DOWNWIND REAL-TIME $PM_{2.5}$ AND CO MONITORING DURING PRESCRIBED FOREST BURNS AT FORT BENNING, GA

by

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(Under the Direction of Luke P. Naeher)

ABSTRACT

Background: Prescribed forest burning has long been recognized as a significant source of various air pollutants including particulate matter with an aerodynamic diameter $\leq$ 2.5 μm ($PM_{2.5}$) and carbon monoxide (CO). However, few studies have evaluated downwind exposures, especially using real-time monitoring methods with a strategy to capture instantaneous downwind exposures with mobile samplers to accommodate change of wind directions.
Objectives: Our specific objectives were to: 1) estimate ground-level smoke exposure levels (as indicated by $PM_{2.5}$ and CO); 2) determine if distance to the fire and time since burn ignition have any significant effect on the exposure levels of $PM_{2.5}$ and CO. **Methods:** Smoke data was collected from air samplers mounted on three trucks that were assigned to three different sampling zones downwind from the prescribed forest burns. Sampling zones were within a 60 degree arc started downwind from the center of the burn with a sampling scale of 1-3 kilometers (Km) in Zone 1; 3-5 Km in Zone 2; 5-7 Km in Zone 3. In order to capture as much smoke as possible, trucks moved within their designated sampling zones to the best degree possible to remain under the plume. $PM_{2.5}$ was sampled using TSI DustTrak Model 8520 aerosol monitors. CO was sampled with Langan CO Monitor Model T15v and Draeger PAC III CO Monitors.

Sampling started around 12:00 and continued until approximately 15:30 for each of the 11 sampling days. **Results:** Exposure to $PM_{2.5}$ was highly variable and significantly affected by the distance to burn area ($P = 0.018$) and the time since burn ignition ($P < 0.001$). Geometric mean (GM) concentrations of $PM_{2.5}$ calculated from 15-minute moving averages ranged from 3 $\mu g/m^3$ to 104 $\mu g/m^3$, with a maximum 15-minute moving average of 403 $\mu g/m^3$. In comparison with $PM_{2.5}$, CO levels were fairly low, with a highest maximum 15-minute moving average at 3.1 ppm and all daily (3-hour sampling duration) GM values less than 2 ppm. **Conclusion:** Our findings suggest that smoke exposures downwind from prescribed forest burns may at times be high enough to warrant public health concern.

INDEX WORDS: Air quality, area monitoring, community exposure, CO, $PM_{2.5}$, prescribed forest burns

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DEDICATION

I dedicate this work to my uncle and mentor, Youcheng Liu. Thank you for your constant encouragement and strong faith in me. Without your never-ending spiritual and financial support on my studies, I could not get this far. I also want to dedicate this thesis to my parents: thank you for your love and numerous investments in me over the years.

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

Prescribed forest burning has long been recognized as a significant source of various air pollutants, including particulate matter with aerodynamic diameter less than or equal to 2.5 µm ($PM_{2.5}$) and carbon monoxide (CO). Both firefighters and community residents can be exposed to high levels of air pollutants generated from forest fires. Exposure to these air pollutants, particularly $PM_{2.5,}$ may cause adverse health effects such as respiratory symptoms and reduced pulmonary functions. It may also exacerbate existing health conditions such as cardiorespiratory diseases. However, few studies have been done to evaluate exposure levels and emission behaviors using a downwind sampling scheme. In addition, previous downwind studies mostly used traditional gravimetric analysis method for assessing $PM_{2.5}$ exposure that limited the assessment of peak exposures which are also of importance in understanding exposures and related health effects.

To better evaluate environmental exposures to air pollutants from forest fires and identify significant exposure determinants, we conducted a study to evaluate ground level concentrations of downwind real-time $PM_{2.5}$ and CO during a series of prescribed forest burns conducted at Ft. Benning, GA between Year 2008 and 2009. The specific objectives of this study were to: Our specific objectives were to: 1) estimate ground-level smoke exposure levels (as indicated by $PM_{2.5}$ and CO); 2) determine if distance to the fire and time since burn ignition have any significant effect on the exposure levels of $PM_{2.5}$ and CO. The exposure determinants identified in this study, such as distance to the fire and the effect of wind direction may help the planning of future prescribed forest burns and community intervention measures to reduce exposure to forest fire pollutants. This study will also provide data to improve exposure assessment methodologies for future studies.

This thesis includes 4 chapters. Chapter 1 is the introduction and outlines the information presented in each chapter. Chapter 2 is a review of current literature on forest fires, including background information, the history of forest fires and their sources, associated health effects on firefighters and the affected communities, exposure assessment strategies and methodologies, previous downwind studies on forest fires and their limitations, and our objectives for the current study. Chapter 3 is a manuscript to be submitted to the *Journal of Occupational and Environmental Hygiene* that describes our study in Ft. Benning in detail. This study evaluated exposure levels of downwind $PM_{2.5}$ and CO from prescribed forest burns using real-time sampling instruments, and identified factors which significantly influenced exposures to $PM_{2.5}$. Chapter 4 summarizes discussion from previous chapters as well as findings of the current study.

CHAPTER 2

LITERATURE REVIEW

In this chapter a current literature review of forest fires is presented. First, the history, sources and impacts of forest fires are discussed. Then air pollutants from forest fires and chemical composition of PM are introduced. Following this, a current review of exposure and health effect assessment studies on forest firefighters and affected communities is presented. After this, the discussion is narrowed down to downwind smoke exposure assessment studies from prescribed forest burns. Finally, the objectives of this thesis research are outlined.

Forest fires

Forest fires burn millions of hectares of forest worldwide (Moore et al. 2003). The first evidence of the forest fire can be cast back to the early carboniferous era – approximately 350 million years ago (Narendran 2001). The sources of forest fires can be natural or anthropogenic. Natural causes of forest fires are usually lighting strikes and burning coal seams, while anthropogenic causes of forest fires are mainly associated with human activities such as incendiarism and controlled prescribed forest burning. The impacts of forest fires are various. For example, forest fires impact forest ecosystems by endangering lives of animals and plants in the forest and altering the structure and composition of forests. Further, forest fires can be devastating if the impacts are strong enough to jeopardize property, crops, and even human lives. In addition, forest fires can adversely affect the environment by impacting biodiversity, degrading the regional air quality and reducing visibility (Robinson et al. 2004). Numerous studies worldwide have reported the occurrence, behavior, and impacts of forest fires (Naeher et al. 2007). For example, in Australia, a forest fire regarded as “the worst bushfire seen in this century”, impacted the State of New South Wales from January 5 to 12, 1994. The highest hourly peak concentration of particles with an aerodynamic diameter less than or equal to 10 µm (PM_{10}) obtained during the time period was 250 $\mu g/m^3$, a value nearly two times as high as EPA’s 24-hour standard for PM_{10} (Smith et al. 1996). Also in Australia, during January to March 2003, the northeast and Alpine regions of the State of Victoria experienced smoke from a major forest fire over the entire state for an extended period of time (Tham et al. 2009). In Europe, smoke generated from forest fires often times would spread to distant regions and influence remote communities (Hanninen et al. 2009).

Forest fires are frequently observed in the United States as well. For example, in northern New Mexico, a large wildfire called the Cerro Grande Fire, which occurred in 2000, devastated the town of Los Alamos and damaged the Los Alamos National Laboratory (Schollnberger et al. 2002). Throughout August and September 2003, Missoula, Montana was greatly affected by smoke from the fire burning throughout western Montana (Ward et al. 2006). As estimated 3700 tons of CO, 250 tons of volatile organic compounds (VOCs), 340 tons of $PM_{2.5}$ and 50 tons of nitrogen oxide (NOx) were emitted from the wildfires in eastern Texas in August and September 2000 (Junquera et al. 2005).

Air pollutants from forest fires and chemical compositions of PM

Forest fires emit various types of air pollutants into the atmosphere. These air pollutants include, but are not limited to, PM, CO, nonmethane hydrocarbons (NMHCs), NOx, ammonia (NH_3), polycyclic aromatic hydrocarbons (PAHs), and VOCs (Junquera et al. 2005; Reisen and

Brown 2006; Sillanpaa et al. 2005). Every year, substantial amounts of various air pollutants are emitted into the atmosphere from forest fires. For example, it was reported that the annual emission of fine particulate matter from forest fires in Texas was estimated at 40,000 tons per year, which accounted for 1–2% of total annual statewide emissions in years 1996 and 1997 (Dennis et al. 2002). Also in Texas, it was estimated that 3700 tons of CO emissions, 250 tons of VOC emissions, 340 tons of $PM_{2.5}$, and 50 tons of NOx emissions were generated from a wildfire on days of the highest wildfire activity in September of 2000 (Junquera et al. 2005). In a study conducted to investigate the 1997 haze disaster in Indonesia, researchers found that the levels of the PAHs in the affected area were 6-14 times higher than those in the unaffected area (Kunii et al. 2002). It was reported that approximately one-third of PM emissions in Canada originate from forest fires (Rittmaster et al. 2006).

The chemical composition of biomass smoke has already been fully reviewed (Naeher et al. 2007). For the purpose of this thesis, only the chemical composition of PM is discussed. The chemical composition of PM is source dependent. A number of studies have been conducted to identify the chemical components of $PM_{2.5}$ from the smoke of forest fires. For example, one study found that the PM from the smoke of a prescribed forest burn contained high organic carbon levels (typically >90% by mass) and was enriched with components such as ions (K^+, $NH4^+$ and NO^{3-}) and elements (K^+, chlorine, sulfur and silicon), as well as the metals titanium and chromium (Robinson et al. 2004). In another study, physical and chemical characterization of $PM_{2.5}$ emissions from simulated agricultural fires was evaluated. It was found that combustion-derived PM emissions from wheat were enriched in K (31% weight/weight, w/w) and Cl (36% w/w), whereas the PM emissions from rice were largely carbonaceous (84% w/w) (Hays et al. 2005). In addition, a study identified that the major condensable emissions from the smoke of 29 bench-scale fires were acetic acid, 2-furaldehyde, vinyl acetate, acetol and methanol. These oxygenated organic emissions have been shown to be primarily dependent on fuel chemistry and secondarily on combustion efficiency (McKenzie et al. 1995).

Exposure and health effect assessments on the smoke from forest fires

The association between the exposure to smoke of forest fires and the resultant health effects has been studied for many years. These studies can be roughly categorized into two groups in terms of the studied populations: those that assess the exposure and health effects of forest fire fighters are called occupational exposure and health effect studies whereas those that assess the exposure and health effects of individuals in the exposed community are called community exposure and health effect studies.

Occupational exposure and health effect assessment

It is estimated that there are around 80,000 wildland fire fighters in the U.S who are currently working in the fields of prescribed forest burns and wild fires (Betchley et al. 1997). Different from structural fire fighters who are mainly concerned with buildings, wildland fire fighters focus on vegetation fires of forests, rangeland, and other natural fuels (Booze et al. 2004). Since wildland fire fighters are exposed to a great range of air pollutants generated from the smoke of forest fires, the occupational exposures of wildland firefighters to smoke of forest fires have been under intensive scrutiny for many years (Materna et al. 1992).

As early as in 1991, it was reported that a variety of potent air toxins are in the smoke produced by burning forest and range biomass (Reinhardt 1991). In this paper, the author investigated firefighter exposures to CO and formaldehyde exposures at four prescribed forest burns in Western United States and pointed out that formaldehyde may be correlated with CO emissions. Following this in 1992, it was shown in another study that wildland fire fighters might at times be exposed to concentrations of CO, total or respirable particulates, or silica at levels near or higher than recommended occupational exposure limits (Materna et al. 1992). It was also reported that as measured in a few instances, time-weighted average formaldehyde levels were above 0.37 mg/m^3 (0.3 ppm). This indicated that formaldehyde-induced eye or respiratory irritation might occur. In another paper published in 2000, Reinhardt further pointed out that a significant percentage of workers experienced exposure to CO and respiratory irritants that exceeded occupational exposure limits based on smoke data collected during prescribed forest burns in the Pacific Northwest in 1991 and 1994 (Reinhardt et al. 2000). Consistent with above studies, it was found during forest fires in fall 2005 and 2006 in Australia that the primary air toxics of concern in forest fire fighting were CO, respirable particles and formaldehyde (Reisen and Brown 2009).

Forest Firefighter exposures to smoke-related chemicals which are human carcinogens were also investigated in a number of studies. In 1995, it was found that suspected carcinogens 2-furaldehyde and vinyl acetate exceeded the toxic level (McKenzie et al. 1995). This toxic level, as expressed by molar ratios of individual compound emissions to CO emissions, was calculated based on a model developed by Reinhardt in (1994) in which exposure levels of these air toxics can be predicted based on exposure concentrations of CO. Reinhardt and Ottmar reported in a later study that benzene, another well known human carcinogen, was measured and found to be well below permissible exposure limits as set by the US Occupational Safety and Health Administration (Reinhardt and Ottmar 2004). PAHs, many of which are human carcinogens, were evaluated in a study conducted during prescribed forest pile burns of mainly ponderosa pine slash on the White Mountain Apache Tribe reservation in the fall of 2006. In this study, personal PAH exposures were detectable for only 3 of 16 PAHs analyzed based on urine samples collected from 21 firefighters showing overall low exposures to PAHs (Robinson et al. 2008).

To study firefighter exposure to smoke of forest fires, a scheme that is frequently used is to examine cross-season and cross-shift exposure effects on lung functions. By comparing concentrations of air pollutants that firefighters are exposed to before and after an active season or work shift, actual exposures caused by firefighting are estimated. Studies in which cross-season effects were compared appeared earlier than those in which cross-shift exposure effects were compared. Dated back to 1991, Rothman conducted a study to examine cross-seasonal changes in pulmonary function and respiratory symptoms in 52 wildland firefighters in Northern California (Rothman et al. 1991). The mean cross-seasonal change in forced expiratory volume in one second (FEV1) was -1.2% (95% CLs: -0.5% - 2.0%) with a corresponding mean change in forced vital capacity (FVC) of -0.3% (95% CIs: 0.4% - 1.0%). The author also found that there was a significant cross-seasonal increase in symptoms such as eye irritation, nose irritation, and wheezing which were believed to be associated with recent fire-fighting. Consistent with these findings, Liu et al. (1992) found significant mean individual declines of 0.09, 0.15, and 0.44 L/s in post-season values of FVC, FEV1, and forced expiratory flow from 25% to 75% of vital capacity (FEF25-75%), respectively, when compared with preseason values. They also found that when comparing preseason methacholine dose-response slopes (DRS) with postseason dose-response slopes, there was a statistically significant increase in airway responsiveness ($p = 0.02$) suggesting the increase in airway responsiveness in firefighters was associated with cross-season exposure effects.

The earliest study that studied cross-shift effects was conducted by Betchley in 1997 (Betchley et al. 1997). In this study, spirometric measurements and self-administered questionnaire data were collected from firefighters who worked in the north, central and southern regions of Washington's and Oregon's Cascade Mountains before and after the 1992 and 1993 firefighting seasons. The author found significant mean individual declines in lung function as denoted by FVC, FEV1 and FEF (25-75%). From preshift to midshift, FVC decreased by 0.089 L, FEV1 by 0.190 L, and FEF declined by 0.439 L/sec, with preshift to postshift declines of 0.065 L, 0.150 L, and 0.496L/s, respectively. Cross-seasonal (Spring and Winter 1992) declines in FVC, FEV1 and FEF (25-75%) of 0.033 L, 0.104 L, and 0.275 L/s were also observed in this study. These results suggest a concern for potential adverse respiratory effects in forest firefighters. In another study, short-term effects of exposures to $PM_{3.5}$, acrolein, formaldehyde, and CO on lung function were investigated on 65 firefighters performing prescribed forest burns. Spirometric measurements made at the beginning, midpoint, and end of their work shift showed that $PM_{3.5}$ was associated with a -0.030 L change in the cross-shift FEV1 (95% CI: 0.087 - 0.026) while acrolein, formaldehyde and CO exposure were not significantly associated with changes in FVC, FEV1 and FEF(25-75%) (Slaughter et al. 2004).

Other than lung function and respiratory symptom studies, there have not been many studies that investigated forest fire-related health effects. However, in a study conducted in 2004, a health risk assessment was performed to evaluate the upper-bound risks of cancer and non-cancer adverse health effects among wildland firefighters performing wildfire suppression and prescribed forest burn management (Booze et al. 2004). In this study, 15 substances with potential health risks to wildland firefighters were identified and their likelihoods of adverse health effects were evaluated. However, it was found that only benzene and formaldehyde posed a cancer risk greater than 1 per million, and only acrolein and respirable PM exposures resulted in hazard indices greater than 1.0. These findings suggest that future risk assessment efforts should be focused on these few substances such as benzene and formaldehyde that involved in potentially significant risks.

Community exposure and health effect assessment

While sharing many attributes of occupational exposure to the smoke of forest fires, community exposure has its own characteristics. Forest fires affect not only a few numbers of firefighters, but also the whole downwind community where large numbers of people may be exposed.

Several community exposure assessment studies related to forest fires have been conducted thus far. For example, a recent study conducted in Finland, Hanninen et al. (2009) found that populations of 11 Southern Finnish provinces were exposed to an additional population-weighted average $PM_{2.5}$ level of 15.7 $\mu g/m^3$ that resulted from a forest fire in 2002. Another study reported that in a rural Brazilian town, ambient levels of respirable PM averaged 191$\mu g/m^3$, which is high enough to cause adverse health symptoms (Reinhardt et al. 2001). Further, in a study conducted to understand the intervention strategies for residences impacted by scheduled prescribed forest burns and wildfires, Henderson et al. (2005) showed that, houses using air cleaners and with windows shut had much lower exposure levels of $PM_{2.5}$ (< 3 mg/m^3) than houses without interventions.

In comparison with studies that purely assessed community exposure levels, other studies evaluated the relationship between exposure assessment and health effect assessment. In addition, to assess adverse health effects in communities affected by forest fires, hospital admission and emergency attendances were often used as indices. For example, in a study aimed at determining whether there was an increase in the proportion of asthma presentations to emergency departments (ED) in western Sydney as a result of the forest-fire-generated particulate air pollution, retrospective data for asthma presentations from seven public hospitals serving the Western Sydney and Wentworth Health Areas in 1993 and 1994 were analyzed (Smith et al. 1996). However, no increase in asthma presentations to ED in western Sydney caused by smoke of forest fires was observed. In contrast, another study found that medical visits for respiratory illnesses during the weeks of the 1999 California wildfire increased by 217 visits (from 417 to 634 visits, or by 52%) over the previous year (Mott et al. 2002).

Compared to the general population, susceptible populations such as the elderly, children, people with allergies and those who have preexisting respiratory or cardiopulmonary diseases are more likely to develop health symptoms from the exposure to smoke of forest fires even at low levels (Naeher et al. 2006). For example, a survey indicated that those with preexisting cardiopulmonary conditions reported more symptoms before, during, and after the smoke episode (Mott et al. 2002). Mott further pointed out in his 2005 study of the 1997 southeast Asian forest fires that statistically significant increases in fire-related respiratory hospitalizations, specifically those for chronic obstructive pulmonary disease (COPD) and asthma were observed (Mott et al. 2005). The author also indicated that elderly with previous hospital admissions for cardiorespiratory diseases, respiratory diseases, and COPD were significantly more likely to be rehospitalized during the follow-up period in 1997 than during the follow-up periods in the pre-fire years of 1995 or 1996. In another article aimed at studying the acute effects of smoke from 2003 Southern California wildfires on children, a questionnaire was used to assess smoke exposure and occurrence of symptoms among high-school students (n = 873; age, 17-18 yrs) and elementary-school children (n = 5,551; age, 6-7 yrs) in a total of 16 communities. Symptoms such as nose, eye and throat irritations, cough, bronchitis, cold, wheezing and asthma attacks were found to be linked with exposures to PM_{10} during days with highest fire activities (Kunzli et al. 2006).

Downwind smoke studies for forest fires

Smoke from forest fires could cause elevated concentrations of air pollutants in affected communities and potentially give rise to various adverse health symptoms among individuals in these communities. Thus, to better understand the magnitude and levels of community exposures to forest fires, downwind sampling is a reasonable approach. However, only a few studies were found that evaluated downwind smoke exposures from prescribed forest burns.

Lee et al. (2005) measured various organic and inorganic compounds both in the gas and particle phase in the emissions of prescribed forest burnings conducted at two pine-dominated forest areas in Georgia. It was found that the VOC emission from smoldering were distinctly higher than those from flaming except for ethene, ethyne, and organic nitrate compounds. In another study compared $PM_{2.5}$ and CO exposures from prescribed forest burn smoke from a mechanically chipped vs. non-chipped plots on the Francis Marion National Forest in South Carolina in 2003 (Naeher et al. 2006), it was found that time-integrated 12-h $PM_{2.5}$ concentrations in the non-chipped plot collected from the perimeter (mean: 519.9 $\mu g/m^3$ and standard deviation: 238.8 $\mu g/m^3$) were significantly higher (1-tail P-value 0.01) than those at the chipped plot (198.1 $\mu g/m^3$ and 71.6 $\mu g/m^3$) while interior time-integrated 8-h $PM_{2.5}$ concentrations in the non-chipped plot (773.4 $\mu g/m^3$ and 321.8 $\mu g/m^3$) were moderately higher (1-tail P-value 0.06) than those at the chipped plot (460.3 $\mu g/m^3$ and 147.3 $\mu g/m^3$). In another study, field measurements were taken to determine particulate emissions and trace gas emissions downwind from an agricultural burning conducted in China (Li et al. 2007). This study used a vehicle with sampling instruments placed on top to collect downwind particulates.

