SURFACE VEHICLE INFORMATION REPORT

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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

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

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.

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.

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.

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.

6.3.3 Engine- or Vehicle-Based Measurements

Methods for NOx concentration estimation, NOx mass determination, integrated NOx mass, and engine output energy for engine- or vehicle-based measurements are provided in this section.

6.3.3.1 Estimate NOx Concentration - Engine or Vehicle

For the electronic control unit, the corrected and compensated NOx concentrations described in 6.2.2.2 and 6.2.2.3 (xNOx_ECU in ppm) for measurements made at engine out and downstream of the after-treatment system (i.e., tailpipe) are used for mass calculations using methods described below and reported as defined in SAE J1939DA and SAE J1979DA. NOx concentrations shall only be reported when the NOx sensor conditions are stable. These and additional considerations are discussed in Section 7.

6.3.3.2 Estimate NOx Mass - Engine or Vehicle

For the electronic control unit, use the NOx mass rate (mdotNOx_ECU in g/s) parameter from the data stream.

Calculate the NO_x mass rates as described in Equation 5. Corrected NOx readings (i.e., NOx(ppm)) should be computed in accordance with the NOx sensor compensation section of this report. Corrected NOx readings below -5 ppm should be treated as -5 ppm.

$$\text{NOx (g/s)} = 0.001588 * \text{NOx (ppm)} * \text{Exhaust Flow (kg/h)}/3600 \quad \text{(Eq. 5)}$$

6.3.3.3 Integrate NOx Mass - Engine or Vehicle

For the electronic control unit, the integrated NOx mass (mNOx_ECU in g) over the test segment is calculated using the following equation:

$$\text{mNOx\_ECU} = \text{sum(mdotNOx\_ECU)}*\Delta t \quad \text{(Eq. 6)}$$

where:

Δt = the time interval given by $\Delta t = (1/f)$, and f is the data frequency in Hz

6.3.4 Estimate Work-Based NOx Emissions

For demonstration measurements conducted on an engine dynamometer, calculate the work-based NOx emissions (bsNOx in g/kWh) for both the ECU data stream and the reference facility by dividing the integrated NOx mass by the reference facility engine output energy over the test segment using the following equations:

$$\text{bsNOx\_ECU} = \text{mNOx\_ECU/EOE\_ref} \quad \text{(Eq. 7)}$$

$$\text{bsNOx\_ref} = \text{mNOx\_ref/EOE\_ref} \quad \text{(Eq. 8)}$$

For demonstration measurements conducted on a chassis dynamometer, calculate the work-based NOx emissions (bsNOx in g/kWh) for both the ECU data stream and the reference facility by dividing the integrated NOx mass by the engine output energy over the test segment using the following equations:

$$\text{bsNOx\_ECU} = \text{mNOx\_ECU/EOE\_ECU} \quad \text{(Eq. 9)}$$

$$\text{bsNOx\_ref} = = \text{mNOx\_ref/EOE\_ECU} \quad \text{(Eq. 10)}$$

6.3.5 Calculate NOx Measurement Accuracy

Accuracy may be calculated as a percentage or in terms of g/bhp-h using the following equations.

Accuracy (% in terms of mass) =
(Test facility system-out NOx mass emissions - ECU system-out NOx mass emissions)/
Test facility system-out NOx mass emissions x 100% (Eq.11)

Accuracy (in terms of g/bhp-h) =
(Test facility system-out NOx mass emissions - ECU system-out NOx mass emissions)/
Net brake work of cycle (Eq. 12)

7. REAL NOX TRACKING VEHICLE IMPLEMENTATION NOTES

Section 7 includes the notes on the implementation of the REAL NOx tracking for the vehicle including an introduction to the concept of NOx estimation, binning requirements and considerations, parameter estimation, not-to-exceed (NTE), and key differences from greenhouse gas (GHG) tracking.

