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Measurement and Analysis of the Operations of Drayage Trucks in the Houston Area in Terms of Activities and Exhaust Emissions

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Abstract

The effects of exhaust emissions on public welfare have prompted the US Environmental Protection Agency to take various actions toward understanding, modeling, and reducing air pollution from vehicles. This study was performed to better understand exhaust emissions of heavy-duty diesel-powered tractor-trailer trucks that operate in drayage service, which involves the moving of shipping containers to or from port terminals. The study involved the use of portable emissions measurement systems (PEMS) to measure both gaseous and particulate matter (PM) mass emission rates and record various vehicle and engine parameters from the test trucks as they performed their normal drayage service. These measurements were supplemented with port terminal gate entry/exit logs for all drayage trucks entering the two Port of Houston Authority container terminals. The datasets were combined to analyze model year characteristics of drayage trucks over time, evaluate port visit frequencies and durations, assess geographic distributions of trucks that perform port service, and estimate the pollutant emissions related to drayage operations. When compared to certification results, measured pollutant emissions generally exceeded certification standards in terms of nitrogen oxides and PM, although this difference may be partly because these vehicles were not tested on certification cycles but rather actual in-use operation. The findings of this work indicate that less than 3.5 percent of gaseous drayage truck emissions are released during operation within port terminals, as drayage trucks operate at higher engine loads during their extensive travels throughout the region around the port.

Introduction

Diesel engines are an integral part of modern economic activity, and their use is especially important for commercial trade and freight movement [1]. However, the exhaust from these engines contributes to air pollution and impacts air quality, resulting in both health and financial costs to society [2]. There is a body of literature suggesting that air quality effects caused by diesel engine operation can result in greater instances of both cancerous and non-cancerous health effects in the population of the surrounding area [3]. This is especially true in urban regions as diesel-powered vehicles tend to operate in a localized area, further contributing to ambient air quality problems. The effects of exhaust emissions on public welfare have prompted the US Environmental Protection Agency (EPA), under the direction of the Clean Air Act, to continue efforts toward reducing air pollution from vehicles, such as continuing to lower new-vehicle exhaust emissions certification levels to levels that require advanced exhaust aftertreatment, as well as encouraging in-use vehicle inspection and maintenance programs in areas with marginal air quality [4]. Part of EPA's efforts includes creating models, such as MOBILE and MOVES, that estimate the overall pollutant emission rates from in-use vehicles (and other sources), which can then help project the emissions reductions that are possible from various policy actions [5]. These models require continuous updating as vehicle technologies, usage patterns, and regional population densities change over time. This study was conducted in order to help EPA and other administrators involved with air quality in the Houston area improve their understanding of the exhaust emissions effects of heavy-duty diesel-powered tractor-trailer trucks that operate primarily in drayage service, which involves the moving of goods overland to or from port terminals. The findings can be used both to update relevant EPA models as well as to better understand what types of programs, such as retrofit or fleet replacement strategies, could cost-effectively reduce emissions from drayage trucking. Available literature regarding drayage truck operations is limited as it focuses primarily on operational, logistical, and cost-related aspects [6].

Much of the modern non-bulk sea freight is transported in standardized shipping containers. In port, these containers are offloaded from ships, stored, and then loaded onto trailers or railcars for hauling overland to and from port terminals, warehouses, rail yards and other destinations [7]. Trucks that haul container trailers are known as drayage trucks, and are generally diesel-powered class 8 tractors. Drayage trucks travel between warehouses or other freight-handling locations and the port terminal. They enter the freight terminals and drive to prescribed loading and unloading locations within the terminal. Drayage operations result in a large fleet of heavy-duty vehicles servicing a localized area and, as a result, the trucks' operations have an effect on the local air quality.

This work consisted of the measurement and logging of activity and emissions data from actual in-use drayage trucks, followed by a wider analysis of overall drayage fleet operation in the Houston area. The test vehicles were selected using weighted stratified sampling and instrumented for measurements of activity (ie. engine on time, vehicle speed, engine speed and load, location, etc.), or activity and pollutant emission rates (activity measurements plus measurements of exhaust flow and concentration of various pollutants). Forty-six trucks were instrumented in total, with various combinations of activity or emissions and activity

data logging. Emissions tests were usually conducted over a single day for each truck, and activity-only tests were usually conducted over a week for each truck. Once either type of test equipment was installed, the participating drivers were encouraged to operate their trucks normally.

Candidate test trucks were screened by the instantaneous Remote Sensing Device (RSD) emissions measurement of trucks as they entered the Barbours Cut container terminal. Once recruited, trucks were tested by one or both of two types of measurement systems/data loggers in the study. The portable activity measurement system (PAMS) data was collected using Isaac dataloggers to record engine electronic control unit (ECU) data stream information including various engine and vehicle parameters such as vehicle speed, engine speed, and engine load. The portable emissions measurement systems (PEMS) tests were performed using SEMTECH-DS emissions analyzers and exhaust flow meters in order to record gaseous pollutant emission rates of carbon dioxide (CO₂), carbon monoxide (CO), oxides of nitrogen (NO_x), and total hydrocarbon (THC), as well as suspended particulate matter (PM) [8]. During the PEMS tests, the units also recorded the same ECU data as the PAMS units. Compact and practical PEMS systems are a relatively new and continually improving technology, and the ability to measure vehicle operation during normal in-use service represents a novel approach to support the estimation of the air quality impacts of certain fleets of vehicles, either in support of modeling efforts or furthering the understanding of the effects of various emission-reducing technologies or concepts [9]. This work involved the instrumentation of 43 electronically-controlled trucks (the recruited trucks with mechanical controls did not have ECU data for analysis). In this work, there were 46 total days of PEMS testing and over 200 logged days of PAMS testing. Some trucks received both PEMS and PAMS tests, and some PEMS tests extended to more than one day. The PEMS tests established trucks' emissions profiles over a day of various driving conditions (always including some in-port operations), and the PAMS tests allowed for a wider examination of week-long driving conditions. The experiment was designed to allow a small sample of trucks with in-depth PEMS tests to represent the wider population of drayage trucks. This testing of in-use trucks was conducted from December, 2009 through March, 2010.

