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Heavy-Duty Diesel Truck In-Use NO_x Emissions Evaluation Using On-Board Sensors

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Abstract

Governments and regulatory agencies in North America are evaluating the nitrogen oxides (NO_x) emissions of heavy-duty on-road vehicles to effectively regulate these emissions in order to improve public health and meet air quality requirements. This paper provides results from real-world Class 8 tractor-trailer truck activity and emissions data gathering conducted in the Northeast and Mid-Atlantic United States. Unlike some other areas of the United States (US), there is little available data on in-use operation and emissions performance from heavy-duty trucks in this region where temperatures can be consistently cold in winter. The purposes of this study are to add to the literature on real-world truck operation and emissions in the Northeast and Mid-Atlantic regions; to analyze the captured emissions data using recently established calculation methods implemented by the California Air Resources Board (CARB), which have not yet been applied to data from this region; and to assist air quality regulators in identifying priorities for new heavy-duty engine and vehicle emission standards and test procedures.

The Northeast States for Coordinated Air Use Management (NESCAUM) conducted this project jointly with Environment and Climate Change Canada (ECCC). Given the proximity of the truck routes evaluated in this project to the Eastern Canadian provinces, the information is of interest to Canadian regulators as well. The results of this data logging and analysis showed that the CARB's three-bin moving average window (MAW) and sum-over-sum NO_x emissions calculations can be successfully applied to in-use truck data sets. However, the use of the on-board vehicle NO_x sensors for data logging limited the amount of time that data were able to be captured at low loads. The active percentage time of sensors by truck was between 43% and 80% in low-load conditions (69% over all trucks). Therefore, low-load data was "backfilled" with estimated emissions values in order to compensate for the time the sensors were inactive. Backfilled data showed that a range of 21% to 67% of the mass of NO_x emitted by individual trucks occurred in idle and low-load conditions combined, whereas the original data showed values between 10% and 43%. Median daily backfilled sum-over-sum NO_x emissions results by truck specimen ranged from 0.32 g/bhp-hr to 0.75 g/bhp-hr in low-load conditions and from 0.02 g/bhp-hr to 0.16 g/bhp-hr in high-load conditions.

As part of the study, data on over 150 vehicle and engine parameters during 100 days of truck operation were collected. This data can be used by regulators and researchers to evaluate truck emissions and operations in the region.

Keywords

Heavy duty, Truck, NO_x, Nitrogen oxides, Emissions, Fleet, Trucking, In-use

Introduction

Heavy-duty vehicles contribute approximately 20% of total nitrogen oxides (NO_x) emissions in the Northeast and Mid-Atlantic United States [1]. NO_x emissions are a primary precursor to the formation of ground-level ozone and secondary fine particulate matter (PM2.5) and contribute to acid deposition, eutrophication, and visibility impairment [2, 3, 4]. NO_x emissions are the major drivers of surface ozone concentrations at the regional scale in the eastern United States (US) [5]. Epidemiological studies provide strong evidence that ozone is associated with respiratory effects, including increased asthma attacks, as well as increased

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hospital admissions and emergency department visits for people suffering from respiratory diseases. Ozone can exacerbate chronic obstructive pulmonary disease (COPD), and long-term exposure may result in permanent lung damage, such as abnormal lung development in children [6]. There is also consistent evidence that short-term exposure to ozone increases the risk of death from respiratory causes [7]. Furthermore, recent studies show that ozone concentrations below the current National Ambient Air Quality Standards (NAAQS) continue to contribute to the risk of premature death in sensitive populations, such as the elderly [8, 9]. Regulated diesel engine emissions include NO_x, unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM).

Aftertreatment systems are required on modern diesel vehicles to reduce harmful emissions. HC and CO are oxidized using a diesel oxidation catalyst (DOC), where they are converted to water (H_2O) and carbon dioxide (CO_2) [10]. For PM emissions control, diesel vehicles use diesel particulate filters (DPF), which have good efficacy in filtering PM emissions [11]. NO_x emissions are lowered using both exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) technologies [11], which were both installed by the manufacturer on all test vehicles in this study. Current SCR systems require relatively high exhaust temperatures to function correctly, potentially allowing significant NO_x to be emitted in certain operating conditions. According to the Manufacturers of Emission Controls Association, since the introduction of the federal 2007/2010 heavy-duty engine NO_x emissions standards, there have been significant aftertreatment and engine technology advances that provide the technological ability to reduce NO_x emissions a further 90% from the emissions standards require of today's engines [12]. They state that in order to reach this target, manufacturers will need to introduce hardware upgrades and new aftertreatment systems that, while significant, build upon the architecture of current emissions control systems. Such systems have been demonstrated in recent research studies [13, 14].

According to the International Council on Clean Transportation (ICCT), the United States Environmental Protection Agency's (US EPA) federal "not-to-exceed" (NTE) testing standard excludes a significant portion of in-use NO_x emissions [15]. Emissions that occur during low-load operations are of particular concern. The NTE excludes emissions when trucks are operating at low loads, defined as below 30% of maximum engine torque and power, as well as emissions occurring during other so-called "carve-out" conditions. An ICCT analysis of NTE data submitted by manufacturers found that approximately 40% of total truck NO_x emissions were emitted during low-load conditions [15].

A new, more rigorous in-use test protocol was proposed and recently finalized by the California Air Resources Board (CARB) in their "Heavy-Duty Engine and Vehicle Omnibus Regulation and Associated Amendments" [16, 17]. This regulation establishes a moving average window (MAW) approach to segmenting and quantifying NO_x emissions at different in-use load conditions. The MAW procedure and the accompanying proposed emissions standards for idle and low-load operation aim to significantly reduce truck NO_x emissions at low load and idle, and, more broadly, for the operating conditions excluded by the NTE protocol. The CARB MAW approach has been used in this analysis to illustrate the fraction of NO_x emissions that could be reduced with its introduction and to illustrate how the method can be applied to in-use test data. The new US federal emission standards have now been proposed, and changes to the current federal in-use test for heavy-duty trucks, the NTE protocol, are being considered [18]. This paper aims to provide background information that will be useful for this process by showing real-world emissions results using the new CARB approach.

In addition, the introduction of on-board diagnostics (OBD) in heavy-duty vehicles provides an opportunity to collect a wealth of data on vehicle duty cycles, emissions, engine load, exhaust temperatures, sensor operation, and other information. Obtaining data from engines equipped with OBD in the Northeast and Mid-Atlantic region is important for several reasons. First, it is important that truck emissions and operating data representative of the Northeast and Mid-Atlantic region are available to regulators to inform the development of emission modeling tools. Because climate, topography, and truck travel profiles affect vehicle emissions and operating conditions, obtaining and incorporating representative, regionally specific data is important. Emissions and operating profiles are used in developing emissions models such as the EPA's Motor Vehicle Emissions Simulator (MOVES) model [19].

