Field Study of $PM_{2.5}$ Emissions from a Road-Widening Project

Stephen B. Reid, Douglas S. Eisinger, Paul T. Roberts, Erin K. Pollard, and Yuan Du
Sonoma Technology, Inc., 1455 N. McDowell Blvd., Suite D, Petaluma, CA, 94954
doug@sonomatech.com

Beverly T. Chenausky
Arizona Department of Transportation, 206 S. 17th Ave., Phoenix, AZ, 85007

ABSTRACT

Diesel-powered construction equipment is a significant and, historically, relatively unregulated source of air pollution. Sonoma Technology, Inc. (STI) performed a field study for the Arizona Department of Transportation (ADOT) to quantitatively assess the air quality impacts from a rural road-widening project in southern Arizona. The objective of the field study was to characterize and quantify fine particulate matter ($PM_{2.5}$) and particulate precursor emissions contributions from various phases of the construction project. The results of the study would be used to develop a framework for estimating air quality impacts from future construction projects and identify cost-effective methods for reducing emissions from construction projects. Emission estimates were prepared based on construction equipment activity collected using GPS units and fuel consumption logs. Near-field pollutant concentrations were characterized through the collection of air quality and meteorological data at four monitoring stations near the roadway. STI will present the methods used to conduct this field study, as well as an overview of preliminary findings from the study.

INTRODUCTION

Background

Particulate matter (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; particle pollution exposure 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 acid rain. Construction equipment usage at transportation projects is a source of both fine ($PM_{2.5}$) and coarse (PM_{10}) particulate matter. Exhaust from diesel-powered construction equipment includes fine particles (primary $PM_{2.5}$) and other pollutants that contribute to the formation of $PM_{2.5}$ in the atmosphere (secondary $PM_{2.5}$). In addition, the use of construction equipment loosens and disturbs soil; the resulting windblown (or fugitive) dust can contribute to PM_{10} problems. Bulk material operations on construction sites, such as rock-crushing activities, can also contribute to windblown dust.

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-hr 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-hr period. Both PM_{10} and $PM_{2.5}$ are important 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. The Nogales area was designated nonattainment for $PM_{2.5}$.

As of 2010, there were no consistent and widely accepted guidelines for estimating emissions from road construction projects. As a result, the Arizona Department of Transportation (ADOT) sought technical assistance to better understand construction-related activities and resulting air impacts. To accomplish these goals, ADOT worked with Sonoma Technology, Inc. (STI) to perform a field study to quantitatively assess the air quality impacts from an example road-widening construction project. ADOT selected as the study site a roadway lane addition project in a rural area on State Route 92 (SR 92) in the southeastern portion of the state. The selection of the relatively remote SR 92 project enabled the study team to examine construction-related air quality impacts in an area removed from other major pollution sources.

Summary of the SR 92 Road-Widening Project

The selected construction project covered approximately a four-mile portion of SR 92 in Cochise County (see **Figure 1**). 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 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, a center left-turn lane, and an eight-foot shoulder on each side of the roadway. Most portions 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 Hereford Road intersection.

- 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 completed by September 2010. ADOT funded the air quality field study to collect data over one calendar 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 in late 2008, before the air quality field study, included initial land clearing and grubbing along the north end of SR 92; work that took place after the air quality field study included final paving-related construction and some drainage work. However, the field study overlapped some of the land clearing work as well as preliminary paving work; therefore, the field study was able to monitor equipment activity and air quality across virtually all construction activities. During the construction period, work typically took place Mondays through Thursdays from approximately 7:00 a.m. to 3:00 p.m.; unless special construction work was warranted, one lane of traffic remained open in each direction.

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

TECHNICAL APPROACH

The field study took place from January 2009 through January 2010 and 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. These data sets were used to assess background pollutant concentrations, identify construction equipment-related impacts on near-road pollutant concentrations, and help distinguish air quality impacts associated with construction equipment use from impacts associated with on-road vehicle fleet emissions.

Air Quality and Meteorological Data

During the field study, air quality and meteorological data were collected adjacent to SR 92. 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, the monitoring equipment required a nearby electrical power source, and cell phone coverage was needed to facilitate real-time data transfer to STI's server and to support communication with on-site technicians. We selected a monitoring location at a point roughly midway through the construction area (see **Figure 2**). SR 92's direction at the monitoring site is generally from northwest to southeast. Winds in the area are predominantly out of the southwest; thus the monitor locations were aligned in parallel to the prevailing winds. Two monitoring trailers (trailers 2 and 3 in Figure 2) were located approximately 110 feet from the road; two other trailers (trailers 1 and 4 in Figure 2) were located approximately 220 feet from the road. **Figure 3** provides photographs of the trailers.

Figure 2. Monitoring locations in relation to the overall construction site.