Building on what we learned in the literature from the studies discussed above, we designed a study to evaluate ground level exposures of a series of prescribed forest burns at Fort Benning, GA using real-time instruments. In our study, trucks were used as the platform where $PM_{2.5}$ and CO monitors were placed. Moving point sampling instead of fixed-location sampling facilitated the collection of more representative smoke data by following real wind directions, whereas the use of real-time monitoring equipment enhanced our ability to obtain exposure profiles over the whole burning session and capture the instantaneous exposures, particularly the peak exposures, for the whole burning time periods. Our specific objectives were to: 1) estimate ground-level smoke exposure levels (as indicated by $PM_{2.5}$ and CO); 2) determine if distance to the fire and time since burn ignition have any significant effect on the exposure levels of $PM_{2.5}$ and CO.

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CHAPTER 3

DOWNWIND REAL-TIME $PM_{2.5}$ AND CO MONITORING DURING PRESCRIBED FOREST BURNS AT FORT BENNING, GA[1]

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Abstract

Background: Prescribed forest burning has long been recognized as a significant source of various air pollutants including particulate matter with an aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) and carbon monoxide (CO). However, few studies have evaluated downwind exposures, especially using real-time monitoring methods with a strategy to capture instantaneous downwind exposures with mobile samplers to accommodate change of wind directions. **Objectives:** Our specific objectives were to: 1) estimate ground-level smoke exposure levels (as indicated by $PM_{2.5}$ and CO); 2) determine if distance to the fire and time since burn ignition have any significant effect on the exposure levels of $PM_{2.5}$ and CO. **Methods:** Smoke data was collected from air samplers mounted on three trucks that were assigned to three different sampling zones downwind from the prescribed forest burns. Sampling zones were within a 60 degree arc started downwind from the center of the burn with a sampling scale of 1-3 kilometers (Km) in Zone 1; 3-5 Km in Zone 2; 5-7 Km in Zone 3. In order to capture as much smoke as possible, trucks moved within their designated sampling zones to the best degree possible to remain under the plume. $PM_{2.5}$ was sampled using TSI DustTrak Model 8520 aerosol monitors. CO was sampled with Langan CO Monitor Model T15v and Draeger PAC III CO Monitors. Sampling started around 12:00 and continued until approximately 15:30 for each of the 11 sampling days. **Results:** Exposure to $PM_{2.5}$ was highly variable and significantly affected by the distance to burn area ($P = 0.018$) and the time since burn ignition ($P < 0.001$). Geometric mean (GM) concentrations of $PM_{2.5}$ calculated from 15-minute moving averages ranged from 3 μg/m^3 to 104 μg/m^3, with a maximum 15-minute moving average of 403 μg/m^3. In comparison with $PM_{2.5,}$ CO levels were fairly low, with a highest maximum 15-minute moving average at 3.1 ppm and all daily (3-hour sampling duration) GM values less than 2 ppm. **Conclusion:** Our findings

suggest that smoke exposures downwind from prescribed forest burns may at times be high enough to warrant public health concern.

Introduction

Prescribed forest burning has long been recognized as a beneficial tool for forest management. The benefits of prescribed forest burning include, but are not limited to: removal of timber harvest residues and regeneration of new vegetation (Ferguson and Hardy 1994), conservation of threatened fire-dependent ecosystems (Glitzenstein et al. 2006), and reduction of wildfire hazards (Liu et al. 2009). Despite their benefits, prescribed forest burns have disadvantages. One disadvantage is that prescribed forest burning can cause degradation of overall air quality of downwind communities (Hu et al. 2008; Liu et al. 2009; Ward and Hardy 1991). The smoke released from prescribed forest burns contains a variety of air pollutants, such as particulate matter (PM), carbon monoxide (CO), nonmethane hydrocarbons, nitrogen oxides (NOx), ammonia (NH_3), polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs) (Junquera et al. 2005; Reisen and Brown 2009; Sillanpaa et al. 2005). PM and CO emissions are significant pollutants released from forest fires (Dennis et al. 2002). At low levels and for short-term exposure, CO can cause slight headaches, tiredness, fatigue, nausea and dizziness, while at high levels and in prolonged exposure, CO can lead to unconsciousness and even death (Raub et al. 2000). Particles less than or equal to 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$) are harmful to humans because their small size will allow them to enter the lungs and pass through progressively smaller airways until they reach and damage the alveoli (Liu et al. 2009; Wegesser et al. 2009). More specifically, $PM_{2.5}$ is associated with respiratory diseases such as asthma, bronchitis, chronic obstructive pulmonary disease (COPD) (Bell et al.

2008; Delfino et al. 2009; Halonen et al. 2009; Host et al. 2008; Karr et al. 2009) and cardiovascular illnesses (Holloman et al. 2004; Polichetti et al. 2009; Reisen and Brown 2006; Xia et al. 2007).

Smoke generated from prescribed forest burns is a potential risk to nearby communities. This issue is becoming increasingly important as population growth causes many cities to expand into historically forested areas (Liu et al. 2009). In addition, retired people who choose to live in forest areas have the potential risk of exposure to toxic air pollutants from prescribed forest burns. A number of studies have reported the overall hazards resulting from forest fires in surrounding communities (Hu et al. 2008; Junquera et al. 2005; Liu et al. 2009; Speer and Leslie 2000; Ward et al. 2006; Wegesser et al. 2009). For example, Wegesser et al. (2009) reported that 2008 California wildfires severely affected air quality in the region and millions of people were exposed to PM levels in excess of EPA standards Hu et al. (2008) and Liu et al. (2008) both reported in their articles that a severe smoke merged by two large prescribed forest burns passed over the metropolitan Atlanta area and strongly affected the local air quality. To date, a number of studies have been conducted to investigate the associations between the smoke exposure from forest fires and adverse health effects in wildland firefighters (Booze et al. 2004; Mott et al. 2002; Shusterman et al. 1993) as well as individuals in exposed communities (Delfino et al. 2009; Johnston et al. 2007; Kunii et al. 2002; Kunzli et al. 2006; Moore et al. 2006; Mott et al. 2005; Tham et al. 2009; van Eeden et al. 2001; Vedal and Dutton 2006). However, only a few studies have evaluated exposures to wood smoke from prescribed forest burns using a downwind sampling scheme (Li et al. 2007; Naeher et al. 2006).

Compared to other areas in the U.S, the south conducts prescribed forest burning more intensely and frequently (Glitzenstein et al. 2006). It is estimated that 2–3 million hectares of forest and agricultural lands in the southern United States are treated yearly using prescribed forest burning (Glitzenstein et al. 2006), which renders smoke management a great challenge. As a consequence, land managers in the south have to deal with conflicts between the wilderness act and welfare of communities adjacent to forests (Brown and Bradshaw 1994). Both the authorities conducting the prescribed forest burns and nearby communities are concerned with the potential exposure to air pollutants during the burns.

In this study, we evaluated downwind smoke exposures from eleven prescribed forest forest burns at Fort Benning, GA conducted from 2008 to 2009. The objectives of this study were to: 1) estimate ground-level smoke exposure levels (as indicated by $PM_{2.5}$ and CO); 2) determine if distance to the fire and time since burn ignition have any significant effect on the exposure levels of $PM_{2.5}$ and CO.

Methods

Study location

This study was conducted at Fort Benning, a military base located in west-central Georgia, about 6 miles southeast of Columbus, GA (see Figure 3.1). It occupies 73,533 hectares with most of the installation lying in Georgia and a small part extending into Russell County, Alabama (Olsen et al. 2007; Silveira et al. 2009). Elevations at Fort Benning range from 61 to 225 meters above sea level (Graham et al. 2008); mean summer temperature is 27.8 °*C*; mean winter temperature is 9.8 °*C*; and annual rainfall is 130 cm (Graham et al. 2009). Natural resource management at Fort Benning involves not only timber harvest and wildlife management, but also prescribed forest burning (Silveira et al. 2009). Fort Benning has implemented prescribed forest burning programs since the 1960s (Dale et al. 2008). Fort

Benning military base is divided into over 150 different compartments for the purpose of land management. Each compartment is required to be burned with a minimum frequency of 3 years.

Sampling protocol and locations

This study was designed to collect ground-level real-time $PM_{2.5}$ and CO data downwind from prescribed forest burns at Fort Benning as part of an overall study in which the monitored data will be used to test the validity of forest fire smoke dispersion models. Concurrent model building and model validation work is being conducted by researchers from the United States Department of Agriculture (USDA) Forest Service Smoke Management team and researchers from the Georgia Institute of Technology, and will be presented elsewhere.

Downwind real-time $PM_{2.5}$ and CO data were collected during three prescribed forest burns in 2008 and eight burns in 2009. On each burn day, the UGA sampling team was given the burn plan that included burn location (as denoted by compartment number), burn area, and ignition time. A downwind sampling grid was then created using an on-site map; in the grid, a 60 degree arc was established with its apex at the center of burn area and angle's centerline parallel to the predicted wind direction given by local weather station (Figure 3.2). Within this 60 degree arc three sampling zones were created. Zone 1 was 1-3 Km from the center of the burn area; Zone 2 was 3-5 Km; Zone 3 was 5-7 Km. It is noteworthy that in order to observe the plume pattern and behavior for modelling purpose, the sampling scale was changed from kilometers to miles for the April 8th, 2009 burn; Initial sampling locations were set at the most direct downwind position from the burn location, and three trucks were used to sample the three sampling zones. To sample real-time $PM_{2.5}$ and CO, two DustTrak $PM_{2.5}$ aerosol monitors, two Langan CO monitors and one PAC III CO monitor as a back-up were co-located on each truck at a sampling height of 8 feet off the ground (see Figure 3.3). Burn information, including compartment (space into which the whole area of Fort Benning is subdivided) number, acreage burned, burn duration, and sampler information are summarized in Table 3.1. During the burn, trucks moved within the designated sampling zones in an attempt to remain under the smoke plume. The movements were directed through communication between truck drivers and a coordinator located on the top of an observation tower near or within the sampling area. If the coordinator noticed that there was a change in plume direction, he would radio all sampling trucks and inform them to move toward the plume. The number of truck movements per burn was dependent on how variable the wind shifts were on that particular sampling day. The goal was to have the samplers directly under the downwind plume as much as possible by being responsive to wind shifts. However, it should be pointed out that road availability and accessibility during monitoring was a limiting factor for truck movement. Detailed wind speed, direction, and truck locations that match actual wind directions are summarized in Table 3.2. Data collected included sampling duration, truck movement, and any unexpected background events such as vehicle traffic, troop movement, and grenade smoke. For each sampling location, latitude and longitude of the sampling points were recorded using a portable Global Positioning System (GPS) device (Model: Juno ST Handheld, Trimble Inc, Sunnyvale, CA). Figure 3.4 gives an example of sampling truck locations marked with GPS coordinates on a Google Earth map. Sampling started at ignition and continued until approximately one hour after the ignition was completed. For the purpose of this study, ignition was defined as the period of time spent on initiating combustion or actively lighting fire.

Continuous measurement on $PM_{2.5}$ and CO

$PM_{2.5}$ was sampled at 30-second intervals with TSI DustTrak Model 8520 aerosol monitors (range: 0.01 mg/m^3 to 100 mg/m^3; resolution 0.001 mg/m^3) with dataloggers (TSI Inc, Shoreview, MN). CO was sampled at 30-second intervals by two monitors: Langan CO Monitor Model T15v (range: 0 ppm to 200 ppm; resolution 0.1 ppm) with datalogger (Langan Products, Inc., San Francisco, CA); And PAC III Monitor (range: 0 ppm to 2000 ppm; resolution 1 ppm) with datalogger (Draeger Safety, Pittsburgh, PA). All DustTrak monitors were factory calibrated and serviced at the beginning of the project. DustTrak monitors, Langan monitors, and PAC III monitors were calibrated before the study in the Air Quality Lab at UGA and the DustTrak monitors were zero calibrated in the field each day.

Data analysis

Quality Control and Assurance

A number of quality control and assurance procedures were used throughout the study period and data analysis. To help safeguard against lost data due to equipment malfunction, two sets of co-located air samplers were placed on the sampling trucks. The percentage similarity between co-located air samplers is presented in Table 3.3.

After data collection, all data was entered into Microsoft Excel and checked for validity. During this stage of analysis, data with outliers or other problems were removed from the final data analysis. Criteria for removal of problematic data were based on records in our data log sheets. Suspect data was only removed if the field data log showed an abnormal sampling condition. For example, individual data points would be removed if data log sheets indicated an outside event occurred, such as truck movement or any other disturbance from sources but prescribed forest burning (passing by moving vehicles, cigarette smoking, grenade smoke, moving troops, etc.). Figure 3.10 gives an example for such an event. On April 14th, 2008, Truck 1 encountered a simulated battle with smoke grenades, which caused the spike at approximately 15:20, see Figure 3.10; Similarly, on January 20th, 2009, Truck 1 stuck in the mud from 14:30 till 15:00, which caused unusual spikes during this time period, see Figure 3.5 and Figure 3.20.

Comparison of $PM_{2.5}$ concentration from real-time measurement with time-integrated Federal Reference Method

The manufacturer (TSI) calibrates the DustTrak based on standard method ISO 12103-1, A1 test dust (Arizona Road Dust). An over estimation of the DustTrak would occur if particle size and material properties are different from standard test dust. To reduce this over estimation, TSI recommends creating a custom reduction ratio based on instrumentation comparison with a gravimetric sampler. In the current study, a reduction ratio of 3.64 was used based on the results generated from a similar study done by this lab during the 2007 wildfires in South-Eastern Georgia (Dennis. 2007).

During the 2007 Georgia Wildfire Study, the UGA lab co-located 6 DustTrak monitors with 2 PQ200 Gravimetric samplers to obtain a real-time to gravimetric reduction ratio. All samplers were co-located in Fargo, GA and ran from 8:43 pm on May 10, 2007 to 3:42 pm on May 11, 2007. The sample duration was roughly 1120 minutes for each sampler. An average value was then obtained from each of these monitors and a median concentration was chosen as the benchmark value from these six measurements. Second, an average value was calculated from two concentrations obtained from the gravimetric method using PQ 200 filter method - Federal Reference Method (FRM) for measuring $PM_{2.5}$, which was co-located temporally and spatially with the 6 DustTrak monitors during the sampling period. The reduction ratio then was obtained by dividing median concentration from DustTrak monitors by average value from PQ 200 monitors. Information about DustTrak normalization and real-time to gravimetric calibration is summarized in Table 3.4.

The reduction ratio of 3.64 generated in the Fargo, GA study was used for our data reduction due to several corresponding factors. The same six DustTrak $PM_{2.5}$ monitors were used in both studies. There is also a reasonable expectation that the PM monitored would share similar characteristics since both studies were conducted in the same geographical region and monitored PM source was woodsmoke.

Statistical methods

Field data were analyzed with Statistical Analysis Software (SAS, Version 9.1, Cary, NC). For the data generated from co-located instruments, the average was taken for each data point (30-second intervals) before calculating descriptive statistics. To control for the variations caused by occasional spike values or outliers in the dataset, 15-minute moving average values were calculated for daily real-time data for both $PM_{2.5}$ and CO; then geometric means (GM), the lower and upper limits of GM using one geometric standard deviation (±GSD) and maximum values were calculated based on 15-minute moving averages.

To investigate possible factors which might have contributed to the exposure patterns of $PM_{2.5}$ and CO, a mixed model with repeated measures was fit to the data. In this model, two factors were included in the analysis, namely zones and time intervals (5-minute time interval). The time intervals were generated by subdividing the data into 5-minute blocks starting at ignition. The number of time intervals was determined by the length of burn. In addition, variations caused by data from duplicate co-located air samplers were accounted for by treating instrument effect as a random effect in the model. This model allowed for up to 3 hours of real-time data for each zone to be included in the analysis.

Results

From 2008 to 2009, we collected real-time downwind $PM_{2.5}$ and CO data from 11 prescribed forest burns at Ft. Benning, GA, during which 29 truck-days were collected for $PM_{2.5}$ and 32 were collected for CO. All 29 truck-days[2] with collected $PM_{2.5}$ data had CO data as well. Sampling started at around 12:00 and continued until around 15:30 for each of the sampling days. Approximately three hours of real-time data were collected on each sampling truck for each sampling day.[2]

Descriptive statistics for $PM_{2.5}$ and CO

Daily geometric mean (GM) levels of $PM_{2.5}$ and CO calculated from 15-minute moving averages for all sampling days and trucks are presented in Table 3.5. Overall, $PM_{2.5}$ data shows considerable variation across sampling trucks and days. Daily GM concentrations of $PM_{2.5}$ ranged from 3 (Lower and upper limits: 2, 6) $\mu g/m^3$ to 104 (32, 338) $\mu g/m^3$. For $PM_{2.5}$, the highest maximum 15-minute moving average (403 $\mu g/m^3$) and the highest daily GM 104 (32, 338) $\mu g/m^3$ were observed on January 23rd, 2009 on Truck 1. The lowest concentrations were measured on January 13th, January 20th, and April 8th, 2009 whereas it should be pointed out that measurements were taken based on different sampling scales on January 13th and April 8th.

Compared with $PM_{2.5}$, the overall concentrations of CO were low. GM concentrations of CO ranged from 0 to 1 ppm. Similar to $PM_{2.5}$, the highest maximum 15-minute moving average

[2] Truck-day: For the purpose of this study, truck-day is defined as the daily real-time data collected by one truck in one sampling day.

(3.1 ppm) and the highest daily GM 1 (0.5, 2.3) ppm were also observed on January 23rd, 2009 on Truck 1. The rest of daily GM CO values were all below 2 ppm, with 0 ppm as the lowest (Figure 3.7).

Daily real-time data of $PM_{2.5}$ and CO

Figures 3.8 – 3.29 show the real-time data of $PM_{2.5}$ and CO on different sampling trucks for all sampling days. In order to make the figures consistent and comparable to each other, these figures were drawn to the same scale (X axis: 12:00 – up to 15:30; Y axis: 0 – 300 $\mu g/m^3$, with 2 exceptions on January 15th, 2009 and January 23rd, 2009 due to extremely high $PM_{2.5}$ concentrations). If two instruments were co-located with each other, the average value of the co-located data were calculated and presented in these figures[3].

Results from mixed model analysis for $PM_{2.5}$ and CO

The GM values of $PM_{2.5}$ concentrations calculated from the mixed model declines with distance as defined by the zones ($P = 0.018$). The GM values of $PM_{2.5}$ concentrations for 3 zones across all burns are shown in Figure 3.30. Zone 1 had the highest mean value of 16 [95% confidence limit (CL): 9 – 30] $\mu g/m^3$ followed by Zone 2 at 13 (95% CL: 7 - 24) $\mu g/m^3$. Zone 3 had the lowest mean value of 8 (95% CL: 4 - 16) $\mu g/m^3$.

Also, the time interval since burn ignition has a significant influence on $PM_{2.5}$ exposure levels ($P < 0.001$). Figure 3.31 shows the GM $PM_{2.5}$ concentrations for 5-minute time intervals for up to 3 hour periods over all burns. The top panel represents all zones combined; the second panel represents measurements from Zone 1; the third panel represents measurements from Zone

[3] Detailed information of real-time data measured by co-located air samplers are presented in Appendices A and B, with $PM_{2.5}$ data in Appendix A and CO data in Appendix B.

2; and the bottom panel represents measurements from Zone 3. The peak exposure occurs approximately 1.5 hours from the burn ignition in Zone 1. The peak exposure is less defined for both Zones 2 and 3. As defined by the area under the curve, it is clear from the figure that higher $PM_{2.5}$ concentrations were observed in Zone 1 followed by Zone 2 and 3 which corresponds to the data presented in Figure 3.30.

Similarly, mixed model analyses were conducted on CO as well. However, neither the distance to burn area nor the time interval since burn ignition had significant influence on CO exposure ($P > 0.05$). The GM values of CO concentrations for 3 trucks across all burns and the GM CO concentrations for 5-minute time intervals are presented in Figures 3.32 and 3.33.

Discussion

Implications of community exposure

Several community exposure assessment studies have observed elevated levels of air pollutants observed in forest-fire-affected communities (Hanninen et al. 2009; Hu et al. 2008; Reinhardt et al. 2001). The elevated levels of smoke released from prescribed forest burns can adversely affect the health status of nearby communities (Delfino et al. 2009; Hanninen et al. 2009; Kunii et al. 2002; Tham et al. 2009). As a result of the forest-fire-generated particulate air pollution, increased hospital admission and emergency attendances for respiratory illness and cardiopulmonary diseases were observed (Mott et al. 2002). For example, in Atlanta, GA an increase in hospital visits from asthma attacks and pulmonary symptoms was reported one day after exposure to smoke from two prescribed forest burns originating 80 km away (Hu et al. 2008). Further, susceptible populations such as the elderly, children, people with allergies and those who have pre-existing respiratory or cardiopulmonary diseases were reported to be more likely to develop health symptoms from the exposure to smoke of forest fires (Kunzli et al. 2006; Mott et al. 2005; Mott et al. 2002). To date, only a few studies (Lee et al. 2005; Li et al. 2007; Naeher et al. 2006) have evaluated downwind smoke exposures from prescribed forest burns and none of them have evaluated downwind $PM_{2.5}$ and CO exposures with real-time instruments and a moving sampling strategy.

