Research on Super Low Emissions Measurement Technology for Vehicles to which Long-Term Regulations Apply

(Super Low Emissions Measurement Technology Group)
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1. R & D Objectives

Regulations on automobile emissions continue to be made stricter so as to reduce the load on the environment. In Japan, following a report by the Central Environment Council was released in November of 1997 and entitled On Automobile Emissions Reduction Measures in the Future (Second Report) (hereinafter referred to as year 2000 regulations), another report on Automobile Emissions Reduction Measures in the Future (Fifth Report) (draft) was compiled by the Central Environment Council in March of 2002. In this later report, in consideration of reduction measures for both emissions and CO$_2$, numerical targets for even further reduction of NOx, etc., to be reached by passenger cars in 2005, were publicized (hereinafter referred to as year 2005 regulations). Meanwhile, in response to global warming, new regulations on fuel consumption will be introduced between 2008 and 2010 in Japan and Europe. In order to comply with these regulations, the auto makers are developing vehicles equipped with advanced fuel injection technology, as exemplified by direct in-cylinder fuel injection (direct injection), fuel control technology and new modes of catalyst technology. In the evaluation of emissions using vehicles equipped with these new technologies, the concentrations of the emissions targeted have become extremely low. Under the impact of learning and control functions, or catalytic treatment characteristics, for instance, accuracy in repeated measurements becomes poor, and it is now evident that measurements with conventional emissions assessment methods and systems are too limited.

The present research has been undertaken for the purpose of clarifying the impact of automobile emissions reduction technology on accuracy in repeated measurements of emissions. Another objective is to establish assessment conditions/methods and measurement systems in which the same level of accuracy in repeated measurements is achieved as with conventional vehicles when measuring emissions of low concentration under year 2000 regulations (or under the year 2005 regulations envisioned).
2. R & D Contents

2.1 Identification of Problems with Current Testing Methods

In Japan at present, the standard test method for measuring emissions is the TRIAS (Traffic Safety and Nuisance Research Institute’s Automobile Type Approval Test Standard) 10 · 15 mode emissions tests. The impact of each test condition on accuracy in emissions measurements in these tests was investigated. Respecting problems in the analysis of low emissions using the present-day standard emissions measurement system, the accuracies of analyzer units and of the system as a whole were investigated through experiments and simulations.

2.2 Numerical Modeling of Emissions Measurement System

With numerical analysis software (Mathematica), a platform was created for numerical models to represent emissions measurement systems. Each elemental technology of the CVS (Constant Volume Sampler) method and the BMD (Bag Mini Diluter) method was investigated, and error factors in the measurement of LEV (Low Emission Vehicle) were determined quantitatively through simulation.

2.3 Screening for Optimal Measuring Method

Comparisons were made among the CVS method, the E-CVS (Enhanced CVS) and the BMD method. Using direct injection CVT (Continuously Variable Transmission) vehicle, a comparison was made from the standpoint of applicability to the next-generation vehicle between human driver test and automatic driving robot in order to identify issues relevant to accuracy.

2.4 Impacts of Vehicle Conditions

Using PFI vehicle (LEV) mounted with high-performance catalyst and direct injection vehicle with lean NOx catalyst, an investigation was made of the nature and characteristics of variations in emissions measurements and the factors behind such variations.

2.5 Investigation of Low Emission Measurement Methods

Using model gas and vehicular emissions comparable to those of the SULEV (Super Low Emission Vehicle), the applicability of the sampling system for measuring low emissions was confirmed. In addition, measures for improving accuracy in HC (hydrocarbon) measurements, a key factor, were investigated. Bag materials with little impact from outgassing, for instance, and effective methods of purging residual gas after practical gas measurements were investigated. What is more, suitable methods were established for objectively assessing the feasibility of next-generation vehicles driven by robots.

2.6 Impacts of Fuel Properties

Fuel factors impacting on accuracy in repeated measurements of emissions were identified and impacts on measurement accuracy were investigated.