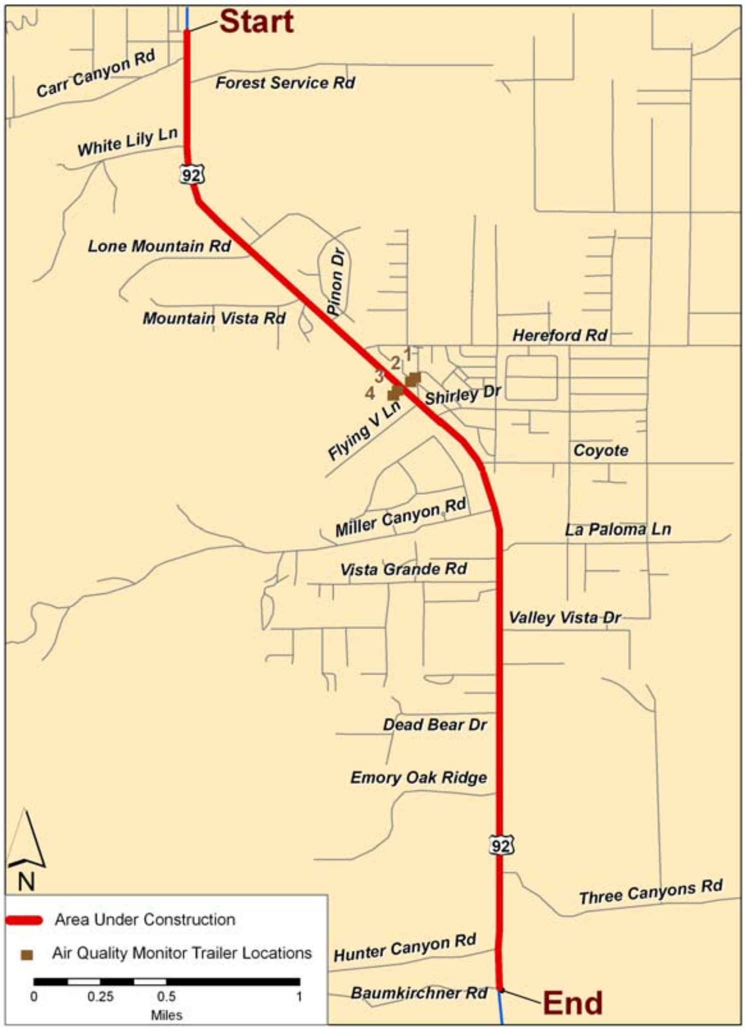


Figure 3. Air quality and meteorological monitoring trailers adjacent to SR 92, looking northeast (left) and southwest (right).

A summary of measurements and respective instruments/instrument housing is presented in **Table 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 to provide consistent characteristics of pollutant dispersion. Details of the parameters that were recorded at each monitoring location are presented in **Table 2**.

Table 1. Measurements and instruments for the 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 Aethelometers™
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

Table 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
Black carbon	x	x	x	x
NO, NO_x, NO_2		x	x	
CO		x	x	
CO_2		x	x	
CH_4			x	
Particulate polycyclic aromatic hydrocarbon (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

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 10 minutes by cell phone modem and transferred to STI's web server; the data underwent auto-screening quality assurance procedures and were posted in graphical format to a password-protected web page for viewing by authorized personnel. STI consolidated data into a database, validated the data to ensure consistency and representativeness, and eliminated errors or identified inaccuracies.

Activity Data

In past studies of emissions from construction equipment, a variety of approaches have been used to collect equipment activity data, including surveys, field-inspector diaries, time-lapse photography, and on-board monitoring equipment. Each data collection method has its strengths and weaknesses, and STI determined that no single data-collection 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 the Bison Construction Company (Bison), ADOT's construction contractor.

First, to gather detailed information on equipment usage patterns, STI worked with Bison and a third-party vendor to outfit construction equipment with GPS data loggers that tracked equipment locations, movements, and engine status (off, idle, or under load). STI worked with Bison to inventory the construction equipment to be used during the roadway work and identify key data, such as equipment horsepower ratings and model year. Once key equipment pieces were identified, the study team instrumented the equipment with Fleet Management Solutions' (FMS) MLT-325o equipment tracking module, which includes a GPS receiver and two-way satellite communications modem. FMS also uses a web-based system for reporting and tracking activity data from the tracking module. **Figure 4** shows a screenshot of this system, which was used to view real-time maps of equipment locations and produce daily reports of equipment usage. **Table 3** lists Bison's equipment fleet for the SR 92 project and indicates which pieces of equipment were instrumented with GPS units.

Figure 4. FMS web-based system for reporting and mapping activity data.

