SURFACE VEHICLE INFORMATION REPORT	J3349™	OCT2021
	Issued 2021-10	

NOx Tracking Parameter Accuracy

RATIONALE

The objective of this SAE Information Report is to provide a standardized means of implementing the real emissions assessment logging (REAL) NOx tracking and accuracy requirements defined in OBD regulations 13 CCR 1971.1 and 13 CCR 1968.2 to ensure consistent and equitable reporting of tracked parameters. This report will also provide instructions on how to conduct the accuracy demonstration as well as implementation notes for REAL NOx tracking.

1. SCOPE

This SAE Information Report provides SAE's recommendations for meeting the requirements for REAL NOx accuracy demonstration and for the implementation of REAL NOx binning requirements as defined in OBD regulations 13 CCR 1971.1 and 13 CCR 1968.2.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J1939DA J1939 Digital Annex

SAE J1979DA Digital Annex of E/E Diagnostic Test Modes

2.1.2 Code of Federal Regulations (CFR) Publications

Available from the United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

40 CFR Part 86 Control of Emissions from New and In-Use Highway Vehicles and Engines

40 CFR Part 1065 Engine-Testing Procedures

40 CFR Part 1066 Vehicle-Testing Procedures

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2.1.3 State of California Air Resources Board Publications

13 CCR Part 1971.1 On-Board Dianostic System Requirements - 2010 and Subsequent Model-Year Heavy-Duty Engines

13 CCR Part 1968.2 On-Board Diagnostic System Requirements - 2004 and Subsequent Model-Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles and Engines

"Staff Report: Initial Statement of Reasons," Public Hearing to Consider Proposed Revisions to On-Board Diagnostic System Requirements, Including the Introduction of Real Emissions Assessment Logging (REAL), For Heavy-Duty Engines, Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles and Engines, 2018.
https://ww2.arb.ca.gov/resources/documents/heavy-duty-obd-regulations-and-rulemaking

"Heavy Duty Engine and Vehicle Omnibus Regulation and Associated Amendments," 2020.
https://ww2.arb.ca.gov/rulemaking/2020/hdomnibuslownox

3. DEFINITIONS

No definitions are specified herein.

4. ABBREVIATIONS

CAN	Controller area network
CARB	California Air Resources Board
CCR	Code of California Regulations
CFR	Code of Federal Regulations
CVS	Constant volume sampling
DPF	Diesel particulate filter
ECT	Engine coolant temperature
ECU	Engine control unit
EOE	Engine output energy
FTP	Federal test procedure
GHG	Greenhouse gas
HDFTP	Heavy-duty federal test procedure
IMT	Intake manifold temperature
ISOR	Initial statement of reasons
MAF	Mass airflow
MIL	Malfunction indicator light
NH_3	Ammonia
NOx	Oxides of nitrogen
NTE	Not-to-exceed

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OBD On board diagnostics

PEMS Portable emissions measurement system

PIDs Parameter identifications

REAL Real emissions assessment logging

SCR Selective catalytic reduction

SPs Suspect parameters

UDDS Urban dynamometer driving schedule

5. INTRODUCTION

The objective of this report is to provide a standardized means of implementing the REAL NOx tracking and accuracy requirements defined in OBD regulations 13 CCR 1971.1 and 13 CCR 1968.2 to ensure consistent and equitable reporting of tracked parameters. SAE J1939DA and SAE J1979DA should be referenced for details on data stream and tracking parameters, as well as calculation methods. The first section describes the requirements for the REAL NOx accuracy demonstration, including determination of reference laboratory and engine- or vehicle-based NOx emissions for comparison. The second section includes on-vehicle implementation notes for the REAL NOx tracking and binning. This report provides SAE's recommendations for meeting the REAL NOx tracking requirements but does not supersede or replace requirements in the OBD regulation. Specific determinations of a manufacturer's compliance with the REAL NOx tracking requirements will be made by CARB's Executive Officer or a designated representative.