2.7 Proposals for Improving Specific Evaluation Methods

Methods for optimizing test vehicle conditions were investigated, as were methods of assessment and analysis appropriate for evaluating super low emissions, and improvements were proposed in specific assessment methods aimed at elevating accuracy in repeated measurements.
3. R & D Results

3.1 Identification of Problems with Current Testing Methods

(1) Problems in Assessment Method

In the present study, various test conditions in the TRIAS emissions test were identified, including test conditions that present no special restrictions on test method (or permit fluctuations within a preset range) (hereinafter referred to as “preconditions”), driver (human driver/robot driver) and mode follow-up, and the impact of these conditions on test results were investigated. Presented here as an example are results pertaining to follow-up on mode designated speed using PFI vehicle (2L complying with year 2000 regulations). Vehicles were driven at the upper limit, central range and lower limit within the range of deviation (±2 km/h) from designated speed permissible in the TRIAS gasoline vehicle emissions test. The degree of impact of this permissible range on accuracy in measurements of low emissions was investigated, and the results are given in Figure 1. The figure shows that even within the permissible range of the test method, differences in speed affect emissions and fuel consumption. A huge difference in the volume of CO emissions in particular was noted. It was also found that even in tests under current TRIAS test conditions, test results vary depending on the test method.

Vehicle: 2.0L in-line, 4-cylinder PFI with three-way catalyst complying with year 2000 regulations
Test mode: 10·15 mode (using low emissions analyzer with dilution air refiner ON)

![Figure 1: Impact of Speed Tolerances in 10·15 Mode Test on Emissions and on Fuel Consumption](image)

(2) Problems with Measurement System

The range of error in low concentration gas measurement results was estimated in relation to the CVS system check method (Propane Shot). In this method, a comparison is made of the weighted value of propane introduced in CVS with the weight of propane calculated from bag measurements. The error factors considered were: 1) analyzer linearity, 2) calibrated gas accuracy, 3) differences in calibrated line and sample line indications, 4) error in CVS flow volume control, and 5) adsorption · outgassing within the system. Overall impact was assessed as the square root of the sum of squares. Figure 2 presents a sample analysis in which it is assumed that the total CVS diluted volume is 180 m³, the maximum THC (Total Hydrocarbon) measurement range is 50 ppmC, and the THC in diluted air is 2 ppmC. In order to keep the maximum value of inclusive error normally at ±2% or below, a bag concentration of 44 ppmC or above is required. Conversely, in order to obtain adequate measurement accuracy within domains of even lower concentration, it is imperative to curtail each error factor to the utmost.
3.2 Numerical Modeling of Emissions Measurement System

Using a numerical model constructed with Mathematica, analysis was made of errors in BMD and CVS (conventional and improved facilities) measurements. As an example, Figure 3 presents a simulation of changes in THC concentration in CVS - BMD bag together with cumulative THC weight in engine emissions. Approximately two-thirds of the gross mass is discharged within the first 40 seconds, followed by a period in which there is almost no discharge (slanted line segment, around 100 ~ 170 seconds). If we assume provisionally that the CVS bag is switched at 100 seconds, the THC concentration in bag at this time becomes approximately 44 ppmC, roughly four times the normal concentration. By shifting the bag changeover timing in this manner, THC of low concentration can be effectively sampled. Since the initial bag measurement error comprises the greatest factor in mode displacement error as a whole, it is conjectured that this method will prove effective in reducing error in the measurement of super low emissions in the future.
3.3 Screening for Optimal Measuring Method