Measurements of the test trucks were supplemented with port terminal entry and exit records of all drayage trucks that traveled to the Port of Houston Authority's (PHA) Barbours Cut and Bayport terminals, which are the two main container port terminals in the Houston area. As a part of port operations, for each entering or exiting drayage truck, the terminals log the license plate, its ownership (or logistics company), and information about the container and trailer attached to the truck. The entry and exit times of each truck were used to determine terminal visit patterns and rates for the drayage truck fleets in the Houston area. This information was brought together with the emission rates for the small representatively-sampled population of trucks for which emissions were measured to get a better understanding of drayage operations and their potential effects on air quality. The results can be used in support of air quality modeling efforts.

Sampling Plan and Recruiting

A stratified sampling plan was created in order to recruit drayage trucks that operated within the Barbours Cut or Bayport container terminals, located in the greater Houston, TX area, for testing. The stratified sampling plan was created so that the test trucks would fill a matrix including a wide range of NO_x emission rates and truck model years in spite of most trucks (ie. those that would have been chosen completely at random) likely being near the average in terms of year and emission levels. The solicitation of test trucks was also intentionally biased toward trucks that visited port terminals most often so their operational data would be of most benefit in terms of better understanding port and drayage operations.

Prior to recruiting, pollutant emission concentrations from in-use trucks were measured using an RSD system, which was able to non-intrusively measure an emission concentration snapshot of each truck that entered Barbours Cut Terminal during a period of a few weeks. The RSD system measures concentrations of exhaust compounds present in the exhaust plume of passing vehicles over a 50 millisecond period. The measurements are performed by shining a light beam to a mirror across the roadway and measuring the wavelengths and intensity of light that is reflected back. The various compounds in vehicle exhaust attenuate the light signal at specific wavelengths. The amplitude of the attenuation is measured at specific frequencies and the readings are processed in order to calculate the concentration of the different exhaust pollutants in the exhaust plume [10]. An RSD system was set up at the entrance to the Barbours Cut terminal, and was used to make about 4500 measurements of the exhaust plumes of about 2000 different trucks during the screening period. After the measurements were completed, trucks were then assigned “priorities” for recruiting purposes based on the truck’s NO_x emission level and model year. The NO_x emission level was chosen because of its importance as a diesel pollutant as well as the strong differences in NO_x emissions levels among the different vehicles. The model year was the other stratification variable due to its common use as a key variable in emissions inventories.

Project staff focused recruitment efforts at various companies that operated large numbers of trucks that received a high priority during the RSD measurements. Companies and independent owner/operators were offered a financial incentive if their trucks were planning to visit either Barbours Cut or Bayport, the two main container ports within the Port of Houston, at some point during the test. As a result of the stratified sampling plan, trucks were recruited for PEMS testing with a relatively wide range of characteristic NO_x emission levels and model years, and also were likely to visit port terminals at some point during their test. During the testing, drivers were asked to operate as they normally would on a day-to-day basis, and, provided they were already planning at least one trip to a container port terminal, operate as though the test equipment was not present. Recruiting trucks with the requirement that they visit a port terminal at least once created a bias in the measured port visitation rate and the overall time spent on port terminal grounds, but this was necessary in order to generate a usable amount of in-port operational data. For PAMS tests, however, all trucks were eligible for participation as long as they thought they would include at least one port visit during the week, which was a far less stringent requirement than for PEMS.

PEMS Test Procedure

Gaseous and PM exhaust emissions were measured using SEMTECH-DS PEMS, manufactured by Sensors, Inc. This device contains a number of detectors for the measurement of the concentrations of various gaseous pollutants in diesel exhaust. The SEMTECH relies on an external exhaust flow meter, attached to the vehicle's exhaust outlet, to measure total exhaust flow rate and provide a tap for the sampling of a fraction of total flow for measurement of pollutant concentrations. The unit also interfaces with the onboard data stream from the trucks' ECU in order to record various engine and vehicle parameters through the dash-mounted diagnostic link connector (DLC).

The SEMTECH-DS system collected the following information in one-second intervals:

- engine speed and engine coolant temperature
- carbon-dioxide (CO₂) concentration in the exhaust stream,
- oxides of nitrogen (NO_x) concentration in the exhaust stream,
- carbon monoxide (CO) concentration in the exhaust stream,
- total hydrocarbon (THC) concentration in the exhaust stream,
- aggregate particulate matter (PM) by gravimetric methods,
- ambient temperature, pressure, and humidity,
- exhaust temperature and mass flow rate
- vehicle location and speed from GPS

About half of the PEMS tests included the measurement of PM in addition to measurements of the gaseous compounds. The PM tests required the addition of a microproportional sampler (MPS) and a 3-chamber gravimetric filter cabinet. The PM sample was drawn separately from the gaseous sample just downstream of the flow meter. The PM sample was then diluted (to allow suspended particles to stabilize in mass and number) by the MPS and sent to a filter cabinet in order to be trapped on 47-mm Teflon filters for gravimetric measurement. Three filters could be mounted in parallel within the filter cabinet, and the active filter was switched via remote control. Typically, filters would be exclusively exposed to flow either within or outside of port boundaries in order to compare PM emission rates within port terminals to emission rates outside of port terminals. All drawn samples were transported by heated sample lines in order to minimize condensation as well as loss of PM due to adhering to cool surfaces. PM testing also utilized blanks (i.e. filters that we subject to similar handling as test filters but were never actually subject to exhaust flow) in order to estimate the extent of ambient PM contamination resulting from gravimetric filter transport and handling activities and from system contamination.

The PEMS methods employed allowed for second-by-second measurements of gaseous emission rates and time-averaged estimates of PM emission rates over the period of sampling time of each filter. By making calculations on the direct measurements, the

SEMTECH software was able to calculate mass-based pollutant emission rates for NO_x, CO, CO₂, O₂, THC, and, with further post-processing, PM.

PEMS Installation

The PEMS equipment was installed the evening before the scheduled test when the recruited truck was not in use. Generally, the SEMTECH unit and, for PM tests, the filter cabinet were installed in the sleeper part of the test truck's cab. A portable generator for power, fuel bottle for the flame ionization detector THC analyzer in the SEMTECH, and the MPS were installed immediately behind the cab on the truck's frame rails. Sample lines and wiring were passed either through sleeper cab windows and hatches, or through the truck's passenger side window. A photograph of a PEMS installation is presented in Figure 1.

