2021

Investigating NO_x vs CO₂ Tradeoff in Heavy Duty Emissions Through the Years Under the Scope of CARB's 3-Bin Moving Average Window Method

Ghadi Sadek

West Virginia University, ghsadek@mix.wvu.edu

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Investigating NO_x vs CO₂ Tradeoff in Heavy Duty Emissions Through the Years Under the Scope of CARB's 3-Bin Moving Average Window Method

Ghadi Sadek

**Thesis submitted
to the Benjamin M. Statler College of
Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements for the degree of
Master of Science in
Mechanical Engineering**

**Arvind Thiruvengadam, Ph.D., Chair
Marc Besch, Ph.D.
Derek Johnson, Ph.D.**

**Department of Mechanical and Aerospace Engineering
West Virginia University
Morgantown, West Virginia
2021**

Keywords: Diesel Exhaust Emissions, CARB regulation, 3-Bin Moving Average Window, Nitrous Oxides, In-Use Testing

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ABSTRACT

Investigating NO_x vs CO₂ Tradeoff in Heavy Duty Emissions Through the Years Under the Scope of CARB's 3Bin Moving Average Window Method

Ghadi Sadek

With the rise in urban pollution level over the last few years, regulatory agencies around the world have taken multiple steps to ensure engine exhaust pollutant are well monitored and properly regulated. Yet there exists a significant difference in emissions rates in various operating conditions between US and European products which currently uses a Moving average window (MAW) approach for their in-use compliance testing and certification program.

Using WVU's vehicle data collected using PEMS devices, this study aims at investigating the NO_x versus CO₂ tradeoff found in heavy duty diesel engines equipped with different aftertreatment technologies, under the scope of the recently proposed CARB 3Bin-MAW heavy duty in-use testing method set to be implemented for model year engines 2024+.

Using the CARB document, the new program was implemented on vehicles from both goods movement and delivery vocation with the aim of highlighting any benefits this method includes. This approach towards engine certification allows for a more comprehensive final result that accounts for low load and idle operations, as opposed to the current Not-to-Exceed (NTE) method encompasses a narrow band of operation, mainly highway. This allows manufacturers and regulators to observe and analyze heavy duty vehicle emissions under the most challenging operations.

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1 Introduction

With increasing weariness over climate change, the world has been focusing its efforts in controlling industries whose byproducts have the most impact on the environment. Since the pre-industrial era until 2018, the concentrations of common greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and Nitrous oxide (N_2O) have increased globally by 46, 165 and 23 % respectively [1]. More recently in the United States (US) alone CO_2 rose by 0.9 %, CH_4 by 1.7 %, and NO_x by 2.4 % from 2017 to 2019 [26]. These greenhouse gases are mostly attributed to the burning of fossil fuels used in transportation, industrial, as well as residential and commercial sectors. With the introduction of the internal combustion engine into these sectors, and especially the transportation sector abandoning steam-based alternatives for the more favorable at the time gasoline alternative. That period marked the true beginning of industrialization's chronic impact on the chemical composition of our atmosphere, and consequently the air we breathe.

In the US alone, transportation activities account for 36.3 % of CO_2 emissions from fossil fuels in 2018, 23% of which is attributed to diesel fuel consumption. Concurrently in 2014, the transportation sector accounted for more than 7 million tons of NO_x emitted in the US, 50 % of which is credited to Heavy Duty Diesel (HDD) applications [1, 2]. Due to the decreasing air quality and negative effects on the environment, regulations aimed at lowering emissions have been present since the 70's, with agencies such as the US Environmental Protection Agency (EPA), the National Ambient Air Quality Standards (NAAQS), and the California Air Resources Board (CARB) that lead the charge on HDD emission standards. Over the years, regulations have pushed manufacturers towards lowering their emissions by implementing new technologies. Initially manufacturers complied by altering the combustion tactics, such as reducing intake temperatures, or exhaust gas recirculation (EGR) among others [3]. This was followed by the introduction of exhaust gas aftertreatment systems, composed of multiple subsystems each designed to target a specific pollutant. These include Diesel Particulate Filters (DPF) and Selective Catalytic Reduction (SCR), which specifically target Particulate Matter and Nitrogen Oxides (NO_x) respectively. These advancements lower tailpipe emissions without much compromise to engine performance and efficiency.

Regulatory agencies have been setting standards for NO_x emissions for HDD engines to meet certification for operation. Programs have been put into place to utilize real-world emissions data, such as the Heavy Duty In-Use Testing (HDIUT) program led by the EPA to enforce policies. Regulations proposed and implemented by CARB and the EPA have led current HDD to meet certification at 0.2 grams per brake horsepower-hour (g/bhp-hr) of NO_x. But due to the complexity of current aftertreatment systems, ensuring proper operation becomes more challenging [4]. Certification data extruded from test cycles are different from real world, on-road vehicle data, forcing regulatory organization to seek better means to process emission data and simulate real operations during certification processes.

Consequently, CARB further looks to refine its certification process by implementing a Three-Bin-Moving-Average Window (3Bin-MAW) method for analyzing real-world data of HDD vehicles. This method would allow an operation-based approach towards analyzing and classifying emissions results.

Using the data collected by WVU CAFEE, this study will be looking at the NO_x and CO₂ rates of selected vehicles through the scope of the proposed 3Bin-MAW method, and investigating the tradeoff using this proposed approach, as well the benefits and shortcomings of employing the recent amendment.

2 Literature Review

2.1 History

In the 1960s, diesel engines were the top source of power for the commercial trucking industry. While automotive emissions were gathering public concern over potential health risks, The US enacted the Clean Air Act in 1963 to help reduce and control pollution, and through the years the diesel engine saw updates and evolutions to help meet these guidelines. Since the mid-2000s, diesel engines have become equipped with various new aftertreatment technologies to help reduce emissions and make them more environmentally friendly [8]. Government agencies around the world set emission standards and certification procedures for diesel engines in an effort to further decrease the pollutants emitted and enhance performance.

In order to ensure the limits, set for engine emissions are maintained, a major improvement included in the EPA 2010 regulation was the requirement of in-use heavy duty vehicle testing. This manufacturer run heavy duty in-use testing program, also known as HDIUT, requires engine emissions to be continuously measured using a portable emission measuring system (PEMS). In order to determine regulatory compliance, the collected data is evaluated under the Not-to-Exceed (NTE) protocol. The average emissions for each valid NTE event are then compared to the NTE emission limit. A valid NTE event must include PEMS data that meet predefined requirements relating to engine speed, engine torque, as well as exhaust and coolant temperatures. These validity requirements mostly target higher operations, such as highway driving, and rejects data attributed to lower/urban driving conditions [32,33]. Under the NTE method, low load and urban operations are disregarded regardless of the vocation of the vehicle, and only a narrow range of operation is represented in the result. This method also allows for a gap between real world emissions and engine certification levels.

The European emission program uses different approach when evaluating heavy duty diesel emissions. The current equivalent for the 2010 US regulation, the Euro VI, uses a moving average window protocol (MAW) for the in-service conformity program (ISC). The European MAW method encompasses a broader range of operation for in-use compliance testing, where the only data exclusion condition is only based on the average window power. This allows for urban and low load operations being included in the final in-use compliance evaluation.

