the three trucks.

2.2 Vehicles used in testing

The three vehicles used in testing were two-ton load diesel trucks with specifications as shown in Table 1-2, and chassis dynamometer exhaust gas testing was conducted using the testing facilities shown in Figure 1-1.

Vehicle A, shown in photographs in Figure 1-2 to Figure 1-4, is compliant with Japan's 1998 exhaust gas regulations (long-term restrictions), using individual injector pumps and an exhaust gas recirculation (hereinafter referred to as "EGR") unit to counter oxides of nitrogen (hereinafter referred to as "NOx"). However it does not have an aftertreatment device fitted as standard.

Vehicle B, shown in photographs in Figure 1-5 and Figure 1-6, is a truck having a common-rail diesel engine compliant with Japan's 2003 exhaust gas regulations (new short-term restrictions). In addition to being fitted with an EGR unit to reduce NOx, exhaust gas countermeasures include standard fitment of an oxidation catalyst unit in the engine's exhaust system, primarily to reduce emissions of particulate matter (hereinafter referred to as "PM"). In order to prevent reactions from producing sulfates from the sulfur content of the diesel fuel, the catalyst used is a unit with weak oxidation performance (hereinafter referred to as a "weak-oxidation catalyst"). The

catalyst carrier is a cordierite honeycomb with a cell density of 400 cel/in2, sized 7.5 (dia.) x 7 inches, giving a catalyst volume of 5 liters, and supporting a platinum catalyst.

Vehicle C also has a common-rail diesel engine compliant with Japan's 2003 exhaust gas regulations (new short-term restrictions), and in addition to turbocharging and an EGR unit, its exhaust system is also fitted as standard with an oxidation catalyst DPF unit (CDPF: catalyzed diesel particulate filter) designed for continuous regeneration (hereinafter referred to as "oxidation catalyst DPF").

2.3 Aftertreatment devices

One of the objectives of the current survey was to discover what influence and effects the sort of oxidation catalyst unit or oxidation catalyst DPF unit likely to be marketed would have on exhaust gas when biodiesel fuel is used. The vehicle compliant with the long-term restrictions, Vehicle A, was not fitted with an aftertreatment device from the start, so additional tests were performed with a commercially-available retrofit DPF unit (this device is hereinafter referred to as "oxidation catalyst", since it had a strong oxidation-catalyst design) for comparison with the emissions when tested without an oxidation catalyst.

With Vehicle B, which was fitted with a catalyst unit (weak-oxidation catalyst: Figure 1-7) as standard equipment, tests were conducted with the catalyst removed (replaced with a dummy catalyst), and with the catalyst replaced with a catalyst having enhanced oxidation performance (strong-oxidation catalyst) as shown in Figure 1-8 to compare these situations with the properties of the exhaust gas using the catalyst originally fitted to the vehicle. To examine the effect on gas emissions of utilizing biodiesel fuel in this sort of commercially-available vehicle, it is arguable that all that is required is to evaluate a standard vehicle with standard catalyst unit conditions, but for the purposes of the current survey, it was considered important to first identify the products of biodiesel fuel combustion in the engine, and then use aftertreatment devices to investigate points such as reduction effectiveness and secondary effects. In particular, the reason why a catalyst with enhanced oxidation performance was made available for the Vehicle B test was that sulfur content in diesel fuel will start being reduced to a maximum of 10 ppm in 2005, which will suppress the production of sulfates. Consequently, it may be possible to increase the purification capacity of the catalyst unit and reduce the level of harmful substances and PM in the exhaust when mixtures of biodiesel fuel and diesel fuel are used. One objective of the survey is to examine the extent to which this is possible. The strong-oxidation catalyst fabricated

for the test was designed with specifications for volume, cell density, etc. virtually identical to those of the catalyst unit fitted as standard in order to eliminate influences due to a change in back pressure. For the tests without a catalyst unit, a dummy catalyst unit (one with no catalyst component on the carrier) with the same carrier structure as the strong-oxidation catalyst was used in order to ensure that back pressure conditions were as close as possible to those when a catalyst is used. Figure 1-9 shows the insides of the strong-oxidation catalyst and the dummy catalyst. Figure 1-10 shows the catalyst container that is used to house the catalyst. As shown in Figure 1-11, when a replacement catalyst has been fitted into the container, flanged connecting parts are fitted upstream and downstream of the catalyst, and the assembly is then incorporated into the exhaust system, installing it into the underfloor space used for the standard catalyst as shown in Figure 1-12. Since the shape is not identical to that of the manufacturer's standard catalyst unit, it is considered possible that there are some minute influences in the engine's EGR characteristics due to the effect of exhaust pressure, etc.

Vehicle C, shown in photographs in Figure 1-13 and Figure 1-14, is fitted with an oxidation catalyst DPF unit (Figure 1-15) having an automatic regeneration mechanism. The vehicle's ECU (electronic control unit) calculates the amount of PM accumulated in the oxidation catalyst DPF on the basis of the way the vehicle has been driven, etc., and changes the fuel injection pattern to switch into automatic regeneration mode when appropriate. In this mode, at low vehicle speeds when the oxidation catalyst DPF temperature does not rise, the injection timing is delayed to increase the proportion of flammable components in the exhaust and thereby raise the oxidation catalyst DPF temperature. Because it has this sort of advanced electronic control, Vehicle C is difficult to drive with the oxidation catalyst DPF functions disabled, so tests were only performed in its normal configuration with an oxidation catalyst DPF. Note that with Vehicle C, when the fuel was changed to biodiesel fuel, the ECU still used the same computation pattern for switching into automatic regeneration mode as it uses for diesel fuel.

2.4 Outline of testing and instrumentation facilities

The exhaust gas testing was conducted using a DC chassis dynamometer (mechanical inertia system enabling up to 5,560 kg inertia weight equivalent) with specifications as shown in Table 1-3. For steady-state testing, the chassis dynamometer was controlled to maintain a constant speed, and then the accelerator pedal adjusted so that the torque produced by the engine matched the rated value. For transient mode testing

like that in JE05 mode, the travel resistance of the chassis dynamometer was controlled, then the inertia was allowed to act on the vehicle in half-loaded state. Figure 1-16 shows how the chassis dynamometer control unit was operated.

For the exhaust gas testing, amounts of emissions of carbon monoxide (hereinafter referred to as "CO"), hydrocarbons (hereinafter referred to as "HC"), NOx and CO2, and particulates (PM) were all measured in accordance with the testing method procedures, and in addition, measurements were simultaneously made of the amounts of emissions of principal volatile organic compounds (VOCs) and aldehydes, which are nonregulated harmful substances. In the tests, all the exhaust gas emerging from each test vehicle's tailpipe, as shown in Figure 1-17, was introduced to a dilution tunnel. There, the exhaust gas was uniformly diluted with air, and part was sampled by suctioning off at a constant flow. The samples thus obtained were analyzed. Table 1-4 shows the specifications for the full dilution tunnel, and Figure 1-18 shows the full dilution tunnel used for exhaust gas and PM measurement together with part of the PM collection filter.

The volumes of emissions of CO and NOx (regulated substances) and of CO2 were measured by taking part of the diluted exhaust gas into a sample bag at constant flow, then analyzing the average diluted gas density with the exhaust gas analyzer system shown in Figure 1-19. The results from the analyzer were then converted to give the volumes of emissions. HC measurements were made by continuous analysis of the diluted gas density.

Figure 1-20 shows the weight of the PM collection filter being measured. The PM collected in the filter during mode operation is measured by accurately weighing the filter before and after the test to determine the difference in weight. In addition to calculating the total weight of PM in the exhaust gas, the proportions by weight of the soluble organic fraction (hereinafter referred to as "SOF") and the insoluble organic fraction (hereinafter referred to as "ISOF") in the collected PM were measured through separation.

2.5 Methods for measuring nonregulated harmful substances
The harmful substances not covered by regulations for which emissions were measured were aldehydes and some volatile organic compounds in the exhaust gas, specifically 1,3-butadiene, benzene, toluene, ethylbenzene, styrene, and M&P-xylene (hereinafter referred to collectively as "VOCs").

The nonregulated substances being analyzed include some substances that are readily soluble in flocculated water, so in order that measurement errors were not produced by water condensation, the negative-pressure gas sampling line was kept heated to 120°C. Figure 1-21 shows how the collection apparatus for nonregulated substances was installed.

For the measurement of VOCs in the exhaust gas, part of the gas that had been uniformly diluted by the tunnel was collected in a tetra bag container by constant flow suction, then, as shown in Figure 1-22, was analyzed by introduction into an automatic gas chromatograph immediately after the test. The 1,3-butadiene, which is a low boiling point component, was separated with a PLOT column, and the other components were separated using a cross-linked methyl silicone capillary column, then quantities were determined using an FID or MS unit. Because of the characteristics of the apparatus used, the lower limit of analysis for each component that could be determined by the FID was 20 ppbC.

For the aldehydes in the exhaust gas, part of the gas uniformly diluted in the dilution tunnel was sampled by constant flow suction into a special cartridge (a silica gel cartridge impregnated with acidified 2,4-DNPH). The aldehydes collected were separated in a high-performance liquid chromatograph and the quantity determined by ultraviolet absorption. Four different types of aldehydes were analyzed -- formaldehyde, acetaldehyde, acrolein, and benzaldehyde. Figure 1-23 shows the pattern of the gas channels inside the aldehyde collection unit. Figure 1-24 shows the aldehydes being extracted from the specimens collected.

