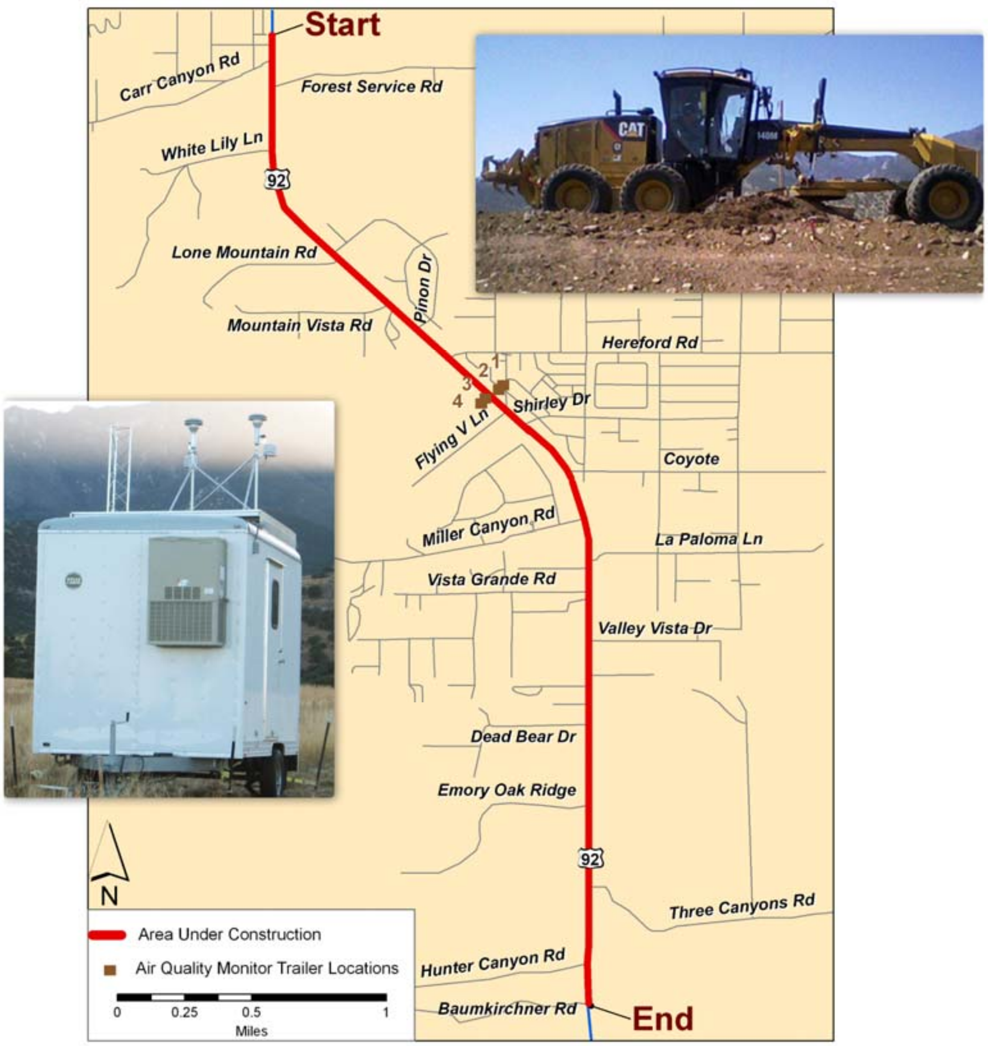
Sonoma Technology, Inc.
Air Quality Research and Innovative Solutions

Construction Activity, Emissions, and Air Quality Impacts: Real-World Observations from an Arizona Road-Widening Case Study



Final Report Prepared for
Beverly Chenausky
Arizona Department of Transportation

October 2010

Construction Activity, Emissions, and Air Quality Impacts: Real-World Observations from an Arizona Road-Widening Case Study

Final Report
STI-908017-3971-FR

Prepared by

Paul T. Roberts, Ph.D.
Stephen B. Reid
Douglas S. Eisinger, Ph.D.
David L. Vaughn
Erin K. Pollard
Jennifer L. DeWinter
Yuan Du
Alison E. Ray
Steven G. Brown

Sonoma Technology, Inc.
1455 N. McDowell Blvd., Suite D
Petaluma, CA 94954-6503
Ph 707.665.9900 | F 707.665.9800
sonomatech.com

Prepared for

Beverly Chenausky
Arizona Department of Transportation
Multimodal Planning Division
206 S 17th Avenue, MD 310B
Phoenix, AZ 95007

October 22, 2010

Cover graphic is a map highlighting the location of the SR 92 road widening project in southeastern Arizona, and photos of construction equipment and a monitoring trailer.

ACKNOWLEDGMENTS

This work was completed under ADOT Contract T08-49-AK001, Task Assignment TPD 21-08, PO No. PG-TD0115. Beverly Chenausky at ADOT served as the project manager and provided invaluable help and technical advice during the study. Dustin Berry at Bison Construction Company, the ADOT contractor responsible for completing the road work, provided STI with access to construction equipment, assisted STI with GPS unit installation, and facilitated the transfer of various data to STI either directly or via ADOT staff. Bill Harmon and Tony Hanna with the ADOT Safford District Office assisted with data collection (e.g., daily fuel use) and kept STI apprised of construction schedules and local conditions that might have an impact on monitored activity and air quality. Joonwon Joo at ADOT helped provide construction diaries. Jackie Watkins of Benson Construction provided STI with site-specific information. Chris Moore of Parsons Brinckerhoff provided STI with construction planning documents that aided in the selection of monitoring locations. Staff from Sulfur Springs Valley Electric Cooperative, the Yaqui Electric Company, and Arizona Land Specialists assisted in providing electrical power to the monitoring trailers. Karole George, a resident in the area near the construction work, allowed STI to place monitoring trailers on his property during the course of the study. Joey Landreneau of STI assisted with the installation of the air monitoring equipment. Alison Ray of STI performed audits of the air monitoring equipment, assisted with the removal of the air monitoring equipment, and performed some of the data validation. Jon Kaiser, Jeff Prouty, Siana Alcorn, and Eric Gray assisted with the setup of the air monitoring database and website. Terry Graham, sometimes assisted by Kathy Graham, performed routine checks of the air monitoring equipment, provided local technical support for the study, and assisted with the removal of the air monitoring equipment. Jennifer DeWinter, Theresa O'Brien, and Joshua Shiffrin performed data validation of portions of the air monitoring data. Dr. H. Christopher Frey, professor in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University, Dr. Deb Niemeier of the University of California, Davis, and Mr. Guido G. Schattanek of Parsons Brinckerhoff each graciously assisted the study team in answering technical questions and obtaining related technical information. Finally, appreciation goes to the STI support staff who assisted with the preparation and delivery of our project work products and generally supported field operations: Chelsea Jennings, Dennis O'Reilly, Jana Schwartz, Mary Jo Teplitz, and Mary Anne Slocum.

TABLE OF CONTENTS

Section **Page**

Section	**Page**

Section **Page**

LIST OF FIGURES

Figure **Page**

Figure		Page

LIST OF TABLES

Table **Page**

EXECUTIVE SUMMARY

ES.1 OVERVIEW

The Arizona Department of Transportation (ADOT) sponsored this investigation, a field study of emissions and air quality impacts generated from a road widening project, to gain insight into construction-related emissions of particulate matter (PM), the near-road pollutant concentration impacts that result from those emissions, and opportunities to mitigate potential impacts. Although the study focused on assessing PM less than 2.5 microns in diameter ($PM_{2.5}$), the research program yielded insight into other pollutants related to construction activities, including larger particles (PM_{10}), carbon dioxide (CO_2), oxides of nitrogen (NO_x, NO, and NO_2), and black carbon (BC).

The study assessed activity, emissions, and air quality impacts associated with construction to widen SR 92, a two-lane highway. The construction project, called the “Sierra Vista—Bisbee Highway (SR 92) Carr Canyon Road—Hunter Canyon Project” covered an approximate four-mile segment of SR 92 in Cochise County (southeastern Arizona). The study site was located in a relatively remote area of Arizona and was selected to minimize background pollution and easily identify observed impacts related to construction equipment use. The construction project involved a number of activities, including widening SR 92 from a two-lane to a five-lane road, improving the roadside with curbs and gutters, and improving an area where SR 92 intersected with a local road.

ES.2 METHODS

Emissions estimates were prepared based on construction equipment activity collected using global positioning system (GPS) units and fuel consumption logs, combined with emission factors available from the U.S. Environmental Protection Agency (EPA). Near-field pollutant concentrations were characterized through the collection of air quality and meteorological data at four monitoring stations near the roadway. Work also included a literature assessment of construction-related activity, emissions, and mitigation opportunities.

ES.3 FINDINGS

The study findings are based on construction equipment activity, meteorological data, and air quality measurements collected from January 19, 2009, to January 19, 2010, near the SR 92 construction zone. Detailed analyses were conducted for key periods to facilitate an understanding of the air quality impacts of construction activity. For example, we examined a week in February 2009 when rock crushing equipment was in use, a week in April 2009 when the highest measured PM_{10} concentrations occurred, and a week in May 2009 that was representative of times when construction activity took place near the monitoring sites and the air quality impacts of construction-related activities could be distinguished from those associated with on-road vehicle activity.

Overall, summarizing across the entire data collection period (January 2009 to January 2010), the study results indicate that construction work did affect near-field PM_{10} concentrations. During the case study periods examined here, construction activity increased PM_{10} concentrations at downwind receptors. The predominant contributor to these impacts was fugitive dust, as opposed to exhaust emissions. PM_{10} concentrations also increased during periods when strong winds brought windblown dust from the relatively uninhabited and undeveloped areas southwest of the construction zone toward the monitoring trailers. In contrast to the PM_{10} findings, the study results indicate that construction work did not substantively affect near-field $PM_{2.5}$ concentrations. $PM_{2.5}$ concentrations may have been influenced somewhat by construction-related activity, but impacts, if they occurred, were relatively small, even on days when PM_{10} impacts were substantial.

1. INTRODUCTION

1.1 STUDY PURPOSE AND MOTIVATION

The Arizona Department of Transportation (ADOT) sponsored this investigation, a field study of emissions and air quality impacts generated from a road widening project, to gain insight into construction-related emissions of particulate matter (PM), the near-road pollutant concentration impacts that result from those emissions, and opportunities to mitigate potential impacts. The findings from this project will also support public and stakeholder communication. Although the study focused on assessing PM less than 2.5 microns in diameter ($PM_{2.5}$), the research program yielded insight into other pollutants related to construction activities, including larger particles (PM_{10}), carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_x, NO, and NO_2), and black carbon (BC).

PM is a complex mixture of small airborne particles and liquid droplets. Exposure to particle pollution is linked to a variety of health problems including reduced lung function, chronic bronchitis, and asthma, and has been associated with heart attacks in people with pre-existing heart disease. In addition, PM pollution is the main cause of visibility impairment and contributes to acid rain. In the context of construction equipment use, two PM-related concerns are of key interest: $PM_{2.5}$ and PM_{10}. The exhaust from diesel-powered construction equipment includes fine particles, virtually all of which are $PM_{2.5}$ or smaller in diameter; exhaust particulate is sometimes called primary $PM_{2.5}$. $PM_{2.5}$ is also chemically formed in the atmosphere from various pollutants, some of which are emitted by diesel-powered equipment, and these particles are referred to as secondary $PM_{2.5}$. In addition, the use of construction equipment loosens and disturbs soil. The disturbed soil contributes to windblown dust problems—sometimes called fugitive dust—and the movement of dirt from the construction site onto nearby roadways. Once dirt from a construction site has been tracked onto a road, passing vehicles can cause the dirt to become suspended in the air, a problem called re-entrained road dust. Bulk material operations on construction sites, such as rock crushing activities, can also contribute to windblown dust. Most fugitive and re-entrained dust particles are larger in size than exhaust particles and construction-related dust can contribute to PM_{10} problems.

The U.S. Environmental Protection Agency (EPA) sets National Ambient Air Quality Standards (NAAQS) for PM and other pollutants. The $PM_{2.5}$ NAAQS are 35 $\mu g/m^3$ for a 24-hour period, and 15 $\mu g/m^3$ averaged over the course of a year. The PM_{10} standard is 150 $\mu g/m^3$ for a 24-hour period. Both PM_{10} and $PM_{2.5}$ concentrations are significant contributors to air quality issues in Arizona. As of January 2010, there were eight PM_{10} nonattainment areas in Arizona (Ajo, Hayden, Miami, Nogales, Cochise County, Phoenix, Rillito, and Yuma) and the Nogales area was designated nonattainment for $PM_{2.5}$.[1]

As of 2010, there were no consistent and widely accepted guidelines for estimating emissions from road construction projects. In addition, there was a comparative lack of data regarding construction equipment activity and emissions. As a result, ADOT sought technical assistance to better understand construction-related activities and resulting air impacts. To

[1] For the latest nonattainment information from the U.S. Environmental Protection Agency, see: http://www.epa.gov/air/oaqps/greenbk/index.html.

accomplish these goals, ADOT sponsored a field study to quantitatively assess the air quality impacts from an example road-widening construction project. ADOT selected a rural area roadway lane addition project on State Route 92 (SR 92) in the southeastern region of the state as the study site. The selection of the relatively remote SR 92 site enabled the study team to examine construction-related air quality impacts in an area removed from other major pollution sources.

In contrast to emissions from on-road motor vehicles, which have been regulated since the 1960s, emissions from off-road equipment remained unregulated until 1996. Given the relatively recent regulatory focus on off-road equipment, the diversity of off-road equipment types, and the resulting challenges associated with measuring real-world in-use equipment emissions, there is substantial uncertainty concerning construction equipment emissions. A key element of this uncertainty revolves around equipment use, or activity. Emissions are a function of two variables: an activity, such as the hours of operation of a piece of equipment, and the emission rate associated with that activity, such as the grams of PM emitted per hour of operation. Although information about construction equipment emission rates is generally available (for example, from EPA's NONROAD emissions model), historically there has been very little data gathered to characterize the activity of construction equipment. Therefore, the study aimed to improve understanding of the real-world equipment used to construct road projects, including information concerning day-to-day activity, equipment age distributions, fuel use, and resulting emissions.

Also of importance was the study's investigation of near-road air quality impacts. There has been a growing body of peer-reviewed literature documenting the fact that roadway-related pollutant concentrations can be higher in near-road environments than in areas further from roads, and that there is a correlation between some observed health impacts and proximity to heavily-traveled roads (e.g., Zhou and Levy, 2007; Gauderman et al., 2007; Health Effects Institute Panel on the Health Effects of Traffic-Related Air Pollution, 2010; Brugge et al., 2007; Karner et al., 2010). Therefore, one of the goals of this study was to monitor near-road pollutant concentrations and to identify whether construction work affected near-road air quality. Accordingly, over the course of an entire year, the study obtained continuous measurements of near-road pollutant concentrations and meteorological conditions.

1.2 SUMMARY OF THE SR 92 ROAD WIDENING PROJECT

The case study involved construction to widen SR 92. The construction project, called the "Sierra Vista—Bisbee Highway (SR 92) Carr Canyon Road—Hunter Canyon Project" covered approximately a four-mile segment of SR 92 in Cochise County (southeastern Arizona). The project boundaries were Carr Canyon Road to the north and Hunter Canyon to the south. Based on U.S. Federal Highway Administration (FHWA) functional classifications, SR 92 is a rural minor arterial. The construction project cost approximately $16 million and involved the following elements:

- Widening the road to five lanes—two lanes in each direction with a center left-turn lane and an eight-foot shoulder on each side of the roadway. Most sections of SR 92 had previously been one lane in each direction, without a center left-turn lane.

- Placing curbs, gutters, and a raised median on SR 92 north and south of the intersection with Hereford Road.
- Extending Hereford Road to the west to provide a new access route to a U.S. Post Office.
- Placing a traffic signal and crosswalks at the intersection of Hereford Road and SR 92.

Construction began in September 2008 and was scheduled to finish by summer 2010. ADOT funded the air quality field study to collect data over one year, beginning January 2009, to ensure that seasonal differences in local meteorology would be observed and to cover the bulk of the construction effort. The construction work that took place before the air quality field study included initial land clearing and grubbing along the north end of SR 92 in late 2008; work that took place after the air quality field study included final paving-related construction and some of the drainage work. Most of the construction work took place during the air quality field study. Exceptions were that the field study missed some of the land clearing work and overlapped only preliminary paving activity. Overall, however, the field study was able to monitor equipment activity and air quality across virtually all construction activities. Construction took place during the day, typically Mondays through Thursdays from approximately 7:00 a.m. to 3:00 p.m. During the construction period, one lane of traffic remained open in each direction, unless special construction work was warranted. **Figure 1-1** illustrates the general geographic location of the SR 92 study site. **Figure 1-2** illustrates the construction area and the placement of the monitoring trailers.

Figure 1-1. Geographic area of the SR 92 study site.

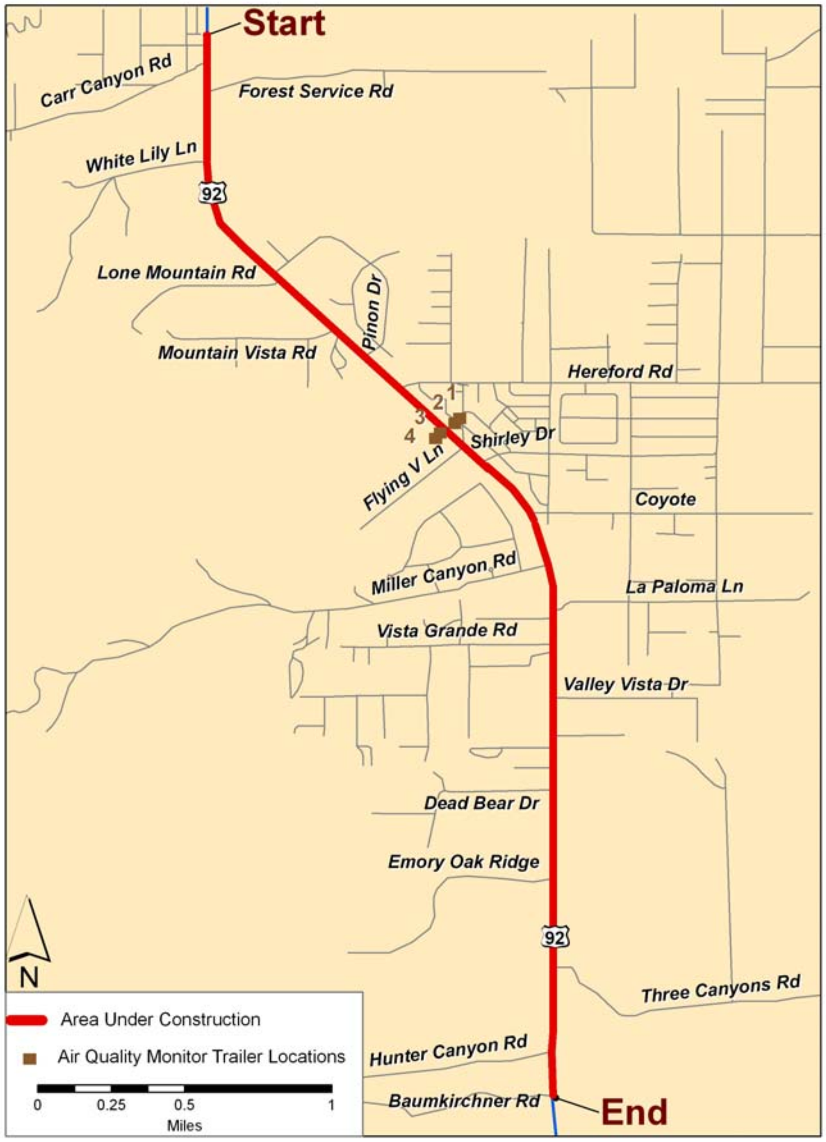


Figure 1-2. Monitoring location in relation to overall construction site.

1.3 OVERVIEW OF ACTIVITY, EMISSIONS, AND AIR QUALITY FIELD STUDY

The field study (January 2009 through January 2010) included two core components. First, construction equipment usage was monitored to quantify equipment activity. Second, air quality and meteorological data were monitored at locations adjacent to SR 92. In addition, daily SR 92 traffic data were obtained from ADOT to facilitate comparisons among monitored air quality, construction equipment use, and on-road traffic. The study also included a literature review and analysis of the collected field data.

Construction equipment usage was monitored using several methods. Working with ADOT's construction contractor (Bison Contracting), the study team inventoried the construction equipment to be used during the roadway work and identified key data such as equipment horsepower ratings and model year. Once key equipment pieces were identified, the study team instrumented the equipment with global positioning system (GPS) units. The GPS units enabled the team to spatially track equipment usage throughout the study period. ADOT also provided daily fuel consumption data by equipment piece; the data provided an indicator of equipment usage and facilitated CO_2 emissions estimation. Finally, ADOT provided daily construction diary data, which was used as a cross reference to document equipment activity.

Air quality and meteorological data were collected adjacent to SR 92. Four monitoring trailers were sited running generally along a southwest to northeast transect of the highway. **Figure 1-3** illustrates the location of the monitors based on construction plans; **Figure 1-4** provides photographs of the monitoring site. Two trailers (Trailers 2 and 3 in Figure 1-3) were located approximately 110 feet from the road; the other two trailers (Trailers 1 and 4 in Figure 1-3) were located approximately 220 feet from the road.

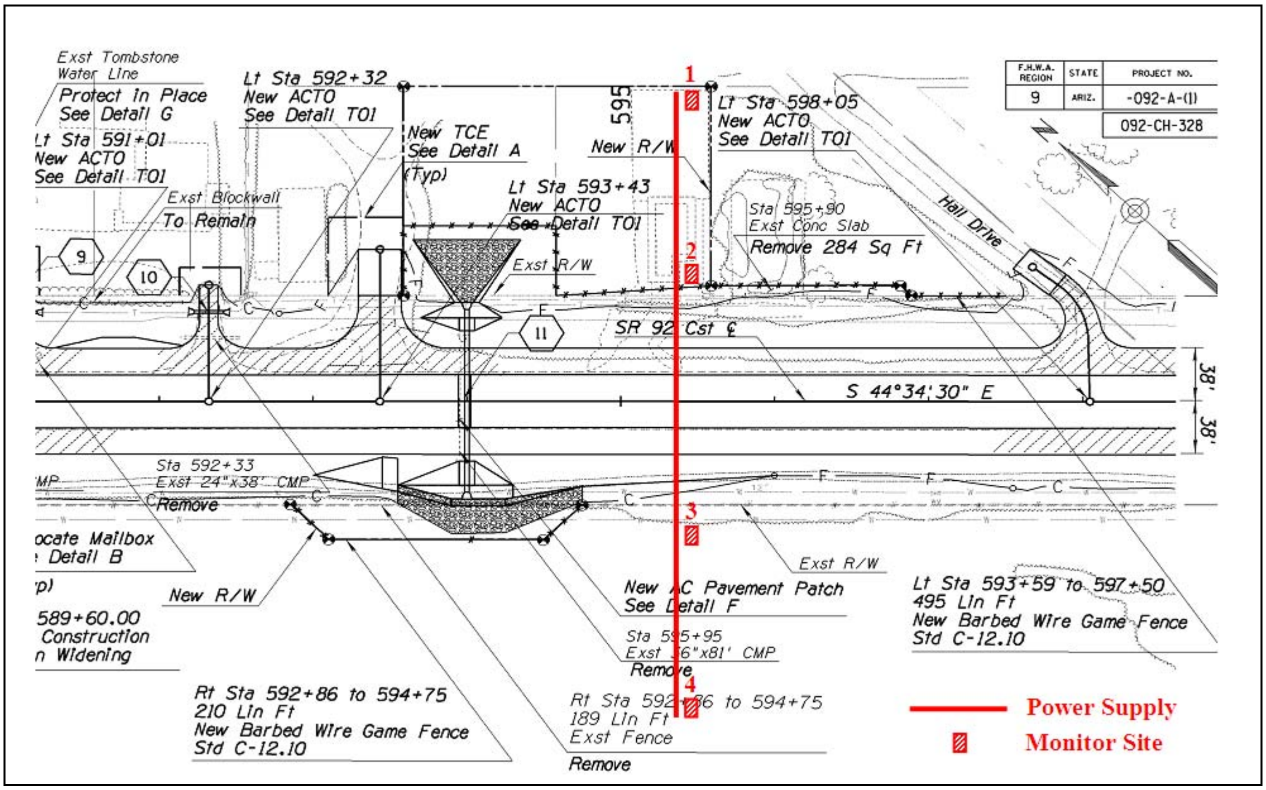


Figure 1-3. Placement of monitoring trailers with respect to SR 92 construction.

Figure 1-4. Air quality and meteorological monitoring trailers adjacent to SR 92, facing northeast (left) and southwest (right).

1.4 PRINCIPAL FINDINGS

The study yielded insights regarding equipment activity, emissions, and near-road air quality impacts. During 2009, construction equipment operated on 238 days. On average, approximately 25-30 pieces of equipment were onsite and 10 were in use each day; equipment was typically used six hours per day. Water trucks were used 81% of the 238 construction work days. Using the fraction of total project-related diesel fuel consumption as a metric to measure activity, four construction phases accounted for 75% of fuel use: roadway excavation work (50%), base and sub-base work (9%), structural excavation (8%), and drainage and landscaping work (8%). Approximately three quarters of fuel use originated from four equipment categories: tractors/loaders/backhoes (24%), water trucks (21%), other trucks (18%), and excavators (13%).

Generally, the breakdown of important $PM_{2.5}$ exhaust emissions contributors parallels the important sources of activity, both by construction phase and equipment type. A notable exception is the use of the diesel-powered rock crusher, which contributed 10% of total $PM_{2.5}$ emissions, despite accounting for only 4% of fuel consumed. Approximately 80% of fugitive $PM_{2.5}$ dust emissions were attributable to the roadway excavation construction phase.

On an average day, approximately 7,200 vehicles traveled through the 4.4-mile SR 92 construction zone. During 2009, on-road vehicle NO_x emissions were approximately 2.5 times greater than construction-related NO_x emissions; on-road PM_{10} and $PM_{2.5}$ emissions were 6% and 19%, respectively, of construction-related emissions.

The main PM-related findings from the study include the following:

- $PM_{2.5}$ concentrations were influenced by construction-related activity, but the impacts were relatively small, even on days when PM_{10} impacts were substantial. Most of the case study observations illustrated that $PM_{2.5}$ concentrations varied little, even when PM_{10} was influenced by nearby construction activity.

- During the case study periods examined here, construction activity increased PM_{10} concentrations at downwind receptors. The predominant contributor to these impacts was fugitive dust, as opposed to exhaust emissions. PM_{10} concentrations also increased during periods when strong winds brought windblown dust from the relatively uninhabited and undeveloped areas southwest of the construction zone toward the monitoring trailers.

1.5 REPORT OUTLINE

The remainder of this report describes the study and related findings in greater detail. Section 2 presents highlights from the literature review, Section 3 provides an overview of the field program, Section 4 discusses the air quality and meteorological measurements completed, Section 5 discusses equipment activity data collection, Section 6 summarizes traffic data collection, Section 7 provides an assessment of the construction emissions from the SR 92 project, Section 8 presents case studies illustrating the near-road air quality conditions observed during the field study, Section 9 summarizes the major findings, and Section 10 identifies major conclusions and opportunities for future research. Appendices provide supplemental information regarding the literature review, the data management system used to process air quality and meteorological data collected in the field, the overall data set obtained, and the fuel used by the construction equipment.

2. EQUIPMENT ACTIVITY, EMISSIONS, AND MITIGATION OPTIONS: A LITERATURE REVIEW

This section provides a digest of key findings from the literature regarding construction equipment activity and emissions, and opportunities to mitigate emission impacts. The material presented here is supplemented by a more detailed discussion of the literature presented in Appendix A.

2.1 OVERVIEW

A key objective of this study was to help the Arizona Department of Transportation (ADOT) determine how to mitigate negative air quality impacts resulting from the construction of transportation projects. Effective mitigation requires an understanding of two things: the most important construction-related emissions sources, and the control options available to reduce emissions from those sources. Although the literature on construction equipment use is not robust—the lack of adequate literature helped drive the need for this study—some general observations can be made to target mitigation efforts.

- A relatively concise list of non-road equipment is typically employed to complete projects. Studies, albeit limited, indicate that air compressors, bore/drill rigs, cranes, excavators, forklifts, generator sets, loaders (rubber tire and skid steer), pavers, rollers, scrapers, tractors/loaders/backhoes, and welders constitute pieces of equipment used most often across various types of construction projects (including, but not limited to, transportation projects). At transportation projects, signal boards also operate for many hours; however, their contribution to emissions may be negligible if they are solar powered.
- In addition to non-road equipment, there are numerous on-road vehicles that contribute to the completion of transportation projects, including trucks hauling materials to and from the job site. However, when completing construction-specific emission assessments, emissions from the on-road fleet are sometimes ignored for the purpose of near-field or hotspot assessment work, since the bulk of the emissions from these vehicles occurs while they are in transit between the job site and other destinations. An exception—one that proved to be especially important in the case of the ADOT project activity observed here—involves the use of watering trucks for dust control at the construction site. Watering trucks, though categorized as on-road vehicles, can operate for substantial periods of time at construction sites.
- The age of non- and on-road diesel-powered equipment plays an important role in its contribution to emissions. Non-road equipment exhaust emissions were unregulated prior to the 1996 model year, and many types of equipment remained unregulated through the 1999 model year; this equipment is referred to as Tier 0 equipment. More stringent emissions standards have been phased in over time. Tier 1 regulations were phased in from 1996-2000 but have since been succeeded by Tiers 2, 3, and 4. Once the most stringent standards (Tier 4) are largely phased in by 2014, they will reduce particulate matter (PM) and NO_x emissions by 90% or more compared to earlier equipment (a good summary of these standards by equipment horsepower rating, model

year, and Tier grouping is available in Lewis et al., 2009). Diesel-powered construction equipment can remain in use for several decades. Therefore, although new equipment is lower-emitting, older (unregulated or regulated but higher-emitting) equipment continues to operate. Similarly, on-road diesel-powered trucks have had to meet increasingly stringent emissions standards over time. On-road, heavy-duty diesel-powered trucks were unregulated for PM emissions until the 1980s, after which increasingly stringent new-vehicle emissions standards took effect through the 1990s and 2000s. As documented by the National Research Council, pre-1980 trucks emit 10 times the PM of post-1996 trucks (1.92 g/mi vs. 0.19 g/mi, see National Research Council, 2004). As of 2010, the required use of ultra-low sulfur diesel (ULSD) fuel for both on- and non-road vehicles has contributed to achieving the most recent federally mandated emissions standards.

- Regardless of equipment age, construction equipment use disturbs soil and contributes to fugitive dust; if left uncontrolled, the dust can be tracked onto roadways, where on-road vehicles resuspend the material and contribute to airborne PM.
- Mitigation options fall into six categories: encouraging use of newer, lower-emitting equipment; retrofitting older equipment to reduce emissions; modifying fuel used to reduce emissions per unit of fuel consumed; curtailing or controlling activity; increasing the distance between activity and receptors; and applying dust suppressant and removal controls. In 2010, the American Association of State Highway and Transportation Officials (AASHTO) published results from a survey of state departments of transportation regarding the state-of-the-practice for mitigating construction equipment emissions; highlights are included in **Table 2-1**.

2.2 EQUIPMENT ACTIVITY

Emission estimates are prepared by pairing emission factors per unit of activity (such as grams of particulate matter emitted per hour of equipment operation) with the total units of activity associated with a particular project or work effort (such as the total hours of equipment operation). Unfortunately, in the construction arena, few published resources document equipment activity. This information gap exists for several reasons. Notably, there is a wide array of construction equipment and it is used across numerous applications that are difficult to generalize. In addition, the first non-road equipment emissions standards were promulgated by the U.S. Environmental Protection Agency (EPA) in 1994, relatively recently compared to other control programs. Therefore, less time has been devoted to assessing and documenting real-world, non-road equipment use than to on-road mobile source activities; as a result, there is a substantial amount of uncertainty associated with construction equipment activity. This discussion presents sample insights from the literature regarding activity; however, readers should understand that much work remains to be done to improve the characterization of construction equipment use.

Table 2-1. Summary state-of-the-practice mitigation efforts among states surveyed by AASHTO.

State	CA	CO	IL	MD	MN	NY	VA	WI
Dust Controls								
Watering and use of chemical palliatives	X	X	X	X	X	X	X	X
Preparing dust control plans	X		X					
Covering trucks hauling material		X	X	X				
Stabilizing or covering stockpile areas		X						
Washing equipment/wheels in contained areas; minimizing dirt track out		X	X			X		
Reducing speed on unpaved roads			X					
Covering exposed areas with straw or hay bales, mulch, vegetation		X	X			X		X
Removing excavated material promptly				X				
Blading off loose material from haul roads				X				
Exhaust Controls								
Limiting idling	X		X					X
Maintaining existing traffic lanes to reduce congestion-related emissions				X				
Retrofitting equipment that does not meet minimum emissions standards (depending upon hp and use)				X				
Limiting use of cutback asphalt during the ozone season							X	
Other Controls								
Staging trucks or siting stationary sources in areas away from sensitive receptors			X					X
Protecting air intakes on buildings						X		
Prohibiting burning that results in dense smoke							X	

Note: Some states shown may require some of the controls listed (or additional controls), even if they are not indicated here; the table only documents findings from the survey, as reported by AASHTO. The AASHTO survey included additional references to control of lead-based paint, aerially deposited lead, and naturally occurring asbestos that are not shown here. Source: Shrouds (2010).

Generally, two information resources are available to characterize equipment populations and activity. “Top-down” information covers regional, statewide, or nationwide estimates of equipment populations and their average use over time, typically distributed by age (model year). Top-down data, embedded in California and federal modeling tools, is usually based on surveys of agencies and private sector construction firms, and is used to prepare regional emissions inventories. “Bottom-up” equipment population and use data are sometimes collected for individual construction projects. Owing to the paucity of published bottom-up studies and the wide array of equipment applications, an ongoing challenge is synthesizing the bottom-up data into information that can be used across multiple project types and at regional or larger scales.

One of the more recent top-down study efforts involved updating the California modeling tool to estimate non-road equipment emissions inventories. In 2006 and 2007, the California Air Resources Board (ARB) sponsored surveys of more than 200 mining and construction equipment owners or operators regarding non-road equipment (Baker, 2009). ARB’s findings indicated that generator sets, air compressors, tractors/loaders/backhoes, bore/drill rigs, and industrial forklifts were used more than other equipment types. However, the top-down studies covered all construction-related activities and did not necessarily focus on transportation projects. Other work has shown that there are differences between the most important equipment used in construction generally compared to construction equipment used for transportation projects (Eisinger and Niemeier, 2007).

Among bottom-up studies, the literature offers varied findings regarding the most important construction equipment types and their hours of operation. For example, a 2005 study of contractors engaged in major construction projects in west Oakland, California, found that the use of air compressors, generators, welders, forklifts, and cranes exceeded that of other equipment, although construction work also involved the use of bore/drill rigs, tractors/loaders/backhoes, and rubber tire dozers (Reid, 2007).

A study of construction equipment used to complete California transportation projects found that the most-used equipment types included signal boards, rollers, tractors/loaders/backhoes, rubber tire loaders, pavers, and generator sets (Kable, 2006) (**Figure 2-1**). A related study found that, based on their contribution to NO_x emissions during transportation project construction work, the most important equipment types included rollers, rubber tire loaders, graders, generator sets, scrapers, and tractors/loaders/backhoes (Eisinger and Niemeier, 2007).

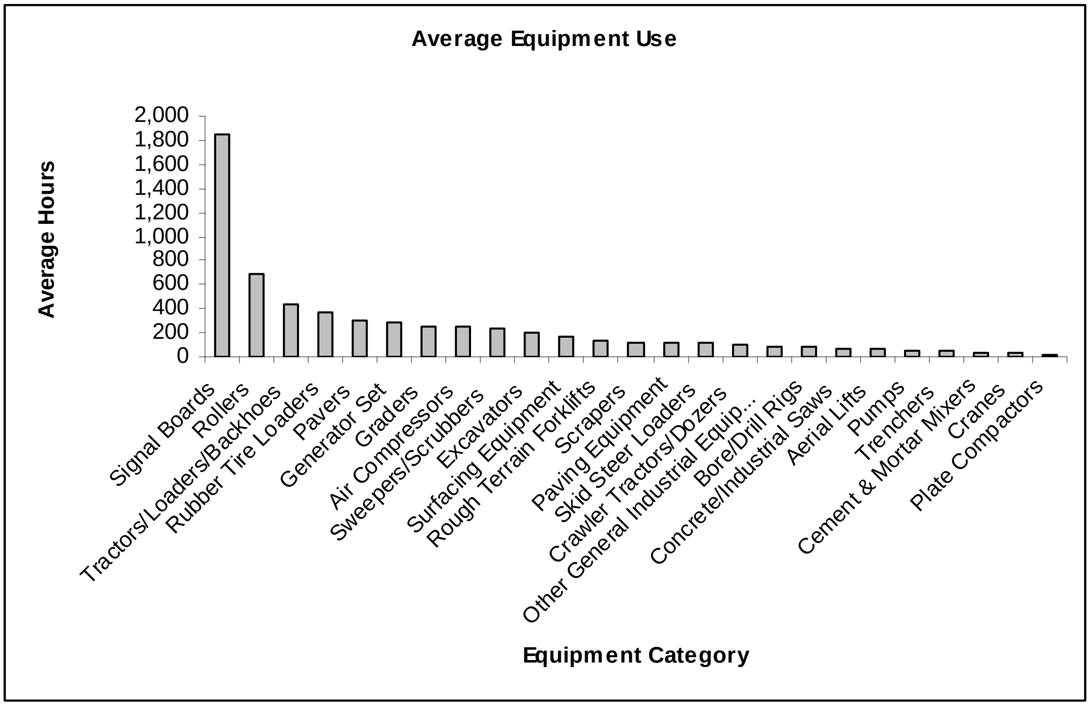


Figure 2-1. Average per-project equipment use by number of hours for 30 California transportation projects. Adapted from Kable (2006).

Among the equipment deployed to construct a transportation project, actual use can vary in terms of time spent under load vs. idling. For example, using global positioning system (GPS) data, interviews, video recordings, and operation logs, researchers found that grader activity in the Texas Department of Transportation's fleet was distributed among three modes: operations (70%), idling (20%), and driving (10%, see Lee, 2009). In another study, researchers in southern California collected onboard activity data for graders, dozers, loaders, backhoes, a compactor, and a scrapper used for street and flood control area maintenance operations and landfill work; they found that equipment idled 25% of the time, on average (Huai et al., 2005). Generally, the time under load is assumed to vary depending upon the equipment used. For example, one study of six important equipment types used in transportation projects found that ARB's OFFROAD model included embedded assumptions that equipment was under load 54% (for rubber tire loaders) to over 70% of the time (e.g., scrapers, see Wang et al., 2008b).

Equipment use varies depending upon the construction work phase. **Table 2-2** summarizes typical transportation project construction phases and examples of the key non-road equipment types used during each phase.

Table 2-2. Roadway construction project phases and associated equipment types.

Construction Phase	Description	Key Equipment Types
Land clearing and grubbing	The removal of trees, vegetation, and other material from the construction area	Excavators, crawler tractors/dozers
Roadway excavation	Excavating, grading, and disposing of soil and other material for the construction of roadway elements such as through lanes and shoulders	Rollers, graders, scrapers, tractors/loaders/backhoes, crawler tractors/dozers, rubber tire loaders, excavators
Structural excavation	Excavating, grading, and disposing of soil and other material for the construction of structural elements such as retaining walls	Tractors/loaders/backhoes, excavators
Base and sub-base	Construction of the road bed foundation with soil and gravel hauled to the construction site from other locations	Graders, rollers, scrapers, crawler tractors/dozers
Structural concrete	Construction of the structural elements of the project (e.g., retaining walls, curbs and gutters)	Rough terrain forklifts, generator sets, tractors/loaders/backhoes, air compressors
Paving	The application of asphalt and/or concrete on a prepared road bed foundation	Rollers, pavers, paving equipment, tractors/loaders/backhoes
Drainage and landscaping	Drainage work, erosion control, planting and irrigation	Generator sets, pumps, tractors/loaders/backhoes

Source: reproduced from Wang et al. (2008a).

Analysts sometimes employ rules of thumb to estimate the construction-related equipment and vehicles required to complete a particular project. Rules of thumb often relate activity and emissions to acreage disturbed and materials (such as soils) that need to be moved. For example, ARB relates construction-related road dust emissions to acres disturbed per mile of road construction; ARB's method of estimating acres disturbed is shown in **Table 2-3**. Once estimates of acres disturbed are obtained, they can be used to estimate materials movements needed to complete a project. One rule of thumb, for example, is to multiply the acres disturbed by a one-yard depth to approximate the total materials movement throughout a construction project; however, that approach is generalized and does not consider site-specific constraints or conditions, which will vary by project and construction phase. Once acres disturbed and materials movement activities are known, analysts can use these assumptions to estimate emissions. For example, a model application used in California to estimate construction emissions relies on estimated acres disturbed and materials movement to generate emission estimates.[2]

Table 2-3. ARB guidance regarding acres disturbed.

Road Type	Freeway	Highway	City & County
Acres disturbed per mile of construction	12.1	9.2	7.8

Source: ARB (1997) Area Source Methods Manual, Section 7.8, "Road Construction Dust," available on the Internet at http://www.arb.ca.gov/ei/areasrc/fullpdf/full7-8.pdf.

Regional-scale equipment activity assumptions are embedded in the ARB and EPA off-road equipment emissions inventory models. The EPA NONROAD model provides default national engine populations for a given base year by equipment, fuel type, and power level (U.S. Environmental Protection Agency, 2005c). Equipment activity and load factors in NONROAD are based on surveys of equipment owners to calculate usage by engine application and fuel type (U.S. Environmental Protection Agency, 2004a). The model can scale these estimates to state or county levels (U.S. Environmental Protection Agency, 2005b). ARB's OFFROAD model represents California's non-road equipment fleet. OFFROAD is based on industry and government agency surveys to establish base-year equipment population and activity information available at the statewide, county, and air basin levels (California Air Resources Board Mobile Source Emissions Inventory Program, 2007b).

2.3 EMISSIONS

2.3.1 Trends and Regulatory Response

In contrast to on-road motor vehicle emissions, which have tended to decrease over time due to fleet turnover to lower-emitting vehicles, non-road mobile source emissions have increased over time due to increased activity and the relatively long life of in-use equipment. The Maricopa County 8-hr ozone plan illustrates these diverging emissions. The plan documents that, from 2002 to 2008, on-road NO_x and volatile organic compound (VOC) emissions decreased approximately 20%, while non-road NO_x and VOC emissions increased 8% and 13%, respectively.[3]

In response to the growing importance of non-road equipment emissions, regulators have promulgated increasingly more stringent emissions standards for new equipment. Therefore, a key factor governing transportation project construction emissions is age of the equipment used

[2] See: Road Construction Emissions Model, from the Sacramento Metropolitan Air Quality Management District, available on the Internet at http://www.airquality.org/ceqa/index.shtml.
[3] See: "Eight-hour ozone plan for the Maricopa Nonattainment Area," Tables 5-3 and 5-4, June 2007, available at http://www.mag.maricopa.gov/pdf/cms.resource/ES_2007_8-HourOzonePlan.pdf.

at the time of the project. Equipment manufactured before 1996 was essentially uncontrolled; equipment manufactured since 1996 has had to meet progressively more stringent emissions standards the later the model year (**Table 2-4**).

Table 2-4. Summary schedule of federal non-road equipment emissions standards.

Standard (Tier)	Phase-in Period	Applicable Model Year
1	1996-2000	1996-2005
2	2001-2006	2001-2010
3	2006-2008	2006-2012
4 (transitional)	2011	2008-2013
4 (final)	2013	2013+

Source: adapted from Schattanek and Weaver (2005).

Unregulated (Tier 0) and older regulated equipment (Tiers 1 or 2) can be much higher-emitting per hour of operation than more modern (Tier 3 or Tier 4) equipment. One study of key transportation project construction equipment types found, for example, that if Tier 0 equipment was replaced by Tier 3 equipment in 2010, exhaust emissions would decrease by 83% for PM and 77% for NO_x; replacing Tier 0 equipment with Tier 4 equipment in 2015 would decrease emissions by 99% for PM and 92% for NO_x (Wang et al., 2008a).

In addition to equipment age or model year (which relates to the emissions standards, if any, the equipment was manufactured to meet), other key factors that govern emissions from a single piece of construction equipment include the degree to which the equipment and its emission controls have deteriorated over time (which relates to the hours of operation accrued on the equipment),[4] the percentage of time the equipment is under load (emission rates are higher when equipment is under load than when it is idling), fuel type, horsepower rating (emission rates increase with horsepower), and hours of operation. For example, Wang et al. document how these factors are accounted for in the OFFROAD model (Wang et al., 2008a).

2.3.2 Emissions Measurements

Historically, non-road emissions have been estimated based on tests of individual engines. The engine, after being removed from a vehicle or piece of equipment, is tested using a dynamometer test bed configured to simulate operations (Gautam et al., 2002). Each engine is operated on the test bed either at constant speed and load (i.e., steady state) for a specified time interval or following a predefined chassis dynamometer test (Frey et al., 2008).

Some studies have used onboard Portable Emissions Measurement Systems (PEMS) to assess typical operation and develop cycles for dynamometer testing (Kean et al., 2000; Singer

[4] ARB, for example, assumes that construction equipment deteriorates continuously until it accrues 12,000 hours of operation; the ARB OFFROAD model includes emission factors that increase with accrued hours of use. Once equipment reaches 12,000 hours of use, ARB assumes the equipment is rebuilt, and does not further deteriorate the equipment for emissions modeling purposes (Wang et al., 2008a).

and Harley, 2000). PEMS can collect emission rates for a range of pollutants, including hydrocarbons (HC), NO, PM, carbon monoxide (CO), and carbon dioxide (CO_2), and engine parameters such as manifold absolute pressure (MAP, see Kean et al., 2000). Other studies have estimated PM emissions with a light scattering technique (U.S. Environmental Protection Agency, 2005a). In addition, some studies have used fuel consumption information to estimate non-road diesel engine emissions, as well as heavy-duty diesel truck emissions (California Air Resources Board Mobile Source Emissions Inventory Program, 2007a). For example, one study team estimated emissions for different applications, including construction, based on multiplying the total amount of consumed diesel fuel by an emission factor that was normalized by fuel consumption (Jones & Stokes and Rimpo and Associates, 2009).

2.3.3 Emissions Modeling

EPA's NONROAD2008 model, released in April 2009, estimates emissions for six pollutants (HC, NO_x, CO, CO_2, sulfur oxides [SO_x], and PM) for specific equipment types based on equipment population, average load factor (percentage of rated power while under load), available power (hp), activity (hours of use), and emission factors embedded in the model. Emissions are allocated over time and geographical areas to several possible scales: national, state, county, and sub-county (U.S. Environmental Protection Agency, 2004b). The ARB OFFROAD model estimates pollutant emissions for 27 types of construction equipment (U.S. Environmental Protection Agency, 2004b; Kable, 2006). The latest version (OFFROAD2007) can be run for different time periods (annual, seasonal, monthly) and scales (statewide, air basin, air district, county). NONROAD and OFFROAD support regional-scale emissions inventory estimation and are not well suited to estimating project-specific emissions.

At the project level, the Sacramento Metropolitan Air Quality Management District (SMAQMD) sponsored development of a spreadsheet tool to estimate emissions from transportation construction projects (STAPPA/ALAPCO, 2006). Emissions are calculated by project phase and for the overall project lifetime. A data entry sheet requires user input of project specifications including name and start year, project type (new road construction, road widening, or bridge/overpass construction), time length and acreage of the project, truck capacity involved, and expected soil volume. The model estimates emissions of reactive organic gases (ROG), CO, NO_x, PM_{10}, $PM_{2.5}$, and CO_2 for different project phases (land clearing, grading/excavation, drainage/utilities/sub-grade, paving).

2.4 MITIGATION

Regulations that mandate new-equipment emissions standards decrease allowable emissions from new engines but are not retroactive to the pre-existing fleet. Older equipment will still contribute to PM and NO_x emissions after newer equipment is introduced into the fleet; it may take more than two decades for the existing fleet to be fully retired (STAPPA/ALAPCO, 2006). A range of mitigation options are available to reduce emissions from non-road construction vehicles and equipment.

2.4.1 Encouraging Use of Newer, Lower Emitting Equipment

Various programs are in place to require or encourage the replacement of older equipment with newer, lower-emitting equipment. Sample state programs include the Carl Moyer Program in California and the Texas Emission Reduction Plan.[5] In addition, funds available via the Congestion Mitigation and Air Quality (CMAQ) Improvement Program—part of the Safe, Accountable, Flexible, and Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)—provide financial support to retire or retrofit outdated non-road equipment.[6] At the project level, there is an opportunity for contract awards to preferentially favor construction bids with commitments to use newer, lower-emitting equipment.

2.4.2 Retrofitting Older Equipment

"After-treatment" technologies are placed in a vehicle's exhaust system to control tailpipe emissions. Diesel Oxidation Catalysts (DOC) and Diesel Particulate Filters (DPF) are common approaches; other options include four-way catalysts, lean catalysts, selective catalytic reduction (SCR), and closed crankcase emissions filtration. DOC use may yield 10-30% $PM_{2.5}$ reductions and 20-50% HC and CO emissions reductions (Zhu et al., 2002b). DPF use may yield 80-90% or greater reductions in $PM_{2.5}$, and 60-93% HC and CO emissions reductions. Implementation of DPF and DOC technologies is encouraged through programs that mandate or provide incentives to retrofit existing engines. EPA and ARB have verified the emissions reduction effectiveness of various retrofit technologies (Appendix A summarizes EPA-verified emissions reduction potential by retrofit, fuel, and replacement strategy as well as by control system manufacturer). The UC Davis-Caltrans Air Quality Project developed a spreadsheet tool to assess emissions reductions from replacement or retrofits of older diesel non-road construction equipment used in transportation projects. Six priority equipment types are included in the modeling tool: roller, rubber tire loader, grader, generator set, scraper, and tractor/loader/backhoe. Case studies suggested that replacing and retrofitting old construction equipment with new equipment would reduce 83% of project-level exhaust PM emissions in 2010.

2.4.3 Modifying Fuel Use

Federal requirements effective in 2010 mandate that only ULSD fuel (fuel with ≤15 ppm sulfur) be used to power non-road equipment. However, other fuel-based mitigation options may further reduce PM. Biodiesel is derived from vegetable oils or animal fat and is high in oxygen with low-sulfur content (STAPPA/ALAPCO, 2006). The additional oxygen in biodiesel may decrease $PM_{2.5}$ emissions up to 50%; however, it can also increase NO_x emissions by up to 10%. Biodiesel use has been excluded as an effective mitigation measure in past projects due to its potential for increasing NO_x (Schattanek et al., 2002; Schattanek and Weaver, 2005). Petroleum diesel fuel can also be blended with water, typically up to 20%, to create emulsified diesel (ED) fuel (Wang et al., 2008b). The water content lowers NO_x emissions by decreasing combustion

---

[5] See: http://www.arb.ca.gov/msprog/moyer/moyer.htm for California's program; and http://www.tceq.state.tx.us/implementation/air/terp/ for the Texas program.

[6] See federal CMAQ guidance available at: http://www.fhwa.dot.gov/environment/cmaqpgs/cmaq08gd.pdf.

temperatures and also decreases $PM_{2.5}$ emissions due to increased fuel atomization (Wang et al., 2008b). Studies in Connecticut have suggested that PuriNOx™, an emulsified diesel fuel manufactured and distributed by Lubrizol Corp., is beneficial because it is applicable across diesel engines, it does not require modification of engines, and it offers EPA-certified emissions reductions (16-58% for PM and 9-20% for NO_x, see Kasprak et al., 2001).

2.4.4 Curtailing or Controlling Activity

In addition to the rate at which an individual piece of equipment emits pollutants, its overall emissions are a function of the degree to which the equipment is used. Therefore, a key use control strategy is to discourage unnecessary equipment and truck idling at construction sites (see Table 2-1). Other options, discussed in more detail in Appendix A, include encouraging preventative equipment maintenance and training equipment operators to reduce fuel consumption and improve efficiency.

2.4.5 Applying Dust Suppressant and Removal Approaches

In addition to exhaust control for construction equipment, mitigation procedures at construction sites have traditionally focused on reducing windblown fugitive dust emissions and reducing dirt trackout, which increases silt loads on adjacent roads and contributes to re-entrained road dust. Studies have indicated that resuspended dust from trucks entering or exiting construction sites contributes to elevated PM_{10} concentrations. Strategies to limit deposition and transport include surface treatments (wet suppression, soil binding agents, gravel or crushed stone beds) and material management (cover piled materials, cover material in transport, install wind screens); these strategies are widely required among state programs (see Table 2-1).

2.4.6 Increasing the Distance Between Sources and Receptors

Construction projects can also minimize pollutant exposure by increasing the distance between emissions sources and receptors (i.e., places where people are exposed to ambient air pollution). Near-road pollutant concentrations decline substantially within 100 to 150 m of the road and can reach near background conditions at approximately 300 to 500 m from the road. Therefore, one opportunity to mitigate the impact of emissions is to increase the size of available buffer zones that separate sources and receptors. As illustrated by an AASHTO survey of best construction management practices (see Table 2-1), one option is to stage equipment operations at locations distant from sensitive receptors. Appendix A includes case studies of mitigation efforts.

3. INTRODUCTION TO THE FIELD PROGRAM

This section describes the overall schedule for the SR 92 construction project,[7] the field study design, and steps used to quality-assure the data collected. The discussion highlights how field study data collection corresponded to specific construction-related activities.

3.1 SR 92 CONSTRUCTION PROJECT

Work officially began on the SR 92 improvement project on September 2, 2008. The first few months primarily involved planning activities; field work involving substantial use of diesel-powered equipment did not begin until 2009. Work in the four-mile construction zone consisted of both pavement widening and pavement reconstruction. Reconstruction work involved the removal of existing pavement and reconstruction of the pavement at a new grade. Starting at the north end of the project (see Figure 1-2 in Section 1), the Arizona Department of Transportation (ADOT) widened the road for the first 4,860 feet; reconstructed the road for the next 2,000 feet; widened the road for the next 1,390 feet; changed back to reconstruction for the next 3,325 feet; then changed back again to widening for completion of the last 9,551 feet. In addition to pavement widening and reconstruction, the work extended and constructed new box and pipe culverts, excavated a detention basin, and installed a storm drain system along with curbs and gutters in the developed (residential) areas near Hereford Road. The project also involved the installation of a traffic signal at the intersection of SR 92 and Hereford Road.

Generally, work proceeded first on the northern part of the project, and then progressed toward the southern half of the project. Chronological highlights of the work, by construction phase, included

- Clearing and grubbing: Work to clear and grub[8] the construction zone began at the northern end (north of Hereford Road) of the east side of SR 92 in November 2008 and work on the entire northern half of the project (east and west) lasted to July 2009. The southern end of the road was cleared and grubbed from July 2009 to April 2010. Based on global positioning system (GPS) data from instrumented construction equipment, as well as daily site diaries provided by ADOT, clearing and grubbing took place adjacent to the location of the air quality and meteorological monitoring trailers on March 17, 2009.
- Roadway excavation: Excavation work began in the north in the early part of 2009. Work on the northern half of the project (including work in front of the air quality monitoring trailers) was mostly completed by June 2009. The southern part of the roadway excavation work took place primarily from July 2009 through February 2010. Based on GPS data from instrumented construction equipment, as well as daily site diaries provided by ADOT, work took place in front of the trailers on several days in April (15-16, 27, 29-30), on May 11, and on June 17-18, 2009.
- Structural excavation (culvert and pipe work): Structural work took place on and off throughout the project, beginning fall 2008. Work typically spanned a few days at a time,

[7] This discussion was prepared with the assistance of Jackie Watkins, ADOT Senior Resident Engineer.
[8] Clearing and grubbing involves the removal of vegetation and debris along the roadside in the construction zone.

with gaps of a few weeks in between work efforts. Generally, this work took place on the east side of the road first, then moved to the west. Work was isolated to small sections of the road where drainage features were located.

- Base and sub-base: Aggregate base (AB) included six inches of aggregate material (a structural material of ground rocks and soil); sub-base is the material under the base; it included material that was already onsite (no fill was brought to the construction site). Construction of the base began in January 2009 and continued throughout the project. Construction of the base corresponded to the paving schedule and was generally completed one month prior to paving.
- Structural concrete: Greater than 90% of the concrete work was for culverts and pipes, although it also supported curb and gutter construction and signal pole installation. This work started approximately February 2009 and continued on and off throughout the project.
- Drainage and landscaping: Drainage and landscaping work continued on and off throughout the project, beginning approximately April 2009.
- Other: Operation of a diesel-powered rock crusher took place during three separate time periods. These periods occurred January 29-March 5, 2009, September 8-21, 2009, and November 16-December 11, 2009. An electrically-powered slurry plant was located adjacent to the rock crusher and operated on and off throughout the project (liquid slurry was used to backfill around pipes and culverts; it consisted of ground pavement, cement, and water).
- Paving: Paving involved completion of three layers. The first (base) layer was approximately three inches in depth and was applied during several paving periods during 2009 and 2010. In the northern portion of the construction zone, the first layer was applied June 4, 8, and 9, 2009. Paving work on June 8 was approximately 200 feet north of the air quality monitoring trailers and on June 9 was adjacent to the trailers. Some of this paving work involved just one side of the road. The southern portion of the project and any remaining unpaved sections of the northern part of the project received a first paving layer during October 12-14, 2009. The October paving work included sections both north and south of the trailers. The first layer of paving work on the curved portion of SR 92 (south of the trailers) was done first on the east side of the road (June 2009), then on the west side (October 2009). A first layer was applied to the southern half of SR 92 during March and April 2010. The second layer (top layer) was approximately two-and-a-half inches in depth and was applied in March and April 2010. A third layer (one-half inch thick) of asphalt rubber—asphaltic concrete friction course (AR-ACFC, a skid-resistance surface) was applied in June 2010.

3.2 OVERVIEW OF THE STUDY DESIGN

The objectives of the field study were to characterize and quantify $PM_{2.5}$, PM_{10}, and particulate precursor emissions contributions from various phases of the construction project. STI simultaneously measured air quality, meteorological conditions, and emissions activity during various construction phases. ADOT worked with STI to simultaneously collect traffic activity data. We used the air quality data collected during the field study to characterize air at the receptor sites. We compared times and days when construction was ongoing to days when construction was not occurring (weekends, for example), and considered the proximity of the in-use construction equipment to the four air quality monitoring field stations. We also used a combination of wind direction, construction logs and reports, equipment activity data, and pollutant concentration data to assess background concentrations and identify construction equipment-related impacts on near-road pollutant concentrations. We also used real-time traffic activity from SR 92 to quantify on-road vehicle emissions, and to help distinguish air quality impacts associated with construction equipment use from impacts associated with on-road vehicle fleet emissions.

Data on the characteristics and activity of the construction fleet provided the information needed to determine when and where different construction activities occurred and to quantify the emissions associated with those activities. Air quality and meteorological data allowed us to quantify changes in pollutant concentrations and to link those changes to periods when construction activity took place upwind of the monitored impact.

3.3 DATA QUALITY ASSURANCE AND QUALITY CONTROL PROCESSES

3.3.1 Air Quality and Meteorological Data

Quality control (QC) activities are ongoing efforts performed by measurement and data processing personnel to assure that operations data meet standard U.S. Environmental Protection Agency (EPA) guidelines for air quality monitoring. They include periodic calibrations and performance tests, whose results are compared to predefined tolerances that should not be exceeded. In practice, these calibrations and performance tests are achieved by challenging the measurement system with a known standard sample traceable to a primary standard. If the tolerances are exceeded, specific actions must be taken to correct the underlying cause.

Data were reviewed at least daily on a website with graphical displays. Hourly $PM_{2.5}$ and PM_{10} concentrations; 5-minute black carbon (BC) concentrations; 1-minute concentrations of gaseous species (carbon monoxide [CO] and oxides of nitrogen [NO, NO_2, NO_x]) and particulate polycyclic aromatic hydrocarbons (pPAH); and meteorological data were captured using a commercially available data acquisition system called "Envidas for Windows" (EnvidasFW, available from the firm DR DAS, Ltd.). The data were stored in an onsite Structured Query Language (SQL) database and transferred to a permanent SQL database at STI's Petaluma office every 10 minutes; they were then delivered to a real-time website (http://appserv1:8080/adot/realtime.jsp?site=5) accessible to ADOT staff. To assure high data recovery rates, irregularities noted during the daily review were resolved via standard procedures (e.g., checking instrument calibration or resolving sampling line issues).

QC procedures were specific for each monitor and are summarized below. We also recorded other details of field operations and visits to the sites in logbooks kept at each monitoring site.

- **$PM_{2.5}$ and PM_{10} monitors**. Met One Beta Attenuation Monitors (BAM) were used to measure hourly concentrations of $PM_{2.5}$ and PM_{10}. These monitors underwent biweekly QC tests that included a leak check, flow check, and temperature and barometric pressure sensor checks. Three-point flow rate calibrations were conducted: at setup, at the midpoint of the study, and when flow checks indicated that flow rates were outside of the recommended tolerance.
    1. **Leak check**. The leak check provided assurance that the 16.7 lpm sample air flow stream entered the measurement system entirely through the inlet and not through leaks in the sample train. The tolerance for the leak check is 1.0 lpm.
    2. **Flow check**. The flow check, measured with a primary flow standard, provided assurance that the volumetric sample flow rate remained within ±4% of the nominal 16.7 lpm.
    3. **Temperature and barometric pressure check**. Measured with annually certified transfer standards, these checks assured that the flow rate was properly modulated for volumetric sampling at local conditions.
- **BC monitors**. Flow rates for the BC monitors were checked monthly.
- **Gaseous monitors**. Continuous gaseous analyzers were calibrated onsite at setup and take-down, remotely over the Internet each quarter, and on an as-needed basis. Automatic zero and span checks were made each day for CO, NO, and NO_2. All QC checks were automatically recorded in the data logger for future review.
- **pPAH**. The flow rate for the pPAH monitor was checked at startup, take-down, and several times throughout the study.
- **Meteorological sensors**. Meteorological sensors were calibrated at startup and take-down and near the midpoint of the study.
- **Dilution calibrator**. The dilution calibrator used to perform the calibrations of the gaseous instruments was itself calibrated at the setup, midpoint, and end of the study.