During 2008 and 2009, we measured real-time $PM_{2.5}$ and CO exposures levels in areas downwind of prescribed forest burns at Fort Benning, Georgia. Sampling with a scale of 1 – 7 Km downwind from prescribed forest burns enabled us to estimate exposure levels in downwind communities. Currently, National Ambient Air Quality Standards (NAAQS) are the universal standards designated by the US EPA to protect public health from air pollution. For $PM_{2.5}$, EPA has established a 24-hour standard of 35 $\mu g/m^3$ and an annual standard of 15 $\mu g/m^3$. Since our study has an average daily sampling duration of 3 hours, the 24-hour EPA standard provides a better benchmark for exposure comparison than the annual standard. Yet it should be pointed out that our 3-hour sampling scheme in the study is limited in comparison with the 24-hour sampling scheme used in EPA method. Our 3-hour sampling scheme might not be sufficiently long to include all exposures, especially low level exposures, which were associated with PM related health effects reported in previous studies. However, we captured all peak exposures in the 3-hour duration which are potentially more likely to cause acute health symptoms (Kunzli et al. 2006).

Our results show that $PM_{2.5}$ levels for 8 of 29 truck-days reached or exceeded the US EPA 24-hour standard of 35 $\mu g/m^3$. Of these truck-days, GM $PM_{2.5}$ value 104 (32, 338) $\mu g/m^3$ on Truck 1 on January 23rd, 2009 was 3 times as high as the 24-hour standard of 35 $\mu g/m^3$. In addition, the highest instantaneous $PM_{2.5}$ levels as indicated by maximum 15-minute moving average were high compared to EPA standard since maximum 15-minute moving averages for 18 out of 29 truck-days exceeded the 24-hour EPA standard.

In addition to comparison with EPA standard, we also compared our daily $PM_{2.5}$ results with background concentrations measured during our sampling periods with US EPA Federal Reference Method (FRM) $PM_{2.5}$ samplers at local or state sampling stations in Phenix City, Alabama and Macon, Georgia. Phenix City was chosen because it is close (10 miles north-west) to Fort Benning and upwind from burn areas; Macon was chosen because it is not immediately close to and not too far (100 miles north-east to Fort Benning) from burn areas. For these reference locations, $PM_{2.5}$ levels for 17 of 29 truck-days exceeded background levels measured in both Phenix City, Alabama and Macon, Georgia (Table 3.6). These comparisons indicate that the smoke from these prescribed forest burns had a potential to increase exposures and potentially impact the health of communities downwind from the fire.

Regarding CO, both EPA and World Health Organization (WHO) have established CO standards to protect public health. The EPA standard for CO is 9 ppm for 8 hours and 35 ppm for 1 hour (US EPA. 1971), whereas WHO standard for CO is 8.7 ppm for 8 hours and 26 ppm for 1 hour (WHO. 1987). However, our results showed that the exposure levels for CO downwind from the fires were low, with all measured GM concentrations based lower than 2 ppm. The highest maximum 15-minute moving average measured for CO was 3.1 ppm for the 3-hour duration, which is below any of the standards. This observation is consistent with two other studies that presented low CO exposures from prescribed forest burns (Naeher et al. 2006; Reinhardt et al. 2001). It is understandable that the measured CO levels were low in the current study considering the distance our sampling locations were from the burn sources and CO’s ability to disperse rapidly into the atmosphere. In contrast, significant levels of CO exposure have been reported for firefighters who worked within designated fire lines (Reinhardt and Ottmar 2004). Although it is our intention not to overstate CO risk , it should be pointed out that low level CO exposures may still pose health risks to nearby communities if exposed subjects are susceptible populations and have pre-existing diseases (Morris and Naumova 1998; Yang et al. 1998).

Factors affecting exposure levels

Many factors may contribute to exposure levels of air pollutants downwind from prescribed forest burns. These factors include, but are not limited to, the distance to the fire, time since the burn ignition, the size of the burn, and meteorological data such as wind velocity and direction. In the current study, we evaluated two factors - the distance to the fire and time since the burn ignition. Both factors affected downwind exposure to $PM_{2.5}$ significantly ($p < 0.05$). Other factors, such as burn acreage and meteorological data will be addressed and discussed elsewhere in more detail through concurrent model building and validation studies by our collaborators from the USDA Forest Service Smoke Management team and Georgia Institute of Technology.

Study strengths

Several strengths were exhibited in this study. First of all, a downwind sampling grid with a 60 degree angle was applied with its apex at the center of burn area and angle’s centerline parallel to predicted wind direction; in addition to this, air samplers were placed on moving trucks which were assigned into different sampling zones. Because wind direction is always a factor influencing the exposure, we conducted moving point sampling instead of stationary sampling to reduce this bias. To evaluate how well sampling trucks followed actual wind directions, we estimated each truck location to its burn area according to actual wind directions. We found that during the sampling period when hourly wind directions were recorded, all 3 trucks were located in the burn area under the exact wind direction ± 22.5º for more than 60% of the time. This percentage increased to more than 80% when including moving point sampling data only, as presented in Table 3.2 and illustrated in Figures 3.34 and 3.35. This suggests our moving point sampling scheme successfully captured most downwind smoke. Our design of the moving point sampling was comparable to another downwind study conducted in China, in which an agricultural vehicle with sampling instruments placed on it was used to collect downwind particulates (Li et al. 2007). However, the size of agriculture burning in the Chinese study was quite small (maize or wheat straw placed in a square with a width of no more than 2 meters). Meanwhile, the sampling site was only 5-10 meters away from the fire, and the sampling time for each test only ranged from 35 to 45 min.

Further, instead of collecting gravimetric data, we collected real-time data, which enhanced our ability to measure the instantaneous high exposure peaks which may be equally or more important than the average concentrations measured gravimetrically. Through evaluation of the exposure patterns from these real-time data, we not only can assess the overall exposure levels over the sampling periods, we can also know exactly at what time the exposure levels would exceed set standards.

In addition, up to 3 hours of continuous sampling from each truck on each sampling day helped us record the active burning profile of the fire. The use of 15-minute moving average and geometric mean instead of arithmetic average in the data analysis reduced the error caused by outlier peak values. Further, the use of a mixed model with repeated measures enabled us to analyse if distance to burn areas and time since burn ignition significantly affected exposures significantly or not.

Study limitations

This study also has some limitations. Although it was our intention to capture as much downwind smoke as possible, our sampling scope was limited by road availability and accessibility. Even with this limitation the moving point sampling successfully captured more downwind smoke than stationary samplers, as demonstrated in Figures 3.34 and 3.35. Also, the real-time to gravimetric reduction ratio we used in the current paper was not generated during sampling at Fort Benning. Instead, it was generated from a similar study during the 2007 wildfires in South-Eastern Georgia. However, since all 6 DustTrak monitors used for generating the reduction ratio were again used in the current study, the inter-instrument error was reduced to a minimal level. Although there were two more additional DustTrak monitors used in the current study that were not used for reduction ratio generation, they correlated with the ones used in both studies very well, as demonstrated in Figure 3.36. In addition, considering that both study locations are within the same geographical region and both studies monitored $PM_{2.5}$ from wood smoke, it is our opinion that the use of this reduction ratio in the current study was reasonable.

Future studies

For future studies, several suggestions are recommended to conduct downwind exposure assessment studies. First, in order to generate a real-time to gravimetric reduction ratio that is more accurate, the new generation of PM samplers (DustTrak DRX aerosol monitor) would be a better choice (TSI Inc, Shoreview, MN). Since new PM samplers can measure real-time data and collect gravimetric data simultaneously, a distinct reduction ratio can be calculated from each sampler on each sampling day. Second, in order to better evaluate exposure pattern and emission behaviors, more air samplers and sampling locations might be needed. Meanwhile, a 3-hour sampling scheme might be insufficient to evaluate downwind exposure levels. A 24-hour sampling duration could be applied. Prolonged sampling duration could also allow us to compare our results to the EPA 24-hour standard more confidently. In addition, for future studies, there could be some added benefit to measuring other air pollutants such as VOCs and PAHs which can also be emitted from wood smoke.

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Table 3.1: Burn information (compartment#, acreage burned, and burn duration) and air samplers used for all 11 burns.

Date	Burn compartment	Burn acreage	Burn duration	Air samplers					
				T1		T2		T3	
				$PM_{2.5}$	CO	$PM_{2.5}$	CO	$PM_{2.5}$	CO
4/9/2008	F5	300 acres	12:30 PM - 14:45 PM	D2, D6	L1, L70152	D1, D5	L2, L3	D4	L4, L70151
4/14/2008	N1	400 acres	12:00 PM - 15:15 PM	D2, D3	L1, L70152	D1, D6	L3	D4, D5	L4, L70151
4/15/2008	BB3	200 acres	12:00 PM - 14:30 PM	D2, D3	L1, L70152	D1, D6	L2, L3	NA	NA
1/13/2009	O7	364 acres	12:30 PM - 14:30 PM	D1	L70152	D4	PAC III 1	D2	L70151
1/14/2009	A9	583 acres	12:30 PM - 14:45 PM	D1	L70152	NA	PAC III 1	NA	L70151
1/15/2009	S1, S2, S3	309 acres	12:15 PM - 14:00 PM	D7	L70152	NA	PAC III 1	D6	L70151
1/20/2009	O11	269 acres	12:20 PM - 14:35 PM	D3, D6	L1	D4, D7	L3	D2, D8	L2
1/21/2009	D15	364 acres	12:30 PM - 14:45 PM	D2, D4	L1,L70151	D7, D8	L2, L3	D3, D6	L70152
1/23/2009	I3	455 acres	12:30 PM - 14:30 PM	D2, D4	L3	D7, D8	L1, L2	D3, D6	L70152
4/8/2009	E2, E3	236 acres	12:30 PM - 15:30 PM	D1, D4	L70152	D3, D6	L70151	D5	L1, L3
4/9/2009	J6	343 acres	12:30 PM - 14:20 PM	D3, D6	L70152	D1, D4	L70151	D2, D5	L1, L3

Note: Burn duration means the period of time during which the fire was ignited; Burn compartment the space into which Fort Benning is subdivided; the end of the burn duration did not mean the fire extinguished, instead, it meant fire fighters stopped ignition at that time point; T1, T2, and T3 stand for different trucks; D stands for DustTrak $PM_{2.5}$ monitor; L stands for Langan CO monitor; NA indicates no data available. Co-located instruments are both shown in the cells if the data was successfully downloaded.

Table 3.2: Wind direction, speed, and truck locations that match wind directions.

date	Time (EST)	observed wind	wind speed (mph)	Truck 1		Truck 2		Truck 3	
				100% Accurate	Wind direction ± 22.5°	100% Accurate	Wind direction ± 22.5°	100% Accurate	Wind direction ± 22.5°
4/9/2008	12:10	ESE	5	NA	NA	NA	NA	NA	NA
	13:10	ESE	6	YES	YES	NO	YES	NO	YES
	14:10	SE	6	NO	YES	NO	YES	NO	YES
	15:10	E	5	NO	YES	NO	YES	NA	NA
4/14/2008	12:10	WNW	7	NA	NA	NA	NA	NA	NA
	13:10	W	7	NO	NO	NO	NO	NO	NO
	14:10	NW	9	NO	YES	YES	YES	YES	YES
	15:10	NW	8	NO	YES	YES	YES	NA	NA
4/15/2008	12:10	NNE	7	YES	YES	**NO**	**NO**	NA	NA
	13:10	NNE	5	YES	YES	**NO**	**NO**	NA	NA
	14:10	NNE	5	YES	YES	**NO**	**NO**	NA	NA
	15:10	NNW	6	NA	NA	**YES**	**YES**	NA	NA
1/13/2009	12:10	WSW	6	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
	13:10	NW	7	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
	14:10	WNW	7	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
	15:10	WNW	8	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
1/14/2009	12:10	WNW	4	NA	NA	NA	NA	NA	NA
	13:10	NW	6	NO	YES	NO	YES	NO	YES
	14:10	WSW	5	NO	NO	NO	NO	NO	NO
	15:10	SSW	4	NO	NO	NO	NO	NO	NO
1/15/2009	12:10	NNW	9	NA	NA	NA	NA	NA	NA
	13:10	NW	11	NO	YES	NO	YES	NO	YES
	14:10	NNW	11	YES	YES	NO	YES	YES	YES
	15:10	NW	10	NA	NA	NO	YES	NO	YES
1/20/2009	12:10	NW	10	NA	NA	NA	NA	NA	NA
	13:10	NW	13	NO	YES	NO	YES	NO	YES
	14:10	NW	14	YES	YES	YES	YES	NO	YES
	15:10	NW	11	YES	YES	NA	NA	NA	NA
1/21/2009	12:10	NNW	6	NA	NA	NA	NA	NA	NA
	13:10	WNW	6	YES	YES	NO	YES	NO	YES
	14:10	WNW	7	YES	YES	NO	YES	NO	YES
	15:10	NNW	6	YES	YES	YES	YES	NO	YES
1/23/2009	12:10	WSW	7	NA	NA	NA	NA	NA	NA
	13:10	WSW	11	NO	YES	NO	YES	NO	YES
	14:10	WSW	9	NO	YES	YES	YES	NO	YES
	15:10	SW	7	YES	YES	NO	YES	YES	YES
4/8/2009	12:10	WSW	8	NA	NA	NA	NA	NA	NA
	13:10	WSW	8	YES	YES	NO	YES	YES	YES
	14:10	WSW	8	YES	YES	NO	YES	YES	YES
	15:10	SW	9	NO	YES	YES	YES	NO	YES
4/9/2009	12:10	SW	5	YES	YES	NA	NA	YES	YES
	13:10	S	5	NO	NO	NO	NO	NO	NO
	14:10	SSW	6	NO	YES	NO	YES	NO	YES
	15:10	S	9	NO	NO	NO	NO	NO	NO

Note: in the table, YES = truck was located under the right wind direction when wind data was recorded; NO = truck was not located under the right wind direction when wind data was recorded; NA: data are not available; Bold letter means data was collected from stationary stations, otherwise data was collected from moving trucks. Wind direction and speed data source: http://mesowest.utah.edu/cgi-bin/droman/station_total.cgi?stn=FBGG1

Table 3.3: Percentages of similarity* for measured exposures by co-located air samplers

Date		$PM_{2.5}$		CO	
		co-located instrument	percentage (%)	co-located instrument	percentage (%)
4/9/2008	T1	D2, D6	94	L1, L70152	66
	T2	D1, D5	78	L2, L3	69
	T3	NA	NA	L4, L70151	43
4/14/2008	T1	D2, D3	71	L1, L70152	94
	T2	D1, D6	82	NA	NA
	T3	D4, D5	91	L4, L70151	91
4/15/2008	T1	D2, D3	80	L1, L70152	83
	T2	D1, D6	88	L2, L3	74
	T3	NA	NA	NA	NA
1/13/2008	T1	NA	NA	NA	NA
	T2	NA	NA	NA	NA
	T3	NA	NA	NA	NA
1/14/2009	T1	NA	NA	NA	NA
	T2	NA	NA	NA	NA
	T3	NA	NA	NA	NA
1/15/2009	T1	NA	NA	NA	NA
	T2	NA	NA	NA	NA
	T3	NA	NA	NA	NA
1/20/2009	T1	D3, D6	52	NA	NA
	T2	D4, D7	87	NA	NA
	T3	D2, D8	40	NA	NA
1/21/2009	T1	D2, D4	89	L1, L70151	79
	T2	D7, D8	39	L2, L3	80
	T3	D3, D6	63	NA	NA
1/23/2009	T1	D2, D4	83	NA	NA
	T2	D7, D8	60	L1, L2	22
	T3	D3, D6	72	NA	NA
4/8/2009	T1	D1, D4	84	NA	NA
	T2	D3, D6	33	NA	NA
	T3	NA	NA	L1, L3	77
4/9/2009	T1	D3, D6	65	NA	NA
	T2	D1, D4	85	NA	NA
	T3	D2, D5	74	L1, L3	77

Note: * = This percentage was the mean of percentages calculated based on each pair of 30-second data from co-located samplers. To calculate the percentage based on the paired data, the following formula was used: The percentage = [1 - (high value - low value)/high value)]%; T1, T2, and T3 stand for Truck 1, Truck 2, and Truck 3. NA = data is not available.

Table 3.4: Real-time $PM_{2.5}$ measurement by DustTrak monitors and calibration by PQ200 gravimetric method in Fargo, GA (Dennis 2007).

DustTrak serial number	**Date**	**Duration (minutes)**	**$PM_{2.5}$ ($\mu g/m^3$)**	**Normalization proportion**
85201221	5/10/2007	1120	364.9	Bench = 1.0
23094	5/10/2007	1120	312.9	1.166
23092	5/10/2007	1120	388.7	0.939
24068	5/10/2007	1120	298	1.224
23093	5/10/2007	1120	396.6	0.92
85201218	5/10/2007	1120	363.3	1.004
Fargo Gravimetric Data				
Average Filter Post-weight in mg		**$PM_{2.5}$ ($\mu g/m^3$)**		
170.7		99.1		
173.5		101.5		
Average		100.3		
Real-time to gravimetric reduction ratio		(364.9 +363.3)/100.3=3.64		

Table 3.5: Maximum and geometric mean of 15-minute moving averages for $PM_{2.5}$ and CO.

		$PM_{2.5}$ ($\mu g/m^3$)					CO (ppm)				
Date	**Truck**	**N**	**Max**	**GM**	**Lower**	**Upper**	**N**	**Max**	**GM**	**Lower**	**Upper**
4/9/2008	T1	373	50	22	13	36	326	0.3	0.2	0.1	0.3
	T2	369	62	27	15	50	348	0.9	0.7	0.5	0.8
	T3	311	62	35	24	51	315	0.6	0.2	0.1	0.3
4/14/2008	T1	397	136	29	9	88	395	0.9	0.4	0.2	0.6
	T2	379	84	13	4	41	385	1.2	0.2	0.1	0.4
	T3	393	64	8	2	24	393	1.1	0.8	0.7	0.9
4/15/2008	T1	354	66	24	12	48	359	0.2	0.1	0.0	0.2
	T2	408	7	5	4	6	469	0.4	0.2	0.2	0.3
	T3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1/14/2009	T1	360	104	37	20	69	360	1.5	0.4	0.1	0.9
	T2	NA	NA	NA	NA	NA	357	0.0	0.0	0.0	0.0
	T3	NA	NA	NA	NA	NA	360	1.0	0.5	0.4	0.7
1/15/2009	T1	383	208	48	21	113	390	2.1	0.9	0.6	1.4
	T2	NA	NA	NA	NA	NA	367	0.0	0.0	0.0	0.0
	T3	352	40	14	7	29	365	0.9	0.6	0.5	0.8
1/20/2009	T1	348	13	3	2	6	345	0.6	0.2	0.1	0.4
	T2	311	16	4	2	8	315	0.4	0.3	0.2	0.3
	T3	314	5	4	4	4	311	0.4	0.3	0.2	0.3
1/21/2009	T1	333	86	47	34	65	339	1.2	1.0	0.9	1.1
	T2	376	85	39	23	66	377	0.5	0.3	0.1	0.5
	T3	382	109	37	15	97	381	1.3	0.8	0.6	1.2
1/23/2009	T1	329	403	104	32	338	331	3.1	1.0	0.5	2.3
	T2	329	171	63	27	150	331	0.6	0.2	0.1	0.4
	T3	340	49	13	6	28	331	0.0	0.0	0.0	0.0
4/9/2009	T1	364	55	17	8	35	362	0.7	0.3	0.2	0.4
	T2	354	35	17	11	26	361	1.0	0.6	0.5	0.8
	T3	392	26	8	4	18	360	0.5	0.3	0.3	0.4
1/13/2009#	T1	327	6	4	3	5	252	0.0	0.0	0.0	0.0
	T2	310	12	7	5	10	315	0.0	0.0	0.0	0.0
	T3	319	13	8	5	12	321	0.2	0.2	0.2	0.2
4/8/2009*	T1	377	21	7	4	11	375	0.5	0.2	0.1	0.3
	T2	315	17	6	3	11	321	0.6	0.3	0.2	0.4
	T3	344	17	3	1	6	361	0.4	0.1	0.0	0.2

Note: $PM_{2.5}$ was sampled at 30-second intervals with TSI DustTrak Model 8520 aerosol monitors and CO was sampled at 30-second intervals by Langan CO Monitor Model T15v. In the table, N = total amount of 15-minute moving averages; Max = Maximum values; GM = geometric means; Upper = upper limit of geometic mean and Lower = lower limit of geometric mean; NA = data not available; # = all 3 trucks were located far from the burn area (>10 Km) without moving around due to very limited road accessibility; * = the sampling scale was changed from kilometers to miles for April 8th, 2009: Zone 1 was 1-3 miles; Zone 2 was 3-5 miles, and Zone 3 was 5-7 miles.