The noise level N was obtained, and S/N 10 was taken as the bottom limit for quantification of each of the components introduced into the HPLC and MS units. The separation and measurement of proportions by weight of SOF and ISOF in PM were handled as shown in Figure 1-25 by first calculating the amount of PM emissions from the difference in weights (as measured by precision electronic scales) of the filter before and after conducting the test using the method specified for the current test. Next, accelerated solvent extraction (ASE) was used to extract the SOF, utilizing a dichloromethane extraction solvent. The filter was weighed again after extraction to obtain the weight of the SOF from the difference in filter weight. Because all the fuels used in the current tests had extremely low sulfur content, and it is considered that there were virtually no sulfate emissions, the weight of the ISOF obtained by subtracting the weight of the SOF from the total PM weight was very close to the weight of soot. The total mode emissions for each of the components examined were

then calculated from the amounts of samples collected and the sampling gas flows in the sampling methods described above, together with the total volume of diluted gas. Figure 1-26 shows the setup of the accelerated solvent extraction apparatus used for extracting the SOF from the PM.

Gas chromatography was used to analyze the components of the SOF extracted by the method described above, and of the diesel fuel and biodiesel fuel. Table 1-5 shows the conditions applying for the analysis by gas chromatograph.

2.6 Fuel blending method

In order to ensure that the fuel matched the specified blending conditions, biodiesel fuel and diesel fuel volumes were weighed so as to achieve the target blend ratios (0% (diesel fuel only), 5%, 20%, 50% and 100% biodiesel fuel volume-by-volume) and then mixed by agitation. Figure 1-27 shows the job of blending the fuels tested. The fuels made in this way were used to fill a special tank (Figure 1-28) installed on the load bed of the test vehicle, and fed from the tank to the engine. When performing a test after changing the fuel, the fuel tank and fuel piping lines were sufficiently flushed before conducting the test in order to ensure that no influence remained from the fuel used in the previous test.

2.7 Testing modes

The driving modes used for biodiesel fuel exhaust gas testing covered two different driving conditions, the JE05 transient mode, and a congested traffic mode. The speed point pattern for the JE05 mode, which represents typical driving for a heavy vehicle in Tokyo, is shown in Figure 1-29, and the pattern for the congested traffic mode utilized in the current test is shown in Figure 1-30. Tests were also conducted under steady-state conditions. The load on the engine was varied in three stages (light load, medium load, heavy load) and engine speed was also varied in three stages (low speed, medium speed, high speed), giving a total of 9 different sets of conditions for steady-state operation.

The JE05 driving mode utilized for the current chassis dynamometer tests for biodiesel fuel is a vehicle speed pattern for engine bench tests designed for use with new long-term regulations that apply from 2005. In order to determine an engine's operating domain in accordance with the procedure for JE05 mode testing specified by the Ministry of the Environment, the shift points for the vehicle under test need to be calculated using a special conversion algorithm. This method utilizes information such as the vehicle speed data for the mode, the vehicle structure information (vehicle

weight, gear ratios, final gear ratio, tire radius, etc.), the engine's maximum torque curve, and the engine speed at maximum output, computing gear choice and shift points during the cycle using a decision algorithm that simulates the driving of a skilled driver.

3. Results of measuring exhaust gas when using biodiesel fuel

3.1 CO, HC, NOx emission characteristics

The results of measuring emissions of the regulated harmful substances CO, HC, NOx when using biodiesel fuel blend fuels are shown below in order for Vehicles A to C. The individual measurement results are compared according to the biodiesel fuel blending conditions, according to whether or not an oxidation catalyst or other aftertreatment device is used, and if used, according to the type of aftertreatment device.

1) CO, HC, NOx measurement results for Vehicle A

Figure 2-1-1 shows the relationship between biodiesel fuel blend ratio and total CO, HC, NOx emissions (emissions per vehicle kilometer g/km and emissions factor g/kWh) for Vehicle A driven in JE05 mode from a hot start. The figure compares the results for emissions with an oxidation catalyst DPF unit installed and for emissions without a catalyst.

When there was no oxidation catalyst, a tendency for CO emissions to increase was observed when using BDF 100%, but with other fuel blend ratios, the biodiesel fuel blend ratio did not have any particular effect. In contrast, CO emissions were substantially decreased when the oxidation catalyst was installed.

For HC, with no oxidation catalyst, the maximum level observed was with BDF 5%. If anything, the level of HC emissions declined with an increase in biodiesel fuel blend ratio. It is considered likely that some sort of effect on combustion occurs when using biodiesel fuel at a low fuel blend ratio. In contrast, if an oxidation catalyst unit is installed, HC is substantially reduced in the same way as CO, and no effect was observed from changes in biodiesel fuel blend ratio. The reason that CO and HC emissions are reduced in this way is the oxidation catalysis provided by the oxidation catalyst unit.

For NOx, little effect was observed from the biodiesel fuel blend ratio. There were small increases or decreases according to whether or not a catalyst was installed, but

at present, it is not clear whether or not the effect on NOx was due to some sort of reaction at the oxidation catalyst or due to variations in the way the truck was driven, etc.

Since it had been determined that whether or not an oxidation catalyst is installed produced large changes in CO and HC emissions characteristics, the next step was to analyze the CO and HC purification behavior in the oxidation catalyst unit by comparing gas concentrations for both 100% diesel and BDF 50%, sampling continuously and simultaneously upstream and downstream of the oxidation catalyst. The results of measurement are shown in Figure 2-1-2 to Figure 2-1-4. From these results, it was found that the concentrations of CO and HC in the gas leaving the engine are substantially reduced by the oxidation catalyst in virtually all of the sets of conditions. It was thought that this indicates that the catalyst used in these oxidation catalysts has very high oxidation performance. In contrast, observations upstream and downstream of the catalyst did not show much change in NOx concentration, except for a tendency for a very small reduction when idling.

Figure 2-1-5 shows the total emissions of CO, HC, NOx (emissions per vehicle kilometer g/km and emissions factor g/kWh) for driving in JE05 mode from a cold start. For CO, in both the case with an oxidation catalyst and the case without an oxidation catalyst, a tendency for emissions to increase slightly was seen as biodiesel fuel concentration rose. In addition, with the oxidation catalyst, there was a tendency for the rate of CO purification to be slightly lower than with a hot start. For HC, there was a slight decrease when BDF 100% was used without the oxidation catalyst, but in contrast, HC increased when BDF 100% was used with the oxidation catalyst.

For NOx, with both BDF 50% and BDF 100%, there was a slight increase in emission levels relative to those with 100% diesel

Figure 2-1-6 shows the results of measurements of total CO, HC, and NOx (emissions per vehicle kilometer g/km and emissions factor g/kWh) when driving in congested traffic mode from a hot start. For CO, a tendency was observed for levels to increase slightly with the rise in the biodiesel fuel blend ratio, both with and without the oxidation catalyst. However, in congested traffic mode the CO purification performance due to the oxidation catalyst declined, and the purification rate fell below 50%.

In congested traffic mode, HC levels increased with an oxidation catalyst when the biodiesel fuel blend ratio was 5%, but this was the same tendency as observed in JE05

hot start mode. That is to say, this tendency indicates the possibility that using a low blend ratio of biodiesel fuel exerts some form of influence on combustion. With the oxidation catalyst, HC levels are still substantially reduced in low speed congested traffic mode, which is a different tendency from that observed for CO. It was thought likely that the cause is that the properties of HCs make them easier than CO for the catalyst to break down.

For NOx levels in congested traffic mode, no particular tendencies were observed in relation to biodiesel fuel blend ratio or whether or not the oxidation catalyst was installed.

Figure 2-1-7 shows the CO, HC, NOx, and CO2 emissions factors (g/kWh) for steady-state tests when the oxidation catalyst is not fitted, with the tests being conducted for the different conditions. Figure 2-1-8 shows the equivalent steady-state test results with the oxidation catalyst installed. Characteristics indicated by a comparison of the results in these two figures are that levels of CO and HC are substantially reduced by this oxidation catalyst with all fuel blend ratios, and that the emissions factor per unit work for CO and HC is extremely high when driven under low loads.

Figure 2-1-9 and Figure 2-1-10 show the amounts of emissions per unit time (g/h) resulting from steady-state testing under the same conditions. Examined in terms of emissions per hour, it can be seen that emissions of each substance increase as engine speeds rise when the oxidation catalyst is not used, and that there is a large amount of NOx at high loads. In contrast, under steady state testing, installation of the oxidation catalyst produces substantial declines in CO, HC in each of the sets of conditions.

2) CO, HC, NOx measurement results for Vehicle B

Figure 2-2-1 shows the relationship between biodiesel fuel blend ratio and total CO, HC, NOx emissions (emissions per vehicle kilometer g/km and emissions factor g/kWh) for Vehicle B driven in JE05 mode from a hot start. The figure compares the results for emissions without a catalyst (dummy catalyst installed), with a weak-oxidation catalyst installed, and with a strong-oxidation catalyst installed.

For CO, with the dummy catalyst and with the weak-oxidation catalyst, a tendency to produce an increase in emissions was seen with high concentration biodiesel fuel. With the dummy catalyst, the gas is effectively emitted directly from the engine, and in these circumstances, the rise in CO with increasing biodiesel fuel blend ratio is

thought to be due to the biodiesel fuel being more viscous than diesel fuel, which means that the fuel particles sprayed from the injector nozzles in the common rail system are larger than those of diesel fuel, so that when the spray is combusted, the surrounding oxygen cannot be used efficiently.