Extensive information about the test truck and its engine was recorded, including engine family, engine serial number, and truck vehicle identification number (VIN). Fuel samples were also taken, labeled, and kept for later laboratory analysis. Stainless steel exhaust tubing was custom fabricated for each installation to allow transport of the complete exhaust flow from the truck's exhaust pipe to the SEMTECH's exhaust flow meter, which was mounted either on the top of the MPS rack (for PM tests) or in place of the tailpipe stack on top of the truck's vertical stack muffler (gaseous-only tests). Any holes in the exhaust system were repaired during the PEMS installation. A schematic of the major PEMS system components is shown in Figure 2.

Once all equipment was installed and connected, the PEMS was connected to A/C power (generally facility power, if available), turned on, warmed up, calibrated, and prepared for the following days' testing. System checks were performed which included verification of the exhaust flow meter measurements and input settings, review of measured exhaust flow rates, and, for PM tests, calibration and verification of dilution ratios. Gas audits and calibrations were then performed as necessary, and all system settings were established and verified. Acquisition of external data, including weather station data, GPS data and engine computer datastream data or external RPM data was also verified at this time. After all systems were prepared for the following day's testing, the vehicle was secured for overnight storage. Generally, the team attempted to leave all systems "hot" if possible, operating on shore power and eliminating the need for lengthy warm-ups the following morning. PEMS installation, operation, and maintenance were scheduled and performed in such a way as to minimize interruption of the recruited drivers' operations.

PEMS Testing

The morning of the test day, field crew members arrived approximately two hours before the truck's scheduled departure time to prepare the truck for testing, verify all system functionality, and calibrate the various pollutant analyzers. One project staff member rode along with the driver of the test truck during PM tests. This staff member monitored the functionality of the test equipment during the test and also switched the active PM filter in order to capture in-port and outside-port PM emission rates on separate filters. The riding staff member would also swap filters out of the filter holders after they had collected PM from approximately one hour of operation as well as maintain a detailed log of port entry

and exit times, the times of all filter swaps, and any available information relevant to the trailer load such as container weight and the time of loading or unloading. PEMS measurements were gathered over a complete working day, usually lasting between six and ten hours. No specific drive cycles were used during testing, and all PEMS testing was based on actual in-use loads and speeds.

Upon return to the base facility at the end of the day's activities, the PEMS test was ended, and a post-test calibration and zero were performed to quantify the measurement instrument's drift throughout the day. All gravimetric filters were logged and then placed in filter holders in sealed plastic bags. After the post-test calibrations, the PEMS data file session was ended and the data was processed, plotted, and reviewed to identify any problems. System settings, flow rates, proportionality, and pollutant concentrations were evaluated to assess test validity. If any suspicious parameters or suspect data was encountered, an equipment evaluation was performed. If the test was considered successful, the PEMS equipment was removed and prepared for installation on the next test truck.

PAMS Test Procedure

The activity measurements consisted of the use of Isaac dataloggers to record a similar stream of ECU data as was recorded by the SEMTECH. These units were configured to record engine on and off status, associated date and time stamps, vehicle location (via GPS), and various ECU data such as engine speed, vehicle speed and other engine data on a 1-Hz basis. This data was recorded in order to better understand typical driving habits of drayage truck drivers including averages of time of operation per day, speed, load and distance traveled. The GPS monitoring also allowed for tracking frequency and duration of trips to port terminals.

PAMS units were installed within the cabs of the test trucks over an evening in which the trucks were not in use, and left to collect data from the truck over the course of about one week with no supervision from project staff. At the end of the test period, project staff returned to the truck during non-working hours and removed the dataloggers. Project staff downloaded and created backup copies of logged data as soon as possible at the time of PAMS removal.

PEMS/PAMS Data Processing and Analysis

Immediately after the completion of PEMS and PAMS tests, test data were analyzed briefly prior to the removal of the measurement equipment. The recorded data was processed, and relevant variables were plotted and reviewed to identify any problems. These reviews included maximum and minimum values in addition to checks of trends and value continuity. If the data appeared valid and there were no apparent problems with the test, the equipment was removed and prepared for the next installation. Filters containing collected PM were stored for weighing under laboratory conditions. Upon completion of fieldwork, data was further analyzed for validity during further quality checks, and then processed in support of the remaining analyses in the program.

Calculations

Exhaust emission rates for heavy-duty vehicles are generally presented in terms of emission mass per unit of engine power output over time, for example grams per brake horsepower hour (g/bhphr). In order to relate emission mass to engine power in the test data, a source of instantaneous engine power output was needed. This information was sourced from the trucks' ECU data streams, and different approaches were needed depending on the individual trucks' communication protocol. There were two types of DLC connectors/communications protocols in use in the trucks tested in this study, SAE J1708 and the newer J1939. [11, 12]

J1708 Protocol ECUs —These engines typically output engine percent load. This can be thought of as the percent of current torque output of the maximum torque available at a given engine speed. Because it is a relative percentage, the value for maximum engine torque must also be found by other means in order to estimate the actual torque output of the engine at that speed. For these engines, the torque curve for the engine type was used to calculate the maximum engine torque at each engine speed to be used for multiplication by the load percent. The available torque curves, which were generally taken from manufacturer-published engine specification sheets, may not have been an exact match for each engine as manufacturers may have made minor changes to fuel/torque maps for a given engine during production. Also, exact torque curves were not available for all test engines so curves from similar engines were used if exact matches were not available. During calculations, an adjustment was made to zero out any non-zero ECU torque reading at idle if present. This was necessary because the ECU data stream did not necessarily account for the torque lost to friction within the engine in the load percent estimation. The calculation used to determine engine power output at each second of logged operation for J1708 trucks is shown in Equation 1.

J1939 Protocol ECUs —The newer J1939 guidance allows for much more detailed engine torque estimations within the ECU data broadcast. The ECU calculates estimates of the total fuel-based load percent as well as the load percent that is lost to friction within the engine. The protocol also supplies a reference torque value, which is intended to be equivalent to the maximum torque value for the engine. Calculating the torque output requires only the subtraction of friction percent from the total fuel-based percent load, multiplied by the reference torque value. As a result, calculations from J1939 ECU datastreams did not require the use of outside-sourced torque curves. The calculation for J1939 trucks is shown in Equation 2.

$$P_{i, 1708} = \frac{(\% load_i - \% load_{idle})}{(100 - \% load_{idle})} \times \tau_{RPM_i} \times RPM_i \quad (1)$$

$$P_{i, 1939} = (\% torque_i - \% torque_{fric, i}) \times \tau_{Ref} \times RPM_i \quad (2)$$

Where,

P_i = Engine power output at given instant, i

RPM_i = Engine speed at a given instant, i

% load $_i$ = ECU reported engine load at given instant i

% load $_{idle}$ = Average ECU reported load at idle

τ_{RPM_i} = Torque curve value at RPM_i

% torque $_i$ = ECU reported engine % torque at given instant i

% torque $_{fric,i}$ = ECU reported friction % torque at given instant i

τ_{Ref} = ECU continuously-reported engine reference torque value

Torque and power values from ECU data were calculated in the same manner for both PEMS and PAMS tests. Using the appropriate method for the two protocols, the engine power output at each second of logged operation can be estimated. This was then used to find the power-specific emission rate of each pollutant in the exhaust by dividing emission rate by engine power at each second of operation.