Shown in Figure 4 are measurements of LEV-equivalent vehicle emissions using the BMD and CVS methods. As gases for BMD dilution, nitrogen and two types of cylinder air of different purity were compared. The running modes used were the stabilized (S) phase and hot transient (HT) phase of FTP75 of the United States. In the emissions value measured by the BMD method, as compared to the conventional CVS method, there was an error of -4.0 ~ -0.3% for CO$_2$ and -3.9 ~ 1.9% for CO. For constituents emitted at a certain concentration level, relatively good correlations could be obtained. On the other hand, it was found that there were large differentials for NOx, a constituent of low concentration (-16 ~ 2.9%), and for THC (-94 ~ 27%). Moreover, when nitrogen was used as the dilution gas for BMD, it was observed that THC tends to become low. It was confirmed, however, that this can be cancelled through corrections, since the FID indication is affected by oxygen concentration in the sample.

3.4 Impacts of Vehicle Conditions

(1) Study of Conditions Leading to Deterioration in Measurement Accuracy

In the present study, the PFI vehicle equipped with advanced technology and the direct injection vehicle were selected as test vehicles in order to facilitate investigation of the impact of vehicle-side technology on accuracy in repeated measurements of emissions. Premium gasoline on the market was used in all but a few of the tests.

For the direct injection vehicle (vehicle A: 1.8L 4 cylinder) and the PFI vehicle (vehicle D: 2L 4 cylinder), 10 · 15 mode tests were performed in accordance with conventional TRIAS procedure, and comparisons of repeatability are presented in Figure 5. Here, repeatability is defined by formula (1) below. It was found that repeatability is extremely poor especially for CO and NOx from the direct injection vehicle.
Repeatability = (maximum value – minimum value) / average value ........................ (1)

<table>
<thead>
<tr>
<th>THC emissions (g/km)</th>
<th>CO emissions (g/km)</th>
<th>NOx emissions (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First time</td>
<td>Second time</td>
<td>Third time</td>
</tr>
<tr>
<td>Direct injection</td>
<td>PFI</td>
<td></td>
</tr>
<tr>
<td>vehicle A</td>
<td>vehicle B</td>
<td></td>
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</table>

In considering the repeatability of emissions with all modes in general, it was assumed that it would be effective to investigate which mode conditions have a controlling impact on variations in general. In the present investigation, the test mode was divided up into individual modes, and the variations in emissions from each divided mode were investigated along with their impacts on mode in general. In 10 · 15 mode testing of two different direct injection vehicles (vehicle A: 1.8L 4 cylinder, vehicle B: 3L 6 cylinder), emissions measurements were taken separately in 10 mode and 15 mode. The impact of each of these emission values on the emissions value for the 10 · 15 mode collectively is represented in Figure 6.

![Figure 5: Emissions Repeatability from Direct Injection Vehicle (Vehicle A) and PFI Vehicle (Vehicle D)](image)

![Figure 6: Impact of Individual Mode Emissions on Measurements of Mode Emissions in General](image)
It was discovered that among direct injection vehicles, the predominant mode varies depending on the type of vehicle. In the case of NOx, for instance, whereas the 10 mode was predominant for vehicle A, the 15 mode was slightly predominant for vehicle B. The pattern of variations in individual modes for NOx is presented in Figure 7. These results show that for vehicle A, whereas the range of variations in 15 mode measurements is relatively narrow, those in 10 mode measurements extend over a broad range.

![Figure 7: Variations Between 10 Mode and 15 Mode in 10 · 15 Mode Testing (Example of NOx)](image-url)
Investigation of Factors behind NOx Variations