Second, as states work to realize heavy-duty vehicle electrification goals, understanding vehicle load, vehicle miles traveled (VMT), the influence of topography on energy demand, and other factors can be used to develop charging infrastructure planning tools. Eighteen jurisdictions, including nine states in the Northeast and Mid-Atlantic, the District of Columbia, and the Canadian province of Quebec, signed a Memorandum of Understanding committing to a transition to electric medium- and heavy-duty trucks in the jurisdictions [20]. In a draft Action Plan for the initiative, vehicle charging infrastructure development has been identified as critical for widespread medium- and heavy-duty electrification [21]. In addition, regionally-specific truck information can also inform and support other air quality initiatives, such as better understanding opportunities to reduce idling-related truck emissions.

Methods

This section provides an overview of the method used in this study. The approach had four components:

1. Select a trucking fleet to participate in the study and identify trucks for data logging.
2. Equip Class 8 tractors with data loggers and collect data over periods of warm and cold weather.
3. Analyze the data for activity and emissions.
4. Bin the data and obtain the results according to the ARB MAW method described in the Omnibus Initial Statement of Reasons (ISOR) [16].

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Fleet and Truck Selection

NESCAUM worked with US EPA Region 1, the Northeast Diesel Collaborative, and others to identify a fleet in the Northeast to participate in the data-gathering project. Regency Transportation was selected as the fleet partner for this study. Regency operates a fleet of 150 Class 8 day cabs and sleeper cabs that operate on a variety of routes, some are confined to the Northeast and Mid-Atlantic United States and others span the entire country. Regency trucks haul a range of freight including beverages, office supplies, home goods, building materials, and other products. The trucks operate in several northern states in the winter, which was desirable for this study given the opportunity to collect data in cold ambient temperatures. Trucks were selected for this project based on their routes—trucks that return to Regency's Franklin, Massachusetts facility were selected to ensure that data loggers could be collected from the trucks after a month or more of data logging was completed.

NESCAUM equipped five Freightliner Class 8 trucks with data loggers. Four of the five trucks selected were sleeper cabs and one was a day cab. Table 1 provides additional information on the participating trucks including their make and model, model year (MY), and engine model. All trucks were equipped with modern emissions control systems, including EGR, DOC, DPF, and SCR systems.

Data Collection

The US EPA loaned NESCAUM five HEM Data Mini Loggers for use in the project. NESCAUM loaded configuration files on the data loggers that defined data sampling frequency; conditions for data collection (e.g., only when the vehicle engine was turned on), which broadcast signals to collect; and other parameters. DawnEdit2 software was used to install software on the data loggers and to make adjustments to files. Once the data loggers were configured for the Freightliner trucks, NESCAUM installed the data loggers on the OBD ports in the truck cabs. The data loggers were fitted with labels indicating the loggers were the property of the US EPA and that drivers should not remove them. The data logging began in February 2020 and continued through the summer of 2020. Data loggers remained in place for three to six weeks, depending on the truck routes. Data loggers were removed when the trucks returned to the Franklin, Massachusetts Regency Transportation facility. The number of days of data logging for each truck varied, in part because of the Covid-19 pandemic and in part related to the truck routes. Table 2 shows the number of shifts captured for each truck, the date of installation, and the date of removal. Some shifts spanned more than one day. A total of 101 shifts of data from the five trucks were gathered as part of the project.

The loggers collected data from each truck engine control modules on over 150 parameters. A sample of the types of data collected is provided in Table 3. Data was gathered at a rate of 1 Hz for each parameter shown in Table 3.

TABLE 1 Test truck information.

Truck make	Model	MY	Type	Engine (HP)	Truck #
Freightliner	CA126SLP	2018	Sleeper cab	DD15 (475)	490
Freightliner	CA126SLP	2019	Sleeper cab	DD15 (475)	530
Freightliner	CA126SLP	2020	Sleeper cab	DD15 (475)	565
Freightliner	CA126SLP	2020	Sleeper cab	DD15 (475)	568
Freightliner	CA116DC	2020	Day cab	DD13 (470)	583

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Truck Operation Locations Figure 1 shows the global positioning system (GPS) traces indicating the locations of operation of the trucks in this study. Note that some GPS data were missing (due to intermittent signal) and this explains the discontinuities in some path data. Truck 490 was operated near the Regency Transportation facility outside of Boston, Massachusetts and stayed in the adjoining states including Connecticut, Rhode Island, and New York. Truck 530 operated on routes from Massachusetts to nearby states including Vermont, New Hampshire, and Maine. Trucks 565 and 568 ranged further afield, to Pennsylvania in the south and the northern part of upstate New York. Finally, Truck 583 operated in Massachusetts and the adjoining states, similarly to Truck 490, but incorporating some northern routes near to those driven by Truck 530.

Data Analysis

General Procedure The raw logger data was converted to CSV format using DawnEdit2 software and was imported

TABLE 2 Number of shifts of data logging for each truck.

Truck no.	Number of shifts logged	Date logger installed	Date logger removed
490	16	5/15/2020	6/13/2020
530	15	2/13/2020	3/10/2020
565	28	7/12/2020	8/14/2020
568	25	7/22/2020	9/1/2020
583	17	2/4/2020	2/27/2020

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TABLE 3 Example parameters measured from the truck engine control modules.

Engine parameters	Engine speed (RPM) Engine fuel mass flow rate (g/s) Engine torque (Nm) Engine load (%)
Aftertreatment parameters	Diesel exhaust fluid (DEF) dosing rate Exhaust temperatures pre/post SCR catalyst NO_x sensor status Exhaust mass flow rate
Vehicle parameters	Vehicle speed (via wheel rotation) Transmission gear selected
Other	Ambient temperature Global positioning system location/speed