Another calculation performed during the analysis involved determining the differences between operations within and outside of port terminals. Boundaries for various port terminals were established and the latitude and longitude of those boundaries were determined. All PEMS and PAMS data with GPS coordinates falling within these boundaries was identified as “in-port” activity.

PEMS Test Results

The test program yielded gaseous emission rates and engine loads over each second of operation as well as time-averaged PM emission rates from the PEMS units. PAMS data contained activity data including operational times, vehicle speeds, locations, engine speeds and loads and other operating data from which typical trip and workday usage patterns (including number and duration of port visits) could be determined. This section presents the findings of the truck emissions/activity measurements and associated calculations.

The PEMS test data for each truck, along with the analysis performed after testing, can be used to present average emission rates on the same basis as that used in emissions certification of new heavy-duty engines. These standards are applied to brake-specific emission rates, in which the total emission mass is divided by the work performed and presented in g/bhphr. By using the engine torque and power calculated as described above, instantaneous and average brake specific emission rates can be found for each measured pollutant for each truck. Figure 3 presents the calculated brake-specific THC emission rate, averaged over the entire test of each truck, by model year. For reference, the EPA heavy-duty diesel certification rates that apply to these engines are presented on the plot as well [13].

The certification values have the same units as those calculated for the test trucks, but they are not necessarily equivalent or directly comparable. The certification test procedure follows a strict torque/engine speed trace and is conducted within specific laboratory-controlled ambient conditions with limited idling. During the in-use testing, there was frequent idling, multiple engine starts and stops, and widely varying environmental conditions and engine loads and speeds. For these reasons, as well as the amount of deterioration that was likely to have taken place among in-use trucks that often had a half a million miles or more on the odometer, there is no reason to expect that trucks will emit at or even near the certification levels when operating on the road, however the certification values provide a basis for comparison and context for the interpretation of the measured values. Note also that, in 2004, the independent THC and NO_x certification values were merged to a single non-methane hydrocarbon (NMHC) + NO_x certification value. In both the THC (and NO_x plots below), the certification levels are approximated by assuming that NO_x will contribute to approximately 85% of the sum of the two pollutants. Also, because the standard includes nonmethane hydrocarbons and the measured data includes total hydrocarbons, it is reasonable to expect that the measured HC values may be somewhat higher than the standard due to the inclusion of methane gas.

Figure 3 shows a declining trend with newer model years. It can also be seen that many of the trucks operated within or near their respective certification value for THC during the on-road testing.

Note again that the 2004–2006 HC emission standard is an estimate based on the HC contribution to the NMHC + NO_x standard. Figure 4 presents similar data for CO emissions. During the model years of the test trucks, there was no change in the CO certification limit so there is only one value applicable to all trucks.

It can be seen that only one vehicle had an average brake-specific emission rate that exceeded the certification value. The data here shows no appreciable decline in the average values over the model years. These trends are reasonable given that the certification limit hasn't changed over this period of time and the CO standard is not as important as NMHC and NO_x; in general if an engine can meet the requirements for THC/NMHC and NO_x, it is likely that it will produce CO emissions well below the standard because HC and CO emissions are often proportionally related because they are both caused by incomplete combustion. Similar data is presented again for NO_x in Figure 5. Three different NO_x emission standards applied to the model years of trucks tested in this study. The test results show a fairly weak decreasing NO_x trend with newer model years. Interestingly, none of the trucks had average brake-specific emissions from their tests that were less than their respective certification values. This could be due to the expected differences described above, most notably the large time spent idling (in which the engine power output is zero), or it could be due to increased deterioration of in-service engines with respect to NO_x emissions as compared to THC and CO. Note again that the 2004–2006 NO_x standard shown on the plot is an estimate based on the assumed contribution of NO_x to the NMHC + NO_x standard.

Figure 6 presents the results for PM in a similar fashion. There are fewer trucks represented in the PM plot because only about half of the trucks were tested for PM. The values represent the time weighted average of the calculated brake specific PM emission rates for each filter on each truck (excluding filters capturing idle-only operation). It can be seen that a small number of the trucks operated within the PM certification, but PM emissions from most trucks were 2 to 8 times greater than the standard. The results do not indicate any effect of deterioration, as the newer trucks showed no indication of emitting lower levels of PM than the older trucks.

Note that the results shown in Figures 3 through 6 are from sampled trucks that do not necessarily represent the typical drayage fleet. The sample of test trucks was intentionally biased so that trucks with a wide range of emission rates would get sampled.

In addition to evaluating emission rates on the same basis as certification standards, total emissions from various model years of trucks were analyzed on the basis of a period of time of operation. The following analysis presents the total mass of emissions per unit time over driving events in order to compare in-port operations to operations outside of port terminals. The average mass emission rates per unit time, both during port terminal visits as well as outside of port terminals, were calculated based on PEMS and PAMS data taken together. Table 1 displays the average mass emission rate (in g/s) of various pollutants emitted during port visits for the trucks, grouped by model year. Table 2 displays the mass emission rates for trucks operating outside of the port terminals. Note that the data in this table has been adjusted in an attempt to de-stratify the bias created by sampling trucks with a wide range of NO_x emissions. The values were adjusted by the ratio of the test truck's average RSD NO_x emissions to the average RSD-based NO_x emissions of the entire fleet of trucks that entered Barbours Cut terminal during the RSD testing. The de-stratification was performed so that the calculated values more closely reflect the true average emission rates of the fleet of trucks serving the two port terminals. It can clearly be seen that the time-based emission rates for the pollutants are much lower when operating within the port terminals. This is because, on a time basis, more operating time is spent at low engine speeds and loads, including idling, while in the port. The trucks drive slowly within the port and spend a much larger time idling while waiting for containers to be loaded and unloaded. Idling and low-load operation tend to produce much lower time-based emission rates than high load operation on a time basis. This is in contrast to the work-based emission rates presented previously, in which excessive idling time biased the emission rates upward.