With the weak-oxidation catalyst, CO levels are actually elevated over those with the dummy catalyst. This is thought to be because a weak-oxidation catalyst has a relatively low capacity for oxidizing CO, and when the HC components are broken down by the catalyst, new CO is produced as an intermediate product of the reaction. In comparison, when a strong-oxidation catalyst is used, the HC oxidization reaction proceeds to completion to produce H2O and CO2, and the incoming CO is also efficiently purified by the catalyst, resulting in post-catalyst CO emissions being kept to extremely low levels.

For HC, with the dummy catalyst and the weak-oxidation catalyst, emissions decline with an increase in biodiesel fuel blend ratio. Since the amount of HC emissions is lower with the weak-oxidation catalyst than with the dummy catalyst, it is thought that the HC is being broken down by the catalyst, which leads to an increase in CO. With the strong-oxidation catalyst, HC levels are substantially reduced just like CO levels, and very little influence is seen from differences in biodiesel fuel blend ratio. This trend with CO and HC emissions appears to demonstrate the importance of incorporating a catalyst with high oxidation performance when using biodiesel fuel.

For NOx, a small increase in NOx emissions was seen with increasing biodiesel fuel blend ratio regardless of the catalyst.

For Vehicle B too, the extent to which CO and HC concentration levels in the exhaust gas change upstream and downstream of the catalyst in accordance with the oxidation performance of the catalyst was investigated. The results of simultaneous continuous measurement of gas concentrations upstream and downstream of the catalyst are shown in Figure 2-2-2 to Figure 2-2-7. From Figure 2-2-2, it can be seen that with the weak-oxidation catalyst, for both diesel fuel and BDF 50%, there was a slightly higher concentration of CO at the catalyst outlet than at the catalyst inlet, and there was a particularly noticeable trend for CO to increase in the high speed section in the second half of the mode cycle when the space velocity of the catalyst is higher. In other words, decomposition of the HC components by the weak-oxidation catalyst progresses less well as the flow of gas increases. This provides evidence to back the assumption stated above that new CO was being produced as an intermediate product. Moreover, from the

results of Figure 2-2-3, it can be seen that the HC is broken down to some extent by the weak-oxidation catalyst. The results in Figure 2-2-4 show that NOx levels are hardly changed at all by passing through the weak-oxidation catalyst. In contrast, the results in Figure 2-2-5 and Figure 2-2-6 show that substantial portions of both CO and HC are purified with the strong-oxidation catalyst. For NOx, as can be seen from Figure 2-2-7, there are some driving conditions where the NOx level is very slightly increased by the catalyst.

Figure 2-2-8 shows the total emissions of CO, HC, NOx (emissions per vehicle kilometer g/km and emissions factor g/kWh) for driving in JE05 mode from a cold start. For CO, in both the case without a catalyst (dummy catalyst) and the case with a weak-oxidation catalyst, a growing tendency to produce an increase in emissions was seen as biodiesel fuel concentration rose. In addition, with the weak-oxidation catalyst, there was a tendency for CO emissions to increase over the levels with the dummy catalyst, similarly to the situation with a hot start. In contrast, for HC, there was an increase with the weak-oxidation catalyst when diesel fuel 100% was used, but it is thought likely that this result was due to something unusual happening with the combustion in the engine in that particular test. In all other tests, HC levels were reduced, even with the weak-oxidation catalyst. In contrast, when driving with a strong-oxidation catalyst installed, both CO and HC components were substantially reduced, and there was no longer any influence from the type of fuel. For NOx, with the dummy catalyst and the weak-oxidation catalyst, there was a slight increase with BDF 100%, but that sort of tendency was not observed with the strong-oxidation catalyst.

Figure 2-2-9 shows the results of measurements of total CO, HC, and NOx (emissions per vehicle kilometer g/km and emissions factor g/kWh) when driving in congested traffic mode from a hot start. For CO, a clear trend was observed for an increase in levels with the rise in the biodiesel fuel blend ratio for both the dummy catalyst and the weak-oxidation catalyst. When the strong-oxidation catalyst was used, there was a large reduction in CO levels, but it was still possible to observe a trend for the levels to increase with the rise in the biodiesel fuel blend ratio.

The HC levels when the dummy catalyst was used were highest when the biodiesel fuel blend ratio was 5% and 20%, and were reduced when the ratio was 100%. That is to say, higher levels of HC were emitted from the engine after combustion with fuels having a lower biodiesel fuel concentration (lower biodiesel fuel blend ratio). Since this tendency had also been observed in the results for vehicle A, it indicates the possibility that

using a low blend ratio of biodiesel fuel exerts some form of influence on combustion.

In contrast, when the strong-oxidation catalyst was used, HC levels declined substantially, even in congested traffic mode, showing similar tendencies to CO levels. For NOx, with the strong-oxidation catalyst, a trend was seen for emissions levels to increase slightly with the rise in the biodiesel fuel blend ratio, which indicates the possibility that the powerful oxidation reaction may bring about new NOx generation.

Figure 2-2-10 shows the CO, HC, NOx, and CO2 emissions factors (g/kWh) for steady-state tests using a dummy catalyst (where there is no catalyst), with the tests being conducted for the different fuel types and the different conditions. Figure 2-1-11 shows the equivalent steady-state test results using a weak-oxidation catalyst, and Figure 2-1-12 shows the equivalent test results using a strong-oxidation catalyst. From the test results shown in these figures, it can be seen that the emissions factor per unit work for CO, HC, and CO2 is higher as the load becomes lower at any engine speed, and that although CO levels cannot be adequately reduced with the weak-oxidation catalyst, they are reduced very efficiently with the strong-oxidation catalyst. This tendency is similar to that seen in transient mode driving.

Figure 2-2-13 to Figure 2-2-15 show the amounts of emissions per hour (g/h) for steady-state testing under the same conditions. Examined in terms of emissions per hour, it can be seen that NOx and CO2 emissions increase as engine speeds and loads rise, but that for CO, there are more emissions when loads are lower when using the dummy catalyst and the weak-oxidation catalyst.

3) CO, HC, NOx measurement results for Vehicle C
For Vehicle C, because of issues with the vehicle's control mechanism, it was not possible to drive the vehicle after removing the oxidation catalyst DPF fitted as standard. For this reason, tests were only conducted under conditions with the oxidation catalyst DPF installed.

Figure 2-3-1 shows the relationship between biodiesel fuel blend ratio and total CO, HC, NOx emissions (emissions per vehicle kilometer g/km and emissions factor g/kWh) for Vehicle C driven in JE05 mode from a hot start.

For CO, the levels were extremely low, even lower than for Vehicle B with the strong-oxidation catalyst, so it was determined that the purification performance of the oxidation catalyst DPF in Vehicle C was extremely high. Even so, a tendency for CO

emissions to increase as the biodiesel fuel blend ratio increased was observed. An extremely low result was obtained with BDF 5% for some reason, but since this was a variation in an already low emissions level, it is still unclear whether this was due to a problem with the testing or to other problem.

For HC, emissions are very much lower when using biodiesel blend fuel than with diesel fuel. For NOx, a tendency for NOx emissions to increase with increasing biodiesel fuel blend ratio was observed, but in contrast, the level with 100% diesel was a little on the high side.

Figure 2-3-2 to Figure 2-3-4 show the results of simultaneous continuous measurement of gas concentrations upstream and downstream of the oxidation catalyst DPF in Vehicle C. The results show that both CO and HC levels are very much reduced by the DPF unit. For NOx, there was virtually no change in the levels upstream and downstream of the oxidation catalyst DPF when the vehicle was moving, but a tendency to decline on the outlet side when idling was observed.

Figure 2-3-5 shows the emissions of CO, HC, NOx (emissions per vehicle kilometer g/km and emissions factor g/kWh) for driving in JE05 mode from a cold start. For CO, the levels of emissions were low, similar to those for Vehicle B with a strong -oxidation catalyst, but a tendency to produce an increase in emissions as biodiesel fuel concentration rose was seen. HC emissions levels were also low, similar to those for Vehicle B with a strong-oxidation catalyst. Levels of emissions declined with BDF 50%, but since this was a comparison between already low emissions levels, it thought that this result was within the scope of variation.

For NOx, a tendency for a small rise together with the rise in biodiesel fuel blend ratio was seen, similar to the tendency for a hot start, but it is considered that the biodiesel fuel blend ratio may have exerted some influence on combustion.

Figure 2-3-6 shows the results of measurements of CO, HC, and NOx (emissions per vehicle kilometer g/km and emissions factor g/kWh) when driving in congested traffic mode from a hot start. For this case too, there was a large reduction in CO and HC levels, similar to that for Vehicle B when the strong-oxidation catalyst was used, but the results leave it debatable whether or not biodiesel fuel blend ratio exerts an influence. Looking just at the results, the CO levels were highest when biodiesel fuel blend ratio was 5%, and the HC levels were highest with BDF 20%. For NOx, a trend was seen for emissions levels to increase with the rise in the biodiesel fuel blend ratio,

but this was slightly reduced with BDF 100%.