Table 3.6: Background $PM_{2.5}$ levels measured at state or local stations in Phenix city, AL and Macon, GA

Date	Location	Latitude measure	Longitude measure	Monitor type	Duration	Concentration (μg/m^3)
4/9/2008	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	13.9
	Macon, GA	32.805408	83.543521	SLAMS	24-hour	16.1
4/14/2008	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	5.8
	Macon, GA	32.777455	83.641096	SLAMS	24-hour	7.1
4/15/2008	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	12
	Macon, GA	32.777455	83.641096	SLAMS	24-hour	15.7
1/13/2009	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	11.5
	Macon, GA	32.777455	83.641096	SLAMS	24-hour	15.3
1/14/2009	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	7.9
	Macon, GA	32.777455	83.641096	SLAMS	24-hour	9.2
1/15/2009	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	8.2
	Macon, GA	32.777455	83.641096	SLAMS	24-hour	10.4
1/20/2009	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	8.9
	Macon, GA	32.777455	83.641096	SLAMS	24-hour	10.3
1/21/2009	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	12.9
	Macon, GA	32.777455	83.641096	SLAMS	24-hour	12.7
1/23/2009	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	18.1
	Macon, GA	32.777455	83.641096	SLAMS	24-hour	16
4/8/2009	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	10.3
	Macon, GA	NA	NA	NA	NA	NA
4/9/2009	Phenix City, AL	32.476389	84.999167	SLAMS	24-hour	8.6
	Macon, GA	NA	NA	NA	NA	NA

Note: All measurements were sampled by Federal Reference Method. SLAMS, state or local air sampling stations; NA, data is not available; Data source: http://www.epa.gov/ttn/airs/aqsdatamart/access/interface.htm

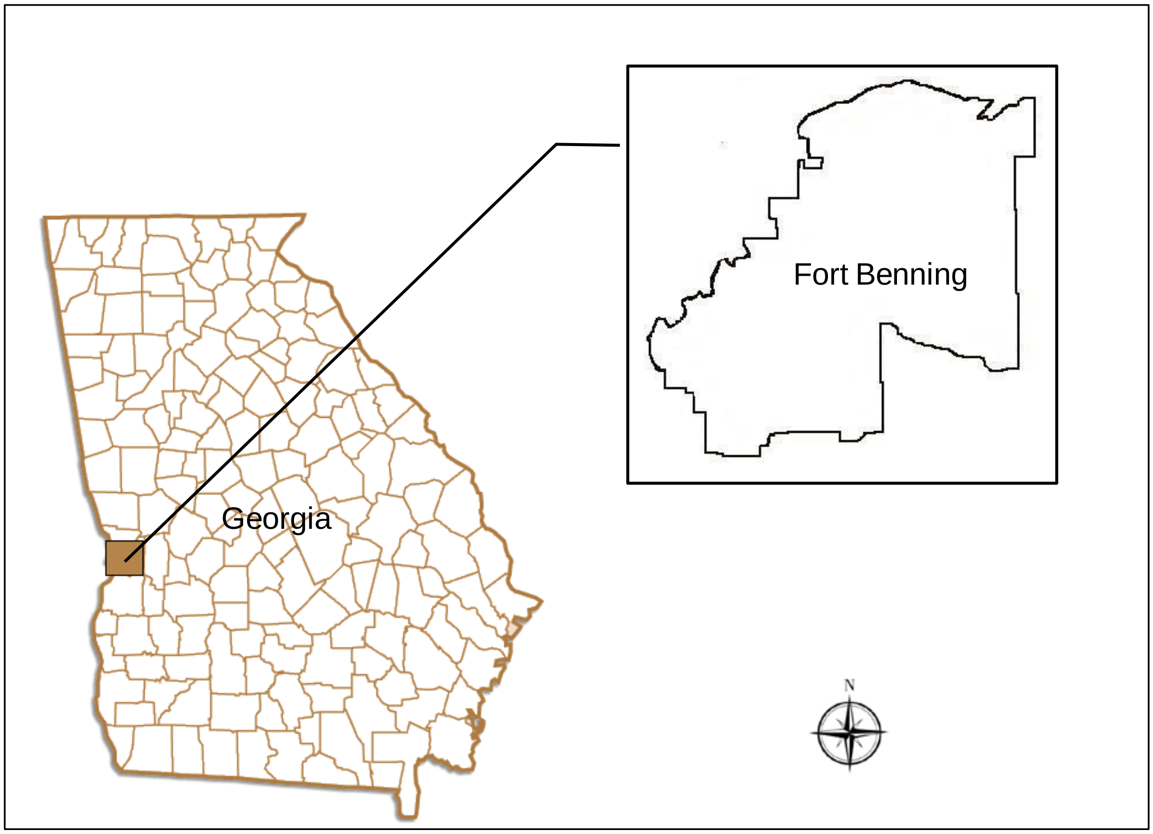


Figure 3.1: Location of Fort Benning, GA.

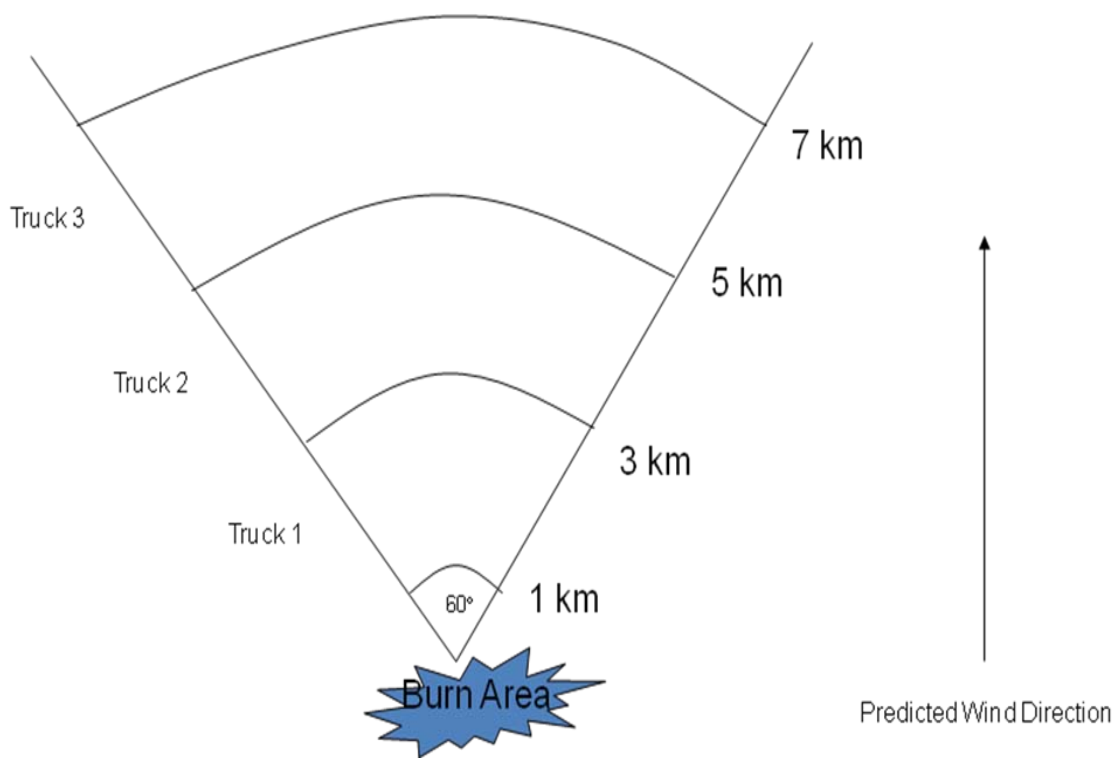


Figure 3.2: Sampling grid, in which a downwind 60 degree arc was established with 3 sampling zones; in each of these 3 zones, Trucks were assigned the following designations: Truck 1 to Zone 1 (1-3 km), Truck 2 to Zone 2 (3-5 km) and Truck 3 to Zone 3 (5-7 km). Note: For April 8^{th}, 2009, the sampling scale was increased: Truck 1 (1-3 miles), Truck 2 (3-5 miles) and Truck 3 (5-7 miles). During the monitoring, each truck was allowed to move around inside the grid to match the shifting wind direction. The 60 degree arc was chosen because this is the typical impact tool for fire-fighters when assessing impacts from winds.

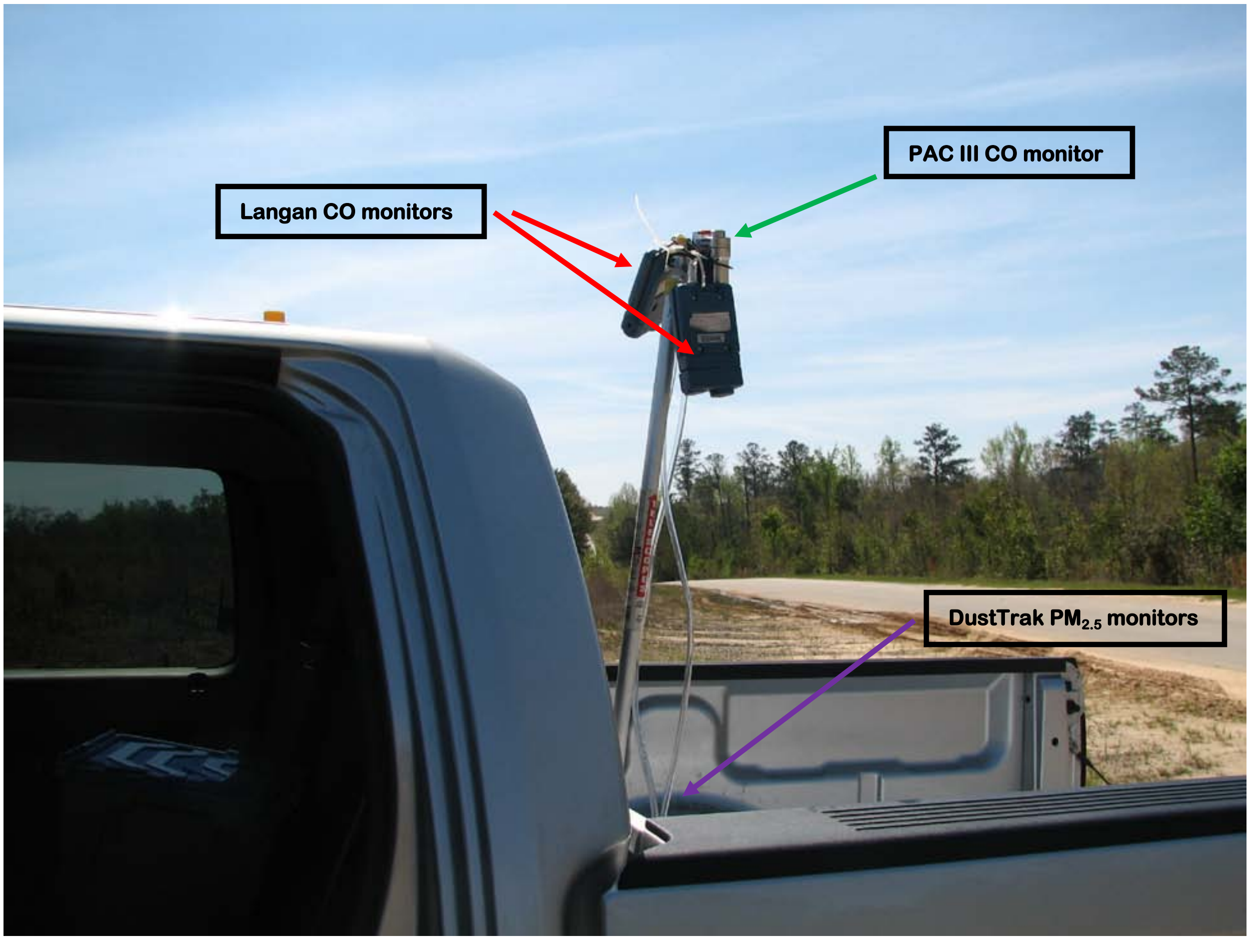


Figure 3.3: Sampling truck with air samplers placed on it.

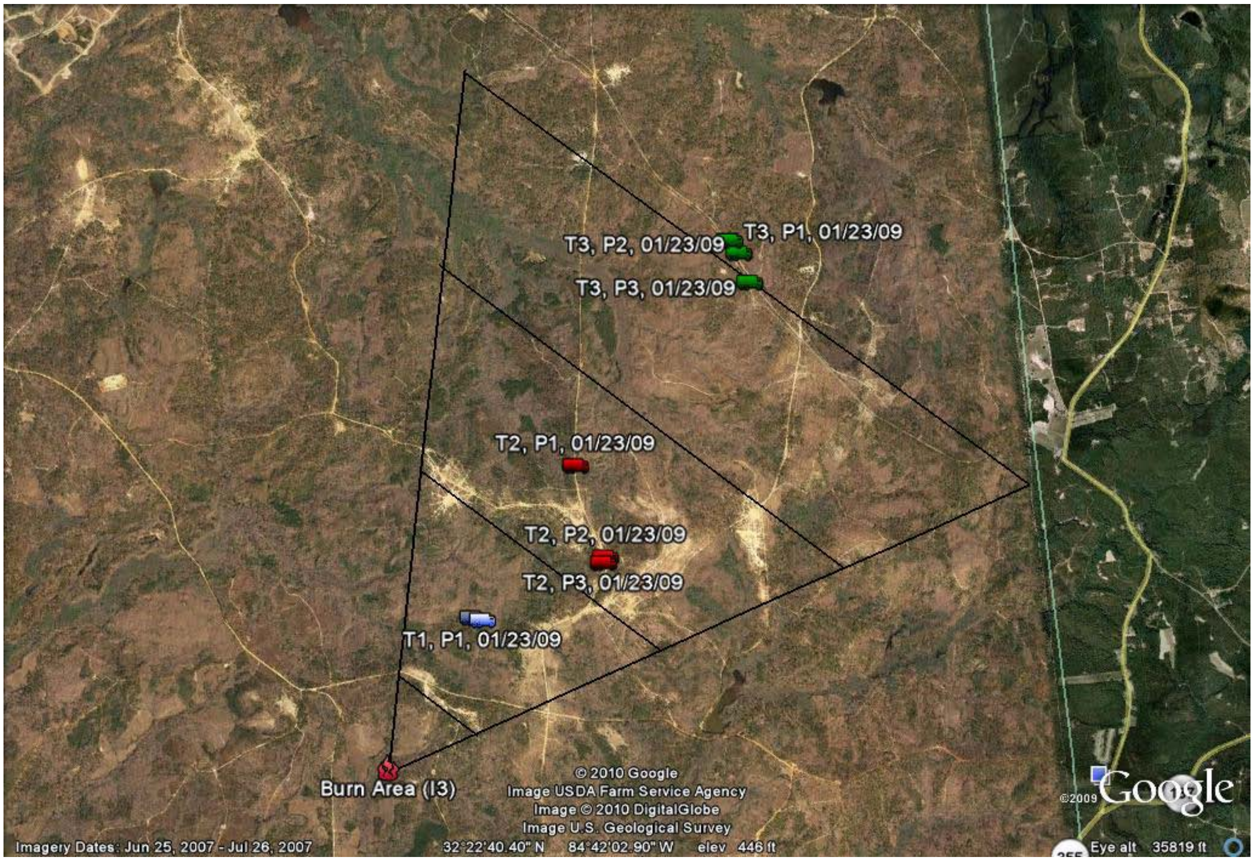


Figure 3.4: Sampling truck locations on January 23rd, 2009. In the figure, blue icon stands for Truck 1, red icon stands for Truck 2, and green icon stands for Truck 3.

Figure 3.5: Truck 1 stuck in the mud on January 20th, 2009

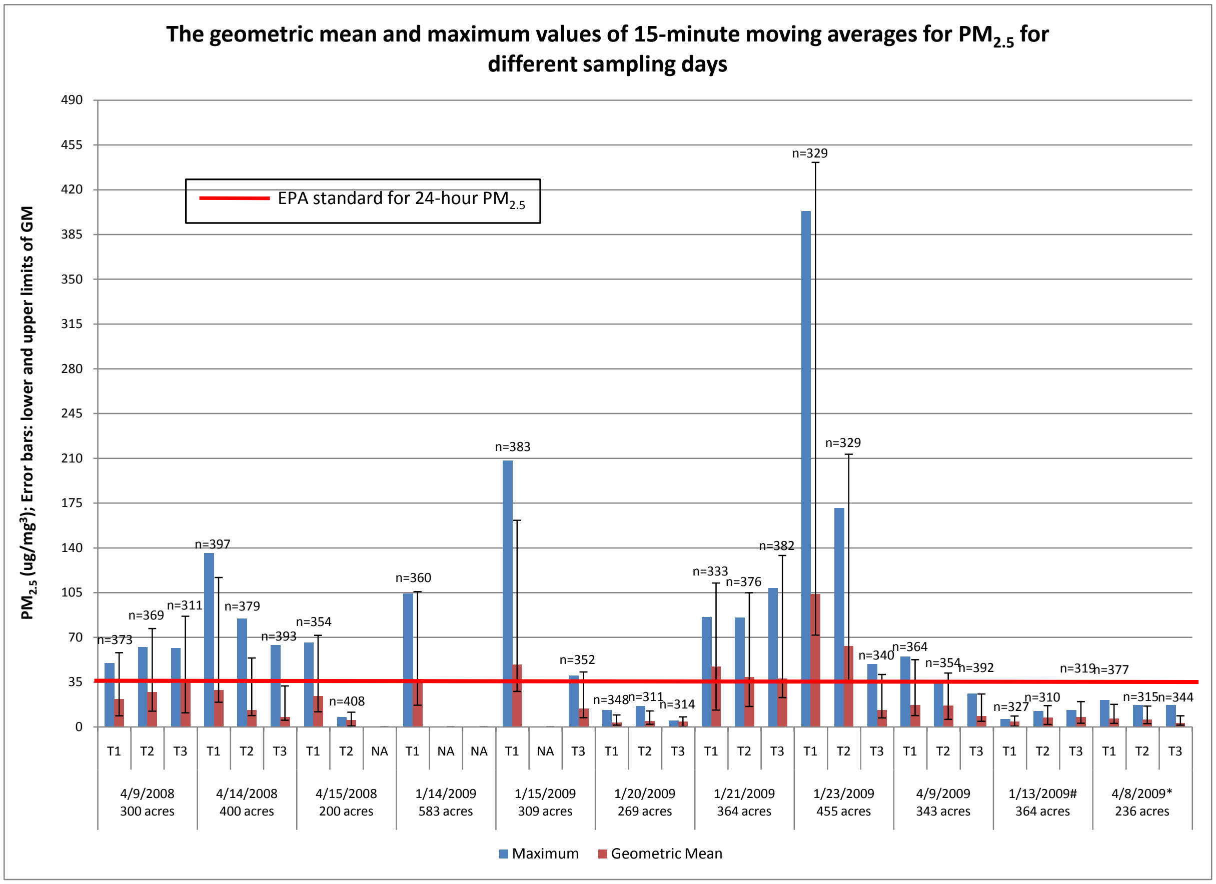


Figure 3.6: The maximum values and geometric means of 15-minute moving averages for $PM_{2.5}$ for different sampling days. The red line across columns represents EPA standard for 24-hour $PM_{2.5}$. T1, T2, and T3 represent sampling trucks. NA means data not available. Burn acreages are given under the sampling dates. Note: #, on January 13th, 2009, all trucks were spread out far away from burn area (>10 Km) due to very limited road access; *, sampling was conducted at a different scale: Truck 1 to Zone 1 (1-3 miles), Truck 2 to Zone 2 (3-5 miles) and Truck 3 to Zone 3 (5-7 miles).