Furthermore, the European model requires specific amounts of driving time under urban, rural, and highway conditions. This inclusive testing program allows for better NO_x control under low and creep operating conditions [32,33].

CARB and the EPA plan on adopting an improved moving average window method for the upcoming 2024+ emissions regulations.

2.2 Background

The diesel engine is an internal combustion engine which produces mechanical work by converting the chemical energy in diesel fuel. It does so by means of combustion. Unlike gasoline and other spark ignited engines, which as the name implies uses a spark to ignite the air/fuel mix, diesel engines initiate the combustion process by compressing the heterogenous fuel/air mix until it reaches a high enough temperature to combust. Most diesel engines run on a four-stroke cycle to achieve the conversion from chemical potential to mechanical work. The first cycle starts by taking in air into the cylinders, where it goes on to be compressed and injected with fuel in the second stroke, leading to combustion within the cylinder. The expansion gas caused by the ignition pushes the piston head down, outputting mechanical work and defining the third stroke. The burnt gas is then discharged (fourth stroke) and the process repeats [9].

An ideal complete combustion of diesel ($C_{12}H_{23}$) can be represented by the following equation:

Yet this completed combustion can only occur in an ideal world, under very specific and controlled parameters. In actuality this combustion is rarely, if ever, fully completed and yields many undesirable pollutants such as nitrous oxides (NO_x), unburnt hydrocarbons (HC), particulate matter (PM), and carbon monoxide (CO) [10].

2.2.1 Reasons for NO_x formation

Although NO_x can be formed naturally in the environment, it is the industrial emittance that is causing a visible degradation in the quality of air. Ambient air and fuel based combustion processes opens opportunities for NO_x formation, notably the following mechanisms [9]:

Thermal NO_x: thermal NO_x formation is controlled by the reaction zone temperature, in diesel engines that would be the combustion temperature, as well as the air-fuel ratio since it affects the atomic oxygen and nitrogen concentration found in the combustion mixture. Lower combustion temperatures (below 1300 °C) coupled with a decreased air-fuel ratio lowers thermal NO_x formation.

Prompt NO_x: Prompt NO_x is formed at the flame front of the combustion, especially in rich fuel mixtures due to the unavailability of oxygen. Nitrogen oxidized alongside the radicals of CH creating cyanhydric acid (HCN) and nitrogen oxide (NO) at the end of the reaction. This mechanism causes hydrocarbon radicals to react with nitrogen to produce amine compounds, which are then converted to intermediate compounds, forming NO_x. The formation of the intermediate compounds are presented below [11]:

The conversion from hydrogen cyanide (HCN) to NO is expressed in the following:

Although NO_x compounds are naturally formed in the environment, any additional formation caused by human activity can lead to an oversaturation of these harmful compounds in the air.

NO on the other hand is mostly produced by human activity, and has been found to cause health problems, mainly complications for blood to absorb oxygen [12]. Nitrogen dioxide (NO₂) is also a toxic gas known to cause abnormal accumulation of fluid in the pulmonary tissues at high concentrations. Acid rain is caused by NO₂, alongside other NO_x reacting with water and sulfur dioxide (SO₂) found in the stratosphere. This increases acid deposits and consequently decreases ecosystem stability [29,12]

2.2.2 Regulation

With the concerns over vehicle emissions rising in the late 1950's, and potential health risks and environmental consequences of industrialization, many governments around the world started taking federal action to mitigate and control air pollutants being release in the atmosphere. In 1955, the US passed the first federal legislation tackling air pollution, named the Air Pollution Control Act. This legislation provided funding for research into air pollution, the reasons and consequences of it, yet offered no information or incentive to research pollution control or mitigation. This led legislators to pass the Clean Air act in 1963, aimed at air pollution control. This act established governmental programs and authorized research into air pollutant control and monitoring, all within the US Public Health Service. From there on, the Clean Air act has featured many amendments over the years, allowing federal agencies more control and monitoring towards air pollutants, including inventories of emissions, control strategies to mitigate pollutants, and ambient monitoring techniques, from both stationary and mobile air pollution [5,8].

The 1970 Clean Air Act amendment brought major changes in the government's role in overseeing air pollution. It introduced the first state regulations aimed at limiting emissions from both mobile and stationary sources. This legislation required a 90 % decrease in HC, CO, and NO_x emissions from new automobiles by 1975, and in order to regulate and monitor the rules being set, Richard Nixon, president at the time, established the Environmental Protection Agency (EPA). This agency was responsible for regulating and monitoring motor vehicle emissions such

as CO, HC, NO_x, particulate matter or soot (PM), and SO₂. The EPA has set standard and limits for these pollutants and continue to build upon them over time [10,13].

The first set of emission standards regarding heavy duty diesel engines was introduced in 1974, targeting CO, HC, and NO_x emissions. The standards were tightened in the following decades, whereby the end of the century there existed a PM emission standard of 0.10g/bhp.hr, and a NO_x limit of 4 g/bhp-hr. EPA and CARB also introduced a set of regulated cycles and test procedures, such as the Federal Test Procedure (FTP) transient and steady state cycles, as well as Not-to-Exceed (NTE) testing. The inclusion of regulated tests and cycles allow for a uniform conformity in emission standards for HDD engines operating in the US. With the new proposed amendment, CARB seeks to better represent the emissions seen during a variety of operations, making its certification process more comparable events seen in real-world operations [4,8].

The following figure 1 [4,5,8] illustrates the emissions limits for heavy duty engines through the years, under an FTP cycle, as well as future emission standards:

Figure 1- NO_x and PM emissions standards for heavy-Duty Diesel Engines Timeline

In the early phases of NO_x and general emissions control initiative, manufacturers could meet the mandated reduction through in-cylinder strategies including injection control and piston

geometry [28]. However, with increasing restrictions on diesel emissions, the newer limits cannot be met without the use of exhaust aftertreatment systems [4,5].

2.2.3 Aftertreatment Systems

With increasing emission restrictions being imposed by regulatory agencies, manufacturers have invested more in both in-cylinder strategies, as well as aftertreatment technology to help meet the required emission standards for each pollutant. Some of the most notable advancements will be described in this section.

2.2.3.1 Diesel Particulate Filters (DPF):

Diesel Particulate Filters (DPF), or sometimes referred to as diesel particulate traps are physical filters, usually made from ceramic materials, that trap diesel particulate matter or soot commonly found among exhaust gasses. The substrate material found in common diesel particulate traps are designed in a honeycomb structure using ceramic based materials that aids in trapping soot and ash. The captured particles are stored within the DPF throughout the operation of the vehicle until it reaches its loading capacity, where a regeneration sequence is initiated to burn off the loaded pollutant [14].

Figure 2-Diagram of Common Diesel Particulate Filter [34]

In most cases, the DPF is located upstream of the SCR in order to reduce the amount of solid particles entering the catalyst. DPFs nowadays rely on material advancements to achieve high filtration efficiencies, specifically ceramic materials including cordierite, silicon carbide and aluminum titanate. These materials coupled with a honeycomb design can achieve large filtration areas and efficiencies while minimizing pressure losses and retaining high thermal durability. Such filters are able to achieve filtration efficiencies well over 90% [15,16].