Port Entry and Exit Logs

In addition to collecting and analyzing PEMS and PAMS data, the 2009 and early 2010 gate entry and exit records from Barbours Cut and Bayport were used to perform additional analysis to better characterize port operations and the usage of the wider fleet of drayage trucks in the Houston area. While the Bayport terminal has only one main gate, the Barbours Cut complex has two main gates for drayage trucks to enter and exit. One gate is operated by PHA, and the other is operated by APM/Maersk. The gate data provided by PHA included only trucks that entered the main PHA gate, not entries to the APM gate. Analysis of the

GPS tracks of the PEMS/PAMS trucks classified trucks that entered the complex from either gate as entering the Barbours Cut Terminal.

Because the only identifying information that gate entry records contained for each truck consisted of the license plate and the logistics company that each truck was associated with, the Texas commercial truck registration database was merged with the gate data in order to provide additional vehicle information. The registration database contained each truck's license plate, truck make, model year, and the date of each truck's registration expiration. This database was provided by the Texas Department of Transportation (TxDOT) and represented two snapshots in time. One was from August of 2009, and the other was from the database as of October 2010. It was important to have multiple snapshots in time because commercial truck license plates can remain with individual trucks for a relatively short time (can be on a one or two year cycle). The two files were merged into one chronological set for this analysis. In order to complete the analyses with the gate data, gate entries were merged with registration data based on the plate as well as the date of entry. This allowed each gate entry to be associated with a particular VIN and truck model year.

PHA/Registration Data Processing and Analysis

The analysis of the data compiled for the port terminal entry/exit database analysis was based on either the emissions/activity measurements of drayage trucks, the terminal gate databases (supplemented by the registration data), or a combination of both. The intent of the analyses was to characterize the nature of drayage truck operations, including truck ages, port visitation frequency, miles driven, and the way these characteristics change over time. These characteristics were then combined with emission rates from the PEMS/PAMS measurement with the final goal of better understanding and describing drayage operations and exhaust emissions so that they may be better accounted for in air quality models. The intent of the first database analysis was to determine the distribution of drayage truck model years as compared to the distribution of model years of similar Class 8 trucks throughout Texas included in the TxDOT registration database. These model year distributions are shown in Figure 7. The registration distribution shown is that of trucks identified in the registration database as class 8 tractors. Note that the drayage trucks tend to be older than the typical registered class 8 tractor. It was also observed that the trucks that visit the terminals most often did not fit a markedly different age profile than the trucks that visited less often.

Geographic Analysis

Geographic analysis involved exploring the counties of each truck's address as listed in the registration data in order to better understand how far typical trucks drive to visit the port terminals. Note that the address used in this analysis was that listed in the registration database, which could cause some inaccuracy in the analysis as this may not always be the actual location where the truck is domiciled. Table 3 shows the top ten most frequent counties from which trucks that entered Barbours Cut or Bayport were registered, the relative location as compared to the Port of Houston area, and the total number of trucks that entered from that county during the sampling period. Note that the values in this table only

represent trucks that had a valid match in the Texas registration database. Half of the counties are within the Greater Houston Metropolitan Statistical Area (MSA), and the other half represent counties in the rest of Texas [14].

It can be seen that trucks visiting the port tend to originate from the Houston area, the commercial centers of Dallas, Ft. Worth, and San Antonio, or cities near the border with Mexico where freight is likely to travel into or out of Northern Mexico.

Port Terminal Visit Rates

For analysis of Port Terminal visit frequencies, the port entry databases were used to characterize the frequency of trips of each truck to Barbours Cut and Bayport. First, for each truck, the average number of daily visits to either port per month was found, along with the maximum and minimum number of visits per day in the month. No truck ever visited either terminal every day they were open in a month, so the minimum number of visits per day in the month for every truck was zero. These values were averaged for all trucks by month, to determine an overall average daily visit rate for the group of trucks that visited each month, along with the average of each truck's maximum number of daily visits in that month. These results are shown in Figure 8. Any truck that entered either terminal at least once in the given month was included in the results for that month in this analysis. As such, vehicles included in this analysis include trucks ranging from trucks primarily dedicated to drayage service to trucks that happened to have a single port visit in the month but did not normally visit these container terminals.

It was typical for there to be some entries into the terminals on Saturdays but Sunday entries were very rare, never occurring at Barbours Cut and occurring a very small number of times at Bayport. For this reason, this analysis includes Saturdays in the day count but excludes Sundays. For example, if a truck visited once each weekday from Monday to Friday, but never on Saturday or Sunday, its average per day would be 0.83 (5 days visited out of 6 possible counted days of the week). So, for modeling purposes, this percentage should be taken into consideration depending on whether the model is based on daily emissions, weekday emissions, or weekly emissions. Again, no truck in any month entered the port every day it was open so the average of all the minimum entries per day is zero across this plot.

Defining the Dedicated Drayage Truck

The next step of the port visitation rate analysis was to use the visit rates found from the port gate database in order to define the number of trucks that perform frequent drayage service. For this analysis, a truck was considered to be "dedicated" to drayage service if it entered either port terminal 20 or more times per month (an average of about once per weekday). For both port terminals taken together, under 5 percent of the visiting trucks were considered dedicated by the definition used in this analysis. These trucks represented about three percent of the trucks registered in the Houston MSA (though many did come from outside the MSA region). Note that only Barbours Cut and Bayport container terminals were included in this analysis. It is possible that some of the trucks that visited these terminals also visited bulk- or liquid-cargo terminals in the Houston area and were more dedicated to

general port service than was apparent with the available data in this work. As an example of port terminal visitation rates, Figure 9 displays a histogram of bins of average monthly port visits to Bayport. The x-axis is the number of trucks falling within each bin, and the total population presented is all of the trucks that visited Bayport during the period of analysis. It can clearly be seen that the vast majority of trucks visited four or fewer times per month on average.

The results of the dedicated drayage truck analysis are presented in Table 4. The table represents the minimum number of trucks and terminal entries associated with various entry frequencies that could be used to define a dedicated drayage truck. This is based on combined Barbours Cut and Bayport gate data from January, 2009 through April, 2010. These values are estimates because many of the trucks were likely to have visited the other non-container-specific port terminals in the Houston area during the analysis time period. As a result, these values are likely minimum counts of the number of dedicated drayage trucks. Using the definition of dedicated drayage truck taken for this analysis (20 or more visits per month), the table shows that 4.2 percent of all visitors met or exceeded 20 visits per month to either or both terminals, and their visits made up a total of 27 percent of all visits to both terminals.