3.3.2 Activity Data

Data collected by GPS units was made available for download and review on a project website maintained by Fleet Management Services, Inc. (FMS), the GPS vendor (**Figure 3-1**). On a weekly basis, STI downloaded all GPS reports for the previous week, processed the data through a custom program that performed basic quality assurance (QA) checks and formatted the data for input to a Microsoft Access database.

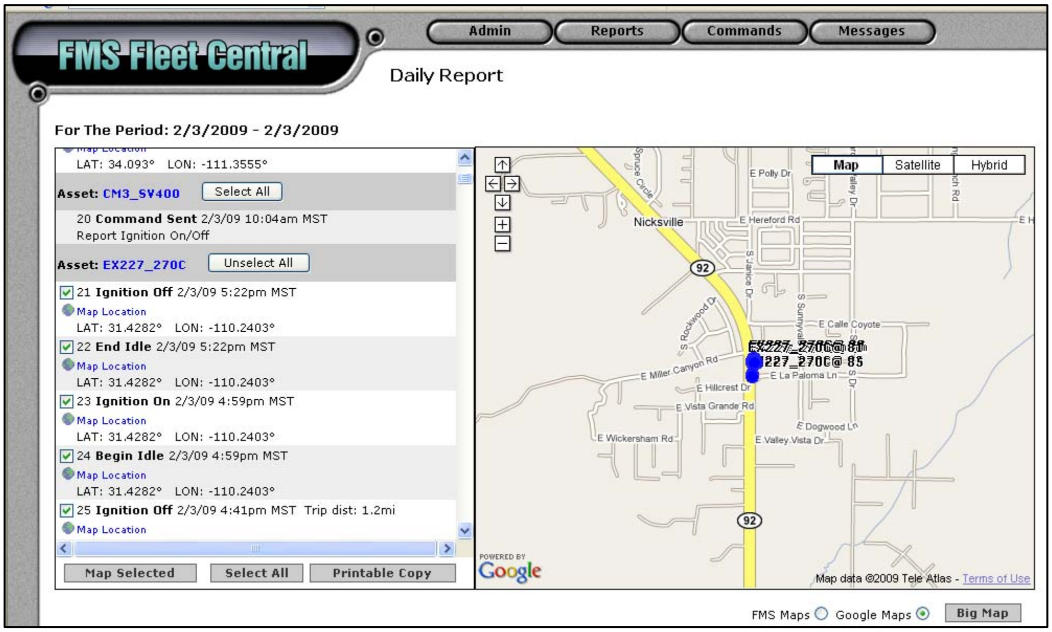


Figure 3-1. Illustration of FMS website with daily equipment activity reports (example shows excavator working south of monitoring trailers, February 3, 2009).

Routine QA checks included:

- Ensuring that reported hours of operation did not exceed reasonable bounds (16 hours) for a given day;
- Comparing reported idling times and total engine hours to verify that idling times did not exceed reported total hours of operation;
- Checking reported locations of equipment activity against latitude and longitude boundaries for the project to verify that reported equipment activity was associated with the SR 92 project.

Reported engine hours were regularly checked against daily fuel consumption data (which was also entered into the Access database) to verify that the same pieces of equipment were showing up in both data sets, and that reported engine hours for individual pieces of equipment were consistent with the amount of fuel consumed. These reconciliations between GPS and fuel data were performed approximately once per month through the duration of the field study.

In addition, we retained and used backup GPS units to correct problems. Of the 25 GPS units that we acquired for use during the study, we initially deployed 23 units and retained two units as backups. During the opening weeks of the project, one of the installed units did not properly transmit data and we had a field technician replace the defective unit with one of the backups. As the study progressed, a second unit that had operated well for several months began to experience data collection problems and we replaced that unit with the remaining backup unit.

4. AIR QUALITY AND METEOROLOGICAL DATA COLLECTION METHODS

This section describes the air quality field study, including monitor site locations, parameters measured, and highlights of the methods used to collect and report measured data for analysis.

4.1 AIR QUALITY AND METEOROLOGICAL PARAMETERS MEASURED

A summary of measurements and respective instruments/instrument housing is presented in **Table 4-1**. We used continuous, or semi-continuous, air quality monitoring methods to collect data for a wide range of conditions. To represent the atmospheric conditions during the construction project, we measured various meteorological parameters, including surface wind speed, wind direction, temperature at two heights (to assess inversion layers), relative humidity, pressure, and solar radiation. These parameters allow estimates of atmospheric stability and identify periods with consistent wind directions and thus consistent characteristics of pollutant dispersion.

Table 4-1. Measurements and instruments for the Arizona Department of Transportation (ADOT) SR 92 field study.

Measurement	Description of Instruments/Instrument Housing
Semi-continuous (hourly) $PM_{2.5}$ and PM_{10} mass	MetOne model 1020 Beta Attenuation Monitors (BAM).
Semi-continuous (5-minute) black carbon (BC) as a surrogate for diesel particulate matter (DPM)	Magee Scientific Aethalometers™
Nitrogen oxides (NO, NO_2, and NO_x)	Thermo Scientific model 42i NO_x monitor
Carbon monoxide (CO)	Thermo Scientific model 48i CO monitor
Carbon dioxide (CO_2)	LI-COR model LI-6252 CO_2 monitor
Methane (CH_4)	Thermo Scientific model 55C hydrocarbon monitor
Particulate polycyclic aromatic hydrocarbon (pPAH)	EcoChem PAS-2000 monitor
Light scattering due to particles	Radiance Research M903 Integrating Nephelometer
Wind speed, wind direction, temperature, pressure, relative humidity, and solar radiation	Monitoring meteorological parameters at one site
Gas-phase calibrator for CO and NO_x	Thermo Scientific 146i calibrator; Thermo Scientific zero air supply Model 111; DR DAS data acquisition system (EnvidasFW) for data collection and instrument control; other pieces of support equipment (e.g., inlet lines and manifolds, UPS, and modems)
Monitoring shelters	Four trailers, each measuring approximately 8 feet by 12 feet and equipped with multiple monitors

4.2 MONITORING SITES AND LOCATIONS

The SR 92 project and air quality monitor locations were shown earlier in this report (see Section 1, Figures 1-1, 1-2, and 1-3). An enlargement of Figure 1-3 is shown as **Figure 4-1**.

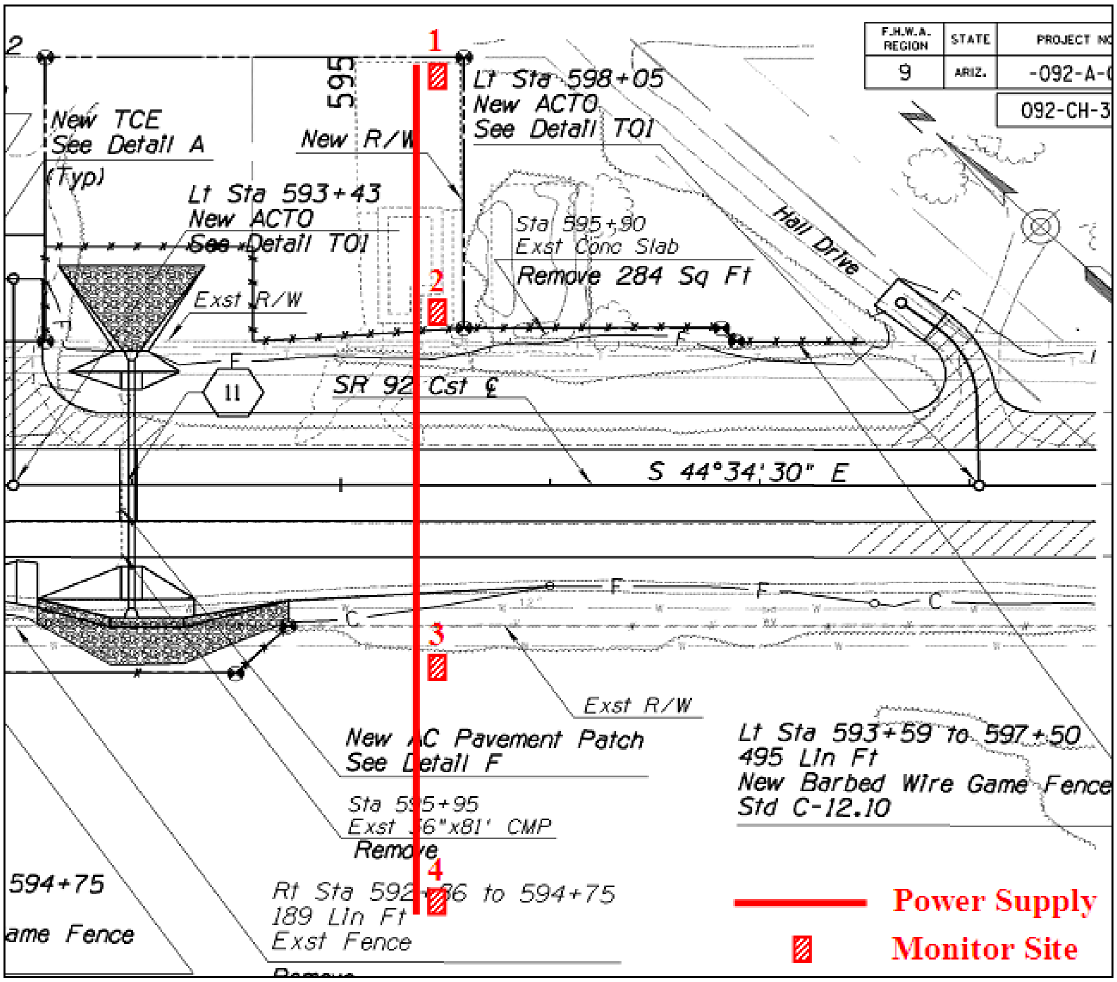


Figure 4-1. Enlarged view of monitor site locations for ADOT SR 92 field study.

A number of issues were considered and resolved when the monitoring site locations were selected. For example, monitoring sites needed to be representative of a near-roadway environment and not near other sources (e.g., major side roads) or places where winds could channel. Also, electrical power needed to be available to power the monitoring equipment and cell phone coverage needed to be available to facilitate real-time data transfer to STI's server and to support communication with onsite technicians. We selected a location for the monitoring at a point roughly midway through the construction area (at approximately station 598; see Figures 1-2 and 1-3). The location was at a point where SR 92's direction is generally from northwest to southeast; winds in the area are predominantly out of the southwest (see **Figure 4-2**); thus the four monitor locations were aligned in parallel to the prevailing winds.

Figure 4-2. Wind rose illustrating winds for 2009 as measured at the SR 92 study site. Colors differentiate apportionment of winds, by direction and speed (in units of mph). A small version of Figure 1-2 is provided to illustrate monitor placement relative to wind direction.

At the selected location, we established four monitoring sites near SR 92: two sites west and two sites east of the roadway. Sites 2 and 3, nearest the road, were 111 and 105 feet from the road centerline, respectively. Sites 1 and 4, farther away from the road, were 222 and 217 feet from the road centerline, respectively (Figure 4-1). This arrangement allowed both upwind and downwind monitoring under all wind conditions, except during periods when the wind was parallel to the roadway. Note, however, that due to diurnal and seasonal wind patterns, a given site was upwind during some conditions yet downwind during other conditions. Thus, by establishing sites on both sides of SR 92 and monitoring for 12 months, monitoring data from both upwind and downwind locations were generally available, except during periods when wind flow was parallel to the road. Details of the parameters that were monitored at each location are presented in **Table 4-2**.

Table 4-2. Measurement parameters, sites, and proximity to SR 92.

Parameter	West Gradient Site (furthest from road)	West Near Road	East Near Road	East Gradient Site (furthest from road)
$PM_{2.5}$	x	x	x	x
PM_{10}	x	x	x	x
BC	x	x	x	x
NO, NO_x, NO_2		x	x	
CO		x	x	
CO_2		x	x	
CH_4			x	
pPAH			x	
Nephelometer			x	
Data acquisition	x	x	x	x
Calibrator		x	x	
Zero air supply		x	x	
Wind speed (WS) and wind direction (WD)		x		
Relative humidity		x		
Temperature (2 & 10 m)		x		
Pressure		x		
Solar radiation		x		
30-ft. meteorology tower		x		
Trailer with A/C	x	x	x	x

4.3 EQUIPMENT INSTALLATION AND OPERATIONS

STI obtained all necessary equipment, prepared the equipment for field deployment, and coordinated siting and logistical arrangements at the selected sites. We worked with Jackie Watkins (ADOT Benson Office), representatives from Bison Construction, and others to coordinate issues such as obtaining permission to use land, maintaining site security, securing regular access to the sites, providing electrical power at the selected sites, and obtaining good cellular phone coverage in the area so that a cellular router combined with an RF-based local area network allowed communications with each of the four monitoring sites. We worked with Sulfur Springs Valley Electrical Cooperative (SSVEC) to bring electrical power to the sites. We set up the infrastructure and installed the equipment.

STI staff handled troubleshooting, non-routine maintenance, and other ongoing procedures required to maintain year-long site operations. On a daily basis, STI staff reviewed the previous 24 hours of data to ensure that equipment was functioning properly and that the data collected were reasonable. Unusual indications (such as a lack of reported data) were addressed as soon as possible and sometimes involved site visits to repair malfunctioning equipment or to further evaluate circumstances if the data appeared anomalous. For example, during the study we reviewed unusual data and identified (in consultation with ADOT staff) site-specific situations such as the presence of smoke due to forest fires. **Figure 4-3** shows a trailer housing meteorological equipment (see Section 1, Figure 1-4, for views of all four trailers).

Figure 4-3. The west, near-road trailer with meteorological tower (on left). The two trailers on the east side of the road are partially visible; the west gradient site is out of view to the left.

4.4 DATA ACQUISITION, STORAGE, AND VALIDATION

STI staff developed a web-based data retrieval system for daily review of continuous and semi-continuous data. Data were retrieved from each site every ten minutes by cell phone modem and transferred to STI's web server, underwent auto-screening quality assurance procedures, and were posted in graphical format to a password-protected web page for viewing by authorized personnel. **Figure 4-4** shows screenshots from the web-based visualization tool and data management system used for the SR 92 ADOT project. STI consolidated data into a database, validated the data to ensure consistency and representativeness, and eliminated errors or identified inaccuracies.

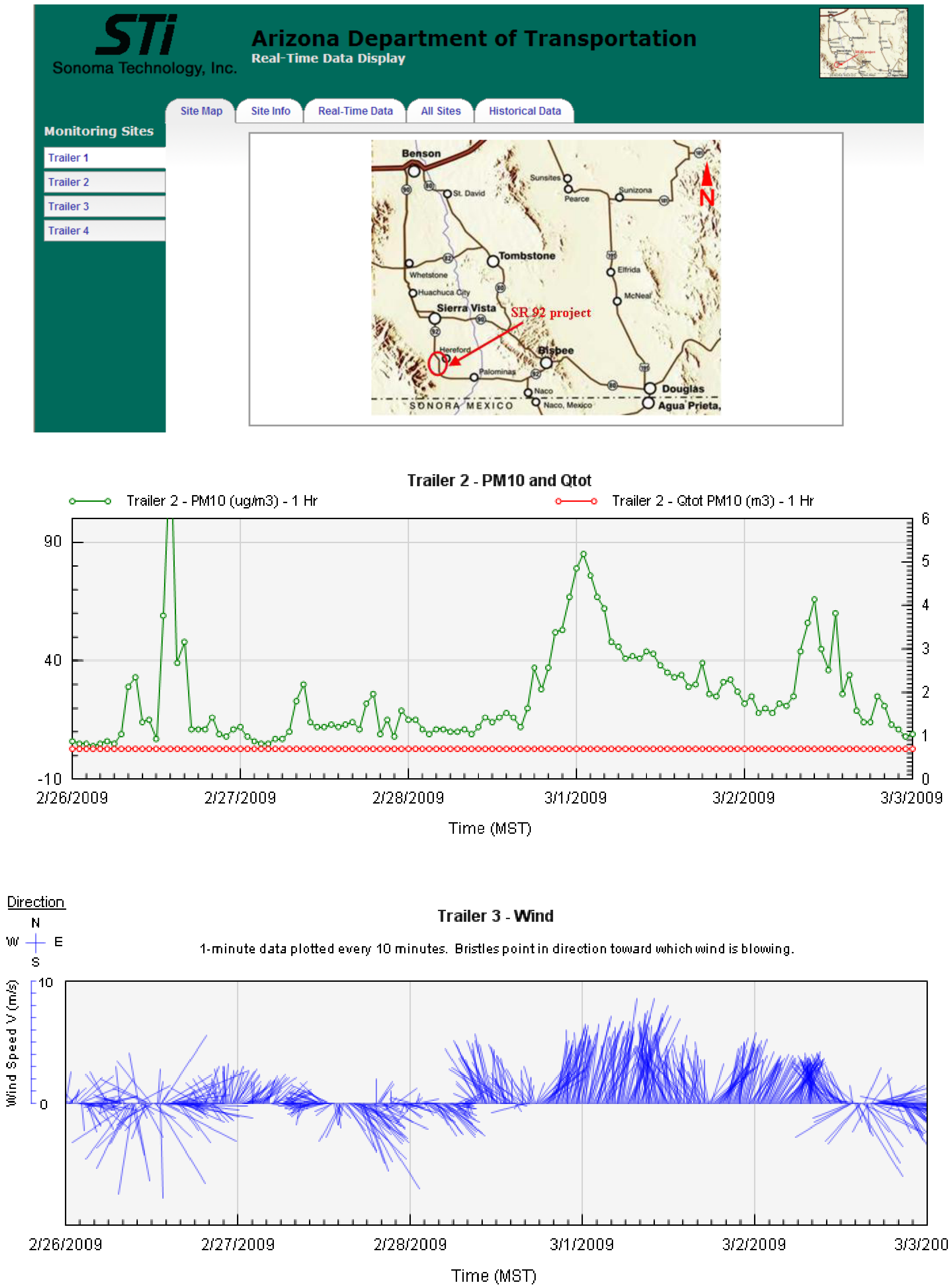


Figure 4-4. Screenshots from the web-based data management visualization tool.

5. EQUIPMENT ACTIVITY

To support quantitative assessment of the air quality impacts of the road construction project, STI collected information on the fleet of construction equipment operating at the SR 92 road widening project and on the timing and location of construction activities. These data were collected for a one-year period beginning January 2009 through a variety of methods, and analyses of the resulting data sets were performed to quantify emissions associated with construction activities.

5.1 ACTIVITY DATA NEEDS

Currently, there is no U.S. Environmental Protection Agency (EPA)-approved model for conducting project-level analyses of emissions from construction activities. However, EPA's NONROAD model calculates county-level exhaust emissions from construction equipment on the basis of equipment usage patterns (e.g., hours of operation and engine load factors), equipment characteristics (e.g., engine size and model year), and emission factors specific to a given equipment type, fuel type, and horsepower range. For project-level analyses, project-specific information on equipment populations and activities should be paired with appropriate NONROAD emission factors by model year and engine size. Alternatively, brake-specific fuel consumption factors (BSFC) from NONROAD can be used to develop fuel-based emission factors (e.g., grams emitted per gallon of fuel burned), and these factors can be applied to project-level fuel consumption data. (This study employed the fuel-based methodology, as described in Section 7.)

The NONROAD model does not characterize fugitive dust emissions associated with construction operations. Fugitive dust emission-producing activities include land clearing, demolition, ground excavation, and earth moving; levels of dust emissions are influenced by variables such as the size of the area under construction, meteorological conditions, the composition of the soil, and the use of control measures such as wet suppression and wind barriers. Emission factors for estimating PM_{10} emissions associated with construction dust are typically based on the number of acres disturbed during construction, though more detailed emission factors are available for specific processes (e.g., general land clearing, topsoil removal).

Characterizing exhaust and fugitive dust emissions from construction equipment activities at the proposed road-widening project required that the following data be collected during the field study:

- equipment types and populations operating on the construction site;
- engine model year and size (horsepower) for all equipment;
- daily hours of operation for each equipment type;
- typical usage patterns for each equipment type (time idling vs. time under load);
- data on the area under construction and/or quantity of earth moved during various construction processes;
- information on dust control measures being used on the project; and
- fuel consumption data by equipment type.

These activity data were collected during each phase of construction so that equipment activities and emission estimates could be classified by construction phase. Methods used to collect these data are described in the section that follows (Section 5.2).

5.2 DATA COLLECTION METHODS

In past studies of emissions from construction equipment, a variety of approaches have been used to collect equipment activity data; these include surveys, field inspector diaries, time-lapse photography, and onboard monitoring equipment. Each data collection method has its strengths and weaknesses, and STI determined that no one method could provide the full range of data required for this project. Therefore, STI used a combination of data collection methods designed to gather the required activity data while imposing minimal obligations on Bison Contracting (Bison), the Arizona Department of Transportation's (ADOT) construction contractor. These methods included:

- equipment instrumentation with GPS units;
- fuel consumption tracking using Bison's daily fuel logs;
- review of ADOT field inspector diaries; and
- onsite observations.

Detailed descriptions of these data collection methods are provided in the sections that follow (Sections 5.2.1 through 5.2.4).

5.2.1 Equipment Instrumentation

To gather detailed information on equipment usage patterns, STI worked with Bison and a third-party vendor to instrument construction equipment with GPS data loggers that track equipment locations, movements, and engine status (off, idle, or under load). STI used the MLT-325o equipment tracking module, which is sold by Fleet Management Solutions, Inc. (FMS) and includes a global positioning system (GPS) receiver and two-way satellite communications modem. A picture of the device and a list of key features of the MLT-325o Mobile Location Tracking System are shown in **Figure 5-1**. **Figure 5-2** shows a screenshot of FMS's web-based system for reporting and mapping activity data from the tracking module. Through the FMS website, we were able to view real-time maps of equipment locations and produce daily or weekly reports of equipment usage.

Key features of the MLT-325o and the FMS satellite solution:

- Near real-time asset location, speed and direction
- Protected, installer friendly, integrated enclosure
- Lightweight, low profile design (1.3 lbs., 5.9"L x 2.8"W x 1.9"H)
- ORBCOMM transceiver for satellite coverage
- Automatic reporting of all asset information
- Stop and idle reports
- Excessive speed alerts
- Boundary and geofencing with automated alerts
- Scheduling and dispatch functions
- Optional two-way messaging terminal (MDT-PRO)
- Choice of antennas
- Additional sensors available for overheat, temperature, weight, fuel, etc.

Source: FMS, Inc. *http://www.fmsgps.com/frontend/mlt325q.aspx*

Figure 5-1. MLT-325o Mobile Location Tracking System.

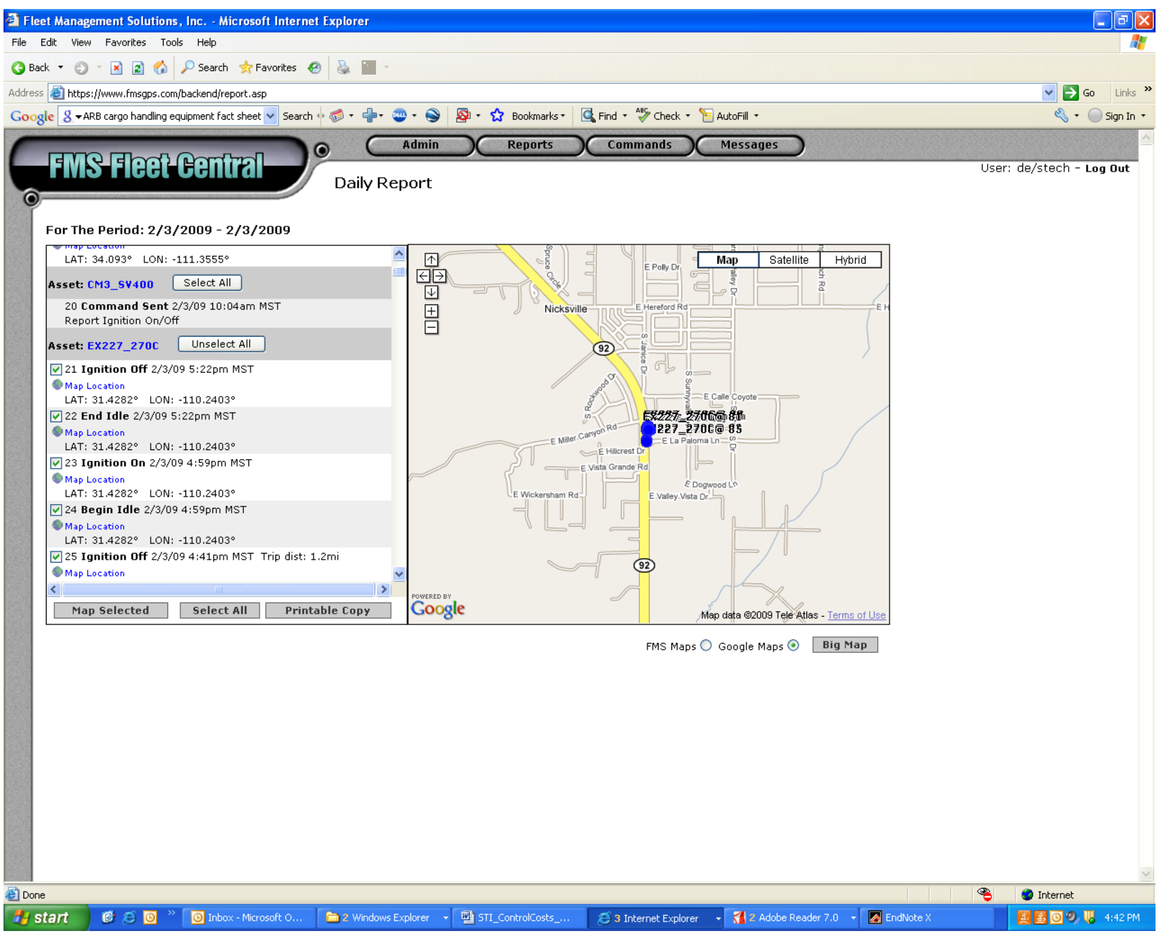


Figure 5-2. FMS web-based system for reporting and mapping activity data.

At the start of the SR 92 project, Bison provided STI with a list of equipment that would be largely dedicated to the project. Bison also provided STI with key characteristics for each piece of equipment, including horsepower rating and model year. **Table 5-1** lists the fleet of equipment identified by Bison and indicates the pieces of equipment that were instrumented with GPS units. The selection of equipment for instrumentation was based on engine size, anticipated usage, and availability for GPS installation. GPS units were installed in December 2009 and data were collected for a year beginning January 2009.

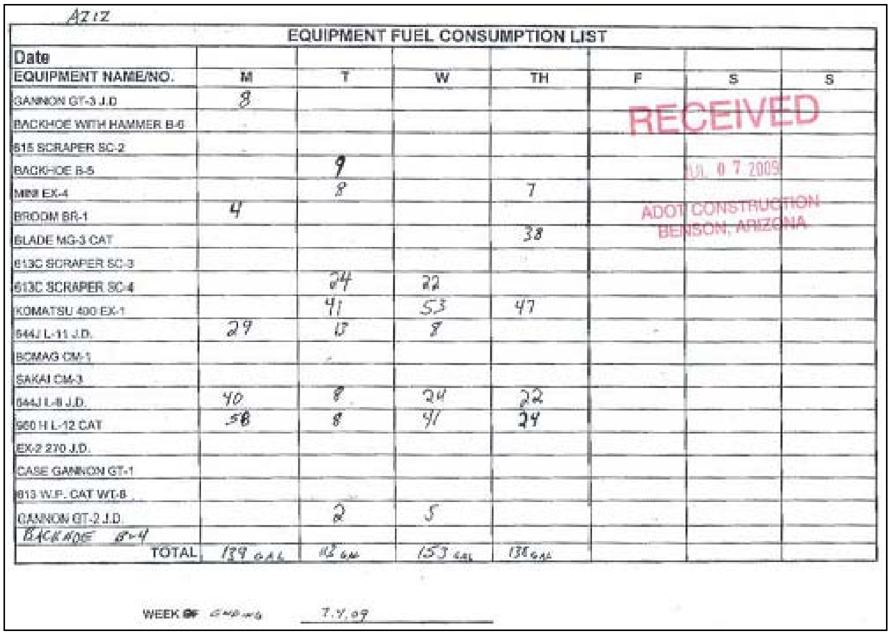
Table 5-1. Bison Contracting's fleet of equipment for the SR 92 project.

Equipment Type	Make	Model	Model Year	HP[a]	GPS Unit
1. Backhoe	John Deere	310G	2001	75	Y
2. Backhoe	John Deere	410G	2004	96	Y
3. Backhoe	John Deere	410G	2004	96	Y
4. Cement Truck	Mack	RD690S	1989	300	Y
5. Compactor	Bomag	T400	1998	44	N
6. Compactor	Sakai	SV400	2006	100	Y
7. Crane	Lorain	35 ton	1989	152	N
8. Excavator	John Deere	270CLC	2004	159	Y
9. Excavator	Komatsu	400	1995	276	N
10. Gannon Tractor	Case	570XLT	1996	79	Y
11. Gannon Tractor	John Deere	210LE	2006	84	Y
12. Loader	Caterpillar	950H	2007	217	Y
13. Loader	John Deere	644J	2005	225	Y
14. Loader	John Deere	644J	2006	225	Y
15. Motor Grader	John Deere	772D	2004	185	Y
16. Motor Grader	Caterpillar	140M	2008	191	Y
17. Scraper	Caterpillar	613C	2005	175	Y
18. Scraper	Caterpillar	613C	2005	175	Y
19. Scraper	Caterpillar	615C	1990	265	Y
20. Semi-Tractor	Freightliner		1989	--	Y
21. Sweeper	Roscoe	RB48	1995	80	Y
22. Water Truck	Caterpillar	613C	1987	175	Y
23. Water Truck	Freightliner		2007	--	Y
24. Water Truck	Freightliner	FL80	2003	--	Y
25. Water Truck	GMC	Brigadier	1986	--	Y
26. Water Truck	Ford	LN9000	1995	--	Y

[a] Engine horsepower ratings were not provided for on-road trucks, as emissions from these vehicles were not calculated from horsepower-specific data from the NONROAD model.

5.2.2 Daily Fuel Logs

Near the end of each work day, a fuel truck visited the SR 92 project site to refuel Bison's construction equipment. The amount of fuel pumped into each piece of equipment was recorded on a fuel log, which was provided to ADOT on a weekly basis for billing purposes. ADOT provided the fuel logs to STI, and these data allowed us to track day-by-day fuel consumption by piece of equipment and correlate fuel consumption to activity data reported by the GPS units. **Figure 5-3** shows an example fuel log from the SR 92 project.



AZIZ

EQUIPMENT FUEL CONSUMPTION LIST

Date							
EQUIPMENT NAME/NO.	M	T	W	TH	F	S	S
GANNON GT-3 J.D	8						
BACKHOE WITH HAMMER B-6							
615 SCRAPER SC-2							
BACKHOE B-5		9					
MINI EX-4		8		7			
BROOM BR-1	4						
BLADE MG-3 CAT				38			
613C SCRAPER SC-3							
613C SCRAPER SC-4		24	22				
KOMATSU 400 EX-1		41	53	47			
644J L-11 J.D.	29	17	8				
BOMAG CM-1							
SAKAI CM-3							
644J L-8 J.D.	40	8	24	22			
960 H L-12 CAT	58	8	41	24			
EX-2 270 J.D.							
CASE GANNON GT-1							
613 W.P. CAT WT-8							
GANNON GT-2 J.D.		2	5				
BACKHOE B-4							
TOTAL	139 GAL	117 GAL	153 GAL	138 GAL			

RECEIVED
JUL 0 7 2009
ADOT CONSTRUCTION
BENSON, ARIZONA

WEEK OF [illegible] 7.7.09

Figure 5-3. Sample fuel log from the SR 92 project.

5.2.3 Field Inspector Diaries

ADOT field inspectors maintain daily diaries on each active project that document the type of work performed on a given day, the times work started and stopped, an inventory of equipment used, summaries of work completed, and other information. During the course of the SR 92 project, ADOT provided STI with electronic copies of these diaries on a weekly basis. STI input pertinent information from the diaries into an Access database that was used to track progress and assign equipment activities to various phases of the construction project. **Figure 5-4** shows a sample daily diary from the SR 92 project.

Arizona Department of Transportation
DAILY DIARY
Quantities Report

Diary No. 137
Page 1 of 1

ITEM	Sub-Item	Section	Item Description	Location	Qty	Unit

EQUIPMENT ON PROJECT

EQUIP NO.	MAKE & MODEL	SUBCONTRACTOR	WORK DESCRIPTION	HOURS

LABOR ON PROJECT

SUBCONTRACTOR	CLASSIFICATION	WORK DESCRIPTION	WORKERS	HOURS
ANNCOLE CONTRACTING CORP.	Laborer	radius at hereford cub and gutter and pipe instal at pipe 17	3	10
ANNCOLE CONTRACTING CORP.	Power Equipment Operator	instal of pipe 17 for driveway	1	10

DESCRIPTION OF WORK

ITEM: 3 - Non-Item related
Benson Office 0700
Upload and corrected Timesheets

Onsite 0900

Anncole poured 11 yds for Curb and gutter sta 586+00 LT Hereford rd. sta 18+88 @ intersection for S end radius
Finished and cured
Began forming N end radius @ Hereford rd. intersection
Continued placing pipe 17 for driveway with slurry placed for backfill

Bison crew continued grading From Hereford rd. to Bison Office with hubs in place. Should be ready for stringline first thing in the morning
Crew stripping forms at BE 5 outlet for wingwall footer

3 message boards set in place for upcoming paving operations, 10 type II 's set at each location

requested that Hereford intersection be swept due to excessive gravel

Offsite 1530

6915 1hr
6925 1hr
6525 4hrs
6415 2hrs

Weather: FAIR
Day of Week: Monday

Signature: Title: Inspector
Project No. STP 092-A(001)B Tracs No. H459601C Date: 06/01/2009
Checked By: Date: 06/03/2009
Logged By: Date:

Figure 5-4. Sample daily diary from the SR 92 project.

5.2.4 Onsite Observations

An STI field technician visited the SR 92 project site on a periodic basis to perform maintenance on air quality and meteorological monitoring equipment. During these visits, the technician also took photographs of the construction site and wrote a brief summary of onsite activities. During periods when construction activities were in close proximity to the monitors, the field technician made additional visits to observe and record construction activities. These onsite observations were used to validate and interpret data collected from other sources.

5.3 OVERVIEW OF DATA COLLECTED

During 2009, there were a total of 238 days of active construction on the SR 92 project; **Table 5-2** provides a summary of the data completeness for each data collection method during those 238 days. For fuel logs, which served as the primary basis for emissions estimation, data completeness was 92% for 2009. Some issues were encountered with the GPS data, as units periodically stopped reporting data and had to be repaired or replaced, but the overall GPS data completeness of 81% provided ample information for assessing equipment usage patterns.

Table 5-2. Summary of 2009 data collected at the SR 92 project by method.

Data Collection Method(s)	Data Completeness	Notes
GPS units	81%	Out of 1,772 possible equipment days of data that could have been reported by the 23 deployed GPS units, a total of 1,427 equipment days of data were collected.
Fuel logs	92%	Fuel data was unavailable for 4 weeks of construction during 2009.
Daily diaries	94%	Daily diaries were unavailable for 3 weeks of construction during 2009.
Onsite observations	5%	An STI field technician photographed and documented progress on the SR 92 project on 12 days in 2009.

6. TRAFFIC DATA

Real-time traffic activity data on SR 92 was required to separate the contributions of on-road vehicles, especially heavy-duty vehicles, from the contribution of construction activities to ambient pollutant concentrations measured downwind of the construction zone. To address this issue, the Arizona Department of Transportation (ADOT) provided STI with access to its online Transportation Data Management System (TDMS), which contains traffic count data for Highway Performance Monitoring System (HPMS) sites across the state.

Two HPMS sites in TDMS provide traffic count data on SR 92 near the construction project site. HPMS site 101103 is just north of Carr Canyon Road, near the north end of the SR 92 construction project, and HPMS site 101105 is about 1.4 miles south of Hunter Canyon Road near the south end of the project (see **Figure 6-1**). These sites provide traffic counts every 15 minutes by the vehicle classifications shown in **Table 6-1**. TDMS traffic counts were provided according to traffic direction: eastbound, westbound, and two-way (see **Figure 6-2**). For purposes of calculating on-road emissions associated with traffic on SR 92, the two-way traffic counts from the two HPMS sites were averaged to establish a representative traffic volume for the roadway.

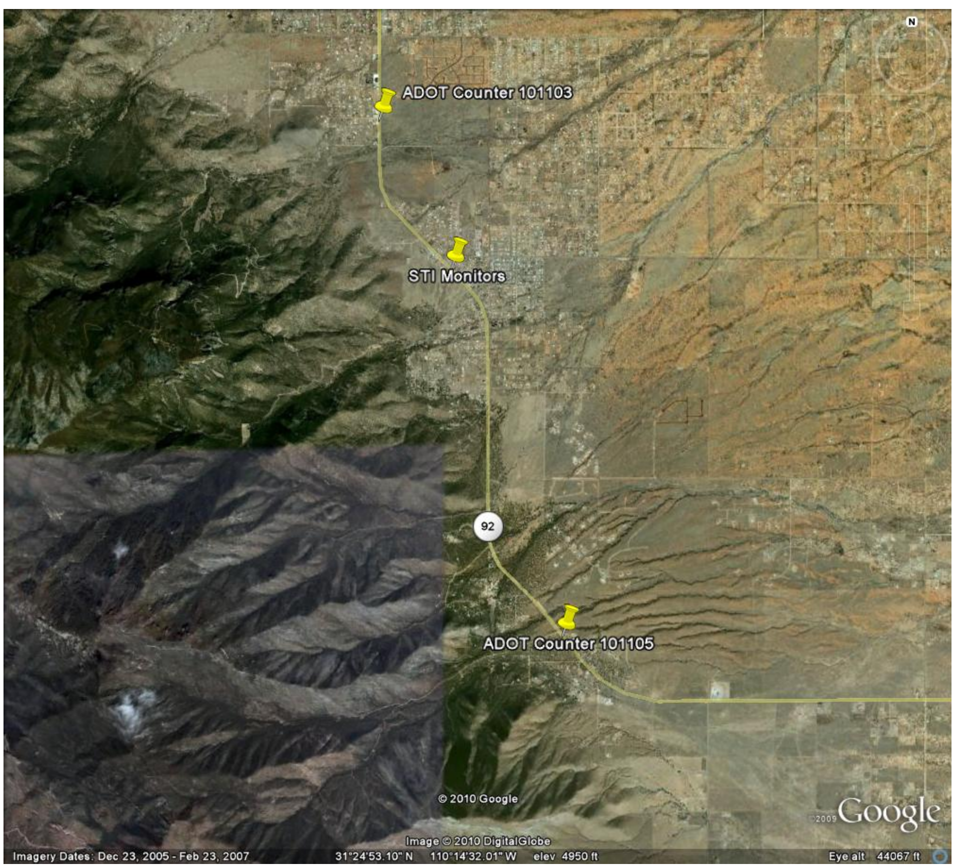


Figure 6-1. Location of ADOT HPMS sites on SR 92.

Table 6-1. Vehicle classifications associated with HPMS traffic counts on SR 92.

Vehicle Classifications [a]
Bike
Car
Pick-up truck
Bus
2-axle, single-unit truck
3-axle, single-unit truck
>3-axle, single-unit truck
<5-axle, 2-unit truck
5-axle, 2-unit truck
>5-axle, 2-unit truck
<6-axle, >2-unit truck
6-axle, >2-unit truck
>6-axle, >2-unit truck
Other

[a] These categories correspond to U.S. Federal Highway Administration (FHWA) vehicle classifications (see http://www.fhwa.dot.gov/policy/ohpi/vehclass.htm). Traffic data by vehicle type was binned into one of 11 speed bins for purposes of estimating emissions: one bin for 0-44 mph, nine bins in 5-mph increments for speeds from 45-89 mph (45-49, 50-54, and so on), and one bin for speeds at or above 90 mph.

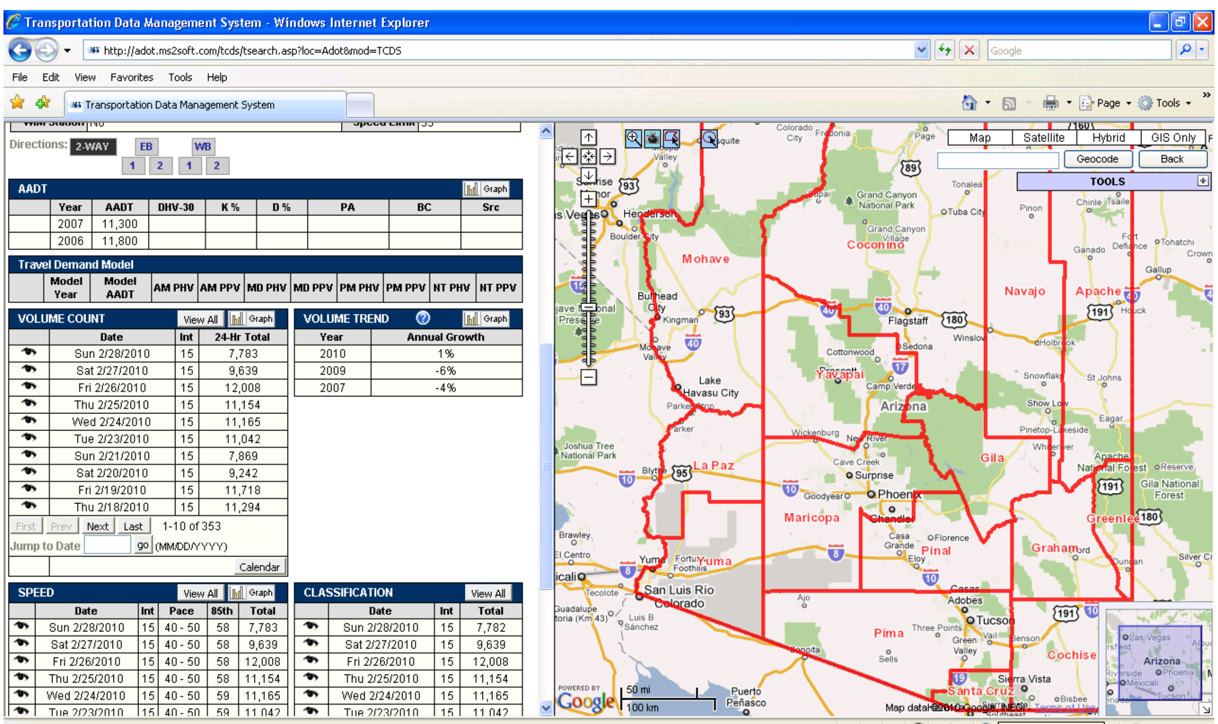


Figure 6-2. Screenshot of traffic count data available from ADOT’s TDMS website.

Table 6-2 provides a summary of data completeness for the two SR 92 HPMS sites in 2009. For days with missing data, average daily activity for the same month was used as a surrogate.

Table 6-2. Summary of 2009 data completeness for HPMS sites on SR 92.

Site ID	Missing Days	Data Completeness
101103	21	94%
101105	7	98%

7. EMISSIONS ASSESSMENT

To provide a quantitative assessment of $PM_{2.5}$, PM_{10}, and NO_x emissions from the various phases of a road-widening project, STI used the activity data collected during the field study described in Sections 5 and 6 to develop emission estimates for construction activity (equipment exhaust and fugitive dust) and on-road vehicle traffic. STI compared these emission estimates to alternative emissions inventories prepared from readily available tools and default activity estimates so that the impact of using project-specific activity data to quantify emissions could be assessed.

7.1 CONSTRUCTION ACTIVITY AND EMISSIONS

7.1.1 Methodology for Estimating Equipment Exhaust Emissions

Exhaust emissions from a given type of construction equipment are typically estimated using the U.S. Environmental Protection Agency's (EPA) NONROAD model, which calculates emissions as the product of engine population, hours of operation, engine power, engine load factor, and pollutant-specific emission factors. For example, particulate matter (PM) emissions from excavators during the land-clearing phase of construction are calculated in NONROAD as follows:

$$PM = \sum \left(POP \times HRS \times HP \times LF \times PM_{EF} \right) \qquad \textbf{(7-1)}$$

where:

PM	=	total PM emissions from excavators in the region of interest
POP	=	population of excavators with a given engine size (horsepower) in the region of interest
HRS	=	average hours of operation per excavator during the time frame of interest
HP	=	engine horsepower rating
LF	=	engine load factor (percentage of rated power while under load)
PM_{EF}	=	deterioration-adjusted PM emission factor in g/hp-hr (specific to each horsepower rating and engine model year)

Emissions calculated using this equation are clearly sensitive to the load factor assumed for a given type of equipment. For example, increasing the assumed load factor from 0.4 to 0.8 would result in a doubling of emissions. NONROAD contains a look-up table of default load factor values for each type of equipment addressed by the model, values which were developed from non-road engine test data performed over various transient cycles (U.S. Environmental Protection Agency, 2004a).

Because NONROAD default load factors for construction equipment may not be representative of the way equipment is used on a given project, one alternative is to calculate emissions using fuel-based emission factors, which are not dependent upon engine loads or equipment duty cycles. In addition to activity-based emission factors, NONROAD contains brake-specific fuel consumption (BSFC) factors (gal/hp-hr) for various equipment types. These fuel consumption factors can be used to develop fuel-based emission factors (g/gal). Given the availability of day- and equipment-specific fuel consumption data for the SR 92 project, STI chose to use a fuel-based emissions estimation approach using fuel-based emission factors derived from NONROAD.

Figure 7-1 diagrams the process that was followed to estimate exhaust emissions from construction equipment. Since data from the daily fuel logs covered only equipment owned by Bison, fuel consumption for other equipment (e.g., subcontractors' construction equipment and haul trucks) was estimated using equipment usage information from field inspector diaries and BSFC factors from NONROAD. In addition, equipment activity reports from global positioning system (GPS) units were used to determine the location and timing of equipment fuel consumption. Once total fuel consumption estimates were developed and allocated spatially and temporally, fuel based emission factors derived from the NONROAD model were applied to estimate emissions.

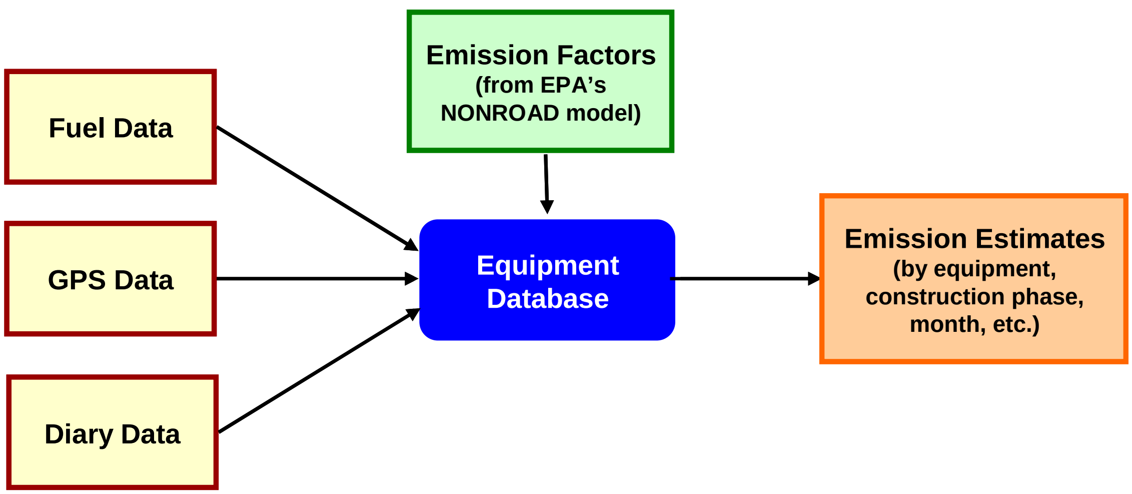


Figure 7-1. Process diagram for estimating exhaust emissions from construction equipment.

7.1.2 Methodology for Estimating Fugitive Dust Emissions

Emission factors for estimating PM emissions associated with construction dust are typically based on the number of acres disturbed during construction (California Air Resources Board, 1997). However, more detailed emission factors are also available for specific processes, such as general land clearing and topsoil removal (U.S. Environmental Protection Agency, 1995). To estimate fugitive dust emissions associated with the SR 92 project, the process-specific emission factors from **Table 7-1** were applied to activity data gathered from Arizona Department of Transportation (ADOT) daily diaries and GPS units.

Table 7-1. Process-based activity data and emission factors for construction dust.

Process	Activity Data (Source)	PM Emission Factor [a]	References
Clearing and grubbing – hole drilling	Number of holes drilled	0.59 kg/hole	(U.S. Environmental Protection Agency, 1998)
Clearing and grubbing – general land clearing	Equipment work hours	$0.45(s)^{1.5}/(M)^{1.4}$ kg/hr where: s = material silt content (35%) M = moisture of soil (20%)	Emission factor (U.S. Environmental Protection Agency, 1998) Soil characteristics (U.S. Customs and Border Protection, 2003)
Excavation – bulldozing	Equipment work hours	See above	See above
Excavation – topsoil removal (with scraper)	Scraper vehicle miles traveled (VMT)	20.2 lb/VMT [b]	(U.S. Environmental Protection Agency, 1995)
Filling truck with material	Mass of debris or excavated material	$k*(0.0032)*(U/5)^{1.3}/(M/2)^{1.4}$ lb/ton where: k = particle size multiplier U = mean wind speed (m/s) M = moisture of soil (20%)	(U.S. Environmental Protection Agency, 2006)
Compacting	Equipment work hours	$0.45(s)^{1.5}/(M)^{1.4}$ kg/hr where: s = material silt content (35%) M = moisture of soil (20%)	Emission factor (U.S. Environmental Protection Agency, 1998) Soil characteristics (U.S. Customs and Border Protection, 2003)
Motor grading	Grader VMT	$0.051(S)^{2.0}$ lb/VMT where: S = mean vehicle speed (mph)	(U.S. Environmental Protection Agency, 1998)
Rock crushing	Tons of aggregate produced	0.0337 lb/ton	(U.S. Environmental Protection Agency, 2004c)

[a]Except where noted, emission factors shown are for total suspended particulates (TSP). Calculations of emissions for PM_{10} and $PM_{2.5}$ were based on scaling factors provided in the reference documents. In general, PM_{10} was assumed to compose 75% of TSP, and $PM_{2.5}$ was assumed to compose 15% of PM_{10}. Adjustments for emission controls (watering) were also made where applicable and were based on control factors provided in the reference documents.
[b]For excavation–topsoil removal, the emission factor shown is for PM_{10}.

7.1.3 Summary of Construction Activity

During calendar year 2009, the SR 92 project was active for 238 working days. Work was primarily performed Monday through Thursday from about 7:00 a.m. to 3:00 p.m., and water trucks were active on 192 of the 238 working days (81%). On an average day

- Approximately 25-30 pieces of construction equipment (including water trucks and haul trucks) were onsite
- Ten pieces of equipment were actively in use
- Each active piece of equipment was used for about 6 hours
- A total of 319 gallons of diesel fuel were consumed onsite

Peak fuel consumption occurred on June 17, 2009, and December 9, 2009, when just over 800 gallons were consumed during construction activities. Over the course of the year, about 76,000 gallons of diesel fuel were consumed by construction equipment at the SR 92 site. **Figure 7-2** provides a breakdown of fuel consumption by equipment type and by phase of construction; this figure shows that about 60% of total fuel consumption was attributable to tractors, loaders, backhoes, trucks, and to the roadway and structural excavation phases of construction. Fuel consumption averaged 6,329 gallons per month for 2009, with a peak fuel consumption of 8,146 gallons occurring in September (see **Figure 7-3**).

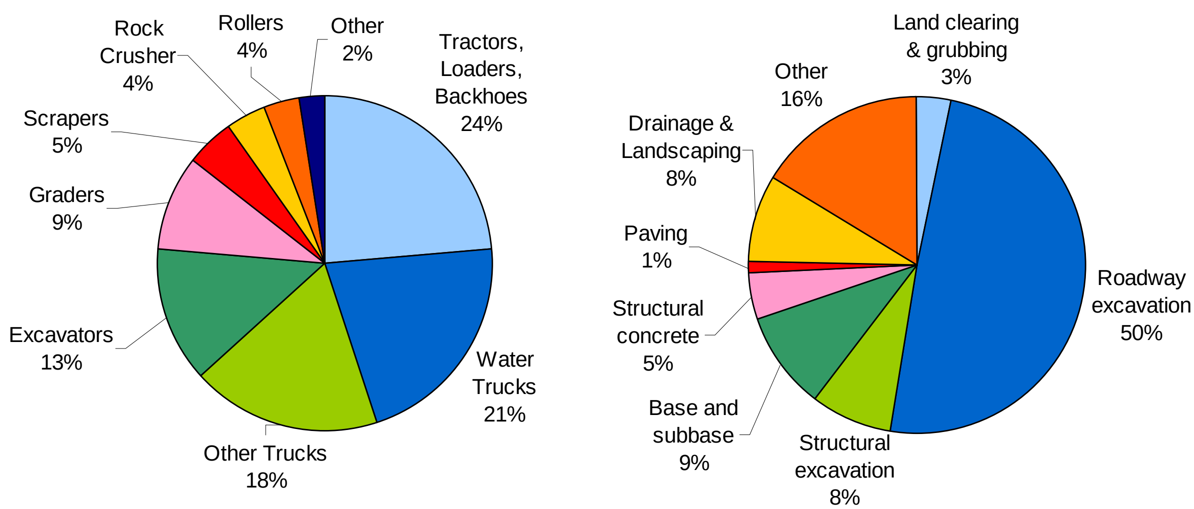


Figure 7-2. Total fuel consumption by equipment type (left) and construction phase (right) for 2009.

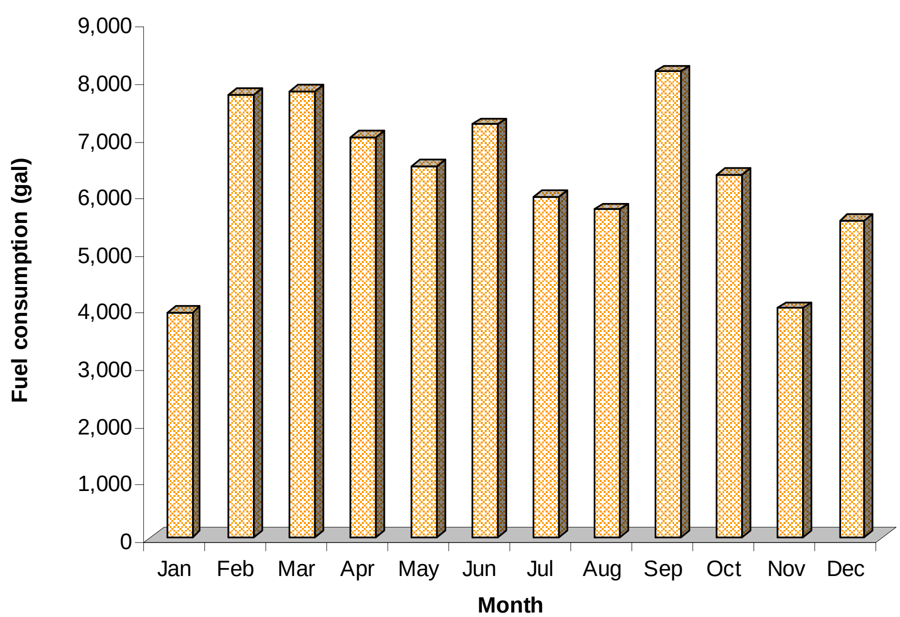
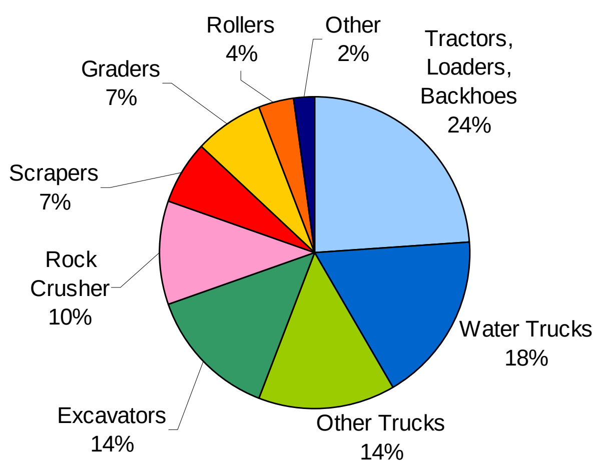


Figure 7-3. Total fuel consumption by month for 2009.

7.1.4 Summary of Construction Equipment Exhaust Emissions

On an emissions basis, construction equipment operating at the SR 92 project during 2009 produced exhaust emissions totaling 553 kg of PM_{10}, 537 kg of $PM_{2.5}$, and 7,102 kg of NO_x. **Figure 7-4** provides a breakdown of exhaust $PM_{2.5}$ emissions by equipment type and by phase of construction; this figure shows that over half of exhaust $PM_{2.5}$ emissions was attributable to tractors, loaders, backhoes, trucks, and to the roadway and structural excavation phases of construction. On a model-year basis, over half of the total exhaust NO_x, PM_{10}, and $PM_{2.5}$ emissions were associated with vehicles of model year 2004 or newer (see **Figure 7-5**).

On a monthly basis, exhaust emissions were highest in February and September, partly because of crushing operations that occurred during those two months with a diesel-powered rock crusher (see **Figure 7-6**). Exhaust emissions were also evaluated by proximity to the air quality monitors, using equipment locations derived from GPS and daily log data. These analyses showed that 43% of total $PM_{2.5}$ exhaust emissions for 2009 occurred within 500 m of the monitors (see Figure 7-6).[9]



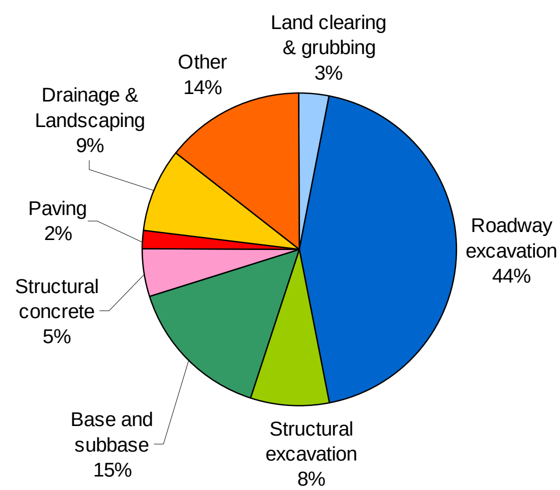


Figure 7-4. Exhaust $PM_{2.5}$ emissions by equipment type (left) and construction phase (right) for 2009.

[9] We used 500 m as a geographic reference since studies indicate that in the near-road environment, vehicle emissions result in pollutant concentrations that are generally highest near the source and diminish to background concentrations approximately 300 m to 500 m from the source (Health Effects Institute Panel on the Health Effects of Traffic-Related Air Pollution, 2010).

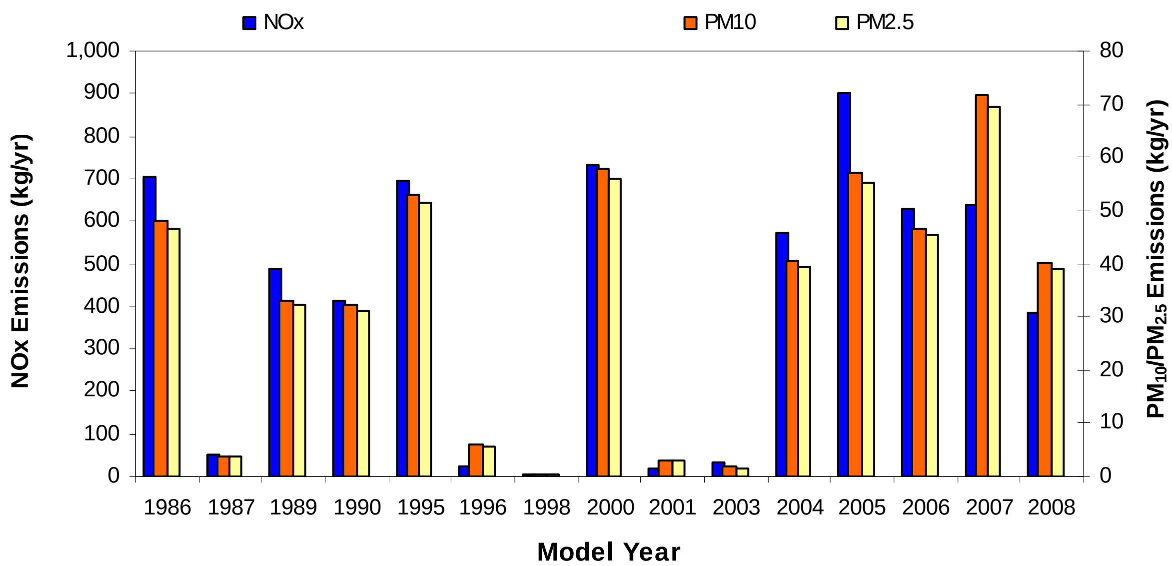


Figure 7-5. Exhaust NO_x, PM_{10}, and $PM_{2.5}$ emissions by engine model year.