2.2.3.2 Selective Catalyst Reduction (SCR):

An SCR is an aftertreatment technology introduced into diesel exhaust systems that converts NO_2 , NO , and any pollutant with significant oxygen content (O_2) found in exhaust gases into molecular oxygen and nitrogen. It does so by injecting a liquid nitrogen compound, ammonia or urea, into a reactor housing covered by a catalyst incorporating base metal oxides, precious metals or Zeolite. The injected solution coupled with the catalyst material and exhaust gases converts the harmful pollutant to nitrogen, oxygen, water and minimal amounts of CO_2 , which are natural component of ambient air [12,19].

Diesel Emissions Control System

Figure 3- Diagram of Selective Catalytic Reduction (SCR) [35]

In SCR diesel applications, ammonia (NH_3) or Diesel Exhaust Fluid (DEF) is injected into the inlet gas upstream of the catalyst bed. Once injected and in the catalyst bed, the ammonia reacts with the nitrous oxides and oxygen in the gas stream to form nitrogen (N_2) and water (H_2O). The efficiency achieved ranges from 70 to 90 %. The ratio of NH_3 injected and NO_x in

the stream, as well as the catalyst material and operating temperature will impact the reducing efficiency of the SCR [11,12].

Ideal operating temperatures for base-metal catalysts falls within the range of 600-750° F, or 315-400° C. Platinum catalyst require lower temperature, whereas zeolite catalysts requires operating temperatures from 600 to 900°F (315-485°C), and sometimes as high as 1100°F (590°C). When an SCR operates below the ideal temperature ranges, the catalyst performance is reduced and the likelihood of un-reacted NH₃ existing the tailpipe increases. This is referred to as ammonia slip. When operating above the required range, the NH₃ may oxidize and form NO_x, opposing the device purpose [17, 18].

The performance of SCR systems can be described using the outlet NO_x concentrations, the NH₃ to NO_x ratio, as well as catalyst bed temperature, exhaust gas flow rate through the SCR, differential pressure across the bed and outlet NH₃ concentrations [12, 18].

2.2.4 Measurement Devices and Techniques

Figure 4-PEMS Gas Path Diagram [36]

In order to confidently certify a vehicle/engine as emission compliant, researchers in that field have developed multiple emission measuring systems, and analyzers capable of accurately measuring the amount of pollutants emitted, as well as the concentration and number of particles being released in a given cycle. These analyzers and sensors are used in both on-road and chassis/dynamometer testing environments to describe the emission profile of the engine/vehicle being tested.

Portable Emission Measurement Systems, or commonly referred to as PEMS are emission measurement devices that are small and light enough to be used on-board a vehicle being driven on a road for testing, rather than on dynamometer. PEMS allow for accurate and reliable real-time measurement of multiple gases, including NO_x, CO, CO₂, and HC's. They can accomplish that by using one of the following technologies [19,20]:

2.2.4.1 *Fourier Transform Infra-Red (FTIR)*

Fourier Transform Infra-Red spectroscopy, or FTIR, is a method that measures the range of wavelengths in the infrared region that are absorbed by a material, in this case pollutant gases. It works off the principle that molecular bonds between different elements absorb light at different frequencies. It does so by using an interferometer, a device capable of producing an optical signal with a wide range of infrared frequencies through the gases, and a detector, in this case a sample cell that relays the information to be decoded using a Fourier Transformation [21].

Figure 5- FTIR Interferogram Representation [31]

FTIRs are capable of measuring a wide variety of gasses simultaneously, including NO_x , NH_3 , N_2O , as well as some HCs like CH_4 .

2.2.4.2 *Non-Dispersive Infrared (NDIR)*

Non-Dispersive Infrared analyzers are much like FTIR in their working principle. The gas flow is guided through a chamber where it uses an infrared light through the gasses to measure the absorption and returns information about the gas composition of the stream. But this system is only capable of measuring specific wavelength bands at a time. Although NDIR is typically reserved for CO/CO_2 as well as N_2O measurements, it is also capable of measuring CH_4 and SO_2 [24].

2.2.4.3 *Non-Dispersive Ultraviolet (NDUV)*

Commonly used to measure NO_x , the NDUV technique operates much like the NDIR. The analyzer guides the gasses through a chamber where the gas composition is determined by the absorbed UV wavelength. The ultraviolet absorption method functions on the principle that ozone absorbs ultraviolet rays in the wavelength around 253 nm [22].

2.2.4.4 Chemiluminescence Detectors

Figure 6- Chemiluminescent gas path diagram [30]

Chemiluminescence sensing takes advantage of the light producing reaction between NO and Ozone (O_3) to measure the concentration of NO in the gas sample. Under a controlled volume of ozone and sample gas, the light level emitted from the reaction is proportional to the concentration of NO in the sample. This light is measured using a photomultiplier tube able to detect photons [30, 19]. NO_x can also be measured when reduced to NO by passing the sample over a heated catalyst [30, 19].

2.2.5 Moving Average

A moving average window, or sometimes simply referred to 'moving average', is a statistical tool used to analyze data points by creating a series of averages of different subsets of the full data (windows). This method creates a type of finite impulse response filter since the window sizes are pre-defined. Given the amount of fluctuations we encounter with emission measuring equipment, as well as some on board sensors put in place by engine manufacturer, a moving average data analysis smoothens the aforementioned fluctuations, but also highlights long-term trends, crucial for large dataset analysis.

Figure 7 depicts the effect a moving average has on vehicle speed, where a much smoother curve is generated rather than a fluctuation one representative of the raw vehicle speed data points [5,25].

Figure 7- Comparison between Raw Data and Average windowed Data

The moving average replaces a set of data points (pre-defined at 300 seconds above) with its average. The window is then moved over by one time step, excluding the first number of the previous window and adding the next value in the subset that was not included in the first window. This allows the windowed values to mitigate any instabilities while retaining a similar resolution to the raw data.

3 Methodology

3.1 Data Reduction

By using MATLAB®, a code was generated to analyze each vehicle trip's continuous data availability and quality, and extract the relevant channels for this study, mainly: vehicle speed, exhaust temperature, instantaneous mass specific CO₂ (downstream of DPF), instantaneous mass specific NO_x (downstream of SCR), and engine exhaust temperature. Each of the mentioned channel's contents were evaluated for their zero and Not-a-Number entries to insure proper vehicle selection suited for this study.

3.1.1 CARB 3Bin-Moving Average Window.

The proposed CARB method specifies a MAW reference time of 300 seconds, meaning the window length must be 300 seconds of valid data, with each window overlapping by a time increment equal to the sampling rate of at least 1Hz. Any invalid data encountered will be skipped, and valid data will be included at the end of the window to compensate and remain at the same length of 300 [5]. The length of the window is predefined to allow for proper temperature distribution and account for the thermal inertia of the exhaust gases Based on the report, data is excluded from the windows if it was collected during the following conditions:

- Atmospheric pressure less than 82.5 kPa
- Ambient air temperature less than -7 deg C (19°F)
- Altitudes greater than 5,500 ft above sea-level
- Zero drift check or conditioning of PEMS instruments.

Further exclusions involve engine coolant temperature, where data is considered valid when one the following coolant temperature requirements are met:

- The coolant temperature has reached 70 °C (158°F) for the first time since starting the engine.
- The coolant temperature has stabilized withing +/- 2 °C (3.6 °F) over a period of 5 minutes.