The findings from the port terminal visit rate analyses indicate that the port terminals are not served only by the same small group of dedicated vehicles making repeated local trips back and forth each day. While a small number of trucks visit each terminal regularly, many trucks either operate infrequently or only visit the port terminals occasionally among other pickup and delivery locations, pulling the average visit rate down below 0.5 visits per day for each truck for all months. This, coupled with the registration county analysis showing that the second most common registration county for trucks visiting these terminals was 370 miles away, indicates that drayage trucks operate over a wide area and operate over different routes with varying destinations.

Vehicle Miles Traveled and Engine Run Time

The next group of analyses was sourced from the PEMS and PAMS datasets. These focus on understanding the nature of the trips that drayage trucks take. Distributions of the number of miles traveled in each trip, each day will be presented, along with time and distance traveled inside and outside of port terminals (based on GPS data). The engine data in these datasets was collected using ECU datastreams. Each datalogger was also configured with a GPS antenna in order to record truck speed and location. The truck's location was used to assign each truck's operation into three categories of operation: outside of port terminals, within Barbours Cut, or within Bayport.

Calculations were made of average daily mileage traveled for the participants in the PEMS/PAMS testing. A histogram of these mileages is presented in Figure 10. There are two peaks in the histogram. The first peak in the smallest bin probably corresponds to trucks that either didn't run on a given day or just traveled briefly around the area near their base of operations. The other peak occurs in the 100 to 120 mile bin, which is likely to represent a more typical full work day for a drayage truck including multiple trips. Note that the bin

labeled 690 miles includes trips of 690 miles and over, of which there were only 5 trips in the dataset.

The operational analysis included an evaluation of the balance of port and non-port operational activity for the instrumented trucks, including an assessment of engine loads, speeds, and engine operation times. Table 5 presents total engine run time and idle time for the trucks instrumented with PAMS units, divided by non-port and port activity. For reference, there were 212 total PAMS truck-days of testing logged during the program.

The next PEMS/PAMS analysis was to calculate the average time spent within the terminal boundaries during each visit by the test trucks. For this analysis, both the port gate data and the test truck GPS routes were used in order to estimate the duration of the port terminal visits. Table 6 contains the average visit durations calculated from both the GPS routes in the PEMS/PAMS test data and the entry/exit times listed in the port gate data. Note that the PEMS/PAMS visit duration is based only on engine-on time. The average length of time of in-port shut downs was found to be about 1.1 minutes, which can be added to the values for the PEMS/PAMS visit durations. The date range of both data sets in the table are approximately the same.

For the Barbours Cut and Bayport data, it can be seen that, while the two sources of data report similar duration results, the GPS data indicates longer average visit durations than the gate data, even when ignoring the time that was not logged due to engine shutdowns. The most likely cause for this is that the PEMS/PAMS route data could include any wait encountered at the terminals' entrance gate. Most of the surface area of the terminals' driveways outside of the gates was considered part of the terminal when laying out the latitude and longitude boundaries of the terminals used for GPS port entry and exit determinations. If a truck needed to wait in a gate queue in order to enter, much of the time spent waiting could have been counted as in-port due to the limited resolution of the GPS map, but the port database wouldn't count the entry until the truck actually passed through the gate and was checked in.

Total Drayage Truck Emissions Estimation

To bring the emissions testing and port gate database analysis together, the final analysis is an overall estimation of the gaseous emission rates of all drayage trucks operating in container service to Barbours Cut and Bayport. This analysis focused on generating an emissions estimate for the time period from November 1, 2009, through April 30, 2010. The aim was to use the PEMS/PAMS data to estimate a truck's typical port and non-port activity and emissions, and use the port gate data to estimate the total number of port visits by all trucks. By combining this information, the total emissions levels could be estimated from drayage trucks over this time period.

During the PEMS/PAMS test program, trucks were recruited in a stratification scheme based on NO_x emission rate and model year with the goal of ensuring that trucks with a wide range of NO_x emission rates and model years were tested. The stratification of the sample of tested trucks did result in a bias in terms of the sample representativeness of the population,

however. This was corrected based on destratifying the emissions rates as well as performing the total emissions estimation based on treating trucks in each different model year bin (used during recruiting) separately. To destratify the emission rates, the calculated average emission rates within each model year group were weighted based on the number of candidate trucks in the RSD test population that the sample truck represented in terms of model year and RSD NOx bin.

The destratified average emission rates are presented for operation within port terminals and outside of port terminals in terms of grams per second in Table 7 and grams per mile in Table 8. The values are based on the measured emission masses and presented for each port visit or each entire day of non-port operation. To find the emission rates on a per-second or per-mile basis, average times and distances were used based on values from the PEMS/PAMS truck operation. The average port visit was 2,622 seconds at an average speed of 2.46 mph. The average duration of non-port daily engine operation was 22,899 seconds (~6 hrs) at an average speed of 26.44 mph. These factors can be used with the factors in the table to find the total emissions per port terminal visit or per day of non-port operation. The reason the non-port approach is calculated on a per-day basis (as compared to per-port visit) is because of the fact that the only information regarding actual specific fleet activity is from the port entry database. There is no information regarding the actions of the fleet outside of port terminals on any given day, so this activity is assumed to mimic the daily non-port activity of the PEMS/PAMS trucks for the entire fleet of trucks that visited the terminals during the analysis period. Note that gaseous emissions were measured on a second-by-second basis, and PM was collected in batch on filters, however both methods were used to yield per-port visit or per-day non-port emissions based on the average port visit durations and daily non-port driving durations.

The average emission mass per port terminal visit is presented by model year bin in Table 9. These values represent the destratified average emission rates based on the typical visits by the PEMS/PAMS trucks. Likewise, Table 10 represents the destratified average daily non-port emissions from the PEMS/PAMS trucks (i.e. excluding any in-port operation that was performed).

The average emission rates for a port visit and for a day of non-port operation were then used in order to calculate overall drayage related emissions for the fleet of trucks that visited Bayport and Barbours Cut. The average emissions per port visit was multiplied by the total number of visits to both terminals during the analysis time period to yield an estimate of the total in-port emissions for the period. The number of visits to each port terminal by trucks in each model year group is presented in Table 11.