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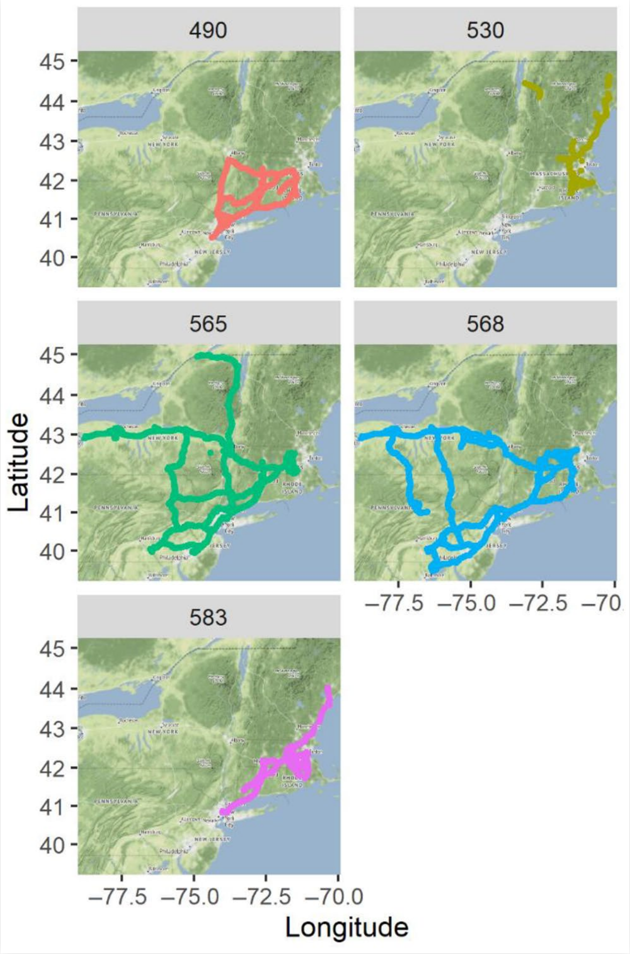
FIGURE 1 Truck operating regions, Northeastern United States.



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into RStudio for additional processing. Using the recorded timestamp, the data was collected into "test days." These test days include a cold start and a full shift of driving operation, including breaks and loading/unloading time when the vehicle was turned off.

For vehicle speed, the J1939 vehicle speed signal was used instead of the GPS as it was deemed more reliable. Using these available sources of data, a time-speed trace for the test days was determined.

The on-board computer–reported fuel consumption rates of trucks were used to determine the window normalized average CO_2 emission rate using estimated fuel specifications. This CO_2 emission rate was then used to apply the binning rules as specified by the CARB [16]. The NO_x emissions broadcast from the engine control module as parts per million were converted to mass emissions rates using the on-board computer–reported exhaust gas flow rate. Due to the limitations of on-board NO_x sensors, these sensors were not active a portion of the time and so did not report any NO_x emissions during some start-up and low exhaust temperature conditions. The missing data was backfilled using estimated emissions rates, both original and backfilled sum-over-sum NO_x emissions rates are reported. The following sections expand upon each step in this process.

Moving Average Window The CARB has approved an amendment that replaces the current NTE-based methodology with a new moving average window "MAW" methodology for 2024 and subsequent MY engines [16, 17]. For this analysis, we used the procedure for 2024 to 2026 engines, which have a cold start and low power exclusion, as described in the ISOR document [16]. For diesel engines, three bins related to the applicable standards are used to determine compliance. The three diesel-cycle MAW-based bins represent idle, low-load, and medium/high-load operations based on their respective normalized CO_2 emission rates, which are used as a proxy for the engine load.[1] Compliance is determined by comparing the sum-over-sum NO_x emissions for each bin to the in-use threshold, defined as one-and-a-half times the applicable NO_x standard for the MY.

In order to apply the proposed binning and MAW calculations to the data set, the window normalized average CO_2 emissions rate is required, which must be calculated based on the instantaneous CO_2 emissions rate and the Family Certification Limit (FCL)[2] [22]. The J1939 data includes only the instantaneous fuel consumption rate, and this was combined with estimated fuel specifications to determine an approximate instantaneous CO_2 mass emissions rate using Equation 1.

$$\dot{m}_{CO2} = \dot{m}_{fuel} * FFC * \frac{M_{CO2}}{M_C} \qquad \text{Eq. (1)}$$

where

- $\dot{m}_{CO2}$ is the mass emission rate of CO_2 in g/s
- $\dot{m}_{fuel}$ is the mass flow rate of fuel in g/s
- FFC is the fuel fraction carbon (estimated based on typical diesel fuel composition, a value of 0.87 was used)
- M_{CO2} is the molar mass of CO_2 (44.0095 g/mol)
- M_C is the molar mass of carbon (12.0111 g/mol)

Using this calculated mass emissions rate of CO_2 and the FCL for the engine model in grams per brake horsepower hour (g/bhp-hr), the window normalized CO_2 emissions rate was calculated using the CARB-specified calculation, shown in Equation 2.

$$\begin{array}{c}\text{Window normalized}\\ \text{average } CO_2 \text{ rate}\end{array} = \frac{\left(\sum_{t=1}^{n} \dot{m}_{CO2}(t)\right)}{FCL * \left(P_{max} * {}^{n}\!/\!_{3600}\right)} \qquad \text{Eq. (2)}$$

where

- Window normalized average CO_2 rate is a value between 0 and 1 (corresponding to 0–100% load)
- $\dot{m}_{CO2}$ is the mass emission rate of CO_2 in g/s, as calculated using Equation 1

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[1] For Otto cycle engines, a single bin encompassing all operations is used. This is not relevant for this study because we have only gathered data from diesel engines.

[2] CO_2 FCLs serve as the CO_2 emission standards for the engine family with respect to certification and confirmatory testing.

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- FCL is the family certification limit of the engine in g CO_2/bhp-hr [22]
- P_{max} is the maximum rated power of the engine in brake horsepower (bhp)
- n is the window length in seconds (300 s for this procedure)

Binning Procedure Based on the window normalized average CO_2 emission rate, the test data was split into three bins: idle (Bin 1), low load (Bin 2), and medium/high load (Bin 3). These bins correspond to different operating modes for the vehicle and have separate NO_x emissions limits [16]. The test data were classified based on the window normalized average CO_2 emissions rate with the values specified in Equation 3, based on the CARB regulation [16].

$$\begin{cases} \text{norm}_{CO2} \le 6\% \rightarrow \text{idle bin} \\ 6\% < \text{norm}_{CO2} \le 20\% \rightarrow \text{low load bin} \\ \text{norm}_{CO2} > 20\% \rightarrow \text{med / high load bin} \end{cases} \qquad \text{Eq. (3)}$$

NO_X Emissions Conversion from Concentration to Mass Rate The raw tailpipe NO_x concentrations were converted to mass emission rates using Equation 4.

$$\dot{m}_{NOx} = \frac{\text{Conc}_{NOx}}{10^6} * \dot{m}_{exh} * \frac{M_{NOx}}{M_{exh}} \qquad \text{Eq. (4)}$$

where

- $\dot{m}_{NOx}$ is the mass emission rate of NO_x in g/s
- Conc_{NOx} is the reported concentration of NO_x from the on-board sensor
- $\dot{m}_{exh}$ is the mass emission rate of exhaust gas in g/s as reported by the on-board computer
- M_{NOx} is the molar mass of NO_x (46.01 g/mol, est.)
- M_{exh} is the estimated molar mass of exhaust gas (28.965 g/mol, est.)