7.1 REAL NOx Estimation Introduction

The following discussion guides the estimation of selected parameters. The estimates comprise the addends for the NOx binning arrays described in CARB regulations [13 CCR 1971.1, 13 CCR 1968.2] for REAL, which must be estimated each second. Displayed data should be no more than 10 seconds old when its broadcast is initiated. The same data estimates should be used for NOx binning and GHG addends. There is no need to estimate these parameters more than once. Not all parameter estimates have been defined as available SPs. Parameter estimates that are defined as SPs are noted below. CARB does not expect visibility to other data not listed in these messages or in the regulation.

Figure 1 depicts a notional framework for the collection of NOx binning data. Multiplexed NOx sensors provide 50 data frames per second to the engine ECU. In contrast, fuel injection and the torque created are event driven; determined by degrees before top dead center. Vehicle speed and vehicle distance are found in multiple configurations. In some cases, vehicle speed is multiplexed from another ECU that counts pulses; in other cases, the ECU counts pulses based on tire revolutions per mile (or kilometer). NOx mass and engine output energy are inferred from NOx concentrations, exhaust mass flow, engine speed, and fuel quantities.

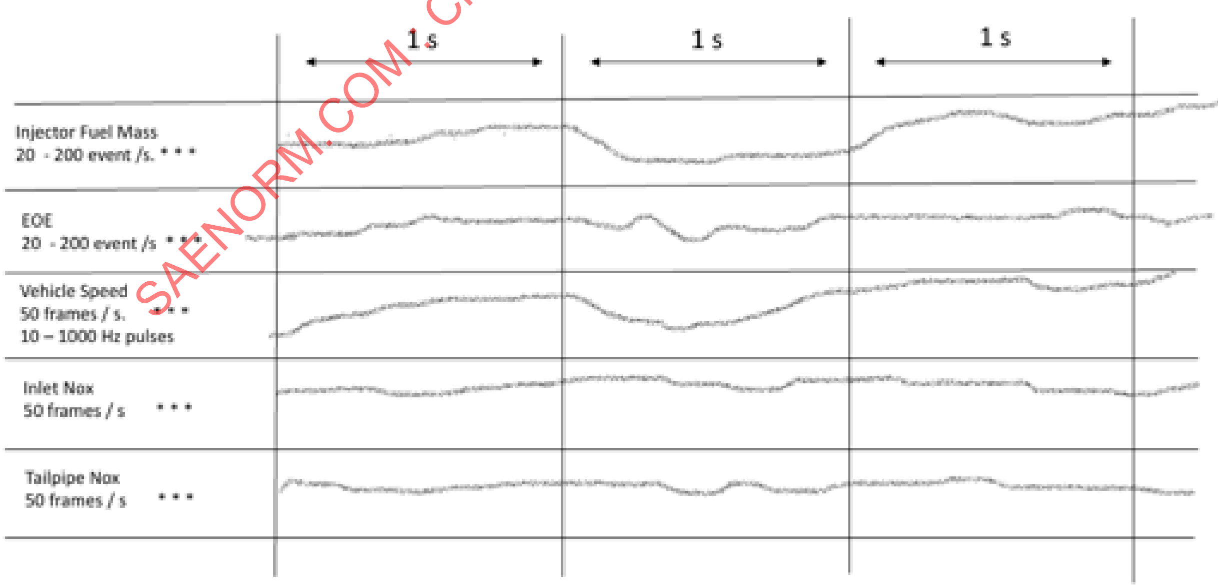

Figure 1 - NOx estimation and binning data framework

Each 1 second interval estimates of NOx mass, fuel consumption, EOE, vehicle distance, plus 1 second of time must be summed into two or more bins, Bin 1 (the total Bin) and one of Bin 2 to 14. When NTE conditions are met, the summed signal data is additionally summed into the NTE Bin. When DPF regeneration conditions are met, the summed signal data is additionally summed into the active DPF regeneration Bin, but not into the NTE Bin. NTE and active DPF regeneration bins are mutually exclusive. The disparate time frames of the signals challenge the creation of a cohesive, correlated summary of engine operation for the 1 second interval.