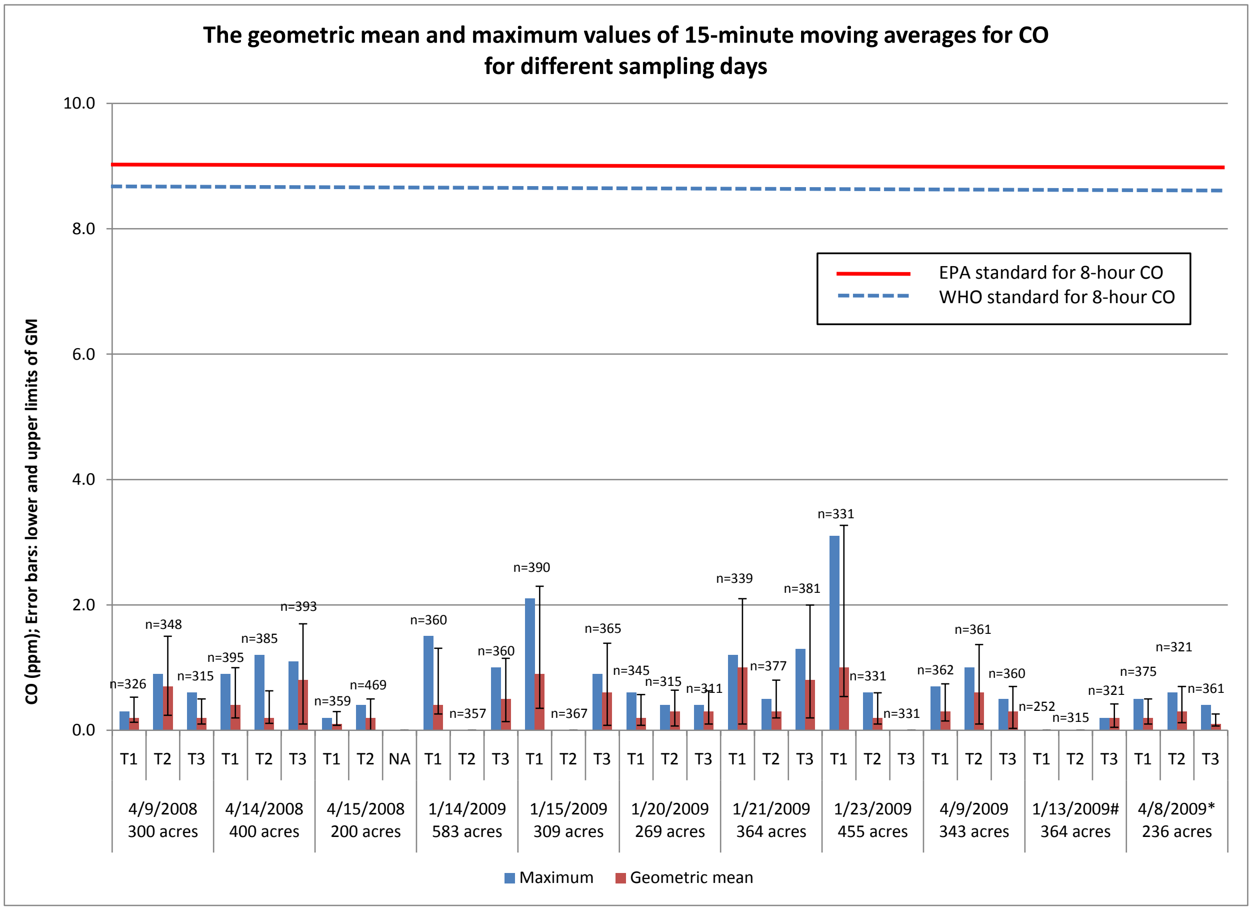
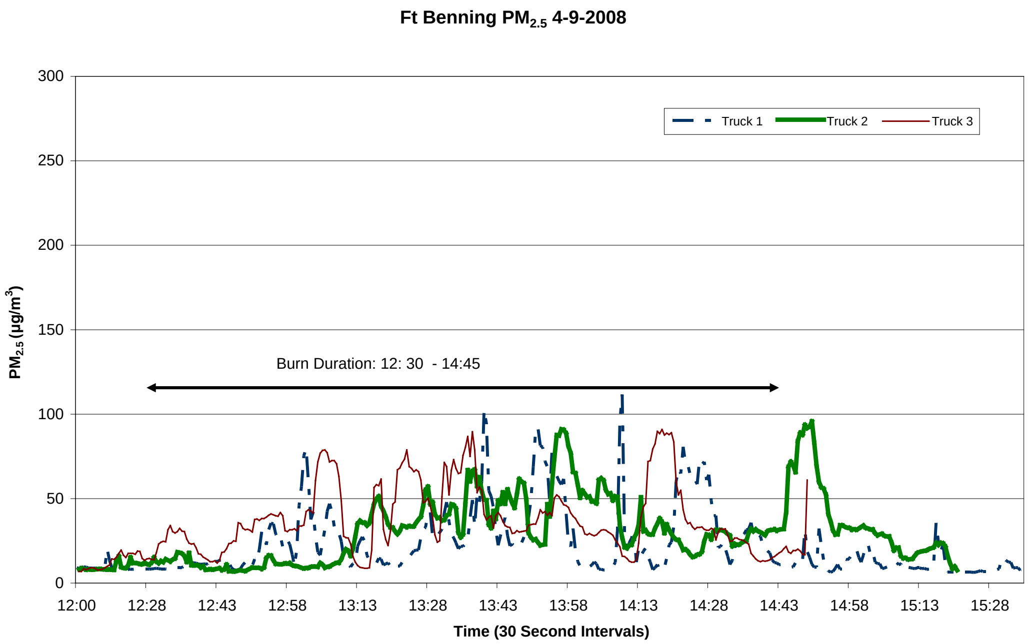
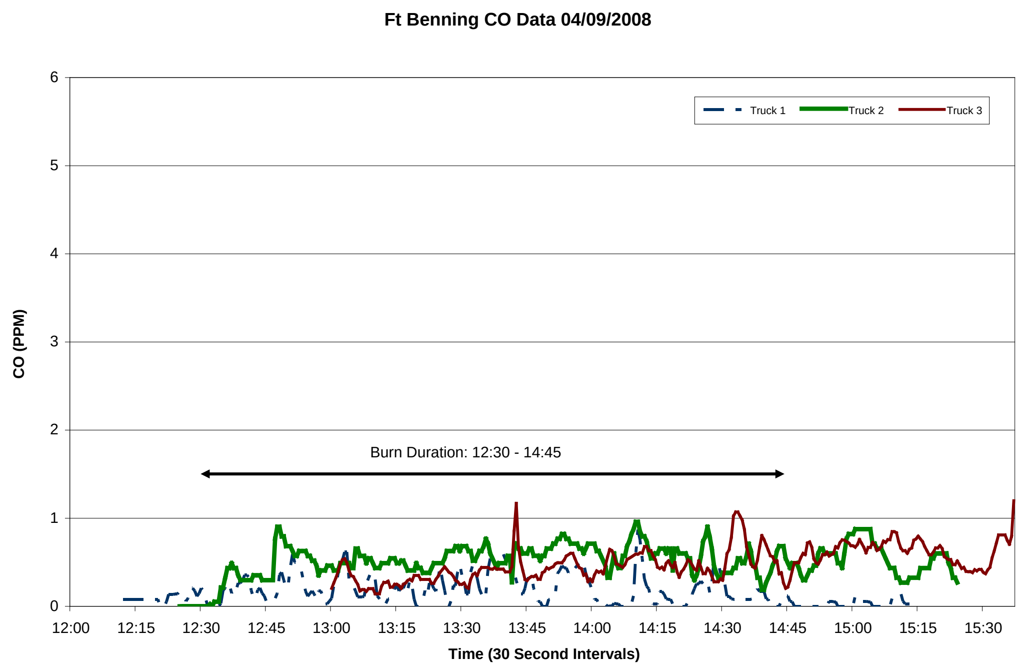
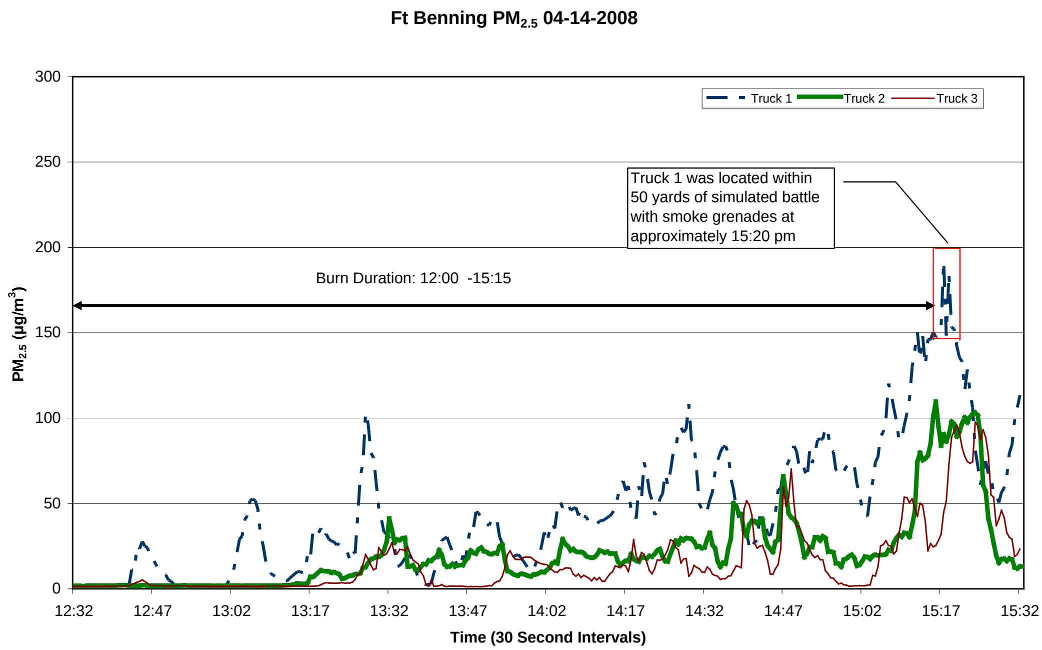


Figure 3.7: The maximum values and geometric means of 15-minute moving averages for CO for different sampling days. The red line across columns represents EPA standard for 8-hour CO; The blue line across columns represents WHO standard for 8-hour CO. T1, T2, and T3 represent sampling trucks. NA means data not available. Burn acreages are given under the sampling dates. Note: #, on January 13th, 2009, all trucks were spread out far away from burn area (>10 Km) due to very limited road access; *, sampling was conducted in a different scale: Truck 1 to Zone 1 (1-3 miles), Truck 2 to Zone 2 (3-5 miles) and Truck 3 to Zone 3 (5-7 miles).





Figures 3.8 – 3.9: Real-time data collected on April 9th, 2008. The blue dashed line represents Truck 1, the thick green line represents Truck 2, and the thin red line represents Truck 3. The burn duration is outlined with a straight dark arrowed line for each figure, and unusual events are marked by squared callouts on certain sampling days (same for the follow figures). For $PM_{2.5}$, there is a trend that truck 1 had the highest exposure, followed by trucks 2 and 3, but multiple peaks appear for all trucks, with the highest value appeared on truck 1 around 14:00. For CO, no obvious trend is illustrated.



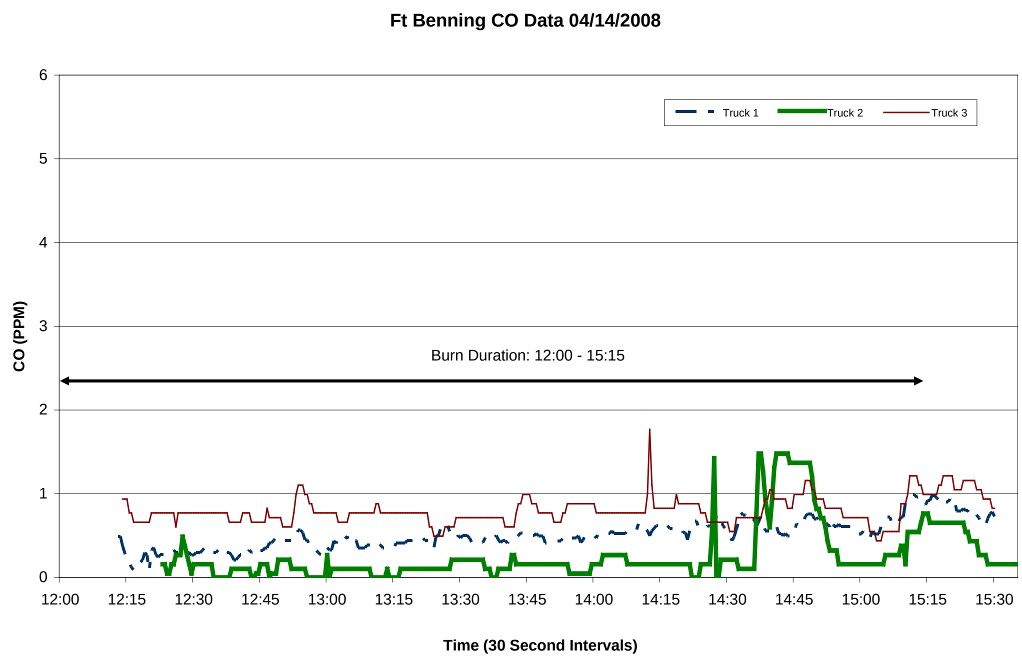
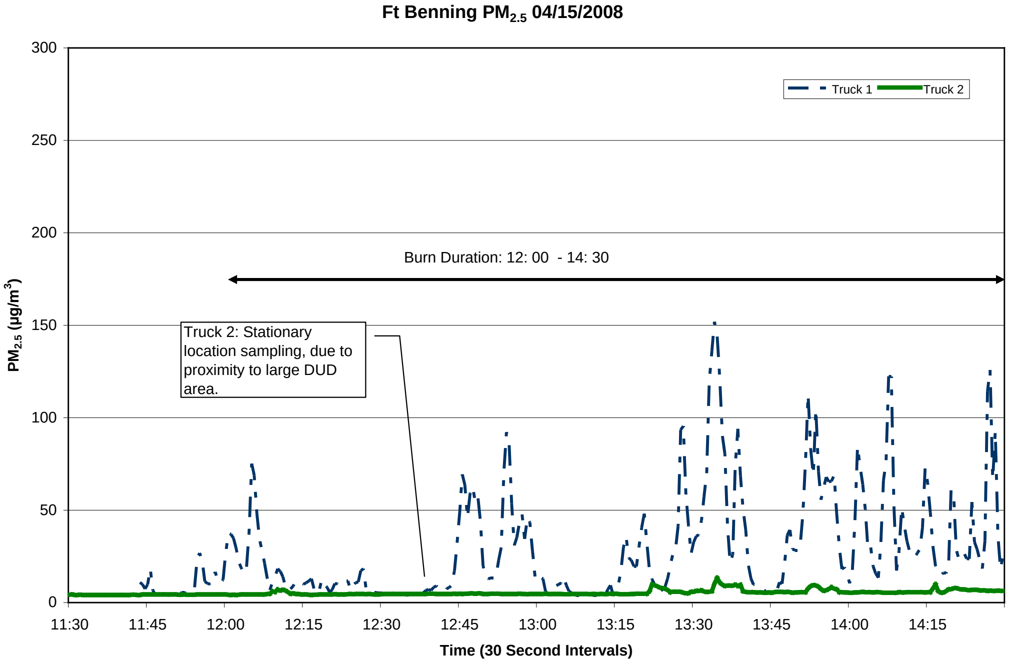


Figure 3.10 – 3.11: Real-time data collected on April 14th, 2008. In Figure 9, the trend shows that the overall $PM_{2.5}$ concentration for truck 1 is higher than truck 2, followed by truck 3. There are similar patterns of exposure among all the 3 trucks although high peaks appear much earlier for truck 1.The first 4 peaks are all from truck 1. The highest peak appears at 15:16 on Truck 1, probably because Truck 1 was located within 50 yards of simulated battle with smoke grenades at approximately 15:20. In comparison, as shown in Figure 3.11, Truck 3 captured more CO than Truck 1 and followed by Truck 2.



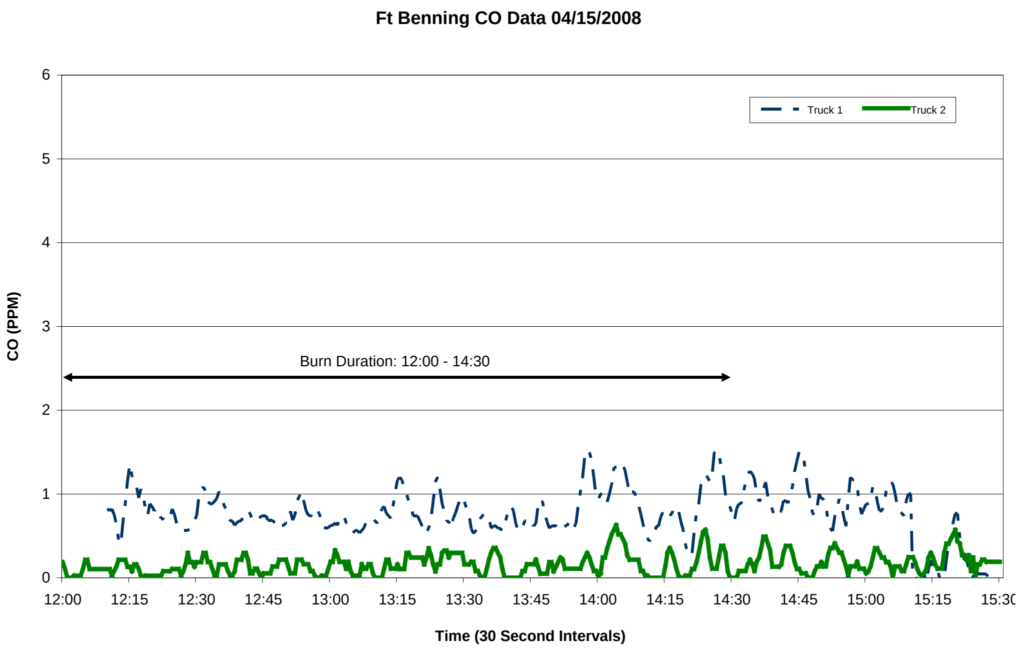
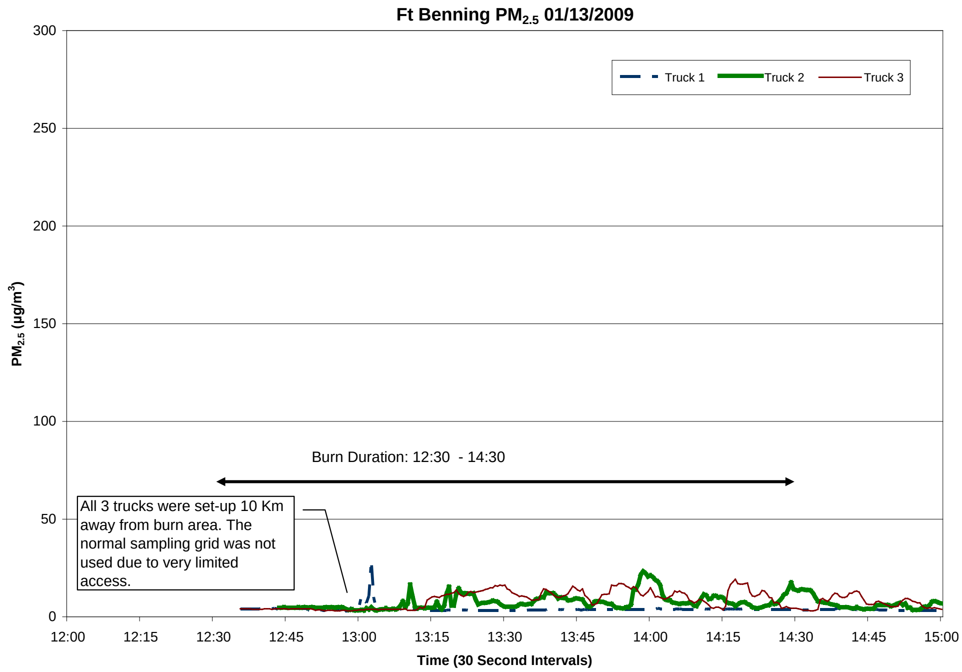


Figure 3.12 – 3.13: Real-time data collected on April 15th, 2008. On April 15th, only one mobile unit and one stationary location were used for sampling due to proximity to large DUD area. Truck 2 equipment was used as stationary location nearest to predicted wind direction at ignition time. Truck 1 had very limited mobility due to lack of roads, but was able to position directly downwind of the burn. As shown in Figure 3.12, truck 1 obviously catches more $PM_{2.5}$ than truck 2, and showed multiple peaks. As demonstrated in Figure 3.13, CO levels measured by Truck 1 are consistently higher than those measured by Truck 2.



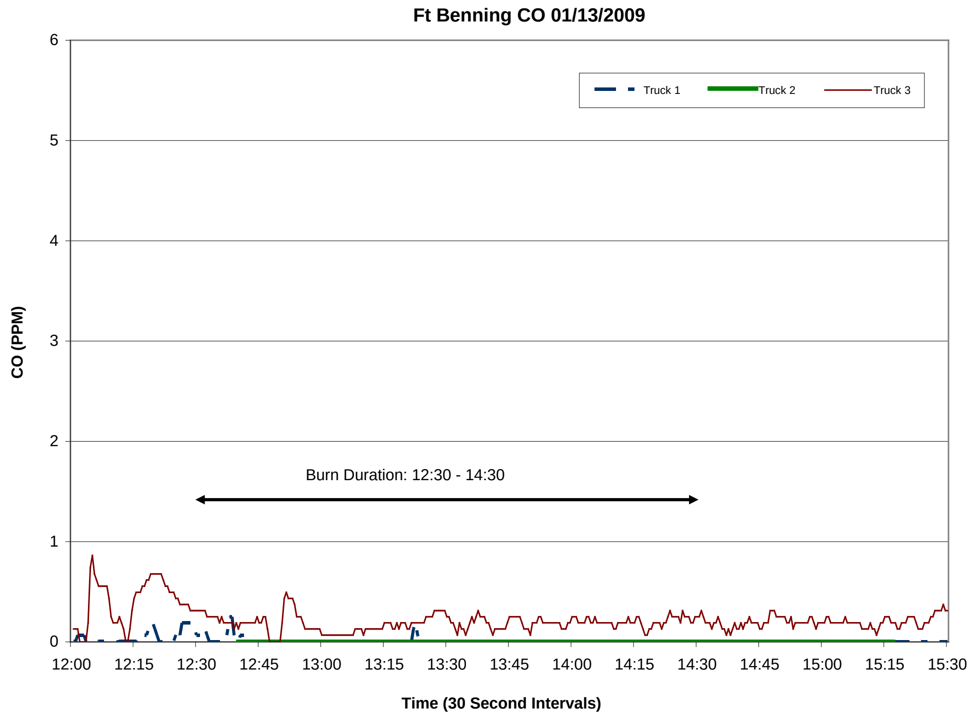
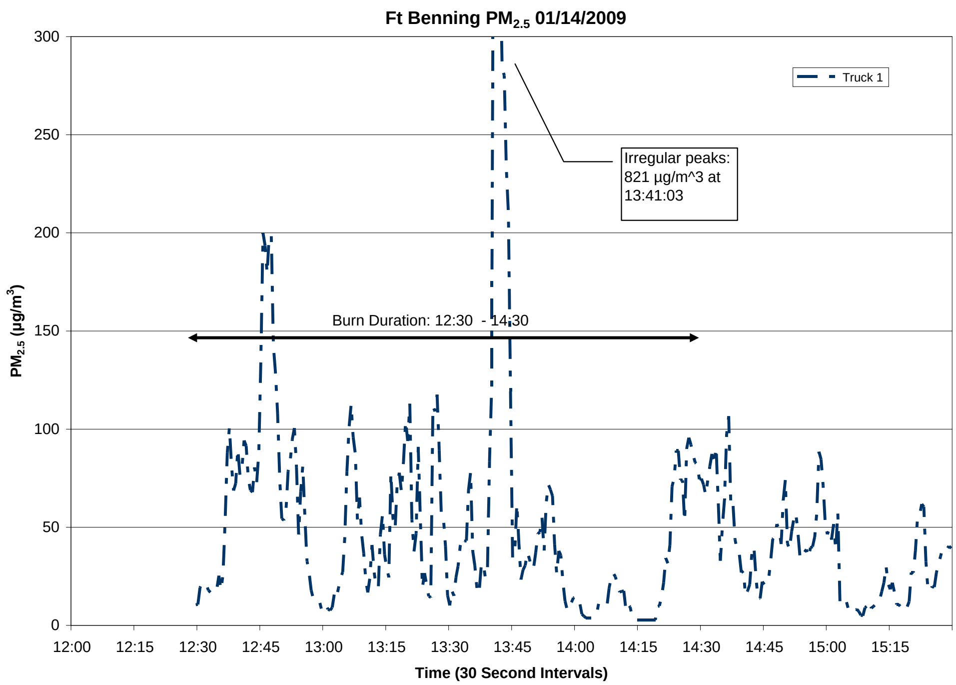


Figure 3.14 – 3.15: Real-time data collected on January 13th, 2009. All 3 Trucks were set-up 10 Km away from the burn area without moving along with the plume direction due to very limited road access. Consequently, the normal sampling grid was not used, which could explain the evenly low $PM_{2.5}$ concentrations measured by all 3 trucks as demonstrated in Figure 3.14. For CO, it appears Truck 3 catches more CO than Truck 1 and followed by Truck 2. Note: data on Truck 2 was measured by PAC III CO monitor instead of Langan CO monitor.