Sum-Over-Sum Emissions Calculations The protocol described by ARB uses the sum-over-sum emissions when comparing binned emissions to regulated limits. Calculating the sum-over-sum emissions of NO_x varies between bins, with Bin 1 having a separate calculation method to obtain values in g/hr, as shown in Equation 5, while Bins 2 and 3 report values in g/bhp-hr, as shown in Equation 6.

$$e_{sos\ NOx,idle} = \frac{\sum_{k=1}^{n} \dot{m}_{NOx} * \Delta t}{\sum_{k=1}^{n} \Delta t} * \frac{3600\ \text{s}}{1\ \text{hr}} \qquad \text{Eq. (5)}$$

$$e_{sos\ NOx,Bin2/3} = \frac{\sum_{k=1}^{n} \dot{m}_{NOx} * \Delta t}{\sum_{k=1}^{n} \dot{m}_{CO2} * \Delta t} * e_{CO2,FTP,FCL} \qquad \text{Eq. (6)}$$

where

- $e_{sos\ NOx,idle}$ is the sum-over-sum NO_x emissions for the idle bin
- $\dot{m}_{NOx}$ is the MAW-based mass emission rate of NO_x in g/s
- Δt is the time step (1 s)
- n is the length of the bin in seconds
- $e_{sos\ NOx,bin2/3}$ is the sum-over-sum NO_x emissions for either Bin 2 or Bin 3 (same equation used for both bins)
- $\dot{m}_{CO2}$ is the MAW-based mass emissions rate of CO_2 in g/s
- $e_{CO2,FTP,FCL}$ is the engine family FTP FCL work-specific CO_2 rate in g CO_2/bhp-hr [22]

Additional Calculations and Assumptions—Backfilling Missing Sensor Data Using the on-board NO_x sensors to measure NO_x emissions, the HEM logger is able to provide emissions data for weeks (or months) at a time without intervention. However, the on-board NO_x sensors were inactive at low loads or when exhaust temperatures dropped below (approximately) 190°C. Some NO_x data at low loads was available when, for example, a truck went from high-load operation to moderate- or low-load operation, and the conditions were still favorable for sensor operation. The NO_x sensors were operational approximately 33% of the time in Bin 1, 69% of the time in Bin 2, and 89% of the time in Bin 3 overall. However, there was a significant variation in the operating time between test days and trucks. The potential for NO_x sensor damage due to condensation is one reason for this interruption in operation at low exhaust temperatures since manufacturers do not want to risk sensor damage by operating them in such conditions [23]. Improving the accuracy of NO_x sensors after vehicle start-up and during low-load operation is also an area of ongoing research for sensor manufacturers [24]; however, the generation of trucks used in this study did not include such improvements.

To create "backfilled" sum-over-sum emissions, missing NO_x sensor data was substituted using relevant estimates for emissions rates. Specifically, missing idle NO_x emissions were assumed to be 30 g/hr (based on the Certified Clean Idle standard in California, as well as laboratory test results provided to the authors by CARB), while missing low-load NO_x emissions were assumed to be 1.0 g/bhp-hr (based on data included in the detailed report prepared by a Southwest Research Institute researcher for the CARB's low NO_x program [25]), and the average medium/high-load bin value for the rest of the test was used for the medium/high-load bin (since the majority of Bin 3 test time was captured successfully by the on-board sensors). Both unmodified and backfilled sum-over-sum emissions results are presented in the results section.

Results and Discussion

Ambient Temperatures

Up to three of the five trucks operated at the same time, with data loggers being used for nine months during the winter,

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spring, and summer of 2020. The range of average ambient temperatures during the test days is shown in Figure 2. Each dot represents the average temperature during a full shift of data logging. The minimum instantaneous temperature recorded was −18°C (0°F) while the maximum was 43°C (109°F), spanning the full range of winter, summer, fall, and spring temperatures typical of the Northeast and Mid-Atlantic United States. This very high peak temperature recorded may be due to the fact that localized temperatures on roadways can exceed those of surrounding ambient areas because of the roadway surface radiating additional heat.

As shown in Figure 2, Trucks 583 and 530 operated in the coldest average ambient temperatures, while Trucks 565 and 568 operated in the warmest average ambient temperatures. Trucks 490, 565, and 568 were monitored during May and June 2020, while Trucks 530 and 583 were logged during the winter months (February and March). Box plots like Figure 2 show the median values as central bars while the box limits denote the locations of the 25th and 75th percentiles in the data. The overlaid dots denote the result from each individual test day, showing the spread of daily values during testing.

VMT and Vehicle Speeds

Figure 3 shows the variation in truck VMT over the 101 shifts of data logging. Some trucks, such as number 490, saw very little variation in daily VMT. Truck 490 was driven between 450 and 500 miles per day nearly all of the 16 days of observed driving. Trucks 530 and 565 had the greatest overall variation in miles traveled per day. Truck 565 was driven between 200 and 600 miles per day, with the median being just under 500 miles per day. Truck 530 traveled between 150 and 490 miles per day with a median of 332 miles per day. Truck 568 traveled a median of 549 miles per day, but daily mileage varied between 100 and 700 miles. Lastly, Truck 583 traveled a median of 214 miles per day with a low of 50 miles and the highest single day of travel at 950 miles. This 950-mile trip was a double shift over 24 hours and was achieved with separate drivers for each half of the overall time.

FIGURE 2 Average ambient temperatures during each shift of data logging.