In order for a test to be considered valid, the coolant temperature at the start of the test must not exceed 86 °F, as well as a minimum of 3 hours of non-idle operation. In addition, the average power of the engine over the duration of the test must be equal to or greater than 10% of the engine's peak power [5].

3.1.2 Vehicle Selection

In order to obtain a comprehensive study, vehicles were selected based on vocation, and the availability of channels providing the needed parameters.

In addition, vehicles from different model years were used in this study to highlight the differences in aftertreatment advancements and their impact on the amount of pollutants released into the atmosphere. Although most of the vehicles selected feature common aftertreatment systems such as DPF and SCR, the differences in model years as well as manufacturers would allow for a more inclusive study of the differences in them.

The proposed amendment's data exclusion guidelines were followed in order to properly select vehicles of different vocations for this study. Due to the limited database of valid data fit for this study, only two vocations would be considered, Goods Movement and Delivery Vehicles. But in order to conduct this study with the available data, the restriction for the engine coolant temperature at the start of the test has been bypassed for the vehicles selected, since the vehicle data collected was not originally intended for this application. However, the stability criteria as well as the minimum threshold regarding the coolant temperatures will be accounted for. The following table showcases the selected Vehicles.

Table 1- Goods Movement Vehicles Selected.

	Goods Movement							
	Make	Model Year	Mileage (mi.)	Max HP (bhp)	FTP FCL (g CO ₂ /bhp-hr)	Trip mileage	Hours of operation	% Idle Operation
Vehicle 1	Detroit Diesel	2013	482,998	410	539	235.84	9.96	37%
Vehicle 5	Mack	2016	89,397	417	543	147.05	9.50	33.2%
Vehicle 50	Cummins	2015	197,371	385	579	152.51	8.55	50%
Vehicle 57	Mercedes-Benz	2006	858,122	450	509	94.29	3.15	18.2%
Vehicle 69	Volvo	2016	66,299	407	543	218.1	8.60	27%
Vehicle 88	Volvo	2011	398,291	400	543	148.32	8.52	43.2%

Table 2- Delivery Vehicles Selected.

	Delivery Vehicles							
	Make	Model Year	Mileage (mi.)	Max HP (bhp)	FTP FCL (g CO ₂ /bhp-hr)	Trip mileage	Hours of operation	% Idle Operation
Vehicle 46	Paccar	2013	40,510	260	553	12	3.35	79%
Vehicle 52	Paccar	2015	28,127	330	553	22.62	6.83	80%
Vehicle 54	Paccar	2008	66,541	315	553	23.92	5.31	72%
Vehicle 149	Cummins	2015	84,486	280	564	56.86	8.90	68%

3.1.3 Normalized Average CO₂

Once the windows have been compiled, the normalized average CO₂ rate of each window will be used as the reference for binning the data [5]. The normalized average CO₂ rate is calculated as follows:

$$\text{Normalized Average } CO_2 = \frac{CO_{2\text{average}}}{FCL * HP_{\text{max}}}$$

Where,

$CO_{2average}$: average emission rate of the window in $\frac{g}{hr}$.

FCL : family certification level in $\frac{g}{bhp - hr}$.

HP_{max} : Maximum rated engine horsepower in bhp.

3.1.4 Binning Criteria

The windows are categorized into one of three bins: idle, low load, and medium/high load. Classification of the window is determined by the normalized CO2 rate over the 300 second period of operation [5]. The 1Hz data corresponding to the 300 second window is placed into the appropriate bin as follows:

- *Idle Bin* - Normalized average CO2 rate **less than or equal to 6%.**
- *Low Load Bin* – Normalized average CO2 rate **greater than 6% and less than or equal to 20%.**
- *Medium/High Load Bin* – Normalized average CO2 rate **greater than 20%** [5].

3.1.5 Emissions Evaluation

Once the windows have been binned appropriately, the bin emissions for each pollutant (NMHC, CO , NOx, and PM or soot) will be calculated for each bin using a Sum-over-Sum (SOS) evaluation to determine the pass criteria. For the low load and medium/high bins, the SOS emissions are calculated using the following equation [5]:

$$e_{sos,a,b} = \frac{\sum_{k=1}^n \dot{m}_a * \Delta t}{\sum_{k=1}^n \dot{m}_{CO2} * \Delta t} * e_{CO2,FTP,FCL}$$

Where,

$e_{sos,a,b}$: sum over sum emissions, a is the criteria pollutant and b is the bin $\frac{g}{bhp - hr}$

$\dot{m}$: mass of criteria pollutant in $\frac{g}{s}$

$e_{CO2,FTP,FCL}$: engine FTP CO2 family certification level in $\frac{g}{bhp-hr}$

n : number of seconds in bin

Δt : data sample rate

For the low load bin, the following equation is used:

$$e_{sos,a,idle} = \frac{\sum_{k=1}^n \dot{m}_a * \Delta t}{\sum_{k=1}^n \Delta t} * \frac{3600sec}{1hr}$$

Where,

$e_{sos,a,idle}$: sum over sum emission of criteria pollutant in g/hr.

3.1.6 Pass Criteria

Once the sum-over-sum values for each pollutant, in each bin have been calculated, the engine pass criteria is then determined by comparing each sum-over-sum emission rate to the in-use thresholds in table 3:

Table 3- CARB 3-BIN MAW Bin structure and thresholds [5].

<u>Bin</u>	<u>Normalized average CO2 rate</u>	<u>SOS In-use threshold</u>
IDLE	$\leq 6\%$	$e_{sos,a,idle} \leq 1.5 \text{ Idle std}$
LOW	$6\% < CO2_{norm} \leq 20\%$	$e_{sos,a,low} \leq 1.5 \text{ LLC std}$
MEDIUM/HIGH	$20\% <$	$e_{sos,a,M/H} \leq 1.5 \text{ FTP/RMC std}$

Yet it is important to note that these in use thresholds will be applicable to 2024+ year models, as shown in table 4.

Table 4- Proposed NOx standard for MY 2024+

<u>Test</u>	<u>NOx</u>
IDLE	10 g/hr
LLC	0.2 g/bhp-hr
FTP&RMC	0.05 g/bhp-hr

Since this study will be looking at vehicles as far back as 2006, the standards used in this paper will be adjusted to accommodate the earlier model year vehicles, specifically for the idle and low bins due to the lack of a low load standard and limited idling restriction. Table 5 holds two standards for the idle bin. One based on the 2024 standard and the other on the optional idle standard of 30 g/hr for 2010 models. The Med/High passing criteria also holds two values, using the 2010 FTP standard as well as the proposed 2024 limit.

Table 5- Proposed thresholds for each Bin.

$e_{NOx,idle}$	$e_{NOx,Low}$	$e_{NOx,Med/High}$
15 -45 g/hr	0.3 g/bhp-hr	0.075-0.3 g/bhp-hr

4 Results

4.1 3B-MAW Results for Goods Movement Vehicles

By implementing the methods discussed in Section 3.2, the following graphs for the Goods movement vehicles were generated. Figure 8 shows the percentage of individual datapoints collected from the vehicle that have been distributed across the three bins or excluded according to the CARB proposed moving average window method and binning criteria mentioned in sections 3.1.2 and 3.1.5 respectfully.