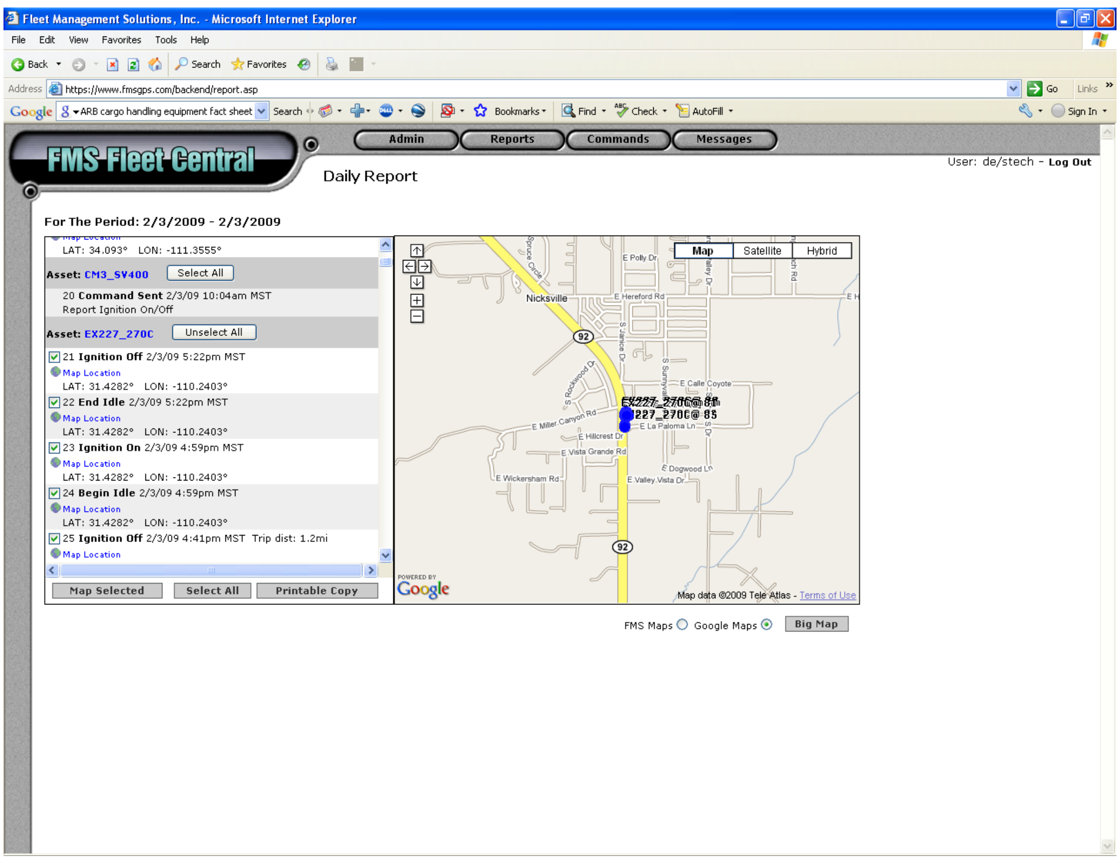


Table 3. Bison Construction Company's fleet of equipment for the SR 92 project.

Equipment Type	Make	Model	Model Year	Horse-power	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

In addition, ADOT provided STI with supplemental data on equipment activities, including daily fuel consumption logs that recorded for billing purposes the amount of fuel pumped into each piece of equipment at the conclusion of each work day. ADOT also provided STI with daily diaries produced by ADOT field inspectors; the diaries documented 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. STI correlated relevant data from these sources with GPS data to verify the data provided by the GPS units, account for equipment that was not instrumented with GPS units (e.g., Bison equipment used on a short-term basis or subcontractors' equipment), and assign equipment activities to various phases of the construction project.

Emissions Estimation

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 to assess the impact of using project-specific activity data to quantify emissions.

Exhaust emissions from a given type of construction equipment are typically estimated using EPA's NONROAD model, which calculates emissions as the product of engine population, hours of operation, engine power, engine load factor, and pollutant-specific emission factors[1]. For example, PM emissions from excavators during the land-clearing phase of construction are calculated in NONROAD as follows:

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

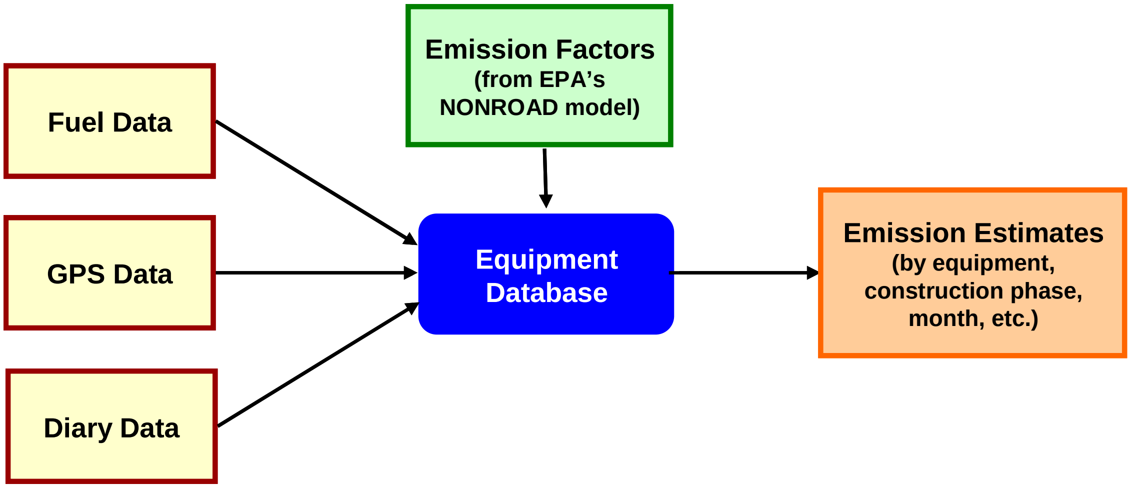
where:

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. Because NONROAD default load factors for construction equipment may not represent the way equipment is used on a given project, one alternative is to calculate emissions using fuel-based emission factors, which do not depend on 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 based on fuel-based emission factors derived from NONROAD.

Figure 5 diagrams the process 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 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 5. Process diagram for estimating exhaust emissions from construction equipment.



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[2], though more detailed emission factors are available for specific processes (e.g., general land clearing and topsoil removal)[3]. To estimate fugitive dust emissions associated with the SR 92 project, STI assembled process-specific emission factors from EPA guidance documents[4-6] and applied these factors to activity data gathered from ADOT daily diaries and GPS units.

Finally, 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 during 2009 based on inputs derived from local data, including vehicle registration data for Cochise County and fuels characteristics provided by the Arizona Department of Weights and Measures. Hourly traffic count data by vehicle class were obtained from two automated ADOT counters installed near the north and south ends of the project.

RESULTS AND DISCUSSION

The field study yielded insights regarding equipment activity, emissions, and near-road air quality impacts, as discussed in the subsections that follow.

Equipment Activity

During calendar year 2009, the SR 92 project was active for 238 working days. Work was performed primarily Monday through Thursday from about 7:00 a.m. to 3:00 p.m. On an average day:

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

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

Figure 6. Total fuel consumption by equipment type (left) and construction phase (right) for 2009.