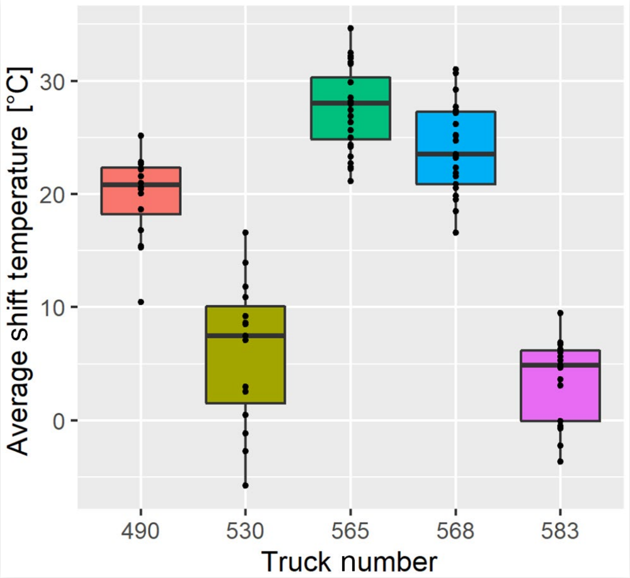

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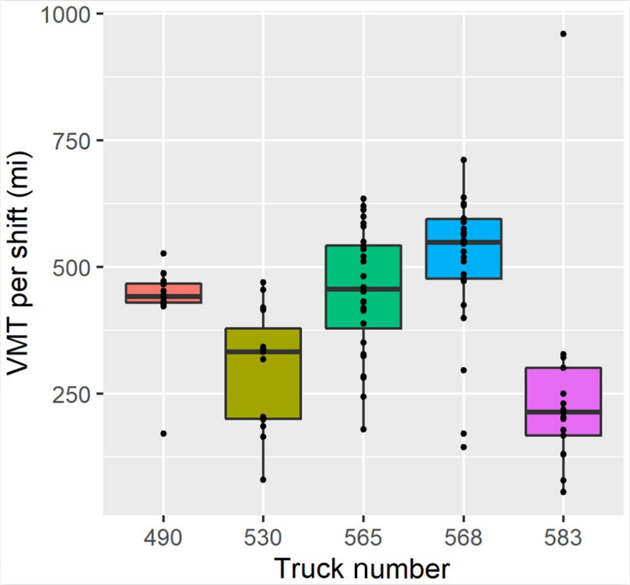
FIGURE 3 VMT for each shift and truck.



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Regency reported that, in general, its day cabs can be driven more miles per year than their sleeper cabs. The reason for this is a new day cab driver often takes over at the end of a shift, allowing the truck to continue on its route. The only day cab shown in Figure 3 is Truck 583, and this “double shifting” did occur in one instance. However, Truck 583 had, on average, the lowest VMT. This truck was data logged at the beginning of the Covid-19 pandemic so this may have affected its VMT.

The median VMT for Trucks 530 and 583 are well below 500 miles (as shown by the black horizontal line in the figure), while Trucks 490 and 565 approached 500 miles, and only Truck 568 had a median VMT over 500 miles. There were generally half-hour or longer breaks within each shift. While tractors are considered a worst-case application for zero-emission vehicles such as battery electric trucks, the duty cycle observed in this study is within the range of what could be supported with appropriate fast-charging or fueling infrastructure for battery electric or hydrogen fuel-cell-based zero-emission vehicles.

The median average daily speed for the trucks ranged from 44 miles per hour (mph) to 58 mph. However, there was a range of individual daily average speeds. Figure 4 shows the percentage of time each truck spent at different speeds. Trucks 490 and 565 spent the greatest amount of time at highway speeds (>60 mph). Truck 583 spent the lowest amount of time at highway speed.

Figure 5 shows the spread of average daily speeds for each truck. Trucks 490, 565, and 568 generally had average daily driving speeds between 50 mph and 60 mph. This corresponds to the routes each truck operated on with consistent highway driving. Trucks 530 and 583 had greater variability in average daily vehicle speeds.

The average driving speed (excluding idle time) in Figure 5 shows similar trends to the VMT: Vehicles traveling faster

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FIGURE 4 Percentages of time spent at different vehicle speeds.

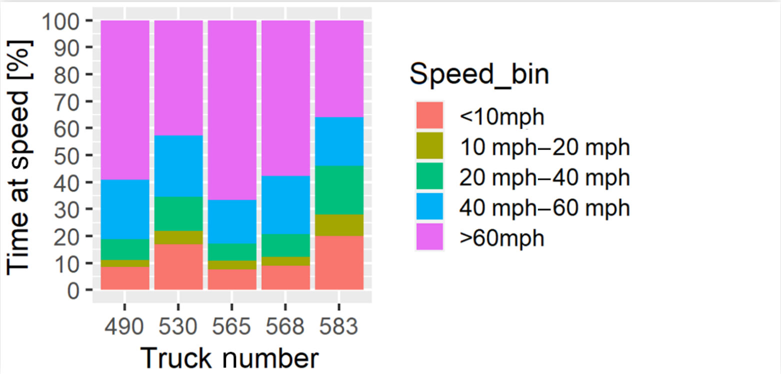

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FIGURE 5 Range of shift average driving speeds for each truck (driving only, idle time excluded).

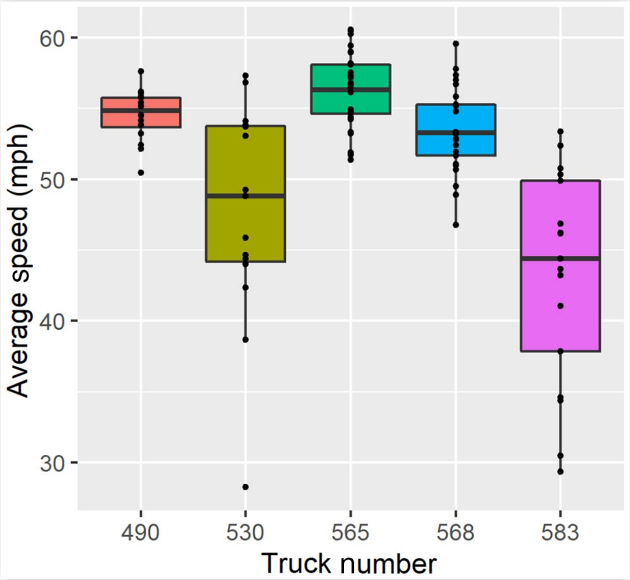

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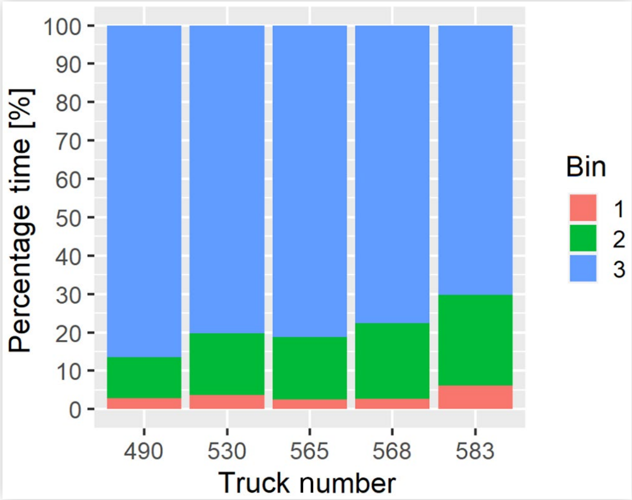
FIGURE 6 Percentages of time spent at idle (Bin 1), low-load (Bin 2), and medium/high-load (Bin 3) operation for each test truck.