Figure 2-3-7 shows the CO, HC, NOx, and CO2 emissions factors per unit work for steady-state tests for Vehicle C. Figure 2-3-8 shows the emissions factor per unit time. A tendency for HC levels to increase when using biodiesel fuel with a high blend ratio was observed at low speed with high load, but in other conditions, no particular tendencies relating to biodiesel fuel were observed.

4) Summary and discussion of CO, HC, NOx emission characteristics when using biodiesel fuel

The test results for CO, HC, NOx up to this point are summarized and discussed below.

(1) The level of CO included in exhaust gas immediately after leaving the engine (gas upstream of the aftertreatment device) tends to increase as biodiesel fuel blend ratio rises. The reason for this is thought to be that the biodiesel fuel is more viscous than diesel fuel, which means that the fuel particles sprayed from the injector nozzles in the common rail system are larger and more tightly packed than those of diesel fuel, so that when the spray is combusted, the air introduced to the combustion chamber is insufficient for the diesel fuel, and that as a result, this effect is stronger than the effect of having oxygen contained in the fuel itself.

(2) No clear cause-and-effect relationship was observed between the biodiesel fuel blend ratio and the level of HC included in exhaust gas immediately after leaving the engine. That is thought to be because the various HC components have the property of being relatively easy to break down. However, when using fuel with a low blend ratio, such as BDF 5%, there was an increase in the amount of HC. More detailed research is required into the influence on combustion at low blend ratios.

(3) NOx emissions were observed to increase with a rise in biodiesel fuel blend ratio, but it was noted that the relationship between NOx level and biodiesel fuel blend ratio was not necessarily a uniform one. This was thought to be because oxygen in the biodiesel fuel is a factor increasing the NOx level, but at the same time there is an opposing effect produced by a fall in combustion temperature due to a reduction in the amount of heat emitted. No firm conclusion was reached, however.

(4) The CO and HC emission characteristics when using biodiesel fuel vary greatly according to the sort of catalyst unit used in the vehicle's exhaust system. In diesel vehicles where a catalyst with low oxidation performance is used as a sulfate countermeasure, it may be the case that CO is increased by the reaction on the catalyst. In contrast, HC is more easily broken down than CO, so some reduction is seen, even when using a catalyst with low oxidation performance.

(5) When a catalyst with high oxidation performance is used, both CO and HC are

substantially reduced by the catalyst, with the result that their emission characteristics are hardly influenced by the biodiesel fuel blend ratio at all. However, during a cold start, congested traffic, or other conditions where the exhaust gas temperature is low, which lowers catalyst performance, biodiesel fuel can be seen to exert some degree of influence.

(6) Considering that with biodiesel fuel combustion, CO readily increases and HC emissions are present as unburned substances, it was judged that when biodiesel fuel is used as an automobile fuel, it is desirable to also utilize a catalyst with high oxidation performance.

3.2 PM emission characteristics

The results of measurement of total PM emissions when using biodiesel fuel, and the results of analysis of the relative proportions of SOF and ISOF by weight in the PM are shown below in order for Vehicles A to C. Summaries of the results of measurement are shown below for the biodiesel fuel blend ratio and for the presence/type of catalyst unit or oxidation catalyst DPF unit.

1) PM measurement results for Vehicle A

Figure 3-1-1 shows the relationship between biodiesel fuel blend ratio and total PM emissions (emissions per vehicle kilometer g/km and emissions factor g/kWh) together with the proportions of SOF and ISOF for Vehicle A driven in JE05 mode from a hot start. The same figure compares the results for emissions with and without an oxidation catalyst in the form of a retrofitted oxidation catalyst unit.

Without the oxidation catalyst, there was a clear tendency for total PM emissions to rise as biodiesel fuel blend ratio rose. As can be seen from the figure, the cause of the rise in PM levels is a rise in SOF. In contrast, when the oxidation catalyst was fitted, the proportion of SOF in PM was substantially reduced, such that it was no longer possible to observe effects of biodiesel fuel on total PM emissions. This means that when a vehicle such as Vehicle A (compliant with long-term restrictions), which is not fitted as standard with an aftertreatment device such as an oxidation catalyst, is used in unmodified base specifications, using biodiesel fuel would lead to a deterioration in PM emissions performance. To counter that, it is essential to use an oxidation catalyst unit with oxidation capability.

Figure 3-1-2 shows the relationship between biodiesel fuel blend ratio and total PM emissions when driven in JE05 mode from a cold start. Tendencies similar to those in the hot start test in the preceding figure emerged, and it was determined that using

biodiesel fuel without an oxidation catalyst would lead to a deterioration in PM emissions performance. Despite it being said that under cold start conditions, exhaust gas level reduction does not function until the catalyst reaches its active temperature, it was discovered that even under cold start conditions, PM levels were greatly reduced with this oxidation catalyst unit. That is to say, the SOF component in the PM consisted of substances that were relatively easily broken down by the catalyst.

Figure 3-1-3 shows the equivalent measurements in congested traffic mode. When there is no oxidation catalyst unit, it can be seen that deterioration in total PM performance corresponds to the biodiesel fuel blend ratio and SOF increases. In contrast, when an oxidation catalyst is installed, SOF levels are substantially reduced and there is no longer any apparent influence from using biodiesel fuel. These tendencies are identical to those shown in the preceding two figures for JE05 mode with a hot start and cold start.

Figure 3-1-4 shows the relationship between biodiesel fuel blend ratio and PM emissions without an oxidation catalyst for steady-state operation under combinations of three different loads and three different engine speeds. The amounts of emissions are expressed in terms of emissions per unit time. First of all, operating under low load conditions, the proportion of ISOF is low, but the SOF level tends to rise rapidly as the biodiesel fuel blend ratio increases. In contrast, with operation under medium load, as the biodiesel fuel blend ratio rose, ISOF levels declined but SOF levels increased. This tendency was particularly clear at high engine speeds. There was a similar tendency under high load and medium engine speed conditions, but influence of biodiesel fuel blend ratio on total emissions did not stand out under high load and low engine speed conditions. However, under high engine speed and high load conditions, there was a peculiar increase in SOF with BDF 100%. It is not yet clear whether this was due to some influence of the high concentration of biodiesel fuel on combustion, or due to problems in the analysis of SOF.

Figure 3-1-5 shows the results of investigating tendencies for total PM emissions for the same steady-state conditions, but with the oxidation catalyst installed. In the top part of the figure, showing low load operation, the levels of PM emissions are substantially reduced from the levels without the oxidation catalyst. It shows that the oxidation catalyst is particularly effective at purifying SOF. Operating under medium load conditions at low or medium engine speeds, SOF is reduced, but the increase in ISOF produced by combustion as shown in the preceding figure resulted in total PM emissions being higher than when operating under low load conditions. Even in this

case, ISOF production is reduced when the biodiesel fuel blend ratio is high, so there is a fall in total PM levels. That is to say, using both biodiesel fuel and an oxidation catalyst with a catalyst function brings a reduction in PM. At the same time, when operating under medium load at high engine speeds, then there the amount of SOF did not change from the level of Figure 3-1-4, even though there was an oxidation catalyst installed. In sum, the SOF is no longer broken down by the oxidation catalyst. This indicates that the increase in the amount of exhaust gas passing the catalyst at high engine speeds weakens the breakdown of SOF in the oxidation catalyst. When there is a high biodiesel fuel blend ratio, the amount of ISOF produced by combustion is reduced, with the result that total PM emissions are reduced. This is because biodiesel fuel is an oxygen-containing fuel that does not contain aromatics. This sort of tendency also appears under high load and medium engine speed conditions.

Summarizing these results of measuring PM for Vehicle A, under conditions like JE05 or congested traffic mode where there is a high proportion of operation under low load, the amount of SOF generated during combustion increases along with an increase in biodiesel fuel blend ratio, resulting in an increase in total PM emissions. However, when a catalyst unit providing high performance oxidation is also used, SOF is reduced effectively, and for this reason, PM emissions become less liable to being influenced by biodiesel fuel.

These sorts of tendencies are similar to those for steady-state operation under low load conditions. However, under high load operating conditions, when the biodiesel fuel blend ratio is increased, the ISOF produced by the engine is reduced, with the resulting effect being a reduction in PM emissions. Despite this, at high engine speeds, the exhaust gas flow is faster, weakening the functioning of the oxidation catalyst, reducing the SOF-reducing effect.

2) PM measurement results for Vehicle B
Figure 3-2-1 shows the relationship between biodiesel fuel blend ratio and total PM emissions (emissions per vehicle kilometer g/km and emissions factor g/kWh) together with the proportions of SOF and ISOF for Vehicle B driven in JE05 mode from a hot start. The same figure compares the results for emissions with a dummy catalyst, with a weak-oxidation catalyst, and with a strong-oxidation catalyst.

First of all, for the dummy catalyst, SOF increased and ISOF decreased as biodiesel fuel blend ratio rose. This tendency is similar to that observed in the results for vehicle A. With the weak-oxidation catalyst fitted as standard equipment to Vehicle B, it was

possible to achieve substantial reduction in SOF, one of the engine's products of combustion, and this consequently led to a reduction in total PM emissions. With a strong-oxidation catalyst, SOF was also reduced but it was the weak-oxidation catalyst that had higher decomposition performance. In other words, it is not simply the case that raising the oxidation performance of the catalyst increased the capability to break down SOF. On the contrary, it is the weak-oxidation catalyst designed specifically to work for PM and fitted to Vehicle B as standard equipment that provides the most effective PM reduction. However, because of lack of information about the weak-oxidation catalyst in Vehicle B, it is difficult to be certain about what sort of adjustment gives rise to the PM reduction effect.