Figure 8- Percentage of single data points excluded and appearing in 1,2, or 3 bins simultaneously for Good Movement vehicles.

With the proposed exclusion conditions in effect, vehicles in the goods movement category show an average of approximately 53.7% of data points attributed to one bin, whereas 27.8% of individual data points were found in two bins at the same time and around 1.4% of points in three bins simultaneously.

Among the valid windows not excluded, Figure 9 serves to illustrate the distribution of valid windows among the three Bins, according to section 3.1.5.

Figure 9- Percentage count of windows attributed to each bin for Goods Movement vehicles.

For vehicles in the goods movement category, as expected due to most of their operation being on-highway or long-haul, the majority of windows collected were placed into the Med/High Bins. Each vehicle in the category with the exception of vehicles 5 and 88 include the larger percentage of valid windows in their Med/high bin. To review more closely the operation of each window found in the three bins, Figures 10 and 11 describes the average operating speeds and exhaust temperatures of each bin for vehicles in the goods movement category.

Figure 11- Average Vehicle Speed (mph) for each bin for Goods Movement Vehicles.

Figure 10- Average Exhaust Temperatures for Goods movement vehicles

Figure 11 highlights the operational speeds found in each category bin. Since CARB's proposition intends to classify the data based on operation, idle, low, and medium/high load, as

expected the figures above show the increasing trends between the three bins for each vehicle for both temperature and speed.

As shown in section 3.1.5, the Idle bin includes an emissions result measured in g/hr for each criteria pollutant, whereas the Low and Med/high bin's sum-over-sum results are brake specific (i.e. g/bhp-hr). For that reason, it is more beneficial to analyze the Idle Bins individually.

Goods Movement Idle Bin:

Figure 12- Idle Bin NOx in g/hr (left) and brake specific CO₂ in g/bhp-hr (right) for Goods Movement Vehicles

The results shown in Figure 12 were generated following the proposed CARB Idle bin classification based on a normalized averaged CO₂ rate less or equal to 6 %, and the specific calculations for the sum-over-sum results for NO_x. The results were compared to the standards/thresholds described in section 3.2.6.

As it shows, all vehicles in this category meet the Optional 2010 idle standard for NO_x emission, including Vehicle 57 which lacks an SCR. It is also worth noting that although Vehicles 5 and 69 are more recent and equipped with an SCR, their idle NO_x rate are higher than that of Vehicle 57. Relating back to Figures 10 and 11, Vehicle 5 features the lowest exhaust temperature between the idle bins at 115.3 deg °C, and Vehicle 69 shows the highest in the category average speed of about 2.9 mph, more than double that of Vehicle 5 and triple that of

vehicle 50. Vehicles 1, 50, and 88 produced an Idle sum-over-sum result for NO_x near or below the proposed 2024+ Idle NO_x standard.

Based on the 3-Bin approach and its results shown in Figure 12, Vehicles 1, 50, and 88 include the lowest Idle bin results in the category despite Vehicles 1 and 88 being MY2011 and MY2013 respectively, whereas Vehicles 5 and 69 are the newest of the category (MY 2016).

Looking at the right side figure, the CO₂ rates for the idle bins show an overall increase over the different model year vehicles. Where the oldest vehicles in this study feature the lowest CO₂ rates in the category.

Based on the right side of the figure, the lowest Idle NO_x producing vehicles mentioned above also features the second highest CO₂ rates in the category, and Vehicle 69 having the highest rates of NO_x and CO₂ in the category, including the SCR lacking Vehicle 57.

Table 6- Averaged Temperature and Vehicle speed for Idle Bins of Good movement Vehicles

Idle Bin	Vehicle 57	Vehicle 88	Vehicle 1	Vehicle 50	Vehicle 5	Vehicle 69
Temperature (°C)	125.7	142.8	141.4	161.0	115.3	158.8
Vehicle Speed (mph)	1.5	1.4	2.0	0.8	1.3	2.9

The low temperatures found in the Idle Bin are the main cause for the underperformance of SCR equipped vehicles, where Figure 12 shows the two most recent vehicles in the category surpassing the oldest vehicle without an SCR in the Idle NO_x results. This might be indicative of the different in-cylinder strategies adopted by manufacturers to mitigate the emitted NO_x before it reaches the aftertreatment system. Vehicles built with a fully equipped aftertreatment would rely on its components and technology to reduce the bulk of the exhaust emission, specifically NO_x, but still try to maximize the reduction of nitrous oxides before reaching the exhaust system, without compromising the performance of the aftertreatment systems in place. This allows a slightly elevated effort for in-cylinder CO₂ reduction. This relates the elevated NO_x results for the newer vehicles 5 and 69 in the idle bin. With an SCR in place, these vehicles depend on the aftertreatment to reduce the bulk of the NO_x emitted, so in operations where the SCR is below its operating temperature range (as seen in the idle bins), the NO_x emitted from these vehicles is the highest in the category. Although these vehicles might be able to further reduce the NO_x emitted in the idle phase, this might come at the cost of lesser SCR performance or a delay in the SCR

reaching its ideal efficiency in higher operational modes. This approach fits in with this vocation since most of the operation of these vehicle is assumed to be highway operation, with little idling.

Vehicles that do not feature an SCR aftertreatment system, such as Vehicle 57, rely on the efficiency of the engine and the combustion strategies to mitigate the emitted NO_x with no consideration for aftertreatment systems that other, more recent vehicles would account for.

The Idle Bins aims to show more the performance of aftertreatment systems at lower temperatures and operations, but also demonstrates the efficiency of in-cylinder strategies on emissions profiles.

Figure 13- Normalized CO₂ percentage alongside windowed average speed of Vehicle 69.

Looking at the normalized CO₂ percentage of Vehicle 69 alongside its speed, there exists some deficiencies of the 3Bin-MAW method regarding its bin classification criteria. The intended classification of the gathered data points into different bins was to sort and filter the data according to operating level, Idle bin intended for idle operations, Low for simulating near dock and urban operation at intermediate speeds, and Med/High bin for highway operation at

higher speeds. Yet, Figure 13 shows some inconsistencies between the operating speeds and the attributed normalized CO₂ rate dictating the binning of the window.

The left side box includes a decrease in speed from a highway level operation above 45 mph to a lower state close to 20 mph, then an idle or creep state (around 0-2 mph) before increasing. The windows in that box with a high speed are matched with suitable normalized CO₂ percentage to place them in the appropriate Med/High bin, but the windows where the vehicle speed is around 15 mph are also placed into the higher Bin, rather than the Low bin. Shortly after, windows with the same range of speeds were placed in the Idle bin, whereas windows displaying Idle operation in this box are placed in the second, Low bin.

The right-side yellow box further confirms the inaccurate bin placement. It shows windows with low speeds (less than 5 mph) are placed in the Low bin according to their respective normalized CO₂ percentage falling between 6 and 20%, but also windows with averaged speeds greater than 25 mph, and even peaking around 30 mph, are also placed in the same Low bin.