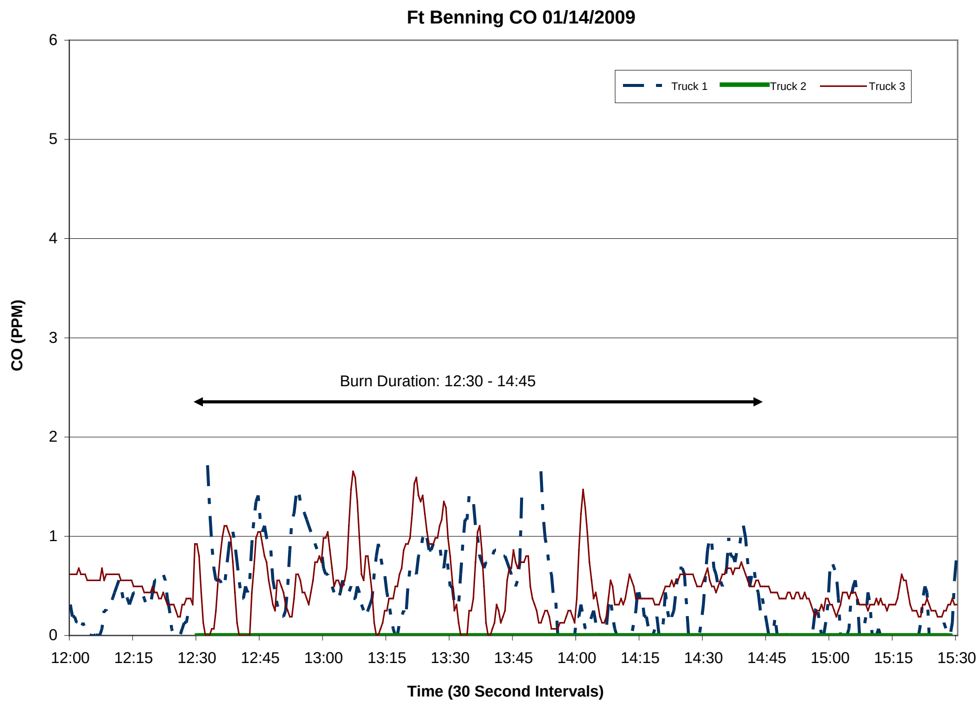
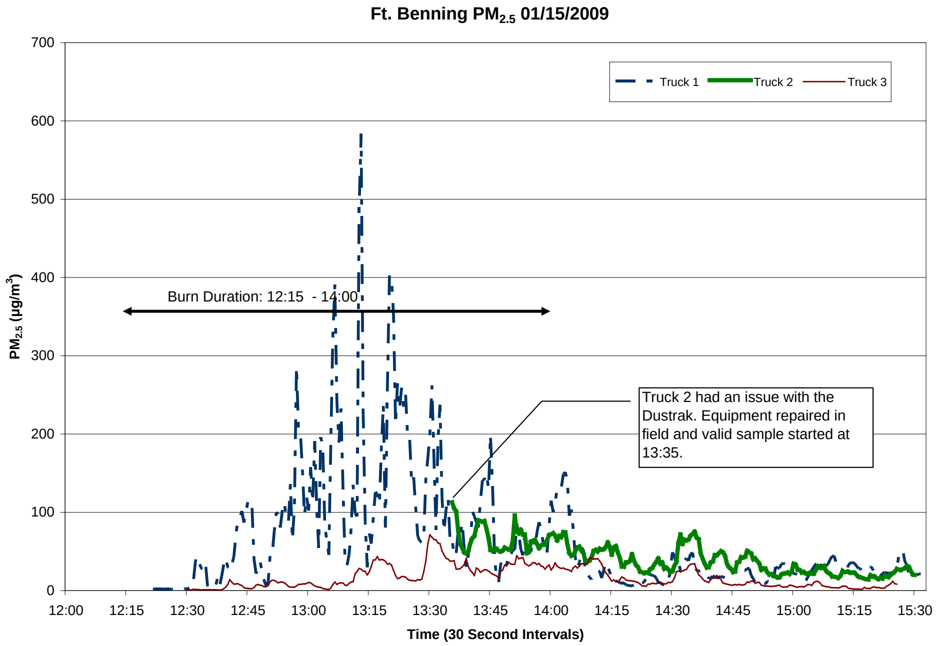


Figure 3.16 – 3.17: Real-time data collected on January 14th, 2009. Truck 1 data shows quite variable $PM_{2.5}$ levels with multiple peaks. The highest value 821 µg/m^3 (not shown in the current figure) was measured at 13:41. All $PM_{2.5}$ data from trucks 2 and 3 were corrupted due to download failure. This data was not recoverable. For CO, there is no obvious trend can be detected. Note: data on Truck 2 was measured by PAC III CO monitor instead of Langan CO monitor.



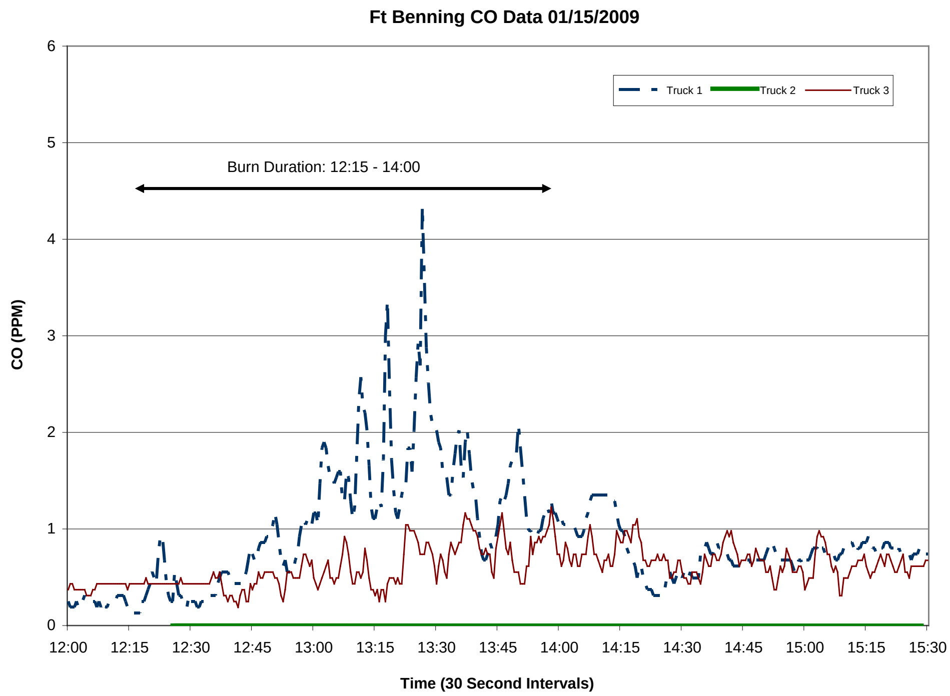
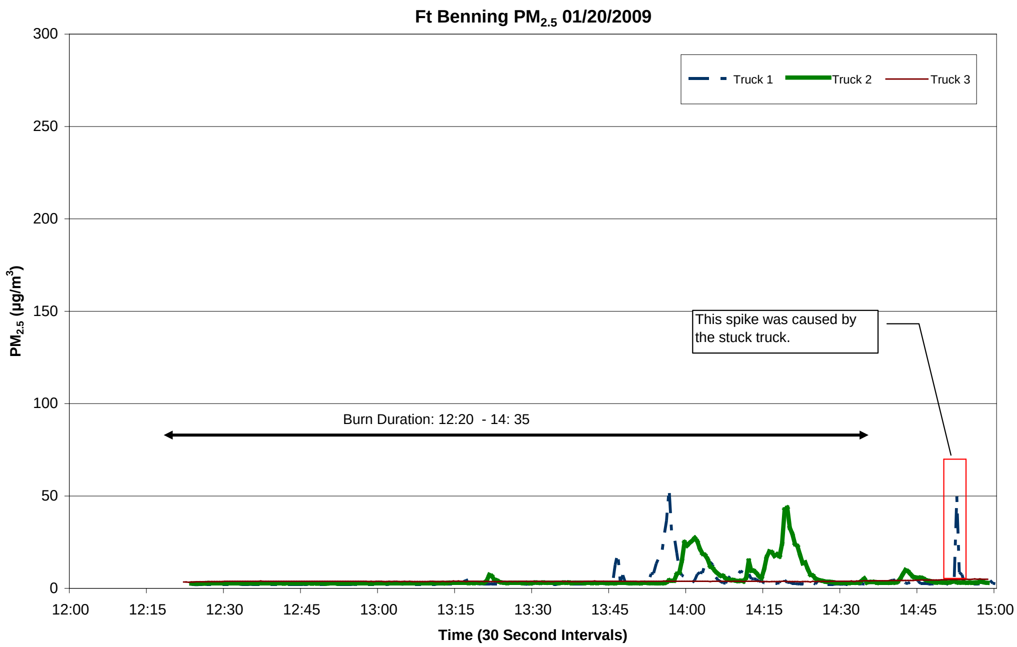


Figure 3.18 – 3.19: Real-time data collected on January 15th, 2009. As shown in Figure 3.18, Truck 2 underwent a malfunction with the DustTrak and being repaired in the field. In consequence, the valid sample started at 13:35 instead of 12:20. It is clear from the graph that Truck 1 catches more smoke than truck 2 and truck 3, especially in the early stage. The highest peak value appears at 13:14. CO data on Figure 3.19 has the similar pattern with $PM_{2.5}$ data on Figure 3.18. Note: data on Truck 2 was measured by PAC III CO monitor instead of Langan CO monitor.



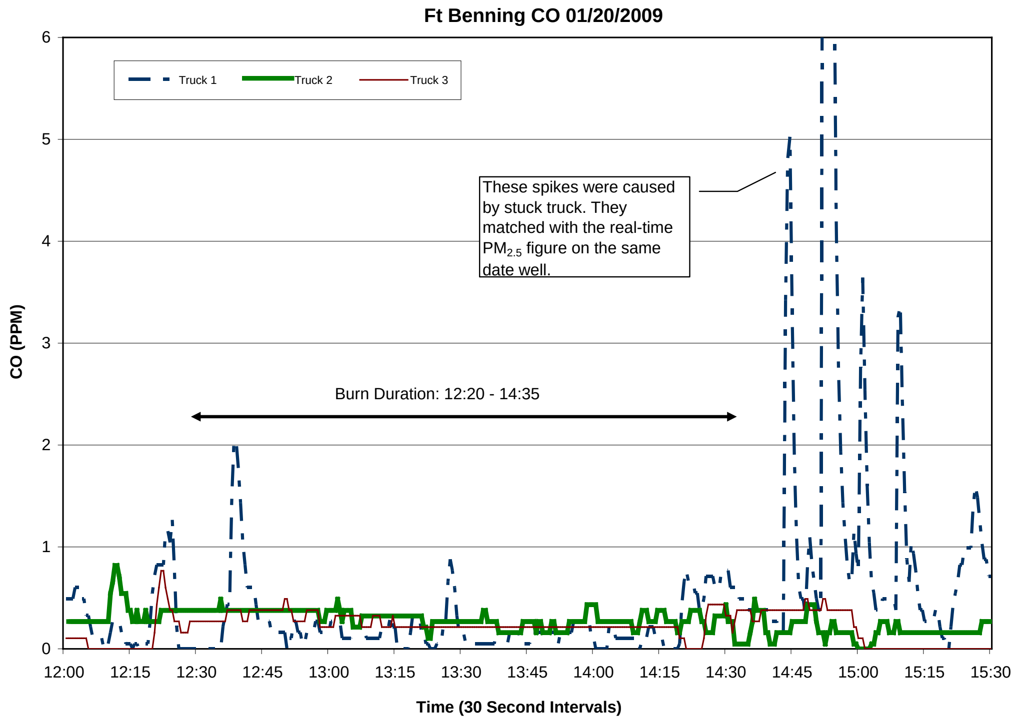
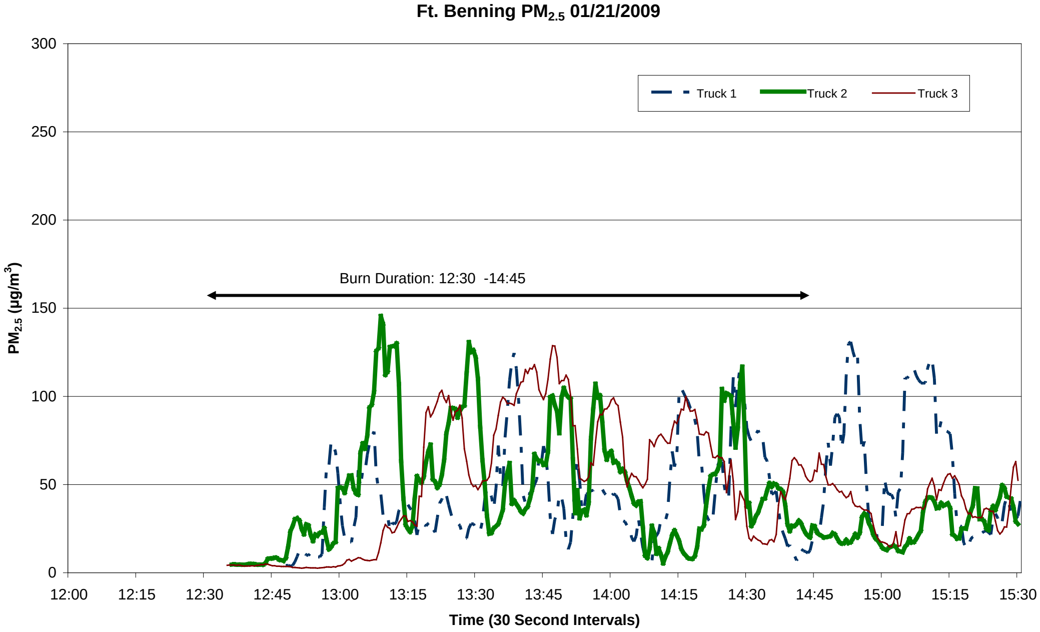


Figure 3.20 – 3.21: Real-time data collected on January 20th, 2009. Truck 1 was stuck in the mud from 14:30 till 15:00, which caused an unusual spike on both PM $_{2.5}$ data and CO data during this time period. As shown in Figure 3.20, both truck 1 and 2 have several peaks, while truck 3 is almost a flat line which indicates its low exposure to $PM_{2.5}$.



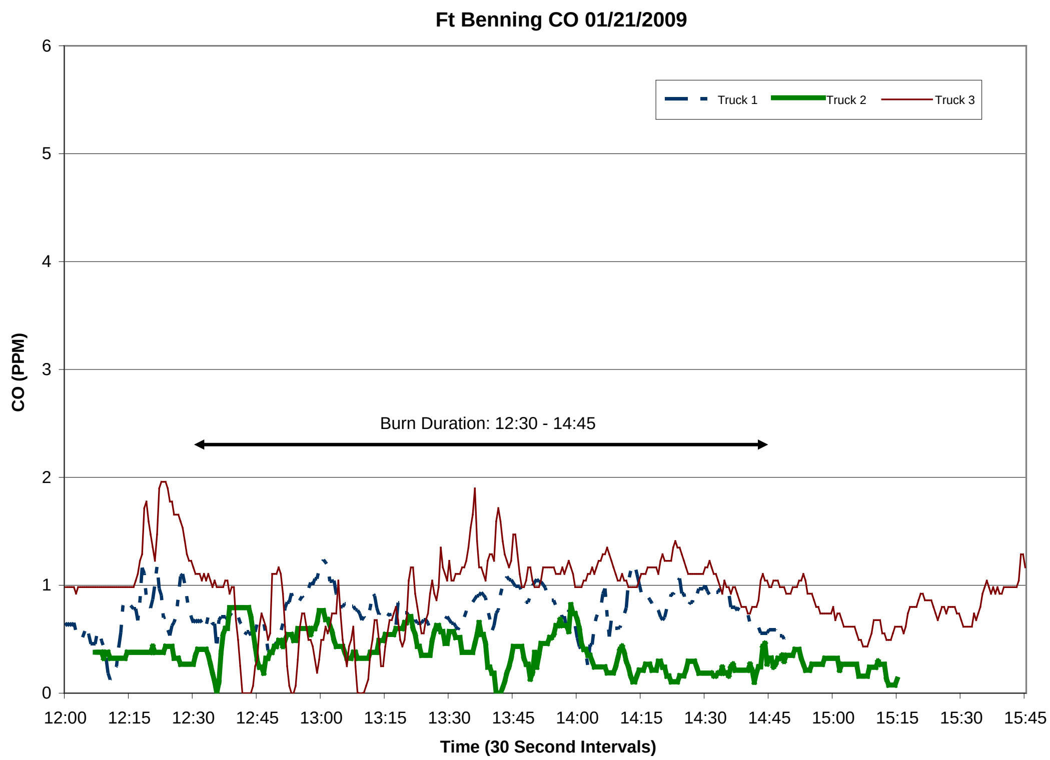
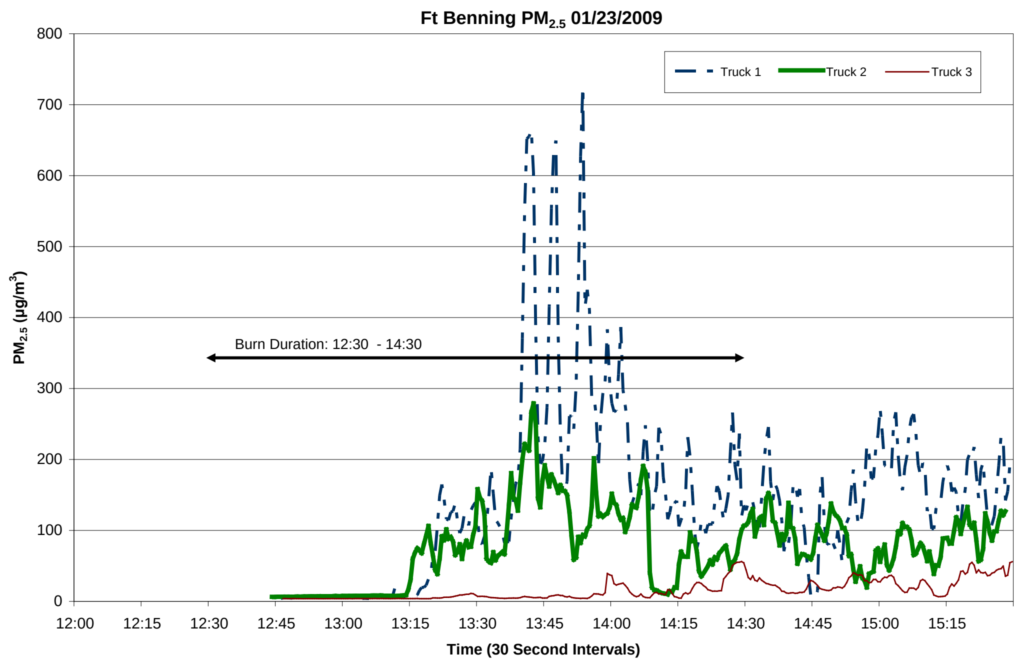


Figure 3.22 - 3.23: Real-time data collected on January 21st, 2009. No clear trend can be seen on Figure 3.22. it looks all 3 trucks detected some level of smoke right after the ignition, but after 14:30, truck 2 and 3 have declined levels of $PM_{2.5}$ while truck 1 still have two higher peaks until 15:15 when it begins to decline. As show in Figure 3.23, Truck 3 captures more CO than Truck 1, and followed by Truck 2.