6. REAL NOX ACCURACY DEMONSTRATION

Section 6 pertains to the REAL NOx accuracy demonstration requirements per 13 CCR 1971.1 (h)(5.3.4) and (j)(2.26) and 13 CCR 1968.2 (g)(6.12.4) and (i)(2.32). This section describes the test conditions, general considerations for NOx measurement, measurement methods, and data calculations for the accuracy demonstration and the determination of the reference laboratory NOx emissions and engine- or vehicle-based NOx measurement.

6.1 Test Conditions

This section describes the test conditions for the NOx binning accuracy demonstration.

6.1.1 Accuracy Requirement

Accuracy of the rear-most NOx sensor is assessed against test facility emissions measurement. The NOx accuracy requirement is ±20% of total integrated mass or ±0.1 g/bhp-h, at the discretion of the manufacturer. The most favorable accuracy limit may be used. The accuracy requirement applies to integrated NOx mass emissions over the demonstration cycle [40 CFR 1065, 40 CFR 1066].

6.1.2 Accuracy Demonstration Cycle

Accuracy is only to be demonstrated under laboratory conditions as defined in 40 CFR 1065 for dynamometer certified vehicles, medium- and heavy-duty, and 40 CFR 1066 for chassis certified vehicles. HDFTP or UDDS cycles are to be used for accuracy demonstration for NOx mass emissions per 13 CCR 1971.1 (j)(2.26) for heavy-duty dynamometer certified vehicles and per 13 CCR 1968.2 (i)(2.32) for medium-duty chassis certified diesel vehicles. Each test should be immediately preceded by a hot- or cold-start HDFTP or UDDS cycle, depending on the cycle to be used for demonstration, without a key cycle or restart to warm up the engine and ensure that all NOx sensors are online and reporting data throughout the test.

For medium-duty diesel vehicles certified on chassis dynamometer, a hot-start FTP72 cycle may be used for accuracy demonstration instead of the UDDS cycle. The hot-start FTP72 cycle must be preceded by a cold- or hot-start FTP72 cycle.

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A representative, production intent engine and aftertreatment or vehicle and aftertreatment should be used for the accuracy demonstration. The vehicle, engine, and aftertreatment do not need to be aged to a specific level. For certification test groups that encompass multiple vehicles, test weights, and road loads, manufacturers should propose a demonstration plan and request Executive Officer approval.

6.1.3 Accuracy Demonstration Cycle - Data to Provide

As defined in 13 CCR 1971.1 (j)(2.26) and 13 CCR 1968.2 (i)(2.32), manufacturers shall provide data from both the ECU and the reference test facility during the accuracy demonstration cycle. The following data shall be provided for both the prep cycle and the official test at a frequency of at least 1 Hz in a .csv file format.

- ECU: Engine out and system out NOx mass emission rates and engine output energy. These parameters can be directly recorded from the ECU provided the selected ECU parameters are equivalent to the corresponding data stream and tracking parameters.

- Test facility: Engine speed, torque, net brake work, and system out NOx mass emission rate.

If the demonstration cycle is a vehicle-based (or chassis) test, engine speed, torque, and net brake work may be omitted.

Refer to SAE J1939DA or SAE J1979DA for specific parameters provided by the engine ECU. A summary of relevant labels from SAE J1939DA and SAE J1979DA are displayed in Appendix A.

6.1.4 NH_3 Slip

NH_3 slip during the accuracy demonstration cycle shall be minimized by using preconditioning cycles. These cycles shall be determined by the manufacturer and disclosed.

6.1.5 DPF Regeneration Status

Accuracy demonstration should not be performed with a system in active DPF regeneration mode. System is classified in active DPF regeneration mode if one of the following conditions are in progress:

- ECU has recognized that the DPF needs to be regenerated and control logic started the warm-up of DPF inlet temperature.