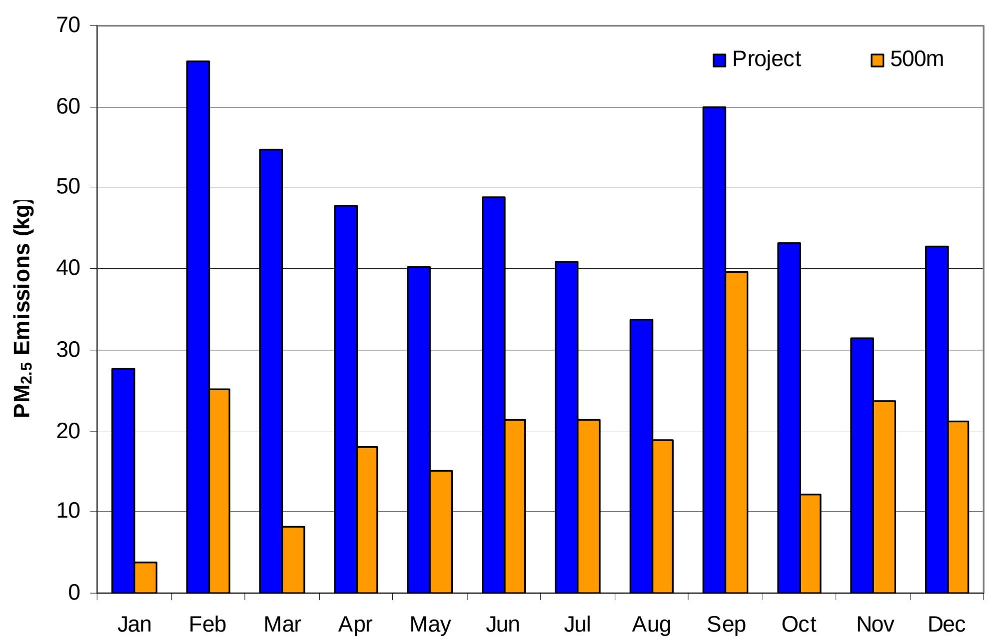


Figure 7-6. Exhaust $PM_{2.5}$ emissions by month and proximity to the air quality monitors.

7.1.5 Summary of Fugitive Dust Emissions

Fugitive dust associated with year-2009 construction activity at the SR 92 project produced 6,490 kg of PM_{10} and 924 kg of $PM_{2.5}$ emissions. **Figure 7-7** provides a breakdown of fugitive $PM_{2.5}$ emissions by phase of construction; this figure shows that 80% of fugitive $PM_{2.5}$ emissions were attributable to the roadway excavation phase of construction. On a monthly basis, fugitive dust emissions were highest in January and December, largely due to significant roadway excavation activity during those two months (see **Figure 7-8**). Fugitive dust emissions were also evaluated by proximity to the air quality monitors, using equipment locations derived from GPS and daily log data; these analyses showed that 39% of total fugitive $PM_{2.5}$ emissions for 2009 occurred within 500 m of the monitors (see Figure 7-8).

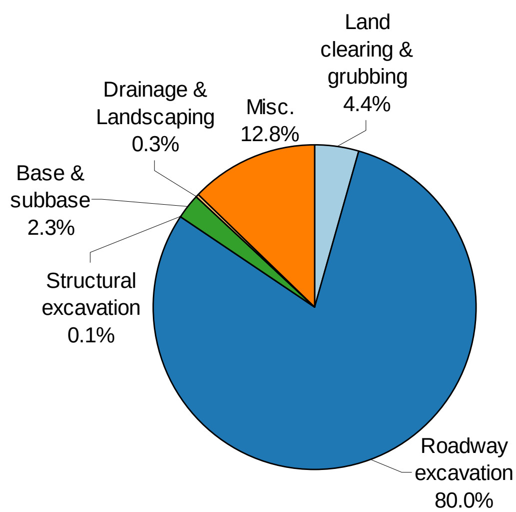


Figure 7-7. Fugitive $PM_{2.5}$ emissions by construction phase for 2009.

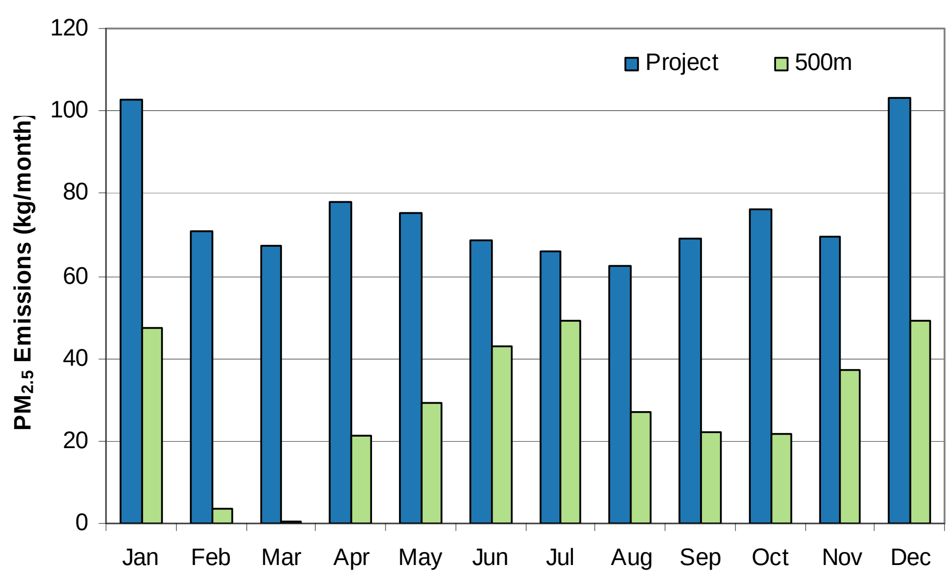


Figure 7-8. Fugitive $PM_{2.5}$ emissions by month and proximity to the air quality monitors.

7.1.6 Summary of Overall Construction-Related Emissions

Year-2009 construction activity at the SR 92 project produced 7,043 kg of PM_{10}, 1,461 kg of $PM_{2.5}$, and 7,102 kg of NO_x. Fugitive dust accounted for 92% of the total PM_{10} emissions associated with construction activities and 63% of the total $PM_{2.5}$ emissions associated with construction activities. On an average day in 2009, construction activity at the SR 92 project produced 29 kg of PM_{10}, 6 kg of $PM_{2.5}$, and 30 kg of NO_x. Daily peak emissions occurred on December 9, 2009, when construction activities on the SR 92 project produced 173 kg of PM_{10}, 31 kg of $PM_{2.5}$, and 93 kg of NO_x (see **Figure 7-9**). Fugitive dust accounted for 96% of the peak day PM_{10} emissions and 79% of the peak day $PM_{2.5}$ emissions.

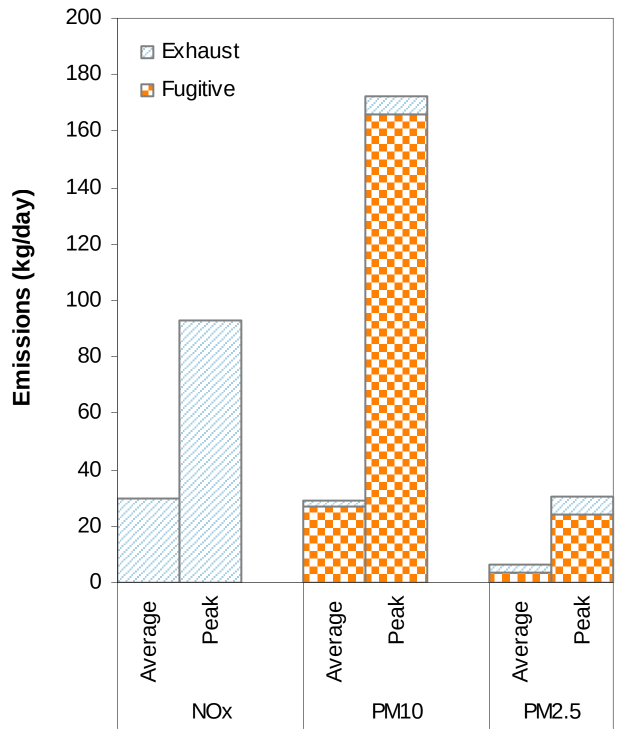


Figure 7-9. Average and peak day (12/9/2009) emissions produced by construction activity.

7.2 ON-ROAD ACTIVITY AND EMISSIONS

7.2.1 Methodology for Estimating On-Road Vehicle Emissions

To estimate emissions from on-road vehicle traffic on SR 92, emission factors from EPA's MOBILE6 model were applied to traffic count data obtained from ADOT. MOBILE6 was run on a monthly basis for 2009 using the following input data sources:

1. Age distributions calculated from vehicle registration data for Cochise County provided by ADOT;

2. Fuels characteristics (e.g., sulfur content) for Cochise County provided by the Arizona Department of Weights and Measures;
3. Average VMT mix and hourly VMT fractions calculated from traffic counts collected at the two Highway Performance Monitoring System (HPMS) sites on SR 92;
4. Hourly temperature and relative humidity for an average day during each month of 2009 calculated from meteorological data collected by STI at the SR 92 construction site;
5. Diesel fraction data for Cochise County from EPA's National Mobile Inventory Model (NMIM).

MOBILE6 emission factors (g/mile) by vehicle type and speed bin were generated for each month in 2009 and applied to VMT derived from traffic count data to estimate hourly emissions. Resulting emission estimates were imported into a Microsoft Access database for further analysis.

7.2.2 Summary of On-Road Vehicle Activity

On an average day in 2009, 7,213 vehicles passed through the SR 92 construction zone (both travel directions included). Average weekday traffic volumes (7,596 vehicles) were 22% higher than average weekend day traffic volumes (6,245 vehicles). The daily peak volume occurred on March 4, 2009, when 11,503 vehicles passed through the construction zone. Weekday traffic volumes on SR 92 peaked at 7:00 a.m. and 5:00 p.m., while weekend traffic volumes were highest during the middle of the day (see **Figure 7-10**). Traffic volumes on Saturdays and Sundays were 11% and 24% lower, respectively, than average weekday traffic volumes (see **Figure 7-11**). Traffic volumes were consistent on a monthly basis with the exception of October, during which traffic volumes were about 20% lower than the monthly average for 2009 (see **Figure 7-12**).

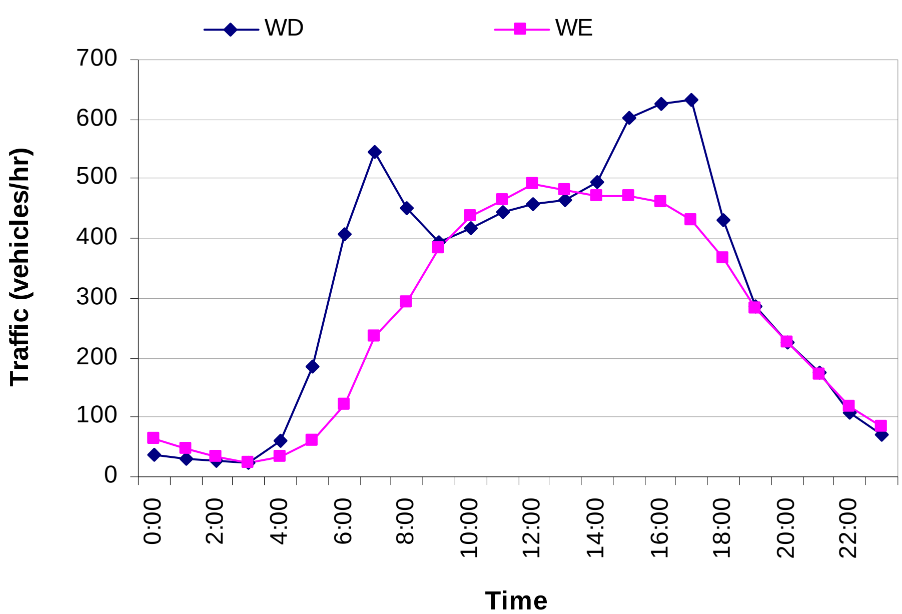


Figure 7-10. Diurnal pattern of traffic counts on SR 92.

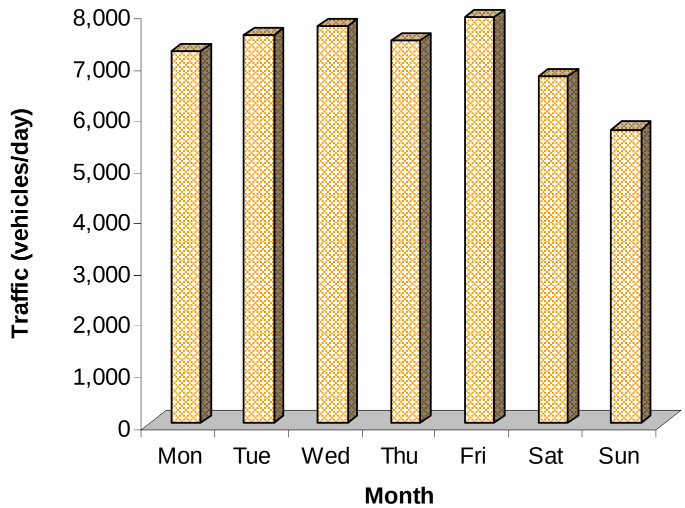


Figure 7-11. Traffic counts by day of week.

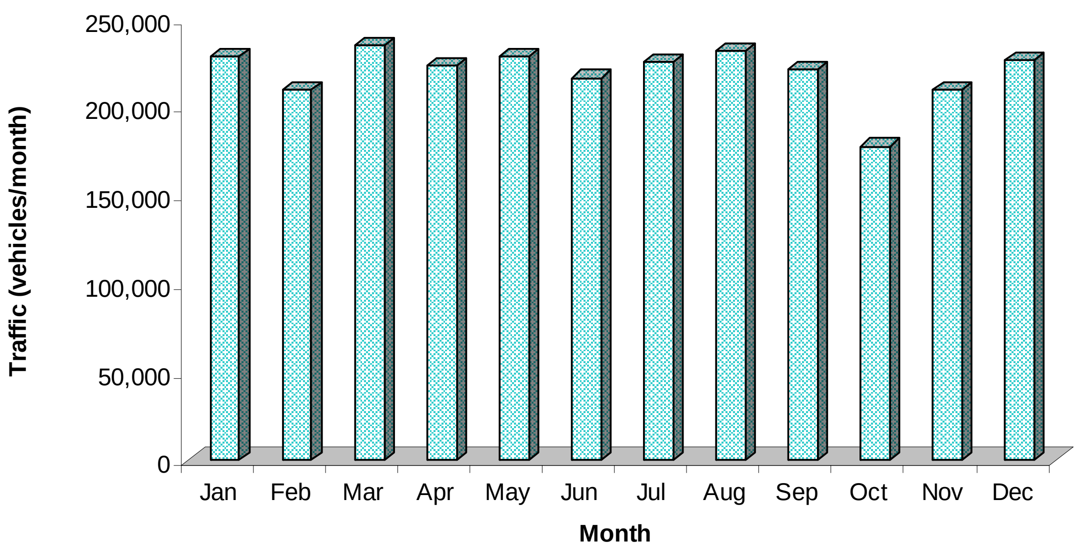


Figure 7-12. Traffic counts by month.

7.2.3 Summary of On-Road Vehicle Exhaust Emissions

Table 7-2 shows annual and daily estimates of NO_x, PM_{10}, and $PM_{2.5}$ exhaust emissions from on-road motor vehicles traveling on SR 92 through the project area (for emission estimation purposes, we assumed each vehicle traveled 4.4 miles through the project zone). On-road NO_x emissions for 2009 were about 2.5 times higher than total NO_x emissions from construction activities. However, on-road PM_{10} and $PM_{2.5}$ emissions for 2009 were only 6% and 19%, respectively, of the emissions produced by construction activities.

Table 7-2. On-road motor vehicle exhaust emissions on SR 92 for 2009.

Period	Emissions (kg)		
	NO_x	PM_{10}	$PM_{2.5}$
Annual	17,538	445	280
Peak day (10/21/09)	146.1	3.7	2.7
Average weekday	56.9	1.4	0.9
Average weekend	42.6	1.1	0.6

On-road emissions by hour and day of week were consistent with the traffic volume plots shown in Figures 7-10 and 7-11. However, monthly on-road emissions showed a significant increase in September relative to other months, as shown in **Figure 7-13**. Analysis of on-road vehicle traffic data indicated that this September peak in emissions resulted from increased heavy-duty diesel vehicle (HDDV) traffic along SR 92, as shown in **Figure 7-14**. During September, HDDVs accounted for 12% of the total traffic volume, while HDDVs only accounted for 4% of the total traffic volume in other months.

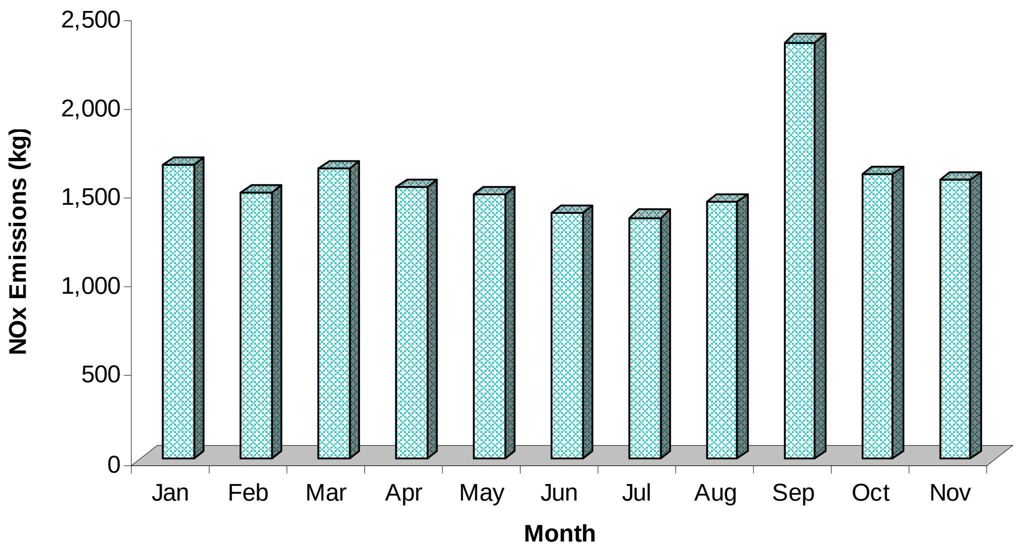


Figure 7-13. On-road motor vehicle NO_x emissions by month.

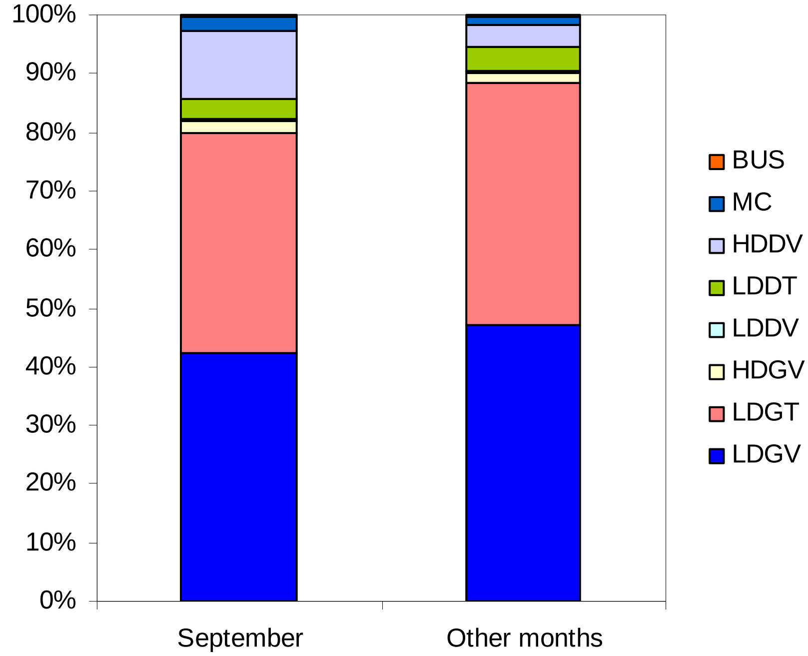


Figure 7-14. Traffic volumes by vehicle type and month.

7.2.4 Summary of Road Dust Emissions

In addition to exhaust emissions from on-road vehicles, we also evaluated road dust re-entrained by traffic on SR 92, which is a potentially significant source of PM_{10} emissions. Fugitive dust emissions from paved roads are a function of several factors, including the silt loading present on the road surface, the average weight of vehicles traveling on the road, and precipitation levels (U.S. Environmental Protection Agency, 2003). For the section of SR 92 under construction, inherent uncertainties in road dust emissions estimates are compounded by the potential for increased silt loading on the roadway due to construction activities and by the activity of water trucks, which operated on 81% of the construction project's work days and kept portions of the roadway moist (see Figure 7-15).

Figure 7-15. SR 92 roadside watered for dust suppression.

To estimate PM_{10} emissions from re-entrained road dust, we applied fugitive dust emission factors for paved roads used by the Maricopa County Air Quality Department in the development of a 2008 PM_{10} emissions inventory (see **Table 7-3**). These emission factors were derived on the basis of road surface silt loadings of 0.02 g/m^2 for freeways, 0.067 g/m^2 for high-traffic arterials, and 0.23 g/m^2 for low-traffic arterials, with arterials carrying a traffic volume of less than 10,000 vehicles per average weekday classified as low-traffic (Maricopa County Air Quality Department, 2010).

Table 7-3. Fugitive dust emission factors for paved roads.

Road Type	PM_{10} (g/mi)	$PM_{2.5}$ (g/mi)
Freeways	0.18	0.00
High-traffic arterials	0.65	0.00
Low-traffic arterials	1.69	0.13

Assuming 7,213 vehicles per day (the 2009 average) traveling 4.4 miles through the construction zone, applying the low-traffic emission factor of 1.69 g/mi of non-exhaust PM_{10} would result in daily PM_{10} emissions of approximately 54 kg/day. This estimate is nearly double the average daily PM_{10} emissions of 29 kg/day estimated for construction activities (see Figure 7-9). However, this estimate of PM_{10} emissions from re-entrained road dust does not correlate with the real-world air quality data collected during the field study. Though results of air quality measurements will be described in detail in Section 8, it is worth noting that PM_{10} concentrations were observed to be low on days when construction was dormant and significantly higher when construction activities occurred near the monitoring sites. For example, **Figure 7-16** shows PM measurements collected at Trailer 1 during the week of May 25-31, 2009. On Monday, May 25, when construction was halted for the Memorial Day holiday, PM_{10} concentrations were consistently around 8-10 µg/m³. Approximately 5,576 vehicles operated on SR 92 on May 25 (77% of the daily average). On subsequent days when construction resumed, peaks in PM_{10} concentrations can be observed starting at about 6-8 a.m. and lasting until about 4-6 p.m., coinciding with times of construction activity. Similar PM_{10} relationships were found during other time periods. For example, when reviewing data from Fridays when construction was halted but when SR 92 was open to normal on-road traffic, we did not observe PM_{10} concentration spikes related to routine traffic.

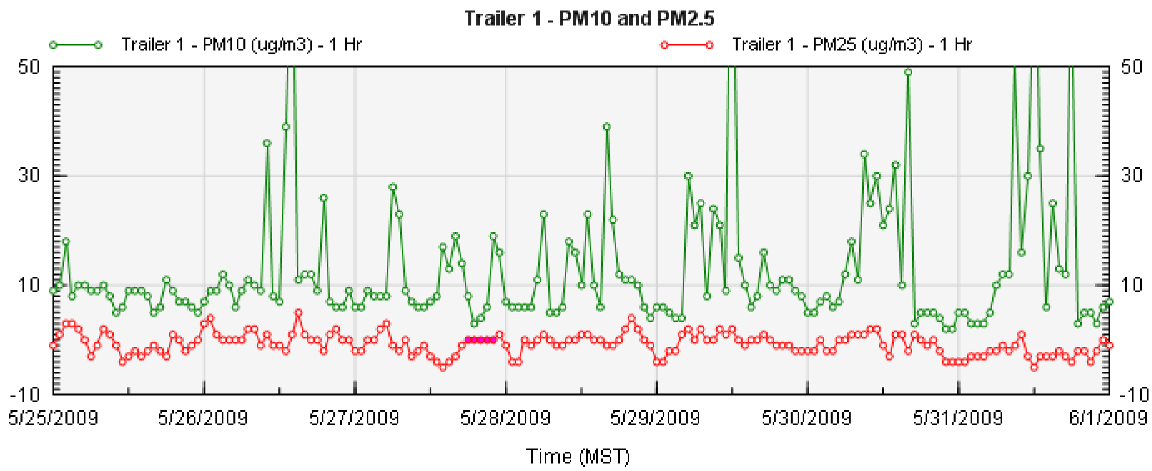


Figure 7-16. PM concentrations from Trailer 1 during May 25-31, 2009. Note that on Monday, May 25, 2009, there was no construction and on-road travel activity was approximately 77% of the daily average; thus no PM_{10} concentration spikes were measured.

These findings indicated that road dust emission estimates for SR 92 developed using default methods were overestimated relative to fugitive dust estimates for construction activity. Note that others have also found that default methods can over-predict road dust emissions. For example, PM_{10} measurements collected in Clark County, Nevada, with a vehicle-based mobile sampling system resulted in paved road dust emission factors that were one-third the magnitude of emission factors calculated on the basis of the EPA AP-42 silt loading method (the standard method used in most applications to estimate road dust emissions) (Langston et al., 2006). As a result of the uncertainties related to re-entrained road dust emissions on SR 92, and documentation in the literature indicating these emissions can be over-predicted using standard approaches, we omitted road dust emissions from the air quality data assessments presented in Chapter 8 of this report.[10]

[10] In June 2010, EPA released draft revised road dust estimation procedures (see: http://www.epa.gov/ttn/chief/ap42/ch13/draft/d13s0201.pdf). The new procedures, when applied to the SR 92 case study, result in a 0.18 g/mi fleet-averaged road dust PM10 emissions rate. The 0.18 g/mi rate is approximately 10% of the low-traffic arterial value shown in Table 7-3; thus, application of the 0.18 g/mi emission rate would substantially reduce the estimated contribution of SR 92 on-road vehicle dust emissions to PM_{10}, compared to the estimates we prepared based on information derived from the Maricopa County 2008 PM_{10} inventory.

7.3 EMISSIONS COMPARISONS

In an effort to contrast real-world activity data collected during this project with typical (or default) equipment usage patterns, STI prepared alternative emission estimates using readily available data and tools, including EPA's NONROAD model and the Roadway Construction Emissions Model (RCEM), a spreadsheet tool developed for the Sacramento Metropolitan Air Quality Management District (SMAQMD) (Jones & Stokes and Rimpo and Associates, 2009). RCEM estimates road construction project emissions from simple user inputs (e.g., project type, project length, total soil imported and exported) and default assumptions for equipment activities. STI ran this tool using input data representative of the SR 92 project, as shown in **Table 7-4**.

Table 7-4. Input parameters used to run RCEM for the SR 92 project.

Parameter	Input Value	Input Alternatives and Units
Construction start year	2009	Year
Project type	2	1. New road construction 2. Road widening 3. Bridge/overpass construction
Project construction time	12	Months
Predominant soil/site	1	1. Sand/gravel 2. Weathered rock-earth 3. Blasted rock
Project length	4	Miles
Total project area	18.2	Acres
Maximum area disturbed	15 or 4.5	Acres per day
Water trucks used?	1	1. Yes 2. No
Soil imported	103	Cubic yards per day
Soil exported	0	Cubic yards per day
Average truck capacity	20	Cubic yards (assume 20 if unknown)

As described in Section 1.1.1, the NONROAD model calculates exhaust emissions from a given type of construction equipment as the product of engine population, hours of operation, engine power, engine load factor, and pollutant-specific emission factors. **Table 7-5** compares default NONROAD input parameters for key pieces of equipment used at the SR 92 project with data derived from the year-long field study. In general, the age distribution of the equipment fleet used on the SR 92 project is similar to average equipment ages derived from default NONROAD input data, particularly for equipment types that were used the most on the SR 92 project (e.g., excavators and loaders). Default annual equipment usage (hours per year) rates in the NONROAD model are significantly higher than the equipment usage rates observed during the year-long field study with the exception of excavators and loaders.[11] Load factors derived from field study data[12] were generally comparable to NONROAD default values; however, load factors calculated for motor graders and scrapers were significantly lower than NONROAD defaults (see Table 7-5).

Table 7-5. Comparison of NONROAD default data with data derived from the SR 92 field study.

Equipment Type [a]	Make	Model	Model Year		Annual Hours		Load Factor	
			Actual	NON-ROAD [b]	Actual	NON-ROAD	Actual [c]	NON-ROAD
1. Backhoe	John Deere	310G	2001	1999	246	1135	0.27	0.21
2. Backhoe	John Deere	410G	2004	1999	248	1135	0.24	0.21
3. Backhoe	John Deere	410G	2004	1999	292	1135	0.18	0.21
4. Compactor	Bomag	T400	1998	2006	--	760	--	0.59
5. Compactor	Sakai	SV400	2006	2004	145	760	0.37	0.59
6. Crane	Lorain	35 ton	1989	2003	--	990	--	0.43
7. Excavator	John Deere	270CLC	2004	2005	988	1092	0.64	0.59
8. Excavator	Komatsu	400	1995	2005	--	1092	--	0.59
9. Gannon Tractor	Case	570XLT	1996	1999	22	1135	0.26	0.21
10. Gannon Tractor	John Deere	210LE	2006	1999	189	1135	0.28	0.21
11. Loader	Caterpillar	950H	2007	2004	1378	1135	0.28	0.21
12. Loader	John Deere	644J	2005	2004	936	1135	0.24	0.21
13. Loader	John Deere	644J	2006	2004	1225	1135	0.23	0.21
14. Motor Grader	John Deere	772D	2004	2005	598	962	--	0.59
15. Motor Grader	Caterpillar	140M	2008	2005	1244	962	0.34	0.59
16. Scraper	Caterpillar	613C	2005	2005	116	914	0.48	0.59
17. Scraper	Caterpillar	613C	2005	2005	22	914	--	0.59
18. Scraper	Caterpillar	615C	1990	2005	207	914	0.41	0.59
19. Sweeper	Roscoe	RB48	1995	2004	3	1220	--	0.43

[a] On-road trucks (e.g., water trucks and haul trucks) are not included in these non-road equipment comparisons.
[b] Model years shown for the NONROAD model represent the average model year for equipment of a given type and horsepower range based on national equipment populations in the model.
[c] Actual load factors were derived by dividing fuel consumption data by total engine hours, BSFC factors from NONROAD (gal/hp-hr), and engine horsepower ratings. Load factors could not be calculated for equipment for which GPS-based engine hours or fuel consumption data were not available.

[11] Note that default equipment usage values in NONROAD are not project-specific or representative of only transportation construction projects in general. Rather, these values represent an average of a particular type of equipment (e.g., graders) used across all applications on an annual basis.
[12] Load factors were calculated by dividing fuel consumption data by total engine hours, BSFC factors from NONROAD (gal/hp-hr), and engine horsepower ratings.

Figure 7-17 shows a comparison of exhaust emission estimates prepared using STI's field study data, NONROAD default inputs (for average equipment use per year, rather than for a transportation project per se) and RCEM run with the parameters shown in Table 7-3. Emission estimates derived from field study data fall between estimates prepared using NONROAD and RCEM. Field study-derived emission estimates are about half of emission estimates prepared using NONROAD defaults, largely because of differences in equipment activity (i.e., annual hours of operation).

Figure 7-18 shows a comparison of fugitive dust emission estimates prepared using STI's field study data and two default options for the RCEM model (NONROAD does not estimate fugitive dust emissions). For default maximum area disturbed inputs to RCEM, an SMAQMD guidance document for air quality assessments (Sacramento Metropolitan Air Quality Management District, 2009) recommends using 15 acres or 25% of the total project area, whichever is greater. STI ran RCEM using both options, which for the SR 92 project would be 15 acres or 4.5 acres; STI's estimate that used field study data fell between the two RCEM default values. For $PM_{2.5}$, STI's estimate was approximately the same as the RCEM estimate prepared using a maximum area disturbed of 4.5 acres (see Figure 7-18).

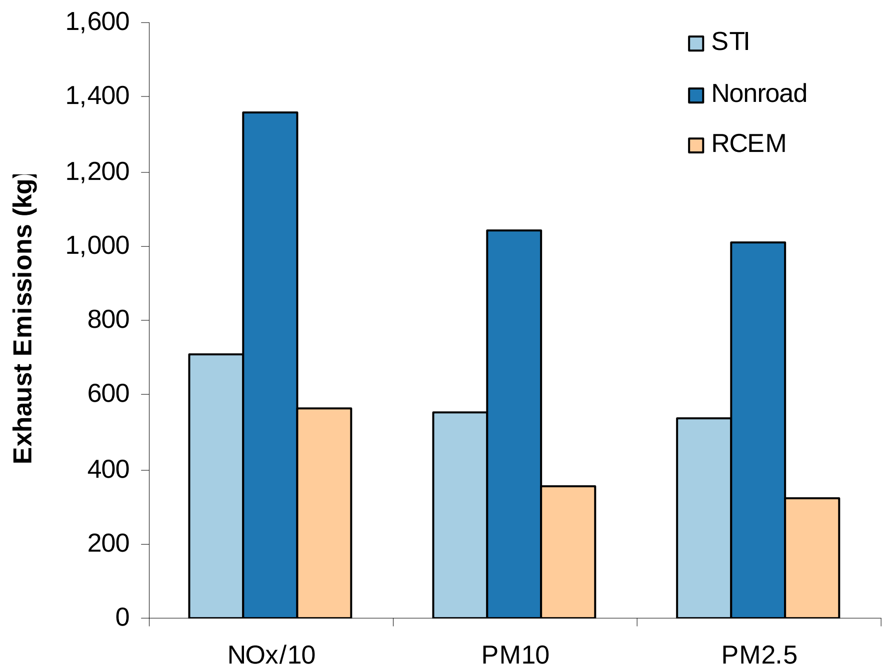


Figure 7-17. Comparison of alternative exhaust emissions calculations for the SR 92 project (note that NO_x emissions have been divided by 10 for scaling purposes).

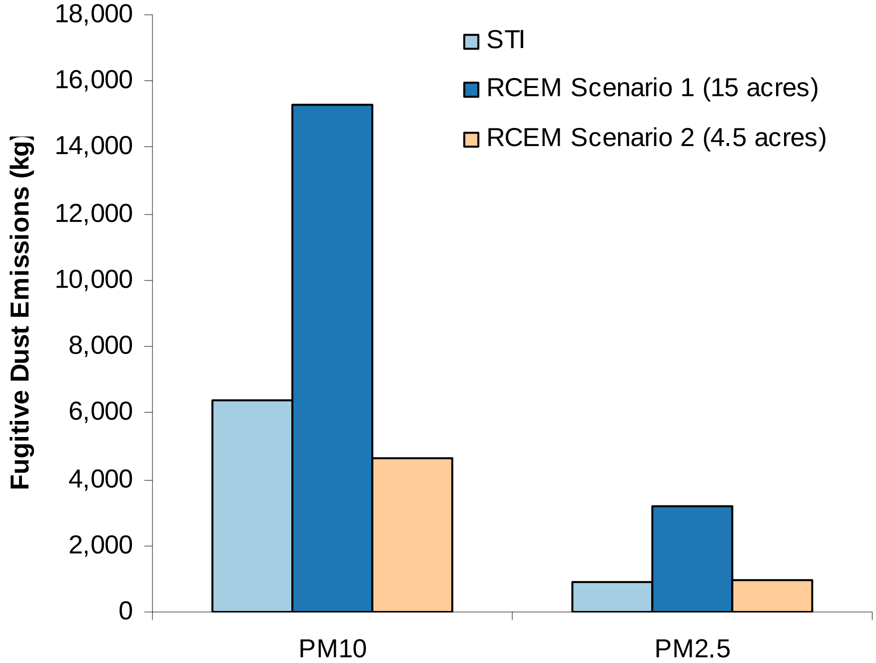


Figure 7-18. Comparison of alternative fugitive dust emissions calculations for the SR 92 project.

8. AIR QUALITY CASE STUDIES

8.1 INTRODUCTION

8.1.1 Overview

This section presents the major air quality-related findings from the field program. The monitoring program lasted for more than a year and generated a substantial array of data, from which numerous insights can be gained. The goal of this discussion is to highlight key observations and present them in a way that facilitates understanding. Accordingly, this discussion presents data and findings from six perspectives. The material begins with a case study of one week in May 2009 that represents a mix of days with and without construction activity; it then presents a focused examination of one day during the case study week. Next, the text presents a case study of one week in February 2009 when rock crushing equipment was in use. Following the rock crusher case study, the text presents findings from a week in April 2009 when the highest measured 24-hr PM_{10} concentrations occurred. The section then presents data for a Sunday in November, used to illustrate background concentrations. The discussion then provides summary statistics that characterize a twelve-month period (January 19, 2009, through January 19, 2010). The section closes with overall observations regarding the relationship between construction activity and PM impacts.

A few introductory points are offered here to help interpret the data presented. When evaluating the data to discern construction-related impacts, some basic principles apply. If construction work took place in the immediate vicinity of the monitoring trailers, measured air quality impacts should be greater at the monitors downwind of the activity. Thus, one measure of whether pollutant concentrations were linked to construction activity, as opposed to general background conditions, was the difference between monitored concentrations at the upwind and downwind trailers. In addition, some pollutants—such as particulate matter (PM) and oxides of nitrogen (NO_x, NO_2, and NO)—are emitted by on-road vehicles as well as construction equipment. For the case studies illustrated here, we estimated emissions from each source category to differentiate their relative contribution to monitored values. We also measured black carbon (BC, or soot) concentrations as an indicator of construction-specific emissions, since BC is typically emitted in much greater quantities from diesel-powered engines than from gasoline-powered engines. Thus, for example, if monitored PM concentrations were increased over background, and BC was also increased over background at the same place and time, there was a greater likelihood that the PM concentration increases were associated with construction activity.

The data analyses presented here use several methods to estimate background concentrations compared to pollutant impacts related to construction. These methods include, for example, comparing concentrations measured in the evening (when no construction took place) to concentrations measured during the day when construction work was in progress; comparing concentrations upwind of the construction to concentrations measured downwind of construction work; and comparing concentrations on days when construction work took place to concentrations on days (such as most weekends) when construction work was halted. Later discussions detail the assessment of background conditions; however, it may be useful to note that on a weekend day selected to represent background conditions (November 22, 2009; see Section 8.6) maximum PM_{10} concentrations ranged from 15 to 25 $\mu g/m^3$, while minimum PM_{10} was as low as 1 $\mu g/m^3$, depending on wind speed and direction, and $PM_{2.5}$ concentrations varied between less than 0 to 8 $\mu g/m^3$.

8.1.2 Discussion of Time Periods Illustrated

Table 8-1 summarizes the case studies presented. First, the discussion presents findings for May 2009. The May 25-31, 2009, case study includes reasonably representative times when construction activity took place near the monitoring sites, when PM concentrations were observed to be relatively high in comparison to background, when water trucks were actively engaged in suppressing dust, and when the air quality impacts of construction-related activities could be distinguished from those associated with on-road vehicle activity. In addition, the week included the Memorial Day holiday (Monday, May 25, 2009), a date when there was no construction activity. Field study measurements on Memorial Day established background conditions for comparison to days when construction work took place. Also, the week was free from confounding events, such as wildfires,[13] that influenced measured PM during other times of the year.

Second, the discussion takes a more focused look at one of the days during the May case study week: Sunday, May 31, 2009. Construction work took place that Sunday and on-road traffic was relatively light in comparison to other days (although coincident in time with the construction work).

Third, the discussion includes material from February 2009 to supplement the May case study. During the May case study, one noteworthy piece of construction equipment was not in operation—a diesel-powered rock crusher that operated during several multi-week periods throughout 2009. The discussion presents findings for several days in February 2009 when the rock crusher was in use.

Fourth, the discussion examines data from the week of April 13-19, 2009. During that week, on April 15, 2009, the field program recorded the highest-measured 24-hr PM_{10} concentrations of the one-year (January 19, 2009 to January 19, 2010) period assessed here. The discussion relates those measurements to construction work.

Fifth, the discussion provides a November 22, 2009, illustration of air quality on a day when construction work was halted and meteorological conditions did not include unusually strong winds. The November data help represent background conditions and are used as a point of comparison in other case study materials.

Sixth, the discussion presents summary statistics that characterize air quality observations across an entire year. The summary statistics place the case study illustrations in context, and serve to capture the range of air quality conditions that occurred across all seasons of the year.

[13] For example, wildfires occurred during July 2009 that resulted in higher-than-average PM concentrations measured at the study site.

Table 8-1. Summary description of case studies evaluated.

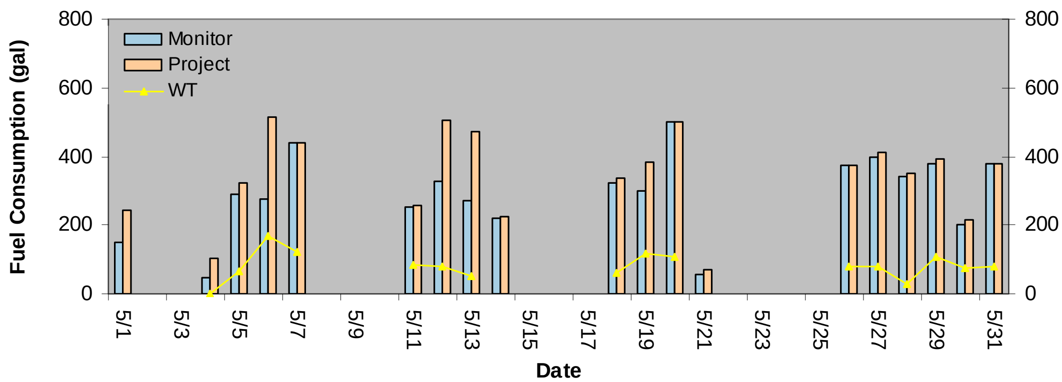
Case Study	Time Period
1. Example week that included periods with and without construction work near the air quality monitoring sites.	May 25-31, 2009 (Monday/Memorial Day through Sunday)
2. A day when construction work took place and on-road traffic was relatively light in comparison to other days.	May 31, 2009 (Sunday)
3. Example construction period when diesel-powered rock crusher was in use.	February 2-8, 2009 (Monday through Sunday)
4. Identified period that included the highest monitored 24-hr PM_{10} concentrations.	April 13-19, 2009 (Monday through Sunday)
5. Day used to illustrate background (no construction activity) air quality conditions.	November 22, 2009 (Sunday)
6. Summary description of measurement results obtained over a twelve-month period.	January 19, 2009 through January 19, 2010

Air quality observed during each of the case study periods, as well as throughout the year, was a function of several key factors that are worth keeping in mind when reviewing the findings presented here. The three most important factors were: 1) meteorological conditions (wind direction, wind speed, atmospheric mixing); 2) construction activity (type of construction activity, distance to the construction activity, equipment used, and emissions generated by that equipment); and 3) the dryness of disturbed dirt (meaning, in particular, whether water was sprayed on it to suppress dust).

8.2 CASE STUDY FOR MAY 25-31, 2009

8.2.1 May 25-31, 2009, Compared to all of May and an Entire Year of Data Collection

Before presenting the May 2009 case study findings, this discussion graphically illustrates the May 25-31, 2009, case study week in comparison to other weeks in May and briefly highlights how this case study week compared to the data collected over an entire one-year period. **Figure 8-1** illustrates construction equipment activity—as measured by fuel consumption—for the month of May 2009. Fuel consumption was relatively uniform during the case study week (May 25-31) on days when construction took place, with the exception of Saturday, May 30, when fuel use (and, by extension, equipment use) was approximately half that of the other days. Note that, as illustrated in Figure 8-1, water truck fuel consumption declined on Thursday, May 28, which was due to rain on that date.



Notes:
1. "Monitor" means fuel consumed by all construction equipment, including water trucks, within 1000 m of monitors.
2. "Project" means fuel consumed by all construction equipment, including water trucks, for the whole project.
3. "WT" means fuel consumed by water trucks.

Figure 8-1. Construction equipment fuel consumption during May 2009.

Figure 8-2 shows exhaust PM_{10} emissions for construction equipment and fuel use by water trucks (as an indicator of the amount of watering done) during May 2009. The variations in daily exhaust NO_x, PM_{10}, and $PM_{2.5}$ emissions from construction equipment were consistent with fuel consumption (see Figure 8-1); however, only exhaust PM_{10} emissions are shown to illustrate that point.

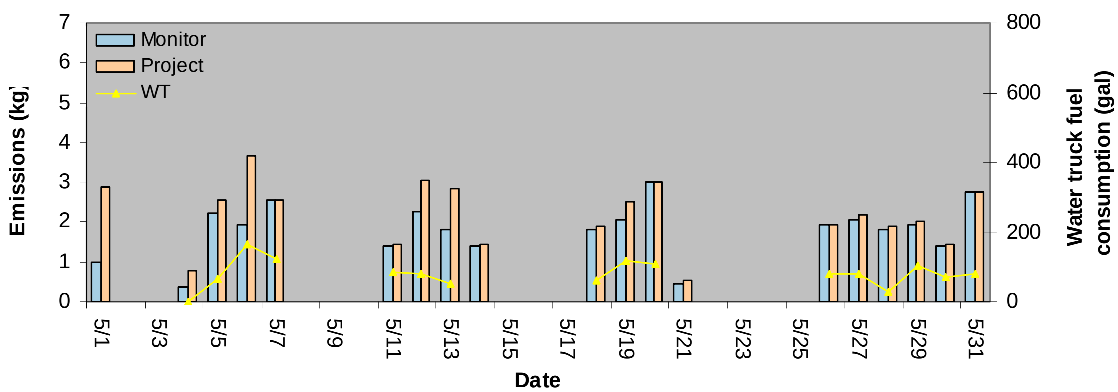


Figure 8-2. Exhaust PM_{10} emissions in May 2009.

Fugitive PM_{10} and $PM_{2.5}$ emissions for the month of May 2009 are shown in **Figure 8-3**. Note that the fugitive PM emissions are higher on May 26-29 than on May 30-31—this is because one Freightliner dump truck transported materials full-time during May 26-29, causing almost half of the fugitive PM emissions that resulted from all construction related activities.

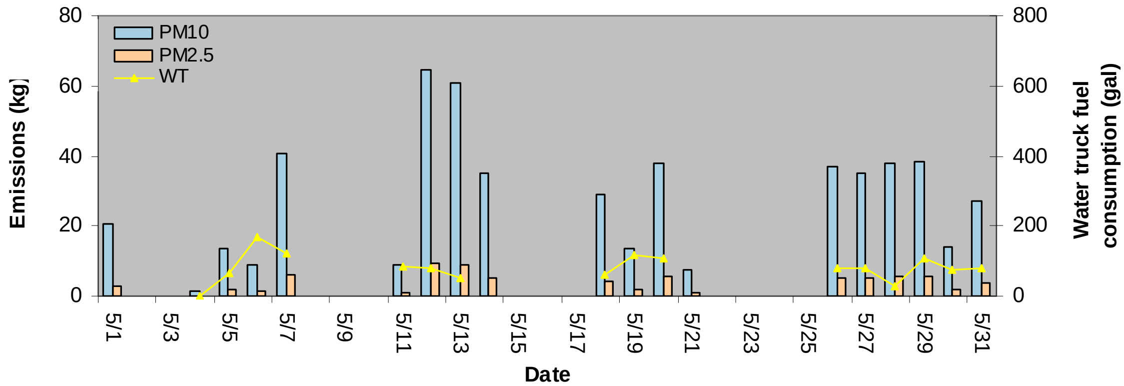


Figure 8-3. Fugitive PM_{10} and fugitive $PM_{2.5}$ emissions in May 2009.

It is also helpful to understand how air quality during the case study week compared to observations across an entire year. Given that the week included construction activity relatively near the monitors, pollutant concentrations for the week as a whole were above average when compared to conditions averaged across the entire year. **Table 8-2** presents summary statistics comparing the case study week to measurements made across an entire year (January 19, 2009 to January 19, 2010). As shown in Table 8-2, maximum 24-hr average PM_{10} concentrations were approximately 29 $\mu g/m^3$ during the study week; this was among the highest values observed during the year, although not the maximum. Material later in this section examines the conditions that resulted in the maximum measured PM_{10} concentrations. Section 8.7 provides further details for an entire year.

Table 8-2. Summary PM statistics for May 25-31, 2009, compared to the period January 19, 2009, to January 19, 2010.

	Parameter	Min	Max	Median	Mean	SD
1/19/2009 – 1/19/2010	$PM_{2.5}$ ($\mu g/m^3$)	-4.3	10.0	1.0	1.0	2.2
	PM_{10} ($\mu g/m^3$)	-1.8	72.0	11.3	12.7	7.5
5/25-5/31, 2009	$PM_{2.5}$ ($\mu g/m^3$)	-2.5	2.8	2.0	1.3	1.5
	PM_{10} ($\mu g/m^3$)	6.8	29.4	13.4	14.1	4.9

Notes: Units are 24-hr averages. Further details describing the entire year of data are presented in Section 8.7. Minimum and maximum values shown were from measurements from a single monitor. Median, mean, and standard deviation (SD) measurements were calculated by averaging data collected across all monitors. Note that minimum measurements included negative values. Negative measured concentrations meant that when real-world PM concentrations were low (approaching zero), the monitor's precision range (e.g., ±1.5 $\mu g/m^3$) included concentration values below zero. In general, monitor operations, calibration checks, and audits were designed to meet standard U.S. Environmental Protection Agency (EPA) guidelines for air quality monitoring. Appendix B includes further detail on the precision of the equipment deployed.

To illustrate the location of construction equipment relative to the air quality monitors during the case study week, **Figure 8-4** shows the GPS-determined construction activity on May 31, 2009. The geographic location of equipment activity on May 31 was similar to the location of activities that took place during other work days that week. As illustrated by Figure 8-4, during the case study week (May 25-31, 2009), most of the construction activity occurred within about 1000 m of the monitoring sites. The following sections discuss air quality as well as activity and emissions during this case study.

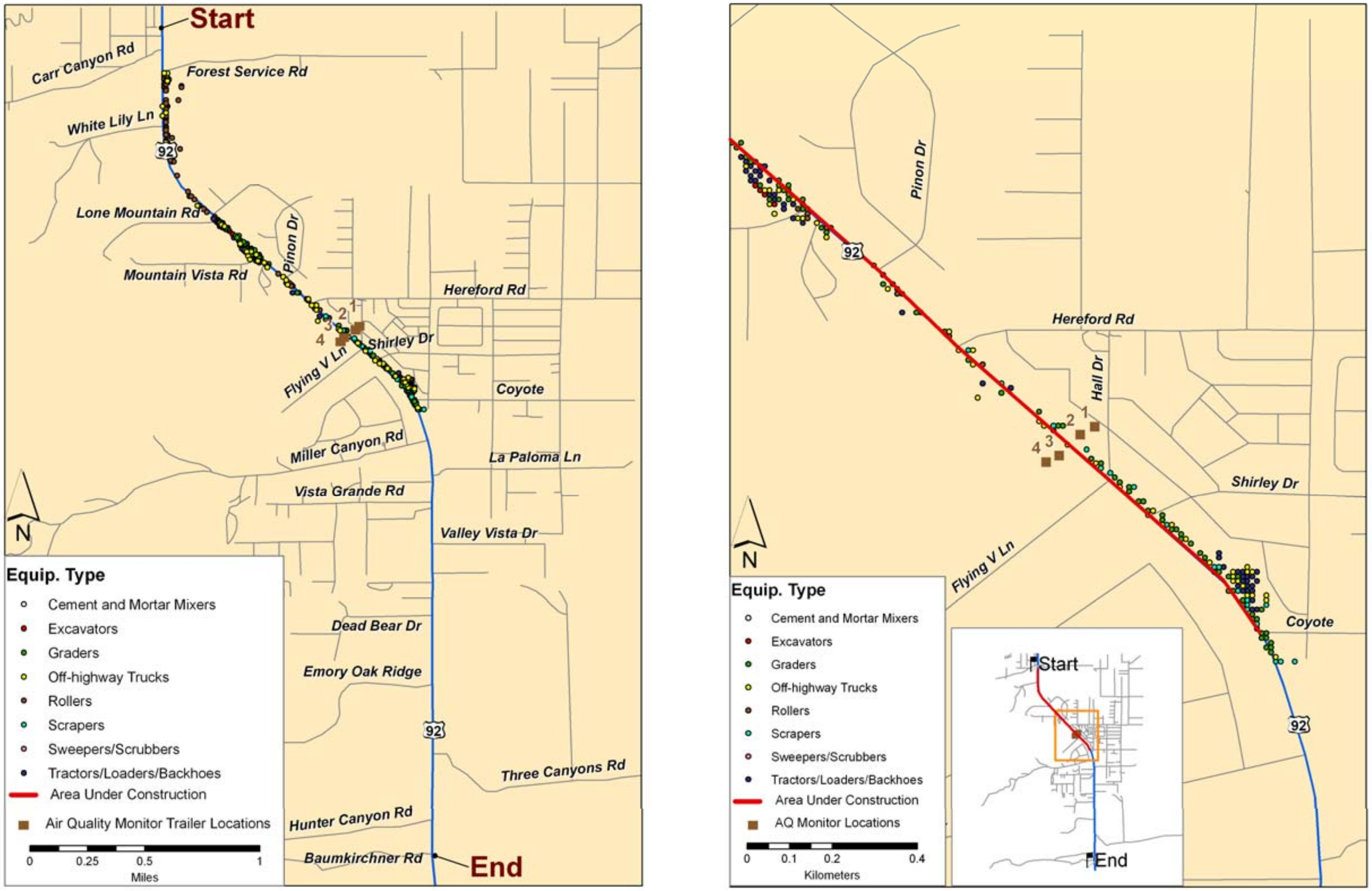
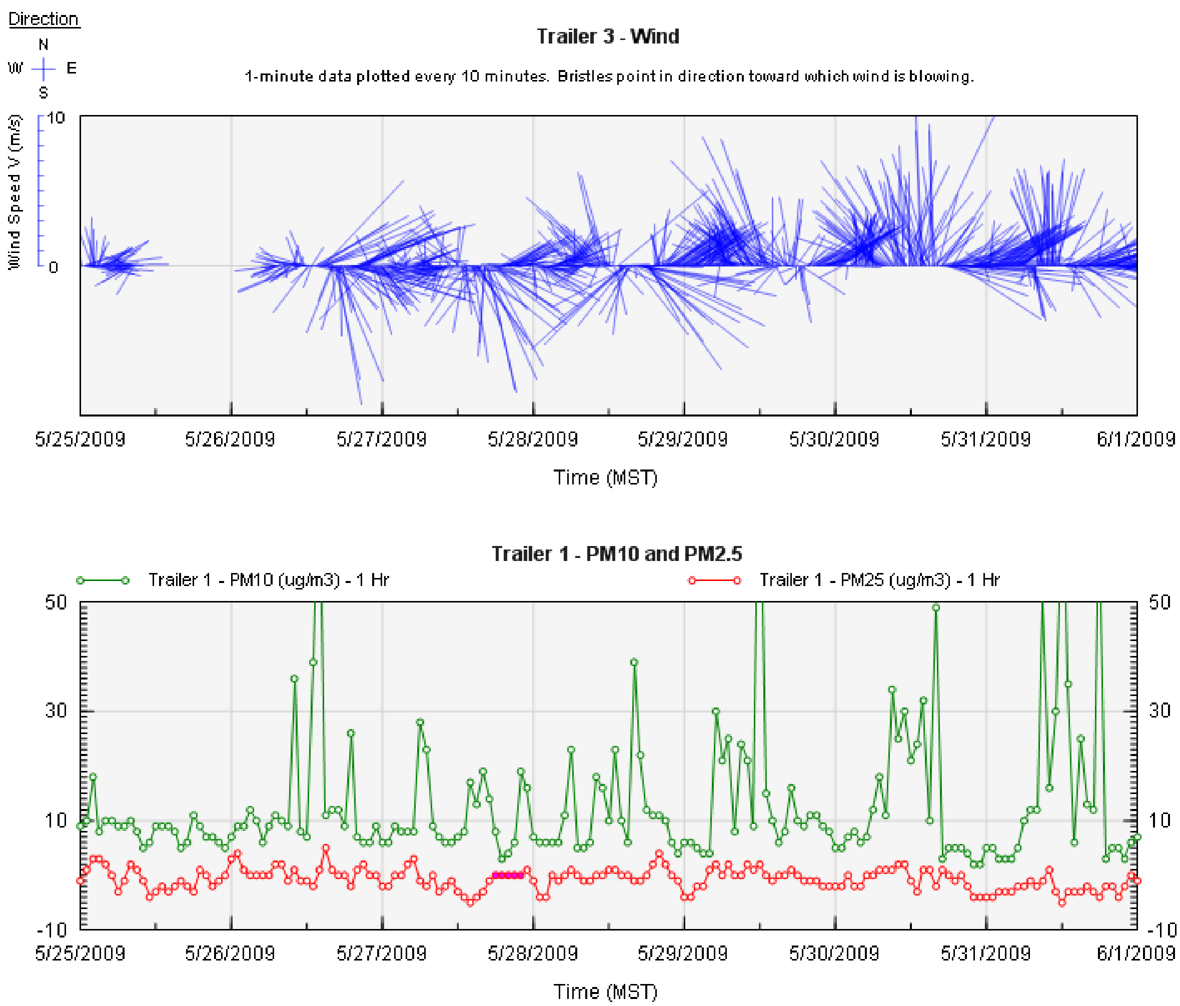


Figure 8-4. May 31, 2009, illustration of construction activity locations (based on GPS tracking reported every five minutes; activity was similarly located during other days in the May 25-31, 2009, case study period).

8.2.2 Air Quality for May 25 to 31, 2009

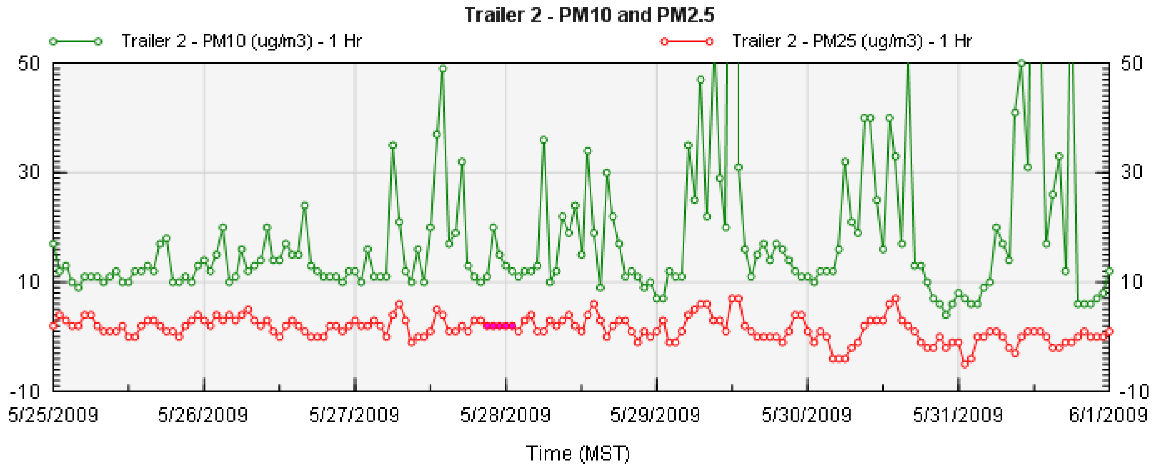
An overview of the air quality during this week is shown in **Figure 8-5**, which illustrates winds measured at Trailer 3 and PM concentrations measured at Trailer 1. Figure 8-5 is also included here to introduce the type of figures used throughout this section to display air quality and meteorological data collected at the trailers. Figure 8-5 presents only two panels, although later figures present multiple panels for various observation periods. In Figure 8-5, the top panel illustrates wind direction and wind speed; the bottom panel illustrates pollutant concentration measurements. The wind data are graphed in a manner analogous to a flag on a flag pole—the line points in the direction that the wind is blowing (just as a flag flies in the direction the wind blows); the longer the line, the greater the wind speed. The pollutant concentration data are displayed for time periods that overlap the wind data display—as concentrations vary, readers can observe how those concentrations vary with wind speed and direction. The wind data in Figure 8-5 also illustrate that on rare occasions during the year-long field program, data collection was interrupted when an intermittent problem occurred.

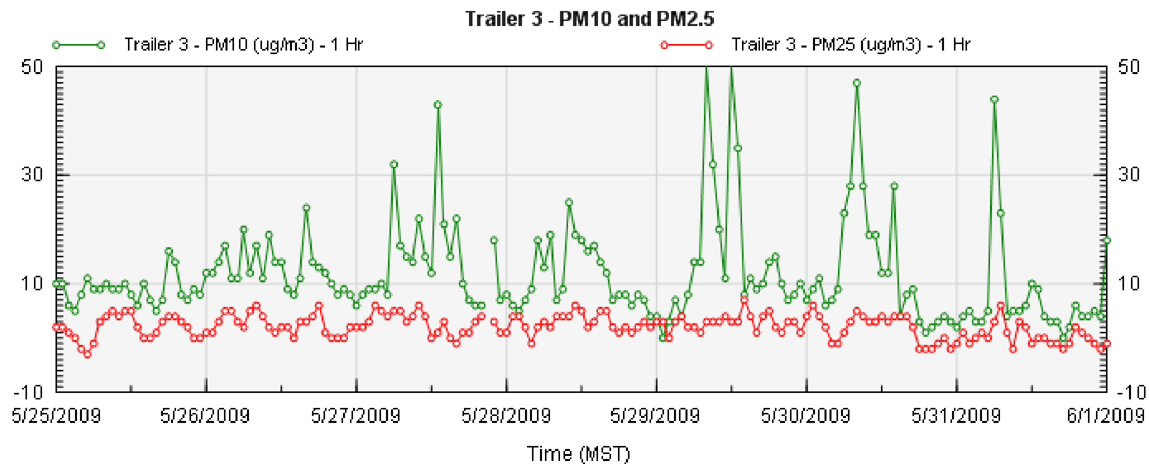
Although some wind data is missing on Monday, May 25, note that a variable wind pattern is present each day, often with a shift in direction about midday. For PM_{10}, concentrations were consistently around 8-10 $\mu g/m^3$ on Monday, the Memorial Day holiday, when no construction occurred; the lowest concentrations each day slowly drifted down over the week and ended near 2 $\mu g/m^3$ on Sunday, May 31. There were peaks in PM_{10} concentrations on each work day, starting at about 6-8 a.m. MST and lasting until about 4-6 p.m., which coincided with construction activity on these days. $PM_{2.5}$ concentrations were low and variable throughout the whole week and thus apparently did not show much influence from the nearby construction. PM_{10} concentrations measured at the other trailers for this week are shown in **Figure 8-6**. (Later figures generally include all trailer panels in one group; Figures 8-5 and 8-6 separated the panels to help introduce their use.) Figure 8-6 indicates that PM_{10} concentrations at Trailers 2, 3, and 4 displayed patterns similar to the pattern for Trailer 1, although concentrations varied due to changes in wind direction, wind speed, and construction activity locations. $PM_{2.5}$ concentrations at all four trailers were low and variable all week. Note that during this week in May 2009, the atmosphere was weakly stable overnight. However, by about 6 or 7 a.m., this overnight stability was broken and the atmosphere was well-mixed when construction activity started, so all construction emissions were injected into a well-mixed atmosphere.