It is insufficient to select a single instant within each 1 second interval and use the signal value present to represent the interval. Poorly structured sampling regimens can interject systematic biases into the 1 second summary. Fuel injection quantities are known to exhibit wide shot to shot variation, which is reflected in instantaneous torque values. Variation in NOx concentration signals are sensitive to sampling frequency. Where signal data is multiplexed, implementers must account for the "jitter" when one CAN message frame is delayed from the end of a 1 second interval into the beginning of the next interval.

The variety among the signals will be reflected in disparate sampling frequencies, each of which must support the cohesive 1 second operating summary. In some cases, all available samples will be used to create the sum used in the 1 second summary.

Section 7.2 discusses the data to be binned, and describes the bins as they are defined in CARB regulations. Section 7.3 describes the calucation methods for the individual data summed into bins. Section 7.4 describes the conditions for collecting data into the NTE Bin. See Appendix A for an index of SAE J1939DA SPs and SAE J1979DA PIDs and infotypes used to estimate parameters.

7.2 REAL NOx Binning Requirements and Considerations

7.2.1 NOx Binning Criteria

The REAL program given in 13 CCR 1971.1 (h)(5.3) requires the collection of six parameters based on vehicle operating conditions.

1. NOx mass: engine out (g).
2. NOx mass: tailpipe (g).
3. Engine output energy (EOE) (kWh).
4. Distance traveled (km).
5. Engine run time (hours).
6. Vehicle fuel consumption (L).

7.2.2 Key operating condition provisions are reviewed below for the collection of these six parameters. Each parameter shall be estimated for a common 1 second window, and then added to bins that are determined by operating conditions described in Table 1.

Table 1 - REAL parameter bin definitions

Vehicle Speed Engine Power	**0 km/h**	**>0 to 16 km/h**	**>16 to 40 km/h**	**>40 to 64 km/h**	**>64 km/h**
kW% > 50% rated	Bin 2 [one bin for all power levels at 0 km/h]	Bin 11	Bin 12	Bin 13	Bin 14
25% rated < kW% ≤ 50% rated		Bin 7	Bin 8	Bin 9	Bin 10
kW% ≤ 25% rated		Bin 3	Bin 4	Bin 5	Bin 6
All [MIL-off]	Bin 1 is the sum of Bins 2 through 14.				
All, NTE conditions met	Bin 15, all NTE conditions are met as described in 40 CFR 86.1370. This subtotal is kept independently of Bin 16 and concurrently with Bins 1 to 14.				
All, engine commanding active DPF regen	Bin 16, active PM filter regeneration is being commanded (e.g., the HC doser is being (was recently) used to ignite the carbon black in the DPF). This subtotal is kept independently of Bin 15 and concurrently with Bins 1 to 14.				
All [MIL-on]	*Bin 17, MIL-on Bin. Bins 1 to 16 are used only with the MIL-off.*				

Notes:

1. Bin 1 stores the total value of the parameter in a given array. The values in Bins 2 through 14 must sum to equal the value in Bin 1.

2. Bin 2 stores data when the vehicle speed is 0 km/h for any level of engine power output.

3. Bins that store data when the engine power output is less than or equal to 25% of rated power:

   a. Bin 3 is for vehicle speeds greater than 0 km/h and less than or equal to 16 km/h (10 mph);

   b. Bin 4 is for vehicle speeds greater than 16 km/h and less than or equal to 40 km/h (25 mph);

   c. Bin 5 is for vehicle speeds greater than 40 km/h and less than or equal to 64 km/h (40 mph);

   d. Bin 6 is for vehicle speeds greater than 64 km/h.

4. Bins that store data when the engine power output is greater than 25% of rated power and less than or equal to 50% of rated power:

   a. Bin 7 is for vehicle speeds greater than 0 km/h and less than or equal to 16 km/h (10 mph);

   b. Bin 8 is for vehicle speeds greater than 16 km/h and less than or equal to 40 km/h (25 mph);

   c. Bin 9 is for vehicle speeds greater than 40 km/h and less than or equal to 64 km/h (40 mph);

   d. Bin 10 is for vehicle speeds greater than 64 km/h.