- ECU has recognized that the DPF needs to be regenerated and control logic is actively managing the burning of the soot in the DPF.

- ECU control logic is performing the cool down of the system after the regeneration and some intrusive action are taken to assist it.

A DPF regeneration cycle can be included as preparation cycle to avoid active DPF regeneration happening during the demonstration cycle. Similarly, other infrequent regeneration events such as desulfurization or deposit cleaning should be avoided for accuracy demonstration.

6.2 General Considerations for NOx Measurement

This section describes general considerations for NOx measurements for both the reference laboratory and NOx sensors.

6.2.1 General Considerations for Reference Laboratory NOx Measurements

Humidity corrections are to be excluded from laboratory data. 40 CFR 1065 and 40 CFR 1066 should be referenced for reference laboratory emissions measurement specifications for engine and chassis dynamometer test facilities, respectively.

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6.2.2 General Considerations for NOx Sensor Measurements

6.2.2.1 Frequency for Data Collection

An internal sensor sampling frequency greater than 5 Hz is recommended for calculations to improve accuracy.

6.2.2.2 NOx Sensor Signal Corrections

Based on good engineering judgement and first principles knowledge, the NO_x concentration measurements should be compensated appropriately before the values are reported in the data stream and then used to estimate NO_x masses and mass rates for the data stream. Raw sensor signals may need to be compensated by the sensor's control module or an engine control module for temperature, exhaust flow, pressure, offset, gain, drift, H_2O, NO_2, NH_3, O_2, and oxidizable species (soot, diesel, CO, etc.). The NO_x sensor may be cross-sensitive to a number of other constituents (e.g., H_2O, NO_2, NH_3, and O_2) that may be measured using additional sensors or inferred from information about the engine's operation (e.g., air-fuel-ratio considerations, expected NO_2/NO ratios, etc.). In some cases, secondary vehicle sensors used to measure non-target species (e.g., NH_3) may need to be compensated for cross-sensitivities before they are used to correct the NO_x measurement. Manufacturers should disclose NOx sensor compensation and correction strategies to their Executive Officer representative.

6.2.2.3 Management of Negative NOx Sensor Values

After careful and robust data review and discussion, it was determined on technical grounds that negative NOx sensor readings should be included in the bin and data-stream integration methodology. Negative values in corrected data from NOx sensors are known to typically result from Gaussian noise, sensitivity to changes in water vapor concentration, or other noise sources. The engine manufacturer should use good engineering judgment when determining whether to include the resulting negative errors as the natural counterbalance to positive errors that will also be included in bin totals and data-stream parameters.

Results of committee investigations indicate that negative NOx sensor readings are meaningful, making an important contribution to measurement accuracy at very low NOx concentrations, and that -5 ppm is a reasonable lower bound threshold to use for inclusion in NOx mass calculations. NO_x sensor readings greater than or equal to -5 ppm as measured by the engine's ECU preferably should be considered in the NOx mass REAL bins and NOx sensor data stream parameters, so that the binned and data-stream values, as well as the associated second-by-second readings, can be compared more directly to standard CVS and PEMS measurements during both the vehicle accuracy demonstration and in-use.

For "low NOx" systems (i.e., CARB MY2023 and prior), including the referenced negative NOx sensor readings will be consequential for only a subset of drive cycles. However, for "ultra-low NOx" systems (e.g., CARB MY2024 and later), the inclusion of negative NOx sensor readings as measured by the engine's ECU will be critical for the accurate measurement of cumulative emissions over most drive cycles.

6.3 REAL NOx Accuracy Demonstration NOx Measurements and Calculations

The methods for calculating reference laboratory and engine- or vehicle-based NOx emissions are described in this section. The calculation methods are provided using continuous notation as it is expected that the emissions measurement cell instrumentation will provide a fixed sampling interval. Methods for estimating NOx emissions from the reference laboratory and from the subject engine/vehicle, or ECU, will be described. The accuracy metric is also defined.