Note: The x-axis hash marker halfway between dates is at noon on this and subsequent figures.

Figure 8-5. Winds from Trailer 3 and PM concentrations from Trailer 1, May 25-31, 2009.





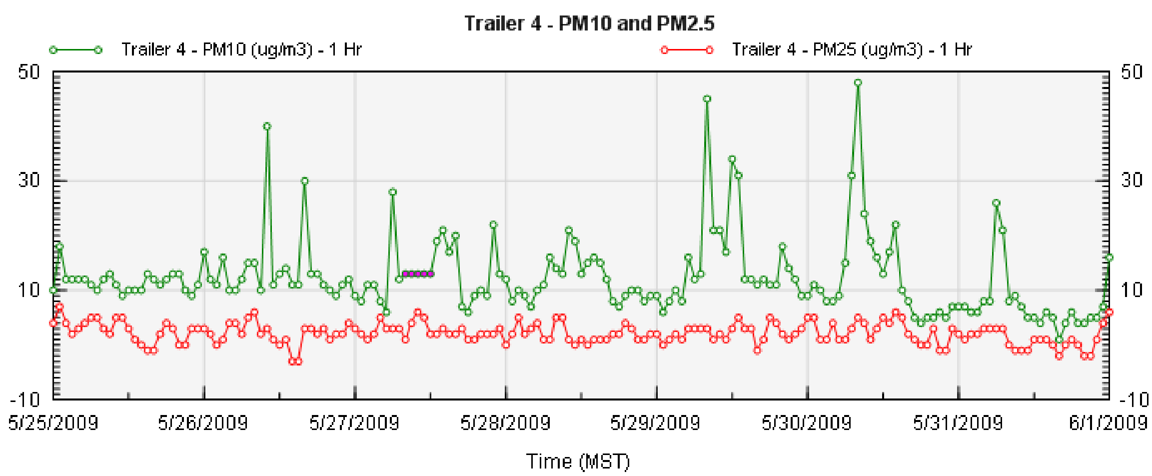


Figure 8-6. PM concentrations from other trailers during May 25-31, 2009.

Figure 8-7 shows average NO_x, NO_2, PM_{10}, $PM_{2.5}$, and BC concentrations among all trailers on each day from May 25-31, 2009, versus the average concentrations among all trailers on a background day (November 22, 2009; see Section 8.2.) Note that PM_{10}, NO_x, NO_2, and BC concentrations on working days, May 26-31, 2009, are generally higher than on May 25 or the background day of November 22, 2009. However, $PM_{2.5}$ concentrations on all of these days, including the background day, are low and are generally less than 3 $\mu g/m^3$; this is within the precision of the monitor. This data is summarized by day in **Figure 8-8** for BC, NO_x, PM_{10}, and $PM_{2.5}$, which shows that pollutant concentrations on May 25, 2009, are similar to those on the background day of November 22, 2009, for all four pollutants. However, there is a significant increment for BC, NO_x, and PM_{10} on all working days, with an even greater increment for PM_{10} during May 29-31, 2009.

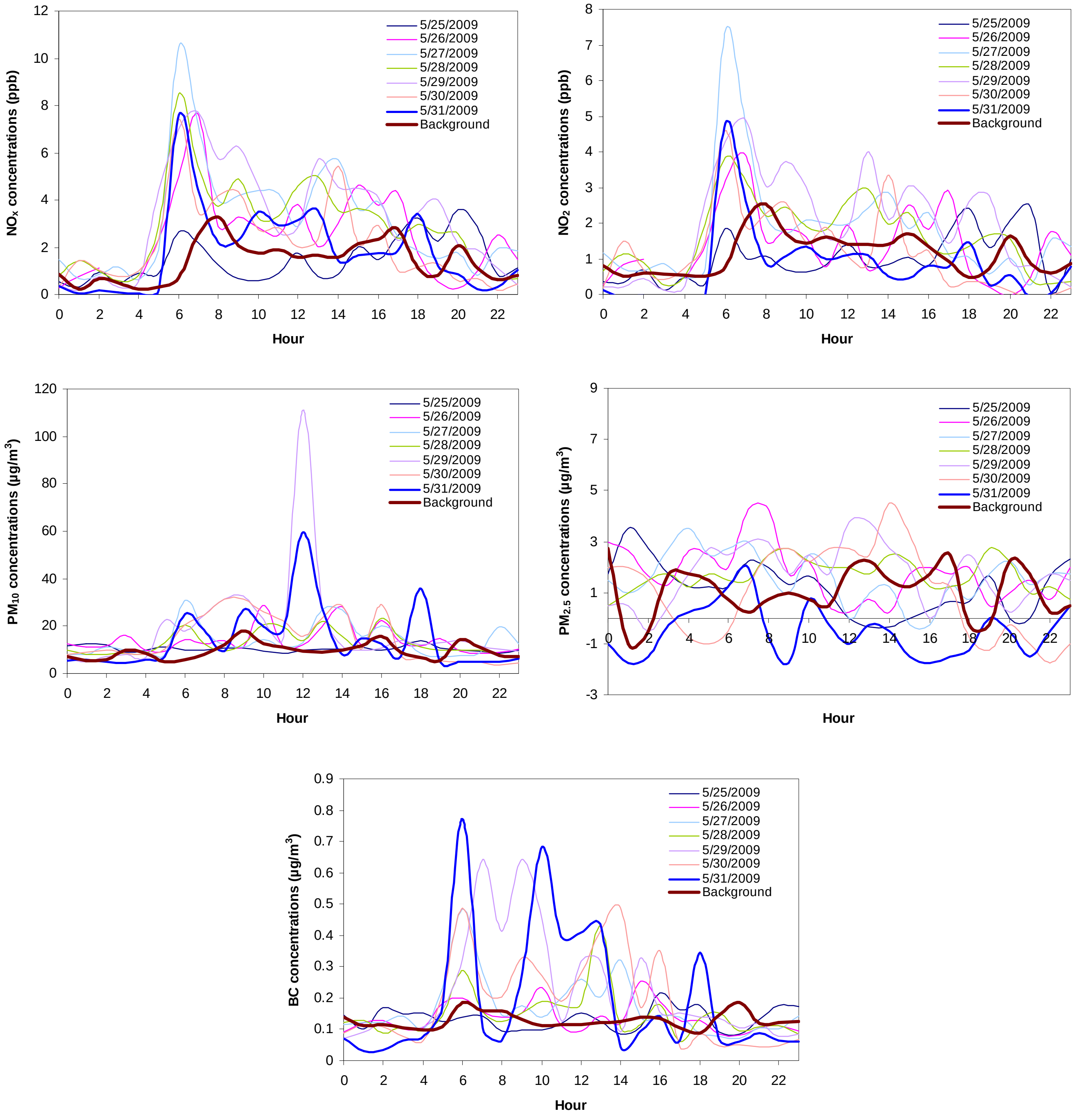


Figure 8-7. Concentration comparison: May 25-31, 2009, vs. November 22, 2009 (a background day, see Section 8.6).

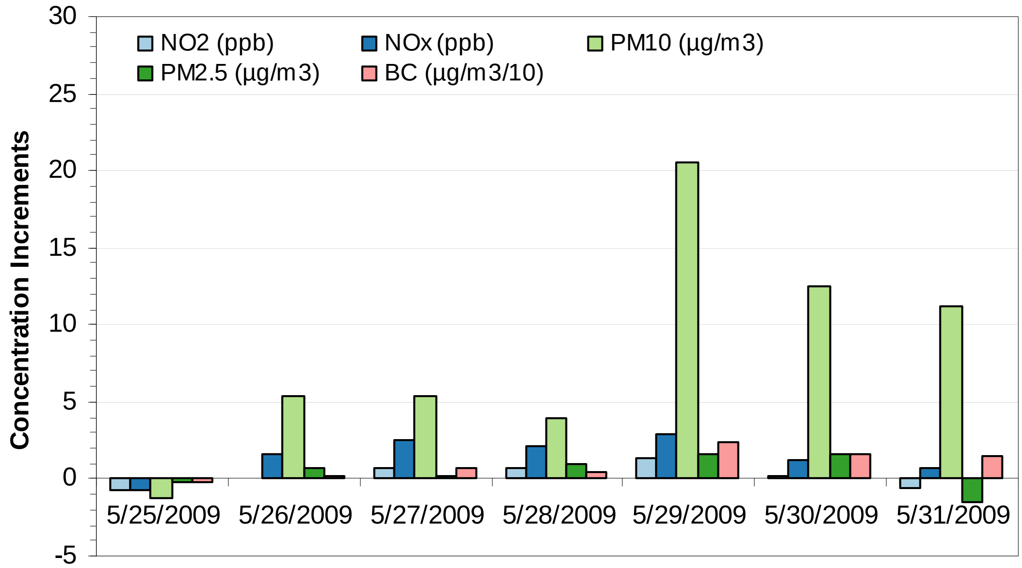


Figure 8-8. Increments of daily concentrations during May 25-31, 2009, compared to background daily concentrations measured on November 22, 2009 (all trailers averaged).

Another way to estimate the increment contributed by construction activities is shown in **Figure 8-9**, where the average concentration during non-working hours has been subtracted from the average concentration during working hours on the same day. Pollutant concentrations on May 25, 2009, are similar to those on the background day of November 22, 2009, for all four pollutants. However, there is a noticeable increment for BC, NO_x, and PM_{10} on all working days, with an even greater increment for PM_{10} during May 29-31, 2009.

8.2.3 Activity and Emissions for May 25 to 31, 2009

This discussion summarizes construction equipment activity and construction-related emission estimates for the case study period. The emissions data shed further light on the potential influence of these emissions sources on nearby air quality.

Figure 8-10 shows the hourly normalized equipment usage of all GPS-installed construction equipment for each working day during this week. A normalized equipment usage is a ratio of the sum of the engine-on time of all equipment during an hour to the sum of the engine-on time during the day. For example, on May 31, there were eight GPS-instrumented pieces of equipment working. For all these equipment, from 8:00 a.m. to 9:00 a.m., the sum of engine-on time was 4.24 hours while the sum of engine-on time for the entire day was 59.12 hours. The normalized equipment usage would be 4.24 divided by 59.12, which is 0.07. Note that on most days, work begins at 6 a.m. and ends by 5 p.m., although work ended later (by 7 p.m.) on May 26 and May 31, 2009. There was often a dip in work during the 11-to-noon hour.

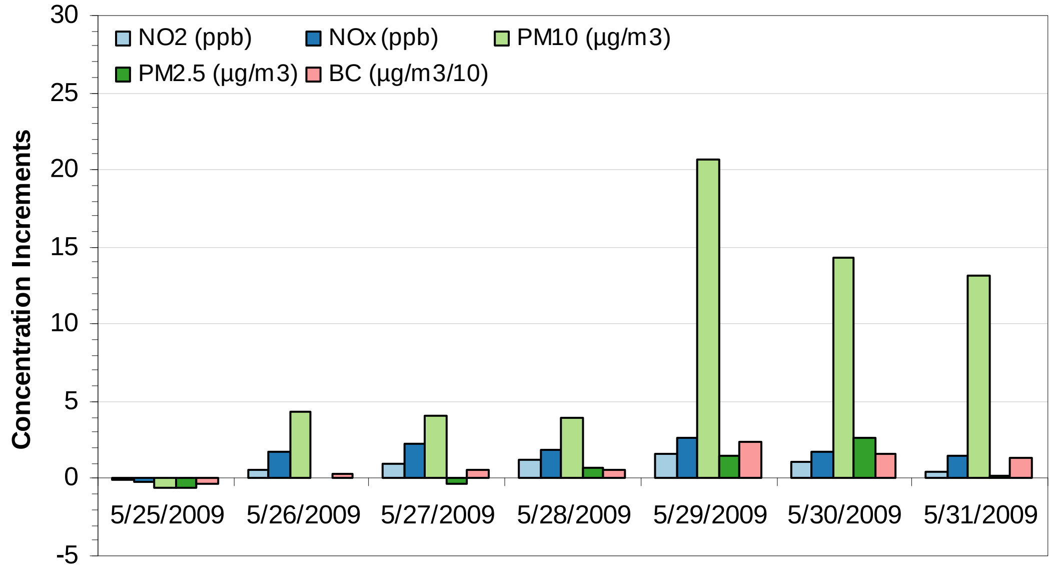
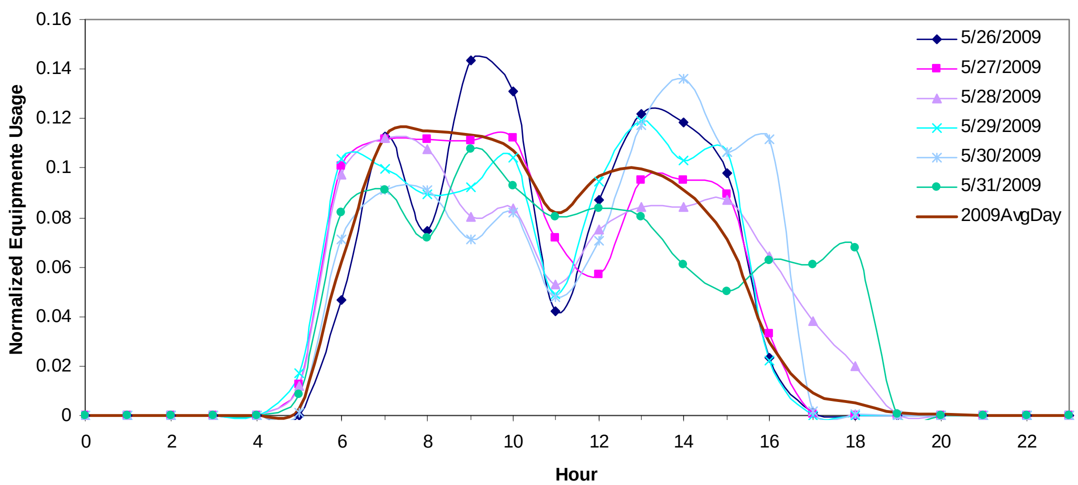


Figure 8-9. Increments of hourly-average concentrations during equipment operating hours during May 25-31, 2009, compared to non-operation hours on the same days (all trailers averaged).



Note: **77%** of operating equipment during the case study period was instrumented with a GPS unit.

Figure 8-10. Normalized usage of GPS-instrumented equipment for the case study period.

Figures 8-11 through **8-17** illustrate construction phases and equipment that contributed most to fuel consumption and emissions during the case study period.

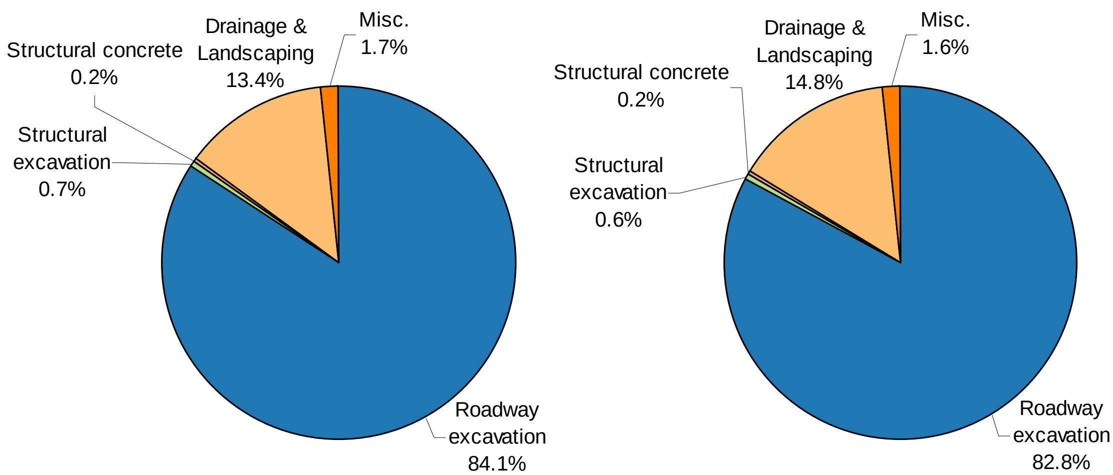


Figure 8-11. Construction equipment fuel consumption distribution by construction phase for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

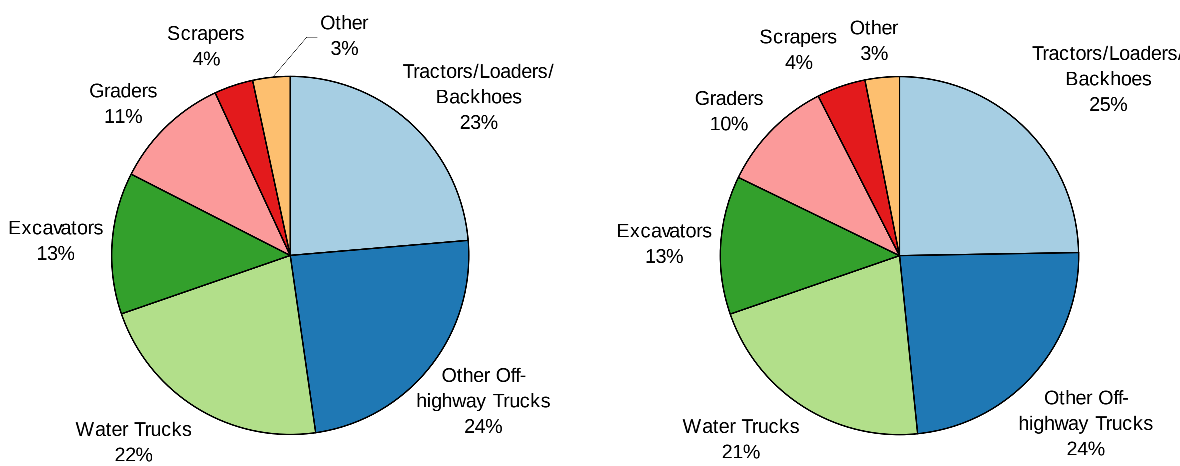


Figure 8-12. Construction equipment fuel consumption distribution by equipment type for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

Off-Highway Truck
(freightliner w/ belly dump trailer)

Source: Google Images

Excavator (EX227_270C)

Water Truck (WT6)

Loader (L11_644J)

Figure 8-13. Key equipment consuming the most fuel during May 25-31, 2009.

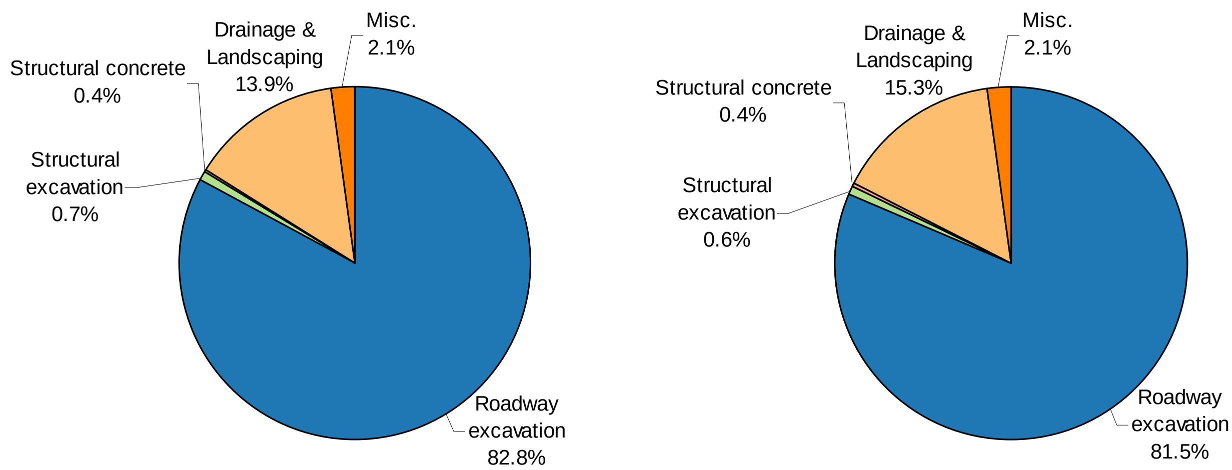


Figure 8-14. Construction equipment exhaust NO_x emissions distribution by construction phase for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

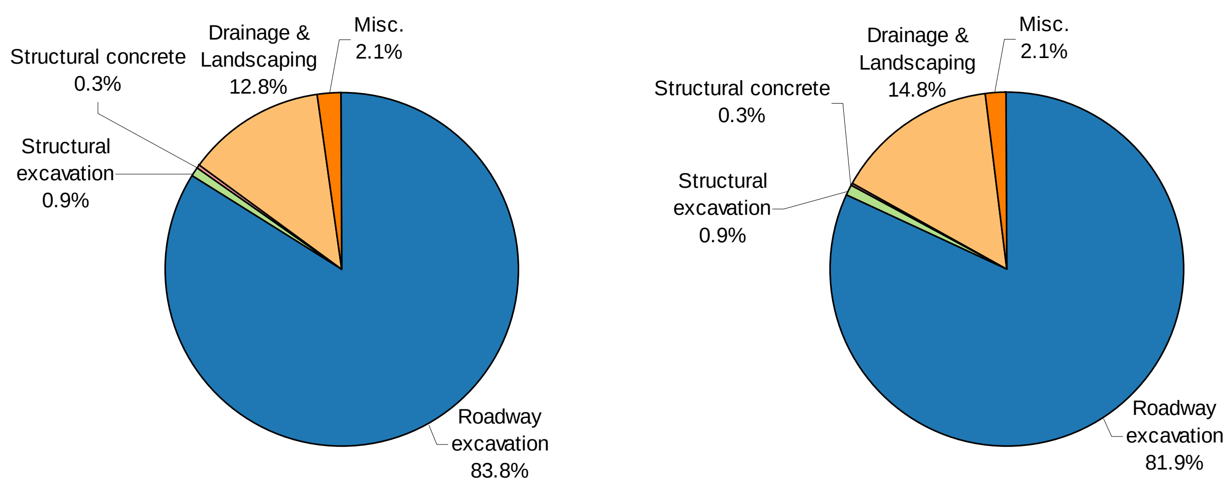


Figure 8-15. Construction equipment exhaust PM_{10} emissions distribution by construction phase for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

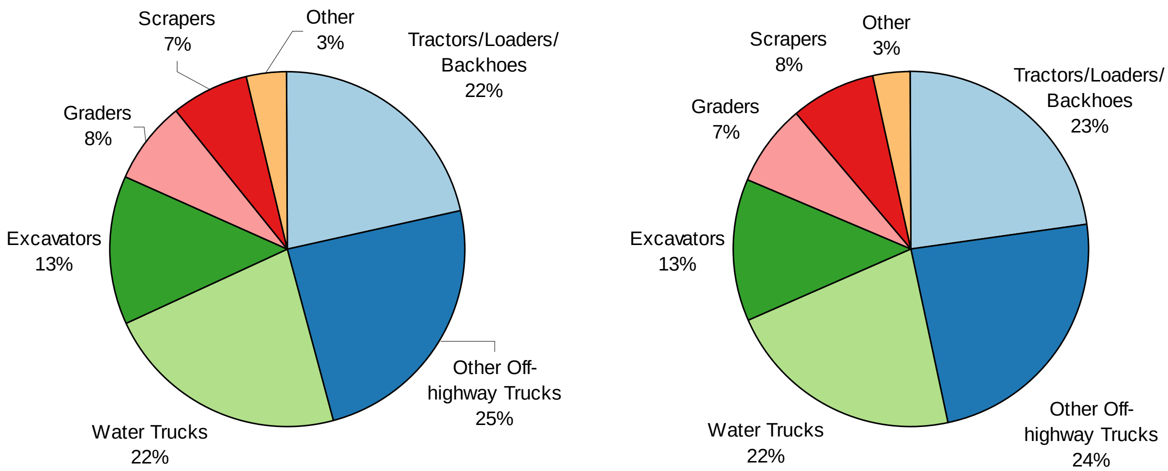


Figure 8-16. Construction equipment exhaust NO_x emissions distribution by equipment type for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

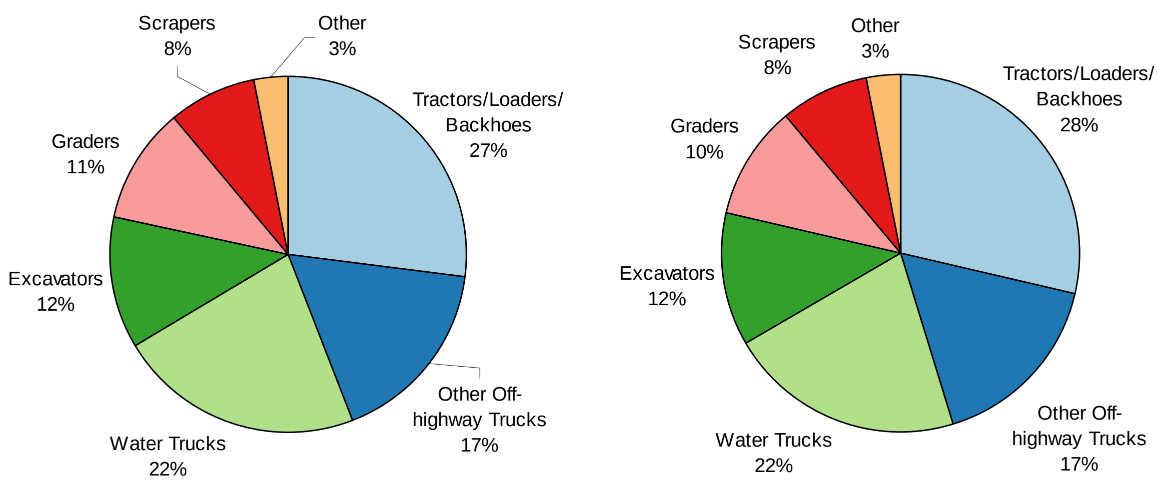


Figure 8-17. Construction equipment exhaust PM_{10} emissions distribution by equipment type for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

Figure 8-18 shows the on-road emissions for PM_{10} for the week of May 25-31, 2009. Note that although the daily PM_{10} on-road emissions are substantially less than the construction fugitive dust emissions shown in **Figure 8-19**, the on-road emissions occur mostly during the same hours as the construction emissions. Also note that the daily and hourly on-road emissions are similar on the holiday (Monday, May 25, 2009) and Sunday May 31, which were both lower than on most other days during this week.

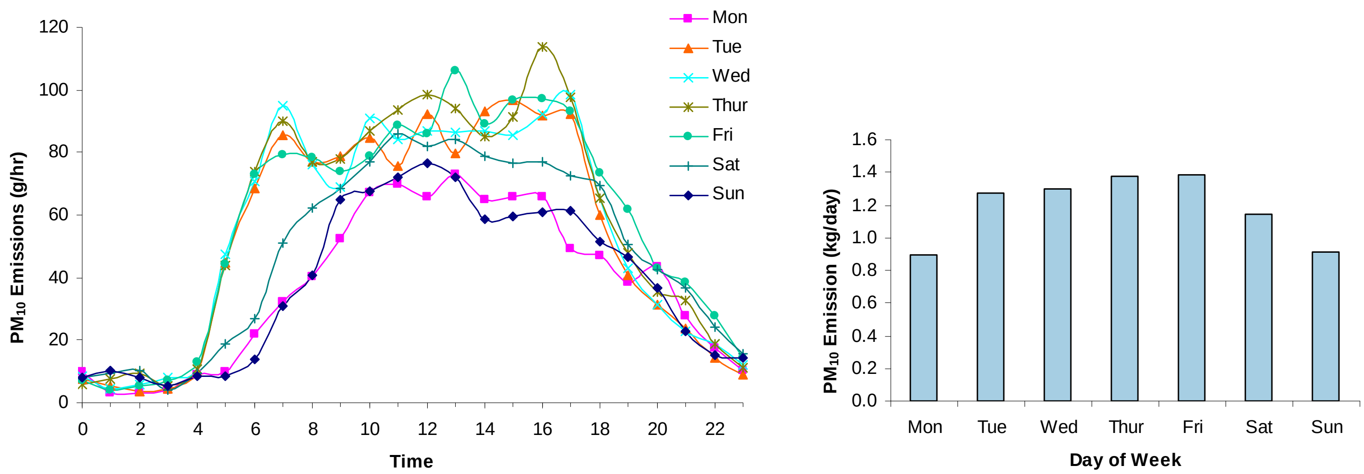
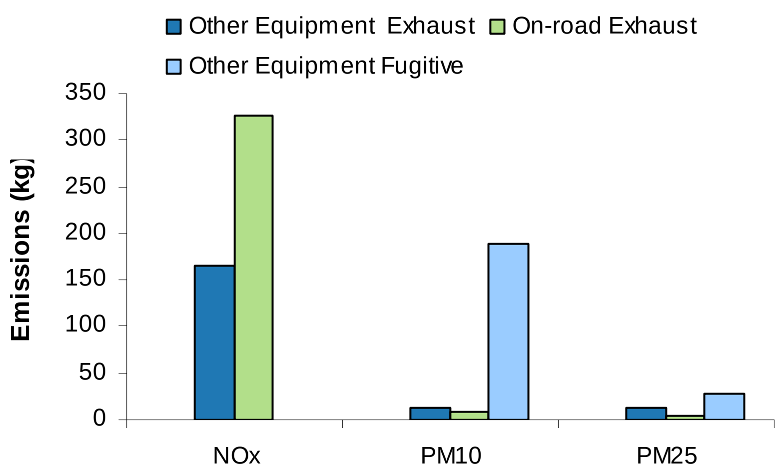


Figure 8-18. On-road emissions (left) and diurnal pattern (right) by day of week during May 25-31, 2009.



Note: During May 25-31, 2009, "Other Equipment" includes all construction related on- and off-road equipment except for the rock crusher, which was non-operational then.

Figure 8-19. Emission comparisons by source categories (May 25-31, 2009).

8.2.4 Case Study Summary: May 25-31, 2009

In summary, the main observations from the May 25-31, 2009, case study are as follows:

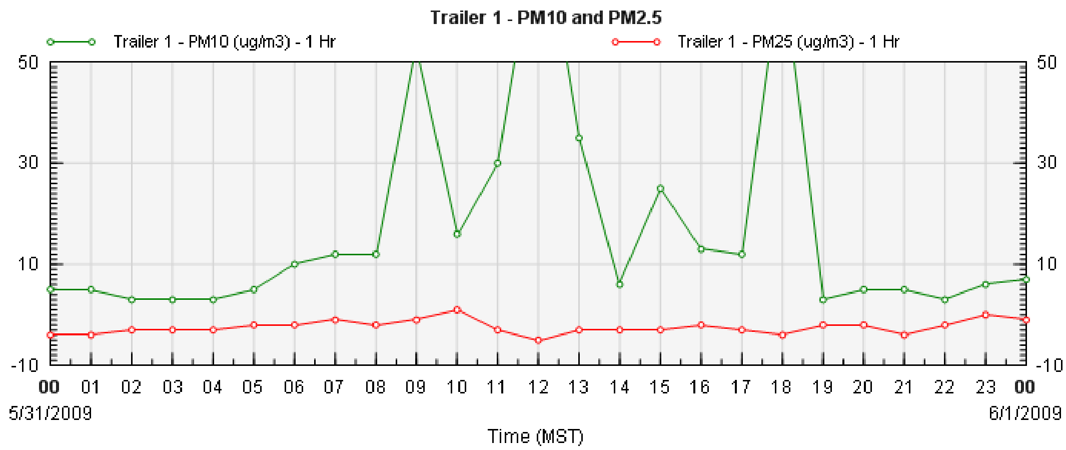
- Construction activity occurred from approximately 6:00 a.m. to 5:00 p.m., with decreased equipment use during the midday lunch break (usually 11:00 a.m. to noon). Most of the activity during this week focused on roadway excavation, and three equipment categories —water trucks, tractors/loaders/backhoes, and off-highway trucks—accounted for approximately 70% of the total activity (as measured by fuel consumption).

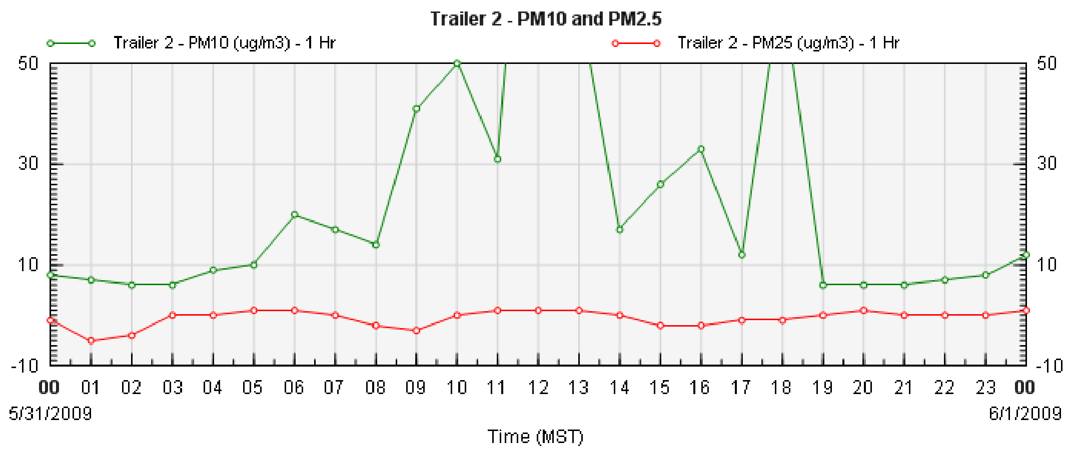
- PM and NO_x emissions paralleled activity breakdowns for construction phase and equipment type.
- On-road vehicle NO_x emissions were greater than construction-related emissions and generally occurred during the same time period as the construction NO_x emissions.
- On-road vehicle exhaust PM_{10} emissions (less than 2 kg/day) contributed far less to the local emissions inventory than did construction-related fugitive dust (30-40 kg/day).
- Monitoring data indicate that PM_{10} concentrations were affected (increased) by the construction work; $PM_{2.5}$ impacts, however, were far less pronounced. PM_{10} concentrations peaked near midday (in contrast to the peak periods for observed NO_x, NO_2, and BC, as discussed next).
- NO_x, NO_2, and BC concentrations increased during periods when construction activity took place, particularly during the morning hours (see Figure 8-7). Maximum NO_x, NO_2, and BC concentrations were noticeably higher on construction work days compared to the Memorial Day holiday (and compared to another background day, Sunday, November 22, 2009). The increase in monitored NO_x concentrations also coincided with increased on-road travel activity.
- Wind direction and strength varied throughout the week; thus, the observed PM_{10} impacts from the construction work were measured, at various times, by each of the four trailers.

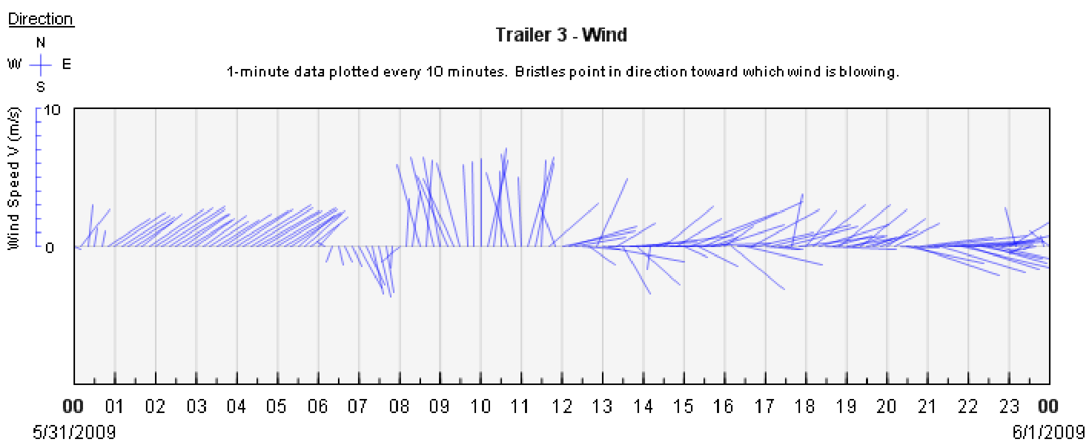
8.3 FOCUSED EXAMINATION OF MAY 31, 2009

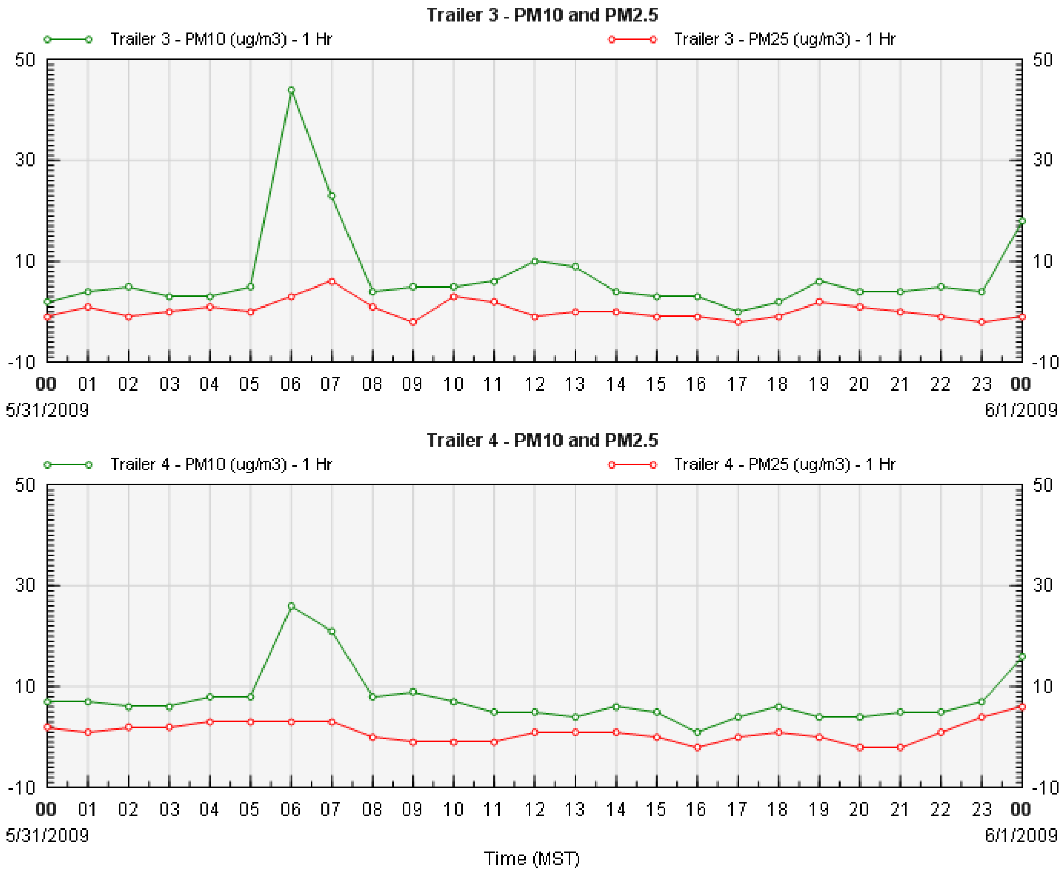
8.3.1 Air Quality for May 31, 2009

This discussion examines in detail the factors contributing to air quality measured on Sunday May 31, 2009. **Figure 8-20** shows winds in one panel and PM_{10} and $PM_{2.5}$ concentrations in four separate panels for each trailer: Trailers 1 and 2 on the northeast side of SR 92 and Trailers 3 and 4 on the southwest side of SR 92. Note that when construction work starts at about 6 a.m., there is a short time during which winds flow from the north, from about 6 to 8 a.m., and a corresponding sharp peak in PM_{10} concentrations at Trailers 3 and 4 on the southwest side of SR 92. Then, once the winds turn around and flow from the south (from about 8 a.m. to noon), there are increased PM_{10} concentrations on the north side of SR 92 at both Trailers 1 and 2. With continuing variable winds after noon, there continue to be high PM_{10} concentrations at Trailers 1 and 2 until construction work stops at 7 p.m.


Trailer 1 - PM10 and PM2.5
Trailer 1 - PM10 (ug/m3) - 1 Hr
Trailer 1 - PM25 (ug/m3) - 1 Hr
50
30
10
-10
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
5/31/2009
6/1/2009
Time (MST)


Trailer 2 - PM10 and PM2.5
Trailer 2 - PM10 (ug/m3) - 1 Hr
Trailer 2 - PM25 (ug/m3) - 1 Hr
50
30
10
-10
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
5/31/2009
6/1/2009
Time (MST)


Direction
N
W
E
S
Trailer 3 - Wind
1-minute data plotted every 10 minutes. Bristles point in direction toward which wind is blowing.
Wind Speed V (m/s)
10
0
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
5/31/2009
6/1/2009



Note: PM concentrations are plotted on a scale with a maximum value (y-axis) of 50 µg/m^3 to facilitate visualization of trends. On some occasions, maximum PM concentrations were in excess of 50 µg/m^3. Maximum values not plotted here include: 53 µg/m^3 at 9:00 a.m., 81 µg/m^3 at noon, and 69 µg/m^3 at 6:00 p.m. from Trailer 1; 142 µg/m^3 at noon, 63 µg/m^3 at 1:00 p.m., and 66 µg/m^3 at 6:00 p.m. from Trailer 2.

Figure 8-20. PM concentrations from four trailers and wind on May 31, 2009.

Figure 8-21 shows the NO_2, NO_x, and NO concentrations at Trailers 2 and 3 on May 31, 2009. Note that there is a sharp NO_2, NO_x, and NO peak between 6 and 8 a.m. at Trailer 3, similar to the sharp PM_{10} peak (there is also a modest peak at Trailer 2 at the same time, just as there was a modest PM_{10} peak during this time). Then NO_2, NO_x, and NO peaks occurred during the rest of the construction day at Trailer 2, with much lower concentrations at Trailer 3. **Figure 8-22** shows the BC concentrations at the four trailers on May 31, 2009— there is a BC peak between 6 and 8 a.m. at Trailers 3 and 4, with low BC concentrations the rest of the working day at Trailers 3 and 4 but higher BC concentrations at Trailers 1 and 2.

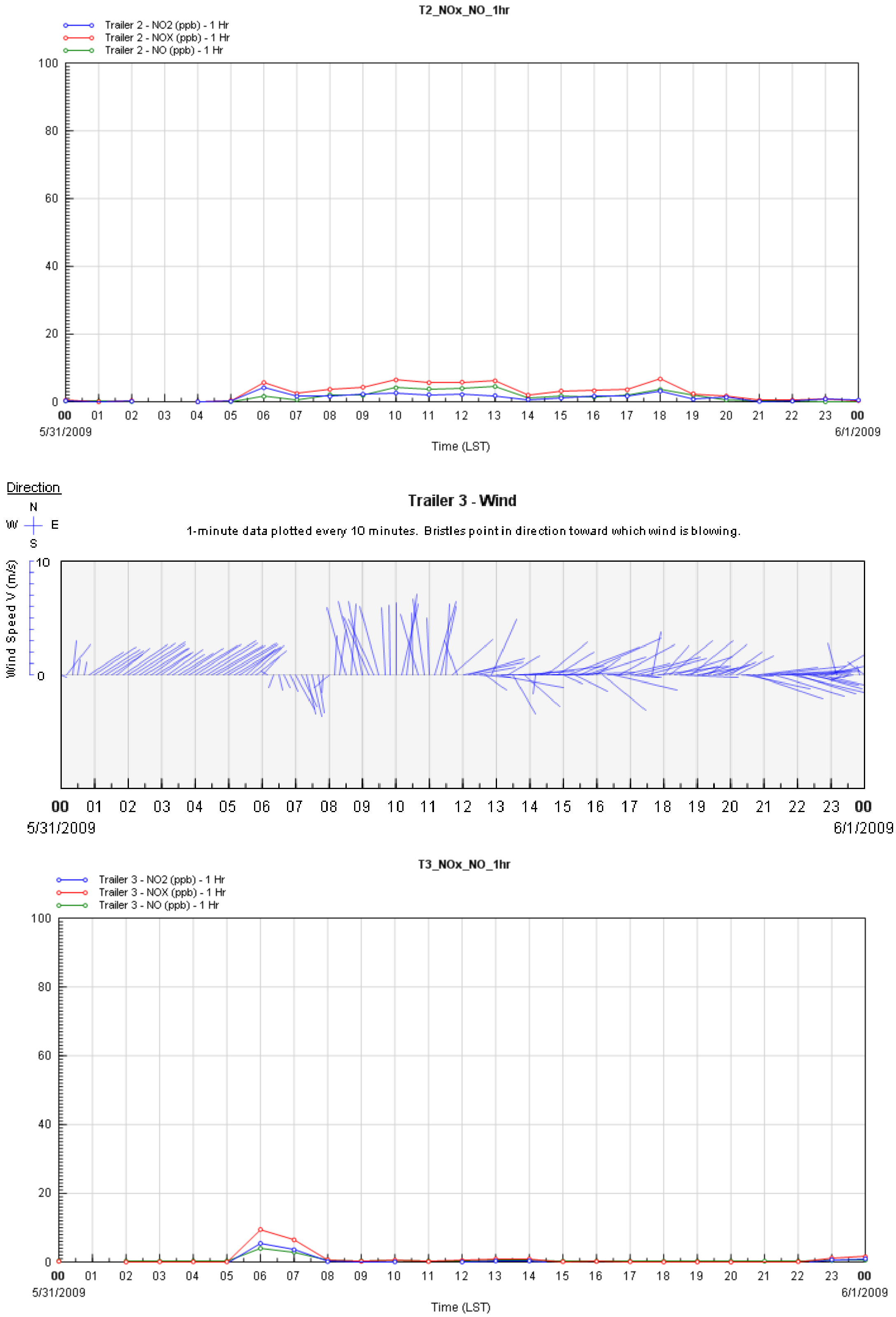
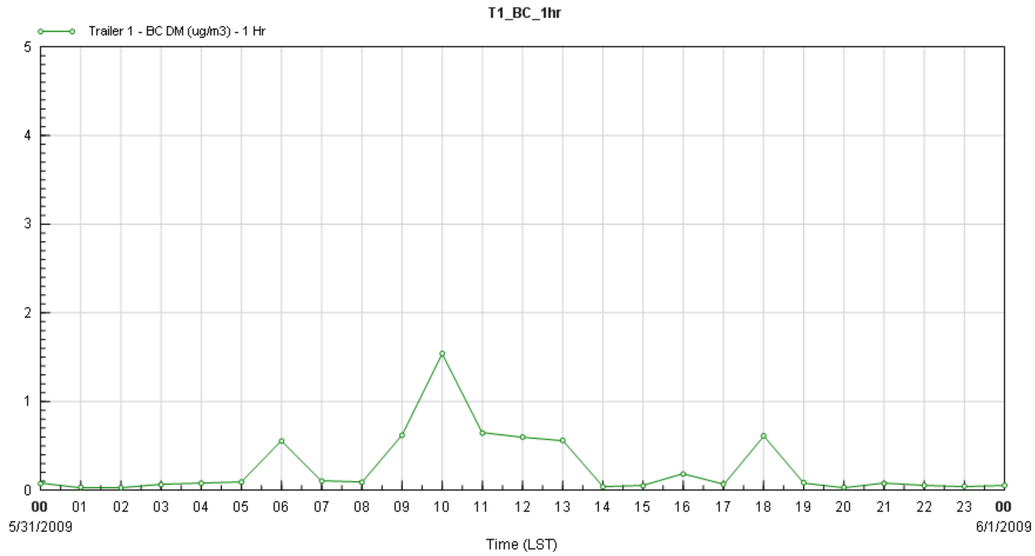
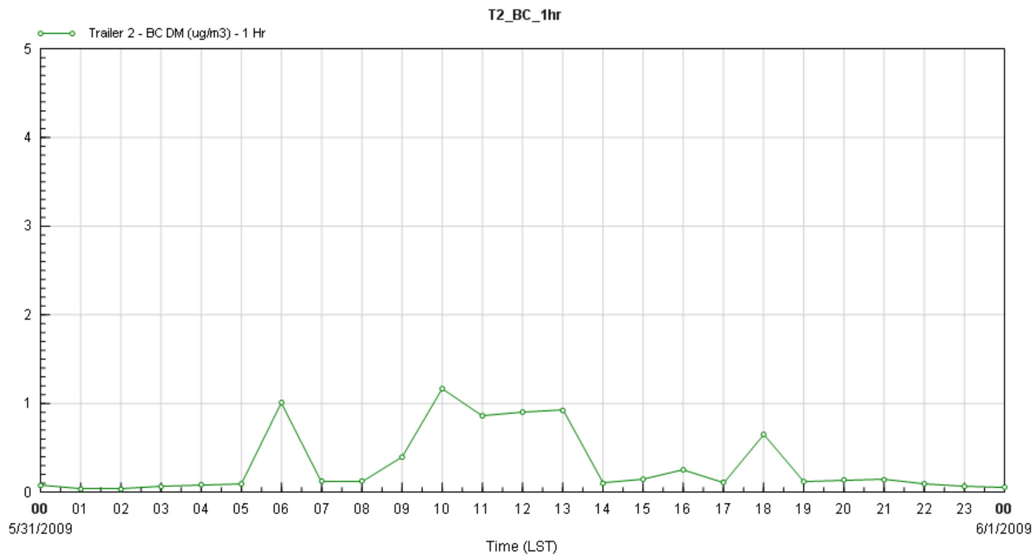
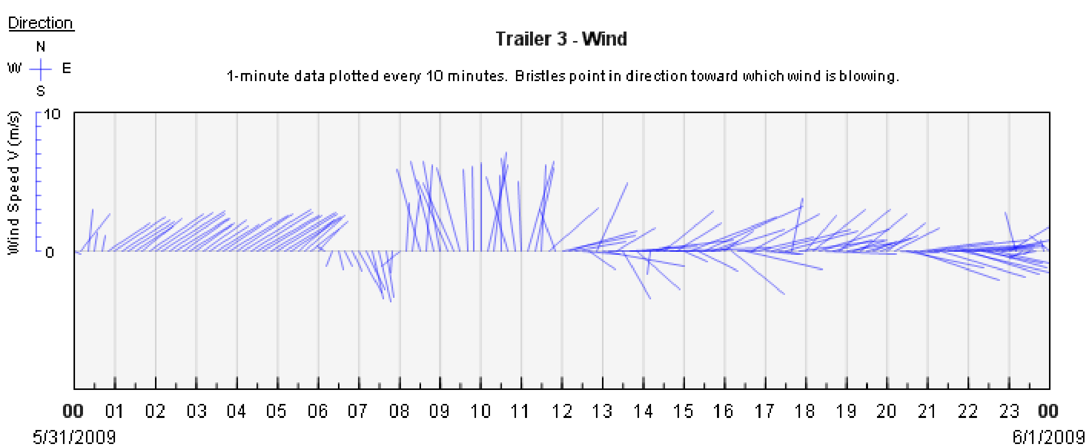
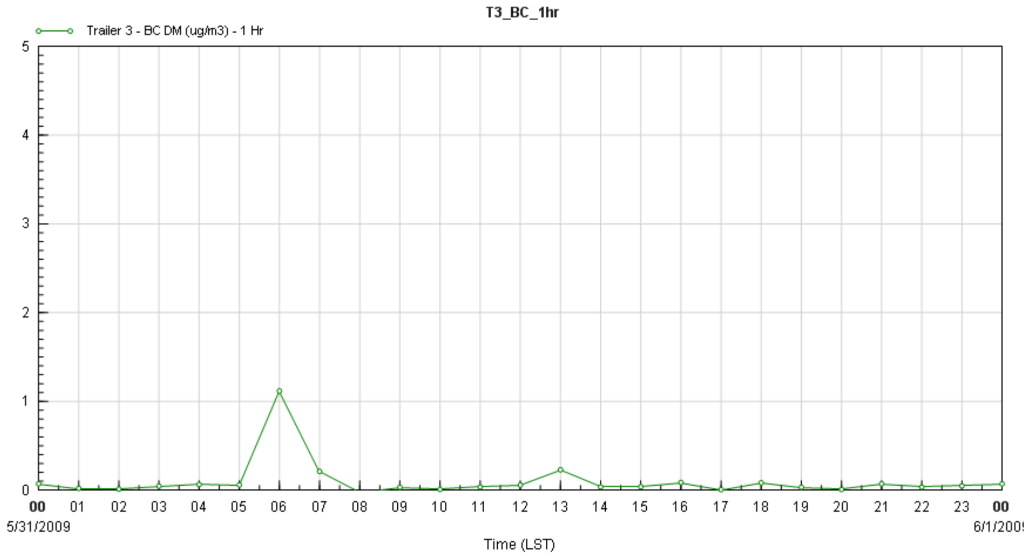


Figure 8-21. NO_2/NO_x/NO concentrations from Trailers 2 and 3 and wind on May 31, 2009.


T1_BC_1hr
Trailer 1 - BC DM (ug/m3) - 1 Hr
5
4
3
2
1
0
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
5/31/2009
6/1/2009
Time (LST)


T2_BC_1hr
Trailer 2 - BC DM (ug/m3) - 1 Hr
5
4
3
2
1
0
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
5/31/2009
6/1/2009
Time (LST)


Direction
N
W E
S
Trailer 3 - Wind
1-minute data plotted every 10 minutes. Bristles point in direction toward which wind is blowing.
Wind Speed V (m/s)
10
0
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
5/31/2009
6/1/2009



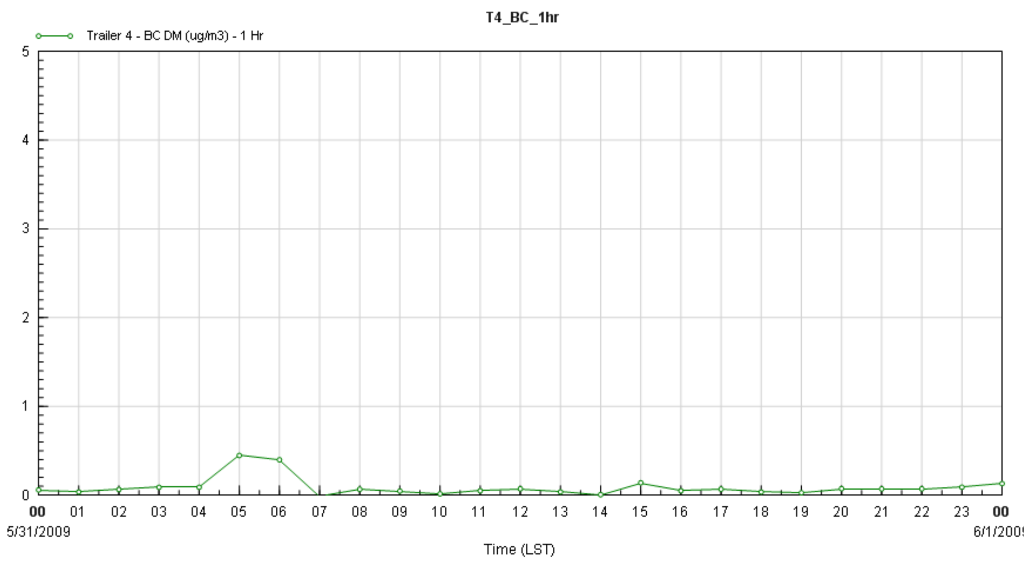
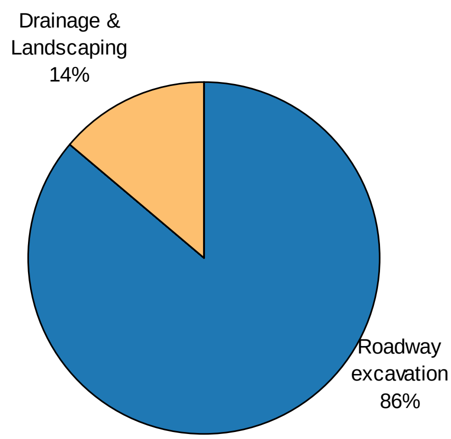


Figure 8-22. BC concentrations from four trailers and wind on May 31, 2009.

The data allow assessment of the contribution of construction exhaust emissions, and associated fugitive dust, to PM concentrations at nearby monitoring sites. Key considerations include comparing PM concentrations during hours when construction operations occurred with PM concentrations during other periods without construction operations (non-operating hours, weekend days, or holidays); and comparing PM concentrations during operating hours on the downwind side of the construction with PM concentrations on the upwind side on an hour-by-hour basis. We illustrate these methods in the next sub-section. These methods are reasonable assuming that there are no other major sources of PM influencing the sites (such as fires, regional haze, or on-road vehicle emissions). However, it was shown generally (in Sections 7.1 and 7.2) that daily on-road exhaust PM emissions were substantially lower than the sum of construction exhaust and fugitive dust emissions. For example, construction emissions for PM_{10} are about 15 times greater than on-road PM_{10} emissions, while construction emissions for $PM_{2.5}$ are about five times greater than on-road $PM_{2.5}$ emissions. However, for NO_x, we need to take into account on-road emissions, since construction NO_x emissions were less than on-road NO_x emissions.

8.3.2 Activity and Emissions for May 31, 2009

To support the illustration of air quality on May 31, 2009 (Section 8.1.2), this discussion provides additional detail concerning the activity and emissions that occurred on that date. As **Figure 8-23** shows, only road excavation and drainage/landscaping work was performed on May 31, 2009. **Figure 8-24** shows the key equipment that consumed the most fuel on May 31, 2009. Note that 87% of exhaust NO_x and 90% of exhaust PM_{10} emissions came from road excavation (such as grade material transportation and compaction). Note that these same activities are also an important source of fugitive dust emissions. The largest emitters of exhaust NO_x are the water trucks (26%) distributing water for dust control, while the largest emitters of exhaust PM_{10} are the tractors/loaders/backhoes (28%) transporting, grading, and placing materials onsite. The scrapers were the second largest emitters of both NO_x and PM_{10} (**Figures 8-25** and **8-26**).



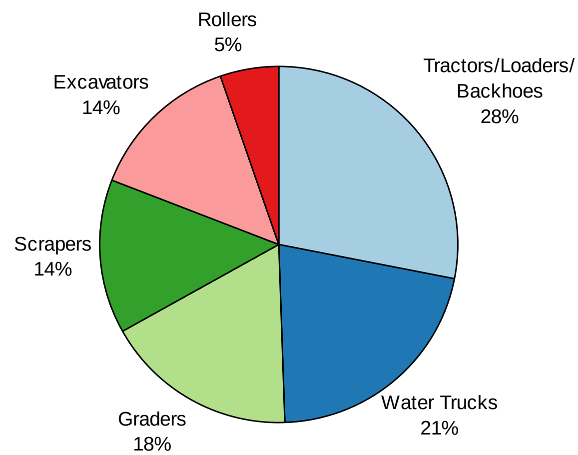


Figure 8-23. Construction equipment fuel consumption distribution by: construction phases (left); equipment types (right) for May 31, 2009. Note that most of the construction activities occurred within 1,000 m of trailers.

WT2 (Water Truck)

L1_950H (Loader)

MG1_140M (Grader)

SC2_615C (Scraper)

Figure 8-24. Key equipment consuming the most fuel on May 31, 2009

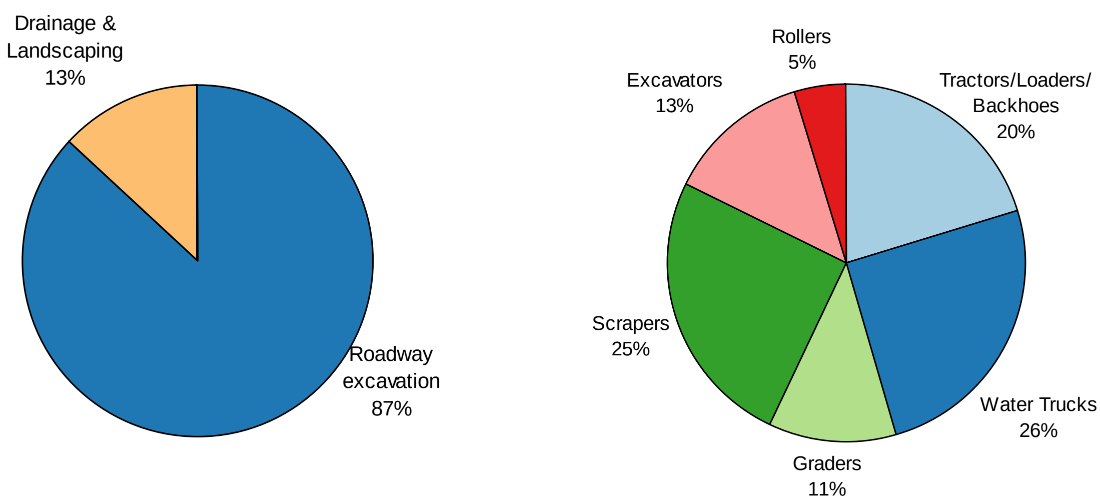


Figure 8-25. Construction equipment exhaust NO_x emissions distribution on May 31, 2009, by construction phase (left) and equipment type (right).