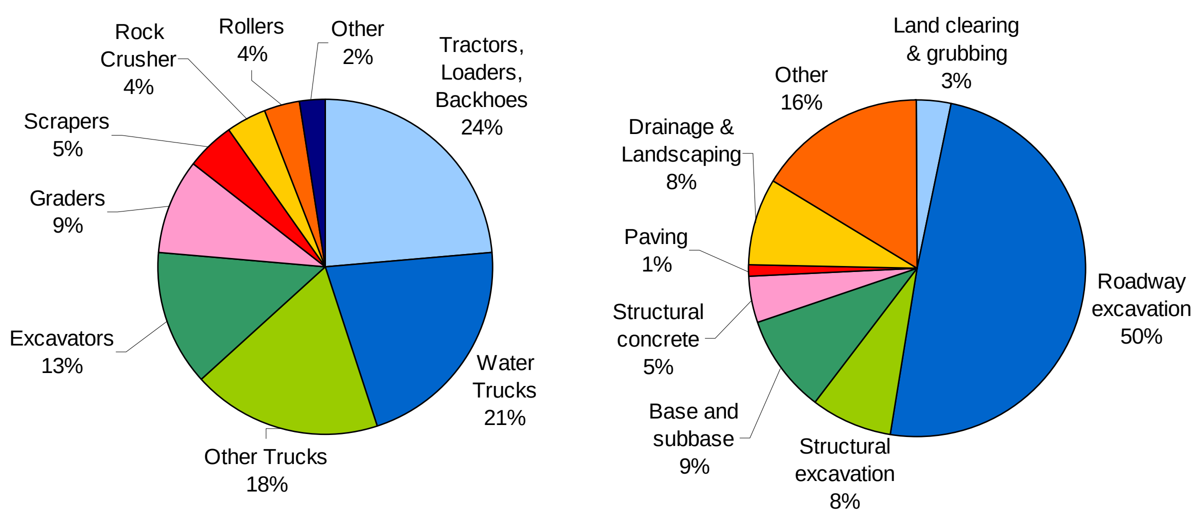
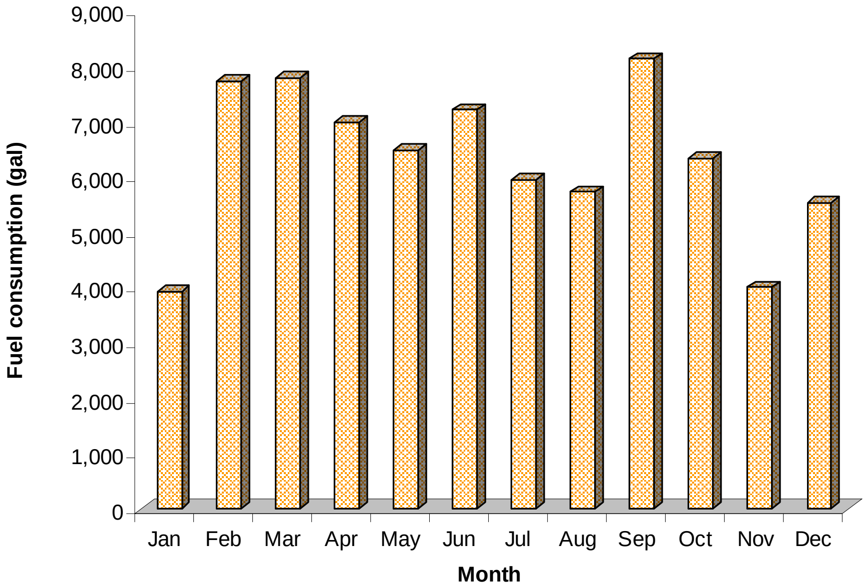


Figure 7. Total fuel consumption by month for 2009.



In an effort to contrast real-world activity data collected during this project with typical (or default) equipment usage patterns, STI compared the project-level activity data with default data from the NONROAD model, which represent average usage patterns for a given type of equipment across all applications. **Table 4** 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 most frequently on the SR 92 project (e.g., excavators and loaders). Default annual equipment usage rates (hours per year) 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. Load factors derived from field study data were generally comparable to NONROAD default values; however, load factors calculated for motor graders and scrapers were significantly lower than NONROAD defaults (see Table 4).

Table 4. 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.

Summary of Construction-Related Emissions

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 8** breaks down exhaust $PM_{2.5}$ emissions by equipment type and phase of construction; this figure shows that over half of exhaust $PM_{2.5}$ emissions were attributable to tractors, loaders, backhoes, and trucks, as well as to the roadway and structural excavation phases of construction. On a monthly basis, exhaust emissions were highest in February and September, partly because of the diesel-powered rock crusher used for crushing operations during those two months (see **Figure 9**). 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 9).

Figure 8. Exhaust $PM_{2.5}$ emissions by equipment type (left) and construction phase (right) for 2009.