To gain a more detailed understanding of factors behind variations in NOx, attention was focused on NSR catalyst. Emissions and temperature before and after NSR catalyst were measured under each driving condition. Shown in Figure 8 are temporal changes in NOx and temperature before and after NSR catalyst during 10 · 15 mode testing of two cases in which NOx level differs. For NOx, in particular, there were great differences in emissions volume in both cases under 15 mode, and it appears that these differences were ultimately linked to the variations in measurements in 10 · 15 mode. More detailed investigation of these results disclosed that for NOx prior to NSR catalyst, differences in the two cases can be seen not so much in the acceleration component of 15 mode as in the idling component (t=469s) immediately prior to acceleration and in the component prior to idling. As for temperature before and after NSR catalyst, whereas the emissions temperature in both cases is roughly the same while flowing to NSR catalyst, differences could be noted in the post NSR catalyst emissions temperatures from the second half of 10 mode to the first half of 15 mode. These findings suggest that the differences in NOx emissions noted with 15 mode are greatly affected by changes in catalyst temperature and in NOx volume flowing to catalyst from the second half of 10 mode to the start of 15 mode. In the present study, a correlation was identified between post NSR catalyst temperature and pre NSR catalyst THC and CO. This suggests that with NSR catalyst, THC and CO act as a NOx reducing agent and impact on the reaction temperature with NSR catalyst.

Figure 8 Impact of NOx Concentration and Temperature before and after NOx Catalyst on Measurements of Tail Pipe NOx (Vehicle B)
3.5 Investigation of Low Emissions Measurement Methods

(1) Investigation of Bag Materials

Outgassing from bag material could have a major impact on THC measurement accuracy. Accordingly, comparative tests were performed in which TFM/PTFE resin was added to PVF (Polyvinyl Fluoride), a common material, and to FEP (fluorinated ethylene propylene copolymer).

Figure 9 shows differences in THC outgassing volume by bag material and treatment. The left figure gives data on dry air injection and the right figure, on injection of wet air with water vapor included at room temperature saturation. With bag made of TFM/PTFE, hydrocarbon outgassing normally remains stable at a low level and there is hardly any variation with or without the addition of moisture. In CO₂ permeability test conducted separately, it was confirmed that the permeability of CO₂ with TFM/PTFE is half that with FEP or less and that it has relatively little impact on fuel consumption measurements. In light of the aforementioned, TFM/PTFE can be considered as a candidate bag material for use in measuring low emissions.

![Figure 9: Comparative Investigation of Bag Materials](image)

(Under room temperature, 25degC)
(2) Methods for Purging Residual HC in Bag

Figure 10 presents the results of comparative tests on purge method effectiveness and required time periods, using bag made of TFM/PTFE. The purge method commonly used (repeated diluted air filling · ejection through CVS system line) is denoted by A. B and C are methods of air injection and storage after performing air filling and ejection (one time each). D is a method in which air is filled and ejected repeatedly via pump directly connected to bag. Results are presented as differences in concentration of sample bag and diluted air bag. When residual HC was observed at an initial value of around 200 ppbC, it was not completely purged by regular purge method even after 15 repetitions (requiring 90 minutes). With pump directly connected, however, residual HC was reduced to virtually zero after approximately 30 minutes, confirming that direct pump connection method is an effective means of purging residual HC. A certain level of effectiveness was also demonstrated by the injection method, so it is considered a viable purge method when there is plenty of time, as for example at night.

![Figure 10: Effectiveness of Bag Purging and Required Time Periods](image-url)
(3) Confirmation of CVS Accuracy by Model Gas Testing

CVS system accuracy and the effectiveness of dilution air refiner (DAR) were evaluated by means of model gas tests in which indoor air was assumed to have low concentrations of HC emissions. So long as the vehicle is not running, the test method is the same as the regular test mode. HC measurements with and without DAR are presented in Figure 11. Variations in HC concentration under the same conditions were corrected with integrated values of modal measurements. The dilution factor (DF) (about 5.7) was calculated from measurements of diluted air flow volume and CVS dilution flow volume. When measurements under both conditions are represented in terms of the modal measurement standard, they become +13% with use of DAR and +7.6% without DAR. It was thus found that results are lower without DAR. This is attributed to the impact of error (plus side) in the DF calculated from flow volume measurements, which acts as system error. Among the reasons why reproducibility is somewhat poor without DAR are the following. 1) The higher the concentration under analysis, the more analyzer noise tends to increase. 2) The impact of accidental error in DF can be felt more readily without DAR than with DAR. In model gas test, however, there are few factors behind accidental error in DF, and differences in reproducibility are not as conspicuous as differences in system error.