6.3.1 Engine Out NOx Measurement

Engine out NOx measurement is subject to accuracy requirements of ±20% of total integrated mass or ±0.1 g/bhp-h, like tailpipe NOx measurement. However, it cannot be assessed during the accuracy demonstration cycle due to lack of 40 CFR 1065 or 40 CFR 1066 capable measurement at the engine out position. Engine out NOx measurements are only to be reviewed qualitatively for trends. Therefore, the calculation methods described in the subsequent sections should be applied to both engine out and downstream, or tailpipe, NOx measurements.

6.3.2 Reference Laboratory Measurements

Methods for NOx concentration estimation, NOx mass determination, integrated NOx mass, and engine output energy for the reference laboratory are provided in this section.

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6.3.2.1 Estimate NOx Concentration - Reference Laboratory

NOx concentration measurements (xNOx_ref in ppm) for the reference facility shall comply with instrument requirements specified in 40 CFR 1065, subpart C (§1065.270, §1065.272). If water is removed from the sample stream upstream the concentration measurement of the reference instrument (i.e., “dry” measurement), correct the NOx concentration for the removed water following 40 CFR 1065, §1065.659. Humidity corrections for reference laboratory data are to be excluded per 6.2.1. If applicable, apply drift correction according to §1065.672 to the reference NOx measurement [40 CFR 1065].

6.3.2.2 Estimate NOx Mass - Reference Laboratory

Calculate NOx mass rate from the reference instrument (mdot_NOx_ref in g/sec) according to 40 CFR 1065, §1065.650(c). Use the molecular weight of NO_2 = 46.0055 g/mol for calculation of NOx mass. If reference NOx measurements are performed in the raw exhaust stream, use good engineering judgement to select an exhaust flow quantification method to calculate reference NOx mass rates.

If the reference laboratory uses CVS bag emissions for certification quality emissions tests per allowance and methods defined in 40 CFR 1066, CVS bag mass emissions (mcvs_NOx_ref in g) may be used as the reference.

6.3.2.3 Integrate NOx Mass - Reference Laboratory

Calculate the total integrated mass of NOx (mNOx_ref in g) for the reference facility according to 40 CFR 1065, §1065.650(c). If the reference measurement was performed on a dilute basis (i.e., CVS), correct the integrated NOx mass for dilution air background NOx concentrations following 40 CFR 1065, §1065.667.

If the reference laboratory uses CVS bag emissions, calculate the total mass of NOx (mNOx_ref in g) according to 40 CFR 1066.

6.3.2.4 Estimate Engine Output Energy

For the reference facility, if measurements are performed on an engine dynamometer, calculate the total EOE (EOE_ref in kWh) over the test segment according to 40 CFR 1065, §1065.650(d). If measurements are performed on a chassis dynamometer, the EOE shall be calculated from the engine electronic control unit parameters and will be the same as EOE_ECU.

When the test equipment does not provide an estimate for EOE due to the test cell descriptions in 40 CFR 1065 and 40 CFR 1066, data from the engine ECU shall be used to support assessment of the brake specific accuracy metric. For the electronic control unit, the estimated engine output energy (EOE_ECU in kWh) is calculated using actual (indicated) engine percent torque (Tact in %), nominal friction percent torque (Tfric in %), reference torque (Tref in Nm), and engine speed (N in rpm) using the following equations:

$$T = (Tact - Tfric) * Tref \quad \text{(Eq. 1)}$$

$$P = T*\omega \quad \text{(Eq. 2)}$$

$$P = T*2*\pi*N/60 \quad \text{(Eq. 3)}$$

$$EOE_ECU = sum(P)*\Delta t/3600 \quad \text{(Eq. 4)}$$

where:

$\Delta t = (1/f)$, and f is the data frequency in Hz

$P(P < 0) = 0$

See Section 7 for a discrete formulation for estimating EOE by an engine ECU.

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