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went further, assuming a similar shift time. We see that Truck 583 traveled both shorter distances and at lower average speeds than the others. Trucks 490, 565, and 568 appear to have spent significant time on expressways, while Truck 530 had more variation in driving conditions. Trucks 530 and 583 were tested in winter conditions, and thus lower speeds may be partially attributable to poor driving conditions.

Binned Operation

Time in Each Bin The daily shifts for each truck were analyzed to determine how much time was spent at idle (Bin 1), low-load (Bin 2), and medium/high-load (Bin 3) operation using the three-bin method finalized in the CARB Omnibus regulation. Figure 6 provides a summary of the time each truck spent in each of the three bins. The total number of seconds spent at idle, low load, and high load during data logging were counted, and these numbers were divided by the total number of seconds the ignition was turned on for each truck to determine the percentage of time in each bin (ignition status was determined based on engine speed).

Trucks spent between 13% on the low end and 30% on the high end at idle and low-load conditions combined. The time spent at high load ranged from 70% on the low end to 87% on the high end. Idling time ranged from 2% to 6%. Trucks with other vocations are likely to exhibit different load profiles in use. Tractor-trailer trucks, as tested in this study, are members of one of the vocations which exhibits the most consistent uninterrupted high-load operation.

An EPA study presented at the 2021 CRC Real World Emissions Workshop found that line haul trucks spent 23% of their average shift day in city driving, which is similar to the time Trucks 530, 565, and 568 spent in their combined idle and low-load operation [26]. Truck 490 spent significantly less than this amount of time in idle and low-load operation while Truck 583 spent more than this amount of time in idle and low-load operation.

Percentage of Time NO_x Sensors Active by Bin The type of NO_x sensor commonly used on heavy-duty diesel-engine vehicles requires appropriate temperature and

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humidity conditions in order to operate without damaging the sensor. Although sensors generally have additional heating elements to assist in warm-up, their operation may still require a significant time delay for exhaust system conditions to reach safe levels.

Operation of the NO$_x$ sensors was especially limited in Bin 2, as well as during low ambient temperature conditions, as shown in Figure 7. Trucks 530 and 583, which were operated in cold winter conditions, captured lower median time percentages than the other vehicles. In Bin 3 (medium/high load, shown in Figure 8), the sensors on the trucks that were operated in warm conditions (Trucks 530, 565, 568) were operational almost all of the time, whereas Trucks 530 and 583 again had lower active time percentages. The NO$_x$ mass emission percentages and sum-over-sum emissions for each truck are shown in the following section for both original (without backfilling for times when the sensor was inactive) and backfilled data sets.

NO$_x$ Emission Results

As described in the Method section, the authors calculated vehicle NO$_x$ emissions for three categories of operation, idle (<6% load), low load (6%–20% load), and high load (>20% load), using the method developed by CARB in its Omnibus regulation, where the window normalized average CO$_2$ emissions rate is used as a proxy for the engine load.

Sum-Over-Sum NO$_x$ Emissions In terms of sum-over-sum NO$_x$ emissions, only values for Bins 2 and 3 are shown in this section because these are the two bins that result in g/bhp-hr NO$_x$ sum-over-sum emissions values, similar to the current NTE method, while Bin 1 results in g/hr values instead.

The NO$_x$ sensors were working and providing data approximately 69% of the time over all trucks in Bin 2; however, this varied significantly by truck as shown in Figure 7.

FIGURE 7 Percentage of time that NO$_x$ sensor was active during testing, Bin 2.

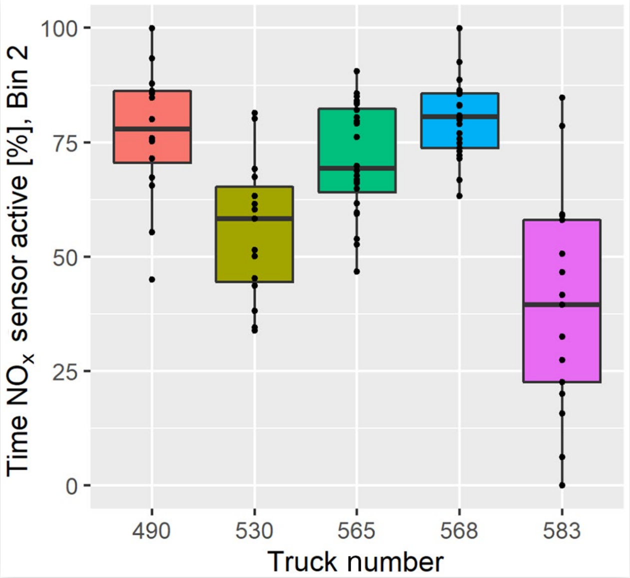

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FIGURE 8 Percentage of time that NO$_x$ sensor was active during testing, Bin 3.