![Figure 11: Assessment of CVS System Accuracy Using Room Air](image)

3.6 Impact of Fuel Properties

Results of investigations conducted thus far suggest that the automobile-side factors that impact on accuracy in emissions measurements are mostly fuel combustion control technology, centering on fuel injection control, and treatment effect of catalyst. It is believed that the sulfur content in fuel in particular has an impact on catalytic treatment performance, so the repeatability of emissions was evaluated while varying the concentrations of sulfur in fuel. Nevertheless, in the short-term test just completed, results indicated that sulfur concentration in fuel has little impact on emissions repeatability.
3.7 Proposals for Improving Evaluation Methods

(1) Study of Method for Optimizing Test Vehicle Conditions

Using an ECU control unit, an investigation was made of the relationship between direct injection vehicle control status and stability in emissions measurements, together with optimum preconditioning. With vehicle control status and stability in diluted NOx catalyst state taken as preconditions, the preconditioning pattern in which forced stoichiometric (theoretical air-fuel ratio) operation was introduced was investigated and the impact on repeatability was examined with attention focused on NOx measurements. Consequently, as shown in Figure 12, it was found that constant driving (60km × 20 min.) with stoichiometric air-fuel mixture prior to each test is effective in curtailing NOx variations. (See Figure 13 for status of NOx variations.) This is ascribed to the fact that introducing stoichiometric driving prior to each test stabilizes computer control status and NOx storage in catalyst.

![Figure 12: Preconditioning Pattern with Introduction of Stoichiometric Driving](image1)

**Stoichiometric driving at 60km/h × 20 min. before test**

<table>
<thead>
<tr>
<th>Stoichiometric precondition</th>
<th>Stoichiometric precondition</th>
<th>Stoichiometric precondition</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 km/h × 20 min.</td>
<td>N=1</td>
<td>60 km/h × 20 min.</td>
</tr>
<tr>
<td>60 km/h × 20 min.</td>
<td></td>
<td>60 km/h × 20 min.</td>
</tr>
</tbody>
</table>

![Figure 13: NOx Variations in Preconditioning with Introduction of Stoichiometric Driving (Vehicle B)](image2)

**Figure 13:** NOx Variations in Preconditioning with Introduction of Stoichiometric Driving (Vehicle B)

**Average = 0.054 g/km  σ = 0.038 g/km**

![Test No.](image3)
Investigation from the standpoint of operation confirmed that operation with robot driver is stable. Concerning repeatability of NOx measurements, as indicated in Figure 14, it was found that variations in NOx tailpipe measurements tend to improve with driving by robot. Nevertheless, among the results given in Figure 14, some NOx measurements of exceptionally high concentration can still be observed. As indicated in Figure 15, this is ascribed to the impact of vehicle learning and control, which are also associated with the state of ECU electrical continuity. In order to achieve uniformity in learning status, attention was focused on ECU continuity at soaking time as one method. An attempt was made to abstract data only with the ECU power supply ON, and when this data alone was collected, it was discovered that data of extremely good repeatability could be obtained as shown in Figure 16.

**Figure 14**: Variations in NOx Measurements with Human Driver and Robot Driver (Vehicle B)

**Figure 15**: Temporal Changes in Air-Fuel Ratio and in Exhaust Pipe NOx with ECU Power Supply ON/OFF (Vehicle B)
(2) Super Low Emissions Measurement System

In following the conventional method of measuring low emissions, E-CVS, in which the CVS system has been optimized, serves as the base. Of the various optimization methods, use of DAR is believed to be highly effective. From numerical model analysis or model gas test using atmospheric air, for instance, it was confirmed that in the refinement of diluted air, this method acts to cancel the impact of error included in DF, especially the impact of system error. On the other hand, emissions measurement tests conducted under the present study indicate that the new BMD method offers the potential of securing a correlation with CVS by means of CO₂. Stability, however, remains an issue.