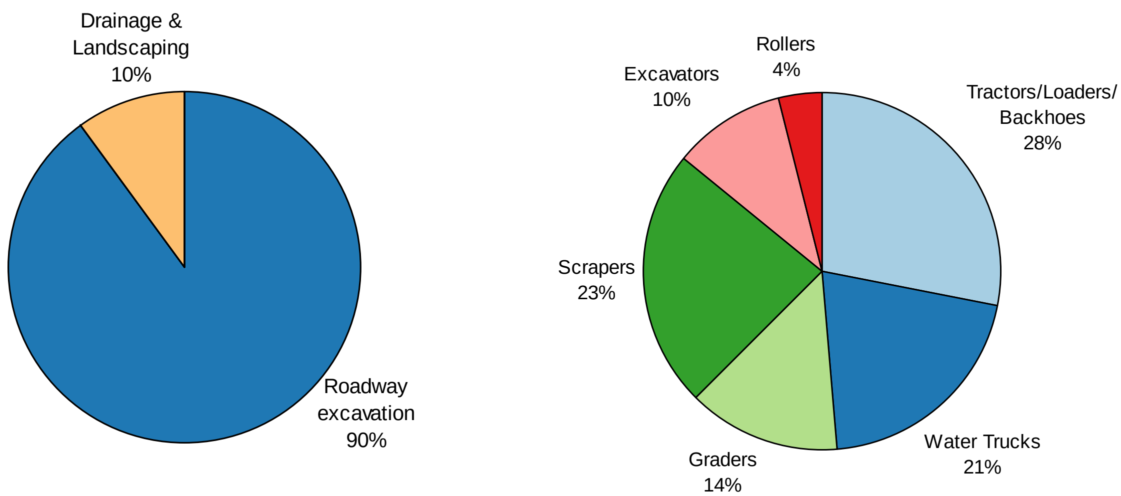
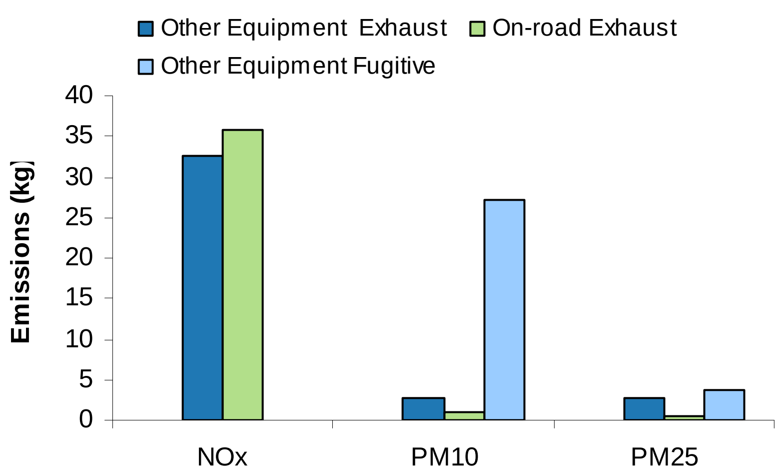


Figure 8-26. Construction equipment exhaust PM_{10} emissions distributions on May 31, 2009, by construction phase (left) and equipment type (right).

Figure 8-27 shows the relative emission comparison by source type for NO_x, PM_{10}, and $PM_{2.5}$ on Sunday, May 31, 2009. The NO_x emissions from construction equipment were slightly lower than emissions from on-road vehicles. Both PM_{10} and $PM_{2.5}$ emissions from construction equipment were higher than emissions from on-road vehicles. Fugitive dust was the dominant source of PM_{10} emissions, while fugitive $PM_{2.5}$ was comparable to construction exhaust $PM_{2.5}$ emissions.



Note: On May 31, 2009, "Other Equipment" includes all construction related on- and off-road equipment except for the rock crusher, which was non-operational on that date.

Figure 8-27. Emission comparisons by source categories (May 31, 2009).

8.3.3 Case Study Summary: May 31, 2009

In summary, the main observations from the May 31, 2009, case study are as follows:

- May 31 resembled the rest of the case study week in terms of the type of construction work performed and the relative importance of the equipment in use.
- Air quality impacts were similar in nature to those observed for the week as a whole:
  - Construction work resulted in increased PM_{10} concentrations but did not substantially affect $PM_{2.5}$ concentrations.
  - NO_x-related concentrations (NO_x, NO_2, NO) increased during the day, when construction and on-road vehicle activity increased. Note, however, that NO_2 concentrations peaked at less than 10 ppb and averaged less than 2 ppb across the entire day. These values are far below the EPA's NO_2 National Ambient Air Quality Standards (NAAQS), which is 100 ppb for 1-hr.
  - The May 31 case study day clearly illustrates how wind direction influenced monitored concentrations. Winds out of the south resulted in increased PM and NO_x-related concentrations at Trailers 1 and 2 (northeastern side of SR 92). Winds out of the north resulted in increased concentrations at Trailers 3 and 4 (southwestern side of SR 92).

8.4 OPERATION OF THE ROCK CRUSHER: SUPPLEMENTAL CASE STUDY I (FEBRUARY 2-8, 2009)

The May 2009 case studies did not include time periods when the Arizona Department of Transportation (ADOT) construction contractor (Bison Contracting) operated a rock crusher. The rock crusher was located approximately 450-650 m to the southeast of the monitoring trailers. The rock crusher was diesel-powered and therefore produced exhaust emissions and fugitive dust associated with the rock crushing itself. This discussion briefly highlights air quality impacts observed during one of the rock crushing periods. The time frame examined here is Monday, February 2, 2009, through Sunday, February 8, 2009. The rock crusher, which was used to produce aggregate base materials, operated Monday through Thursday (February 2-5, 2009), during the work hours when the rest of the construction work took place. Other construction equipment was also in operation Monday through Thursday. There was no construction work—or crusher operation—Friday, February 6 through Sunday, February 8, 2009.

Figure 8-28 illustrates the location of construction activities during the February 2009 case study week. Note that the rock crusher is located to the southeast of the air quality monitoring trailers. As with the May 2009 case study, the February case study involved use of construction equipment in the same area, southeast of the trailers, as the crusher location. During May 2009, construction activities to the southeast of the trailers involved use of graders and scrapers; during February 2009, coincident with rock crusher operations, equipment use in this area involved off-road truck activity (compare Figures 8-4 and 8-28).

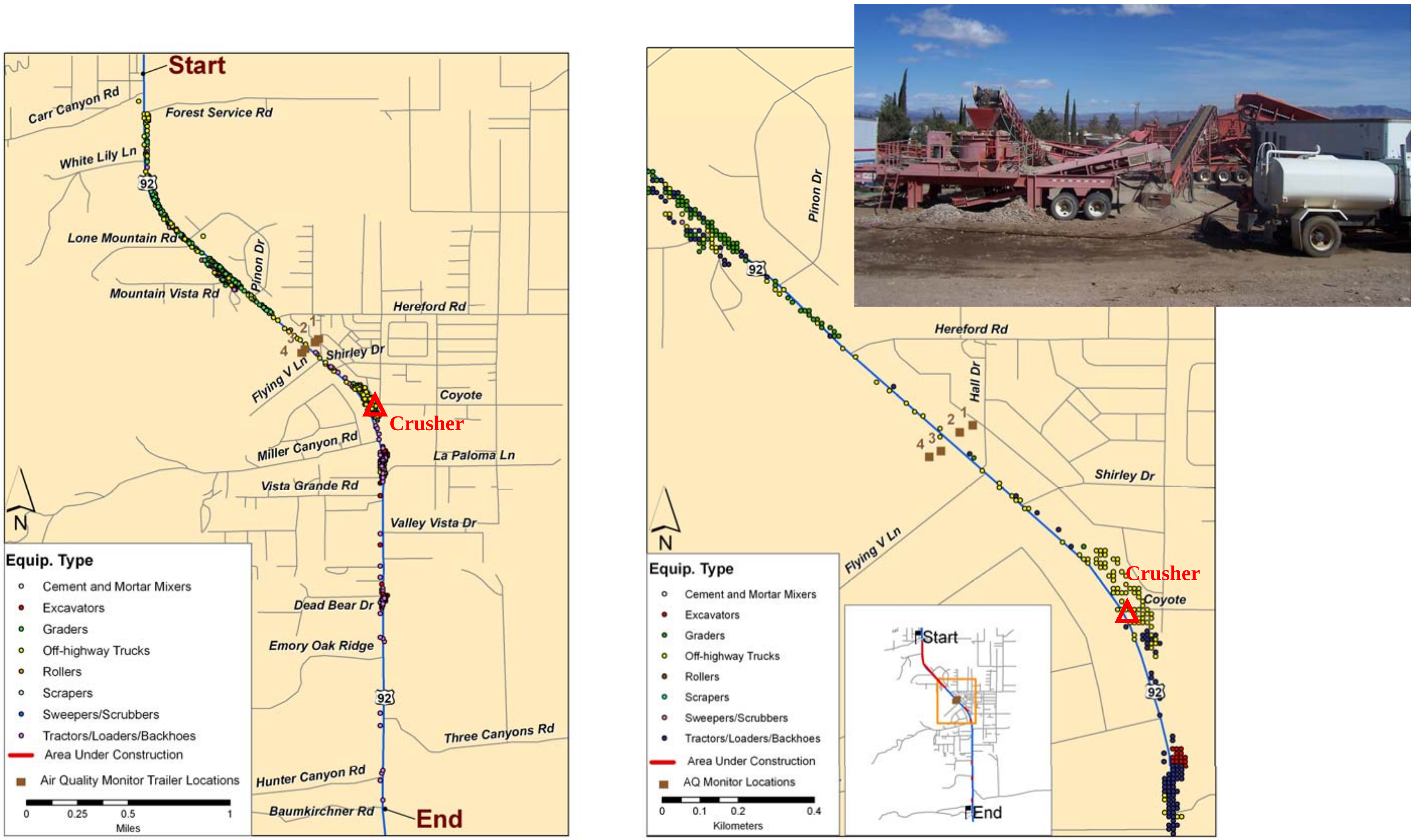
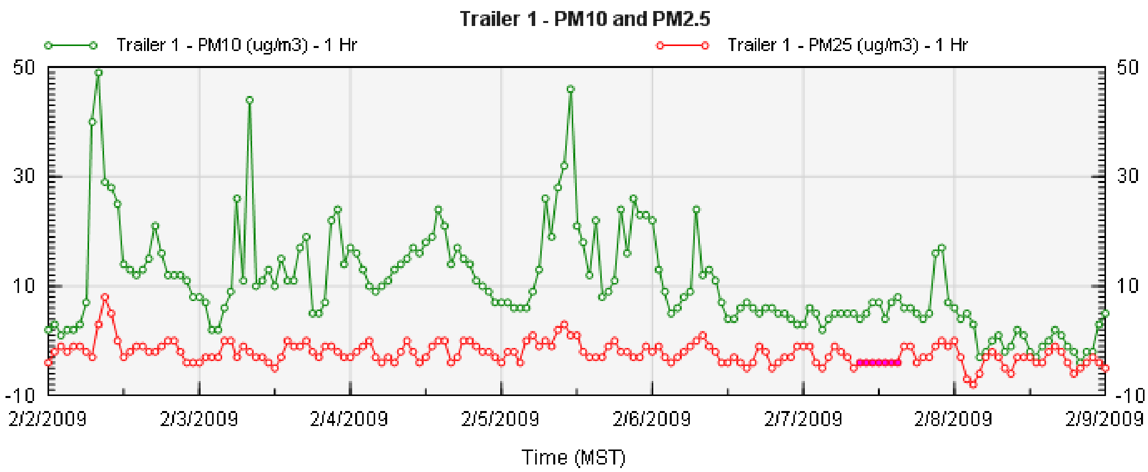


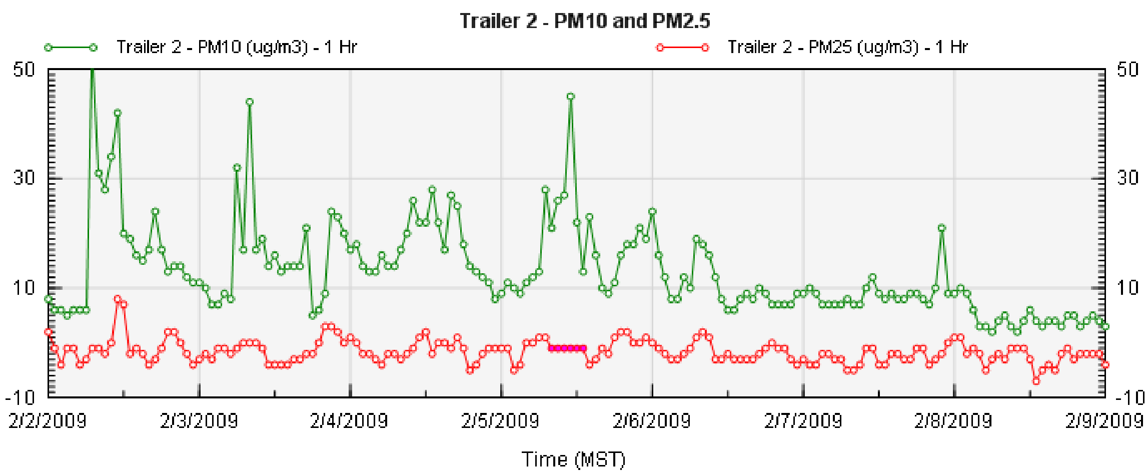
Figure 8-28. Construction activity locations during February 2-5, 2009, when construction work took place during the case study period (mobile equipment locations based on GPS tracking reported every five minutes; rock crusher location based on ADOT-supplied data). Inset photo shows the rock crushing equipment.

The focus for this case study is to assess whether the rock crusher appeared to influence observed concentrations. Our assessment involved qualitatively examining whether air quality concentrations during the February time period differed substantially from the concentrations observed during the May case study, and also involved quantifying the exhaust and fugitive dust emissions from the rock crusher and other sources.

8.4.1 Air Quality for February 2-8, 2009

As shown **Figure 8-29**, PM pollutant concentrations during the February case study were qualitatively similar to those during the May case study. In other words, $PM_{2.5}$ concentrations appear relatively unaffected by construction-related activity, while PM_{10} concentrations appear to show more pronounced upward spikes that correspond to construction work days (Monday, February 2 through Thursday, February 5) and time periods (morning through afternoon).





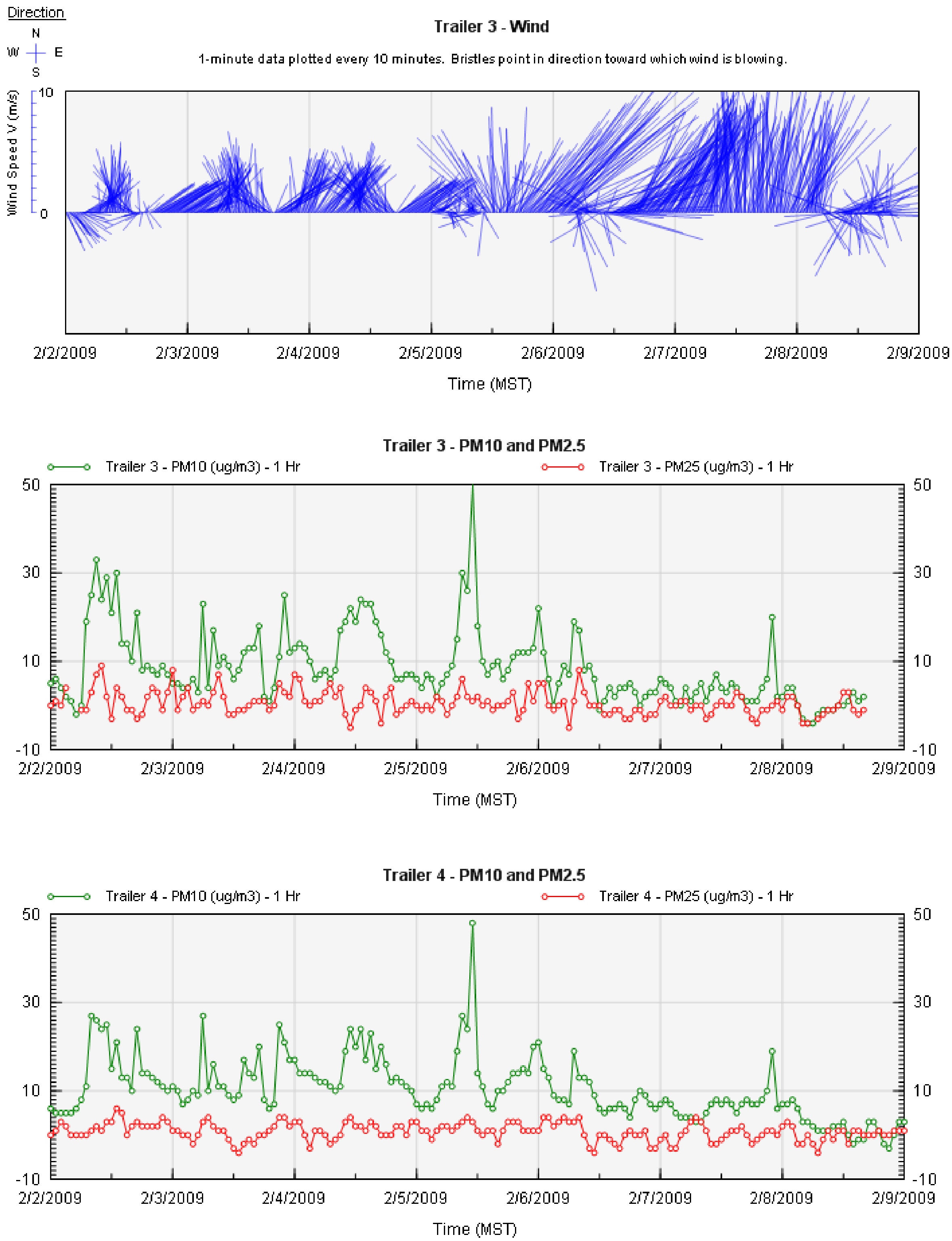


Figure 8-29. PM concentrations and winds during February 2-8, 2009.

Of particular interest for this case study are pollutant concentrations coinciding with periods when winds originated from the southeast, blowing from the crusher toward the monitoring trailers. Visual examination of Figure 8-29 shows that, for example, on February 3 and 4, midday, Trailers 1 and 2 measured higher PM_{10} at times when winds blew from the southeast, and that on February 5, all four trailers measured higher PM_{10} coinciding with southeast winds. The PM_{10} values increased to approximately 20-30 $\mu g/m^3$ on February 4, and to 40-50 $\mu g/m^3$ on February 3 and 5 during midday episodes of southeast winds. Note that these PM_{10} concentration values were approximately on the same scale (or perhaps a bit lower than) concentrations measured during the May 2009 case study period during comparable wind conditions (see Figure 8-4).

Also, it is interesting to note that during a period of strong southerly winds, on Saturday, February 7, 2009, PM concentrations briefly increased very late in the evening (at approximately 11:00 p.m.), at all four monitoring trailers. The February 7 episode demonstrated how windblown dust could affect localized PM_{10} concentrations, absent construction activity.

8.4.2 Activity and Emissions for February 2-8, 2009

Emissions from on- and off-road sources during the February case study week were roughly comparable to the emissions estimated for the May 2009 case study. Noteworthy points include: on-road NO_x emissions were approximately the same during both periods; however, non-crusher construction equipment NO_x emissions were substantially lower in February compared to May 2009. Non-crusher construction equipment fugitive dust PM_{10} emissions were much higher (roughly triple) in February compared to May 2009**. Figures 8-30** and **8-31** illustrate emissions for the February case study week.

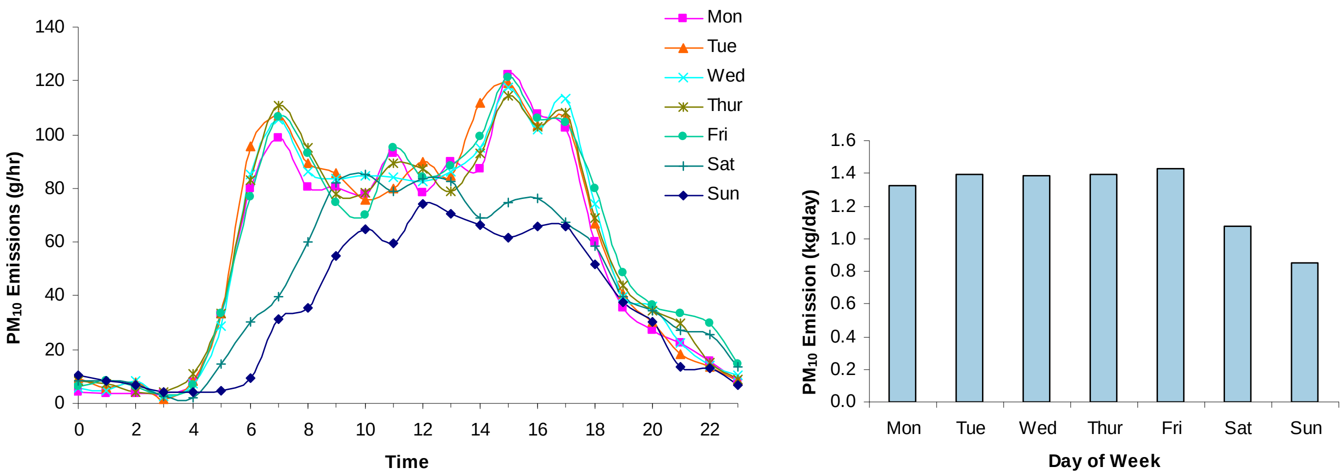
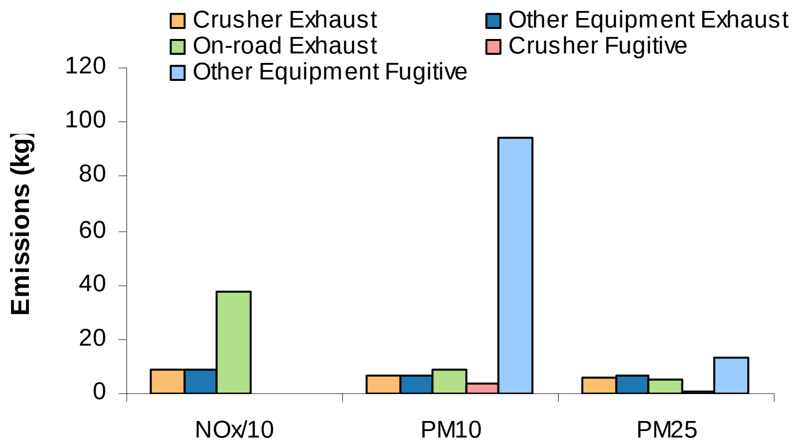


Figure 8-30. On-road emissions (left) and diurnal pattern (right) by day of week during February 2-8, 2009.



Note: "Other Equipment" includes construction-related equipment emissions, except for the rock crusher.

Figure 8-31. Emissions by source categories, February 2-8, 2009.

8.4.3 Case Study Summary: February 2 to 8, 2009

In summary, the main observations from the February 2009 case study when the rock crusher was operational are as follows:

Overall Emissions (including all construction equipment regardless of location)

- The rock crusher's exhaust emissions were comparable to other construction-related exhaust emissions for NO_x, PM_{10}, and $PM_{2.5}$.
- Fugitive dust emissions from the rock crusher were substantially less than fugitive dust emissions from other construction-related equipment.
- When summing across all PM_{10} emissions sources, crusher-related emissions, combined with other exhaust emissions of PM_{10}, were overwhelmed by the fugitive dust emissions from other construction equipment.

Emissions Occurring to the Southeast of the Monitoring Trailers

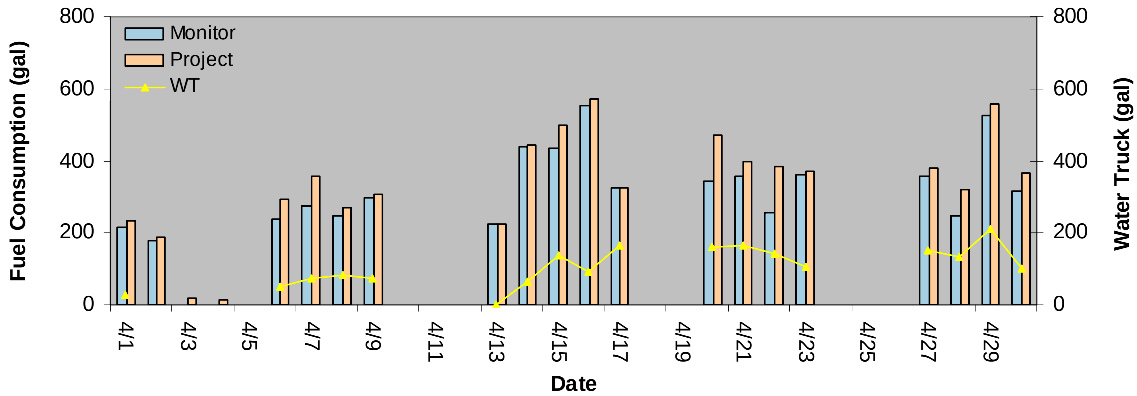
- When winds originated from the southeast, blowing from the rock crusher toward the monitoring trailers, PM_{10} concentrations increased at the trailers. A key question is whether the crusher's PM_{10} emissions made an important contribution to these measured concentration increases. Though PM_{10} emissions from the crusher were a small fraction of project-wide PM_{10} emissions during February 2-8, as shown in Figure 8-31, further data analysis is needed to assess whether, *just for the construction equipment operating due southeast of the monitoring trailers*, the crusher's PM_{10} emissions were an important fraction of total PM_{10} emissions along that vector.
- To address the issue discussed above, we qualitatively refined our understanding of the rock crusher's contribution to PM_{10} when the crusher was upwind of the trailers. To approximate the fractional contribution of the rock crusher's PM_{10} compared to other

equipment, we estimated the fraction of total, non-crusher, construction PM_{10} emissions that occurred to the southeast of the trailers. To complete this assessment, we counted the total number of pieces of construction equipment operating during February 2-5, 2009, and separately counted the equipment operating just on the stretch of SR 92, due southeast of the trailers during that same period (the equipment shown in Figure 8-28 as located on a straight line heading southeast of the trailers until, roughly, SR 92 bends to the south). The count indicated that nine percent of the total construction equipment (exclusive of the crusher) operated to the southeast of the trailers. If one visually applies the nine percent fraction to the "other equipment's" exhaust and fugitive PM_{10} emissions shown in Figure 8-31, it is apparent that the crusher's emissions are approximately on the same scale as (roughly equivalent to) the other construction-related PM_{10} emissions that occurred upwind of the trailers when winds blew from the southeast. (Note that this assessment is a rough guide to the fraction of equipment emissions originating upwind of the monitors, since it does not disaggregate equipment by type.)

- Given that the monitoring stations measured PM_{10} concentration spikes when winds blew from the southeast, and that the crusher accounted for (roughly) half of the PM_{10} emissions occurring upwind of the trailers, it is likely that crusher operations contributed to measured PM_{10} impacts.

8.5 HIGHEST MEASURED 24-HR PM_{10}: SUPPLEMENTAL CASE STUDY II (APRIL 13-19, 2009)

The highest 24-hr PM_{10} concentration across the one-year period assessed here (January 19, 2009 to January 19, 2010) was recorded by Trailer 1 on April 15, 2009: 72 μg/m^3. An obvious question is whether the SR 92 construction activity played a role in the concentration observed, and if so, what fraction of the measured concentration was attributable to the construction effort. We address those questions here by identifying, as with the previous case studies, the concentration and wind patterns for the days leading up to and extending beyond the episode event by identifying the spatial placement of the construction activity in relation to the monitor locations, and identifying the emissions associated with construction activity. **Figure 8-32** begins the case study by highlighting fuel consumption (and therefore equipment use) for the month of April 2009; the figure helps place overall equipment activity for April 15 in the context of other construction activity that took place during the month. Similar to the activity that occurred during May 2009, construction activity during April consumed several hundred gallons of diesel fuel each working day; fuel consumption on April 15, 2009, was not an outlier in comparison to other days in April or May (compare Figures 8-1 and 8-32). Similarly, as presented in **Figures 8-33** and **8-34**, exhaust and fugitive dust PM emissions on April 15 were relatively comparable to other case study periods. As shown in **Figure 8-35**, there was considerable construction activity surrounding and immediately adjacent to the air quality monitoring trailers during the week of Monday, April 13, 2009, through Sunday, April 19, 2009. Of particular note is the fact that, on April 15—the day when the highest PM_{10} concentrations were measured during the entire one-year period assessed here—roadway excavation work took place immediately adjacent to the monitoring trailers (see Section 3.1 for a discussion of when construction work took place adjacent to the monitoring trailers).



Note: Monitor-fuel consumed within 1000 m to monitors; project-fuel consumed for the whole project; WT-fuel consumed by water trucks.

Figure 8-32. Construction equipment fuel consumption during April 2009.

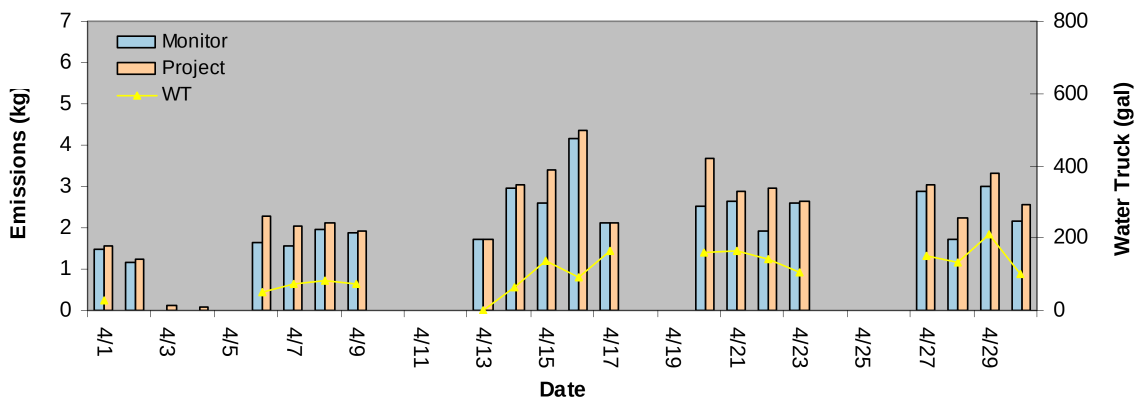


Figure 8-33. Exhaust PM_{10} emissions in April 2009.

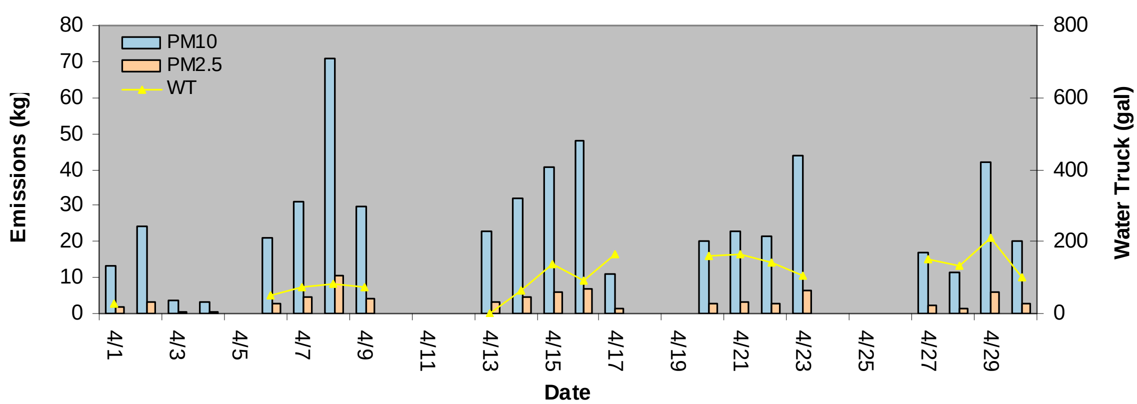


Figure 8-34. Fugitive PM_{10} and fugitive $PM_{2.5}$ emissions in April 2009.

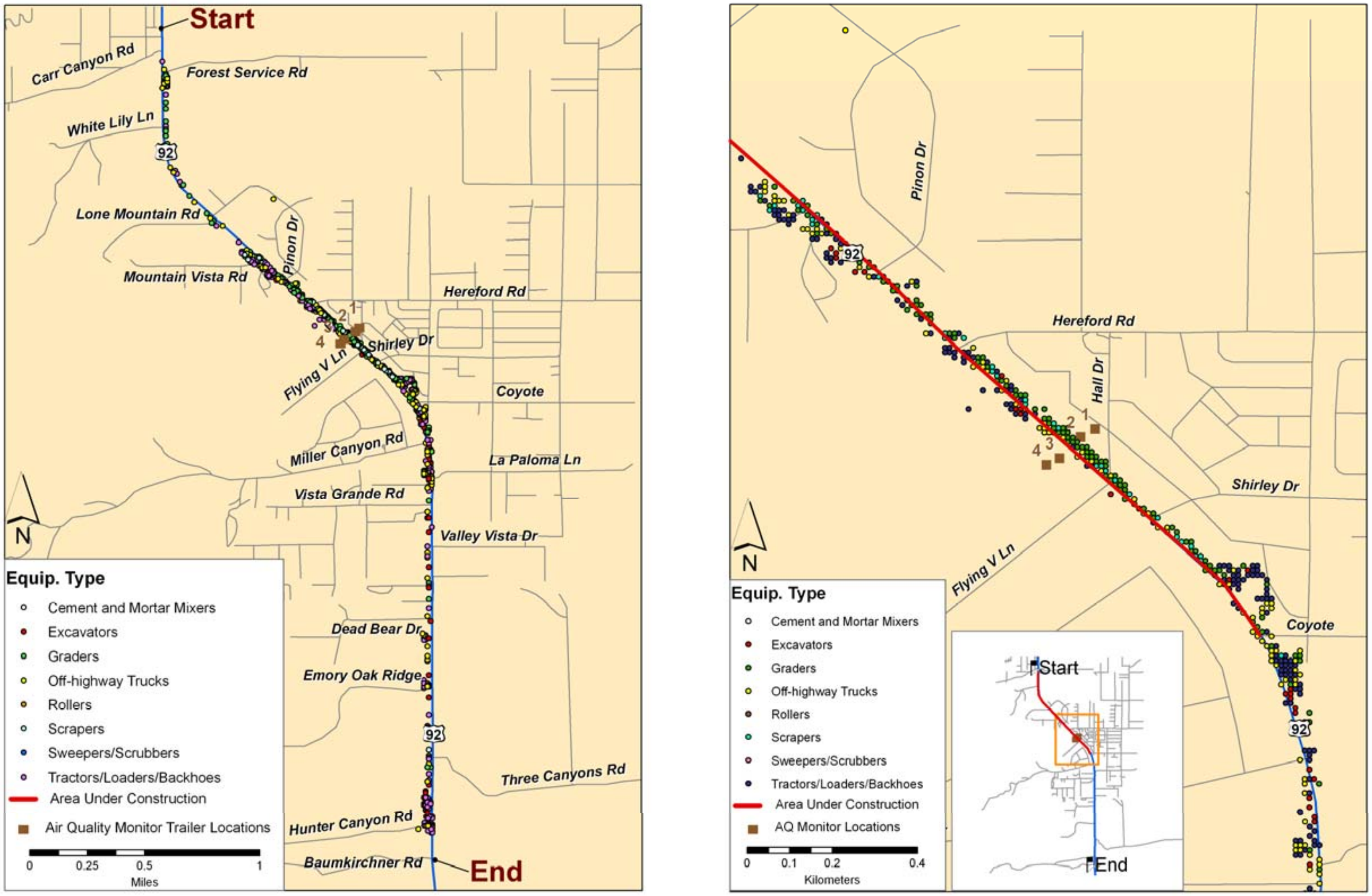
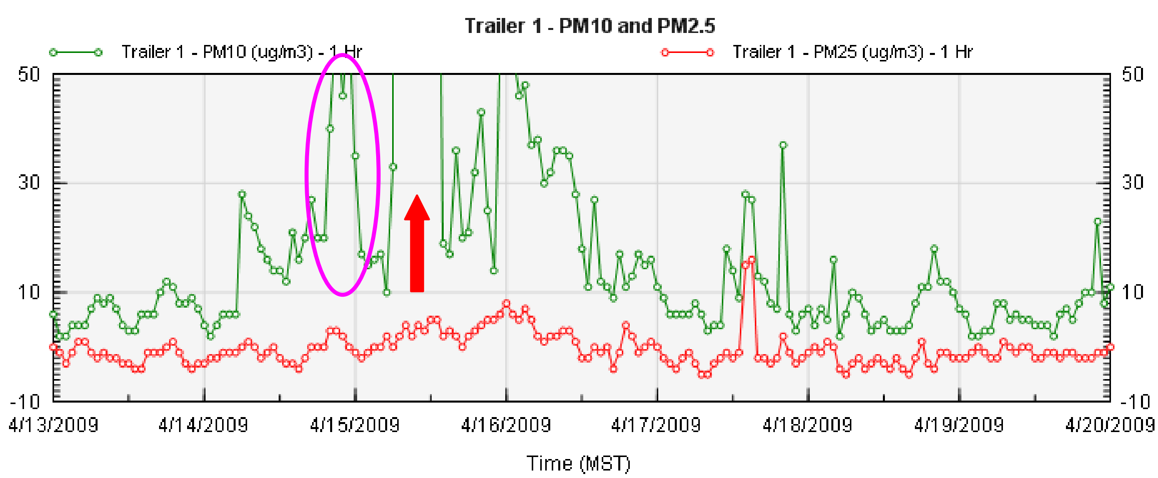


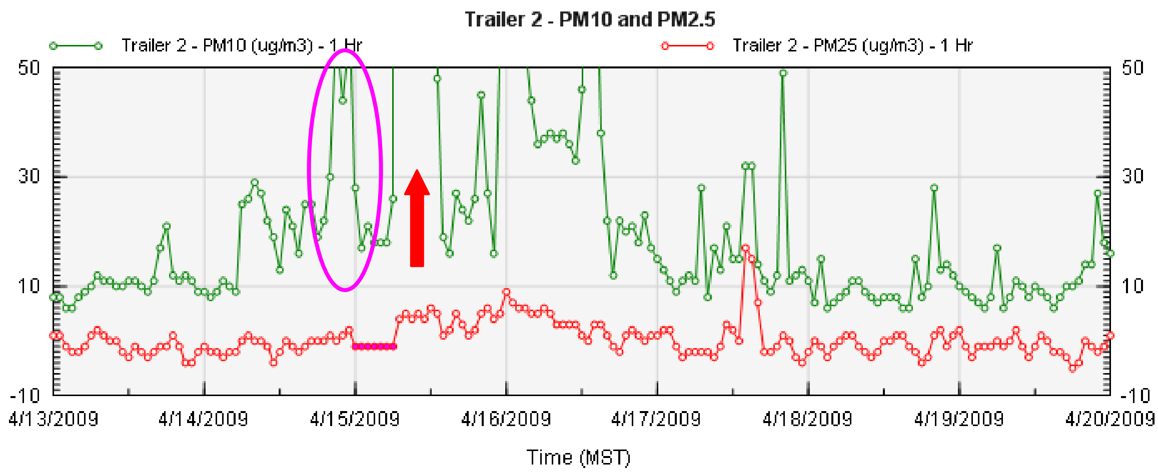
Figure 8-35. Construction activity locations, April 13-17, 2009 (workdays during the case study week of April 13-19; based on GPS tracking reported every five minutes).

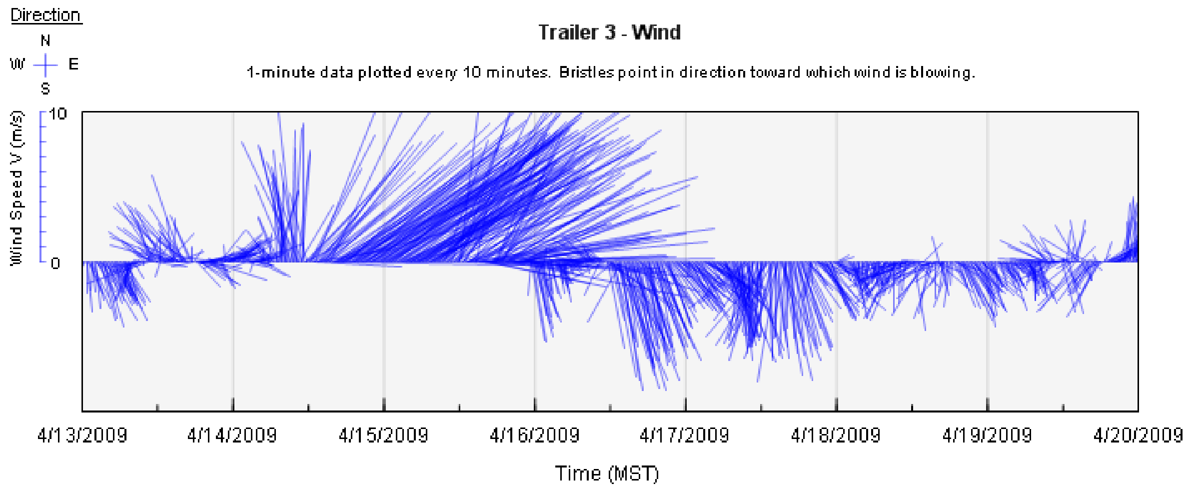
8.5.1 Air Quality for April 13-19, 2009

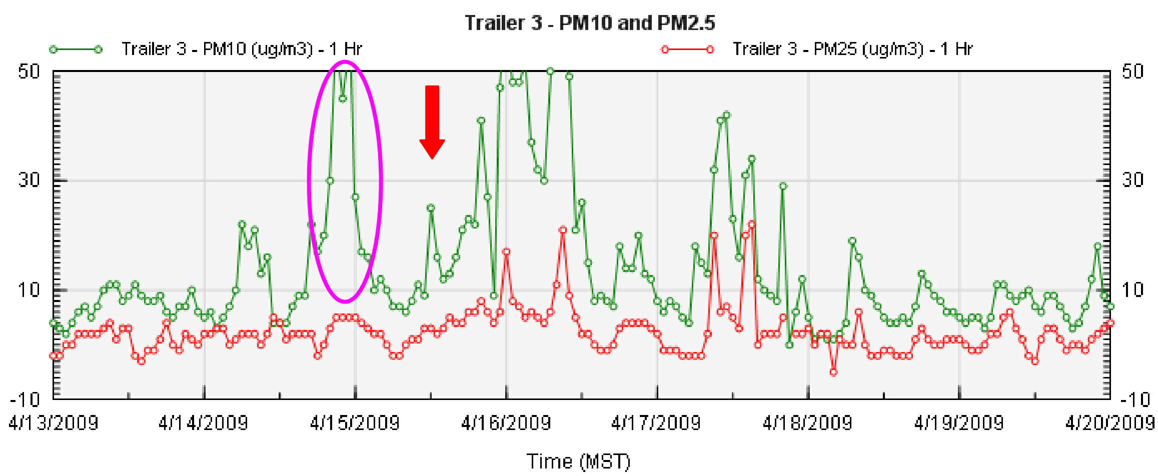
Figure 8-36 shows winds and PM_{10} and $PM_{2.5}$ concentrations during the case study period, including a focused examination of April 15, 2009. There were strong southwest winds starting approximately noon on April 14, 2009, which lasted until approximately the end of the day (near midnight) on April 15, 2009. At approximately 9:00 p.m. on Tuesday, April 14, 2009, all four trailers measured substantially elevated 1-hr PM_{10} concentrations, which ranged from 56 $\mu g/m^3$ to 62 $\mu g/m^3$. Averaging across all four trailers, the 1-hr PM_{10} value measured late that night was 58 $\mu g/m^3$ (see circles in the figure; values measured are off-scale).

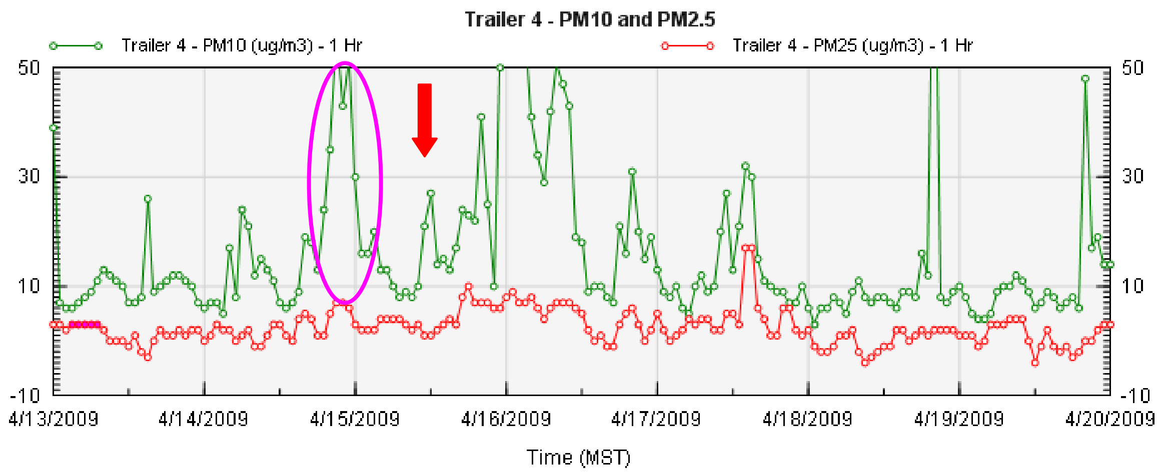
The next day, Wednesday, April 15, 2009, the highest 24-hr average PM_{10} concentration of the one-year period was recorded: 72 $\mu g/m^3$. Two elevated PM_{10} episodes occurred on that day (see last panel in Figure 8-36). From 7:00 to 8:00 a.m., Trailer 1 recorded a PM_{10} concentration exceeding 300 $\mu g/m^3$. From noon to 1:00 p.m. Trailer 1 recorded the highest PM_{10} value observed that day: 332 $\mu g/m^3$ (see red arrows in Figure 8-36 and last panel in that figure). During this 7:00 a.m. to 1:00 p.m. episode, Trailers 3 and 4 were upwind of SR 92, and Trailers 1 and 2 were downwind of SR 92. PM_{10} values measured at Trailers 3 and 4 were much lower than those observed at Trailers 1 and 2. During the entire episode, 1-hr PM_{10} concentrations measured downwind of the road (average of Trailers 1 and 2) ranged from 54 to 300.5 $\mu g/m^3$ higher than values measured upwind of the road (average of Trailers 3 and 4). On April 15, 2009, the incremental difference between the downwind and upwind trailers was 47 $\mu g/m^3$ of PM_{10}, averaged over a 24-hr period.




Trailer 2 - PM10 and PM2.5
Trailer 2 - PM10 (ug/m3) - 1 Hr
Trailer 2 - PM25 (ug/m3) - 1 Hr
50
30
10
-10
4/13/2009
4/14/2009
4/15/2009
4/16/2009
4/17/2009
4/18/2009
4/19/2009
4/20/2009
Time (MST)


Direction
N
W
E
S
Trailer 3 - Wind
1-minute data plotted every 10 minutes. Bristles point in direction toward which wind is blowing.
Wind Speed V (m/s)
10
0
4/13/2009
4/14/2009
4/15/2009
4/16/2009
4/17/2009
4/18/2009
4/19/2009
4/20/2009
Time (MST)


Trailer 3 - PM10 and PM2.5
Trailer 3 - PM10 (ug/m3) - 1 Hr
Trailer 3 - PM25 (ug/m3) - 1 Hr
50
30
10
-10
4/13/2009
4/14/2009
4/15/2009
4/16/2009
4/17/2009
4/18/2009
4/19/2009
4/20/2009
Time (MST)



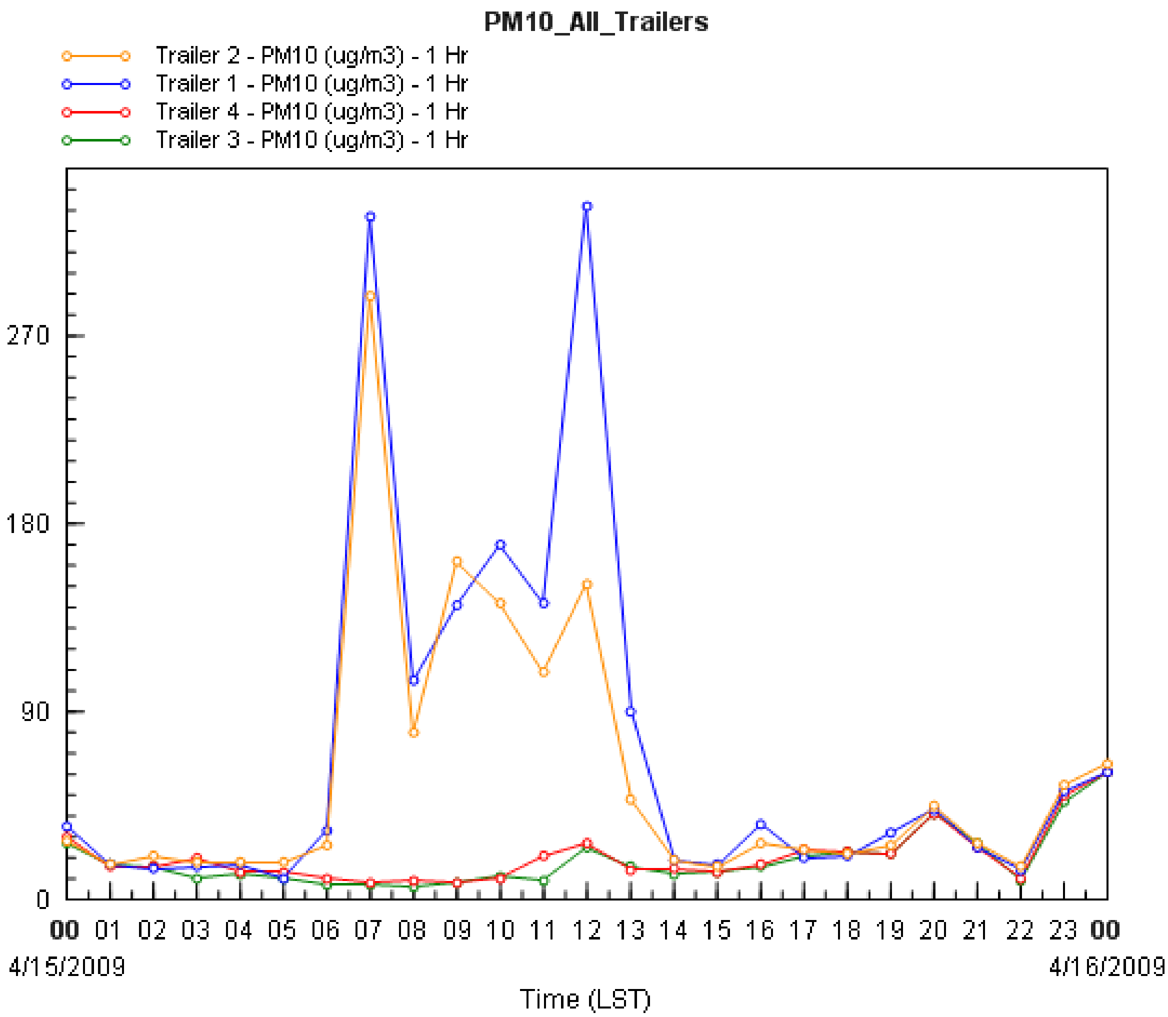


Figure 8-36. PM concentrations and winds measured April 13-19, 2009.

For this case study, it is particularly helpful to recall the general area surrounding the SR 92 construction zone. The construction zone was in a relatively remote area of southeastern Arizona, removed from other major sources of pollution. Winds during the high-PM_{10} episode originated from the southwest, a relatively undeveloped and uninhabited area, as illustrated by **Figure 8-37**.

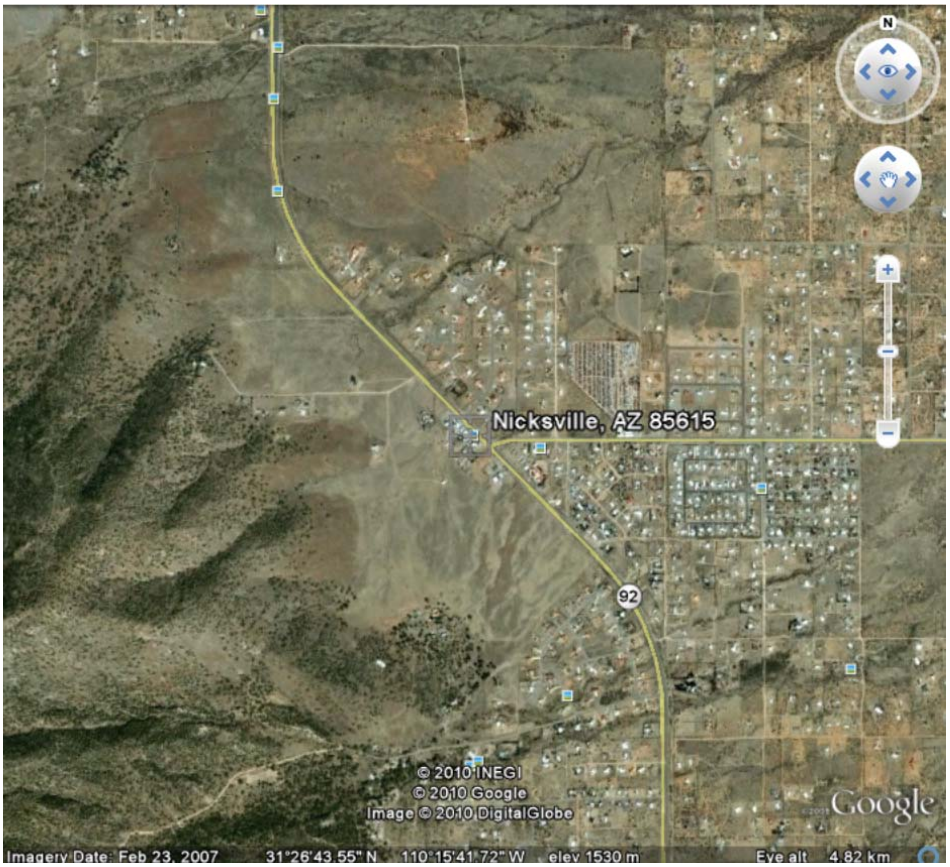


Figure 8-37. A broad representation of the land uses in the SR 92 construction zone area, as illustrated using Google Earth. Note the lack of development in the area southwest of Nicksville; this area approximates the region from which winds were blowing during the high-PM_{10} episodes of April 15, 2009.

We also assessed BC concentrations as a further indicator of whether the high PM_{10} events during this case study week were related to equipment use. **Figures 8-38** and **8-39** illustrate pollutant concentrations compared to background conditions. Note that BC concentrations were also noticeably higher than background concentrations on days when PM_{10} concentrations were substantially elevated above background.

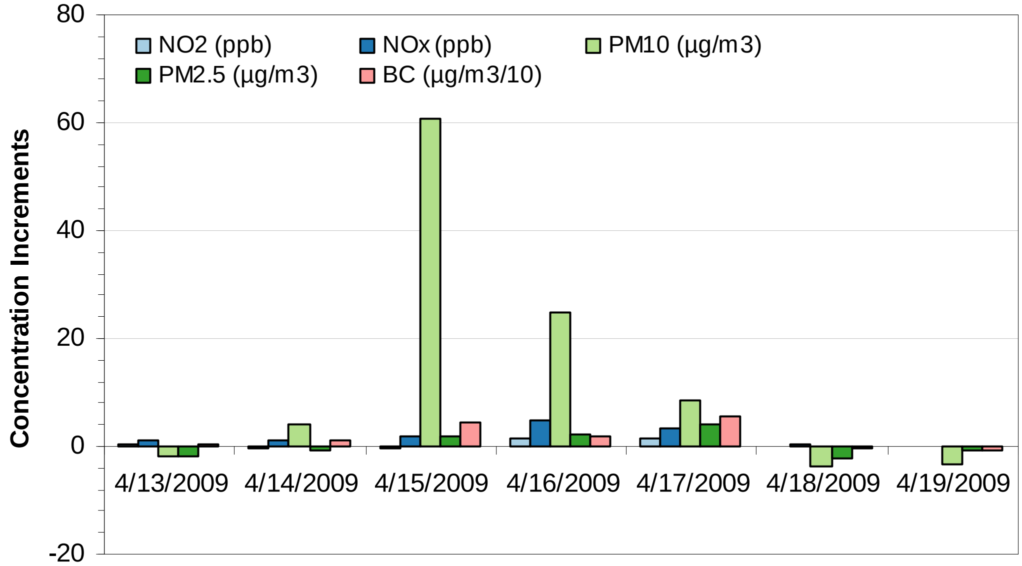


Figure 8-38. Increments of daily concentrations during April 13-19, 2009, compared to background daily concentrations from November 22, 2009 (all trailers averaged).

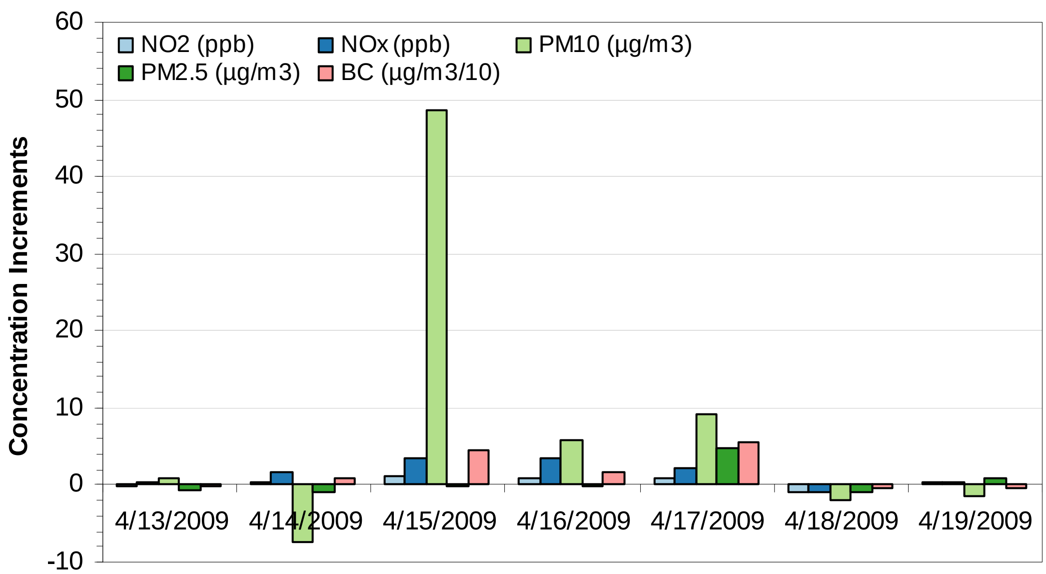
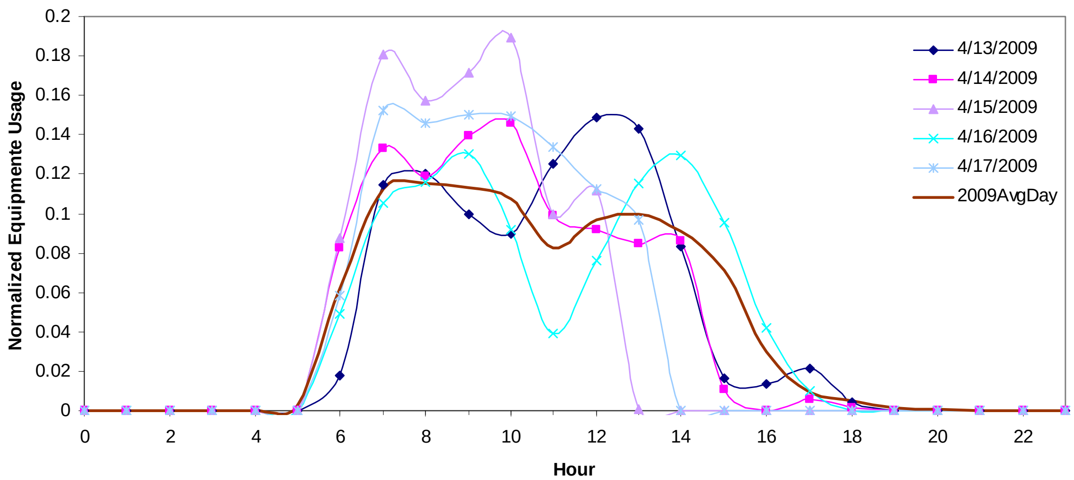


Figure 8-39. Increments of hourly-average concentrations during operation hours to that during non-operation hours during April 13-19, 2009 (all trailers averaged).

8.5.2 Activity and Emissions for April 13-19, 2009

Figures 8-40 through **8-48** illustrate activity and emissions associated with the April 13-19, 2009, week involving the highest PM_{10} concentrations. Figure 8-40 shows that equipment activity was highest on April 15, the date when PM_{10} concentrations reached their peak value, although instrumented equipment use peaked by 10 a.m., in advance of the measured peak PM_{10} values.[14] Figure 8-41 shows that, in contrast to the prior case studies, much of the construction work involved "miscellaneous" activities, although roadway excavation was still a large fraction of the activity. As with the previous case studies, water trucks, tractors/loaders/backhoes, and off-highway truck use continued to dominate fuel consumption (approximately 65-70%) among equipment types employed (Figure 8-42). Figure 8-47 shows that on-road traffic activity followed typical diurnal use patterns during the April case study period.



Note: **66%** of operating equipment during the case study period was instrumented with a GPS unit.

Figure 8-40. Normalized usage of GPS-instrumented equipment for the case study period.

[14] One caveat is that only two-thirds of the equipment present during this construction period were instrumented with GPS units, so it is possible that the remaining equipment was active at periods that do not mimic the diurnal profile shown in Figure 8-40.