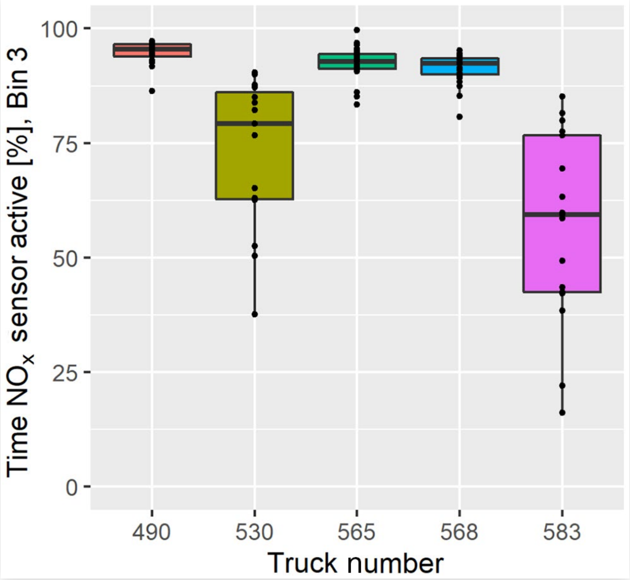

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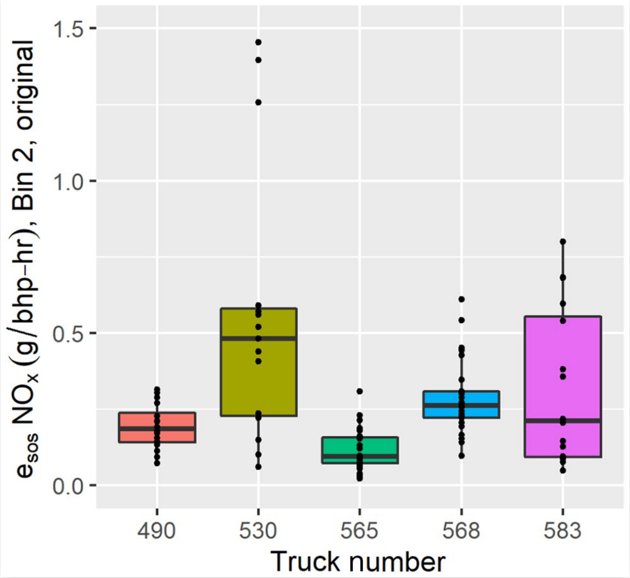
Figure 9 shows the sum-over-sum emissions in Bin 2 calculated using only available data from the NO$_x$ sensors on board the vehicles, while Figure 10 shows the sum-over-sum emissions in Bin 2 using backfilled data for times that the sensor was inactive. Because of the effect of backfilling using the value of 1.0 g/bhp-hr, the backfilled values tend to be drawn toward this number. The original, non-backfilled, values are considered to be slightly optimistic since the times that the NO$_x$ sensor was inactive tend to correspond with colder exhaust temperatures when the emissions control systems are not able to work as effectively. The backfilling was used to obtain a less optimistic result for comparison.

FIGURE 9 Sum-over-sum NO$_x$ emissions in low-load operation by truck, original (not backfilled) data.



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Looking at Figure 9, sum-over-sum NO_x emissions varied significantly by truck, from low values near zero up to 1.5 g/bhp-hr for different tests. The backfilled results in Figure 10 show the backfilled truck sum-over-sum NO_x emissions in Bin 2 ranging from about 0.1 to 1.25 g/bhp-hr on different test days. It is apparent in both graphs that the low ambient temperatures experienced by Trucks 530 and 583 had a negative effect on their sum-over-sum emissions rates, as expected since SCR systems to control NO_x may not work effectively when they are cold.

Bin 3 sum-over-sum data are presented in Figure 11, showing that Truck 530 had, by far, the highest maximum emissions rates of the five trucks in this bin. Number 530 had individual sum-over-sum NO_x emissions rates of up to nearly 0.4 g/bhp-hr under high load (Bin 3). The truck emitted lower rates of NO_x than this extreme most of the time, with a median NO_x emission rate of 0.16 g/bhp-hr. This truck was tested in low-temperature conditions, which could have added additional warm-up time for the SCR system and the NO_x sensor. In fact, the highest test emission rates correlate with the coldest test temperatures for this truck. However, a much lower emissions rate was captured in the Truck 583 data, which operated under similar conditions to Truck 530. It is possible that Truck 530, being a slightly older model and different truck type (2019 versus 2020, sleeper cab versus day cab) and having a different engine model (DD15 versus DD13), could have contributed to this discrepancy, or perhaps Truck 530 had an undiagnosed emissions system issue.

All other trucks emitted very low levels of NO_x during high-load operation—frequently reaching levels lower than 0.1 g/bhp-hr in Bin 3 and easily besting the NTE requirement of 0.2 g/bhp-hr (noting that sum-over-sum emissions do not correspond exactly to the methods used in the NTE procedures, but the regulated limit of 0.2 g/bhp-hr is used simply for comparison purposes).

FIGURE 10 Sum-over-sum NO_x emissions in low-load operation by truck, backfilled results using 1.0 g/bhp-hr NO_x for the time when the sensor was non-operational.

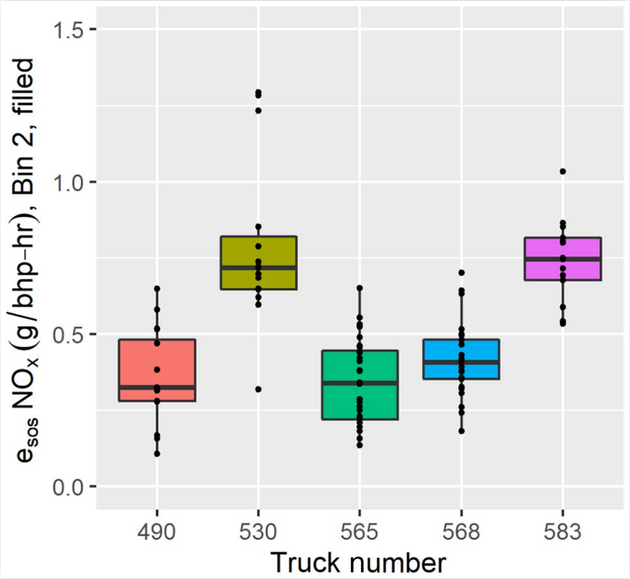

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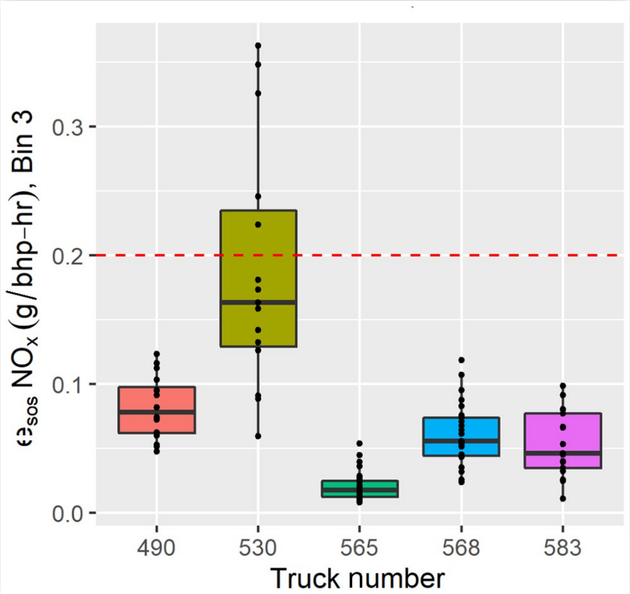
FIGURE 11 Sum-over-sum NO_x emissions high-load operation (Bin 3), by truck, also showing the current NTE limit of 0.2 g/bhp-hr (sum-over-sum results for Bin 3 are the same whether original or backfilled data is used, so this graph is not repeated).



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Mass of NO_x Emitted per Bin Figure 12 shows the percentage mass of NO_x emitted at idle (Bin 1), low load (Bin 2), and medium/high load (Bin 3) for each of the tested trucks, using original (non-backfilled) data. The values of percentage NO_x emitted in Bins 1 and 2 combined varied from 10% to 43% of the total, depending on the truck. The percentage mass

FIGURE 12 Percentage of NO_x mass emissions in Bins 1, 2, and 3 for each truck, original data (not backfilled).