In securing accuracy in the measurement of low HC, curtailment and stabilization of the volume of outgassing from system material or the volume of adsorption/desorption of HC in emissions are also key points. It was confirmed that use of TFM/PTFE bag and introduction of an efficient new purge method are effective countermeasures for adsorption/desorption and for outgassing from bag, which has an especially large impact.

Moreover, with the so-called, next-generation vehicle, there may be cases in which the concentration of emissions produced does not remain stable even when the vehicle is driven by robot. In such cases, operational behavior and emissions repeatability must be evaluated objectively in real time. Figure 17 presents a sample application of assessment methods investigated in the present study. Although such factors as vehicle speed, engine rpm and emissions (not shown in figure) in bag analysis are all stabilized, variations in THC emissions in real time are large. In this way, it can be seen that the variations in time series data can be easily visualized with the present assessment method. Figure 18 presents an outline of the evaluation process.
Figure 17 Sample Evaluation with Robot Driver
(Direct injection CVT vehicle run 7 times in 10 · 15 mode)

(1) Calculation of average time series data $D_{ave}(t)$ from time series data $D_n(t)$ ($n=1, 2, ...$)

(2) Calculation of error $E_n(t)$ ($n=1, 2, ...$) from $D_{ave}(t)$ (Unit %)

(3) Error standard value ($\Delta E$) is set and error $E_n(t)$ is converted to percentile $S_n(t)$ ($n=1, 2, ...$) (right upper figure)

(4) Percentile data is classified by running conditions
   (V: target vehicle speed, $\alpha$: target acceleration)
   - Startup (s): $\alpha > 0$, $V < 10$ km/h
   - Acceleration (a): $\alpha > 0$
   - Cruising (c): $\alpha = 0$, $V > 10$ km/h
   - Deceleration (d): $\alpha < 0$, $V > 0$ km/h

(5) Totaling of results ($N$: data count)
   - General: $S_n_{total} = \sum S_n(t) / N$
   - Startup: $S_{sn_{total}} = \sum S_{sn}(t) / N_s$
   - Acceleration: $S_{san_{total}} = \sum S_{san}(t) / N_a$
   - Cruising: $S_{scn_{total}} = \sum S_{scn}(t) / N_c$
   - Deceleration: $S_{sdn_{total}} = \sum S_{sdn}(t) / N_d$

(6) Plot on reader chart (right lower figure)

Figure 18: Flow in Evaluation of Robot Driving
4. Synopsis

From 1999 to 2001, investigations were conducted on both emissions assessment methods and measurement systems for the purpose of improving repeat accuracy in technologies for measuring super low emissions from vehicles equipped with the very latest emissions technology.

Investigations of super low emissions assessment methods disclosed that vehicle conditions such as direct injection control and catalyst control, as well as test conditions such as operational method (human or robot driver) and mode follow-up, have huge impacts. Following these investigations, introduction of stoichiometric driving conditions to preconditioning was proposed as a means of improving repeat accuracy, as was an improved method of assessment aimed at elevating accuracy, which includes operational control, for instance, by means of robot drivers.

In the investigation of super low emissions measurement systems, a constant volume sampling (CVS) method was assumed as a candidate measuring system combined with air refiner, as was a bag mini diluter (BMD) method; and points in securing accuracy were analyzed by means of numerical models and tests. In HC measurements, in particular, (the key to measuring low concentrations) it was determined that adsorption/desorption becomes problematic since it varies with bag or system component materials. Selection of appropriate bag material and optimization of bag purge method were confirmed as effective means of improving accuracy. As for robot driver (an indispensable part of the measurement system), an effective assessment method was proposed in which operational performance with various types of vehicle is judged.

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