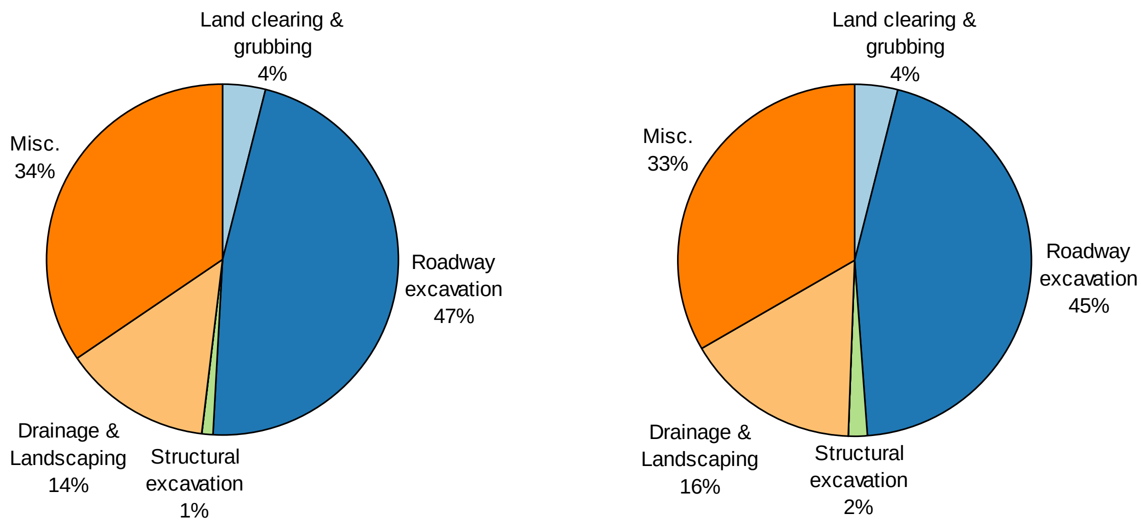


Figure 8-41. Construction equipment fuel consumption distribution by construction phase for case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

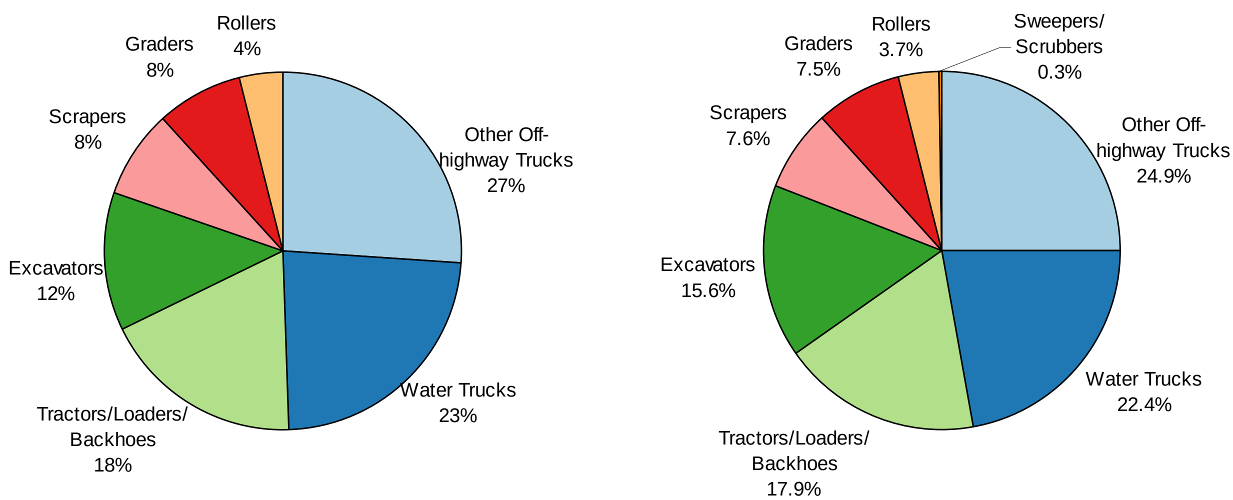


Figure 8-42. Construction equipment fuel consumption distribution by equipment type for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

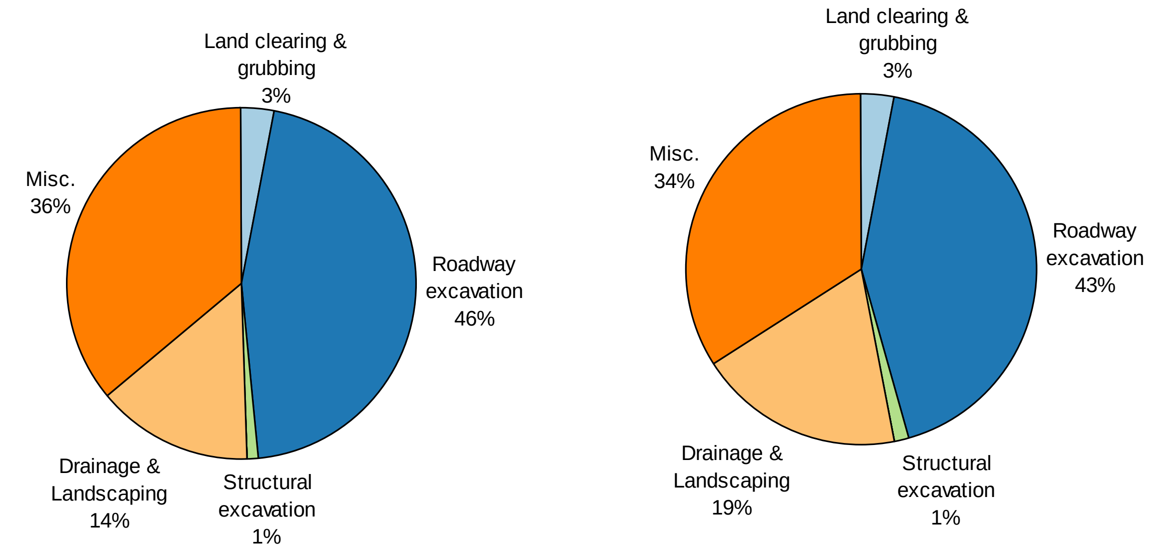


Figure 8-43. Construction equipment exhaust NO_x emissions distribution by construction phase for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

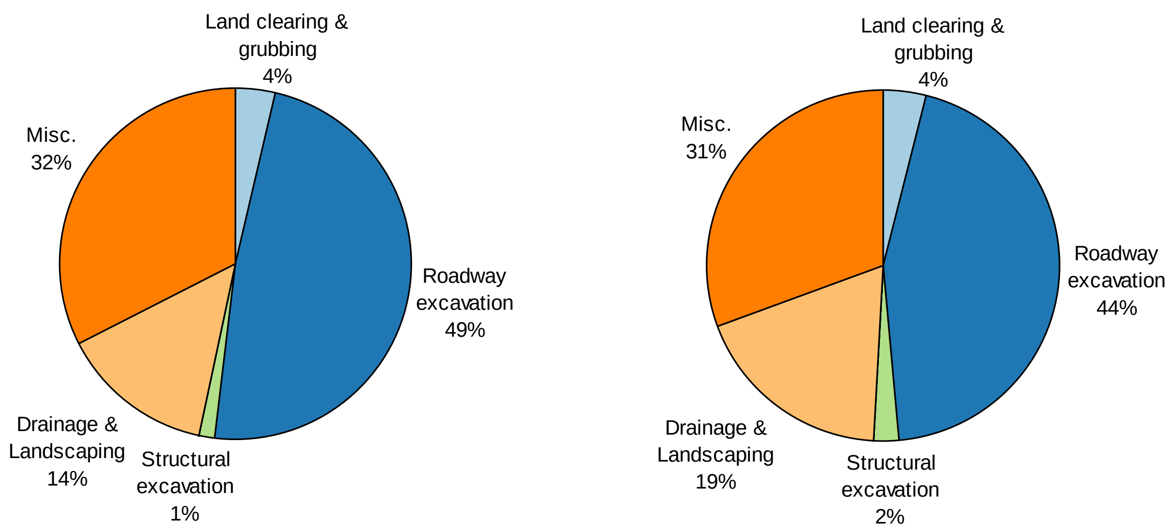


Figure 8-44. Construction equipment exhaust PM_{10} emissions distribution by construction phase for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

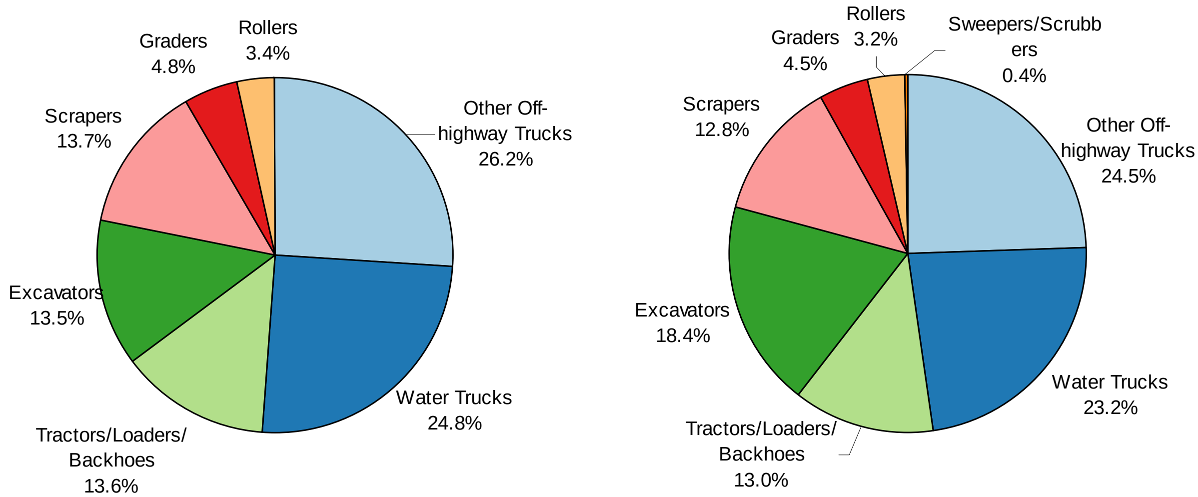


Figure 8-45. Construction equipment exhaust NO_x emissions distribution by equipment type for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

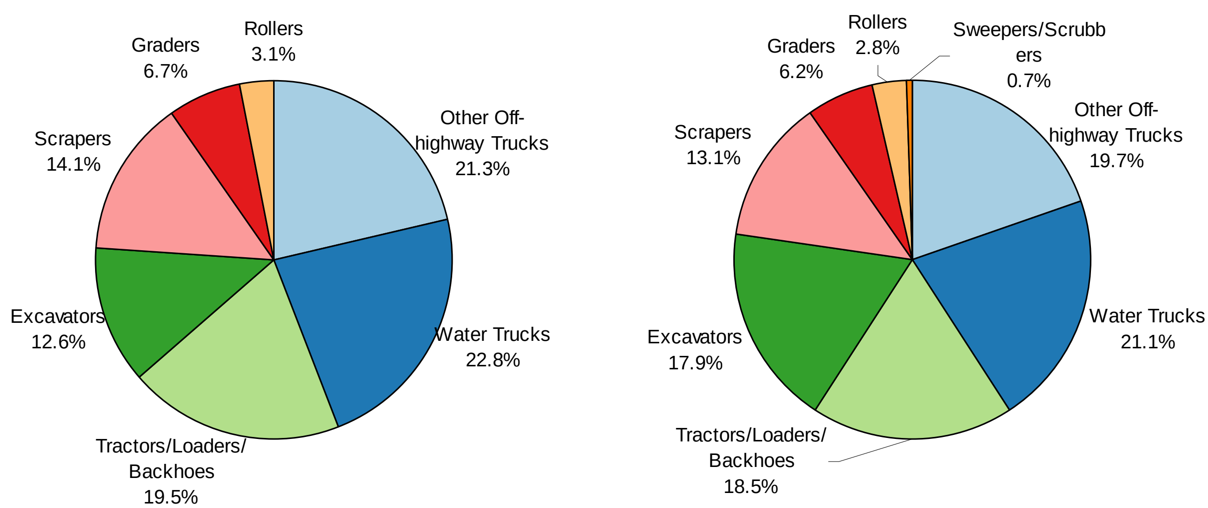


Figure 8-46. Construction equipment exhaust PM_{10} emissions distribution by equipment type for the case study period: left—fuel consumed within 1,000 m of trailers; right—fuel consumed within entire construction area.

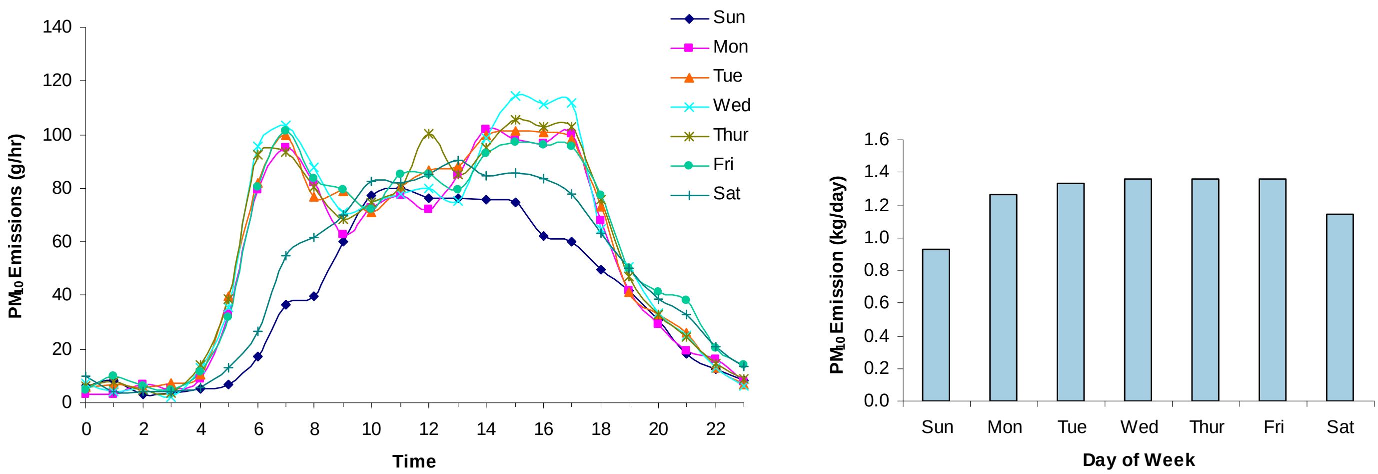
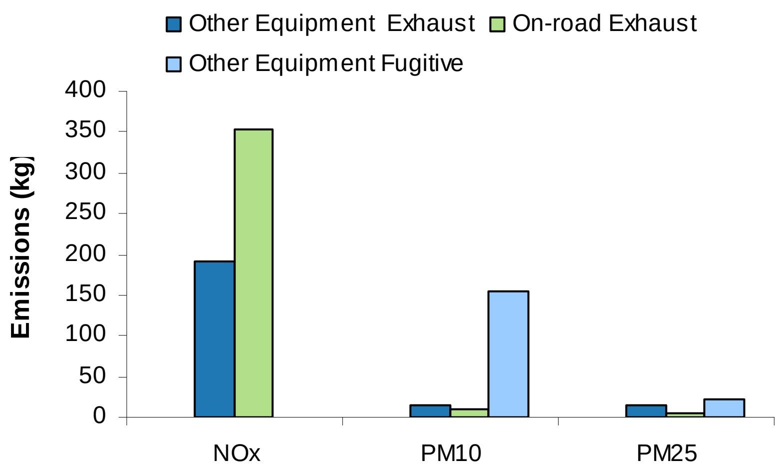


Figure 8-47. On-road emissions (left) and diurnal pattern (right) by day of week during April 13-19, 2009.

Figure 8-48 illustrates emissions by source category during the April case study week. Fugitive dust emissions during April were on the same scale of those that occurred in the February and May case study weeks. Recall that during the February 2-8 case study period, construction-related fugitive dust PM_{10} was approximately 100 kg and included emissions from the rock crusher (see Figure 8-31). During the May 25-31 period, fugitive dust PM_{10} was approximately 200 kg, excluding the rock crusher, which was not operating during that period (see Figure 8-19). As shown in Figure 8-48, during the April case study, total fugitive dust PM_{10} emissions were between 150 and 200 kg, excluding the rock crusher, which was not operating during that period. On April 15, 2009, the day with the highest observed 24-hr PM_{10} concentrations, construction-related PM_{10} emissions totaled 44.1 kg (40.7 kg of fugitive dust PM_{10} and 3.4 kg of exhaust PM_{10}), substantially more than the average of approximately 29 kg per day.



Note: "Other Equipment" includes all construction related on- and off-road equipment except for the rock crusher, which was non-operational on that date.

Figure 8-48. Emission comparisons by source categories (April 13-19, 2009).

8.5.3 Case Study Summary: April 13 to 19, 2009

In summary, the main observations from the April 2009 case study when the highest PM_{10} values were observed are as follows:

- Unusually high PM_{10} was associated with strong winds out of the southwest.
- One high PM_{10} episode occurred at approximately midnight, at the start of Wednesday, April 15, 2009. No construction activity was taking place at that time, and on-road traffic was extremely light. In addition, PM_{10} concentrations were uniformly elevated at all four trailers, indicating that the emissions source was unrelated to the road. As shown in Figure 8-37 (see also Figure 1-4), the area to the southwest of SR 92, upwind during this event, is relatively uninhabited land with minimal vegetative ground cover such as trees or bushes. It is likely, therefore, that the elevated PM_{10} originated from windblown dust in the surrounding countryside.
- In contrast to the midnight episode, the midday episode on April 15, 2009, resulted in elevated PM_{10} concentrations at Trailers 1 and 2 downwind of SR 92, during a period when substantial construction activity occurred near the trailers.
- The 7:00 a.m. to 1:00 p.m. April 15 event resulted in an incremental difference between the upwind trailers (3 and 4) and the downwind trailers (1 and 2) that ranged from 54 to 300.5 $\mu g/m^3$ of PM_{10} (1-hr averages); the downwind vs. upwind increment, averaged over a 24-hr period, was approximately 47 $\mu g/m^3$. In addition, the event was qualitatively consistent with the prior case studies (February and May 2009) which showed that peak PM_{10} concentrations occurred in the middle of the day and were a function of the construction work. Therefore, it can be concluded that the construction activity in close proximity to the trailers on this day resulted in the incrementally high PM_{10} values measured at Trailers 1 and 2.

- Note that, even during the somewhat extreme PM_{10} events of April 15, 2009, $PM_{2.5}$ concentrations remained relatively consistent with the values observed at other times that week and in prior case studies, further confirming that $PM_{2.5}$ concentrations were relatively unaffected by the construction work.

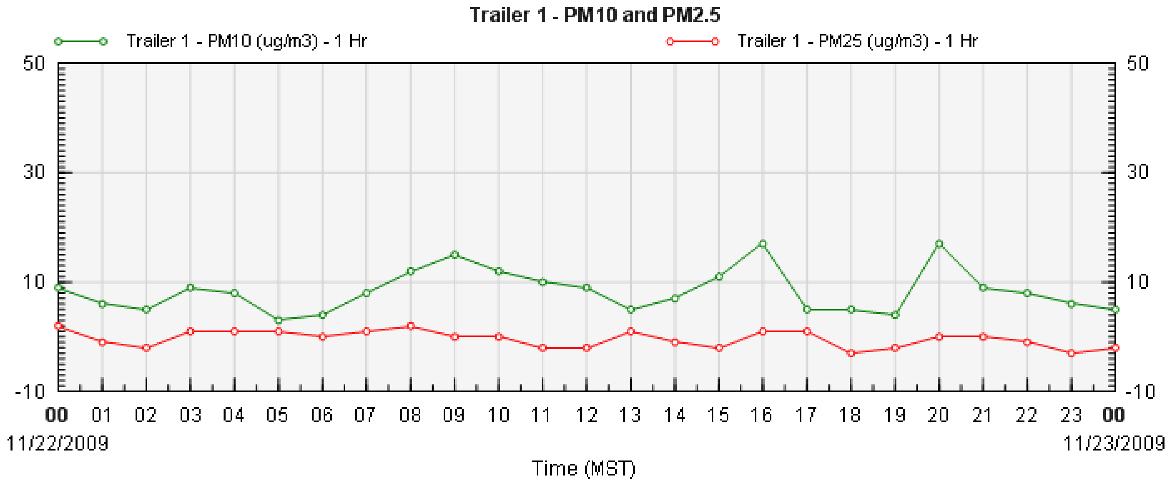
8.6 BACKGROUND CONDITIONS: SUPPLEMENTAL CASE STUDY III (SUNDAY, NOVEMBER 22, 2009)

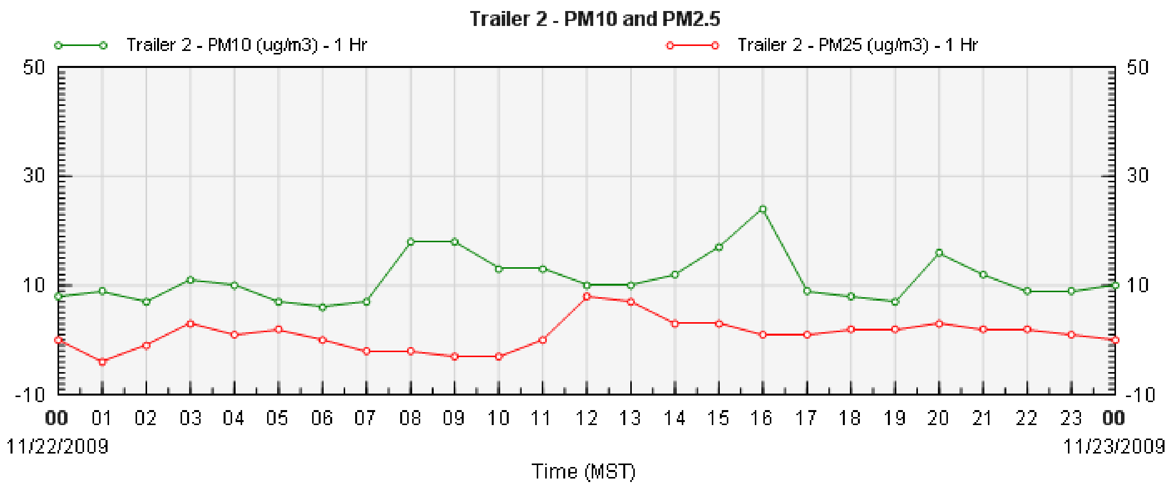
In order to understand the incremental impact of the construction activity on nearby pollutant concentrations, concentrations measured during construction needed to be compared to control scenarios without construction. The controls serve to define "background" conditions—meaning the range of pollutant concentrations that occurred at the site, absent any influence from construction. Several opportunities existed to define background conditions at the construction zone, including measurements made at night, on the weekend, and during holidays. Earlier in this chapter, for example, measurements made on Monday, May 25, 2009 (the Memorial Day holiday) were used to define background conditions for comparison to other measurements made in May. In addition, as described earlier, we also compared pollutant concentrations measured during the time when construction activities occurred (early morning to late afternoon) to measurements made at other times of the same day (evening hours).

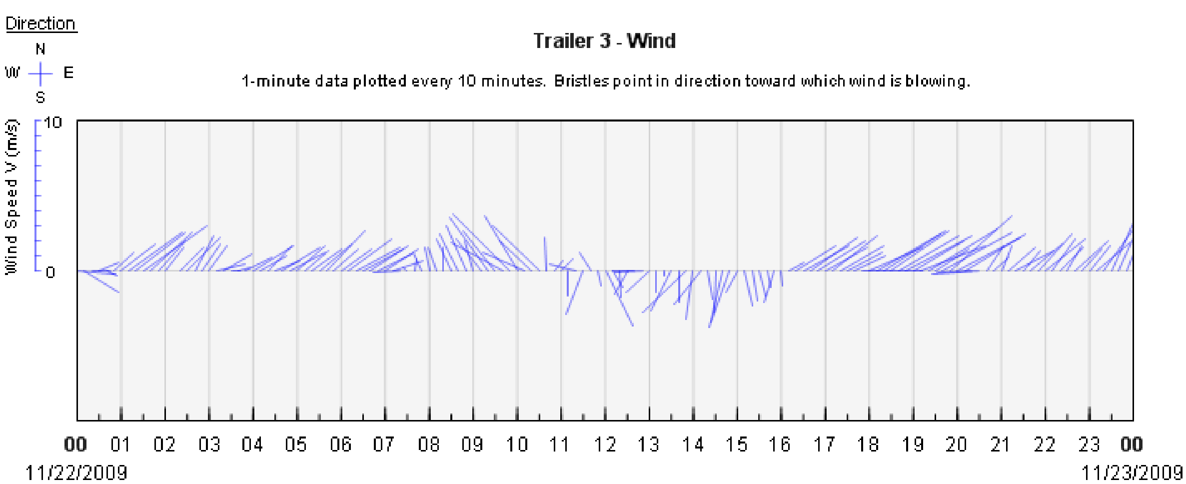
One of the methods we employed to characterize background conditions was to select a weekend day when construction work was halted, when on-road traffic did not include work-week activity, and when winds were not unusually strong (as was the case during the April high PM_{10} episode). Sunday, November 22, 2009, was chosen to represent such a case, although it is possible that a variety of weekend days could have served in a similar capacity.

This discussion briefly profiles the concentration and wind data for November 22, 2009. Some of the earlier discussion sections (e.g., comparisons between Figures 8-8 and 8-9) utilize the November 22, 2009, data to differentiate construction-related pollutant impacts from background conditions.

Figure 8-49 illustrates data for November 22, 2009, that represent background concentrations of PM_{10} and $PM_{2.5}$. Maximum PM_{10} concentrations ranged from 15 to 25 $\mu g/m^3$, while minimum PM_{10} was as low as 1 $\mu g/m^3$, depending on wind speed and direction. The $PM_{2.5}$ concentrations varied between less than 0 to 8 $\mu g/m^3$.


Trailer 1 - PM10 and PM2.5
Trailer 1 - PM10 (ug/m3) - 1 Hr
Trailer 1 - PM25 (ug/m3) - 1 Hr
50
30
10
-10
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
11/22/2009
11/23/2009
Time (MST)


Trailer 2 - PM10 and PM2.5
Trailer 2 - PM10 (ug/m3) - 1 Hr
Trailer 2 - PM25 (ug/m3) - 1 Hr
50
30
10
-10
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
11/22/2009
11/23/2009
Time (MST)


Direction
N
W E
S
Trailer 3 - Wind
1-minute data plotted every 10 minutes. Bristles point in direction toward which wind is blowing.
Wind Speed V (m/s)
10
0
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
11/22/2009
11/23/2009

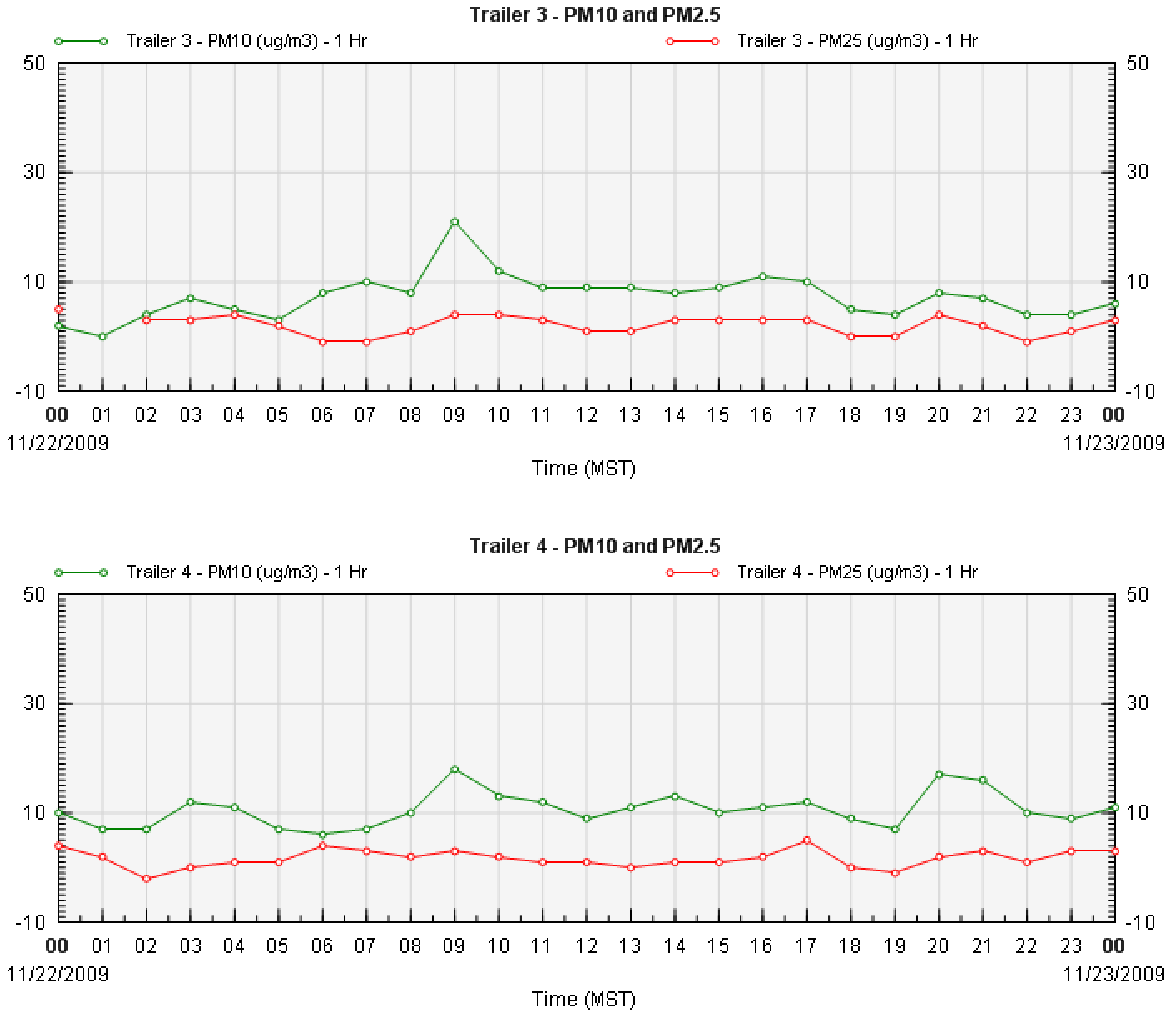


Figure 8-49. PM concentrations and wind on November 22, 2009.

8.7 SUMMARY STATISTICS CHARACTERIZING AIR QUALITY MEASUREMENTS ACROSS AN ENTIRE YEAR

This discussion presents summary data for January 19, 2009, to January 19, 2010 (**Figure 8-50** and **Table 8-3**). The data facilitate placing the previous case studies in the context of measurements made throughout an entire year. In addition, the data identify how air quality at the study site compared to allowable concentrations, as defined by the NAAQS.

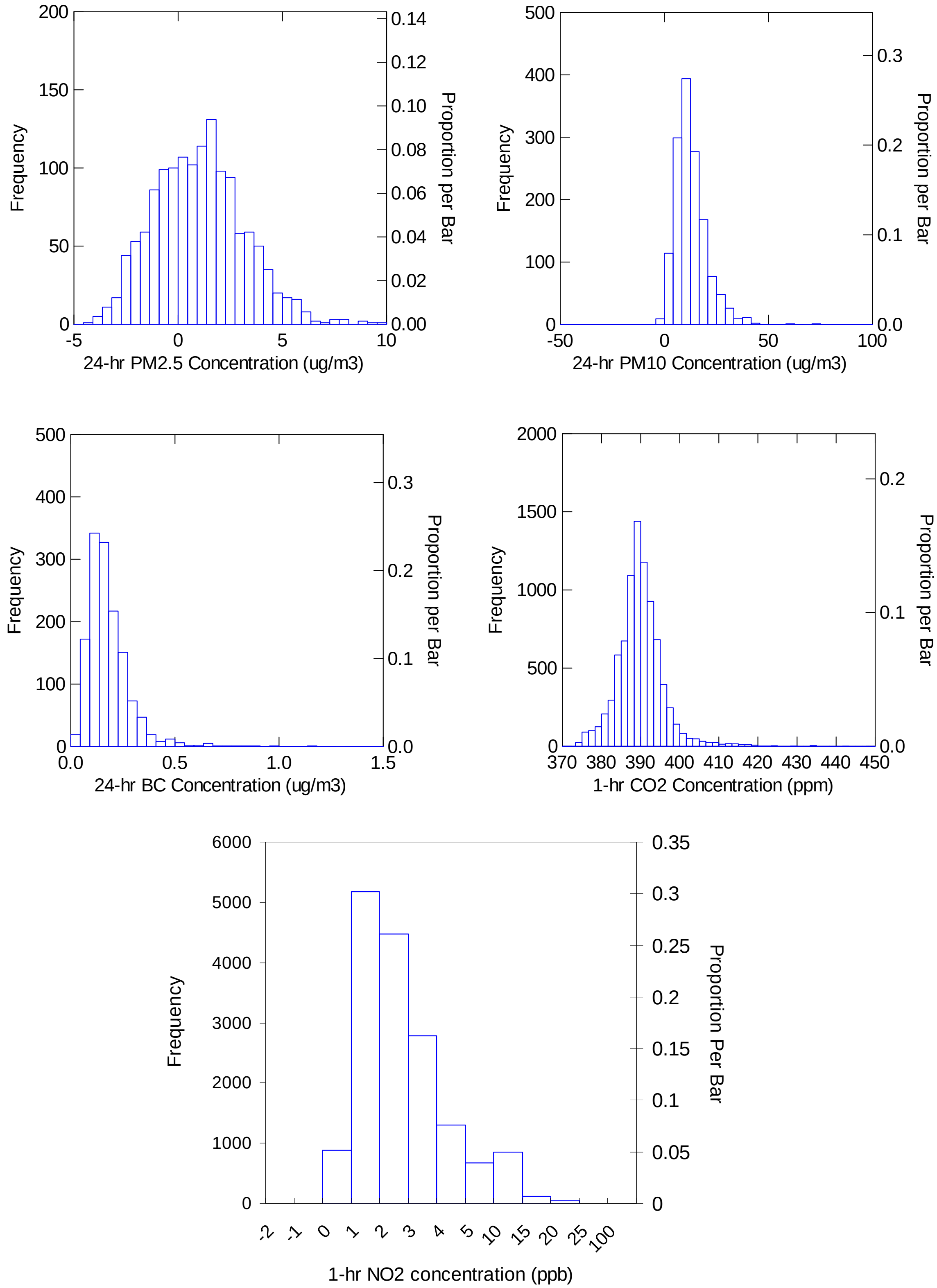


Figure 8-50. Summary of air quality measurements for January 19, 2009, to January 19, 2010.

Table 8-3. Summary PM statistics for May 25-31, 2009, compared to the one-year period of January 19, 2009, to January 19, 2010.

	Parameter	Min	Max	Median	Mean	SD
1/19/09 – 1/19/10	NO_2 (ppb)	-1.6	27.7	1.4	1.9	2.0
	$PM_{2.5}$ (μg/m^3)	-4.3	**10.0**	**1.0**	**1.0**	2.2
	PM_{10} (μg/m^3)	-1.8	**72.0**	**11.3**	**12.7**	7.5
	BC (μg/m^3)	0.0	1.1	0.2	0.2	0.1
5/25-5/31, 2009	NO_2 (ppb)	-0.3	8.8	1.1	1.4	1.4
	$PM_{2.5}$ (μg/m^3)	-2.5	**2.8**	**2.0**	**1.3**	1.5
	PM_{10} (μg/m^3)	6.8	**29.4**	**13.4**	**14.1**	4.9
	BC (μg/m^3)	0.1	0.3	0.2	0.2	0.1

Notes: Maximum, median, and mean PM concentration values are highlighted to facilitate comparison. PM and BC units are 24-hr averages; NO_2 units are 1-hr averages. Minimum and maximum values shown were from measurements from a single monitor. Median, mean, and standard deviation (SD) measurements were calculated by averaging data collected across all monitors. Note that minimum measurements included negative values. Negative measured concentrations meant that when real-world concentrations were low (approaching zero), the monitor's precision range included concentration values below zero. In general, monitor operations, calibration checks, and audits were designed to meet standard EPA guidelines for air quality monitoring. Appendix B includes further detail on the precision of the equipment deployed.

In summary, the main observations from the one-year data collection period are as follows:

- $PM_{2.5}$ concentrations did not exceed either the 35 μg/m^3 24-hr NAAQS or the 15 μg/m^3 annual average NAAQS.
- PM_{10} concentrations did not exceed the 150 μg/m^3 24-hr NAAQS.
- NO_2 concentrations did not exceed the 100 ppb 1-hr NAAQS.
- Concentrations of BC—collected as a surrogate for diesel PM to identify construction equipment air quality impacts—were typically a few tenths of 1 μg/m^3 when averaged over a 24-hour period, but reached 1.1 μg/m^3 for a maximum 24-hr value. There is no BC air quality standard to use as a benchmark for comparison to the measured concentrations. For comparison, measurements taken over several weeks within approximately 20 m of heavily-traveled freeways in Los Angeles found that average BC concentrations were approximately 5 μg/m^3 near the 405 freeway (less than 5% diesel traffic), and exceeded 20 μg/m^3 near the 710 freeway (greater than 25% diesel traffic) (Zhu et al., 2002a).

8.8 MAJOR CONCLUDING OBSERVATIONS REGARDING PM

In summary, the overall study resulted in the following major air quality related findings:

1. $PM_{2.5}$ concentrations were influenced by construction-related activity, but the impacts were relatively small, even on days when PM_{10} impacts were substantial. Most of the case study observations illustrated that $PM_{2.5}$ concentrations varied little, even when

PM$_{10}$ was influenced by nearby construction activity. There were some exceptions, such as a brief PM$_{2.5}$ concentration spike measured at all four trailers on April 17, 2009, illustrated in **Figure 8-51** using Trailer 1 data (images excerpted from Figure 8-36). However, these relatively short-term impacts were infrequent among the case studies examined and, upon closer investigation, appear to be linked to non-construction-related causes. On April 17, 2009, for example, there was a wildfire to the northwest of the construction zone; the fire location is shown in **Figure 8-52**.

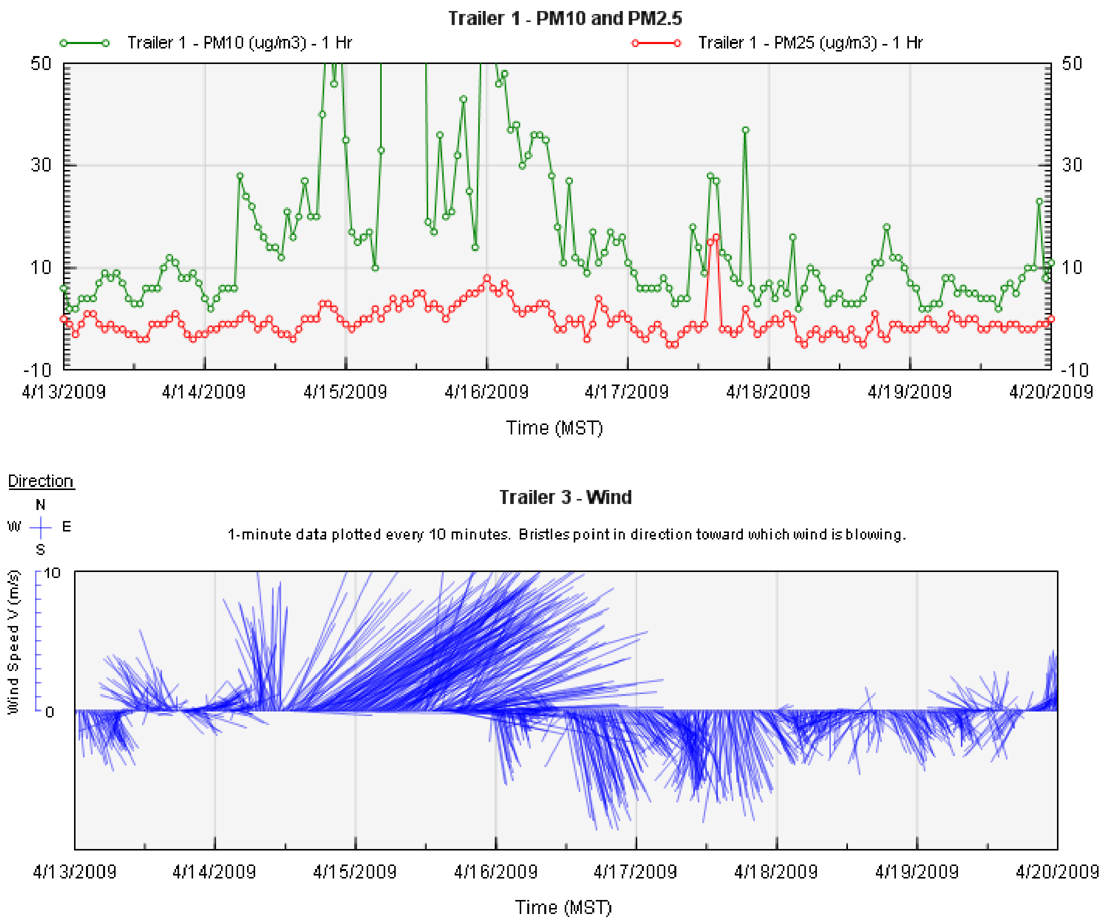


Figure 8-51. April 17, 2009, illustration of PM$_{2.5}$ and PM$_{10}$ concentration spikes correlated with construction activity.

Note that the April 17 PM$_{2.5}$ concentration spikes occurred at all monitoring trailers when winds blew from the north and fire impacts (smoke) were likely directed by area topography to flow toward the monitors. As illustrated by the April 17, 2009, data, the PM$_{2.5}$ concentration spikes were on a scale of approximately 10-20 µg/m^3 (for 1-hr). As a point of comparison, note that, on the November 22, 2009, background day, PM$_{2.5}$ was observed to range from 0 to 8 µg/m^3.

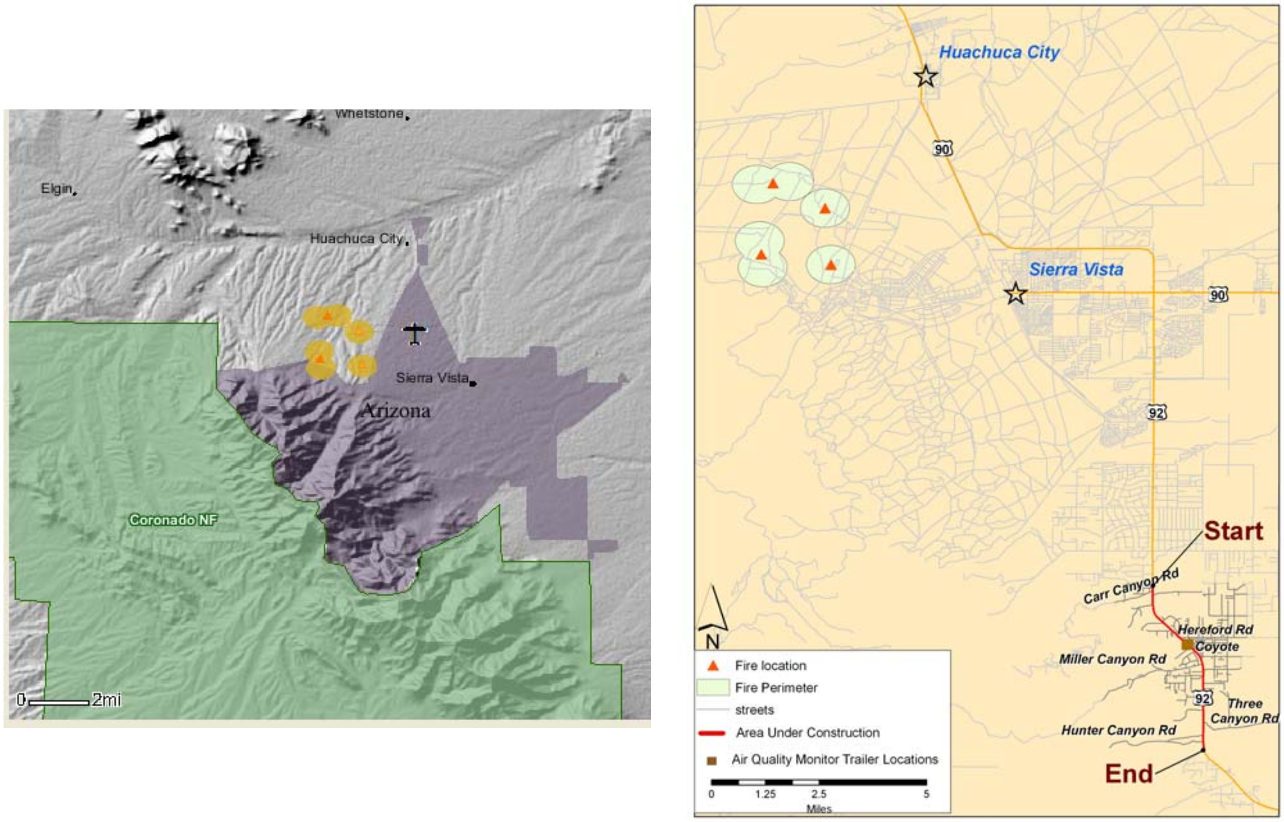


Figure 8-52. Location of the April 17, 2009, wildfire. Left image: fire in relation to topography (provided by STI's SMARTFIRE[15] fire tracking and mapping tool). Right image: fire in relation to construction zone.

2. During the case study periods examined here, construction activity increased PM_{10} concentrations at downwind receptors. As shown by the breakdown of emissions by source type and category, the predominant contributor to these impacts was fugitive dust, as opposed to exhaust emissions. PM_{10} concentrations also increased during periods when strong winds brought windblown dust from the relatively uninhabited and undeveloped areas southwest of the construction zone toward the monitoring trailers (see Figure 8-37). Concentration measurements across all four trailers helped to distinguish between source conditions that were outside the construction zone (when all four trailers showed concentration increases) and construction-related impacts (when trailers downwind of the construction zone monitored increased concentrations). When construction impacts overlapped strong wind events, and construction-related PM_{10} combined with windblown dust, resulting PM_{10} concentrations reached peak 24-hr levels

[15] The Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE) is an algorithm and database system that operate within a geographic information system (GIS) framework; the system, created for the USDA Forest Service, reconciles fire data from space-borne sensors and ground-based reports. Further information is available at: http://www.getbluesky.org/smartfire/.

that exceeded concentrations at all other times during the one-year period assessed here (see discussion of April 15, 2009, data).

3. BC concentrations also increased during periods of construction work (see Figure 8-7). The coincident increase in BC impacts helped to distinguish PM_{10} increases associated with construction activity, compared to windblown dust or sources.

The findings presented here are based on a study of a modestly-sized transportation construction project—widening of a two-lane highway over a four-mile stretch of road. During the project, the ADOT construction contractor (Bison Contracting) deployed a fleet of approximately 26 pieces of equipment (see Table 5-1). Other construction projects will vary in terms of their scale, design elements, and construction equipment used. To give just one illustration, a sizeable bridge replacement and 7.2-mile freeway reconstruction in Connecticut included over 200 pieces of diesel-powered construction equipment (Schattanek and Weaver, 2005). Other projects may employ fewer or greater numbers and types of equipment than those used at SR 92.

In addition, the equipment used by Bison Contracting to complete the SR 92 project ranged in age from a 1986 water truck to a 2008 motor grader. The fleet-average age was a 1999 model year piece of equipment (averaged across all model years and not weighted by use; see Table 5-1). Equipment exhaust emissions are a function of model year, as well as maintenance, hours of use on the equipment, and other factors. Exhaust emissions would be expected to differ for a vehicle fleet performing similar work as that done at SR 92, if the equipment used was substantially older or newer than the fleet deployed by Bison.

Overall, it is important to note that the work performed at the SR 92 site, and the equipment used to complete the work, may vary substantially from construction activity at other transportation projects. The findings presented here serve to illustrate potential construction-related air quality impacts based on the real-world conditions observed at the SR 92 site. To apply these findings to other construction projects, analysts should consider how a particular project compares to the SR 92 construction effort in terms of project size and location in relation to receptors, site characteristics such as topography and meteorological conditions, and equipment use characteristics.

9. SUMMARY FINDINGS

This section provides a summary of key findings from the two core components of the SR 92 field study: 1) tracking of construction equipment activity and subsequent estimate of emissions produced by those activities; and 2) collection of air quality and meteorological data adjacent to SR 92.

9.1 ACTIVITY DATA

At the start of the SR 92 project, Bison Contracting provided STI with information about the fleet of equipment that would largely be dedicated to the project. This fleet was comprised of the 26 pieces of equipment (listed in Table 5-1), including:

- 5 water trucks;
- 3 backhoes;
- 3 scrapers;
- 3 loaders;
- 2 excavators;
- 2 compactors;
- 2 gannon tractors;
- 2 motor graders
- 2 heavy-duty trucks;
- 1 sweeper; and
- 1 crane.

Several methods were used to track the activities of this construction fleet over the one-year field study that began in January 2009, including equipment instrumentation with global positioning system (GPS) units, the collection of Bison's daily fuel logs, and the review of ADOT field inspector diaries. Data collected via these methods were synthesized and used to quantify equipment usage by day, month, and phase of construction. **Table 9-1** provides a summary of equipment usage for calendar year 2009.

Table 9-1. Annualized and daily equipment usage for the SR 92 project during calendar year 2009.

Parameter	Annual Total	Average Day	Peak Day
Days of active construction	238	--	--
Pieces of equipment used [a]	73	10	18
Total hours of equipment usage	15,070	63	131
Total fuel consumption (gallons)	75,945	319	806

[a] Includes equipment temporarily brought onsite by Bison or Bison's subcontractors.

In addition, analyses showed that about 60% of total fuel consumption was attributable to tractors, loaders, backhoes, trucks, and to the roadway and structural excavation phases of construction (see Figure 7-2). Fuel consumption averaged 6,329 gallons per month for 2009, with a peak fuel consumption of 8,146 gallons occurring in September (see Figure 7-3).

9.2 EMISSIONS ESTIMATES

To provide a quantitative assessment of $PM_{2.5}$, PM_{10}, and NO_x emissions from the various phases of a road-widening project, STI used the activity data described above to develop equipment exhaust and fugitive dust emissions estimates for construction activity. STI also compared these emission estimates to alternative emissions inventories prepared from readily available tools and default activity estimates so that the impact of using project-specific activity data to quantify emissions could be assessed.

9.2.1 Emissions Summary

Analyses showed that construction equipment operating at the SR 92 project during 2009 produced exhaust emissions totaling 553 kg of PM_{10}, 537 kg of $PM_{2.5}$, and 7,102 kg of NO_x. Over half of the exhaust $PM_{2.5}$ emissions produced during calendar year 2009 were attributable to tractors, loaders, backhoes, trucks, and to the roadway and structural excavation phases of construction (see Figure 7-4). On a model-year basis, over half of the total exhaust NO_x, PM_{10}, and $PM_{2.5}$ emissions were associated with vehicles of model year 2004 or newer (see Figure 7-5).

Fugitive dust associated with year-2009 construction activity at the SR 92 project produced 6,490 kg of PM_{10} and 924 kg of $PM_{2.5}$ emissions. Analyses showed that 80% of fugitive $PM_{2.5}$ emissions were attributable to the roadway excavation phase of construction (see Figure 7-7). On a monthly basis, fugitive dust emissions were highest in January and December, largely due to significant roadway excavation activity during those two months (see Figure 7-8).

In total, year-2009 construction activity at the SR 92 project produced 7,043 kg of PM_{10}, 1,461 kg of $PM_{2.5}$, and 7,102 kg of NO_x. Fugitive dust accounted for 92% of the total PM_{10} emissions associated with construction activities and 63% of the total $PM_{2.5}$ emissions associated with construction activities (note that these figures do not include consideration of on-road vehicle emissions). On an average day in 2009, construction activity at the SR 92 project produced 29 kg of PM_{10}, 6 kg of $PM_{2.5}$, and 30 kg of NO_x. Daily peak emissions occurred on December 9, 2009, when construction activities on the SR 92 project produced 173 kg of PM_{10}, 31 kg of $PM_{2.5}$, and 93 kg of NO_x (see Figure 7-9). Fugitive dust accounted for 96% of the peak day PM_{10} emissions and 79% of the peak day $PM_{2.5}$ emissions.

9.2.2 Emissions Comparisons

These emission estimates fell within the bounds of alternative emission estimates produced using the U.S. Environmental Protection Agency's (EPA) NONROAD model run with default activity data and the construction emissions tool developed for the Sacramento Metropolitan Air Quality Management District (SMAQMD). For exhaust emissions, field study-derived emission estimates are about half of emission estimates prepared using NONROAD defaults, largely because of differences in equipment activity (i.e., annual hours of operation). However, field study-derived emission estimates are 25% to 67% higher than exhaust emission estimates prepared using the Roadway Construction Emissions Model (RCEM) tool (see Figure 7-15) due to different assumptions about the fleet and usage of equipment required to complete the project.

For fugitive dust, STI ran the RCEM tool with two different options for maximum area disturbed, the key parameter used by RCEM to estimate fugitive dust emissions (NONROAD does not estimate fugitive dust emissions). STI's fugitive dust emissions estimate for $PM_{2.5}$ prepared using field study data was 70% lower than the RCEM estimate prepared using the recommended default value for maximum area disturbed of 15 acres per day. However, when RCEM was run using an alternative maximum area disturbed value of 4.5 acres (or 25% of the total project area), STI's fugitive dust emissions estimate for $PM_{2.5}$ was within 6% of the RCEM estimate (see Figure 7-16).

9.3 AIR QUALITY DATA

This discussion pools the main observations drawn throughout the study. The findings are summarized from the February 2009 case study when the rock crusher was in operation; the April 2009 case study when 24-hr PM_{10} concentrations reached their highest recorded values; the May 2009 case study when concentrations reflected the Memorial Day holiday as well as days when construction took place near the monitors; and data collected over the entire January 19, 2009, to January 19, 2010, study period.

- Monitoring data indicate that PM_{10} concentrations were affected (increased) by the construction work; $PM_{2.5}$ impacts, however, were far less pronounced. The predominant contributor to these impacts was fugitive dust, as opposed to exhaust emissions.
- NO_x, NO_2, and black carbon (BC) concentrations increased during periods when construction activity took place. These impacts were observed by comparing maximum NO_x, NO_2, and BC concentrations on construction work days compared to the Memorial Day holiday and the Sunday, November 22, 2009, background day.
- On-road vehicle NO_x emissions were greater than construction-related emissions, and on-road travel activity generally peaked during periods when monitored NO_x concentrations increased. Thus, it is likely that on-road emissions were responsible for a substantial fraction of the increased NO_x and NO_2 concentration increases observed at the monitoring trailers.
- BC concentrations increased during periods when construction activity took place. The coincident increase in BC impacts helped to distinguish PM_{10} increases associated with construction activity, compared to windblown dust or sources.
- The observed PM_{10} impacts from the construction work were measured, at various times, by each of the four trailers, depending upon wind speed and direction.
- Generally, the rock crusher's contribution to overall PM_{10} emissions was relatively small, in comparison to total construction emissions occurring on a given day. However, during

the February 2009 case study examined here, when the rock crusher was upwind of the monitoring trailers, its emissions constituted a sizeable fraction (on the order of half) of the construction-related PM_{10} emissions (exhaust and fugitive dust combined) that occurred upwind of the trailers. Given that PM_{10} concentrations increased when the crusher and other construction equipment was upwind of the monitors, it appears that crusher emissions contributed to the monitored concentration changes.

- Some of the highest recorded PM_{10} concentrations were associated with strong winds out of the southwest. Among the highest concentrations were those recorded at approximately midnight, at the start of Wednesday, April 15, 2009, when no construction activity was taking place and on-road traffic was limited. During the late-night episode, PM_{10} concentrations were uniformly elevated at all four trailers, indicating that the emissions source was unrelated to the road. During this period, the elevated PM_{10} likely originated from windblown dust in the surrounding countryside.
- In contrast to the April midnight episode, a midday episode on April 15, 2009, resulted in the highest measured 24-hr PM_{10} concentrations of the one-year study period. During this episode, construction activity occurred near the trailers, and Trailers 1 and 2 were downwind of SR 92. The April 15 event resulted in an incremental difference between the upwind trailers (3 and 4) and the downwind trailers (1 and 2) that ranged from approximately 54 to 300 $\mu g/m^3$ of PM_{10} (1-hr averages). Thus, the construction activity in close proximity to the trailers on this day resulted in the incrementally high PM_{10} values measured at Trailers 1 and 2. Even during relatively high PM_{10} events (such as those on April 15, 2009), $PM_{2.5}$ concentrations remained relatively consistent with the values observed at other times, confirming that $PM_{2.5}$ concentrations were relatively unaffected by the construction work.
- Across the entire one-year study period, $PM_{2.5}$ concentrations did not exceed either the 35 $\mu g/m^3$ 24-hr National Ambient Air Quality Standards (NAAQS), or the 15 $\mu g/m^3$ annual average NAAQS, and PM_{10} concentrations did not exceed the 150 $\mu g/m^3$ 24-hr NAAQS. NO_2 concentrations tended to peak at or below 10 ppb, and did not exceed the EPA's NO_2 1-hr NAAQS of 100 ppb.
- Concentrations of BC—collected as a surrogate for diesel PM to help identify construction equipment air quality impacts—were typically a few tenths of 1 $\mu g/m^3$ when averaged over a 24-hour period, but reached 1.1 $\mu g/m^3$ for a maximum 24-hr value. Measured increases in exhaust BC during periods of construction operations helped to distinguish construction-related PM_{10} impacts from concentration increases related to windblown dust or other sources unrelated to construction work.
- On some days, $PM_{2.5}$ concentrations were observed to spike upwards. However, these events appear to be relatively unrelated to the construction work, as illustrated by an April 17, 2009, wildfire to the northwest of the construction zone, the winds that occurred out of the north during that day, and the resulting $PM_{2.5}$ impacts measured at the trailers.

10. CONCLUSIONS AND FUTURE RESEARCH NEEDS

10.1 CONCLUSIONS

During 2009 and 2010, when Arizona Department of Transportation (ADOT) contractors were widening SR 92 in a remote section of southern Arizona, STI collected onsite data to evaluate whether the construction activity resulted in measureable air quality impacts. The STI field study collected air quality, meteorological, on-road travel, and construction equipment spatial and temporal activity and fuel use data for a one-year period (January 19, 2009, to January 19, 2010).[16] Field study measurements covered all phases of construction activity, although some of the construction work began in late 2008 prior to data collection, and final paving work was completed in 2010 after the air quality study ended. Previous to this study, there had been few efforts to comprehensively examine how roadway construction activities affect emissions and air quality. This study provides important new data resources to facilitate a variety of construction-related assessments.

Overall, the study results indicate that construction work did affect near-field PM_{10} concentrations, but did not substantively affect near-field $PM_{2.5}$ concentrations. Construction-related fugitive dust overwhelmed all other PM_{10} sources. **Figure 10-1** illustrates PM_{10} emissions by source category, using data collected during calendar year 2009.

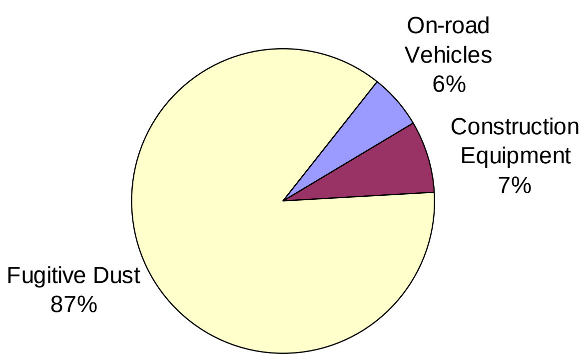


Figure 10-1. PM_{10} emissions in the SR 92 construction zone (calendar year 2009). On-road and construction categories refer to exhaust emissions. Total emissions were 7,488 kg (8.3 tons).

[16] Note that, to ensure a full twelve months of data collection, some of the field work began earlier and ended later than the January 19, 2009, to January 19, 2010, period described here for data evaluation purposes. For example, we began to instrument construction equipment with global positioning system (GPS) units on October 20, 2008, and completed the GPS installation process on December 23, 2008. GPS data collection ended January 29, 2010. We installed the monitoring trailers onsite in mid-November 2008. Electrical power was provided at all trailers during the first week in January 2010; partial data collection began January 9, 2009, and full data collection began January 14, 2009. Following start-up quality assurance reviews, we identified January 19, 2009, as the first date for which we began full air quality and meteorological data collection once all equipment operations were quality checked. We removed the monitoring equipment from the field in the first week of February 2010. Data presented here are for a 12-month period to facilitate analysis across all seasons of the year, and to enable assessment of annual average pollutant concentrations.

Over the 12-month period investigated here, monitored pollutant concentrations did not exceed National Ambient Air Quality Standards (NAAQS) for PM_{10}, $PM_{2.5}$, CO, or NO_2.

Under the worst-case conditions observed, the incremental impact of the construction equipment was 47 $\mu g/m^3$ of PM_{10}, averaged over a 24-hour period. This impact was observed on April 15, 2009, and is shown in **Table 10-1**. The incremental impact of the construction, on its own, did not violate the PM_{10} NAAQS of 150 $\mu g/m^3$ over a 24-hour period. However, if meteorological conditions and construction activity were to occur in an area with relatively high PM_{10} background concentrations (i.e., greater than 100 $\mu g/m^3$ measured over 24 hours), the incremental result would be to exceed the 24-hr PM_{10} NAAQS.

Table 10-1. Maximum observed construction-related 24-hr PM_{10} impacts (in $\mu g/m^3$) across the January 19, 2009, to January 19, 2010, period. Values are from April 15, 2009, when winds originated from the southwest.