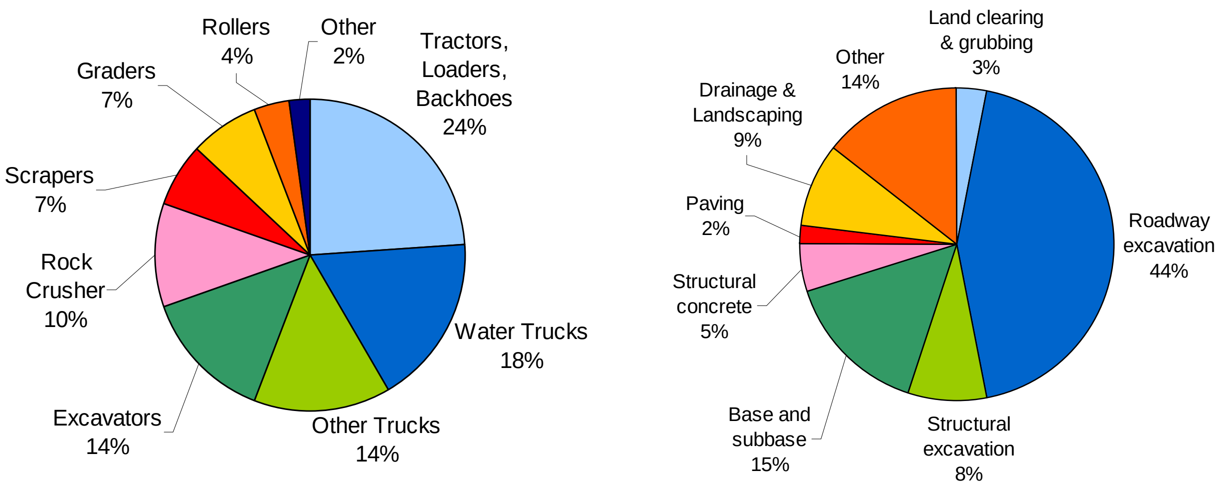
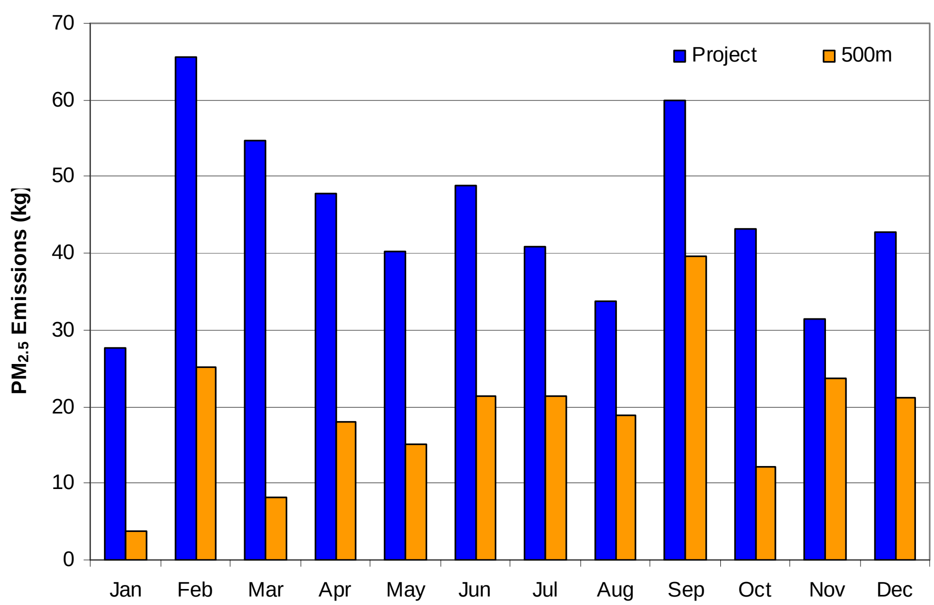


Figure 9. Exhaust $PM_{2.5}$ emissions by month and within 500 m of the air quality monitors.



In terms of fugitive dust emissions, construction activity at the SR 92 project during 2009 produced 6,490 kg of PM_{10} and 924 kg of $PM_{2.5}$ emissions. **Figure 10** breaks down 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 11**). Fugitive dust emissions were also evaluated by proximity to the air quality monitors (equipment locations were derived from GPS and daily log data); these analyses showed that 39% of total fugitive $PM_{2.5}$ emissions occurred within 500 m of the monitors (see Figure 11).

Figure 10. Fugitive $PM_{2.5}$ emissions by construction phase for 2009.