5. Bins that store data when the engine power output is greater than 50% of rated power:

   a. Bin 11 is for vehicle speeds greater than 0 km/h and less than or equal to 16 km/h (10 mph);

   b. Bin 12 is for vehicle speeds greater than 16 km/h and less than or equal to 40 km/h (25 mph);

   c. Bin 13 is for vehicle speeds greater than 40 km/h and less than or equal to 64 km/h (40 mph);

   d. Bin 14 is for vehicle speeds greater than 64 km/h.

6. Bin 15 stores data only when the engine is operating within the NOx NTE control area and no exclusions apply as defined in 40 CFR 86.1370.

7. Bin 16 stores data only when an active PM filter regeneration event is being commanded. Bin 16 stores data independently of Bin 15 and concurrently with Bins 1 through 14.

8. Bins 15 and 16 are defined as mutually exclusive conditions (with each other and Bin 17) but not with Bins 1 through 14.

9. Bin 17 is the only Bin that shall be used when the MIL is on. Bins 1 through 16 are only used when the MIL is off.

10. When the MIL is off, each sample is added to Bin 1.

11. Each sample shall also be added to Bin 15 when all the NTE conditions given in 40 CFR 86.1370 have been met, unless the conditions for Bin 16 apply.

12. The engine output energy estimate for 1 second shall be divided by engine rated power to determine the engine power percent.

13. Additional criteria are defined in 13 CCR 1971.1 for the suspension of data binning altogether.

14. The threshold vehicle speed value of 1.6 km/h may be implemented such that all vehicle speeds that are detected as 0 km/h, using existing vehicle speed measurement technology, may be considered to meet the idle threshold. It is not proposed or intended that new vehicle speed technology must be employed to accurately discriminate vehicle speeds between 0 km/h and 5 km/h.

7.2.3 MIL-On Status and Other Failure Conditions for REAL Data Collection.

Data shall be collected into Bin 17 when MIL is illuminated. Bin 17 tracking shall start within 10 seconds of MIL illumination. Bin 17 shall stop tracking within 10 seconds of MIL illumination stop. Data is still collected into Bins 1 through 16 if faults are pending but MIL has not yet been illuminated.

Exception: Bin 17 shall not collect information in case MIL is illuminated during presence of a fault that stops any binning. See 7.2.4.

Certain failures to vehicle speed measurement, NOx sensors, and exhaust mass flow estimation stop the collection of binning data altogether, including engine activity arrays. Data collection is also halted when the engine stop lamp is illuminated. A complete description of all possible failures for all known engine component architectures is beyond the scope of this explanation. Fault tree analyses of sensor system design and parameter estimation may be needed and compared to the regulation text to determine all possible causes to stop data collection. Examples of failures are shown in Table 2.

Table 2 - Potential failure conditions

Draft (h)(5.3.1) Parameter	Example Potential Failures
(A) NOx mass - engine out (g)	Engine out NOx PPM failure. MAF sensor failure (which may impact estimated exhaust mass air flow).
(B) NOx mass - tailpipe (g)	Tailpipe NOx PPM failure. MAF sensor failure (which may impact estimated exhaust mass air flow).
(C) Engine output energy (EOE) (kWh)	Fuel system quantity and/or timing failure could impact estimated torque samples; this impacts bin selection, too.
(D) Distance traveled (km)	Vehicle speed sensor failures, e.g., VSS open circuit. All data must not be sent into Bin 1. *The inability to estimate vehicle speed must stop data collection; the MIL must be illuminated when data collection is stopped.*
(E) Engine run time (hours)	Failures for engine run time (i.e., the microprocessor clock or the microprocessor power feed) are failures that would disable the microcontroller all together, or prevent the injection of fuel altogether)
(F) Vehicle fuel consumption (L)	Fuel system quantity failure would potentially disable fuel accumulation, if the engine continues to run.