Goods Movement Low Bin

Figure 14- Low Bin Sum-over-Sum NOx in g/bhp-hr (left) and brake specific CO₂ in g/bhp-hr (right) for Goods Movement Vehicles

Table 7 Averaged Temperature and Vehicle speed for Low Bins of Good movement Vehicles

Low Bin	Vehicle 57	Vehicle 88	Vehicle 1	Vehicle 50	Vehicle 5	Vehicle 69
Temperature (°C)	191.9	174.3	194.3	186.7	159.4	173.5
Vehicle Speed (mph)	9.7	22.8	26.9	8.8	28.1	15.8

Although the Sum-over Sum NO_x results for the Low bins vary significantly from vehicle to vehicle, the brake specific CO₂ rate appears to remain within a tighter interval centered around 600 g/bhp-hr. A notable instance of this is vehicle 1 and 5. The latter has a Low bin result almost 4 times that of vehicle 1, yet the CO₂ rate between the two slightly decreases.

Vehicle 57 features the highest emission rates for both NO_x and CO₂. Unlike in the idle bin, the vehicle lacking an SCR stands out in its category when analyzing both the Low and Med/high bins, where overall exhaust temperatures have risen alongside operation speed allowing for SCR equipped vehicles to mitigate their nitrous oxides emissions. It also highlights the progress achieved in diesel emission from pre-2010+ standard to the current and future limits.

Goods Movement Medium/High Bin:

Figure 15- Med/high Bins Sum-over-Sum NOx in g/bhp-hr (left) and brake specific CO₂ in g/bhp-hr (right) for Goods Movement Vehicles.

Table 8-Averaged Temperature and Vehicle speed for Med/High Bins of Good movement Vehicles

Med/High Bin	Vehicle 57	Vehicle 88	Vehicle 1	Vehicle 50	Vehicle 5	Vehicle 69
Temperature (°C)	363.9	246.0	222.8	269.0	221.2	233.6
Vehicle Speed (mph)	48.1	42.1	45.3	35.8	47.9	41.5

Although the values in the Med/high Bins are attributed to a higher normalized CO₂ rate, both the brake specific CO₂ rates and Sum-over-Sum Med/High bin NO_x results are lower than the low bin values. The higher exhaust temperatures coupled with more consistent higher speed driving attribute to the lower emission seen in the Med/High bins of good movement vehicles. It would be assumed that data points placed into these bins were from highway/interstate operation, with minimal stopping and more consistent operation.

Comparing with the Low bins, the CO₂ rate between the vehicles fall within a shorter range from one another in the Med/High bins with an average decrease of 15% from the previous bin, yet the NO_x results do not follow the same pattern but decreases by 60 %.

Furthermore, all vehicles in the category show a noticeable decrease of at least half in the sum-over-sum NO_x results between the Low and Med/high bins except for vehicle 1, which only decreases around 9.5%. it is also worth mentioning that the newer vehicles of the category, mainly vehicles 5, 50, and 69 decreased their NO_x rate by 65.2, 67, and 85% respectively. The highest in the selection.

The more recent vehicles, mainly 5 and 69 have some of the highest Idle and Low bin NO_x results in their category, yet in the Med/High bin they drop below the rest, with Vehicle 69 being the only vehicle in the group to meet the 3-Bin MAW 2007 standard of 0.3g/bhp-hr. Furthermore Vehicle 69 features the highest Idle NO_x rate, as well as one of the highest Low Bin sum-over-sum NO_x. This is an insight towards the operational focused strategies or pathways that manufacturers take to reduce their emissions, where vehicle 69, allows for a higher Idle rate and Low bin sum-over-sum NO_x, in favor of a significantly reduced rate at higher operations, as well as a more consistent CO₂ rate. The presence of a DPF in each vehicle allows for closer CO₂ rates between the vehicles in each bin, when compared to the NO_x results.

4.2 3B-MAW Results for Delivery Vehicles

Figure 17- Percentage of single data points excluded and appearing in 1,2, or 3 bins simultaneously for Delivery Vehicles.

Figure 16- Percentage count of windows attributed to each bin for Delivery Vehicles.

In this category, the majority of the valid windows fall into the Low bin, on average 55% of all valid windows in the group falling in that Bin. The Idle bins hold the second most amount of windows in the category average, as well as in each individual vehicle, with the exception of vehicle 149 whose Idle bin holds more than 50% of the windows.

Due to the exclusion and restrictions proposed by CARB regarding the validity of data points, this vocation category has a high number of excluded points. Vehicles in this category have over 60% of their data points excluded, with the exception of Vehicle 149. Yet the latter features the most amount of data points found in two bins simultaneously. In fact, compared to the goods movement vehicles, delivery vehicles on average feature more excluded points, as well as more points in two bins simultaneously than points only in one bin. This category also has a lower percentage of points found in three bins simultaneously, with Vehicle 52 having none. The overall low operating modes used in delivery vehicles coupled with constant stopping and

Figure 18- Average Vehicle Speed (mph) for each bin for Delivery Vehicles.

inconsistent variable speeds prevent these vehicles from overcoming the 3B-MAW exclusion and allows for a higher amount of excluded data points.

Much like the goods movement category, the trend in vehicle speeds across the bins observed in figure 16 remains the same for all vehicles in this category. However, the differences between the Low and Med/High bin average speeds are within 3 mph for both Vehicles 54 and 52. This is relatively low compared to the goods movement category, and even compared to the delivery vehicles.

Figure 19- Delivery vehicle Average Exhaust Temperatures (deg C)

The temperatures displayed above show Vehicle 54, which lacks an SCR, having the highest temperature averages for each bin. Its Idle bin exhaust temperature not only surpasses the other idle bin temperatures but is also higher than the low bin temperature of Vehicle 52. Furthermore, the Low bin average temperature of Vehicle 54 exceeds the Med/High bin temperatures of all other cars in the category.

The recurring transient conditions this category might face allows for more data points being repeated between the bins, and thus unequal weighing of some data points. Figure 20 looks at the change in the normalized CO₂ rate alongside the window averaged vehicle speed for Vehicle 149.

Figure 20- Normalized CO₂ percentage alongside windowed average speed of Vehicle 149.

In the areas near the Idle and Low bin separation line (6% Norm), the normalized CO₂ curve shows repetitive fluctuations contributing to an overlapping of points between the neighboring bins. In the same area, mainly below the 6% line belonging to the Idle bin region, there exists a rise in vehicle speed not usually associated with idle operation, as well as inconsistent bin placement based on vehicle operation or speed. The yellow areas highlight the mentioned inconsistencies and shows some deficiencies of the proposed CARB 3Bin-MAW method. The right box features the highest vehicle speed for the whole operation, yet the normalized CO₂ percentage fluctuates between the Low and Med/High bin. Whereas the middle box shows relatively lower speeds with a normalized CO₂ percentage attributed to the Med/High bin, rather than the expected Low bin.

A more detailed look at the left-most highlighted area is displayed in the figure below. It reveals that for the same averaged window speeds, the normalized CO₂ percentage dictating the bin placement differs by a substantial margin to allow for distinct bin placement for windows displaying similar averaged vehicle speed.

Figure 21- Closeup on Normalized CO₂ and Speed for Vehicle 149.

The Normalized CO₂ average above fluctuates around the 6 % threshold between the Idle and Low bins. This translates to neighboring windows being placed in different bins, and due to the proximity of the overlapping windows their respective data points are being repeated across these two bins. The repeated changes in Normalized CO₂ within a range of neighboring bins allows for higher data point duplicity between the idle and low bins. This is reflected in Figure 16, where 58 % of the collected datapoints are placed in two bins simultaneously.