Figure 3-2-2 shows the relationship between biodiesel fuel blend ratio and total PM emissions (emissions per vehicle kilometer g/km and emissions factor g/kWh) together with the proportions of SOF and ISOF for Vehicle B driven in JE05 mode from a cold start. This cold start test was conducted with fuel conditions of diesel fuel 100% and of biodiesel fuel blend ratio 50% and 100%. The figure shows comparisons of the results with a dummy catalyst, with a weak-oxidation catalyst, and with a strong-oxidation catalyst. An error in the analysis procedure means that there is no data for the case of the dummy catalyst with BDF 50%.

In this cold start test, the emissions levels and exhaust trends were virtually the same as those under hot start conditions in the preceding figure. In other words, when biodiesel fuel with a high blend ratio was used, a large SOF was produced in the engine, but this was efficiently reduced by the weak-oxidation catalyst fitted as standard equipment, with the consequence that total PM emissions was reduced.

Figure 3-2-3 shows the relationship between biodiesel fuel blend ratio and total PM emissions (emissions per vehicle kilometer g/km and emissions factor g/kWh) together with the proportions of SOF and ISOF for Vehicle B driven in congested traffic mode from a hot start. This test was conducted with fuel conditions of diesel fuel 100% and of biodiesel fuel blend ratio 5%, 20%, 50% and 100%. The same figure shows that emissions per vehicle kilometer increase when driven in congested traffic mode. Emissions trends observed include that the ISOF levels produced by combustion fell as biodiesel fuel blend ratio rose, but that SOF levels rose to take their place. However, each of the catalyst units was able to efficiently remove this SOF, so in consequence, the result was that the higher the blend ratio of the biodiesel fuel, the greater the decline in overall PM emissions.

From the measurement results described above, it was discovered that if an effective catalyst unit were used in conjunction when utilizing biodiesel fuel, total PM emissions can be made lower than when diesel fuel is used.

Figure 3-2-4 shows the relationship between biodiesel fuel blend ratio and PM emissions with a dummy catalyst for steady-state operation under combinations of three different loads and three different engine speeds. The amounts of emissions are expressed in terms of emissions per unit time. First of all, operating under low load and low engine speed conditions, the proportion of ISOF is low, but the SOF level tends to rise rapidly as the biodiesel fuel blend ratio increases. However, even when maintaining a low load, the effect of biodiesel fuel blend ratio is lower in medium speed and high speed operation than in low speed operation. In contrast, with operation under medium and high load, there was an increase in ISOF, particularly at high engine speeds, but ISOF levels declined as the biodiesel fuel blend ratio rises. However, the effect of biodiesel fuel blend ratio on SOF was smaller than when operating under low loads.

Figure 3-2-5 shows the relationship between biodiesel fuel blend ratio and PM emissions when Vehicle B is fitted with a weak-oxidation catalyst and tested for steady-state operation under combinations of three different loads and three different engine speeds. Under the low load and medium load conditions, the top row and center row of the figure show that ISOF declines as biodiesel fuel blend ratio rises; consequently resulting in a fall in overall PM emissions. Under the high load conditions shown in the bottom row of the figure, similar results are obtained for ISOF, but the proportion of SOF increases at low and medium engine speeds.

Figure 3-2-6 shows the results for Vehicle B fitted with a strong-oxidation catalyst and tested for steady-state operation under combinations of three different loads and three different engine speeds. The strong-oxidation catalyst produced very similar emission trends to the weak-oxidation catalyst of the preceding figure.

3) PM measurement results for Vehicle C
Figure 3-3-1 shows the relationship between biodiesel fuel blend ratio and total PM emissions (emissions per vehicle kilometer g/km and emissions factor g/kWh) together with the proportions of SOF and ISOF for Vehicle C driven in JE05 mode from a hot start. The figure shows the results for the oxidation catalyst DPF unit installed in Vehicle C. PM emissions levels are lower than the levels for Vehicle A and Vehicle B when fitted with oxidation catalysts. When biodiesel fuel is used, emissions are lower

than for 100% diesel regardless of the blend ratio, but differences in blend ratio do not have such a large influence on PM emissions. Furthermore, for all fuel conditions, PM included more SOF than ISOF.

Figure 3-3-2 shows the PM measurements when driven in JE05 mode from a cold start. Under these conditions, emissions levels are lower than for Vehicle A and Vehicle B. The level of ISOF was higher when using BDF 100%, but the reason for this is unclear. The amount of SOF was slightly low with BDF 50%, but can be said to be virtually the same level. There is not much of a difference between the levels of PM emissions in this test and the levels in the preceding figure when driven from a hot start.

Figure 3-3-3 shows the PM measurements when driven in congested traffic mode. Under these conditions, the ISOF levels were low, with SOF making up the bulk.

Figure 3-3-4 shows the relationship between biodiesel fuel blend ratio and PM emissions for steady-state operation under combinations of three different loads and three different engine speeds. In the figure, the amounts of emissions are expressed in terms of emissions per unit time (g/h). The overall tendency is for PM emissions to fall when biodiesel fuel is utilized, whatever the operating conditions. The principal reason for that is a decline in ISOF levels in the PM. Measurements were not taken for Vehicle C, but it is probably the case that SOF rises at the stage upstream of the oxidation catalyst DPF unit when biodiesel fuel is utilized. However, it is thought that the oxidation reaction due to the oxidation catalyst DPF unit causes a reduction in SOF, reducing total PM emissions. Overall, the amount of SOF in PM downstream of the oxidation catalyst DPF unit was greater with diesel fuel than with biodiesel fuel. The SOF produced in the combustion of biodiesel fuel is thought to be easily broken down by the oxidation catalyst DPF unit.

4) Summary and discussion of PM emission characteristics when using biodiesel fuel
(1) When biodiesel fuel is used, SOF tends to increase, but this can be substantially reduced by an aftertreatment device in the form of an oxidation catalyst unit, oxidation catalyst DPF unit or other unit, making it possible to reduce the total PM emissions level. This of course assumes that the oxidizing power of the catalyst can be sufficiently used. If the oxidizing power is insufficient, this leads to an increase in PM, so it is particularly important to check and manage the performance of the catalyst when biodiesel fuel is being used.
(2) However, there is a trend for the proportion of ISOF in PM to decrease as the

biodiesel fuel blend ratio is raised. This is due to biodiesel fuel being an oxygen-containing fuel, and due to the fact that it does not contain aromatics.

(3) Considering the effect on PM emissions associated with the use of biodiesel fuel, if biodiesel fuel is utilized unchanged in diesel vehicles that do not have aftertreatment, SOF levels are higher than when operated with diesel fuel, which results in an increase in total PM emissions. Special care needs to be taken on this point when operating in-use vehicles with biodiesel fuel.

3.3 Aldehyde emission characteristics

1) Aldehyde measurement results for Vehicle A

Figure 4-1-1 shows the relationship between biodiesel fuel blend ratio and emissions of the different aldehydes (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) for Vehicle A driven in JE05 mode from a hot start. The figure compares the results for emissions with and without an oxidation catalyst in the form of a DPF unit.

From the results in the figure it was determined that of the different aldehydes, there was a lot of formaldehyde, and that there was a tendency for formaldehyde to increase as the biodiesel fuel blend ratio rose when the oxidation catalyst was not used. In contrast, when the oxidation catalyst was used, formaldehyde levels were somewhat reduced, but as described above, the effect was much lower than purification performance with respect to CO and HC. In terms of amounts, acetaldehyde levels were lower than formaldehyde levels, but are very similar in having a tendency to increase as the biodiesel fuel blend ratio rose. Acrolein and benzaldehyde emissions were found when no oxidation catalyst was used, but there were virtually no emissions when the oxidation catalyst was used.

Figure 4-1-2 shows the relationship between biodiesel fuel blend ratio and emissions of the different aldehydes for driving in JE05 mode from a cold start. Whether or not the oxidation catalyst was used, emissions of all aldehydes were slightly increased from the levels for a hot start, but the tendencies observed were similar.

Figure 4-1-3 shows the relationship between biodiesel fuel blend ratio and emissions of the different aldehydes for driving in congested traffic mode from a hot start. Compared with JE05 mode, there is a substantial increase in emissions per vehicle kilometer. The effect of the oxidation catalyst in purifying formaldehyde and acetaldehyde is higher than for JE05 mode. That is to say, purification of aldehydes appears to be affected by the space velocity in the catalyst. The relationship between

biodiesel fuel blend ratio and emissions of the aldehydes emitted is similar to that in JE05 mode.

Figure 4-1-4 shows the relationship between biodiesel fuel blend ratio and the emissions factors for the different aldehydes without the oxidation catalyst for steady-state operation under combinations of three different loads and three different engine speeds. The emissions factors are expressed in terms of per unit work (mg/kWh). There were large emissions of formaldehyde and acetaldehyde under conditions of low engine speed and high load with BDF 50%, but the reason for this is not clear. For other operating conditions, levels were higher under low load. There was also a tendency to emit acrolein and benzaldehyde when under low loads.