7.2.4 NOx Binning Pause Conditions

(h)(5.3.6) Pause conditions for tracking [13 CCR 1971.1]:
(A) Except for malfunctions described in section (h)(5.3.6)(B) below, the OBD system shall continue tracking all parameters listed in section (h)(5.3.1) if a malfunction has been detected and the MIL is commanded on. Within 10 seconds of the MIL being commanded on, tracked data shall only be stored in Bin 17 as described in section (h)(5.3.3)(H) and storage of data in all other Bins (Bins 1-16) shall be paused. When the malfunction is no longer detected and the MIL is no longer commanded on, tracking of all parameters in section (h)(5.3.1) shall resume in Bins 1-16 and shall pause in Bin 17 within 10 seconds.
(B) The OBD system shall pause tracking of all parameters listed in section (h)(5.3.1) within 10 seconds if any of the conditions in sections (h)(5.3.6)(B)(i) through (iii) below occur. When the condition no longer occurs (e.g., , the engine stop lamp is not commanded on), tracking of all parameters in section (h)(5.3.1) shall resume within 10 seconds:
(i) A malfunction of any component used to determine vehicle speed has been detected and the MIL is commanded on for that malfunction;
(ii) A NOx sensor malfunction has been detected and the MIL is commanded on for that malfunction;
(iii) The engine stop lamp (if equipped) is commanded on.
(C) The manufacturer may request Executive Officer approval to pause tracking of all parameters listed in section (h)(5.3.1) if a malfunction occurs that is not covered under sections (h)(5.3.6)(B)(i) through (iii) above (e.g., , a light is commanded on for vehicles with no engine stop lamps such that the driver is likely to stop the vehicle, the odometer is lost, a malfunction of any component used as a primary input to the exhaust gas flow model occurs). The Executive Officer shall approve the request upon determining based on manufacturer submitted data and/or engineering evaluation that the malfunction will significantly affect the accuracy of the parameter values specified under section (h)(5.3.1).

GHG tracking pause conditions separate GHG data values from traditional HD engine data collection for engine hours, fuel used, vehicle distance, and others. NOx binning pause conditions mirror GHG tracking pause conditions.

7.2.5 Determine Sensor Status

A sensor signal is considered valid according to the following guidelines:

- Sensor is in reading mode.
  - Sensor is on. Sensor is not switched off by any default action, if applicable.
  - NOx sensor dew point is reached. It has been reached the moment from which sensor is able to make a measurement, if applicable.
  - Sensor light off is completed. This is the additional time specified by sensor manufacturer in order to receive a sensor concentration with the proper accuracy, if applicable. Light off time may be included in ECU NOx sensor status determination.
- No faults are present. Note: Diagnostic debouncing needs to be applied in order to understand if a fault is present.

If the NOx sensors have not failed, but one or more of the sensors is inactive, then only the engine activity bins are used to collect data.

7.2.6 DPF Regeneration Status

Data shall be collected into Bin 16 only when system is classified in active regeneration mode. Passive regeneration data shall not be stored in Bin 16. System is classified in active diesel particulate filter (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 actions are taken to assist it.

7.2.7 Debounce for NOx Binning

Debounce time for re-activating binning if binning has been disabled is 10 seconds, as defined in 13 CCR 1971.1 (h)(5.3.6) and in 13 CCR 1968.2 (g)(6.12.5).

7.2.8 Array Update Rates

All arrays shall be updated with information calculated at a frequency of 1 Hz. Supporting variables can be used to store intermediate information at higher resolution respect to their array resolution. In such cases, those supporting variable(s) shall be updated at a frequency of 1 Hz.

NOTE: Bins displayed in an array may not change every 1 second considering the required resolution. Indeed, second-by-second data collection of array data is not possible.

7.2.9 NH_3 Slip

NH_3 slip is a naturally occurring event and cannot be prevented under all operating conditions; therefore, the binned NOx may include NH_3 slip.