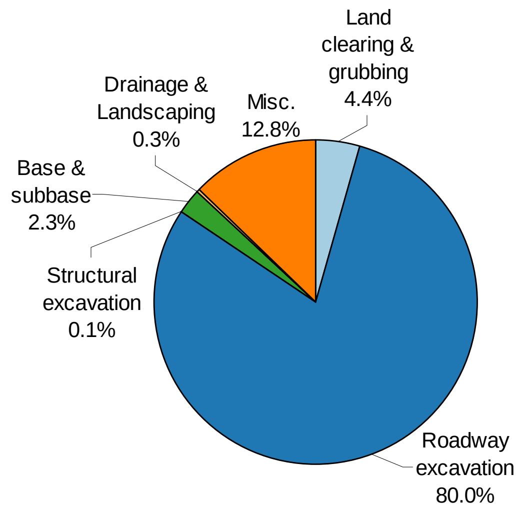
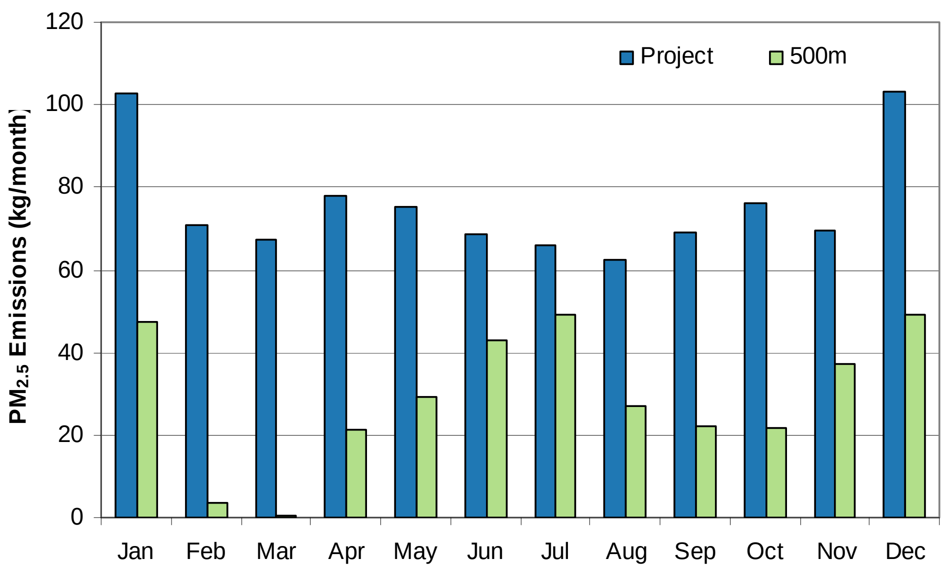
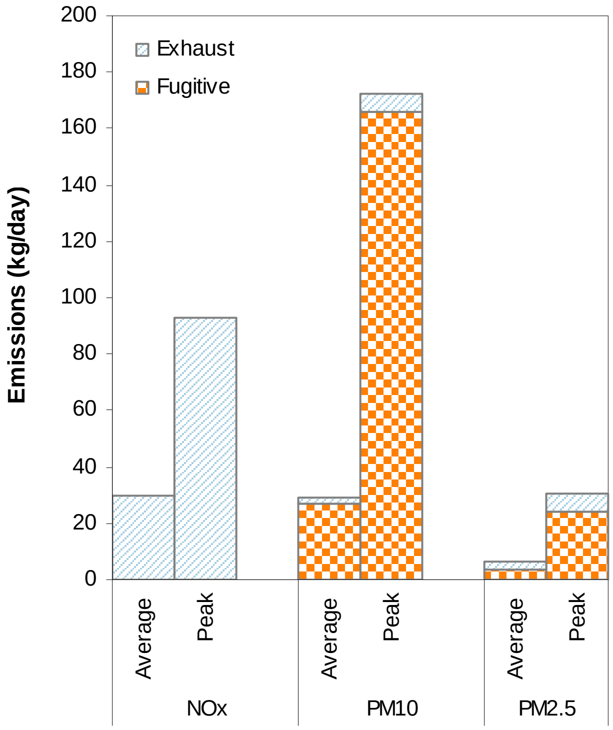


Figure 11. Fugitive $PM_{2.5}$ emissions by month and within 500 m of the air quality monitors.



Overall, construction activity at the SR 92 project during 2009 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 12**). Fugitive dust accounted for 96% of the peak-day PM_{10} emissions and 79% of the peak-day $PM_{2.5}$ emissions.

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



On-Road Activity and Emissions

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-day traffic volumes were highest during the middle of the day (see **Figure 13**). 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.

Table 5 shows annual and daily estimates of NO_x, PM_{10}, and $PM_{2.5}$ emissions from on-road motor vehicles traveling on SR 92 through the project area (for emissions 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.

Figure 13. Diurnal pattern of traffic counts on SR 92.

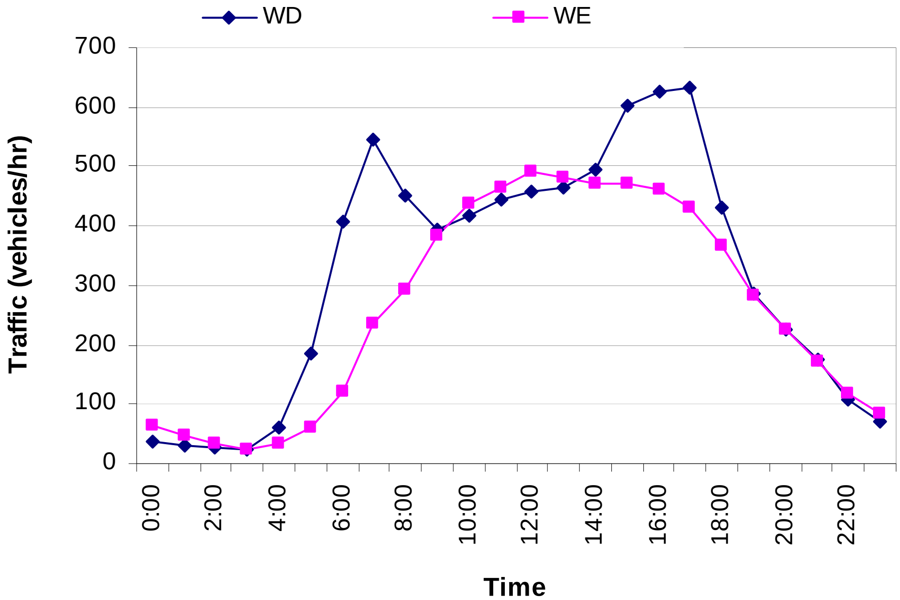


Table 5. On-road motor vehicle emissions on SR 92 for 2009.

Period	Emissions (kg)		
	NO_x	PM_{10}	$PM_{2.5}$
Annual	17,538	445	280
Peak day (October 21, 2009)	146.1	3.7	2.7
Average weekday	56.9	1.4	0.9
Average weekend day	42.6	1.1	0.6

Air Quality Data

The monitoring program lasted more than a year and generated a substantial array of air quality data. These data were summarized for the entire 2009 calendar year, and detailed analyses were conducted on key periods to help assess the air quality impacts of construction activity. For example, we examined data for one week in February 2009 during which 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 represented 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. Summary statistics for the entire calendar year of 2009 show that:

- $PM_{2.5}$ 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

- Virtually all of the NO_2 1-hr measurements were below the 100-ppb NAAQS. However, there were two 1-hr measurements (out of a total of 15,953 1-hr observations) that exceeded 100 ppb: one at 11:00 p.m. on October 28, 2009 (112.4 ppb) and a second at 9:00 p.m. on October 29, 2009 (101.3 ppb)
- Concentrations of black carbon—collected as a surrogate for diesel PM to help identify construction equipment air quality impacts—were typically only a few tenths of a $\mu g/m^3$ when averaged over a 24-hr period but reached 1.1 $\mu g/m^3$ for a maximum 24-hr value

In addition, it is helpful to understand how air quality during the May 25-31 case study week compared to observations for the calendar year as a whole. 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, as shown in **Table 6**. In particular, the construction work resulted in higher PM_{10} concentrations: the maximum 24-hr average PM_{10} concentration during the study week was approximately 29 $\mu g/m^3$, which was among the highest values observed during the year. $PM_{2.5}$ impacts, however, were far less pronounced during the study week. Also, while NO_x-related concentrations (NO_x, NO_2, and NO) increased during day-time hours as construction and on-road vehicle activity increased, NO_2 concentrations peaked at less than 10 ppb and averaged less than 2 ppb throughout the week. These values are far below the EPA NO_2 NAAQS, which is 100 ppb for 1 hour.

Table 6. Summary PM statistics for May 25-31, 2009, compared to calendar year 2009 as a whole.

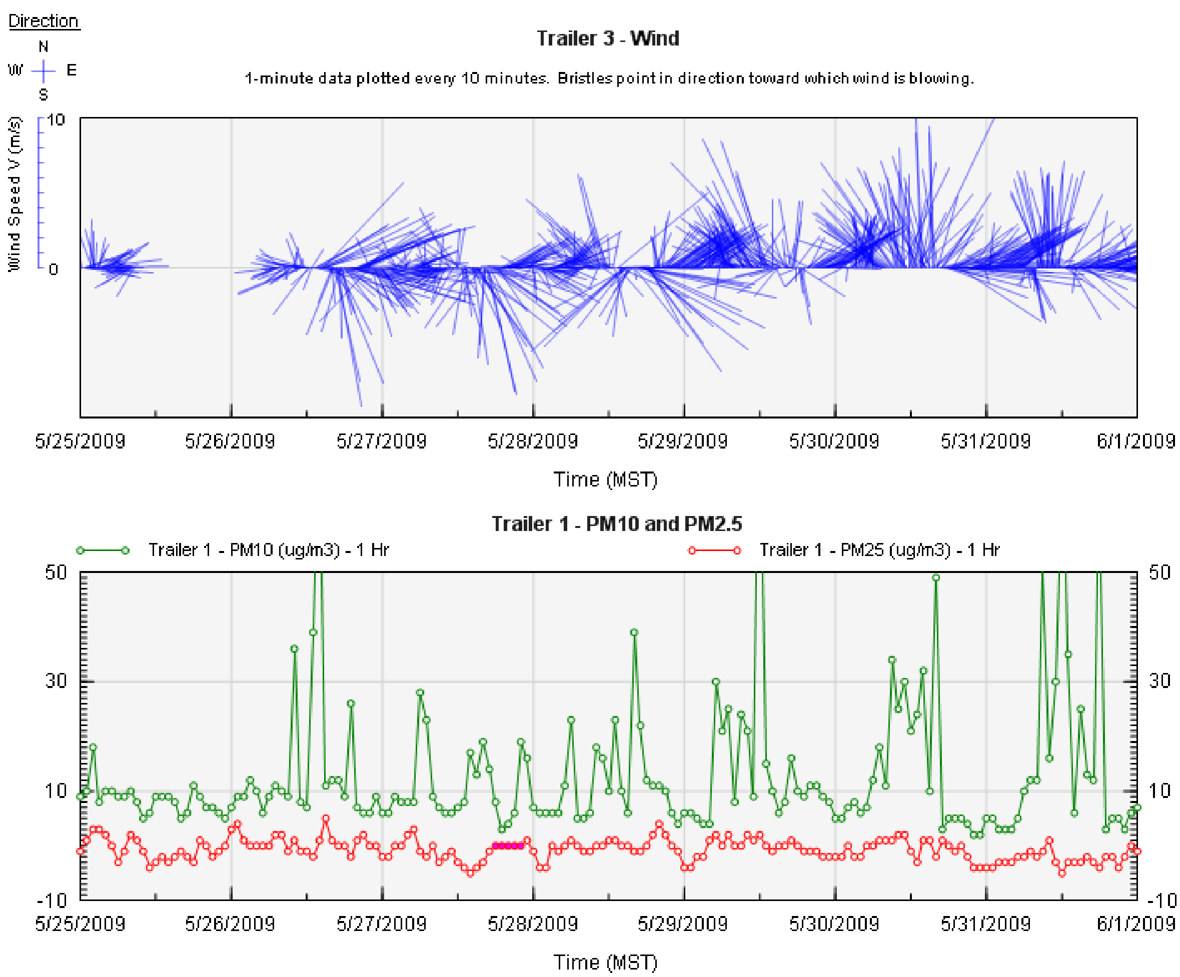
Period	Parameter	Min	Max	Median	Mean	SD
CY 2009	NO_2 (ppb)	-1.6	112.4	1.4	1.9	2.3
	$PM_{2.5}$ ($\mu g/m^3$)	-4.3	**10.0**	**1.0**	**1.0**	2.2
	PM_{10} ($\mu g/m^3$)	-1.8	**72.0**	**11.3**	**12.7**	7.7
	BC ($\mu g/m^3$)	0.0	1.1	0.2	0.2	0.1
May 25-31,2009	NO_2 (ppb)	-0.3	8.8	1.1	1.4	1.4
	$PM_{2.5}$ ($\mu g/m^3$)	-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
	BC ($\mu g/m^3$)	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 measurements from a single monitor. Median, mean, and standard deviation (SD) measurements are calculated by averaging data collected across all monitors.