Figure 4-1-5 shows the results of investigating the trends for aldehyde emissions when driving under the same steady-state conditions, but fitted with the oxidation catalyst unit. The levels of emissions of each of the aldehydes were substantially reduced by the oxidation catalyst. A tendency for emissions to increase was observed here under low load conditions. As can be seen from Figure 4-1-3, the reason for emissions in congested traffic mode being greater than in JE05 mode may be related to this sort of engine usage.

Figure 4-1-6 and Figure 4-1-7 show the tendencies for aldehyde emissions levels with and without the oxidation catalyst for each of the conditions, expressed in terms of per unit time (mg/h).

2) Aldehyde measurement results for Vehicle B

Figure 4-2-1 shows the relationship between biodiesel fuel blend ratio and emissions of the different aldehydes (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) for Vehicle B driven in JE05 mode from a hot start. The figure compares the results for emissions with a dummy catalyst, with a weak-oxidation catalyst, and with a strong-oxidation catalyst.

For the dummy catalyst, as with Vehicle A, there was a lot of formaldehyde, with the largest amount of emissions being with BDF 50% in particular. In contrast, with the weak-oxidation catalyst, formaldehyde was reduced, but one feature of this case was that acetaldehyde was produced in the catalyst, and that tendency became increasingly noticeable as the biodiesel fuel blend ratio rose. When using the strong-oxidation catalyst, all aldehydes were substantially reduced.

Figure 4-2-2 shows the relationship between biodiesel fuel blend ratio and emissions of the different aldehydes (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) for driving in JE05 mode from a cold start. For the dummy catalyst, there was a lot of formaldehyde, with the amount of formaldehyde produced in the engine using biodiesel fuel being about twice the amount produced with diesel fuel. With the weak-oxidation catalyst, the formaldehyde is reduced, but it is a feature of this case that acetaldehyde was produced in the catalyst, similarly to the situation with a hot start. That tendency became increasingly noticeable as the biodiesel fuel blend ratio rose. When using the strong-oxidation catalyst, all aldehydes were substantially reduced, even with a cold start.

Figure 4-2-3 shows the aldehyde emission characteristics of Vehicle B in congested traffic mode. Driving in congested traffic, there is a substantial increase in emissions per vehicle kilometer. With the dummy catalyst, the most formaldehyde was produced with BDF 50%, and with the weak-oxidation catalyst there was a similar tendency for acetaldehyde to increase in the catalyst. Aldehyde levels were lowest with the strong-oxidation catalyst, but this effect was slightly less than that observed in JE05 mode.

Figure 4-2-4 shows the relationship between biodiesel fuel blend ratio and emissions of the different aldehydes with a dummy catalyst for steady-state operation under combinations of three different loads and three different engine speeds. The emissions factors are expressed in mg/kWh units. No particular noticeable difference between diesel fuel and biodiesel fuel in the production of aldehydes was observed in steady-state operation.

Figure 4-2-5 shows the results of investigating the trends for aldehyde emissions when driving under the same steady-state conditions, but fitted with a weak-oxidation catalyst. The levels of formaldehyde emissions were slightly reduced by the weak-oxidation catalyst, but there was a tendency for a substantial increase of acetaldehydes in their place. Biodiesel fuel produced more emissions of formaldehyde and acetaldehyde than diesel fuel.

Figure 4-2-6 shows the results of investigating the trends for aldehyde emissions when driving under the same steady-state conditions, but fitted with a strong-oxidation catalyst. The levels of formaldehyde emissions were substantially reduced by the strong-oxidation catalyst, to the extent that changes in fuel type had hardly any influence.

Figure 4-2-7 shows the amounts of aldehyde emissions with a dummy catalyst and the same steady-state operation conditions, but expressed in emissions per unit time. When these results are used to examine aldehyde emissions on a per-hour basis, it can be seen that each type of aldehyde is emitted in greater quantities under low load conditions. Under the same low load conditions, it can also be seen that emissions are more readily produced at low engine speeds. In other words, there is a tendency for aldehydes to be produced more readily when combustion proceeds sluggishly and at low temperatures, such as when the load is low or the engine speed is low.

Figure 4-2-8 shows the amounts of aldehyde emissions with a weak-oxidation catalyst and the same steady-state operation conditions, expressed in emissions per unit time. The emissions of formaldehyde and acetaldehyde at low engine speeds increase when under a high load. It is possible that this result is influenced by the reaction characteristics of the weak-oxidation catalyst.

Figure 4-2-9 shows the amounts of aldehyde emissions with a strong-oxidation catalyst and the same steady-state operation conditions, expressed in emissions per unit time. With the strong-oxidation catalyst, the amount of emissions per hour is reduced for all aldehydes.

3) Aldehyde measurement results for Vehicle C
For Vehicle C, because it was not possible to drive the vehicle after removing the oxidation catalyst DPF fitted as standard, tests were only conducted under conditions with the oxidation catalyst DPF installed. Figure 4-3-1 shows the relationship between biodiesel fuel blend ratio and emissions of the different aldehydes (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) for Vehicle C driven in JE05 mode from a hot start.

Since the oxidation catalyst DPF unit fitted as standard to Vehicle C uses a catalyst with high oxidation performance, emission levels of formaldehyde and acetaldehyde are low, similar to Vehicle B when using a strong-oxidation catalyst. Even so, emissions of both these aldehydes increase when biodiesel fuel blend ratio is high, higher than the levels for diesel fuel. Rather than formaldehyde, there is a greater amount of acetaldehyde, which is similar to Vehicle B with a catalyst under similar conditions.

Figure 4-3-2 shows the relationship between biodiesel fuel blend ratio and emissions of the different aldehydes (emissions per vehicle kilometer mg/km and emissions factor

mg/kWh) for driving in JE05 mode from a cold start. Under cold start conditions, it was observed that the oxidation catalyst DPF unit fitted to Vehicle C could not purify properly until the catalyst in it reaches its working temperature, and for this reason, emissions levels of formaldehyde and acetaldehyde are several times higher than for the hot start in the preceding figure. With biodiesel fuel, emissions of both of these aldehydes were higher than when diesel fuel is used. When using biodiesel fuel under cold start conditions, unlike hot start conditions, the level of formaldehyde is greater than the level of acetaldehyde. That is to say, this is thought to be due to the effect of emissions from before the catalyst reaction starts functioning.

Figure 4-3-3 shows the relationship between biodiesel fuel blend ratio and emissions of the different aldehydes (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) for driving in congested traffic mode from a hot start. The tendency for acetaldehyde emissions to exceed formaldehyde emissions is similar to that seen with JE05 mode hot start, and emissions per vehicle kilometer are of a similar level.

Figure 4-3-4 shows the relationship between biodiesel fuel blend ratio and emissions factors of the different aldehydes for Vehicle C with steady-state operation under combinations of three different loads and three different engine speeds. Figure 4-3-5 shows the same comparison in terms of per unit time (mg/h). In this sort of steady-state operation, no particular noticeable difference between diesel fuel and biodiesel fuel in the production of aldehydes was observed in this sort of steady-state operation.

3.4 VOC emission characteristics

1) VOC measurement results for Vehicle A
Figure 5-1-1 shows the relationship between biodiesel fuel blend ratio and emissions of the different VOCs (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) for Vehicle A driven in JE05 mode from a hot start. The figure compares VOC emissions with and without an oxidation catalyst in the form of a DPF unit.

Without the oxidation catalyst, a tendency was observed for emissions of 1,3-butadiene and benzene to increase slightly as biodiesel fuel blend ratio rose. In contrast, when the oxidation catalyst was used, VOCs showed the characteristic of being easier to purify than aldehydes.

Figure 5-1-2 shows the relationship between biodiesel fuel blend ratio and emissions of

the different VOCs in JE05 mode from a cold start. Both with and without the oxidation catalyst, emissions for each of the VOCs were a little larger than the levels for a hot start, but the tendencies for emissions were virtually the same.

Figure 5-1-3 shows the relationship between biodiesel fuel blend ratio and emissions of the different VOCs in congested traffic mode from a hot start. Without the oxidation catalyst, as biodiesel fuel blend ratio rose, a tendency for benzene in particular to increase was observed. In this hot start congested traffic mode, benzene purification performance of the oxidation catalyst was lower than in hot start JE05 mode.

Figure 5-1-4 shows the relationship between biodiesel fuel blend ratio and the emissions factors for the different VOCs for steady-state operation under combinations of three different loads and three different engine speeds, each without the oxidation catalyst. The units used for the emissions factor are mg/kWh. Figure 5-1-5 shows the emissions factors in the same units for the same operating condition, but with the oxidation catalyst installed. It can be seen that VOCs are reduced effectively by the oxidation catalyst.

Figure 5-1-6 and Figure 5-1-7 show tabulations of the emissions factors with and without the oxidation catalyst in terms of per unit time (mg/h) under the same steady-state operation. The influence of biodiesel fuel can be observed in the emissions of benzene and 1,3 butadiene under medium engine speed and medium load conditions.

2) VOC measurement results for Vehicle B
Figure 5-2-1 shows the relationship between biodiesel fuel blend ratio and emissions of the different VOCs (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) for Vehicle B driven in JE05 mode from a hot start. The figure compares the effects on VOC emissions of the dummy catalyst, the weak-oxidation catalyst, and the strong-oxidation catalyst.