For the non-port activity, the number of trucks used in the per-day analysis is the total number of unique trucks that visited either port terminal during any time in the analysis period. This total number, binned by model year group, is presented in Table 12.

In order to calculate the total non-port emissions, further assumptions were made because specific operational data showing how often the trucks ran was not available as it was with the gate entry data. The number of weekdays of operation in the time period (excluding

weekends and holidays) was multiplied by the average per-day non-port emissions levels (binned by model year group), and then multiplied by the total number of unique trucks in each model year group. This resulted in the total non-port emissions levels for the fleet of trucks that serviced either terminal during the time period. Plates in the gate database that were unmatched to the registration, and therefore had an unknown model year, were accounted for by scaling up the non-port total emission rate for each model year bin by the ratio of the number of non-matched trucks to the number of matched trucks. This assumes that the model year distribution of the unmatched trucks is the same as the distribution of registration-matched trucks.

Table 13 lists the estimate of the overall total emissions of the various pollutants with all model year bins added together, but separated by in-port and non-port operation. The values are presented in metric tons. The percentage of total emissions of each pollutant emitted within the port terminals is also shown. Note that the in-port emission masses for these trucks are relatively small. This is because most trucks, even when largely dedicated to port service, spend most of their work days operating outside of the port terminals, and when within the terminals, operate with relatively low engine loads.

It is important to note that this table describes emissions estimates from the fleet of on-road trucks that serviced the two terminals during the time period. It does not include emissions from the various powered vehicles and equipment that primarily operate within or at the terminal grounds. It could also be biased toward lower average on-road driving times because truck recruiting was partially based on frequency of visits to the port terminals. This selection priority means that local trucks based in the general vicinity of the Port of Houston were more likely to be chosen for testing,

Summary/Conclusions

In this work, the nature of drayage trucks and their port activities were investigated from the perspective of understanding the pollution effects of their exhaust emissions. The study began with the recruitment of test trucks in order to collect activity, emissions, and engine parameter data from these trucks while operating in drayage service. This PEMS and PAMS testing used dataloggers and measurement systems that allowed testing of the vehicles with very little interference as they operated over their normal course of operations. The emissions and activity data was supplemented with PHA gate entry logs for Barbour's Cut and Bayport, as well as the TxDOT vehicle registration database to allow for decoding of the characteristics of port-vising trucks.

Trucks' emission rates were measured while operating both inside and outside of port terminals, and logged internal engine parameters were used to estimate emissions on both a per unit time and per unit work basis. In general, most trucks emitted within their certification levels for THC and CO, but emitted higher than their NO_x certification levels by factors of 2 to 3. Compared to the PM standard, measured emission rates varied widely from within the standard to up to 8 times over the standard. While operating within ports, trucks emitted 2 to 5 times lower amounts of all pollutants on a time basis as compared to their time-based operations outside of port terminals.

The average model year of trucks visiting the port terminals in the 2008 to 2010 time frame used in this analysis was 1999, or around 10 years old. This analysis also included an investigation of the operation time that the PEMS/PAMS trucks accumulated inside and outside of the port terminal boundaries. The instrumented trucks spent about 16 percent of their operational time within the port terminal boundaries, and about 68 percent of this time spent within the terminals was idling time. The results of the activity analyses on Barbour's Cut and Bayport described in this article show that, of all the trucks that visit these port terminals, few trucks operate entirely in port drayage service. Analysis of the matched registration / terminal databases shows that the entire group of trucks that visited either port terminal only visited that terminal approximately one time per week. Of all trucks that visited both terminals, the average one visits either terminal an average of about two and a half times per week. This indicates that most trucks are likely used in a wider network of hauling operations between various warehouses and destinations apart from the port terminals.

These findings can be used to update various emissions modeling efforts in order to properly account for the effect of drayage operation on regional emissions inventories. The results of the study represent a small part of the continual process of gaining a better understanding of various sources of air pollutants and their relative importance in determining the drivers of overall air quality for a region.

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Figure 1.
A completed PEMS installation on a drayage truck

Figure 2.
Schematic of PEMS Component Installation Locations

Figure 3. Average THC emission rates for each truck by model year, with certification standard by model year

Figure 4.
Average CO emission rates for each truck by model year, with certification standard

Figure 5. Average NOx emission rates for each truck by model year, with certification standard by model year

Figure 6.
Average PM emission rates for each truck by model year, with certification standard

Figure 7.
Distribution of model years in PHA port terminal gate databases as well as the class 8 tractor subset of the TxDOT registration database

Figure 8. Average, maximum, and minimum trips per day to either terminal in 2009 and 2010, averaged for all trucks by month

Figure 9. Histogram of bins of number of monthly port visits to Bayport over the entire analysis period. The number of trucks within each bin is presented on the horizontal axis.

Figure 10.
Histogram of daily mileage traveled by each PEMS/PAMS truck

Table 1.

Average in-port mass emission rates (g/s) for the test trucks, averaged by model year group

Model Year Bin	THC	CO	CO ₂	NO _x	PM
1978-1993	0.005	0.033	2.01	0.033	0.0005
1994-1997	0.015	0.025	2.44	0.046	0.0018
1998-2003	0.004	0.021	2.73	0.043	0.0007
2004 and Newer	0.002	0.036	2.88	0.031	0.0012

Table 2.

Average outside-port mass emission rates (g/s) for the test trucks, averaged by model year group

Model Year Bin	THC	CO	CO ₂	NO _x	PM
1978-1993	0.007	0.086	12.18	0.159	0.0115
1994-1997	0.020	0.041	11.34	0.204	0.0034
1998-2003	0.005	0.037	12.46	0.159	0.0013
2004 and Newer	0.002	0.036	13.37	0.143	0.0034

Table 3.

Most common registration counties for drayage trucks visiting Barbours Cut or Bayport, along with the percentage of visitors

County and description including major city and approximate distance from port terminals or part of Houston MSA	Number of Port-Visting Trucks from this County	Percentage of Terminal Visitors (that matched registration) from this County
Harris (Central Houston Area)	9968	66%
Hidalgo (McAllen, TX, ~370 mi)	1000	7%
Fort Bend (SW part of Houston MSA)	511	3%
Dallas (Dallas, TX, ~270 mi)	397	3%
Tarrant (Ft. Worth, TX, ~290 mi)	344	2%
Brazoria (South part of Houston MSA)	307	2%
Montgomery (North part of Houston MSA)	211	1%
Bexar (San Antonio, TX, ~225 mi)	174	1%
Galveston (SE part of Houston MSA)	122	1%
Cameron (Brownsville, TX, ~380 mi)	119	1%
All other TX counties combined	1845	12%
Total	14,998	100%

Table 4.