Site	Monitored Concentration	Averaged Upwind Concentration	Averaged Downwind Concentration	Construction Impact on 24-hr PM_{10}
Trailer 1	72.0		65.0	
Trailer 2	58.5			
Trailer 3	17.2	18.1		
Trailer 4	19.0			
Increment				46.9

The measured peak construction-related PM_{10} coincided with a period when construction equipment operated adjacent to the monitoring trailers, when winds were relatively strong, and when overall construction-related PM_{10} emissions exceeded the daily average (44 kg of PM_{10} on April 15, 2009, vs. 29 kg for an average day in 2009). It is important to note that the April 15, 2009, measurements are not necessarily the maximum possible PM_{10} impact from the construction work. Peak construction-related PM_{10} emissions occurred on December 9, 2009. On December 9, 2009, overall construction-related PM_{10} emissions totaled 173 kg (see Section 9.2.1). Activity on that day however, was primarily located in the southern portion of the SR 92 construction zone, rather than the mid portion of the construction zone adjacent to the monitoring trailers. Of course, the near-field PM concentrations that occurred at any one location were a function of the equipment operating close to that site. Therefore, it is possible that, even though the December 9, 2009, emissions were quite high relative to April 15, 2009, the near-field concentration impacts for both days may have been comparable, depending upon where various pieces of equipment were operating in relation to each other and to a given receptor site. Further analysis would be needed to assess the degree to which the December 9, 2009, peak emissions were in a relatively small zone or were spread over a large geographic area, and how the near-field concentration impacts on December 9, 2009, might compare to those observed on April 15, 2009.

STI completed a literature review as part of this study that identified the range of construction-related emission control options currently in use (see Section 2 and Appendix A). Many of these controls focus on retiring or retrofitting older, higher-emitting equipment as a method of reducing exhaust emissions. However, as demonstrated by this study's findings, to further control PM impacts from construction work, ADOT could deploy additional controls that reduce fugitive dust emissions or their impact on receptors. Therefore, among the control options discussed in the literature review (see Section 2.1), three control areas are of special interest: curtailing or controlling activity; increasing the distance between activity and receptors; and applying dust suppressant and removal controls.

10.2 FUTURE RESEARCH NEEDS

This study produced one of the largest data sets assembled to date on construction-related activity, emissions, and air quality impacts. Accordingly, the data offer a number of important follow-up research opportunities, some of which are mentioned here. Additional research opportunities can be identified in consultation with ADOT, to optimize the department's use of the data to assist with project evaluation and mitigation. Examples of potential uses of the data include:

- Evaluate how default construction activity assumptions, such as those embedded in U.S. Environmental Protection Agency (EPA) modeling tools, compare to the real-world data obtained at the SR 92 site.
- Further evaluate the characteristics of peak-concentration episode days, from the perspective of contributing meteorological conditions and associated construction activity and emissions.
- Assess the relationship between construction-related concentration impacts and compliance with NAAQS.
- Assess the potential costs and benefits of mitigation strategies that target fugitive dust vs. exhaust emissions.
- Assess whether ADOT standard operating procedures for construction work could be modified, at relatively low cost, to facilitate ongoing construction equipment activity data collection at other sites (to improve representation of the construction impacts of various project types).

11. REFERENCES

Baker R. (2009) Characterization of the off-road equipment population. Presented at the *Chair's Air Pollution Seminar Series, California Air Resources Board, January 29* by Eastern Research Group, Inc. (ERG).

Brugge D., Durant J.L., and Rioux C. (2007) Near-highway pollutants in motor vehicle exhaust: a review of epidemiologic evidence of cardiac and pulmonary health risks. *Environ. Health* **6** (23) (doi:10.1186/1476-069X-6-23). Available on the Internet at http://www.ehjournal.net/content/6/1/23.

California Air Resources Board (1997) Miscellaneous process methodologies: road construction dust. Available on the Internet at http://www.arb.ca.gov/ei/areasrc/index7.htm.

California Air Resources Board Mobile Source Emissions Inventory Program (2007a) User's guide for OFFROAD2007. November. Available on the Internet at http://www.arb.ca.gov/msei/offroad/offroad.htm.

California Air Resources Board Mobile Source Emissions Inventory Program (2007b) Program structure of the OFFROAD2007. Available on the Internet at http://www.arb.ca.gov/msei/offroad/offroad.htm.

Eisinger D.S. and Niemeier D. (2007) Construction emissions: using project data to improve regional inventories. Invited presentation at the *86th Annual Meeting of the Transportation Research Board, Workshop 135: Guidelines on Conducting Project Level Air Quality Analysis, Washington, D.C., January 21,* (STI-906044-3130).

Frey H.C., Kim K., Pang S.-H., Rasdorf W., and Lewis P. (2008) Characterization of real-world activity, fuel use, and emissions for selected motor graders fueled with petroleum diesel and B20 biodiesel. *J. Air Waste Manage. Assoc.* **58**, 1274-1287 (doi:10.3155/1047-3289.58.10.1274).

Gauderman W.J., Vora H., McConnell R., Berhane K., Gilliland F., Thomas D., Lurmann F., Avol E., Kunzli N., Jerrett M., and Peters J. (2007) Effect of exposure to traffic on lung development from 10 to 18 years of age: a cohort study. *The Lancet* **369** (9561), 571-577.

Gautam M., Carder D.K., Clark N.N., and Lyons D.W. (2002) Testing for exhaust emissions of diesel powered off-road engines. Final project report prepared for the California Air Resources Board and the California Environmental Protection Agency by the Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, May 29.

Health Effects Institute Panel on the Health Effects of Traffic-Related Air Pollution (2010) Traffic-related air pollution: a critical review of the literature on emissions, exposure, and health effects. Prepared by the Health Effects Institute, Boston, MA, Special Report 17, January.

Huai T., Shah S.D., Durbin T.D., and Norbeck J.M. (2005) Measurement of operational activity for nonroad diesel construction equipment. *International Journal of Automotive Technology* **6** (4), 333-340.

Jones & Stokes and Rimpo and Associates (2009) Road construction emissions model, version 6.3.1. Spreadsheet system prepared for the Sacramento Metropolitan Air Quality Management District. Available on the Internet at http://www.airquality.org/ceqa/index.shtml#models.

Kable J.M. (2006) Collecting construction equipment activity data from Caltrans project records. M.S. Thesis, University of California at Davis, Davis, CA. Available on the Internet at http://www.uctc.net/papers/828.pdf.

Karner A., Eisinger D.S., and Niemeier D. (2010) Near roadway air quality: synthesizing the findings from real-world data. *Environ. Sci. Technol.* **44** (14), 5334-5344 (10.1021/es100008x, STI-3923).

Kasprak A., Schattanek G., and Wan P.K. (2001) Emission reduction retrofit program for construction equipment of the Central Artery/Tunnel Project. Paper No. 206 presented at the *94th Annual Air & Waste Management Association Conference & Exhibition, Orlando, FL, June 24-28*. Available on the Internet at <http://www.masspike.com/pdf/big_dig/dieselemisson.pdf>.

Kean A.J., Sawyer R.F., and Harley R.A. (2000) A fuel-based assessment of off-road diesel engine emissions. *J. Air Waste Manage. Assoc.* **50** (11), 1929-1939.

Langston R., Merle R., Kuhns H., Etyemezian V., Nikolich G., Fitz D., Bumiller K., and James D. (2006) Alternative technologies for evaluating paved road dust emissions potential—mobile sampling methodology as an alternative to traditional AP-42 silt measurements. Presented at the *U.S. Environmental Protection Agency's 15th Annual Emission Inventory Conference, New Orleans, LA, May 18* by the Clark County Department of Air Quality and Environmental Management, Las Vegas, NV.

Lee D.-W. (2009) Characterizations of in-use real world emissions of off-road equipment. Presented at the 19th CRC Workshop, *San Diego, CA, March 24* by the Texas Transportation Institute, College Station, TX.

Lewis P., Rasdorf W., Frey H.C., Pang S.-H., and Kim K. (2009) Requirements and incentives for reducing construction vehicle emissions and comparison of nonroad diesel engine emissions data sources. *J. Constr. Eng. Manage.* **135** (5), 341-351 (doi: 10.1061/(ASCE)CO.1943-7862.0000008).

Maricopa County Air Quality Department (2010) 2008 PM10 periodic emissions inventory report for the Maricopa County, Arizona, nonattainment area. June. Available on the Internet at http://www.maricopa.gov/aq/divisions/planning_analysis/docs/2008_PM10/08_PM10_PEI_Entire.pdf.

National Research Council (2004) *Air quality management in the United States*, The National Academies Press, Washington, D.C. Available on the Internet at <http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=10728>.

Reid S.B. (2007) Documentation of emission estimation techniques for sources of diesel particulate matter (DPM) associated with distribution centers and construction projects in West Oakland, California. Technical memorandum prepared for the Bay Area Air

Quality Management District, San Francisco, CA, by Sonoma Technology, Inc., Petaluma, CA, STI-907006-3174-TM, May.

Sacramento Metropolitan Air Quality Management District (2009) Guide to air quality assessment in Sacramento County. December. Available on the Internet at http://www.airquality.org/ceqa/ceqaguideupdate.shtml.

Schattanek G., Kasprak A., Weaver D., and Cooper C. (2002) Implementation of retrofit/clean fuel programs for diesel equipment during the construction phase of two large transportation projects. Paper No. 42536 presented at the *AWMA 95th Annual Conference & Exhibition, Baltimore, MD, June 23-27*. Available on the Internet at <http://www.i95newhaven.com/poverview/awma_2002_nhhc.pdf>.

Schattanek G. and Weaver D. (2005) Implementation of retrofit program for diesel equipment during the construction phase the I-95 New Haven Harbor Crossing Improvement Program in southern Connecticut. *Air & Waste Management Association's 98th Annual Conference and Exhibition*, Minneapolis, MN (Paper #999).

Shrouds J.M. (2010) Air quality community of practice, short term impacts from construction equipment and operations state-of-the-practice. Report prepared for the Center for Environmental Excellence by the American Association of State Highway and Transportation Officials (AASHTO) March. Available on the Internet at http://environment.transportation.org/pdf/communities_of_practice/airqualconstr.pdf.

Singer B.C. and Harley R.A. (2000) A fuel-based inventory of motor vehicle exhaust emissions in the Los Angeles area during summer 1997. *Atmos. Environ.* **34** (11), 1783-1795.

STAPPA/ALAPCO (2006) Controlling fine particulate matter under the clean air act: A menu of options. Report prepared by the State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials. Available on the Internet at <http://www.4cleanair.org/PM25Menu-Final.pdf>. March.

U.S. Customs and Border Protection (2003) Supplemental environmental assessment for infrastructure within U.S. border patrol Naco-Douglas corridor, Cochise County, Arizona, Appendix D. November. Available on the Internet at http://www.swf.usace.army.mil/pubdata/notices/naco-douglas.asp.

U.S. Environmental Protection Agency (1995) Compilation of air pollutant emission factors, AP-42. Vol. 1: stationary point and area sources. Section 13.2.3, Heavy construction operations. January.

U.S. Environmental Protection Agency (1998) Compilation of air pollutant emission factors, AP-42. Vol. 1: stationary point and area sources. Section 11.9, Western surface coal mining. October.

U.S. Environmental Protection Agency (2003) Compilation of air pollutant emission factors, AP-42. Vol. 1: stationary point and area sources. Section 13.2.1, paved roads. December. Available on the Internet at <http://www.epa.gov/ttn/chief/ap42/ch13/>.

U.S. Environmental Protection Agency (2004a) Median life, annual activity, and load factor values for nonroad engine emissions modeling. EPA420-P-04-005, Report no. NR-005c, April.

U.S. Environmental Protection Agency (2004b) Exhaust and crankcase emission factors for nonroad engine modeling – compression-ignition. EPA420-P-04-009, Report No. NR-009c, April.

U.S. Environmental Protection Agency (2004c) Compilation of air pollutant emission factors, AP-42. Vol. 1: stationary point and area sources. Section 11.19.2, Crushed stone processing and pulverized mineral processing. August.

U.S. Environmental Protection Agency (2005a) User's guide for the final NONROAD2005 model. Technical report prepared by the U.S. EPA Office of Transportation and Air Quality, Assessment and Standards Division, with assistance from Cimulus, Inc., and ENVIRON International Corp., EPA420-R-05-013, December.

U.S. Environmental Protection Agency (2005b) Geographic allocation of non-road engine population data to the state and county level. EPA420-R-05-021, Report No. NR-014d, December.

U.S. Environmental Protection Agency (2005c) Nonroad engine population estimates. EPA420-R-05-022, Report No. NR-006d, December.

U.S. Environmental Protection Agency (2006) Compilation of air pollutant emission factors, AP-42. Vol. 1: stationary point and area sources. Section 13.2.4, Aggregate handling and storage piles. November.

Wang R., Eisinger D.S., Bai S., and Niemeier D. (2008a) Construction equipment retrofits and replacements: a new tool to estimate emission reduction benefits. Final report prepared by the U.C. Davis-Caltrans Air Quality Project, Davis, CA, Task Order No. 81, December 30.

Wang R., Eisinger D.S., Bai S., and Niemeier D. (2008b) Construction equipment retrofit and replacement tool. Prepared by the U.C. Davis-Caltrans Air Quality Project, Davis CA, Task Order No. 81, October.

Zhou Y. and Levy J.I. (2007) Factors influencing the spatial extent of mobile source air pollution impacts: a meta-analysis. *BMC Public Health* **7** (89) (doi:10.1186/1471-2458-7-89). Available on the Internet at http://www.biomedcentral.com/1471-2458/7/89.

Zhu Y., Hinds W.C., Kim S., Shen S., and Sioutas C. (2002a) Study of ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmos. Environ.* **36**, 4323-4335 (27). Available on the Internet at <http://www.sciencedirect.com/science/article/B6VH3-46MBTBP-5/2/1cfd97e9d1d1d605fbdcd5844cc7c4d6>.

Zhu Y.F., Hinds W.C., Kim S., and Sioutas C. (2002b) Concentration and size distribution of ultrafine particles near a major highway. *J. Air Waste Manage. Assoc.* **52** (9), 1032-1042.

APPENDIX A: CONSTRUCTION EMISSIONS LITERATURE REVIEW

1. INTRODUCTION

As part of this study effort, STI reviewed existing literature regarding equipment activity and particulate matter (PM) emissions from construction projects. The reviewed literature comprised a range of individual categories relevant to meeting this field study's objectives, including (a) activity data and fleet characteristics for construction equipment; (b) equipment emissions testing and modeling approaches; (c) non-road diesel-powered equipment mitigation strategies for $PM_{2.5}$, PM_{10} (including fugitive dust measures), and NO_x; and (d) example mitigation measures and strategies for construction equipment used in practice.

This appendix provides the principal findings of the literature review and includes three sections: (1) construction equipment activity, (2) construction equipment emissions, and (3) mitigation measures and strategies. This material expands upon the digest provided in section two. The construction equipment activity section illustrates existing information on activity data and fleet characteristics, such as equipment age distribution, and discusses assumptions for estimating equipment activities in modeling efforts. The construction equipment emissions section describes information on emissions testing and specific modeling approaches. The mitigation measures section summarizes PM emissions standards, regulations, and specific control strategies implemented in practice (e.g., retrofitting/replacing programs); examines observed/estimated effectiveness of controls; and presents common lessons learned from previous mitigation efforts. The appendix concludes with a summary of findings from this review regarding mitigation options and evaluation metrics.

2. CONSTRUCTION EQUIPMENT ACTIVITY

Forecasting construction equipment activity is important to accurately estimate emissions from construction projects and to develop effective mitigation strategies. Overall, there is limited information documenting non-road equipment activity and fleet data. The majority of existing information regarding equipment activities is typically not specific to transportation projects. Equipment types and usage patterns vary widely depending on application. Therefore, it has been difficult to quantify both activity and population characteristics for construction equipment.

Published work describes several approaches and data sources used to collect equipment characteristics and activity data, including surveys, field inspector diaries, time-lapse photography, and on-board monitoring equipment. Each data collection method has strengths and weaknesses; no single study to date has provided the full range of activity data needed to inform emissions inventories or modeling efforts across the wide array of construction projects that take place. For example, in-use or real-world studies more successfully measure typical duty cycles[1]; however, observations are more prone to variability than data from controlled experiments (Abolhasani et al., 2008).

Surveys

Surveys are one tool used to collect equipment population and activity data from manufacturers and users/operators (Kean et al., 2000). Surveys include both written response forms and/or random computer assisted telephone interviews (Reid, 2007; Baker, 2009). Survey questions regarding equipment characteristics typically include equipment category, fuel type, vehicle descriptors (make/model/year), and engine size and horsepower (hp). Equipment activity data can be obtained based on estimated hours of use, temporal profiles (seasonal and weekday versus weekend), and the general site at which activity occurred (Baker, 2009). Survey responses are used to update emission inventories, assess engines suited for preemption status[2], and identify possible equipment retrofits (Baker, 2009).

The literature included surveys conducted in California and Texas to collect equipment activity and population data. As part of an evaluation of diesel particulate matter (DPM) emissions in a west Oakland, California, neighborhood in 2005, STI designed a one-page survey that was used to collect information on equipment populations and activities from contractors engaged in major construction projects in the neighborhood during that year (Reid, 2007). More air compressors, generators, welders, forklifts, and cranes were reported than other equipment for approximately 30 to 365 days on construction job sites, while bore/drill rigs, tractors/loaders/backhoes, and rubber tire dozers also spent 20 to 45 days on job sites (Reid, 2007).

For the Houston area in a 1999 study (Eastern Research Group, 2005), the top seven equipment types (>1,000 units) for a four-county area were (in descending order of population size): tractors/loaders/backhoes, cranes, excavators, crawler tractors/dozers, rollers, skid steer loaders, and rubber tire loaders. Equipment population distributions, combined with horsepower ratings, indicated earthmoving and highway construction activities were found to generate the greatest emissions. Additional operator surveys, on-site observations, and equipment activity profiles from cost estimators and experts for diesel construction equipment were collected in 2005, focusing on equipment used in earthmoving activities, such as dozers and excavators (Eastern Research Group, 2005). The major earthmoving equipment types identified were dozers, loaders, backhoes, and excavators used in different earthmoving-related project phases (e.g., land clearing, mass excavation, grading and dressing, trenching, backfilling, and surfacing).

In spring 2006 and winter/spring 2007, the California Air Resources Board (ARB) surveyed more than 200 mining and construction equipment owners or operators regarding non-road equipment (Baker, 2009). Using a weighted survey count, the results for the

---

[1] A duty cycle is a "sequence of tasks that is repeated to produce a unit of output". The unit of output varies by equipment type and function. For example, an excavator may output a certain volume of dirt after operating a bucket to remove, carry and dump material (duty cycle).
[2] The 1990 amendments to the Clean Air Act name U.S. Environmental Protection Agency (EPA) as having singular authority over emissions standards for farm and construction equipment under 175 horsepower. This preempts California's control; see: http://www.arb.ca.gov/msprog/offroad/preempt.htm.

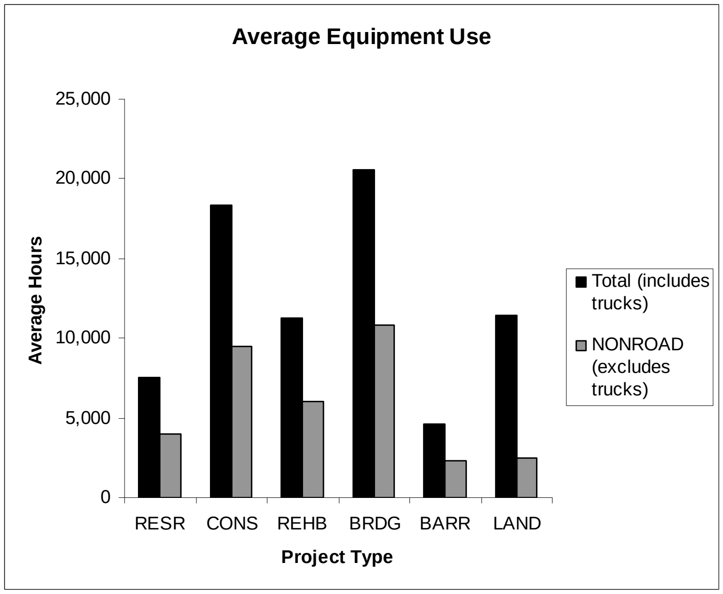
construction sector, although not transportation specifically, indicated generator sets, air compressors, and tractors/loaders/backhoes were the dominant equipment types; annual use of bore/drill rigs, industrial forklifts, and tractors/loaders/backhoes (>1000 average hrs/year) was greater than other equipment types. Fuel use was distributed between diesel (50%), gasoline (46%), and compressed gas (3%), while construction activity was evenly distributed by season (about 25% per season). However, the study author noted that there was substantial uncertainty associated with the collected data, and the survey's population and activity data were lower than model predictions.

Field Inspector Diaries

Field inspectors from some state transportation agencies track contractor activities at roadway construction projects by using daily diaries to record work completed, equipment used, hours worked, and other details. These records are typically used to calculate contractor payments and to resolve disputes, but they can also be used for identifying equipment characteristics and usage patterns.

For example, a database of equipment activity was developed based on Caltrans project diaries for 30 construction projects (Eisinger and Niemeier, 2007). The study reviewed and categorized project records, including daily field diaries, of construction activity in order to relate project phases to equipment usage (Kable, 2006). The results were categorized by project type: (Resurface Existing Highway [RESR], Construct Freeway/Extra Lane [CONS], Pavement Rehabilitation/Widening [REHB], Construct/Reconstruct Bridge [BRDG], Construct Median, and Landscaping [LAND]), as well as by project phase. Project records included duration and award amount, which are useful metrics for determining project complexity and therefore estimating the number, time, and variety of equipment used. Of the six types, CONS and BRDG projects typically lasted the longest (329 to 394 days) and received the largest awards (approximately $5 million to $6 million), while Construct Median and Landscaping projects were the shortest (180 to 270 days) and had the lowest award amounts ($500,000 to $700,000, see Kable, 2006).

Equipment hours by project and equipment type were reviewed; results are adapted in **Figures A-1 and A-2.** The highest average number of total equipment hours (18,000 to 20,000 hours) was observed for the CONS and BRDG projects. Signal boards (>1800 hours) were used more across all projects; however, they had a much lower average horsepower (24 hp) than rollers (92 hp), tractors/loaders/backhoes (93 hp), or rubber tire loaders (243 hp), which have 688, 436, and 376 hours of average annual use, respectively (Kable, 2006). Based on duration (average hours) of equipment use, the top categories of project phases included traffic control/signage/barriers, paving, structural concrete, change orders, and roadway excavation (>1000 average hours, see Kable, 2006).



Resurface Existing Highway (RESR), Construct Freeway/Extra Lane (CONS), Pavement Rehabilitation/Widening (REHB), Construct/Reconstruct Bridge (BRDG), Construct Median, thrie beam barrier (BARR), and Landscaping (LAND).

Figure A-1. Comparing total hours of equipment usage (on average) across different construction project types. The figure is adapted based on data presented in Kable (2006).

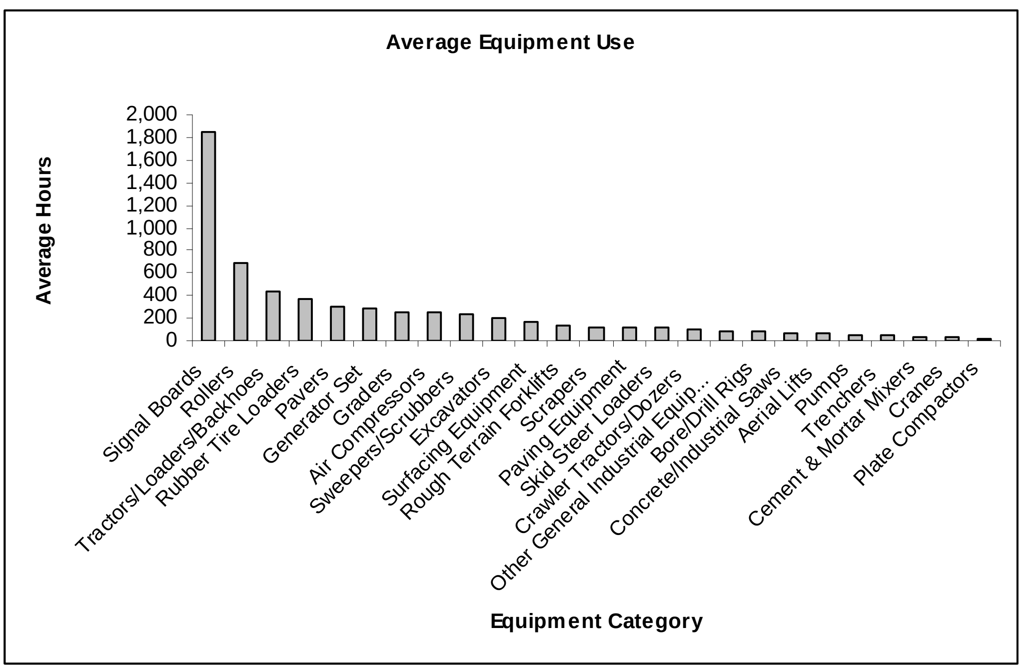


Figure A-2. Comparing total hours of equipment usage (on average) across different construction equipment categories (includes over 30 projects). The figure is adapted based on data presented in Kable (2006).

Time-Lapse Photography

Automated remote monitoring systems (ARMS) are used at some construction sites for collecting productivity data, forecasting delays, and investigating accidents. ARMS take time-lapse digital photographs of construction activities from one or more cameras and transfer them to remote servers from which they can be accessed via a website (Abeid and Allouche, 2001). Time-lapse photographs can be used to assess the equipment types that are onsite and active during various phases of a construction project (Eastern Research Group, 2005). Review of time-lapse photography obtained from nine commercial construction projects (not transportation projects) indicated diesel equipment use for earthwork activities occurred primarily in the first project phase (such as land clearing), and both the quantity and variety of diesel equipment onsite decreased substantially during later project phases (building erection/finishing, see Eastern Research Group, 2005).

On-Board Monitoring Equipment

Different measurement systems are used during construction projects to gather real-world activity and population information. For example, a monitoring study conducted in 1994 during a bridge deck resurfacing project in Albany, New York, indicated PM (TSP and PM_{10}) concentrations were greatest during the blast cleaning phases due to emissions from both the blast agent and the surface (Zamurs and Bass, 2001). Another monitoring tool is the use of on-board measurement such as global positioning system (GPS) tracking units to monitor equipment locations, movements, and engine status (off, idle, or under load) during actual construction projects. These units are used by construction companies to assess the productivity of construction equipment and to prevent theft (Rea, 2008). GPS data, interviews, video recordings, and operation logs indicated non-road equipment activity among the Texas Department of Transportation (TxDOT) fleet was distributed between different task-based modes for selected graders: operations (70%), idling (20%), and driving (10%, see Lee, 2009).

Real-world field studies of construction equipment or transportation projects also employ camcorders and computer systems to collect activity data during typical duty cycles. For example, on-board activity data were collected in southern California for four graders, three dozers, three loaders, six backhoes, a compactor, and a scrapper used for street and flood control area maintenance operations, and typical landfill activities (Huai et al., 2005). Minimums, maximums, and means for daily operational time (20 minutes to 8 hours), the number of starts per day (3 to 11), and average percentage idle time (11% to 65%) were determined using onsite videotaping along with measured activity parameters: exhaust temperature and intake manifold absolute pressure (MAP), engine revolutions per minute (RPM), and throttle position (Huai et al., 2005). Equipment was idling 25% on average across the entire fleet (Huai et al., 2005). Activity patterns varied considerably, but distinct operating, idling, and engine-off modes were determined based on either the MAP or engine RPM curves (Huai et al., 2005). MAP was highly variable but consistently elevated above one atmosphere during operational mode; during idle mode, MAP was one atmosphere with small fluctuations and remained steady at one atmosphere during the engine-off mode (Huai et al., 2005). A profile for a grader used to grade dirt shoulders indicated activity occurred primarily in either idle or full throttle modes (Huai et al., 2005).

Similarly, several studies conducted by the North Carolina Department of Transportation tracked vehicle or equipment activity using a combination of 15-minute video recordings and simultaneous review of different operational modes by a research assistant observing the activity from a safe distance (Abolhasani, 2006; Abolhasani et al., 2008; Frey et al., 2008a; Frey et al., 2008b). Differences in task-oriented modes were observed for motor graders, excavators, backhoes, and front-end loaders to relate to differences in fuel use and engine load and, therefore, emissions. For example, fuel use increased by operational mode from less than 1 g/sec (low and high idle) to more than 2 g/sec (moving) and more than 4 g/sec (pushing) for one dozer studied (Frey et al., 2006). A study of three excavators found "emission rates during non-idle modes (i.e., moving and using bucket) were on average seven times greater than for the idle mode" (Abolhasani et al., 2008).

Modeling Activity Data

EPA's NONROAD model and ARB's OFFROAD model are macroscopic models used to estimate non-road emissions. Both models use an equation to calculate emissions based on the multiplication of engine population, average power, load factor, activity, and an emission factor (U.S. Environmental Protection Agency, 2004a; California Air Resources Board Mobile Source Emissions Inventory Program, 2007b). The NONROAD model provides default national engine populations for a given base year by power level and equipment and fuel type (U.S. Environmental Protection Agency, 2005b). Equipment activity and load factor in the EPA NONROAD model are estimated based on a national database developed using annual surveys of equipment owners to calculate usage by engine application and fuel type (U.S. Environmental Protection Agency, 2004b). The model can scale these estimates to state or county levels (U.S. Environmental Protection Agency, 2005b). OFFROAD estimates were designed to better represent California's non-road equipment fleet. Industry and government agencies were surveyed to inform the statewide base year population estimated in OFFROAD, and population and activity information are divided at the county and air basin levels (California Air Resources Board Mobile Source Emissions Inventory Program, 2007b).

Both NONROAD and OFFROAD were designed primarily as regional-scale emission inventory development tools. They are not as well-suited to prepare project-specific emission estimates. For example, contractor surveys found project-specific construction activity and equipment to be systematically lower than NONROAD model-predicted values (under-reporting suspected, see Baker, 2009). Further, the 1999 Houston survey results were found to be significantly lower than 2004 default NONROAD model populations, primarily due to fewer backhoe and skid steer loaders in the fleet (Eastern Research Group, 2005). Some studies applied adjustment factors to NONROAD population defaults, such as the ratio of county-level construction employment/total state construction employment to account for discrepancies between the model and real-world fleets (Eastern Research Group, 2005).

3. CONSTRUCTION EQUIPMENT EMISSIONS

In addition to equipment activities, pollutant emissions[3] from a single piece of construction equipment or a group of equipment must be adequately quantified in order to design and assess mitigation strategies for construction projects. Typically, emission rates are measured and calculated based on activity estimates by equipment type (equipment populations, annual hours of use, average rated horsepower, load factor) and emission factors in the form of average emissions of a pollutant per unit of use (e.g., equipment operating hour) for that engine type (U.S. Environmental Protection Agency, 1991, 1998; Kean et al., 2000). However, developing emission factors for construction equipment is difficult because (a) data may be limited in terms of the quantity and variety of engines and applications (Kean et al., 2000); (b) emissions can be affected by multiple factors that vary by equipment type (e.g., emissions from excavator engines vary by vehicle weight, duty cycle, and the terrain traveled, see Abolhasani et al., 2008); and (c) specific engine controls such as fuel injection timing may also affect emissions (Abolhasani et al., 2008). Published methods to estimate and measure emissions generally address some, although typically not all, of these variables.

During the 1970s and 1980s, measurement of non-road source emissions was based primarily upon single-engine testing conducted to aid development of early models and regulatory standards. The 1990 Clean Air Act Amendments (CAAA) motivated research to gain a better understanding of the non-road contributions to air pollution. CAAA mandates and increasing contributions of non-road sources to total emissions make better measurement of in-use emissions more important. In the following section, two major approaches for quantifying non-road construction emissions are summarized: (1) single-engine testing and (2) in-use/on-board measurement. Several modeling tools used for estimating construction equipment emissions are also described.

Single Engine Testing

Historically, non-road equipment and vehicle emissions were estimated by testing a single engine (U.S. Environmental Protection Agency, 1991, 1998; Kean et al., 2000; Frey et al., 2008a). After being removed from the vehicle, the engine is tested using a dynamometer test bed configured with additional components (such as intake and exhaust) to imitate operational systems (Gautam et al., 2002). Each engine is operated on the test bed either at constant speed

---

[3] Different definitions of hydrocarbon emissions were used in different studies:

- Total hydrocarbons (THC) = measured hydrocarbon emissions using equipment calibrated with propane (excludes oxygenated HCs such as alcohols and aldehydes);
- Total organic gases (TOG) = THC + alcohols and aldehydes;
- Non-methane hydrocarbons (NMHC) = THC – methane;
- Non-methane organic gases (NMOG) = TOG – methane;
- Volatile organic compounds (VOC) = TOG – (methane and ethane);
- Reactive organic gases (ROG) = TOG – ARB-exempt compounds (such as methane, ethane, and chlorofluorocarbons [CFCs]).

and load (i.e., steady state) for a specified time interval or following a predefined chassis dynamometer test (Frey et al., 2008a; Abolhasani et al., 2008; U.S. Environmental Protection Agency, 1991, 1998).

Single-engine testing is organized into different procedures, each of which consists of multiple modes to test various RPM levels. Testing emissions from non-road compression-ignition engines is regulated under Code of Federal Regulations (CFR) Title 40, Part 89 (Tier 3 and earlier) and Part 1065 (Tier 4). For example, the ISO-C1, an 8-mode test specified in CFR 40, part 89, and used for the EPA NONROAD model, tests the engine at rated RPM for different torque levels (100%, 75%, 50%, and 10% of maximum torque), again at an intermediate RPM and at each torque percentage, and finally at idle (Helmer et al., 2004; Abolhasani et al., 2008). Some weighted combination of the test modes is used to estimate average emissions (Abolhasani et al., 2008). However, there are known limitations to the single-engine testing method. For example, only the engine instead of the entire chassis is tested, and not all engine sizes can be simulated in the laboratory (Abolhasani et al., 2008). Therefore, single-engine tests do not always represent typical operation (Abolhasani et al., 2008)

Some initial single-engine testing efforts estimated that construction-related emissions contribute the following percentages of the total national inventory: 0.25% to 50% (volatile organic compounds, or VOCs), 0.5% to 25% (NO_x), 0.25% to 2.0% (CO), and 0.25% to 2.5% (PM, see U.S. Environmental Protection Agency, 1991). Emission factors were estimated for construction equipment, such as asphalt pavers, rollers, scrapers, and rubber-tired dozers, based on 8-mode procedures (ISO 8178) and weighting factors (U.S. Environmental Protection Agency, 1991). Studies testing post-1988 uncontrolled engines indicated PM emission factors were lower than in previous inventories and range from 0.4-0.72 g/hp-hr, on average (U.S. Environmental Protection Agency, 1998). More recent studies indicate that PM emission factors range from 0.07 to 1.60 g/hp-hr across a wide range of engine types and intended applications (Helmer et al., 2004). Some steady-state tests were conducted on multiple fuel types (U.S. Environmental Protection Agency, 1998; Helmer et al., 2004; Durbin et al., 2007) including a standard sulfur content and higher sulfur content. PM emissions were consistently lower when lower sulfur fuels were tested. A summary of findings from single-engine testing is provided in **Table A-1**.

To aid in the development of State Implementation Plans (SIPs) and to compare real-world data with emissions standards, ARB conducted a study combining real-world activity and emissions data with the single-engine testing approach (Gautam et al., 2002). The study collected on-board engine data from four non-road vehicles: (1) an Elgin Pelican street sweeper (51 to 120 hp), (2) a John Deere 444 rubber-tired loader (121 to 250 hp), (3) a Komatsu PC400LC3 excavator (251 to 500 hp), and (4) a Caterpillar D-11RCD bulldozer (>500 hp). The rubber tire loader operated in transport mode and loading/unloading (scoop) mode, and the excavator performed three operations (digging, hauling, trenching). Engine speed and tailpipe emissions were recorded in the field using a Portable Emissions Measurement System (PEMS). Measurements were compared to engine testing under steady-state operation (via a test called the "ISO 8178" 8-mode test cycle) to infer engine load and develop set points for dynamometer testing. The testing resulted in transient engine dynamometer test cycles developed to match in-field operation. Each vehicle had distinct operational modes involving transport, idling, and specific tasks. Differences were observed between transient and steady-state test emissions. The weighted emissions rates from the 8-mode test exceeded emissions recorded from transient operation; results were 100% to 550% higher for the loader and 10% to 70 % higher for the excavator (Gautam et al., 2002).

Table A-1. Summary of single-engine test literature including test parameters and study results.

Source	Equipment/Intended Application	Fuel	Test Cycles	PM Emission Factors	Comments
(U.S. Environmental Protection Agency, 1998)	18 engines, model year 1988-1995	0.03-0.28 (wt. %)	Steady state	0.2-1.5 g/hp-hr (0.4-0.72 g/hp-hr average)	PM levels were elevated when high sulfur fuels used
"Ten Engine Emissions Program" (SwRI # 08.03316) (Helmer et al., 2004)	10 engines, four-stroke, 7 to 850 hp (trucks, forklift truck, excavator, construction, utility)	2D diesel fuel, a high-sulfur non-road-2D diesel fuel, a California 2D fuel, ARCO®, "ECD" fuel	Steady state and transient	0.08-1.60 g/hp-hr weighted emissions	PM levels elevated when high sulfur fuels used
"Three Engine Program" (EPA Contract #68-C-98-169) (Helmer et al., 2004)	3 engines (forklift truck, construction, rubber tire loader)	2 diesel fuels	Steady state and transient	0.12-0.55 g/hp-hr	PM levels elevated when high sulfur fuels used
"Four In-Use Engines Program" (EPA Contract #68-C-98-158) (Helmer et al., 2004)	4 engines 160-420 hp (motor grader, excavator, tractor, boom excavator)	2 diesel fuels (1 high sulfur)	Steady state and transient	0.07-0.30 g/hp-hr	PM levels elevated when high sulfur fuels used
(Durbin et al., 2007)	2 medium-duty trucks, 2 Humvees, 1 heavy-duty diesel truck, 1 bus, 2 backup generators (BUGs), 1 forklift, and 1 airport tow vehicle	Ultra-low sulfur diesel (ULSD), 3 biodiesel blend ratios, biodiesel blends with NO_x reduction additives	Steady state	0.05-1.125 g/min	Biodiesel blends showed decreased PM emissions relative to ULSD

In-Use/On-Board Measurement

Studies recommend the use of on-board PEMS equipment to better represent typical operation and to develop more accurate transient cycles for dynamometer testing (Gautam et al., 2002). These systems can collect emission rates for a range of pollutants, including hydrocarbons (HC), NO, PM, CO, and CO_2, as well as engine parameters such as RPM and MAP (Frey et al., 2008a). Other studies also measured throttle position (Huai et al., 2005). "Semi-quantitative" PM measurement has been estimated with a light scattering technique (Abolhasani et al., 2008; Frey et al., 2008a). Datasets with in-use/on-board measurements enable evaluation of task-based modes as well as engine-based modes.

Published in-use studies have typically focused on vehicles and equipment that contribute the greatest to emissions[4] of NO_x, CO, and PM_{10} (Frey et al., 2008a; Lewis et al., 2009). The results are summarized in **Table A-2**. The major vehicles and equipment studied are tractors/loaders/backhoes, bulldozers, front end loaders, excavators, generators, motor graders, off-highway trucks, rubber tire loaders, and skid-steer loaders.

[4] Using the EPA NONROAD model (described in a later section of this appendix).

Table A-2. Summary of in-use test literature including test parameters and study results.

Literature	Method	Equipment [a]	Activities [b]	Engine Variables	Pollutants	Findings
(Muleski et al., 2005)	Time-integrating exposure profiling	Scrapers, trucks	Earthmoving (loading, unloading, transit, grading), truck loading, mud/dirt carryout	n/a	PM_{10} and $PM_{2.5}$	$PM_{2.5}$ concentrations were similar downwind and upwind, and only slightly variable with height. $PM_{2.5}$:PM_{10} ratios from scraper loading and unloading are highly variable. Scraper transit mode dominates PM_{10} emissions. AP-42 under-predicts PM_{10}. Truck loading emissions are much greater than truck dumping.
(Goldstein et al., 2007)	Dynamic Dilution On/Off-Road Exhaust Emissions Sampling System (DOES2) integrated sampling system (ISS)	Compressor with SCRT, bulldozer, excavator, and hydraulic drill with PDPF, quarry truck with ADPF, rubber tire loader with CRT-PDPF		engine intake flow, exhaust temperature, and engine RPM, MAP	PM, NO_x, HC, CO, CO_2, NH_3	ADPF installed on the quarry truck reduced PM by 45%. SCRT-equipped compressor reduced PM by over 95% and NO_x by over 65%.
(Abolhasani et al., 2008)	PEMS	3 excavators (diesel engines, 76-300 hp)	Excavating dirt and lifting objects on flat and hilly terrain	MAP, engine speed (ES), intake air temperature (IAT)	NO, HC, CO, PM (light scattering)	Weak relationship between PM emissions rates and engine variables (R^2=0.1-0.6). Average emissions during non-idle modes greater than idle modes. Average emissions change more with intercycle variability than intervehicle variability. PM measurements less than NONROAD estimates.

Literature	Method	Equipment [a]	Activities [b]	Engine Variables	Pollutants	Findings
(Frey et al., 2008a)	PEMS	6 motor graders (2 Tier 0, 2 Tier 1, 1 Tier 2, 1 Tier 3)	Resurfacing, shouldering, roading	MAP, ES, IAT	CO_2, CO, HC, NO_x, PM	MAP was the most explanatory variable for fuel use and emission rates. PM emission rate correlation with MAP was 89%. Increase in MAP indicates increase in fuel use and emissions. Different modes were observed.
(Lee, 2009)	PEMS	4 graders	Task-based duty cycles: idle, max speed, 20 mph, leveling, backup		CO_2, CO, NO_x, HC, PM	PM emissions ranged from <0.5 mg/s (idle) to 1.5 mg/s (driving at max speed). Maximum speed and leveling activity resulted in the highest emission rates for PM, CO, and HC.
(Lewis et al., 2009)	PEMS	Backhoe, bulldozer, excavator, front-end loader, generator, motor grader, skid-steer loader, off-road truck	Idling, moving (forward reverse), using an attachment (bucket or blade)	MAP, IAT, RPM	NO_x, HC, CO, PM	PM emission factor ranges were reported for the backhoe (0.66-1.7), front-end loader (0.49-1.0), and motor grader (0.53-1.1) in g/gal. Comparisons of average emission factors were comparable to NONROAD

[a] Equipment can be fitted with different emissions reduction technologies, including Passive Diesel Particulate Filter (PDPF), Active Diesel Particulate Filter (ADPF), Selective Catalytic Reduction + PDPF (SCRT), and Continuously Regenerating Technology (CRT)

[b] Resurfacing refers to the use of most or all of the blade length to reshape and repair ruts in the surface of an unpaved road. Shouldering refers to the use of a portion of the blade length to scrape and grade the shoulders and ditches beside a paved road. Roading refers to transport of a motor grader from one work location to another. Resurfacing typically has a higher engine load compared with shouldering or roading because a large portion of the blade is in contact with the ground (Frey, 2008). Moving is forward/reverse movement under engine power; blade requires contact between blade and material on the ground while under engine power, and idle requires the engine to be on but performing no work or movement.

Alternative Approaches

As an alternative to single-engine testing or in-use measurements, some studies have used fuel consumption information to estimate non-road diesel engine emissions, as well as heavy-duty diesel truck emissions (Kean et al., 2000; Singer and Harley, 2000). For example, one study team (Kean et al., 2000) estimated emissions inventories for different applications, including construction, based on multiplying the total amount of consumed diesel fuel by an emission factor that was normalized by fuel consumption. In this study, fuel consumption information was obtained from the Annual Fuel Oil and Kerosene Sales Report conducted by the Energy Information Administration of the Department of Energy, and emission factors were obtained from EPA's NONROAD model. Based on this estimation approach, non-road resources in the United States were shown to contribute 122,400 tons of PM_{10} emissions and 1,224,000 tons of NO_x emissions in 1996 (Kean et al., 2000).

Emissions Modeling Tools

Several modeling tools have been developed to assist in estimating emissions from non-road sources at different scales of interest. EPA's NONROAD2008 model, released in April 2009, estimates emissions inventories for non-road engines, equipment, and vehicles for several categories, including construction (U.S. Environmental Protection Agency, 2005a). Tailpipe emissions of six pollutants (HC, NO_x, CO, CO_2, SO_x, and PM) are estimated for each specific equipment type based on equipment population, average load factor, available power (hp), activity (hours of use), and emission factor embedded in the model. Emissions are allocated over time and geographical areas to several possible scales: national, state, county, and sub-county.

Similar to the NONROAD model, the ARB OFFROAD model estimates pollutant emissions of California's non-road mobile sources, including 27 types of construction equipment (California Air Resources Board Mobile Source Emissions Inventory Program, 2007a). The latest version (OFFROAD2007) can be run for different time periods (annual, seasonal, or month) and scales (statewide, air basin, air district, and county). The three main modules are population, activity, and emission factor. The model runs as a desktop application with a graphical user interface (GUI) to manipulate the input parameters and underlying model functions.

In addition to using officially approved emissions models, air quality agencies and researchers have also developed specific modeling tools for local emissions assessment. For example, the Sacramento Metropolitan Air Quality Management District (SMAQMD) developed a spreadsheet tool, the Road Construction Emissions Model (latest version 6.3.1), to assist with estimating emissions from construction projects (Jones & Stokes and Rimpo and Associates, 2009). Emissions are calculated by project phase and for the overall project lifetime. A data entry sheet requires user input of project specifications, including name and start year, project type (new road construction, road widening, or bridge/overpass construction), the time length and acreage of the project, truck capacity involved, and expected soil volume. Optionally, the user can update model default values for time length and number of vehicles involved in different project phases, and equipment defaults (hp, load factor, and hours/day) for each type.

The inputs are used to estimate emissions of ROG, CO, NO_x, PM_{10}, $PM_{2.5}$, and CO_2 for different project phases (land clearing, grading/excavation, drainage/utilities/sub-grade, and paving).

The University of California, Davis (UC Davis) and Caltrans jointly developed a spreadsheet tool for assessing emissions reductions from replacement or retrofits of older diesel non-road construction equipment used in transportation projects (Wang et al., 2008). Based on the underlying emission factors from ARB's OFFROAD2007 model and user-specified equipment characteristics (e.g., equipment type, model year, hp, and population), as well as expected replacement and/or retrofitting information, pollutant emissions (NO_x, PM, CO, THC, and CO_2) can be calculated for a base case (prior to any modifications) and scenarios with retrofits/replacements being implemented. Six priority equipment types are included in the modeling tool: roller, rubber tire loader, grader, generator set, scraper, and tractor/loader/backhoe. Case studies using this modeling tool suggested that replacing and retrofitting old construction equipment with brand new equipment would reduce 83% of project level PM emissions by 2010 and result in 10% to 25% regional-scale PM emission reductions by 2015 (Wang et al., 2008).

4. MITIGATION MEASURES AND STRATEGIES

The first tier of federal non-road equipment emission standards began to be phased in during model year 1996; full implementation for certain hp categories was achieved in model year 1996. Over time, regulations covered equipment across broader hp categories and more stringent emission reduction mandates (Tiers 2 through 4). The most stringent standards in place as of this writing are Tier 4 requirements that phase in through 2014 (as shown in **Table A-3)**.[5]

Standards are separated into four tiers and specify the maximum allowable tailpipe exhaust emissions of different pollutants based on engine horsepower and model year (U.S. Environmental Protection Agency, 2004b). The Tier 4 standards, estimated to impact over 650,000 pieces of equipment sold in the United States, require that emissions of PM and NO_x be further reduced by approximately 50% and 90%, respectively, compared with the current Tier 3 emission standards (Abolhasani et al., 2008).

Table A-3. Summary of diesel emission standards by Tier, phase-in period, and model year. adapted from U.S. Environmental Protection Agency (2004b)

Tier	Phase-in Period	Applicable Model Year	Primary Technology
1	1996-2000	1996-2005	Advanced engine design
2	2001-2006	2001-2010	
3	2006-2008	2006-2012	
4 (transitional)	2011	2008-2013	After-treatment control
4 (final)	2013	2013+	

[5] For further information, see EPA materials available via the National Clean Diesel Campaign (www.epa.gov/cleandiesel), and EPA's non-road diesel equipment website (www.epa.gov/otaq/regs/nonroad/equip-hd).

Regulations that mandate new-equipment emission standards decrease allowable emissions from new engines but are not retroactive to the pre-existing fleet. Older diesel-powered engines, which are often purchased by smaller firms from large construction companies, can remain in operation for many years (Schattanek and Weaver, 2005). Therefore, older equipment will still contribute to PM and NO_x emissions after Tier deadlines; it may take more than two decades before the existing fleet is fully retired (U.S. Environmental Protection Agency, 2004b).

In this section, several mitigation options are identified as being available to reduce emissions from non-road construction vehicles and equipment; these options include operational control strategies, after-treatment and exhaust control measures, dust control measures, and creation of buffer zones that appropriately separate sources and receptors. Example applications of the mitigation options in practice are also highlighted. The application of different options may depend on available funding, as well as on the size of the project and business. Some options may be implemented independently, while others require a combination of multiple technologies or upgrades. For compliance programs as well as SIP development, EPA and ARB recognize verified retrofit technologies, including after-treatment devices, fuel modifications, and repower/replacement techniques. **Table A-4** summarizes EPA-verified emissions reduction potential by control strategy (e.g., equipment retrofits and fuels changes). **Table A-5** summarizes EPA-verified emissions reduction potential by control system manufacturer.

Table A-4. Summary of EPA-verified non-road diesel engine retrofit strategies.

Reduction Type	Reduction Strategy	Pollutants Reduced (%)			
		PM	NO_x	HC	CO
Retrofit Technologies					
	Diesel particulate filters (DPFs)	55-90		55-90	55-90
	Diesel oxidation catalysts (DOCs)	10-50		50+	50+
	Closed crankcase ventilation (CCV)	10			
	Selective catalytic reduction (SCR)	25	60		
	Exhaust gas recirculation (EGR)	Potential with DPF	25-50		
Fuel Technologies					
	Low-sulfur fuels:	5-9			
	ULSD – (15 ppm required on road)				
	Most non-road diesel applications – 500 ppm				
	Emulsified diesel	16-58	9-20		
	Replacing equipment with electric, hybrid, or alternative fuel	Typically, NO_x, PM, HC, CO.			
Repower and Replacement Technologies					
	Equipment replacement	Typically, NO_x, PM, HC, CO.			
	Repower (replace old engine with new engine)	Typically, NO_x, PM, HC, CO.			

Source: Adapted from EPA retrofit verification information (see: http://www.epa.gov/cleandiesel/construction/strategies.htm).

Table A-5. Summary of EPA-verified products by manufacturer for non-road and on-road diesel-powered engines or equipment.

Manufacturer	Technology	Applicability			Reductions (%)			
		Model Year	Non-road	Highway	PM	CO	NO_x	HC
BASF (formerly listed under Engelhard)	CMX catalyst muffler	unknown		✓	20	40	n/a	50
Caterpillar, Inc.	DPF	1996-2005	✓		89	90	n/a	93
Caterpillar, Inc.	Emissions upgrade group	1988-1995	✓		22	13	37	71
Cummins Emission Solutions	DOC and CCV system	1991-2003		✓	30 [a]	50	n/a	74
Donaldson	Series 6000 DOC and spiracle (closed crankcase filtration system)	1991-2003		✓	25 to 33 [a]	13 to 23	n/a	50 to 52
Donaldson	Series 6100 DOC	1991-2003		✓	20 to 26	38 to 41	n/a	49 to 66
Donaldson	Series 6100 DOC and spiracle (closed crankcase filtration system)	1991-2003		✓	28 to 32 [a]	31 to 34	n/a	42
Engine Control Systems (ECS)	Purifilter Plus (DPF+ electrical panel for active regeneration)	1994-2006		✓	90	75	n/a	85
Engine Control Systems	Purifilter - Diesel particulate filter	1994-2003			90	75	n/a	85
Engine Control Systems	AZ Purimuffler or AZ Purifier	1991-2004		✓	40 [a]	60	n/a	75
	DOC with ECSclosed crankcase ventilation and low sulfur diesel (LSD)							
Engine Control Systems	AZ Purimuffler or AZ Purifier	1991-2003		✓	40	40	n/a	70

Manufacturer	Technology	Applicability			Reductions (%)			
		Model Year	Non-road	Highway	PM	CO	NO_x	HC
	DOC with LSD							
Engine Control Systems	AZ Purimuffler or AZ Purifier.	1991-2003		✓	35	40	n/a	70
	plus DOC with LSD							
Engine Control Systems	AZ Purimuffler or AZ Purifier.			✓	20	40	n/a	50
International Truck & Engine Corp.	Green diesel technology - low NO_x calibration	1993-2003		✓	0 to 10	10 to 20	25	50
	plus DOC with ULSD							
Johnson Matthey	Advanced Catalyzed Continuously Regenerating Technology (ACCRT) System	2002-2006		✓	90	50	n/a	n/a
Johnson Matthey	Continuously Regenerating Technology3 (CRT3) particulate filter	1994-2006		✓	90	72	n/a	93
Johnson Matthey	CEM™ Catalytic Exhaust Muffler and/or DCC™ Catalytic Converter	1991-2003		✓	20	40	n/a	50
Lubrizol	PuriNOx water emulsion fuel		✓	✓	16 to 58	-35 to 33	9 to 20	-30 to -120
Various	Biodiesel (1-100%)			✓	0 to 47	0 to 47	-10 to 0	0 to 67
Various	Cetane enhancers			✓	n/a	n/a	0 to 5	n/a

[a] Total PM reduction figures reflect reductions from both tailpipe and crankcase emissions.

Most technologies have additional specifications, including equipment/vehicle duty type (e.g., heavy duty, medium duty) and cycle (two or four cycle). Table A-5 is adapted from EPA data available online as of March 2010 (see: http://www.epa.gov/oms/retrofit/verif-list.htm).

Exhaust Control Measures

Mitigation measures to reduce equipment exhaust emissions are typically associated with equipment operations, fuel modifications, and add-on technologies. Examples of operational control options, implementation, costs, benefits, and sources are summarized in **Table A-6**. Three key operational control measures include (1) minimizing idle time and reducing acceleration from idle, (2) performing preventative maintenance, and (3) training operators.

Table A-6. Example application of operational/management emission control options.

Control	Implementation	Potential Costs	Benefits	Sources
Reduce idle time	Develop an idling policy and raise awareness through training. Install idle management systems (automatic shut-down).	Low administrative costs, monitoring equipment costs	Pollutant reductions, short payback period, lower fuel costs, less engine maintenance, and extended engine lifetime	(U.S. Environmental Protection Agency, 2006; STAPPA/ALAPCO, 2006; ICF International, 2007; U.S. Environmental Protection Agency, 2007; Lewis et al., 2009)
Use restrictions	Develop a voluntary and/or mandatory equipment restriction program on days with high predicted ozone/PM.	Potential project cost increases	Pollutant reductions	(Metropolitan Washington Council of Governments, 2004)
Preventative maintenance	Develop a routine maintenance strategy covering equipment lifetime, track equipment health using software or spreadsheets, train operators to identify problems.	Low administrative costs, may include tracking software costs	Pollutant reductions, lower fuel costs, less engine maintenance, and extended engine lifetime	(ICF International, 2007)
Fleet rating system	Implement a fleet rating system to rank equipment fleets based on management practices and energy and emissions performance.	Administrative costs	Help contractors and fleet managers identify possible areas for improvement, identify emissions reductions, incorporate new technologies	(Lewis et al., 2009)
Operator training	Classroom and hands-on training programs	Upfront training programs—cost varies	Pollutant reductions, increased operator efficiency, less fuel usage	(ICF International, 2007; U.S. Environmental Protection Agency, 2007)

Idling results in pollutant emissions and contributes to inefficient combustion that damages engine components and requires additional maintenance. Construction equipment idling typically occurs due to several practices: operators allow idle time during engine warm-up or cool-down periods; equipment may sit at idle before their intended operation can (such as trucks idling prior to entering a site to load/unload materials); and equipment may be left idling during inactivity (such as operator breaks).

Minimizing equipment idle time is relatively a low-cost operational strategy to reduce emissions and fuel consumption; extending engine lifetimes is an added benefit. Depending on fleet size and characteristics, reducing idle time has shown to decrease company expenditures by $18,000 to $80,000 annually (ICF International, 2007). Additionally, less idle time can reduce noise pollution at a construction site. Inexpensive training of workers and managers can lead to the establishment of operational practices that reduce idle time. If idling occurs to maintain driver comfort, such as heating or cooling in extreme environments, alternate power options can be considered. For example, auxiliary power units (APU), typical for on-road vehicles, can be installed for some non-road equipment; prices for APUs range from $500 to $9,000 (ICF International, 2007).

Poorly performing engines may lead to increased emissions. A study of on-road diesel engines determined that various engine problems resulted in 85% more PM emissions (ICF International, 2007). A preventative engine maintenance strategy, including employee training, routine inspection, and documentation of equipment health (perhaps with tracking software) can reduce operational expenditures and pollutant emissions.

Operator training (e.g., opportunities to reduce unnecessary idling) can reduce emissions, maintenance requirements, and fuel costs, as well as improve worker safety and productivity. Programs vary in time length and cost and are offered for different types of construction equipment. One study estimated the typical 2.5-day Caterpillar course costs $1,500 per person. Courses are also offered from Bobcat Co., and VISTA Training, among others.

Example fuel-related strategies, implementation, costs, benefits, and sources are summarized in **Table A-7**. Key fuel-related strategies include (1) use of reduced sulfur fuel (low or ultra low sulfur diesel), (2) use of biodiesel, and (3) use of water-in-diesel emulsions. Additional options are also discussed.

In response to on-road and non-road equipment and vehicle regulations, cleaner diesel fuels with low sulfur content (LSD) or ultra-low sulfur content (ULSD) are commercially available (STAPPA/ALAPCO, 2006). Prior to regulation, typical non-road diesel fuel contained 3000 to 5000 ppm sulfur content. The sulfur content of LSD is 16 to 500 ppm, while ULSD contains ≤15 ppm sulfur. In 2007, the sulfur content of fuels in non-road equipment was reduced to 500 ppm; further reduction to 15 ppm is required in 2010[6]. Depending on the baseline fuel (e.g., typical non-road diesel or LSD), using ULSD will reduce direct PM emissions from 5% to 9% and increase the effectiveness of after-treatment technologies (ICF International, 2007). For

[6] More information on fuel sulfur control requirements is available online at: http://www.epa.gov/otaq/highway-diesel/regs/2007-heavy-duty-highway.htm.

example, using ULSD with diesel particulate filters (described in the next section) combined with oxidation catalysts can result in 55% to 90% PM reductions (ICF International, 2007).

Table A-7. Example application of fuel-related strategies.

Control	Implementation	Costs	Benefits	Sources
Sulfur content	Switch to ULSD fuel. Same fuel storage tanks and systems can be used.	May be more expensive than petroleum diesel. May require filter changes after initial fuel switch.	Reduce direct PM emissions (5% to 9%), increase effectiveness of retrofit technologies, reduce engine wear (note, however that ULSD fuel use is mandatory effective 2010)	(STAPPA/ALAPCO, 2006)
Biodiesel/blend (defined in main text)	Switch to biodiesel fuel.	Pure biodiesel is 1.5-2.0 times more expensive than petroleum diesel. B20 blend costs \$0.05-\$0.10/gallon more than petroleum diesel base. Potential warranty concerns due to fuel injector damage. Potential NO_x increase 0 to 10%.	0-50% $PM_{2.5}$, HC, and CO reductions, may be more cost-effective as petroleum diesel prices increase	(STAPPA/ALAPCO, 2006)
Emulsions (defined in main text)	Emulsified diesel blended at fuel suppliers and/or on-site.	\$0.01-\$0.20/gallon greater than petroleum diesel. Fuel consumption increased (10% to 20%). Potential HC and CO increase 0-35%.	5% to 30% NO_x reduction, 20% to 50% $PM_{2.5}$ reduction	(Schattanek and Weaver, 2005)

Biodiesel is derived from vegetable oils or animal fat; it is high in oxygen and has low sulfur content (STAPPA/ALAPCO, 2006). The additional oxygen in the biodiesel may decrease $PM_{2.5}$ emissions up to 50% and increase NO_x emissions up to 10%. Biodiesel can be pure vegetable oil (B100) or diluted with petroleum diesel to maximize $PM_{2.5}$ reduction and limit NO_x increases. Typically, a blend with no greater than 20% biodiesel is preferred (B20). B20, and biodiesel in general, is acceptable for most diesel engines but may require fuel filter changes after initial use. Biodiesel use has been excluded as an effective mitigation measure in past projects due to its potential for increasing NO_x emissions (Schattanek and Weaver, 2005).

Petroleum diesel fuel can also be blended with water, typically up to 20%, to create emulsified diesel (ED) fuel (STAPPA/ALAPCO, 2006). The water content lowers NO_x emissions by decreasing combustion temperatures and also decreases $PM_{2.5}$ emissions due to increased fuel atomization (STAPPA/ALAPCO, 2006). Studies in Connecticut have suggested that PuriNOx, an emulsified diesel fuel manufactured and distributed by Lubrizol Corp., is beneficial because it is applicable across diesel engines, it requires no engine modifications, and it offers EPA-certified emissions reductions—16% to 58% for PM and 9% to 20% for NO_x (Schattanek et al., 2002; Schattanek and Weaver, 2005).

Another option is use of synthetic diesel fuels, which are manufactured from natural gas using the Fischer Tropsch process (STAPPA/ALAPCO, 2006) and may be used in any diesel engine without modification (STAPPA/ALAPCO, 2006). Limited information was available regarding commercial retail availability of synthetic diesel products and their potential benefits and costs.

"After-treatment" technologies, which are placed in a vehicle's exhaust system and control tailpipe emissions, are not directly associated with the engine or a fuel and differ from specific engine design strategies (e.g., EGR, engine injection timing/pressure, and natural gas engines (STAPPA/ALAPCO, 2006). The devices typically target PM or NO_x from engine exhaust before it is emitted to the atmosphere (STAPPA/ALAPCO, 2006; ICF International, 2007; U.S. Environmental Protection Agency, 2003, 2007). DOC and DPF are the most common selection, but several additional options are also applied in practice, such as four-way catalysts, lean catalysts, SCR, and closed crankcase emissions filtration. These technologies are summarized in **Table A-8**.