One characteristic that stands out is a trend for emissions of 1,3-butadiene and benzene with the weak-oxidation catalyst to be greater than with the dummy catalyst, a situation where there is no catalyst function at all. Since these substances are substantially reduced with the strong-oxidation catalyst, it is considered possible that the weak oxidation reaction had some influence on the production of these substances.

Figure 5-2-2 shows the relationship between biodiesel fuel blend ratio and emissions of the different VOCs in JE05 mode from a cold start. When the weak-oxidation catalyst

27

is used under the cold start conditions, there is a clear trend for an increase in 1,3-butadiene and benzene production compared to that with the dummy catalyst. Furthermore, when utilizing biodiesel fuel, a tendency was observed for emissions of 1,3-butadiene and benzene to be greater than those with diesel fuel.

Figure 5-2-3 shows the relationship between biodiesel fuel blend ratio and emissions of the different VOCs in congested traffic mode from a hot start. Emissions of VOCs per vehicle kilometer are greater than in JE05 mode. When using biodiesel fuel, a tendency for 1,3-butadiene to increase was observed with the weak-oxidation catalyst. Benzene emissions also increased slightly with the weak-oxidation catalyst. With the strong-oxidation catalyst, there was an increase in VOC emissions when biodiesel fuel was used. The influence of biodiesel fuel in comparison to that of diesel fuel was unclear.

Figure 5-2-4 to Figure 5-2-6 show the relationship between biodiesel fuel blend ratio and the emissions factors for the different VOCs for steady-state operation under combinations of three different loads and three different engine speeds, making a comparison for the three different catalyst conditions. The units used for the emissions factor are mg/kWh. A tendency was observed for the VOC emissions factors (mg/kWh) to increase with low engine speed sand low loads.

Figure 5-2-7 to Figure 5-2-9 show tabulations of the correlations between biodiesel fuel blend ratio, catalyst type, and emissions factor for each VOC (mg/h) under the same steady-state operation. There were no particularly outstanding features in the correlation between VOC emissions factor (mg/kWh) and driving conditions.

3) VOC measurement results for Vehicle C

Figure 5-3-1 shows the relationship between biodiesel fuel blend ratio and emissions of the different VOCs (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) when driven in JE05 mode from a hot start for Vehicle C, which is fitted as standard with an oxidation catalyst DPF unit emissions levels are extremely low, and no influence can be seen from the use of biodiesel fuels.

Figure 5-3-2 shows the relationship between biodiesel fuel blend ratio and emissions of the different VOCs (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) for Vehicle C when driven in JE05 mode from a cold start. When Vehicle C's oxidation catalyst DPF is used under the cold start conditions, influence is exerted by the engine characteristics during the time when the catalyst is not actively functioning,

and a tendency was observed for a slight increase in emission levels, and also for greater 1,3-butadiene and benzene production than with diesel fuel.

Figure 5-3-3 shows the relationship between biodiesel fuel blend ratio and emissions of the different VOCs (emissions per vehicle kilometer mg/km and emissions factor mg/kWh) for Vehicle C in congested traffic mode from a hot start. Emissions factors per vehicle kilometer and per unit work had a tendency to increase in congested traffic mode, but because they are measured under hot start conditions the oxidation function of the oxidation catalyst DPF is working, and no influence of the biodiesel fuel was observed.

Figure 5-3-4 shows the relationship between biodiesel fuel blend ratio and the emissions factors (mg/kWh) for the different VOCs for steady-state operation under combinations of three different loads and three different engine speeds. Figure 5-3-5 shows tabulations of the emissions factor per hour (mg/h) for each VOC under the same operating conditions. In each of these sets of results, the oxidation catalyst DPF unit fitted in Vehicle C functioned to provide sufficient purification, and the effects of operating conditions could no longer be observed.

4. Other effects arising from use of biodiesel fuel

4.1 Influence on fuel economy

Figure 6-1 shows the results of measuring fuel economy (km/l) of Vehicles A to C in JE05 mode (hot start, cold start) and congested traffic mode (hot start) for each of the biodiesel fuel blend ratios. Fuel economy was measured using the carbon balance method, calculating the total consumption (l) for each of the fuel blends from the fuel densities and CH ratios for each of the biodiesel fuel blend ratios. Examining the results showed a tendency for fuel economy (km/l) to decrease as biodiesel fuel blend ratio rose. This is probably a manifestation of biodiesel fuel's different calorific value per unit volume. With Vehicle B in congested traffic mode, fuel economy values varied slightly according to catalyst conditions, but it is thought likely that fuel consumption per unit distance was influenced by variations in driving due to the testing being mode-following driving at low vehicle speeds.

4.2 Influence on engine torque

Figure 6-2 shows the results of using a chassis dynamometer to measure maximum driving force produced by Vehicles A to C for each engine speed with diesel fuel 100% and BDF 100%. The maximum driving force under steady-state conditions was very

slightly less for biodiesel fuel than for diesel fuel, but there was not much difference.

Next, in order to investigate the influence on acceleration performance of using biodiesel fuel, Vehicle B was accelerated from approximately 30 km/h to approximately 60 km/h on the chassis dynamometer with the accelerator fully depressed, measuring the average acceleration over the range. In this test, the chassis dynamometer's inertia setting was set to the overall vehicle weight of Vehicle B (with maximum loading weight), with directly gear linkage maintained during acceleration (3rd gear) so that there were no gearshifts during measurement. Heavy weights were also placed on the test vehicle's load platform to prevent the driving wheels from slipping.

The top row of figures in Figure 6-3 show the results of measuring average acceleration in the range from 30 km/h to 60 km/h, measuring acceleration with the accelerator fully depressed for three times for each biodiesel fuel blend ratio. The bottom row of figures compares the average values for each of the three accelerations with the accelerator fully depressed. When the results of the acceleration tests are compared for each fuel type, there are some variations according to way the vehicle was driven, but a small drop in acceleration performance was discovered with a high biodiesel fuel blend ratio of 50% or higher. Unlike the maximum driving force under steady state operation, where there had been very little difference between biodiesel fuel and diesel fuel, performance differences were manifested in transient conditions such as acceleration with the accelerator fully depressed. For this reason, it is likely that biodiesel fuel has factors causing delays (stumbles) in transient operation.

4.3 Influence on state of combustion (measurement of heat release rate)

Figure 6-4 shows a comparison of the results for heat release rate measurement for diesel fuel 100% and BDF 100% measured under steady-state operation by fitting a combustion pressure sensor to Cylinder 1 of Vehicle B. Some small differences were seen in the combustion characteristics of diesel fuel and biodiesel fuel, but it was decided not to examine this in any greater detail in FY2003. The reason for this decision was that it is more usual to conduct combustion analysis of engines by installing an engine by itself on a test bench. The current test was our first attempt at chassis dynamometer testing incorporating combustion pressure sensors and crankshaft angle sensors into an engine actually installed in a vehicle like Vehicle B. There was insufficient examination of variables like combustion pressure and heat release rate that relate to measurement. Consequently, For these reasons, the current survey did not commence analysis of the effects of biodiesel fuel on combustion, and consequently did not reach any conclusions in this area. Analysis of the effects exerted

on combustion by biodiesel fuel should be included in topics for investigation in the next financial year.

4.4 Discussion of PM emission mechanism for biodiesel fuel based on gas chromatography of fuels and PM

Figure 6-5 shows comparisons of PM emissions for Vehicles A to C when driven in JE05 mode with diesel fuel 100%, BDF 50%, and BDF 100%. The amounts of PM emissions for each vehicle differed according to the presence or absence of a catalyst unit or oxidation catalyst DPF, and according to the type of catalyst, but SOF was found to increase as biodiesel fuel blend ratio rises in Vehicle A with no oxidation catalyst, which was not using a catalyst for SOF purification and in Vehicle B when measured with a dummy catalyst. This resulted in a large increase in PM emissions. It was then decided to investigate the reason for the SOF increase when biodiesel fuel is used as a fuel. In order to do that, in addition to performing composition analysis of the diesel fuel and biodiesel fuel, composition analysis was also performed on the SOF included in the exhaust gas of Vehicle A when run without an oxidation catalyst and utilizing diesel fuel and fuel with biodiesel fuel blend ratio 50%, BDF 100%. This was done to examine the correlation between fuel and exhaust SOF.

Figure 6-6 shows the results of gas chromatography. From the SOF gas chromatograph pattern when run on diesel fuel, it was discovered that of the constituents of the fuel, the emitted SOF was composed of high boiling point constituents with carbon numbers of 16 or more. This discovery signifies that the factors producing the SOF mainly had their origin in unburned fuel constituents with high boiling points.

In contrast, the results of analysis for biodiesel fuel demonstrate that biodiesel fuel is composed of a mixture of methyl esters of higher fatty acids, and from the same figure it can be seen that the boiling points equivalent to diesel fuel constituents with carbon numbers in the range from 18 to 22. For that reason, the fatty acid methyl esters are though to remain unburned and are emitted as SOF. With biodiesel fuel, since it does not contain constituents with boiling points as low as diesel fuel, a high proportion is emitted as SOF. In this way, the characteristic fuel properties of biodiesel fuel are thought to lead to an increase in emitted SOF, as shown in Figure 6-5. Consequently, one conceivable approach for suppressing SOF emissions would be to use biodiesel fuel including fatty acid methyl esters with low carbon numbers and low boiling points.

When biodiesel fuel is used, because a lot of SOF is included in the exhaust that emerges from the engine, it is thought best to also use a catalyst appropriate for

breaking down higher fatty acid methyl esters.