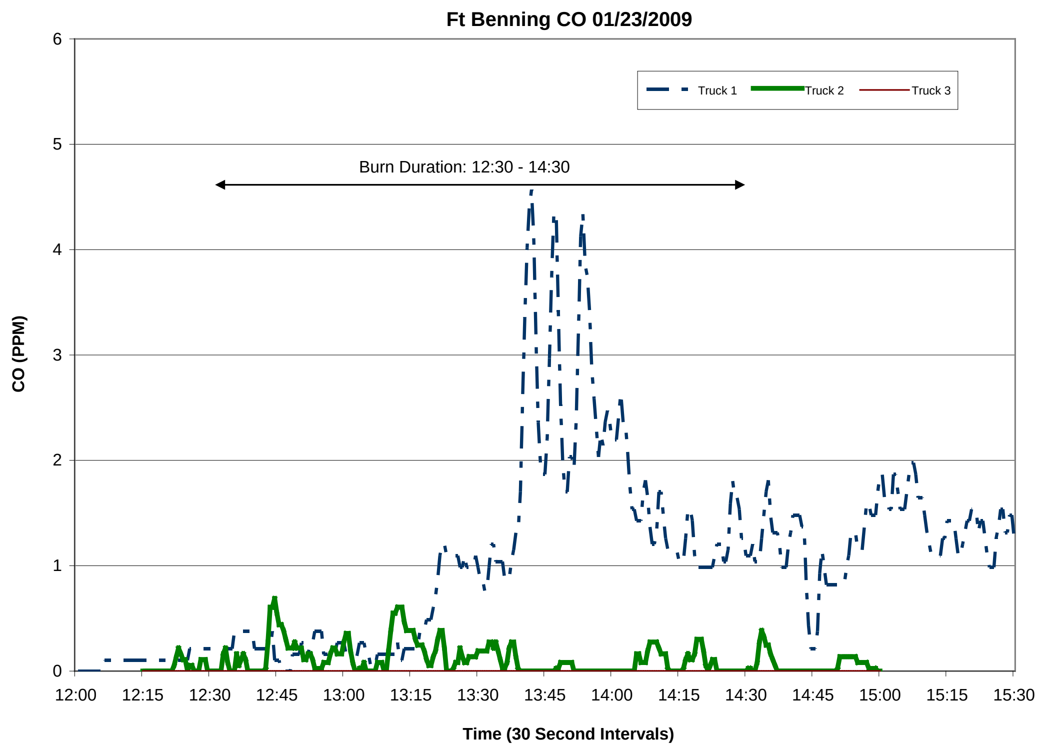


Figure 3.24 – 3.25: Real-time data collected on January 23rd, 2009. A second compartment was burned prior to monitored compartment. The earlier burn of 200 acres was conducted in a nearby compartment and completed at 12:00 which was believed to cause higher levels of $PM_{2.5}$ on all trucks. CO and $PM_{2.5}$ graph matches in this burn well and share the same pattern.

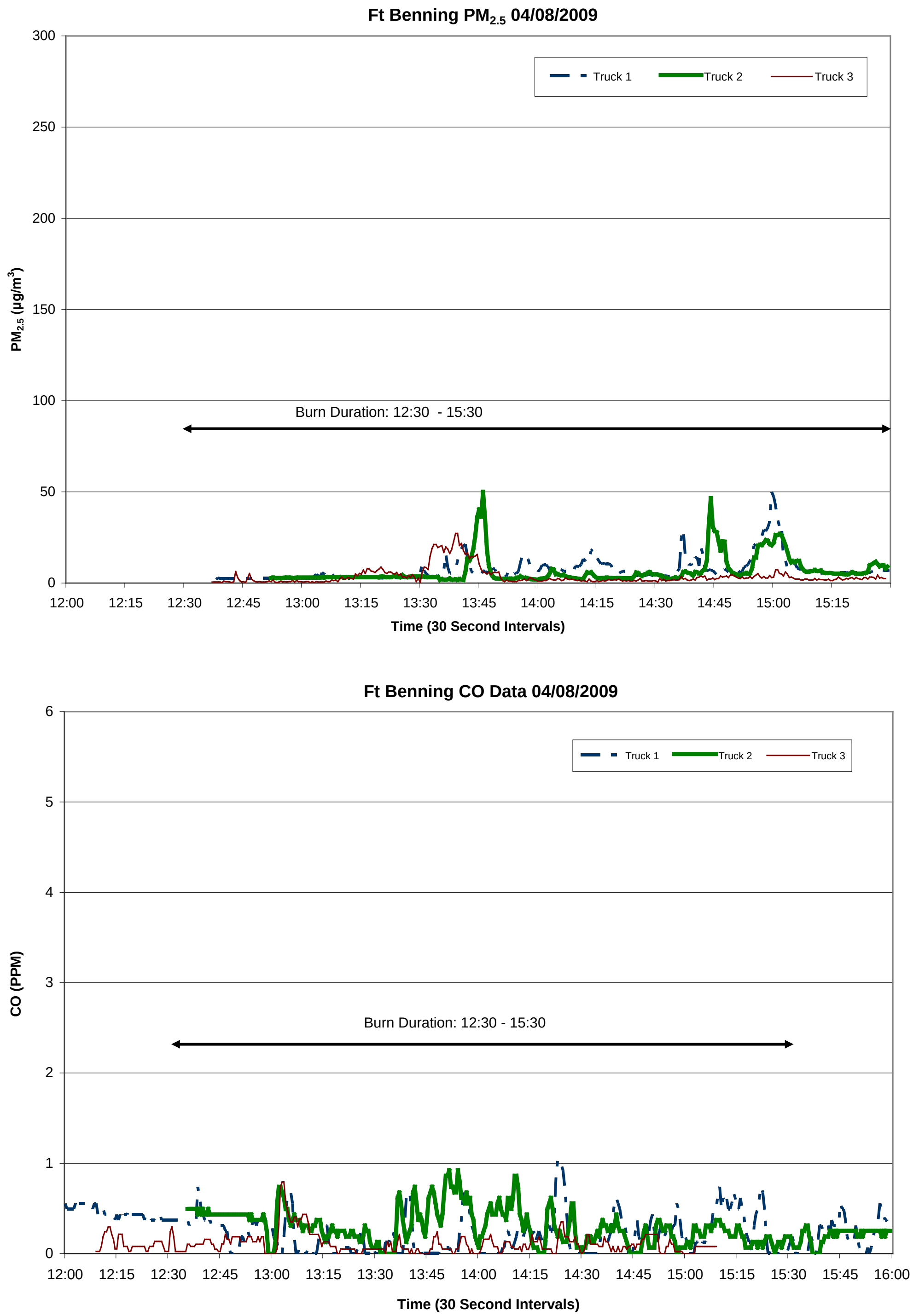
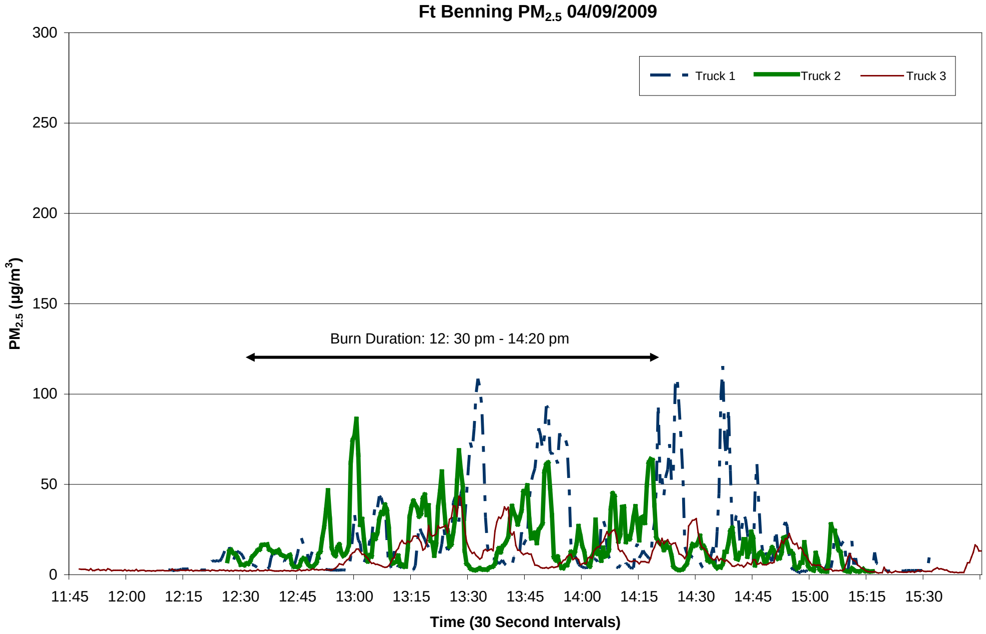


Figure 3.26 – 3.27: Real-time data collected on April 8th, 2009. For $PM_{2.5}$, The highest peak appears at 13:46 on truck 2. Truck 3 still has a quite low exposure, while truck 1 and truck 2 have higher overall $PM_{2.5}$ levels. For CO, no obvious trend is detected. Note: on April 8th, Sampling zones were switched from Km to mile.



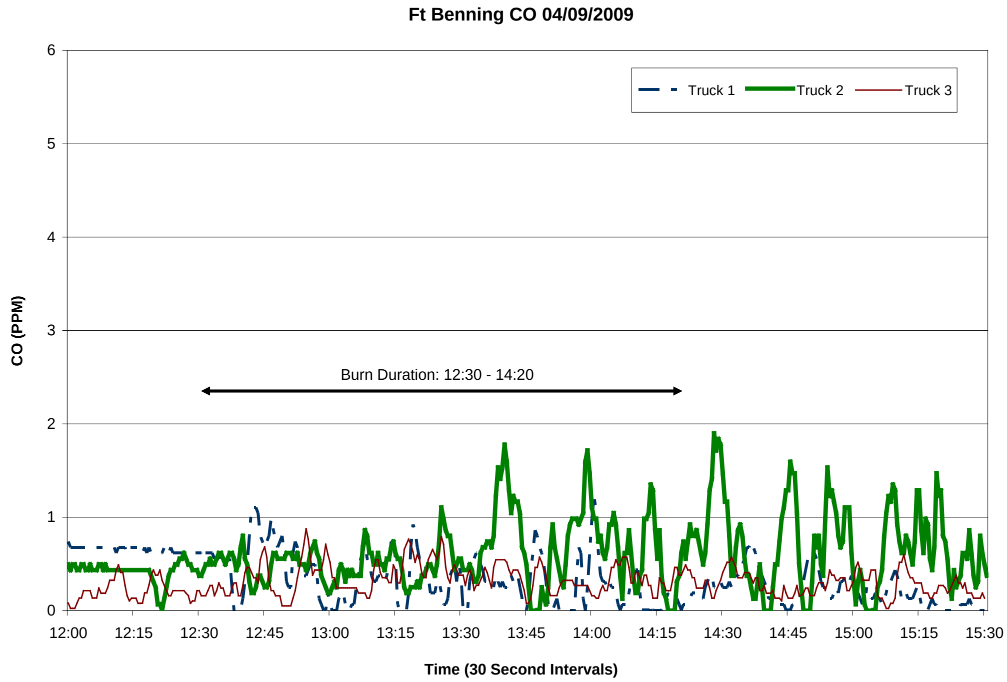


Figure 3.28 - 3.29: Real-time data collected on April 9th, 2009. Truck 2 was located on a high open ridge during monitoring. Overall, truck 1 has higher concentration of $PM_{2.5}$ than truck 2 and 3. In comparison, Truck 2 has higher CO concentration than Truck 1 and Truck 3.

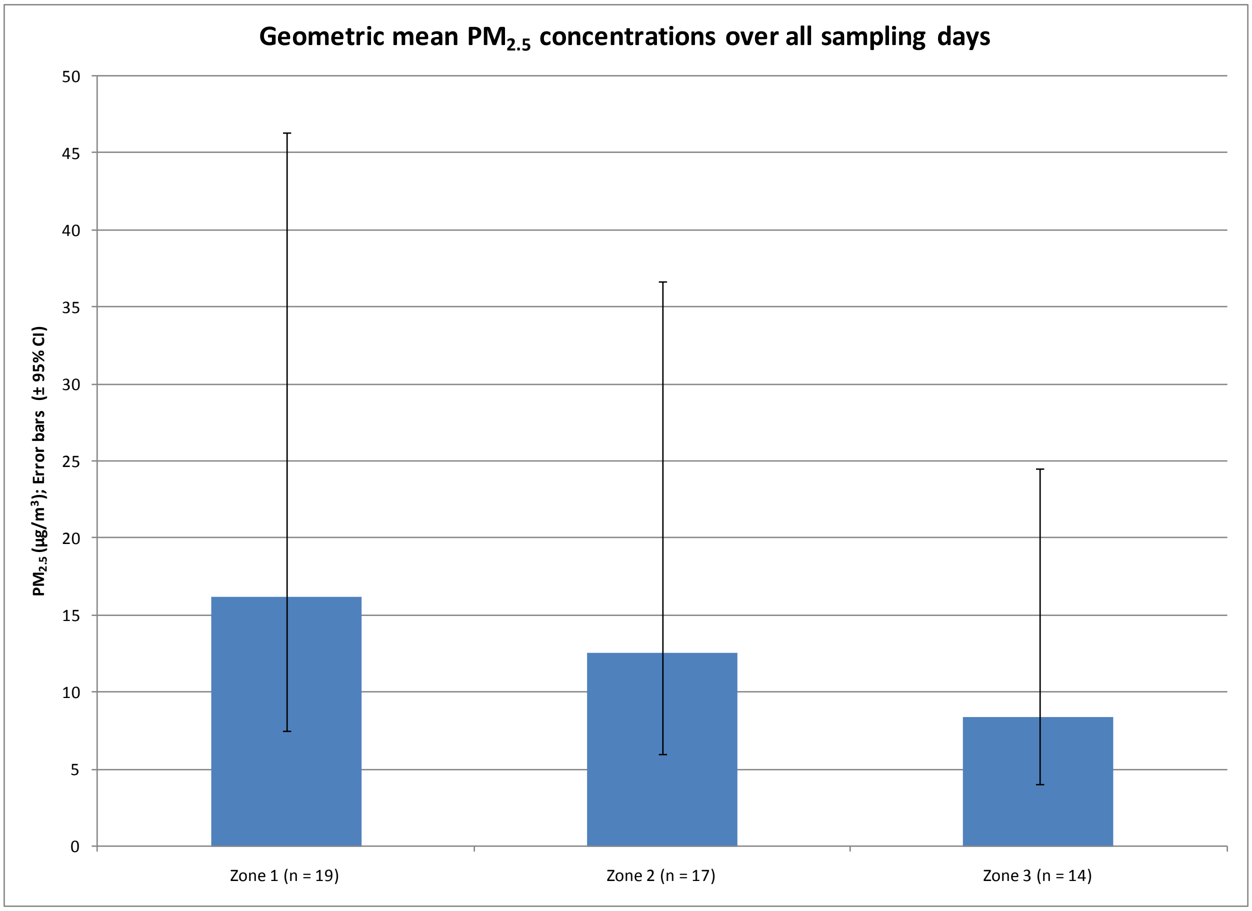


Figure 3.30: Geometric mean values of $PM_{2.5}$ across 3 sampling zones for all sampling days. Note: Data on January 13th, 2009 were removed from this analysis, because on this day, all 3 trucks were located far from the burn area (> 10 Km) without moving around due to very limited road accessibility.

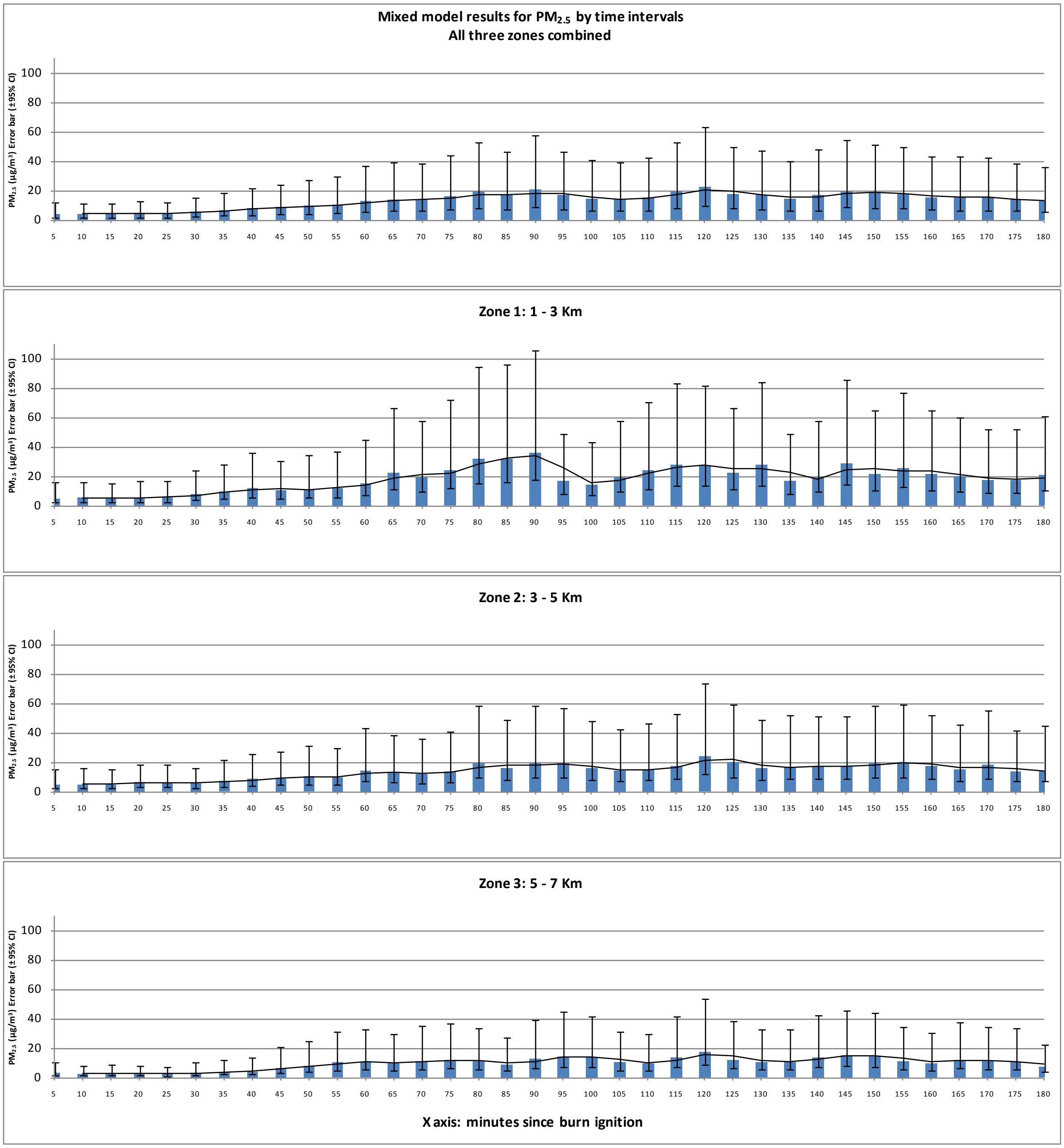


Figure 3.31: Mixed model results for $PM_{2.5}$ by time intervals. The top panel represents the geometric mean values of $PM_{2.5}$ on different time intervals across 3 zones for all sampling days; The second panel represents data from Zone 1; The third panel represents data from Zone 2; The bottom panel represents data from Zone 3. The time intervals were generated by subdividing the data into 5-minute blocks starting at ignition. Note: data on January 13th, 2009 was removed from this analysis due to the same reason as given in legend of Figure 3.30.