Table A-8. Engine modifications and exhaust after-treatment control strategies.

Control	Implementation	Costs	Benefits	Sources
DOC	Installation required to add device to vehicle exhaust system (several hours)	Relatively inexpensive ($1000-$2000 per truck engine).	10% to 30% $PM_{2.5}$ reductions, 20% to 50% HC and CO reductions	(U.S. Environmental Protection Agency, 2003; STAPPA/ALAPCO, 2006; ICF International, 2007; Storey, 2009)
DPF (active or passive)	Installation to vehicle exhaust system (<5 hours)	More expensive than DOC ($5000-$10,000 per truck engine). Can increase the ratio of NO_2 to NO.	80% to 90% $PM_{2.5}$, 60% to 93% HC and CO reductions	(STAPPA/ALAPCO, 2006; ICF International, 2007; Storey, 2009)
SCR	Installs on most diesel engines; often requires urea tank, pump, injector, and pressure/temperature monitors.	SCR systems can cost $10,000-20,000 per truck engine plus additional parts and reductant (urea) supplies.	60% NOx reduction, potential HC, CO and $PM_{2.5}$ reductions in combination with DPF or DOC	(STAPPA/ALAPCO, 2006)
EGR	Install EGR system. May require installation of DPF and/or upgrades to engine cooling system.	Can cost $10,000-15,000 when DPF is also required. May require upgrades and increase maintenance costs.	30% to 40% NO_x reduction, potential HC, CO, and $PM_{2.5}$ reductions in combination with DPF or DOC	(STAPPA/ALAPCO, 2006)

A DOC is typically a honeycomb-like structure containing a metal or ceramic wall coated with a metal catalyst such as platinum or palladium (U.S. Environmental Protection Agency, 2003; STAPPA/ALAPCO, 2006; Storey, 2009). The catalyst encourages chemical reactions in the exhaust that oxidize PM, HC, and CO to produce CO_2 and water. DOCs typically cost less than DPFs (approximately $1000-$2000 for a truck engine) and can be installed on most diesel engines. Installation is also quick (several hours) and relatively simple (U.S. Environmental Protection Agency, 2003). However, DOC devices on their own do not reduce NO_x emissions and require lower sulfur fuels (STAPPA/ALAPCO, 2006; ICF International, 2007). Based on the EPA technology retrofit list, oxidation catalysts are expected to achieve a minimum of 20% reductions for PM, 40% reductions for CO, and 50% reductions for HC in all heavy-duty diesel engines (ICF International, 2007). Toxics such as benzene and formaldehyde may also be reduced by up to 70% (Kasprak et al., 2001).

A DPF combines a DOC to capture the wet or gaseous components of exhaust with a porous filter (typically ceramic, metal mesh, or silicon carbide) to target solid particles in the engine exhaust. Trapped particulates are then oxidized with the aid of a catalyst. ADPFs and passive DPFs are both commercially available. ADPFs employ a heating mechanism, typically fuel injection, to raise the temperature in the filter and promote carbon oxidation in a more extensive set of duty cycles (STAPPA/ALAPCO, 2006).

DPF and ADPF technologies are estimated to reduce PM emissions by approximately 90%, HC emissions by 60% to 90%, and CO emissions between 60% and 90% (ICF International, 2007). However, both DPFs and ADPFs restrict exhaust and can cause ash and carbon to collect in the filter. Therefore, additional yearly maintenance and back-pressure monitoring systems are required. Further, DPF technologies may not be cost-effective for older engines (i.e., pre-1994) or for engines with lightly loaded duty cycles, in which temperatures do not exceed the 210-to-300°C minimum threshold 40% of the time (Schattanek and Weaver, 2005; STAPPA/ALAPCO, 2006). While ADPFs will likely work for a wider range of engine types, they are more complicated and require additional components. Both technologies require fuels with <50 ppm sulfur content. DPF and ADPF technologies cost from $5000 to $10,000 for a standard truck engine.

Dust Control

In addition to exhaust control for construction equipment, mitigation procedures at construction sites have traditionally focused on reducing windblown fugitive dust emissions and reducing dirt trackout that increases silt loads on adjacent roads and contributes to re-entrained road dust. For example, in Maricopa County, Arizona, under Rule 310[7], "control of trackout is required for all work sites having a disturbed surface area of at least five acres or from which 100 cubic yards of materials are hauled each day." Large studies have indicated that re-suspended dust from trucks entering or exiting construction sites contributes most significantly to elevated PM_{10} concentrations (Kasprak et al., 2001). Certain practices and control measures can be used to limit fugitive and nuisance dust from construction operations. Strategies to limit deposition and transport include surface treatments (wet suppression, soil binding agents, gravel or crushed stone beds) and material management (cover piled materials, cover material in transport, install wind screens, see Kasprak et al., 2001; Schattanek et al., 2002; STAPPA/ALAPCO, 2006). Many of these techniques have been in use for years, and state departments of transportation have incorporated these actions into construction best practices guides.[8] **Figure A-3** illustrates site actions to suppress dirt trackout.

[7] ADOT, (http://tpd.azdot.gov/air/blueskies/FB%20English.pdf). To facilitate dust control, ADOT instituted control training programs (e.g., see http://tpd.azdot.gov/air/blueskies/main.htm).

[8] See, for example, California Department of Transportation guidelines at http://www.dot.ca.gov/hq/construc/stormwater/BMP_Field_Manual_Master_5x8_revision5.pdf.

Figure A-3. Example gravel pad and "grizzly" (grate) at construction site entrance.

Buffer Zone

Construction projects have also employed strategies to minimize exposure by increasing the distance between emission sources and receptors (i.e., places where people are exposed to ambient air pollution). Near-road pollutant concentrations decline substantially within 100 to 150 m of the road, and can reach near background conditions at approximately 300 to 500 m from the road (e.g., Zhu et al., 2002). Therefore, one opportunity to mitigate the impact of emissions is to increase the size of available buffer zones that separate sources and receptors. Prior to construction activity, sensitive locations near the construction site, such as residences, hospitals, schools, and areas with high pedestrian traffic, should be identified. Project planners and contractors may then situate buffer zones between construction activity and sensitive areas to safeguard public health. Previous projects have contractually limited the number of truck entrances/exits at sites, located vehicle access points farther from sensitive areas, used embankments to buffer material stockpiles and haul roads, and maintained adequate distance between construction and building air inlets—e.g., windows and air intakes (Kasprak et al., 2001; Schattanek et al., 2002).

Practical Examples of Mitigation Strategies

The following section details the practical application of the strategies and technologies described above to projects of different scale around the country.

National and State Incentives—CMAQ, Carl Moyer, and Texas Retrofit Programs

Funding sources at the national level are available for reducing emissions from non-road construction equipment (Manufacturers of Emission Controls Association (MECA), 2006). The Congestion Mitigation and Air Quality (CMAQ) Program provides federal funding on the order of $1.4 billion per year for retrofits of on-road and non-road diesel engines used in construction projects. The projects must occur in air quality nonattainment or maintenance areas. Funds are typically controlled at the state and local level, most often by metropolitan planning organizations. Other state-specific funds are also available. This discussion profiles programs in California and Texas.

The ARB Carl Moyer Memorial Air Quality Standards Attainment Program (CMP) provides grants to projects involving mobile sources of air pollution (on-road, non-road, marine, locomotive, and stationary agricultural pump engines). Eligible engines and equipment must achieve[9] "cleaner-than-required and early or extra emission reductions." Incentives from the program help California achieve NO_x, PM, and ROG emissions reductions and satisfy clean air commitments under the SIP. The Carl Moyer Program has administered several million dollars annually since 1998. In 2009 and 2010, the program was evaluating potential administrative procedures to maintain program efficiency as well as the quantity of eligible projects in light of changing regulations and the economy.

The Texas Commission on Environmental Quality (TCEQ) administers the Texas Emissions Reduction Plan (TERP) which enables individuals, businesses, and/or local governments to reduce vehicle and equipment emissions[10]. Emissions reduction incentives, rebates, and new technology research and development grants are open for applicants at different times of the year depending upon available funds. For example, a field project was conducted in Houston in 2000 and 2001 to demonstrate the effectiveness of several emissions control technologies and fuel options (Manufacturers of Emission Controls Association (MECA), 2006). Twenty-nine units were field tested, including a Gradall G3 WD excavator specific to construction activities. The Gradall was outfitted with three different technologies and achieved the following Total Particulate Matter (TPM) percentage reductions from baseline: DOC + emulsified diesel fuel (76%), an SCR system (27%), and a combined DPF + SCR system (92%). As a result, the city of Houston received $500,000 of TERP and CMAQ funding to install SCR systems on 33 rubber tire excavators and a dump truck, install a DOC on 30 to 40 non-road engines (backhoes and water pumps), and perform chassis dynamometer emission testing at the University of Houston.

Oregon—Construction Equipment Emissions Reduction Project

The Oregon Environmental Council (OEC) provided matching funds to an EPA grant to reduce diesel emissions from construction equipment in the City of Portland by 20% (West Coast Collaborative, 2009). Diesel emitted from construction equipment is estimated to contribute 90% of added cancer risk and a third of total diesel emissions in the state (more than on-road sources). The strategies planned include using cleaner fuels, performing engine retrofits, and adjusting operations (e.g., less idle time).

Boston Big Dig (Kasprak et al., 2001; Schattanek et al., 2002; Ginzburg et al., 2006)

Boston's Central Artery/Tunnel (CA/T) or "Big Dig" project began in 1992 (concluded 2007) and included an 8- to 10-lane expressway built underground through downtown Boston, a 4-lane tunnel under Boston harbor, and a 10-lane bridge spanning the Charles River. The activity neighbored sensitive locations and took place in an ozone nonattainment area.

---

9 http://www.arb.ca.gov/msprog/moyer/moyer.htm
10 http://www.tceq.state.tx.us/implementation/air/terp/

Therefore, a Construction Air Quality Committee (CAQC) comprised of members of the Federal Highway Administration (FHWA), Massachusetts Highway Department (MHD), EPA, Massachusetts Department of Environmental Protection (MDEP), and the City of Boston guided several major mitigation efforts, costing approximately $30 million through 2004, that were applied before and during construction.

Dust Control: A Dust Control Specification required contractors to apply measures to reduce dirt tracking and nuisance dust. The requirements included wet suppression techniques (or calcium chloride in freezing conditions), soil binding agents, wind screens, stockpile coverings, and covers for material during transport in dump trucks. Additional measures were employed on a contract-specific basis. The contracts limited the number of truck entrances/exits at sites. Dust was minimized in truck loading areas by using a crushed stone base. In addition, stockpiles and haul roads were separated from receptor areas by embankments. Dust control measures were evaluated through pollutant monitoring and dust inspection. Monitoring of PM_{10} in early phases of the project helped establish baseline concentrations for comparison with later construction. Dust inspection in later stages concluded that while pollutant increases were limited to areas close to construction, trucks traveling in or out of a site were the greatest contributors to dust (re-suspended) and elevated PM concentrations.

Odor Control: A Construction Odor Control Specification was established in order to limit diesel emissions, and therefore odor, impacting nearby communities, hospitals, and the public generally. The requirements included operational strategies such as keeping equipment properly tuned and reducing idle time for inactive equipment and trucks in queue to load/unload. The loading zones were also staged in areas to minimize public impacts, and equipment was buffered from air inlets to buildings, including intakes, air conditioning units, and windows.

Retrofit Program: Hundreds of pieces of diesel equipment including bulldozers, excavators, cranes, and generators were used in a variety of construction activities (excavation, utility relocation, demolition, street restoration, etc.). A voluntary program beginning in 1998 and divided into two phases resulted in retrofits on more than 100 pieces of diesel equipment. Both phases focused on high impact equipment used near sensitive locations and scheduled for use over the longest period of time. Diesel oxidation catalysts were selected over diesel particulate filters to maximize reductions in HC, CO, and PM as well as to minimize installation time, maintenance, and cost. Phase 1 successfully retrofit eight pieces of equipment and showed that minimal downtime (i.e., 2 hours) was required for installation. Following Phase 2, oxidation catalysts were installed on more than 200 pieces of equipment. The protocol recommended by the Northeast States for Coordinated Air Use Management (NESCAUM) for SIP calculations was used to estimate emissions reductions for the start and end of post-retrofit construction (years 2000 and 2004): 90 kg/day of CO, 30 kg/day of HC, and 7.4 kg/day of PM_{10}. Reductions of twice these levels were predicted during 2001-2002.

Connecticut I-95 (Schattanek et al., 2002; Schattanek and Weaver, 2005)

The I-95 New Haven Harbor Crossing (I-95 NHHC) project, managed by the Connecticut Department of Transportation (CDOT), began in 2002 with an estimated 12 years to completion. The project includes a 10-lane bridge replacement to serve a predicted 140,000 to 150,000 vehicles by 2015, a new rail station, and a roadway reconstruction/widening. Three municipalities in an ozone nonattainment area (Serious) are affected by the construction: New Haven, East Haven, and Branford. New Haven is also nonattainment for PM_{10} and $PM_{2.5}$. An air quality working group was formed approximately one year prior to the project's start date comprised of members of CDOT, Parsons Brinckerhoff (PB), NESCAUM, Connecticut Department of Environmental Protection (DEP), Department of Motor Vehicles (DMV), and Connecticut Construction Industries Association (CCIA).

The working group's "Connecticut Clean Air Construction Initiative" linked I-95 NHHC to a diesel emission control program, including a retrofit program, to reduce diesel emissions. An estimated 200 pieces of diesel equipment were to be used during five phases of construction. At the time the project began, the existing fleet ranged from new to older equipment (circa 1980s, on average). In 2001, a cost-benefit analysis was conducted to review four potential control technologies: (1) oxidation catalysts and/or (2) four-way catalysts (After Treatment/Add-on), (3) Biodiesel B-20 Blend and/or (4) PuriNOx fuels (Fuel Strategy). Based on predicted emissions calculated from the EPA NONROAD model, the oxidation catalyst and PuriNOx strategies provided the greatest potential reductions. Fitting 222 units with oxidation catalysts was predicted to reduce annual emissions of CO by 93.4 tons/year, HC by 35.2 tons/year, and PM_{10} by 7.8 tons/year across four project contracts for a total cost of approximately $470,000. Similarly, using PuriNOx in 222 units was predicted to reduce annual emissions of NO_x by 93.4 tons/year and PM_{10} by 7.8 tons/year across four project contracts for a total cost of about $427,000.

Vehicle emission control, specified as an incidental item in the contract bid, required all diesel powered construction equipment of a certain size (at or exceeding 60 hp) and time period of use (greater than 30 days) to reduce emissions using oxidation catalysts, a clean fuel strategy, and/or a similar technology meeting minimum emissions reductions listed on the EPA Verified Retrofit Technology List[11]. By 2005, three years into the project, 70 pieces of construction equipment had already received DOC. In order to monitor compliance, contractors and/or sub-contractors were required to provide monthly equipment data for each unit on the project and to include accredited certification of clean fuel deliveries. Non-compliance slips required compliance within 24 hours of receipt of Notice of Non-Compliance or be subject to removal from the construction site.

The project used Boston's CA/T example and implemented several additional strategies to mitigate construction emissions, including dust and odor control specifications, operating strategy, and buffer zones to safeguard workers and residents. Diesel equipment was not operated near fresh air intakes. Idling during inactivity was limited to three minutes for most delivery or dump trucks. Designated areas situated to limit public impacts staged trucks bearing construction materials. Further, a Diesel Emissions Mitigation plan was required for work zones within 50 feet of sensitive locations.

Evaluation Metrics and Lessons Learned

The success of the mitigation strategies presented in the previous section can be evaluated based on the level of emissions reduction achieved as well as the cost-effectiveness of

[11] See: http://www.epa.gov/oms/retrofit/verif-list.htm.

different mitigation measures in meeting reduction thresholds. This section relates some of the lessons and challenges observed in prior work that may assist others in planning specific mitigation strategies for construction equipment.

Emission impacts can be assessed using air quality monitoring prior to and during construction projects. Construction of the Boston CA/T and Connecticut I-95 crossing was supported with PM_{10} and $PM_{2.5}$ monitoring programs (Kasprak et al., 2001; Schattanek et al., 2002; Ginzburg et al., 2006). Pollutant concentrations were measured prior to the start of construction in order to develop background/baseline levels, and monitors were situated to capture concentration increases or decreases during specific construction phases. As a result of the mitigation efforts, PM_{10} and $PM_{2.5}$ concentration increases were localized (Ginzburg et al., 2006). In Boston, 50% reductions of mean PM_{10} levels were achieved and peak PM_{10} levels decreased from 331 $\mu g/m^3$ to 138 $\mu g/m^3$, allowing National Ambient Air Quality Standard (NAAQS) compliance (Ginzburg et al., 2006).

Emissions reductions are often calculated using protocols recommended by NESCAUM for SIP credit (Kasprak et al., 2001; U.S. Environmental Protection Agency, 2007). The first step in the calculation is to estimate baseline emission factors and emissions by equipment type and pollutant. The models and tools described in previous sections can be used to estimate pollutant emissions based on default or user-supplied equipment population, activity, and emission factors. The second step requires calculating anticipated reductions based on the planned mitigation strategies. Certified emissions reduction estimates from different technologies are documented in EPA's List of Verified Technologies (U.S. Environmental Protection Agency, 2007). The Boston CA/T project used this procedure to estimate reductions of CO (90 kg/day), HC (30 kg/day), and PM_{10} (7.4 kg/day, see Kasprak et al., 2001).

To estimate the cost-effectiveness of emissions mitigation efforts, a range of methods are available. One method is to simulate emissions reductions using models such as EPA's NONROAD, and relate those reductions to the cost of mitigation (U.S. Environmental Protection Agency, 2007). EPA's Office of Transportation and Air Quality (OTAQ) has used this methodology to calculate the cost-effectiveness of retrofitting non-road equipment that is widely used and constitutes a large portion of the diesel population: tractors/loaders/backhoes, excavators, cranes, generator sets, agricultural tractors, crawler tractors/dozers, and off-highway trucks (U.S. Environmental Protection Agency, 2007). The technologies studied were DOCs, catalyzed diesel particulate filters (CDPFs), SCR, and engine upgrade kits; these are among the most common PM emissions reduction technologies, and data were readily available from EPA grant projects (U.S. Environmental Protection Agency, 2007). DOC and DPF retrofits ranged from \$18,700 to \$87,600 per ton of PM reduced, while selective catalytic reduction systems and engine upgrade kits ranged from \$1,900 to \$19,000 per ton of NO_x reduced (U.S. Environmental Protection Agency, 2007).

Similarly, a cost/benefit analysis was conducted for the Puget Sound Clean Air Agency using EPA NONROAD (2003 version, see Genesis Engineering and Levelton Engineering, 2003). Twelve pieces of construction equipment were selected from the City of Seattle to represent the approximately 400-unit fleet (Genesis Engineering and Levelton Engineering, 2003). Engine specifications and power ratings were input when possible, but default NONROAD operating modes and load factors were applied (Genesis Engineering and Levelton

Engineering, 2003). Activity data were provided by the city of Seattle (Genesis Engineering and Levelton Engineering, 2003). The greatest cost/benefit opportunity ($2,600/ton total emission reduction) was achieved by combining ultra low sulfur diesel fuels with an EGR/DPF technology. The study also recommended calculating a health effects weighted total by multiplying pollutant emissions with an index related to the species toxicity (Genesis Engineering and Levelton Engineering, 2003).

Key lessons learned from mitigation efforts of previous projects included:

- Large, city-scale projects benefited from a planning and assessment phase prior to construction. An advisory committee was established in Oregon and for the Boston and Connecticut projects to develop and guide the mitigation throughout the construction period. Multiple strategies were evaluated, and the chosen strategy depended on the targeted pollutant(s).
- Certain activities contributed more construction-generated PM_{10} emissions than others, such as grading, excavation, construction and demolition, land clearing, blasting and drilling, material loading operations, and movement of heavy-duty vehicles and equipment (Kasprak et al., 2001).
- $PM_{2.5}$ emissions were mostly related to the exhaust of diesel-powered construction equipment and trucks (Kasprak et al., 2001).
- The mitigation program implemented as part of the Boston CA/T project began as a voluntary retrofit but later opted to incorporate emission control requirements into contract bid packages (Kasprak et al., 2001).
- Mitigation technologies were included in the contract cost for the Connecticut I-95 project from the outset (Manufacturers of Emission Controls Association (MECA), 2006).
- Monitoring and inspection during different phases of a project helped with implementation of more stringent measures when NAAQS exceedances were observed (Kasprak et al., 2001).

5. SUMMARY FINDINGS

This literature review contains information on activity data and fleet characteristics for construction equipment; equipment emissions testing and modeling approaches; mitigation strategies for $PM_{2.5}$, PM_{10} and NO_x; and example mitigation measures used in practice.

Existing work on activity data collection for construction projects, including operator surveys, field inspector diaries, time-lapse photography, and on-board monitoring equipment, indicates several consistent conclusions regarding equipment fleet characteristics. Equipment populations typically consisted of more tractors/loaders/backhoes, cranes, excavators, crawler tractors/dozers, rollers, skid steer loaders, and rubber tire loaders than other types. Air compressors, generators, bore/drill rigs, and industrial forklifts were also widely used. Several sources indicate earthmoving, highway/freeway construction activities, and bridge projects were typically larger and produced higher emissions than other project types. On-board monitoring systems correlated activity modes, such as equipment-specific operational tasks, to higher PM emissions than engine-off or idle situations.

The literature indicated two major approaches for quantifying real-world non-road construction emissions: single-engine testing and in-use/on-board measurement. Single-engine testing indicates PM emission factors range from 0.07-1.60 g/hp-hr across a wide range of engine types and intended applications. However, emission measurements using the single-engine test method differed from typical duty cycles. Transient test cycles and/or in-use measurements may better represent actual emissions. On-board measurement systems found a relationship between MAP and fuel use/emissions; PM increased when operating under higher loads than typical idle or engine-off modes. Single-engine testing and in-use measurement observed PM reductions due to lower sulfur fuels as well as the use of DPF or SCR technologies.

Activity and emissions data are used as inputs to national and state-level models such as EPA's NONROAD model and ARB's OFFROAD model, as well as project-specific spreadsheet tools such as those developed by SMAQMD and UC Davis/Caltrans. Assumptions are made in the models to scale data spatially and temporally. Model assessment of the non-road contribution to national scale pollutant emissions supported regulation (Tiers 1-4) of diesel powered equipment and vehicles.

Existing literature presented an array of mitigation options that can be used to meet regulatory requirements and achieve reduction goals. Mitigation options fall into six categories: encouraging use of newer, lower-emitting equipment; retrofitting older equipment to reduce emissions; modifying the fuel used to reduce emissions per unit of fuel consumed; curtailing or controlling activity; increasing the distance between activity and receptors; and applying dust suppressant and removal controls. Mitigation efforts, including limits to idle-time, diesel retrofits with oxidation catalysts, and dust/buffer control specifications, have been successfully incorporated into large-scale projects conducted in Boston and Connecticut. National funding through the CMAQ program and state incentives such as California's CMP program and TERP were described as model programs that could be applied in other states.

Previous real-world projects showed that construction emissions and control measures can be appropriately evaluated using standardized procedures, such as the protocol recommended by NESCAUM for SIP credit calculation (used for the Boston's CA/T project). The procedure includes estimating baseline emission factors and emissions by equipment type and pollutant, and calculating anticipated reductions based on the planned mitigation strategies. Monitoring programs have also been successfully conducted before and during construction projects to enable dynamic adjustments to mitigation strategy during longer projects in sensitive or nonattainment status areas.

6. REFERENCES

Abeid J. and Allouche E. (2001) Photo.NET: an integrated computer-based system for controlling construction progress. Abstract Available on the Internet at http://www.construction.ualberta.ca/forum.shtml.

Abolhasani S. (2006) Assessment of on-board emissions and energy use of nonroad construction vehicles. Master of Science Thesis, Civil Engineering, North Carolina State University, Raleigh, North Carolina.

Abolhasani S., Frey H.C., Kim K., Rasdorf W., Lewis P., and Pang S.-H. (2008) Real-world in-use activity, fuel use, and emissions for nonroad construction vehicles: a case study for excavators. *J. Air Waste Manage. Assoc.* **58**, 1033-1046 (doi:10.3155/1047-3289.58.8.1033).

Baker R. (2009) Characterization of the off-road equipment population. Presented at the *Chair's Air Pollution Seminar Series, California Air Resources Board, January 29* by Eastern Research Group, Inc. (ERG).

California Air Resources Board Mobile Source Emissions Inventory Program (2007a) User's guide for OFFROAD2007. November. Available on the Internet at http://www.arb.ca.gov/msei/offroad/offroad.htm.

California Air Resources Board Mobile Source Emissions Inventory Program (2007b) Program structure of the OFFROAD2007. Available on the Internet at http://www.arb.ca.gov/msei/offroad/offroad.htm.

Durbin T.D., Cocker D.R., III, Sawant A.A., Johnson K., Miller J.W., Holden B.B., Helgeson N.L., and Jack J.A. (2007) Regulated emissions from biodiesel fuels from on/off-road applications. *Atmos. Environ.* (41), 5647-5658 (doi:10.1016/j.atmosenv.2007.02.048).

Eastern Research Group, Inc. (2005) Ozone science and air modeling research project H43T163: diesel construction equipment activity and emissions estimates for the Dallas/Ft. Worth region. Final report prepared for the Houston Advanced Research Center, ERG No. 3479.00, August 31.

Eisinger D.S. and Niemeier D. (2007) Construction emissions: using project data to improve regional inventories. Invited presentation at the *86th Annual Meeting of the Transportation Research Board, Workshop 135: Guidelines on Conducting Project Level Air Quality Analysis, Washington, D.C., January 21,* (STI-906044-3130).

Frey H.C., Pang S.-H., Kim K., and Abolhasani S. (2006) Real-world measurement and analysis of in-use emissions from nonroad construction equipment. Presented at the *16th CRC On-Road Vehicle Emissions Workshop, San Diego, CA, March 28-30*.

Frey H.C., Kim K., Pang S.-H., Rasdorf W., and Lewis P. (2008a) Characterization of real-world activity, fuel use, and emissions for selected motor graders fueled with petroleum diesel and B20 biodiesel. *J. Air Waste Manage. Assoc.* **58**, 1274-1287 (doi:10.3155/1047-3289.58.10.1274).

Frey H.C., Rasdorf W., Kim K., Pang S.-H., and Lewis P. (2008b) Comparison of real-world emissions of B20 biodiesel versus petroleum diesel for selected nonroad vehicles and engine tiers. *Transportation Research Record: Journal of the Transportation Research Board* **2058**, 33-42 (doi: 10.3141/2058-05).

Gautam M., Carder D.K., Clark N.N., and Lyons D.W. (2002) Testing for exhaust emissions of diesel powered off-road engines. Final project report prepared for the California Air Resources Board and the California Environmental Protection Agency by the Department of Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV, May 29.

Genesis Engineering, Inc. and Levelton Engineering, Ltd. (2003) Non-road diesel emission reduction study. Report prepared for Puget Sound Clean Air Agency, Oregon Department of Environmental Quality, and U.S. Environmental Protection Agency, October 14.

Ginzburg H., Schattanek G., Kasprak A., Dolan J., and Wan P. (2006): Effects of large-scale construction activities on ambient particulate matter levels measured at the Central Artery/Tunnel Project in the Boston area: *The Air and Waste Management Association's 99th Annual Conference and Exhibition*, New Orleans, LA.

Goldstein G.P., Block M.C., and Abolhasani S. (2007) Implementing best available technology for diesel emissions reduction in accordance with New York City Local Law 77. Final report prepared for the New York City Department of Environmental Protection, Croton Water Treatment Project, Capital Project WM-11 by Emisstar LLC, January.

Helmer K., Cook R., Volckens J., Baldauf R.W., and Starr M. (2004) Regulated and air toxic exhaust emissions from nonroad diesel engines and equipment. Presented at the *13th International Emission Inventory Conference*, Clearwater, Florida.

Huai T., Shah S.D., Durbin T.D., and Norbeck J.M. (2005) Measurement of operational activity for nonroad diesel construction equipment. *International Journal of Automotive Technology* **6** (4), 333-340.

ICF International (2007) Cleaner diesels: low cost ways to reduce emissions from construction equipment. Prepared for the U.S. Environmental Protection Agency, National Center for Environmental Innovation by ICF International, Fairfax, VA, March.

Jones & Stokes and Rimpo and Associates (2009) Road construction emissions model, version 6.3.1. Spreadsheet system prepared for the Sacramento Metropolitan Air Quality Management District. Available on the Internet at http://www.airquality.org/ceqa/index.shtml#models.

Kable J.M. (2006) Collecting construction equipment activity data from Caltrans project records. M.S. Thesis, University of California at Davis, Davis, CA. Available on the Internet at http://www.uctc.net/papers/828.pdf.

Kasprak A., Schattanek G., and Wan P.K. (2001) Emission reduction retrofit program for construction equipment of the Central Artery/Tunnel Project. Paper No. 206 presented at the *94th Annual Air & Waste Management Association Conference & Exhibition, Orlando, FL, June 24-28*. Available on the Internet at <http://www.masspike.com/pdf/big_dig/dieselemisson.pdf>.

Kean A.J., Sawyer R.F., and Harley R.A. (2000) A fuel-based assessment of off-road diesel engine emissions. *J. Air Waste Manage. Assoc.* **50** (11), 1929-1939.

Lee D.-W. (2009) Characterizations of in-use real world emissions of off-road equipment. Presented at the 19th CRC Workshop, *San Diego, CA, March 24* by the Texas Transportation Institute, College Station, TX.

Lewis P., Rasdorf W., Frey H.C., Pang S.-H., and Kim K. (2009) Requirements and incentives for reducing construction vehicle emissions and comparison of nonroad diesel engine emissions data sources. *J. Constr. Eng. Manage.* **135** (5), 341-351 (doi: 10.1061/(ASCE)CO.1943-7862.0000008).

Manufacturers of Emission Controls Association (MECA) (2006) Case studies of construction equipment diesel retrofit projects. Washington, D.C., March. Available on the Internet at http://www.meca.org/galleries/default-file/Construction%20Case%20Studies%200306.pdf.

Metropolitan Washington Council of Governments (2004) Complete list of control measures for use in SIP planning. October 12.

Muleski G.E., Cowherd C., Jr., and Kinsey J.S. (2005) Particulate emissions from construction activities. *Journal of the Air and Waste Management Association* **55**, 772-783.

Rea P. (2008) Personal communication with an engineer at Fleet Management Solutions, Inc., San Luis Obispo, CA. February 25, 2008.

Reid S.B. (2007) Documentation of emission estimation techniques for sources of diesel particulate matter (DPM) associated with distribution centers and construction projects in West Oakland, California. Technical memorandum prepared for the Bay Area Air Quality Management District, San Francisco, CA, by Sonoma Technology, Inc., Petaluma, CA, STI-907006-3174-TM, May.

Schattanek G., Kasprak A., Weaver D., and Cooper C. (2002) Implementation of retrofit/clean fuel programs for diesel equipment during the construction phase of two large transportation projects. Paper No. 42536 presented at the *AWMA 95th Annual Conference & Exhibition, Baltimore, MD, June 23-27*. Available on the Internet at <http://www.i95newhaven.com/poverview/awma_2002_nhhc.pdf>.

Schattanek G. and Weaver D. (2005) Implementation of retrofit program for diesel equipment during the construction phase the I-95 New Haven Harbor Crossing Improvement Program in southern Connecticut. *Air & Waste Management Association's 98th Annual Conference and Exhibition*, Minneapolis, MN (Paper #999).

Singer B.C. and Harley R.A. (2000) A fuel-based inventory of motor vehicle exhaust emissions in the Los Angeles area during summer 1997. *Atmos. Environ.* **34** (11), 1783-1795.

STAPPA/ALAPCO (2006) Controlling fine particulate matter under the clean air act: A menu of options. Report prepared by the State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials. Available on the Internet at <http://www.4cleanair.org/PM25Menu-Final.pdf>. March.

Storey J. (2009) Impacts of advanced combustion, fuels and after treatment technologies on diesel PM emissions and mobile source air toxics: a ten-year retrospective. Presented at the Chairman's Air Pollution Seminar Series, *California Air Resources Board, Sacramento, CA, February 11* by the Fuels, Engines, and Emissions Research Center, Oak Ridge National Laboratory, Oak Ridge, TN.

U.S. Environmental Protection Agency (1991) Nonroad engine and vehicle emission study-report. EPA 460/3-91-02, November.

U.S. Environmental Protection Agency (1998) Exhaust emission factors for nonroad engine modeling – compression ignition. Prepared by Megan Beardsley and Chris Lindhjem, U.S. EPA Office of Mobile Sources, Assessment and Modeling Division, Report No. NR-009A, revised June 15.

U.S. Environmental Protection Agency (2003) Questions and answers on using a diesel oxidation catalyst in heavy-duty trucks and buses. Fact Sheet prepared by the U.S. EPA Office of Transportation and Air Quality, EPA420-F-03-016, June.

U.S. Environmental Protection Agency (2004a) Exhaust and crankcase emission factors for nonroad engine modeling – compression-ignition. EPA420-P-04-009, Report No. NR-009c, April.

U.S. Environmental Protection Agency (2004b) Median life, annual activity, and load factor values for nonroad engine emissions modeling. EPA420-P-04-005, Report no. NR-005c, April.

U.S. Environmental Protection Agency (2005a) Geographic allocation of non-road engine population data to the state and county level. EPA420-R-05-021, Report No. NR-014d, December.

U.S. Environmental Protection Agency (2005b) Nonroad engine population estimates. EPA420-R-05-022, Report No. NR-006d, December.

U.S. Environmental Protection Agency (2006) Reducing emissions from construction equipment. Fact sheet prepared by the U.S. EPA New England Office, EPA-901-F-05-022, January.

U.S. Environmental Protection Agency (2007) Diesel retrofit technology: An analysis of the cost-effectiveness of reducing particulate matter and nitrogen oxides emissions from heavy-duty nonroad diesel engines through retrofits. Prepared by the Office of

Transportation and Air Quality, U.S. Environmental Protection Agency, Research Triangle Park, NC, EPA420-R-07-005, May.

Wang R., Eisinger D.S., Bai S., and Niemeier D. (2008) Construction equipment retrofit and replacement tool. Prepared by the U.C. Davis-Caltrans Air Quality Project, Davis CA, Task Order No. 81, October.

West Coast Collaborative (2009) Oregon construction equipment emissions reduction project. Fact sheet prepared by the West Coast Collaborative. Available on the Internet at http://www.westcoastcollaborative.org/files/grants/OEC_Construction_Reduction_fact%20sheet.pdf.

Zamurs J. and Bass J. (2001) Emissions of PM associated with reconstruction of transportation facilities. Presented at the *Transportation Research Board Annual Meeting*, Washington, D.C., January 9.

Zhu Y.F., Hinds W.C., Kim S., and Sioutas C. (2002) Concentration and size distribution of ultrafine particles near a major highway. *J. Air Waste Manage. Assoc.* **52** (9), 1032-1042.

APPENDIX B: SUMMARY OF QUALITY ASSURANCE ACTIVITIES FOR AIR QUALITY AND METEOROLOGICAL MEASUREMENTS

1. QUALITY CONTROL/QUALITY ASSURANCE PROCEDURES

Quality assurance involves two separate activities: quality control (QC), which are ongoing efforts performed by measurement and data processing personnel, and quality assurance (QA) auditing, an external function performed by personnel who are not involved in normal operations.

Two QC activities for this project included the operation of monitors and auditing standard data processing procedures. These procedures define schedules for periodic calibrations and performance tests, set predefined tolerances that cannot be exceeded during performance tests, and determine the actions to be taken when the tolerances are exceeded. We also recorded other details of field operations and visits to the sites in logbooks kept at each monitoring site.

QA audits determine whether the QC procedures are adequate, whether they are being followed, and whether the tolerances for accuracy and precision are maintained in practice. Performance audits establish whether predetermined specifications for accuracy are achieved in practice by challenging the measurement system with a known standard sample traceable to a primary standard.

In general, calibration checks and audits were designed to confirm quality operations and ensure that operations data meet standard U.S. Environmental Protection Agency (EPA) guidelines for air quality monitoring (U.S. Environmental Protection Agency, 2008a) and meteorological sensor operations (U.S. Environmental Protection Agency, 2008b). Specific QC procedures for the field study included performing automatic zero and span checks each day for CO (at 2:00 a.m., span value of 8 ppm), NO (at 3:00 a.m., span value of 440 ppb), and NO_2 (at 3:00 a.m., span value of 385 ppb). CO_2 monitors were zeroed and spanned (1,000 ppm) approximately every two months. As specified by the *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume II: Ambient Air Quality Monitoring Program* (U.S. Environmental Protection Agency, 2008a), if daily zero checks, span results, or calibration results were within three standard deviations or 10% of the expected values, no adjustments were made; if results were outside three standard deviations or 10%, a multipoint calibration was performed. If results were outside 15%, the data would be invalidated, although this did not happen during the study. Because there was some zero drift with the CO monitor, and the CO data were not essential to evaluating the PM issues that motivated the study, we segregated that data for later adjustment as desired or needed by the Arizona Department of Transportation (ADOT). The second section of this Appendix includes a more detailed discussion of the CO data. Note that all QC checks were automatically recorded in the data logger for future review. Continuous gaseous analyzers were calibrated on site at setup and take-down, remotely over the Internet each quarter, and on an as-needed basis. Flow rates for the Beta Attenuation Monitor (BAM) monitors for $PM_{2.5}$ and PM_{10} and for the black carbon (BC) monitors were checked every two weeks. The flow rate for the particulate polycyclic aromatic hydrocarbons (pPAH) monitor and the CO_2 monitors were checked at start-up, take-down, during an October 2009 audit, and several other occasions during the study. Meteorological sensors were calibrated at start-up and take-down using criteria in the *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV: Meteorological Measurements Version 2.0* (U.S. Environmental Protection Agency, 2008b). **Table B-1** summarizes lower quantifiable limits and precision of the continuous instruments in performance at these levels, which have been demonstrated with field data in similar studies (see Hyslop et al., 2003, for example) to be sufficient to support the results presented in this report.

Table B-1. Summary of manufacturer-specified lower quantifiable limits (LQL) and precision for continuous monitors and meteorological sensors.

Parameter	Manufacturer	Model	Sampling Interval	LQL	Precision
$PM_{2.5}$	MetOne	1020 BAM	1 hr.	<4.8 µg/m³	<1.5 µg/m³ (RMS[1])
PM_{10}	MetOne	1020 BAM	1 hr.	<4.8 µg/m³	<1.5 µg/m³ (RMS[1])
BC	Magee Scientific	AE-42 dual wavelength (rack mount)	5 min.	0.05 µg/m³	4%
CO	Thermo Scientific	48i	1 min.	0.04 ppm	2%
NO, NO_x, NO_2	Thermo Scientific	42i	1 min.	0.4 ppb	1%
CO_2	LI-COR	LI-6252	1 min.	0 ppm	0.2 ppm
pPAH	EcoChem	PAS-2000	1 min.	3 ng/m³	10%
Wind speed Wind direction	RM Young	AQ 5305-V	1 min.	0.4 m/s N/A	±0.2 m/s ±3°
Relative humidity	Campbell Scientific	41382VC	1 min.	0.8%	±2%
Temperature	Campbell Scientific	41342VC	1 min.	-40°C	±0.5°C
Pressure	Campbell Scientific	61202V	1 min.	600 mb	±1.5 mb

[1]Root Mean Square error

The continuous gaseous analyzers and flow calibrators were audited in October 2009, near the midpoint of the monitoring. In general, audit criteria require that a comparison with a standard show a difference of less than 15% for flow rates and for a mean absolute difference for CO, CO_2, and nitrogen oxides; additional criteria exist for slope, intercept, and correlation coefficient (U.S. Environmental Protection Agency, 2008a). The gas-dilution calibrators were found to meet audit criteria. Both CO and CO_2 monitors met audit criteria for multipoint slope, intercept, and correlation coefficient. Both NO/NO_x/NO_2 monitors met audit criteria for multipoint slope, intercept, and correlation coefficient; the NO_2 converter efficiency was over 99.5%. The audited sample flow rates of the BAMs and the Aethalometers™ met audit criteria.

Meteorological sensors were audited in October 2009, near the midpoint of the field study, using (U.S. Environmental Protection Agency, 2008b) criteria. Calibration and audit criteria for the various meteorological sensors are listed in Table 0-4 and Appendix C of (U.S.

Environmental Protection Agency, 2008b); for example, wind speed accuracy should be within 0.25 m/s at wind speeds less than 5 m/s, and the recorded wind direction should be within 5 degrees. The wind sensors were found to meet the audit criteria. All the wind sensors were found to meet the audit criteria during the beginning and ending calibration checks. The pair of temperature sensors, relative humidity sensor, solar radiation sensor, and pressure sensor all met audit criteria.

BAM data were captured at hourly intervals using the DR DAS data acquisition system. BC, gaseous species (CO, CO_2, NO, NO_2, NO_x), pPAH, and meteorological data were captured at 1-minute (except for BC at 5-minute) and hourly intervals using the DR DAS data acquisition system. The data were stored in an intermediate Structured Query Language (SQL) database before being transferred to a permanent SQL database at STI's Petaluma office every 10 minutes and delivered to the real-time website for visual review daily (or several times a day). If irregularities were noted during the daily review, they were promptly resolved (e.g., check of the calibration of the instruments, resolve sampling line issues) to assure high data recovery rates.

Data processing and data validation were performed on the continuous data (BAM, BC, gaseous species [CO, CO_2, NO, NO_2, NO_x], pPAH, and meteorological data) in relational databases and via programs which recorded actions performed on the data. A summary of the data processing, data validation, and data quality assurance activities is provided below.

The BC raw data were post-processed using the Washington University Air Quality Lab AethDataMasher Version 6.0e to format date-time stamps, perform data validation, calculate the 5-minute and hourly output, and generate validation log files. Hourly concentrations were determined by averaging each hour's 5-minute data (meeting the 75% data completeness criterion) and daily concentrations were determined by averaging the hourly concentrations. The 5-minute and hourly AethDataMasher output was further quality-assured in SurfDat (STI data viewing and validation program) to enable a visual inspection of minimum and maximum data values, stuck values, and baseline shift, as well as to compare the results to known field activity.

The continuous air quality data were imported into a relational database with automated quality control checks, including minimum and maximum value, rate of change, sticking, and range checks. Data failing these criteria were flagged as suspect. Data were visually reviewed to approve the results of the automated quality control checks and outliers were identified and flagged based on comparison to other parameters and field notes.

The NO, NO_2, and NO_x data were corrected based on zero checks as well as occasional manual calibrations. An automatic correction was calculated and applied for each day based on zero calibration values. Data for days on which additional manual calibrations were made were then adjusted. Data from the daily instrument zero check were exported from the relational database and imported to a Microsoft Access database for processing. Zero averages were calculated for each day based on the last 5 minutes of zero calibration data. Days when data showed a zero average > 3 ppb or < -3 ppb were investigated to determine increasing or decreasing trends in daily zero values. The start and end dates of zero drift were identified and any necessary adjustments were made in the database by scaling the data values (NO_x or NO zero data slopes were used to scale both NO_x and NO; no scaling of NO_2 was required).

The CO_2 data were corrected based on zero and span calibrations that were performed about every 2 months. Changes in zero and span values were assumed to have occurred linearly over the period between calibrations. Based on the linear changes, corrections were applied in daily increments to the CO_2 concentrations. The database automatically calculated hourly averages using valid ambient data (75% data completeness required). Additional queries were run on the database to create 5-minute and 20-minute data sets using valid ambient data (80% data completeness required).

All 1-minute data were averaged to 5-minute, with a requisite 80% data completeness, and included only valid QC codes. Similarly, all 1-minute data were averaged to hourly (required 75% data completeness and included only valid QC codes). Approximately 3% of the average values were invalidated due to insufficient data.

2. DISCUSSION REGARDING ADOT CO DATA VALIDATION

2.1.1 Overview

During the course of our data quality assurance review, STI identified that measurements of CO concentrations needed to be corrected for instrumentation "zero drift." The zero drift problem was quantified during the monitoring period by automated daily Zero-Precision-Span (ZPS) tests, and the data can be reprocessed at a future date if ADOT or others have interest in further examining the CO data. STI did not correct the CO data to address the drift problem, since the overall study focused on particulate matter and CO data were collected as a supplement to the study's core data. This section briefly documents the CO data correction issue. As currently delivered to ADOT, the reported hourly CO data are generally accurate to within a few tenths of a ppm. However, for research purposes, it would be useful to correct the CO data before further processing and evaluation.

2.1.2 Details Regarding CO Data Drift

- Thermo Scientific Model 48i zero drift problem
- The Thermo Scientific 48 CO analyzer, in wide use since the 1980s, has historically had zero drift problems so technical revisions have been implemented to address them. The zero drift difficulty was seemingly resolved for a period, but, in recent years, manufacturing of the Gas Filter Correlation (GFC) wheels, an integral part of the instrument hardware, was subcontracted out and zero drift problems once again became an issue. Thermo Scientific has begun in-house manufacturing of this component, greatly improving the performance (lower zero drift) of the new GFC wheels. Model 48i CO analyzers used in the ADOT monitoring had older GFC wheels with significant zero drift problems.
- Correcting CO zero drift
- Zero drift can be corrected by implementing a daily zero routine, where zero air is introduced to the unit, then employing one of two correction methods: (1) reset the instrument zero point daily at the end of the zero air routine (manually or with a digital

signal) or (2) by logging and maintaining high resolution (1-minute) temporal data and applying post processing corrections. For ADOT, the latter method was chosen and used in combination with periodic manual calibrations where the zero and span of the analyzers was measured and adjusted.

- Implementation of daily ZPS routines and periodic manual calibrations
- During the ADOT study, CO ZPS routines were implemented daily, beginning at 2:00 a.m. Local Standard Time (LST). Zero air was applied for 9 minutes, followed by 11 minutes of CO span gas (8.0 ppm), and then by 9 minutes of 2.0 ppm CO, as a precision point. This was followed by 5 minutes of purge (ambient) air before sampling resumed. Data were averaged over, and recorded at, 1-minute intervals.
- In addition to the daily ZPS routines, manual calibrations were conducted periodically. During these times, the instrument was dosed with zero air and CO at span and precision points, but the set points of the instrument were manually adjusted so that response of the instrument was unbiased.
- Implementation of zero drift corrections
- Since the zero drift of the instrument occurs continuously, an assumption was made that the drift occurred in a linear fashion. For example, if the zero drifted 24 ppb over the course of 24 hours, then the assumption was that the drift occurred at a rate of 1 ppb/hr. Applying a daily correction to the CO data would require that the bias measured during the daily zero be linearly interpolated and then subtracted from all measurements made since the previous correction. In addition, the periodic manual calibrations that included adjustment of the analyzer zero coefficients would have to be taken into consideration, since the adjustments in those cases would not be relative to the previous daily ZPS, but to the data since the manual calibration occurred.

3. REFERENCES

Hyslop N.P., Brown S.G., Gorin C.A., and Hafner H.R. (2003) California Regional $PM_{10}/PM_{2.5}$ Air Quality Study (CRPAQS) data quality summary reports. Final report prepared for San Joaquin Valleywide Air Pollution Study Agency c/o California Air Resources Board, Sacramento, CA, by Sonoma Technology, Inc., Petaluma, CA, STI-999242-2310-FR, February. Available on the Internet at <http://www.arb.ca.gov/airways/Documents/preliminary/STI/STIDQSR.pdf>.

South Coast Air Quality Management District and IQAir North America (2009) Pilot study of high performance air filtration for classrooms applications. Draft report prepared by South Coast Air Quality Management District, Diamond Bar, CA, and IQAir North America, Santa Fe Springs, CA, October.

U.S. Environmental Protection Agency (2008a) Quality assurance handbook for air pollution measurement systems, Volume II: ambient air quality monitoring program. Prepared by the U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division, Research Triangle Park, NC, EPA-454/B-08-003, December.

U.S. Environmental Protection Agency (2008b) Quality assurance handbook for air pollution measurement systems Volume IV: meteorological measurements version 2.0 (final). Prepared by the U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Assessment Division, Research Triangle Park, NC, EPA-454/B-08-002, March. Available on the Internet at http://www.epa.gov/ttn/amtic/files/ambient/met/Volume%20IV_Meteorological_Measurements.pdf.

APPENDIX C: SUMMARY OF DATA

This appendix itemizes the data collected and delivered to ADOT; it identifies what is included in the electronic material delivered as a separate project work product (**Table C-1**). The data are provided in a Microsoft Access database, *ADOT Construction.mdb*.

Table C-1. List of activity, emissions, and air quality data provided electronically.

Access Table Name	Description
Equipment_List	List of construction equipment
Location	Construction equipment location reported by GPS
Final_Fuel_Total	Reconciled final daily fuel consumed by construction equipment
TrafficCount_byVehClass_2009	2009 traffic counts through the SR 92 construction area by HPMS vehicle class
TrafficCount_byVehClass_2010	2010 traffic counts through the SR 92 construction area by HPMS vehicle class
CrusherFuel	Daily fuel consumption estimated for rock crusher
AirQuality_and_Met	Hourly air quality and met data for 1/19/2009-1/18/2010
AirQuality_and_Met_Crosstab	Hourly air quality and met data crosstab format
Equipment_List_Desc	Field description for table 'Equipment_List'
Location_Desc	Field description for table 'Location'
Final_Fuel_Total_Desc	Field description for table 'Final_Fuel_Total'
TrafficCount_byVehClass_Desc	Field description for table 'TrafficCount_byVehClass_yyyy'
CrusherFuel_Desc	Field description for table 'CrusherFuel'
AirQuality_and_Met_Desc	Field description for table 'AirQuality_and_Met'
AirQuality_and_Met_Crosstab_Desc	Field description for table 'AirQuality_and_Met_Crosstab'
Construction_Phase_Desc	Construction phase description for "Phase_ID" field in "Final_Fuel_Total" table and "Default_Phase" field in "Equipment_List" table

The database consists of eight data tables containing information on equipment types and locations, fuel use, traffic counts, and air quality and meteorological data. There are also eight descriptive tables, which contain the field names and field descriptions for the data tables and a descriptive table providing the definition of the construction phases linked to equipment activities.

APPENDIX D: SUMMARY OF CO_2 DATA

Although this study focused on assessing $PM_{2.5}$ emissions, increasing attention is being given to greenhouse gas (GHG) emissions from all source sectors. Therefore, STI prepared estimates of carbon dioxide (CO_2) emissions associated with construction equipment and on-road mobile source activity along the SR 92 project and also collected ambient measurements of CO_2 concentrations as part of the year-long field study. This appendix provides an overview of findings from these CO_2 analyses.

1. CO_2 EMISSION ESTIMATES

As was the case with other pollutants, estimates of CO_2 emissions from construction equipment were based on fuel consumption data (see Equation 1), while CO_2 emissions from on-road vehicles were calculated based on vehicle miles traveled (VMT) data (see equation 2).

$$\text{Equipment } CO_2 = FC \times EF \qquad \text{(D-1)}$$

where:

CO_2 = total CO_2 emissions from a given piece of construction equipment (g)
FC = total fuel consumption for the equipment of interest (gal)
EF = fuel-based emission factor from EPA's NONROAD model (g/gal)

$$\text{On-road } CO_2 = VMT \times EF \qquad \text{(D-2)}$$

where:

CO_2 = total CO_2 emissions from a given type of on-road vehicle (g)
VMT = total VMT for the vehicle type of interest within the project area (miles)
EF = emission factor from EPA's MOBILE6 model (g/mile)

CO_2 emission estimates for construction equipment and on-road vehicles are shown in **Table D-1**. During 2009, construction equipment emitted 781,233 kg (861 tons) of CO_2, or about one-seventh the amount of CO_2 emitted by on-road vehicles passing through the SR 92 construction site. On a monthly basis, construction equipment fuel consumption and CO_2 emissions were highest in September (see **Figure D-1**). About 60% of the CO_2 emissions from construction equipment are associated with tractors, loaders, excavators and trucks and with the roadway and structural excavation phases of construction (see **Figure D-2**).

Table D-1. 2009 CO_2 emissions from construction equipment and on-road vehicles.

Source	CO_2 emissions (kg)			
	Annual	Average Day	Peak Day	Peak Date
Construction equipment	781,233	3,282	8,326	12/9/2009
On-road vehicles	5,670,793	15,536	30,846	10/21/2009

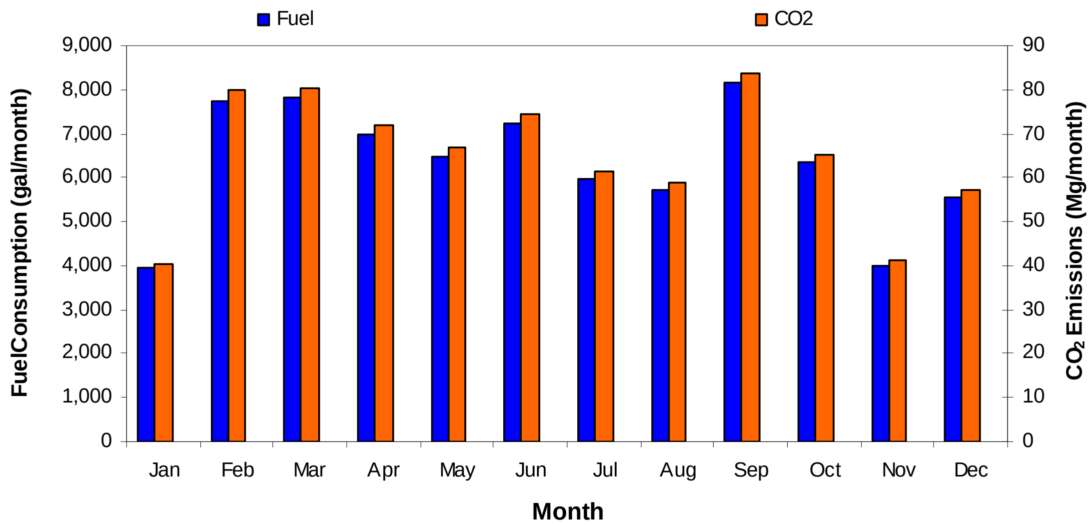


Figure D-1. Construction equipment fuel consumption and CO_2 emissions.

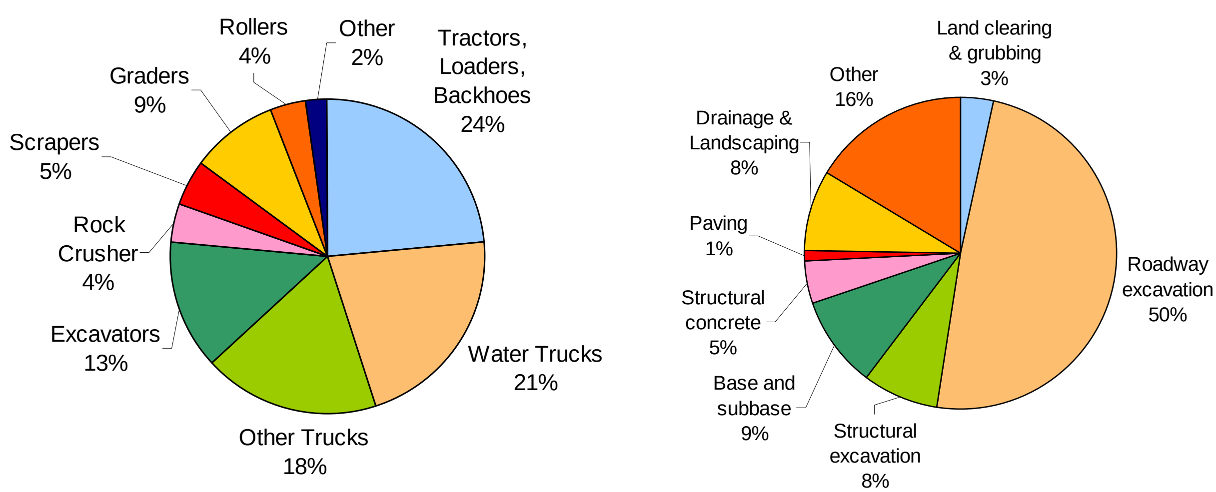


Figure D-2. Construction equipment CO_2 emissions by equipment type (left) and construction phase (right) for 2009.

2. CO_2 AIR QUALITY DATA

As part of the study, STI collected CO_2 data next to SR 92. **Figure D-3** provides an illustration of these data. As shown in Figure D-3, CO_2 concentrations tended to vary by about 5 to 10 ppm from the background CO_2 values reported in the literature (e.g., NASA CO_2 data measured at Mauna Loa on the Big Island of Hawaii averaged approximately 387 ppm during 2009). In 2009, the CO_2 concentrations observed by Trailer 2 (the trailer on the eastern side of SR 92, closest to the road) ranged from 374 ppm to 442 ppm (hourly averaged data). The mean and median concentrations were 389 ppm and 390 ppm, respectively, while the standard deviation was 6.07 ppm (**Figure D-4**).

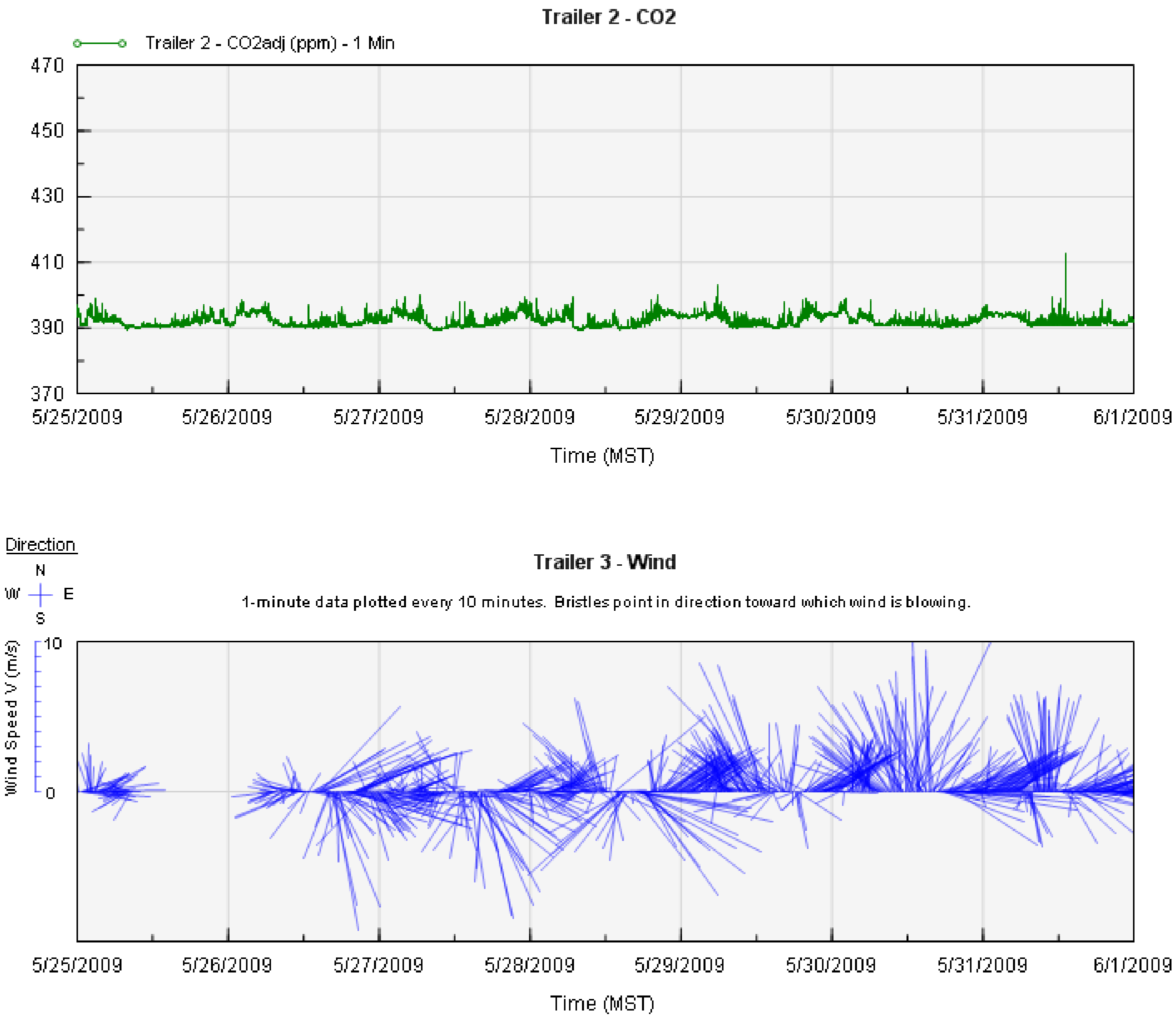


Figure D-3. Illustration of CO_2 concentration, wind direction, and wind speed data near SR 92.

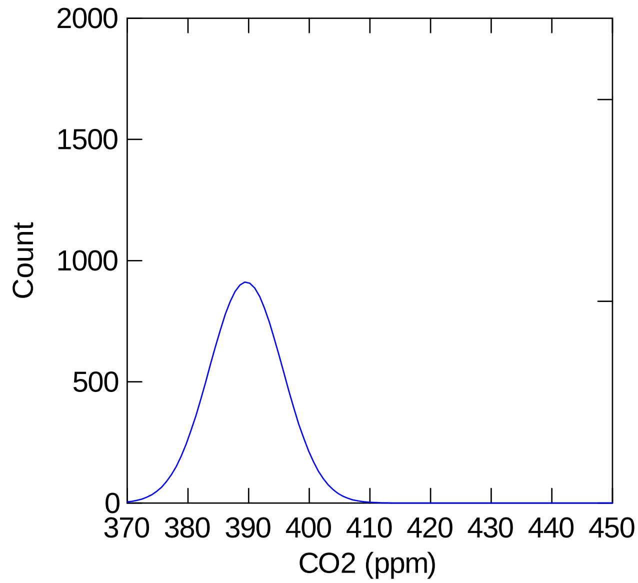


Figure D-4. Distribution of CO_2 concentration observations measured at Trailer 2 for year 2009.