4.5 Problems arising from use of strong-oxidation catalyst

Figure 6-7 shows the results of simultaneously measuring NO2 concentrations in exhaust gas upstream and downstream of a strong-oxidation catalyst in Vehicle B when using BDF 100% for steady-state operation. According to the figure, the NO2 level at the catalyst outlet is higher than that at the catalyst inlet for all running conditions, making it clear that NO2 is being produced in the catalyst. This tendency is particularly noticeable at low engine speeds when the gas flow is reduced, so it is surmised that the space velocity of the gas passing through the catalyst has some effect on the NO2 generation reaction. Because this is diesel (lean) combustion, there are a lot of oxygen molecules in the exhaust gas, and also a lot of NO included in the exhaust gas. The NO2 is thought to be produced when these are linked together by the catalyst with high oxidation performance. This is a general issue affecting the combination of lean combustion with a strong-oxidation catalyst, and is not just limited to biodiesel fuel.

NO2 is considered to be a more harmful substance than NO, badly affecting health. There is a need to avoid as far as possible a situation where NO2 emissions increase as a result of using a catalyst with high oxidation performance because of the use of biodiesel fuel. In that sense, it is important to suppress as far as possible the generation of NO in the engine in association with combustion, so use should be made of EGR systems or other effective measures for reducing NOx.

5. Summary of survey results

Biodiesel fuel (BDF) has the potential to become widely used. In FY2003, one type of RME fuel compliant with EU standards was taken as an example of biodiesel fuel, and used in running chassis dynamometer tests of three diesel trucks that used different approaches to emissions control, to investigate the effects of biodiesel fuel on exhaust gases, etc. The biodiesel fuel used was blended with low (10 ppm) sulfur diesel fuel in proportions ranging from 0% to 100%. From the results of that testing, the following knowledge was obtained about biodiesel fuel.

(1)   When biodiesel fuel was used in a diesel engine, there was a substantial increase in the SOF contained in the PM in the exhaust gas after combustion. In order to investigate the cause of the increase, the fuel constituents of diesel fuel and biodiesel fuel were analyzed in a gas chromatograph, and the constituents of

collected SOF were analyzed. From the results of these tests it was possible to conjecture that the increase in SOF and PM when using biodiesel fuel was due to the fatty acid methyl esters that make up the biodiesel fuel remaining unburned and being emitted unchanged as SOF.

(2) There was a tendency for the level of CO in the engine exhaust gas to increase with higher biodiesel fuel blend ratios. The cause of this was thought to be that the biodiesel fuel is more viscous than diesel fuel, meaning that the droplets of fuel sprayed from the injector nozzles in the vehicle used for the testing, were larger and more tightly packed than diesel fuel droplets, which results in localized oxygen deficiency when the spray auto-ignites and combusts. It is thought that this effect more than overrides the effect of biodiesel fuel being an oxygen-containing fuel.

(3) No clear cause-and-effect relationship could be identified between the biodiesel fuel blend ratio and the amount of HC in the exhaust gas from the engine. This is thought to be because HC is easier to break down than CO.

(4) It was found that there was a tendency for the HC level in the engine exhaust gas to increase with low blend ratios such as BDF 5%. This was thought to be an explainable special phenomenon or some sort of problem with the specific tests, but the answer could not be identified, so further investigation is required.

(5) It was found that there was a tendency for NOx emission levels to increase with the rise in biodiesel fuel blend ratio, but at the same time no clear relationship was found between NOx and biodiesel fuel blend ratio. Further research is required, including an investigation of the differences in diesel combustion of biodiesel fuel and diesel fuel.

(6) The influence on exhaust gas when utilizing biodiesel fuel is greatly affected by the sort of catalyst unit used in the vehicle's exhaust system. The exhaust properties of CO and HC, which are some of the regulated substances, vary greatly according to the oxidation capability of the catalyst. In cases where diesel vehicles use catalysts with weak oxidation performance to keep down sulfates, it was found that catalyst reactions actually increase CO levels. However, it was found that since HC constituents are easier to break down than CO, these are reduced to a certain extent even if the catalyst has weak oxidation performance.

(7) If a vehicle is fitted with a catalyst with high oxidation performance, the CO and HC produced in the engine are both substantially reduced, to the extent that there is hardly any evidence of influence from the biodiesel fuel blend ratio. However, in conditions that are unfavorable to the catalyst reaction, such as during a cold start or when driving in congested traffic, the influence of the biodiesel fuel can be seen even if there is a strong-oxidation catalyst.

(8) Considering CO, which readily increases during biodiesel fuel combustion, and HCs, which emerge as unburned constituents, it was determined that when biodiesel fuel is selected as the fuel, it is necessary to combine biodiesel fuel with a catalyst with a high oxidation performance.

(9) With the combustion of biodiesel fuel, the level of SOF produced in the engine is certain to increase, and if no aftertreatment is used, this results in the level of PM in the vehicle's emissions deteriorating relative to the level when diesel fuel is used. However, since biodiesel fuel is an oxygen-containing fuel and does not contain aromatics, if it is used in a high blend ratio, there will be a reduction in the level of ISOF in the total PM emissions.

(10) This means that if biodiesel fuel were to be used unmodified in existing diesel vehicles that do not have aftertreatment, there would be an increase in SOF resulting in deterioration in PM emissions compared with diesel fuel. From the perspective of preserving the environment, this sort of deterioration in PM emissions cannot be disregarded, so some form of countermeasure would be required.

(11) Since the SOF constituents are substances that are readily broken down by catalysts, if biodiesel fuel is used in diesel vehicles fitted with oxidation catalysts, the result would be a lower level of PM emissions than when the vehicle is run with diesel fuel.

(12) A tendency for production of aldehydes to increase in combustion when the fuel is biodiesel fuel was observed. However, it was also determined that aldehyde emissions could be substantially suppressed by installing a catalyst with a high oxidation performance in the exhaust system. It was also discovered that if a catalyst with a low oxidation performance is used, the capability to eliminate formaldehyde is reduced, and a tendency to produce new aldehydes in the catalyst was observed.

(13) When high blend ratio biodiesel fuel is used in combination with a weak-oxidation catalyst, there are situations where there will be increases of VOCs, particularly benzene and 1,3-butadiene, in the exhaust gas. This means that care needs to be taken with the way catalysts are used when biodiesel fuel is utilized.

(14) A tendency for fuel economy (km/l) to drop a little when biodiesel fuel blend ratio is increased was observed. This is thought to be an issue rooted in the calorific value of the fuel itself, so further investigation is required to accurately analyze the calorific values of the fuels tested and to determine how this relates to fuel economy.

(15) As a result of measuring maximum driving power in steady-state tests for a

range of engine speeds using biodiesel fuel blend fuel, biodiesel fuel did not demonstrate much inferiority to diesel fuel in terms of steady-state torque characteristics, but in transient situations such as under rapid acceleration, a small drop in acceleration performance was observed as biodiesel fuel blend ratio was increased.

(16) Plans had been made to analyze the features of biodiesel fuel combustion by measuring combustion pressure, but this would have been the testing team's first experience of installing combustion pressure sensors and crank angle sensors in an engine in situ in a vehicle and conducting chassis dynamometer tests. There had also been insufficient investigation of a number of variables relating to measurement. For these reasons, the current survey did not commence analysis of the effects of biodiesel fuel on combustion, and consequently did not reach any conclusions in this area.

(17) It was found that when a catalyst with high oxidation performance is used to suppress the effects of biodiesel fuel on exhaust gas, the NO and O2 in the exhaust gas react in the catalyst, producing new NO2. NO2 is a substance that is more detrimental to health than NO, so in order to suppress NO2 emissions, countermeasures (such as a more potent EGR system) need to be taken to reduce NOx at the engine.

From these points, and from the results of exhaust gas testing using biodiesel fuel (RME compliant with EU standards), the following overall knowledge was obtained.

1. If biodiesel fuel is used in existing diesel vehicles not fitted with aftertreatment devices, CO and NOx emissions are at similar levels to emissions with diesel fuel, and in some cases may be at slightly elevated levels. PM levels are clearly raised, with the reason being that fatty acid methyl ester in the biodiesel fuel is emitted unburned as SOF.

2. For this reason, if biodiesel fuel is to be used in diesel vehicles, it is considered necessary to fit their exhaust systems with aftertreatment devices such as a catalyst unit with high oxidation performance (strong-oxidation catalyst) or a DPF unit with oxidation catalyst, in order to counter PM, CO, and other emissions.

3. When biodiesel fuel is used in diesel vehicles fitted with aftertreatment devices, the SOF in the PM is substantially reduced, and ISOF can also be suppressed, giving lower PM levels than with diesel fuel. However, the oxidation function of the catalyst degrades in use, resulting in an increase in SOF and deterioration in PM emission levels, so it is important to consider how to prevent the apparatus from degrading and how to maintain performance.

4. Since using biomass fuels has a direct effect on CO_2 savings in the automobile sector, it is an effective approach in terms of policy for preventing global warming. However, in using biodiesel fuel, it is desirable to give proper consideration to the influence on exhaust gas set out above, and to take the action required.

5. With reference to the findings of this survey, there is great potential for promoting widespread use of biodiesel fuel through developing special vehicles designed from the start to use biodiesel fuel in the optimum manner at the same time as employing atmospheric pollution countermeasures.