7.3 NOx Parameter Estimation

The following sections provide guidelines for the estimation of binning parameters.

7.3.1 Frequency for Parameter Estimation

Data in each array shall be updated at a minimum frequency of 1 Hz. An internal sensor sampling frequency of 5 Hz or greater is recommended for NOx binning parameter calculations to improve accuracy.

7.3.2 NOx Sensor Signal Corrections

NOx sensor signal corrections were addressed in 6.2.2.2 of this report and apply also to REAL NOx tracking and binning as well as the accuracy demonstration.

7.3.3 Management of Negative NOx Sensor Values

Management of negative NOx sensor values was addressed in = 6.2.2.3 of this report and apply also to REAL NOx tracking and binning.

7.3.4 Estimate NOx Mass

The estimation of engine out and tailpipe NOx mass shall use the following conversion method. The corrected NOx concentration in parts per million is multiplied by the estimated exhaust mass flow (kg/h) and multiplied by a constant factor of 0.001588. The constant factor 0.001588 includes the ratio of the NOx molecular weight and the standard molecular weight of air, thus estimating the average molecular weight of the exhaust stream.

$$\text{NOx (g/s)} = 0.001588 * \text{NOx (ppm)} * \text{Exhaust Flow (kg/h)}/3600 \qquad \text{(Eq. 13)}$$

If the estimated exhaust flow is in units of (g/s), the constant factor should be adjusted and the division by 3600 omitted.

$$\text{NOx (g/s)} = 1.588 * \text{NOx (ppm)} * \text{Exhaust Flow (g/s)} \qquad \text{(Eq. 14)}$$

The number of significant digits are defined in the ISOR ["Staff Report: Initial Statement of Reasons"]:

> *Here, 0.001588 is calculated as Molecular Weight of NO_2 [g/mol]/ Molecular weight of air[g/mol]/1000 [g/kg]. Molecular weight of NO_2 = 46.01 g/mol and molecular weight of air = 28.97 g/mol.*

7.3.5 Estimate Engine Output Energy

Engine output energy (EOE) is estimated as the sum of the torque samples/divided by the number of samples (this second) * engine speed (r/min) * 104.725. Torque is calculated using actual (indicated) engine percent torque (Tact in %), nominal friction percent torque (Tfric in %), and reference torque (Tref in Nm), as shown in Equation 15. Negative torque samples should be ignored, as they represent momentum absorbed by the engine from the vehicle in conditions when the engine is not fueled or other infrequent occurrences such as vehicle operation downhill with low engine fueling. Equations 16 through 20 show the derivation of the constant term in Equation 15.

$$EOE = \sum (T/n) * N * 104.725 \qquad \text{(Eq. 15)}$$

where:

$T > 0$

$$T = (Tact - Tfric) * Tref \qquad \text{(Eq.16)}$$

$$P = T\ \omega \qquad \text{(Eq. 17)}$$

$$P = T * 2\pi\ N/60 \qquad \text{(Eq. 18)}$$

$$P = T * N/9.5488\ \text{(kW)} \qquad \text{(Eq. 19)}$$

$$1/9.5488 * 1000 = 104.7252\ \text{(W)} \qquad \text{(Eq. 20)}$$

This definition of engine output energy will be divided by rated engine power as part of the NTE Bin (Bin 15) selection for vehicles where NTE is required. When the engine is not producing power, negative values of torque may reflect the operation of exhaust or compression brakes, in addition to circumstances where momentum is absorbed from the vehicle or flywheel.

7.4 Not-to-Exceed (NTE)

The not-to-exceed (NTE) conditions are described in U.S. federal regulations including 40 CFR 86.1370, as well as the draft California HD Omnibus regulation ["Heavy Duty Engine and Vehicle Omnibus Regulation and Associated Amendments"]. Key aspects of the regulations defining NTE conditions are summarized below.

- NTE zone control area.
- Barometric pressure ≥82.5 kPa.
- Exhaust temperature not too cold.