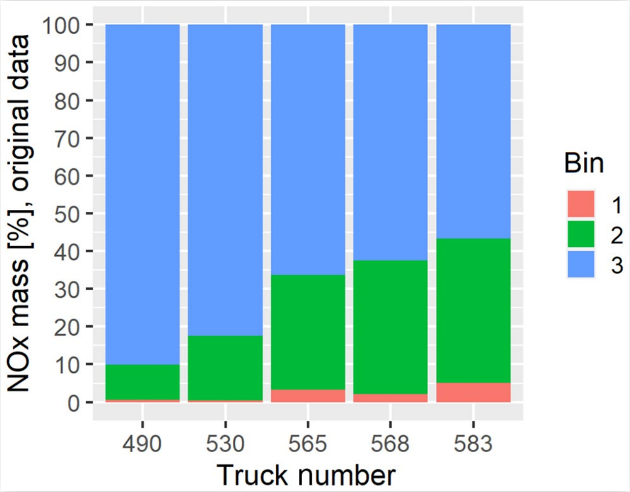

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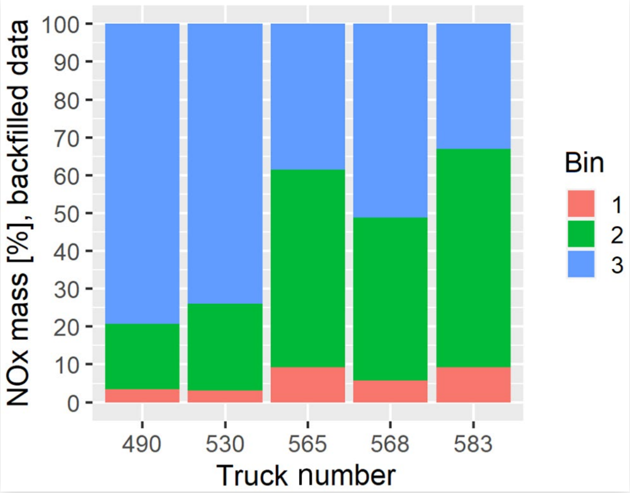
FIGURE 13 Percentage of NO_x mass emissions in Bins 1, 2, and 3 for each truck, backfilled data.



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NO_x emissions in these bins were affected by the percentage of time spent in the different load conditions (shown in Figure 6), and the percentage values in these two graphs are generally similar. However, when adding backfilling, the percentage of NO_x mass emitted in each bin shifted, as shown in Figure 13.

Figure 13 shows the percentage mass of NO_x emitted at idle (Bin 1), low load (Bin 2), and medium/high load (Bin 3) for each of the tested trucks, using backfilled emissions for all bins (using the emissions factors described in the Data Analysis Section). Just like the results without backfilling, the percentage mass NO_x emissions in each bin was affected by the percentage of time spent in the different load conditions (shown in Figure 6). For example, Truck 490 spent most of its time in medium/high-load operation and correspondingly most of the NO_x emitted from this truck was in Bin 3, the medium/high-load bin. However, with backfilling, the Bin 2 NO_x mass emission percentages tended to increase when compared to the percentage of time spent in this bin, emphasizing the potentially outsized contribution of low-load operation to NO_x emissions. The percentage mass NO_x emitted in Bins 1 and 2 combined (using backfilled data) ranged from a low of 21% (in the case of Truck 490) to a high of 67% (in the case of Truck 583, which was particularly clean in Bin 3 operation compared to Bin 2).

Conclusions

The following conclusions may be drawn from this analysis:

- The CARB MAW approach can be effectively applied to in-use data sets to evaluate and set standards for low-load NO_x emissions; however, the use of on-board NO_x sensors introduces significant gaps in the sensing data, especially during exhaust system warm-up or idle and low-load conditions.
  - NO_x sensors operated between 43% and 80% of the time (by truck) in low-load conditions (69% of the time overall) and 89% of the time overall in Bin 3 operation.
  - To more accurately measure NO_x emissions in use using on-board vehicle sensors, new NO_x sensors that can operate at lower exhaust temperatures and during start-up conditions are needed.
- Median backfilled sum-over-sum NO_x emissions results by truck number ranged from 0.316 g/bhp-hr to 0.746 g/bhp-hr in Bin 2 (Figure 10), and from 0.018 g/bhp-hr to 0.164 g/bhp-hr in Bin 3 (Figure 11).
- Backfilled data showed that a range of 21% to 67% of the total mass of NO_x emitted by individual trucks occurred in idle and low-load conditions combined, whereas the original data showed values between 10% and 43%.
- Only tractor-trailer vehicles were data logged in this study. These trucks spent majority of their time, between 70% and 87%, at high-load conditions (Bin 3).
- The median VMT of all trucks was 432 miles per day, with individual truck median values varying from 214 miles to 549 miles per day.

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List of Abbreviations

bhp - Brake horsepower
bhp-hr - Brake horsepower hour
CARB - California Air Resources Board
CO - Carbon monoxide
CO_2 - Carbon dioxide
COPD - Chronic obstructive pulmonary disease
CRC - Coordinating Research Council
CSV - Comma separated value
DEF - Diesel exhaust fluid
DOC - Diesel oxidation catalyst
DPF - Diesel particulate filter
ECCC - Environment and Climate Change Canada
EGR - Exhaust gas recirculation
EPA - Environmental Protection Agency (of the United States)
ERMS - Emissions Research and Measurement Section of Environment and Climate Change Canada
e_{SOS} - Sum-over-sum emissions rate (in g/bhp-hr)
est. - Estimated
FCL - Family Certification Limit (CO_2 emissions over the FTP cycle in g/bhp-hr)
FFC - Fuel fraction carbon
FTP - Federal Test Procedure, referring in this document to the FTP Heavy-Duty Transient Engine Dynamometer Cycle rather than the FTP-75 cycle
g - Grams
g/bhp-hr - Grams per brake horsepower hour, the amount of emissions per unit work
GPS - Global positioning system
HC - Hydrocarbon
HP - Horsepower
ISOR - Initial Statement of Reasons
MAW - Moving average window
med - Medium
MY - Model year
NAAQS - National Ambient Air Quality Standards (of the United States)
NESCAUM - Northeast States for Coordinated Air Use Management
NO - Nitrogen oxide
NO_2 - Nitrogen dioxide
NO_x - Nitrogen oxides (includes both NO and NO_2)
NTE - Not-to-exceed
OBD - On-board diagnostic
PM - Particulate matter
PM2.5 - Particulate matter < 2.5 μm in diameter
PM10 - Particulate matter < 10 μm in diameter
SCR - Selective catalytic reduction
SOS - Sum-over-sum
US - United States
US EPA - United States Environmental Protection Agency
VMT - Vehicle miles traveled

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