Visit rate statistics for various definitions of a dedicated drayage truck. The statistics are for Barbours Cut and Bayport, taken together (Jan 2009-Apr 2010)

Avg # of visits per month ¹	Total # of trucks in this group ²	Total % of port-visting trucks in this group	% of Class 8 Trucks Registered in MSA	% of Class 8 Trucks Registered in TX
0 or more (all visitor)	27,926	100%	76.41%	0.000568%
4 or more	8,395	30.06%	22.97%	0.000171%
8 or more	4,894	17.52%	13.39%	0.000099%
12 or more	2,987	10.70%	8.17%	0.000061%
16 or more	1,862	6.67%	5.09%	0.000038%
20 or more	1,167	4.18%	3.19%	0.000024%
24 or more	682	2.44%	1.87%	0.000014%
28 or more	443	1.59%	1.21%	0.000009%
32 or more	281	1.01%	0.77%	0.000006%
36 or more	141	0.50%	0.39%	0.000003%
40 or more	81	0.29%	0.22%	0.000002%
44 or more	52	0.19%	0.14%	0.000001%

¹— Calculated as the total # of visits by truck over all months of gate data / # of months of data

²— This is the total number of trucks which fall in the associated “avg # of visits per month” range grouping (note it is cumulative)

³— This is the total number of visits to the port terminal in the time period by all trucks in this group;

Table 5.

Engine run and idle time per day for PAMS-tested trucks, Port and Non-port

PAMS	Non-Port		Port		Total, Port+NonPort	
	Engine-On	Idle	Engine-On	Idle	Engine-On	Idle
Total PAMS per day (Minutes)	343	133	59	41	402	174
% of Total Port + NonPort	85%	76%	15%	24%	100%	100 %
% of Engine on Time	100%	39%	100%	69%	100%	43%

Table 6.

Average port terminal visit durations as measured by GPS tracks and by the port gate database (Oct 2009 – Apr 2010)

	From PEMS/PAMS ¹		From Gate DB Data ²	
	Avg Visit Duration (min)	Std Dev (min)	Avg Visit Duration (min)	Std Dev (min)
Both BC & BP	47.9	31.2	42.4	29.2
Barbours Cut	49.6	31.1	43.5	28.1
Bayport	45.1	31.3	41.8	29.9

¹— This is the length of time within the port terminals in which the engine was running

²— The gate database data was adjusted by dropping obviously erroneous values

Table 7.

Estimated average in-port time-based emission rates for drayage trucks (g/s)

Model Yr Bin		HC	CO	CO ₂	NO _x	PM
In-Port	1978-1993	0.005	0.033	2.006	0.033	0.0005
	1994-1997	0.015	0.025	2.438	0.046	0.0018
	1998-2003	0.004	0.021	2.732	0.043	0.0007
	2004 +	0.002	0.036	2.881	0.031	0.0012
Non-Port	1978-1993	0.007	0.086	12.183	0.159	0.0115
	1994-1997	0.020	0.041	11.336	0.204	0.0034
	1998-2003	0.005	0.037	12.461	0.159	0.0013
	2004 +	0.002	0.036	13.367	0.143	0.0034

Table 8.

Estimated average in-port distance-based emission rates for drayage trucks (g/mi)

Model Yr Bin		HC	CO	CO ₂	NO _x	PM
In-Port	1978-1993	7.64	47.50	2,930.4	47.77	0.66
	1994-1997	22.39	37.15	3,562.1	67.83	2.58
	1998-2003	6.13	31.14	3,991.4	62.75	1.03
	2004 +	3.03	52.39	4,208.7	45.62	1.81
Non-Port	1978-1993	0.92	11.69	1,658.6	21.71	1.57
	1994-1997	2.73	5.55	1,543.3	27.73	0.46
	1998-2003	0.67	5.02	1,696.5	21.68	0.17
	2004 +	0.33	4.86	1,819.8	19.48	0.46

Table 9.

Estimated average total emissions mass (grams) per port terminal visit, by model year bin

Model Year Bin	HC	CO	CO ₂	NO _x	PM
1978-1993	13.72	85.25	5,259.53	85.73	1.1926
1994-1997	40.19	66.67	6,393.26	121.73	4.6383
1998-2003	11.01	55.88	7,163.75	112.62	1.8420
2004 and newer	5.44	94.03	7,553.62	81.87	3.2565

Table 10.

Estimated average total non-port emissions mass (grams) per day of drayage truck activity, by model year bin

Model Year Bin	HC	CO	CO ₂	NO _x	PM
1978-1993	154.64	1965.37	278,974.9	3,651.09	264.30
1994-1997	459.26	933.72	259,581.8	4,663.52	76.91
1998-2003	112.91	843.66	285,347.3	3,645.92	29.17
2004 +	55.12	817.38	306,090.6	3,275.7	78.04

Table 11.

Number of visits to each terminal, by model year, from November 2009 through April 2010

Model Year Bin	BC Visits (Main Gate Only)	Estimated Total BC and APM Visits	BP Visits
Unmatched	29,434	73,994	34,019
1978-1993	6,477	16,282	9,585
1994-1997	26,209	65,887	49,506
1998-2003	56,860	142,940	101,529
2004 and newer	12,638	31,771	20,174
Total	131,618	330,873	214,813

Table 12.

Total number of unique trucks, by model year, that entered either Barbours Cut or Bayport between November 2009 and April 2010

Model Year Bin	Number of Trucks	Percentage of Total
Unmatched w/ registration	4,585	40.1 %
1978-1993	401	3.5 %
1994-1997	1,671	14.6 %
1998-2003	3,719	32.5 %
2004 and newer	1,069	9.3 %
Total	11,445	

Table 13.

Estimated total emissions from trucks that entered either Barbours Cut or Bayport between November 1, 2009 and April 30, 2010, separated by in-port and non-port, in metric tons

	HC	CO	CO ₂	NO _x	PM
Estimated In-Port Emissions	9.93	35.5	3,762	59.9	1.48
Estimated Non-Port Emissions	277.20	1,347.5	409,791	5,576.3	90.35
Total Emissions	287.13	1,383.0	413,553	5,636.2	91.83
In-port percentage of total	3.5%	2.6%	0.9%	1.1%	1.6%