Delivery Vehicle Idle Bins

Figure 22- Idle Bin NOx in g/hr (left) and CO2 in g/-hr (right) for Delivery Vehicles.

Table 9-Averaged Temperature and Vehicle speed for Idle Bins of Delivery Vehicles.

Idle Bin	Vehicle 54	Vehicle 46	Vehicle 52	Vehicle149
Temperature (°C)	135.7	91.6	96.4	95.8
Vehicle Speed (mph)	1.0	0.6	0.9	1.4

The Idle bin NO_x of the newer vehicles, Vehicles 52 and 149, are the lowest in the category. Both these vehicles meet the Idle 2010 Optional Standard for this method of 45g/hr, as well as the 2024 standard of 15g/hr. The 2008 Vehicle 54 ranks as the highest in Idle CO₂ and NO_x rate among its vocation given its age and that it lacks an SCR. Vehicle 5 on the other hand features the lowest Idle NO_x in the group but also the second highest CO₂ between the Idle bins. Among the SCR equipped entries, Vehicle 46 shows a substantially higher NO_x results for the Idle bin then it's newer counter parts (Vehicle 52 and 149), yet also features the lowest CO₂ rate in the Idle bin. The decreasing NO_x results for the newer vehicles in the group is indicative of SCR efficiency improvement over the last 8 years, specifically at lower exhaust temperatures and idle operations.

Delivery Vehicle Low Bins

Figure 23- Low Bin Sum-over-Sum NOx in g/bhp-hr (left) and brake specific CO₂ in g/bhp-hr (right) for Delivery Vehicles.

Table 10-Averaged Temperature and Vehicle speed for Low Bins of Delivery Vehicles

Low Bin	Vehicle 54	Vehicle 46	Vehicle 52	Vehicle149
Temperature (°C)	217.3	129.4	186.2	155.3
Vehicle Speed (mph)	10.5	8.4	10.4	8.9

The NO_x result ranking among the delivery vehicles remains the same between the Idle and Low bins, with Vehicles 52 and 149 having the lowest sum-over-sum result, falling very close to the 2024 standard of 0.3 g/bhp-hr. However, when looking at the CO₂ for the group, Vehicle 46 remains the most emitting. Vehicle 54 falls in second place in terms of highest CO₂ rate, with a rate more than twice as much as it was for the Idle bin.

Delivery Vehicles Med/High Bins.

Figure 24- Med/High Bin Sum-over-Sum NO_x in g/bhp-hr (left) and brake specific CO₂ in g/bhp-hr (right) for Delivery Vehicles.

Table 11-Averaged Temperature and Vehicle speed for Medium/High Bins of Delivery Vehicles

<u>Med/High Bin</u>	Vehicle 54	Vehicle 46	Vehicle 52	Vehicle149
Temperature (°C)	279.3	184.7	213.4	212.4
Vehicle Speed (mph)	12.2	20.8	13.0	30.8

The Med/High bins show the same trends found in the previous Bins when looking at the sum-over-sum NO_x results. Vehicles 54 and 149 remains the least emitting vehicles in the category, with Vehicle 54 meeting the 2024 3Bin MAW threshold of 0.075g/bhp-hr. The older vehicles however have relatively small changes in the sum-over-sum NO_x result between the Low and Med/High bins. Where Vehicles 52 and 149 decrease their sum-over-sum NO_x results by 82.3 % and 55.74 % respectively, between the Low and Med/High bins, Vehicles 46 and 54 feature results only decrease by 18.63 % and 13.95 %, respectively, from the previous bin.

On the right side of the figure, we can see that the ranking in the CO₂ results is similar to the S-o-S NO_x ranking. Although Vehicle 46's brake specific NO_x for the Med/High bin doesn't decrease to same extent as Vehicles 52 and 149 do, the brake specific CO₂ decreases by 10.5%

which is the highest in the category. Vehicle 54's CO₂ rate in the Med/High bin however has increased from the Low bin, by a relatively small 0.55 %. Vehicles 46 and 52 are the only vehicles with both lower NO_x and CO₂ in the Med/High bin than in the Low bin.

4.3 Comparing Delivery and Goods Movement

Table 12-Average Percentage of single data points excluded, or placed in either 1, 2, or 3 Bins simultaneously for Goods movement Vehicles.

Good Movement Vehicles	Percentage of total data points collected (%)			
	Excluded	Points in 1 Bin	Points in 2 Bins	Points in 3 Bins
Vehicle 1	28.10	38.71	30.01	3.17
Vehicle 5	11.36	59.51	28.43	0.68
Vehicle 50	5.26	50.57	41.56	2.61
Vehicle 57	26.99	56.27	16.73	0
Vehicle 69	21.39	56.73	21.53	0.34
Vehicle 88	9.55	60.33	28.59	1.52
Average	17.11	53.68	27.81	1.38

Table 13- Average Percentage of single data points excluded, or placed in either 1, 2, or 3 Bins simultaneously for Delivery Vehicles.

Delivery Vehicles	Percentage of total data points collected (%)			
	Excluded	1 Bin	2 Bins	3 Bins
Vehicle 46	74.72	15.56	9.22	0.48
Vehicle 52	65.42	17.17	17.41	0
Vehicle 54	63.28	17.16	19.39	0.16
Vehicle 149	5.01	34.51	57.93	2.55
Average	52.11	21.10	25.98	0.80

Figure 25- Comparison of Idle Bin NO_x results (left) and CO₂ rate (right) for both GM and Delivery Vehicles.

With the exception of Vehicle 54, all vehicles in both categories meet the optional 2007 idle NO_x emission standard of 45 g/hr. Overall, the Delivery vehicles feature lower NO_x and CO₂ for the Idle bins than the goods movement category, among both vocational categories.

Vehicles 1 and 46 show very close Idle NO_x results, 15.49 and 16.11 g/hr respectively, both near the 2024 standard of 15 g/hr. Yet looking at the right side it appears that the idle CO₂ rate of Vehicle 1 is around 75 % higher than that of Vehicle 46. In addition, Vehicle 54 which is not equipped with an SCR, showcases the highest NO_x rate in both categories, but also still features a lower CO₂ than most the goods movement vehicles, except for vehicle 57.

The plots in Figure 26 highlight the differences in both categories by comparing their Low load sum-over-sum NO_x on the left side, and their bs-CO₂ on the right side.

Figure 26- Comparison of Low Bin S-o-S NO_x results (left) and CO₂ rate (right) for both Goods Movement and Delivery Vehicles.

Vehicle 54 remains the entry with the highest sum-over-sum Low bin NO_x result between the two categories, but now its CO₂ rate ranks among the top three in both groups.

Despite Vehicles 52 and 149 having lower Low bin sum-over-sum results than the goods movement vehicles, they also fall close to the goods movement CO₂ average. With Vehicle 149 even having the lowest rate between the two categories.

Tables 14 and 15 display the average speeds of each bin of each of the selected vehicles, as well as the averages of the Idle, Low, and the Med/high bins for each vehicle category.

Table 14- Average Speeds of Goods Movement Vehicles.