An overview of the air quality during this week is shown in **Figure 14**, which indicates the winds and particulate matter concentrations measured at trailer 1. Although some wind data for Monday, May 25, is missing, the winds have a variable pattern 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. On each work day, peaks in PM_{10} concentrations started about 6 a.m. to 8 a.m. (all times are

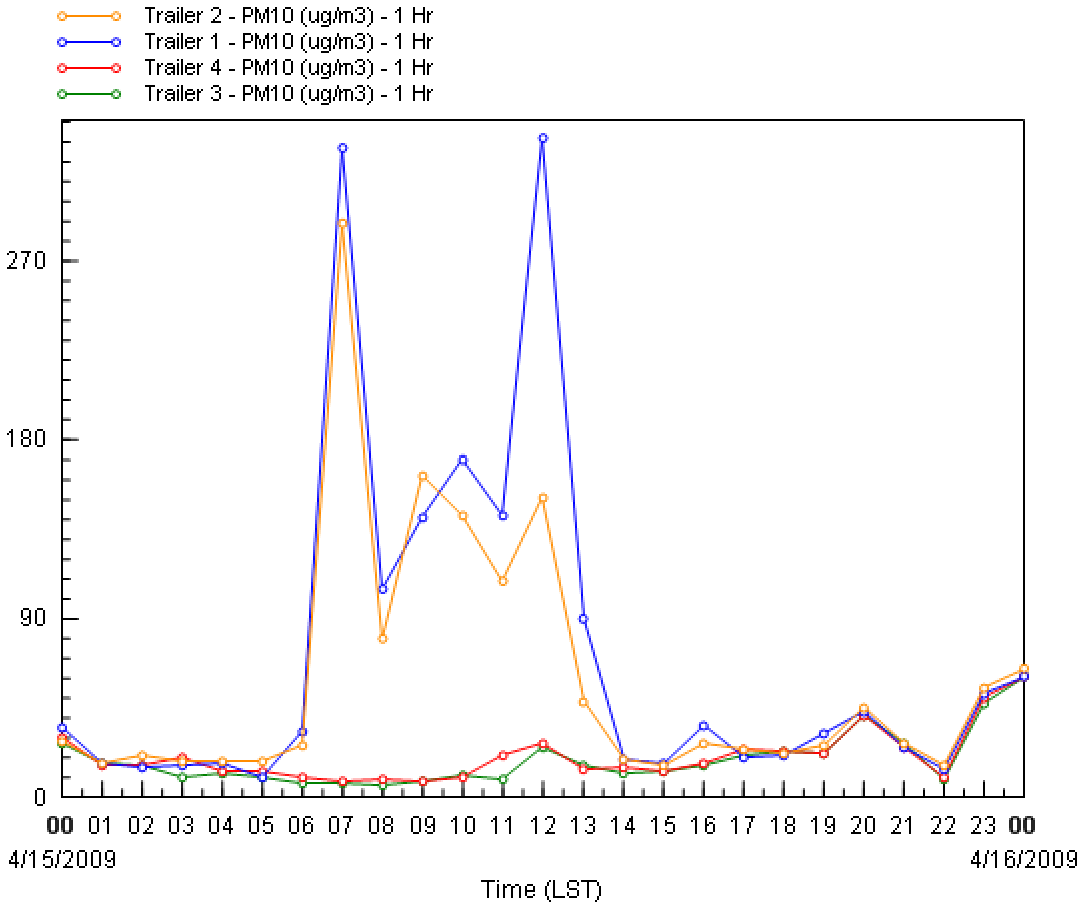
Mountain Standard Time) and lasted until about 4 p.m. to 6 p.m., which coincided with construction activity on these days. $PM_{2.5}$ concentrations were low and variable throughout the week and thus apparently did not show much influence from the nearby construction. Note that during this week in May 2009, the atmosphere was weakly stable overnight. However, by about 6 a.m. or 7 a.m., the 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.

Figure 14. Winds and PM concentrations from trailer 1, May 25-31, 2009.



Another case study related to a midday episode on April 15, 2009, that 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), as shown in **Figure 15**. 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. However, even during this high PM_{10} event, $PM_{2.5}$ concentrations remained relatively consistent with the values observed at other times, confirming that $PM_{2.5}$ concentrations were relatively unaffected by the construction work.

Figure 15. PM_{10} concentrations and winds measured April 13-19, 2009.



CONCLUSIONS

The overall field study yielded insights regarding equipment activity, emissions, and near-road impacts. During one year of study, construction equipment operated on 238 days; on average, approximately 25-30 pieces of equipment were on site 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 subbase 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%). In general, equipment usage rates observed during the year-long field study were significantly lower than default annual usage rates in the NONROAD model.

Generally, the breakdown of important $PM_{2.5}$ exhaust emissions contributors parallels the important sources of activity, both by construction phase and equipment type. Approximately

80% of fugitive $PM_{2.5}$ dust emissions were attributable to the roadway excavation construction phase.

Analyses of air quality data collected during the field study showed that, while $PM_{2.5}$ concentrations were influenced by construction-related activity, 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; 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 (e.g., wildfires in the vicinity of the construction zone).

Results of the field study also indicated that, during the case study periods examined, construction activity increased PM_{10} concentrations at downwind receptors. The predominant contributor to these impacts was fugitive dust from the construction zone, though 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. 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 levels that exceeded concentrations at all other times during the year.

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KEY WORDS
Emissions inventories
Construction equipment
NONROAD model
Nonroad mobile sources
GPS data
$PM_{2.5}$

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