<u>Goods Movement Vehicles</u>	<u>Average Bin Speed (Mph)</u>		
	Bin1	Bin2	Bin3
Vehicle 57	1.52	9.71	48.14
Vehicle 88	1.39	22.78	42.12
Vehicle 1	2.03	26.96	45.26
Vehicle 50	0.82	8.77	35.82
Vehicle 5	1.31	28.14	47.98
Vehicle 69	2.87	15.80	41.48
Average	1.66	18.69	43.47

Table 15-Average Speeds of Delivery Vehicles

<u>Delivery Vehicles</u>	<u>Average Bin Speed (Mph)</u>		
	Bin1	Bin2	Bin3
Vehicle 54	1.01	10.54	12.18
Vehicle 46	0.63	8.44	20.79
Vehicle 52	0.96	10.44	13.01
Vehicle 149	1.47	8.96	30.85
Average	1.02	9.59	19.21

The average speeds differ drastically between the categories, especially in the Low and Med/High bins. The Low bin average speed of the goods movement group is almost twice that of the delivery vehicles, and slightly lower than their Med/High bin average speed. In addition, Vehicles 52 and 54 have a relatively small increase in average speed from their low to Med/High bins, compared to the rest of the vehicles. Tables 14 and 15 show the goods movement vehicles Med/High bin average speed being more than twice that of the delivery category.

Figure 27 compares the Med/High bins of both good movement and delivery vehicles. The left plot displays the sum-over-sum NO_x results, whereas the differences in bs-CO₂ are shown on the right.

Figure 27- Comparison of Medium/High Bin S-o-S NO_x results (left) and CO₂ rate (right) for both GM and Delivery Vehicles.

Both categories have a decrease in their sum-over-sum NO_x emissions results between their Low and Med/high bins, but the delivery group's rates do not decline as much as the good movement's. On average, the goods movement sum-over-sum NO_x results decrease by 60 %, compared to the delivery vehicles decrease of 20 %. Meanwhile their respective brake specific CO₂ rate decreased by 15 and 1.5 %.

Despite the lower speeds, as well as lower decrease in both NO_x and CO₂ between the upper two bins, the delivery category features two 2015 vehicles which meet the 2010 standard, but also Vehicle 52 meeting the 2024 standard. Yet both vehicles feature higher brake specific CO₂ rate higher than all of the goods movement vehicles.

Vehicle 57 despite lacking an SCR, outperforms both its delivery counterpart Vehicle 54, but also Vehicle 46, which is 7 years newer and includes an SCR. The poor aftertreatment performance of Vehicle 46 relates back to its low exhaust temperature of 184 °C, the lowest in both categories for Med/High bins.

Figure 28- Decrease of S-o-S NOx from Low to Med/High Bins for Both GM and Delivery Vehicles.

Looking at the vehicles ordered by model year, the decrease in NO_x for the later model years between the Low and Med/High bins is higher than that of the older year models, regardless of vocation. Yet it is also noticeable that the percent decrease in brake specific CO₂ is lower in the recent models compared to the previous one, showing an inverse relation between the changes in NO_x and CO₂ between the Low and Med/High bins across the years.

Although Vehicles 52 and 149 achieve the lowest sum-over-sum NO_x in both Low and Med/High bins, the further decrease in NO_x between the two upper bins results in minor CO₂

decreases for Vehicle 52, and an increase in the brake specific CO₂ of Vehicle 149. Furthermore, compared to the earlier vehicles, the more recent year model vehicles produce a greater difference between the decrease in sum-over-sum NO_x and bs-CO₂.

4.4 Limitations

The proposed MAW method displays certain limitations for analyzing the NO_x and CO₂ tradeoffs of a vehicle. Initially, the exclusions stated in the proposal decreased the amount of vehicles with datasets viable/applicable to this approach. This is especially the case with vehicles operating in dense urban areas, such as delivery vehicles, which might fail to meet the average engine power and the 3hrs non-idle requirements. The coolant temperature also proved to exclude a large amount of data points in both categories.

Another limitation to this method is comparing the Idle Bins with the other ones. The only meaningful comparisons possible with this method is between the Low and Med/High bins, since both use the same evaluation method and unit of measurements, g/bhp-hr. Whereas the Idle Bin uses a time-based evaluation method in g/hr.

The normalized CO₂ that this method uses as a reference for bin placement displays inconsistencies when applied. As Figure 13 and 19 show, the normalized CO₂ rate does not always assign the windows to their intended bins. Windows with averaged speeds above 30 mph placed in idle bins and similar inconsistencies found when applying this method allows for more inaccuracies in the individual bin results. With this method including a specific passing criterion based on the intended operations each bin represents (idle, urban/low, highway/med/high), an inconsistent bin placement dependent on the normalized CO₂ percentage allows for a misrepresentation of the vehicle's performance under the proposed bins.

Furthermore, the fluctuation experienced by the normalized CO₂ among neighboring windows causes an increase in the amount of individual data points being placed in multiple bins. A normalized CO₂ rate fluctuating around the limits that determine bin placement (6 % and 20 %) increases the amount of repeating data points between neighboring bins. A sudden high spike in the normalized CO₂ rate allows for more data-points to be placed in more than one bin simultaneously due to the configuration/overlapping of the windows. This unequal weighing of points distorts the result of each bin.

5 Conclusion

Overall, regarding the correlation between NO_x emission and CO₂, this method still succeeds in showing the improvements made over the years regarding both pollutants with the help of in-cylinder strategies and aftertreatment technology advancements, while considering operating conditions.

The CARB 3-Bin Moving Average Window allows for a more isolated look into the tradeoff between CO₂ and NO_x. Each bin represents an operation mode where the result dictates the performance of its emission reduction strategies and aftertreatment devices. But the use of a normalized CO₂ rate and the differences in evaluation methods (g/hr and g/bhp-hr) between the Idle bin and the others obscures the details of that tradeoff. Although this method allows for an operational based analysis on emission profiles, it prevents a proper assessment of the changes and progression of the NO_x and CO₂ tradeoff. It only leaves the two upper bins to observe the tradeoff, and with the low bin compromising of normalized CO₂ rate between 6 and 20%, and the higher bin ones above 20 %, as the sum-over-sum NO_x result decrease, the normalized CO₂ rate is constantly increasing. The only valuable information regarding that tradeoff is produced using individually calculated brake specific CO₂ rates for each bin, not included in the proposed amendment.

Nonetheless, this method still allows the correlation between NO_x and CO₂ rates to be analyzed using the Low and Med/high bins. Figure 28 highlights the different rates the change between bins, with the latest models featuring the greater decreases in NO_x, but relatively smaller improvements in bs-CO₂. The older models feature overall greater improvements in CO₂ between the two upper, and consequently a smaller decrease in NO_x emissions.

Analyzing the nitrous oxide rate using this method allows for a segregated look into the performance of the vehicle based on its operating conditions. It also allows to look at the control strategies and effectiveness of aftertreatment components at those different operations. Yet the shortcomings of the sorting method based on the normalized CO₂ average rate compromises the accuracy and efficacy of this method. Analyzing the NO_x and CO₂ rates in each bin based on operation is a challenge if the binning criteria is compromised, leading to emissions rate from varying operating conditions are placed in one bin as shown in Figure 13.

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