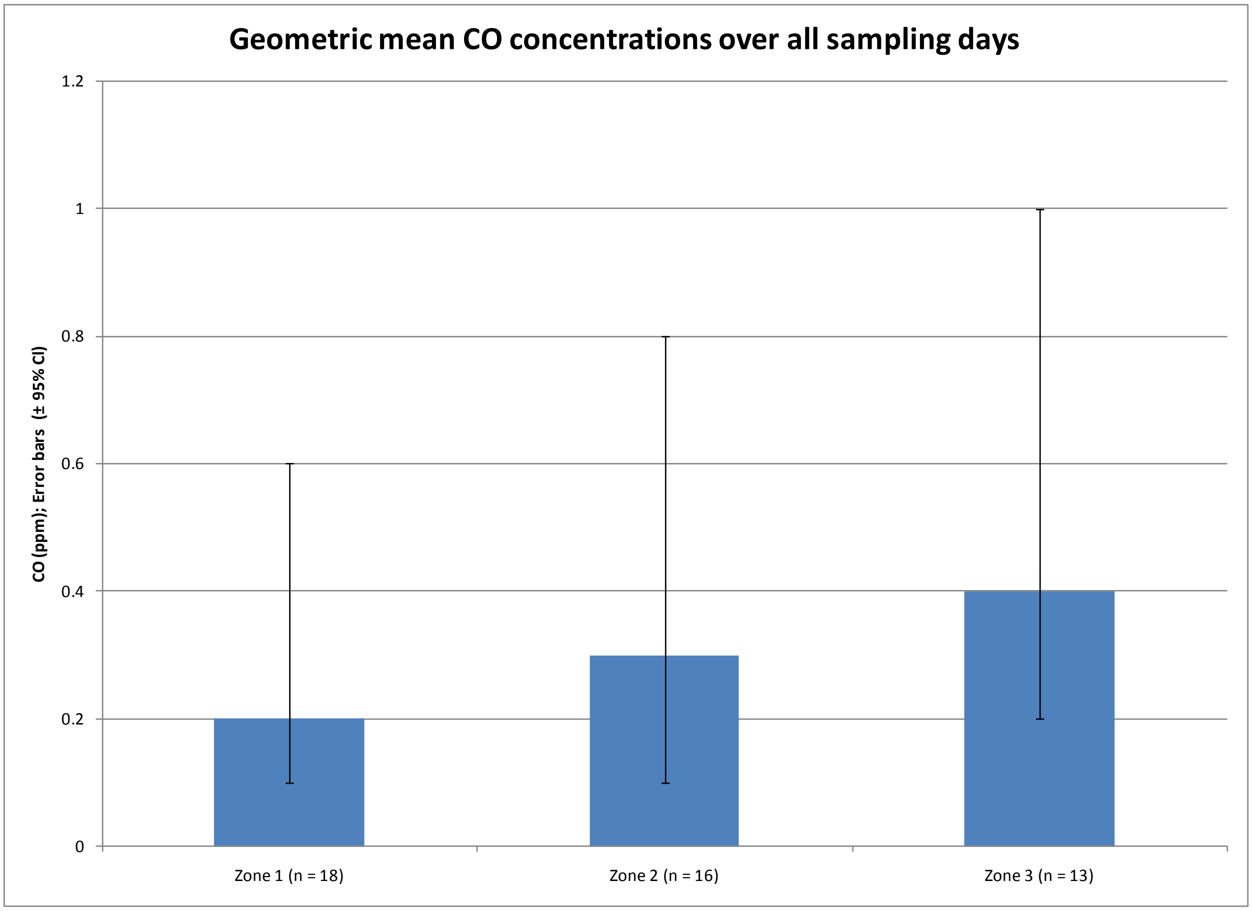


Figure 3.32: Geometric mean values of CO across 3 zones for all sampling days. Note: Data on January 13th, 2009 was removed from this analysis, because on this day, all 3 trucks were located far from the burn area (>10 Km) without moving around due to very limited road accessibility.

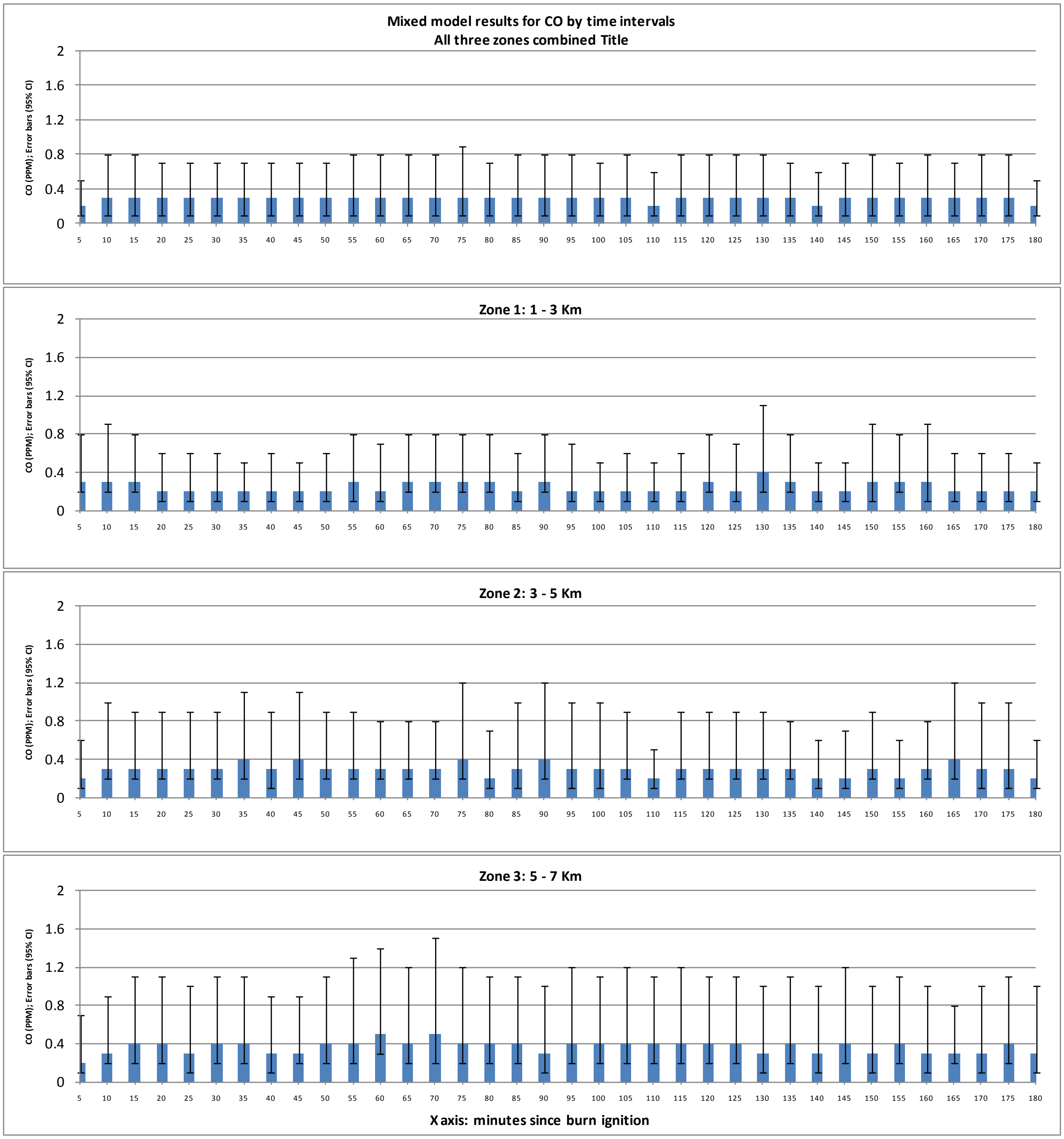


Figure 3.33: Mixed model results for CO by time intervals. The top panel represents the geometric mean values of CO on different time intervals across 3 zones for all sampling days; The second panel represents data from zone 1; The third panel represents data from zone 2; The bottom panel represents data from Zone 3. The time intervals were generated by subdividing the data into 5-minute blocks starting at ignition. Note: data on January 13th, 2009 was removed from this analysis due to the same reason as given in legend of Figure 3.30.

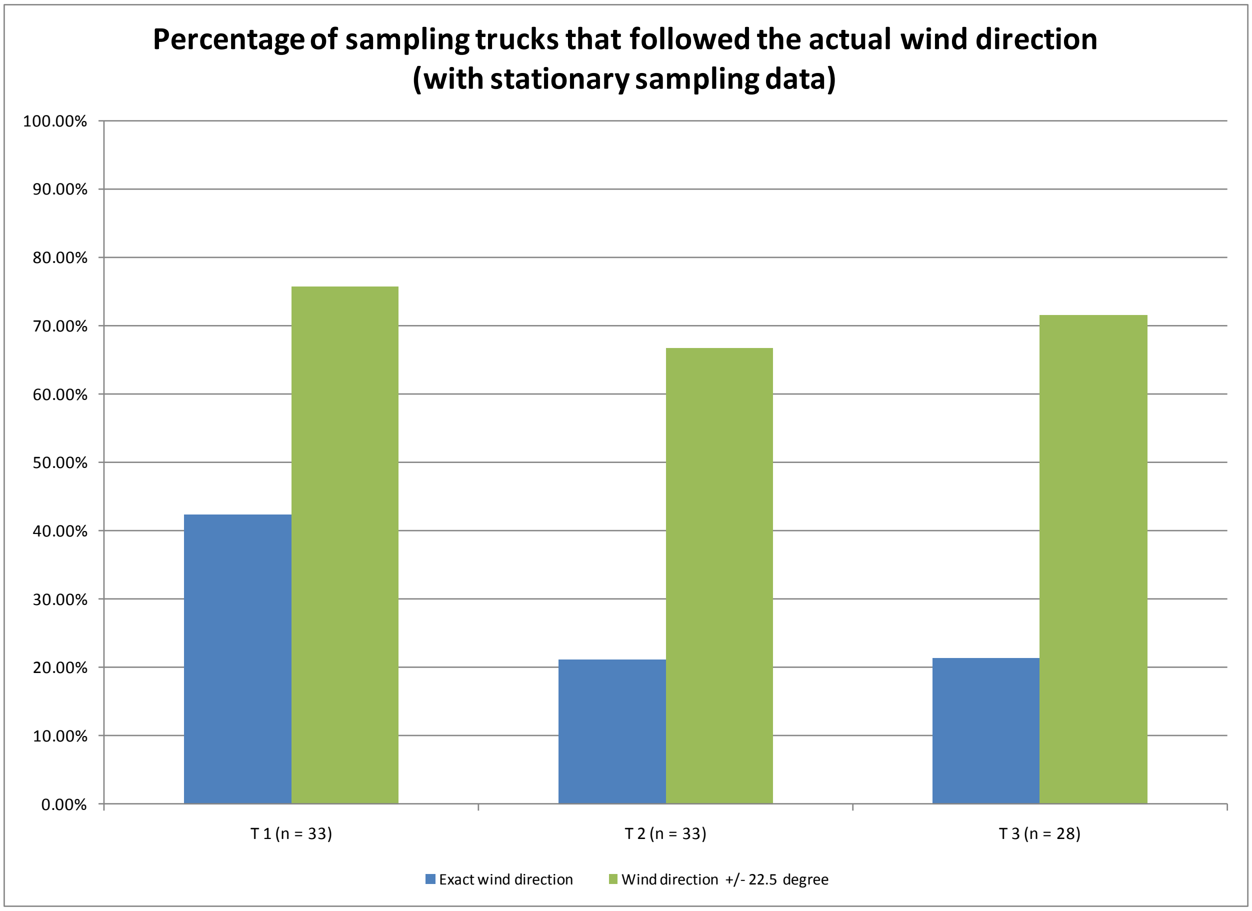


Figure 3.34: The percentage of sampling trucks that followed the actual wind direction (with stationary sampling data). In the figure, Blue column represents the percentage of sampling trucks that followed the exact wind direction; Green column represents the percentage of sampling trucks that followed the wind direction with a ± 22.5º window.

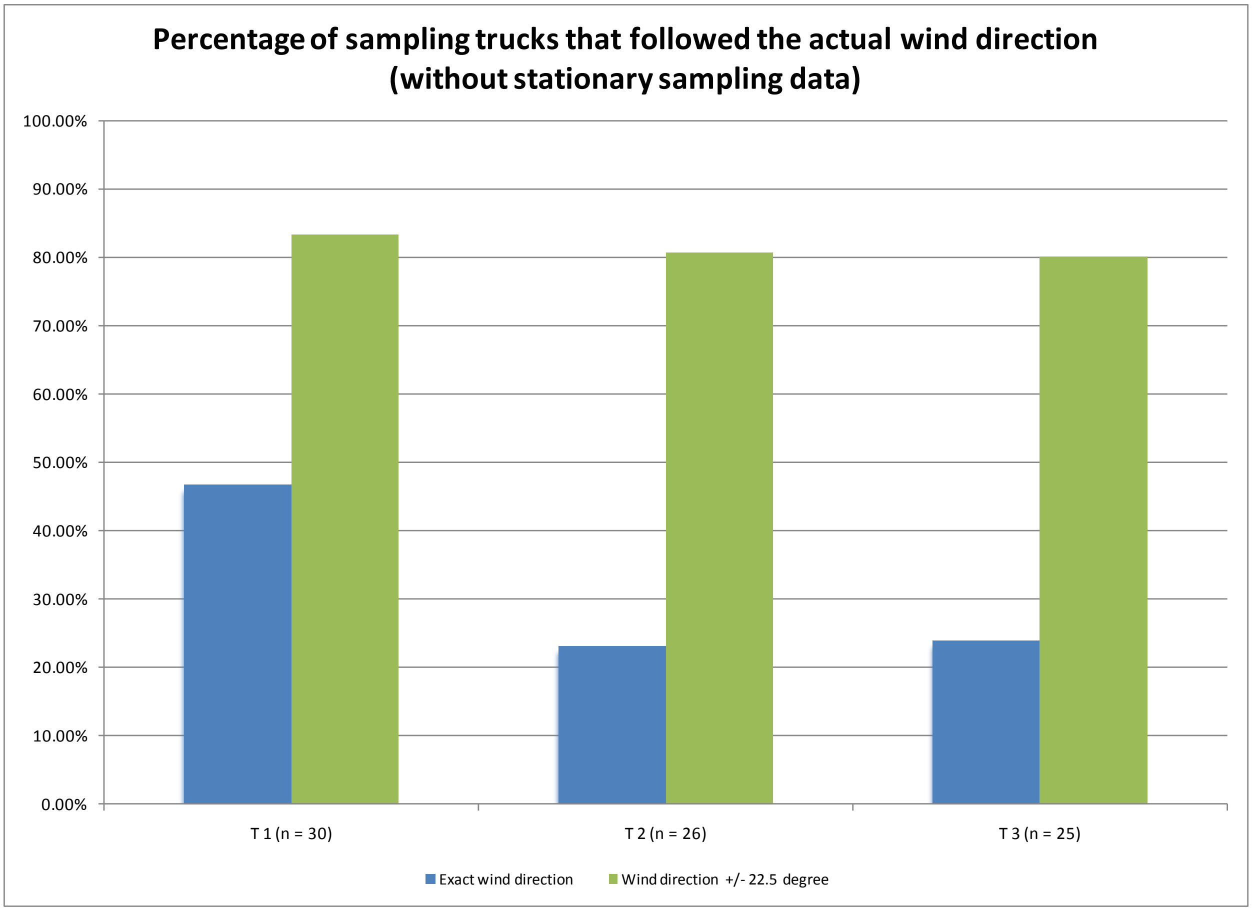


Figure 3.35: The percentage of sampling trucks that followed the real wind direction (without stationary sampling data).

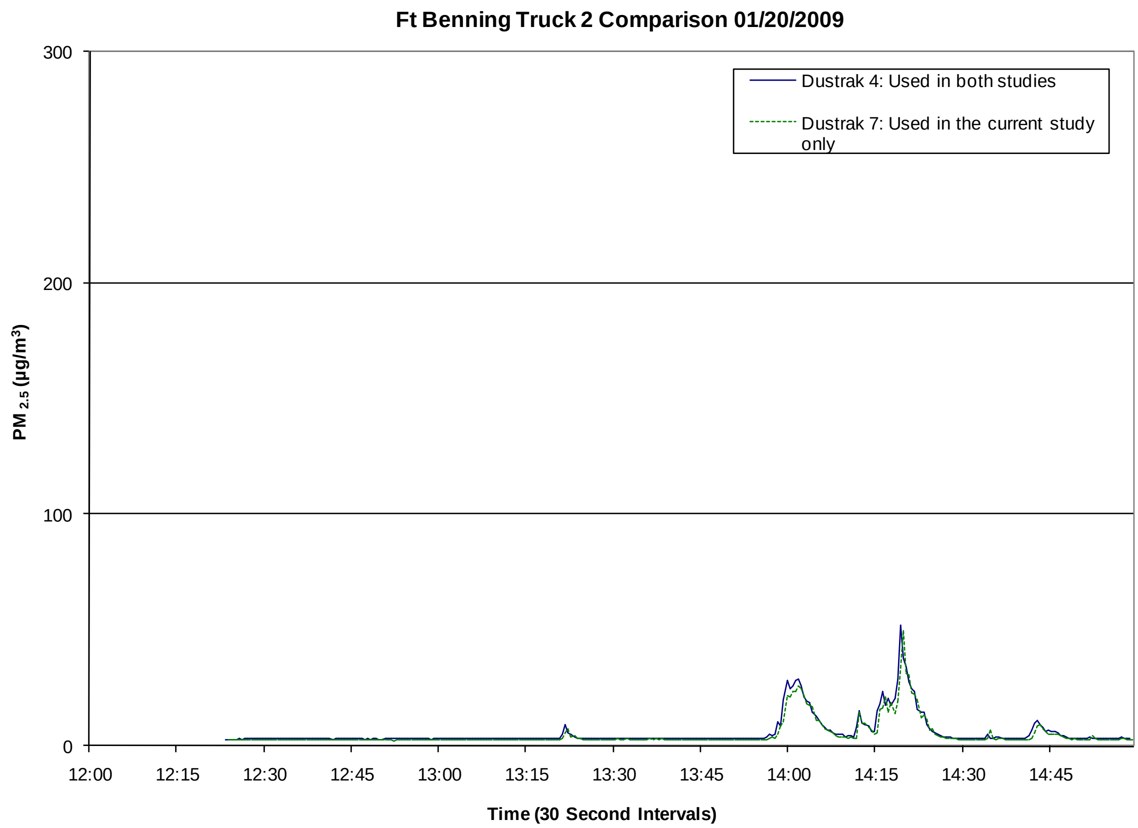


Figure 3.36: Real-time $PM_{2.5}$ data collected from two co-located DustTrak $PM_{2.5}$ monitors on January 20th, 2009. Note: DustTrak 1 – 6 were used for reduction ratio generation as well as in Fort Benning study while DustTrak 7 – 8 were used in Fort Benning study only.

CHAPTER 4

CONCLUSIONS

In this study, downwind exposure to the smoke of prescribed forest burns was evaluated based on real-time $PM_{2.5}$ and CO data collected from 11 prescribed forest burns in years 2008 and 2009 at Fort Benning, GA. Overall, our results suggest that $PM_{2.5}$ levels downwind from prescribed forest burns were elevated while CO levels remained low. Throughout the entire study period, average $PM_{2.5}$ levels for 8 of 29 truck-days reached or exceeded the US EPA 24-hour standard of 35 $\mu g/m^3$ while no CO levels exceeded neither 8-hour EPA standard of 9 ppm nor 8-hour WHO standard of 8.7 ppm. Meanwhile, $PM_{2.5}$ levels from 17 of 29 truck-days exceeded background levels measured in both Phenix city, Alabama and Macon, Georgia. These results suggest that downwind smoke from prescribed forest burns are a potential health risk for downwind communities.

This research also shows that the distance to burn area and time since burn ignition are two factors that significantly ($P < 0.05$) influence downwind exposures to $PM_{2.5}$. This implies two facts: 1) the closer a downwind community is to the fire, the higher exposure this community will receive; 2) peak exposures to $PM_{2.5}$ would occur at certain time period (1.5 hours in this study) after burn ignition started if the affected community is located close enough to the burn area. Due to its ability to disperse rapidly into the atmosphere, downwind CO levels were uniformly low and not affected by either of the two factors. Meteorological data such as wind velocity and direction are other factors that affect the exposure to the smoke from prescribed forest burns. For the purpose of this study, we designed a moving point sampling scheme which reduced errors caused by changes in wind directions to a minimal level. In consequence, this scheme enabled us to capture most of the smoke.

Thesis summary

Forest fires can be roughly classified into two groups - wildland fires and prescribed forest burns. Wildland fires refer to those uncontrolled, non-structure fires that occur in the wildness. On the opposite, prescribed forest burns refer to fires which are preplanned, well controlled, and burned for the purposes such as maintaining a good ecosystem and reducing the chances of wild fires. Forest fires, including both wildland fires and prescribed forest burns, can adversely impact the human society by damaging properties, crops, biodiversity, and regional air quality (Robinson et al. 2004). More importantly, smoke generated from forest fires contains many air pollutants that can potentially impact human health.

A number of health effects are associated with exposures to the smoke from forest fires. For example, it was reported lung function of firefighters declined after exposure to a forest fire (Betchley et al. 1997). Also, in an investigation of 1997 haze disaster in Indonesia, people who were exposed to smoke had various respiratory symptoms. Susceptible populations such as the elderly and those with pre-existing diseases even suffered a more serious deterioration of overall health. Further, the exposure to forest fires was reported to be associated with increased cardiovascular hospital admissions and acute bronchitis admissions (Delfino et al. 2009). Meanwhile, smoke-related symptoms also include chronic obstructive pulmonary disease (COPD) and asthma (Mott et al. 2005).

Exposure assessment of forest firefighters and individuals in affected communities who were affected by forest fires has been conducted in many studies. However, few studies have evaluated exposure levels downwind of prescribed forest burns (Hu et al. 2008; Li et al. 2007; Naeher et al. 2006). To sample $PM_{2.5}$, gravimetric methods and stationary sampling strategies were mostly used in these few studies. Therefore, previous studies had limitations of inability to assess the exposure profiles during the whole period of burning and identify high exposure peaks that might be of equal or more importance to related health effects. In our study, we monitored $PM_{2.5}$ and CO using real-time samplers placed on moving sampling trucks. Moving point sampling facilitated the collection of more smoke exposure data by following real-time wind directions; similarly the use of real-time monitoring equipment enhanced our ability to obtain exposure profiles over active burning session and capture the instantaneous peak exposures.

In summary, this study improved the sampling methodologies and exposure assessment strategies for downwind forest fire smoke exposure studies in current literature and allowed for the investigation of more objective identification of exposure profiles over the entire period of prescribed forest burns.

Reference:

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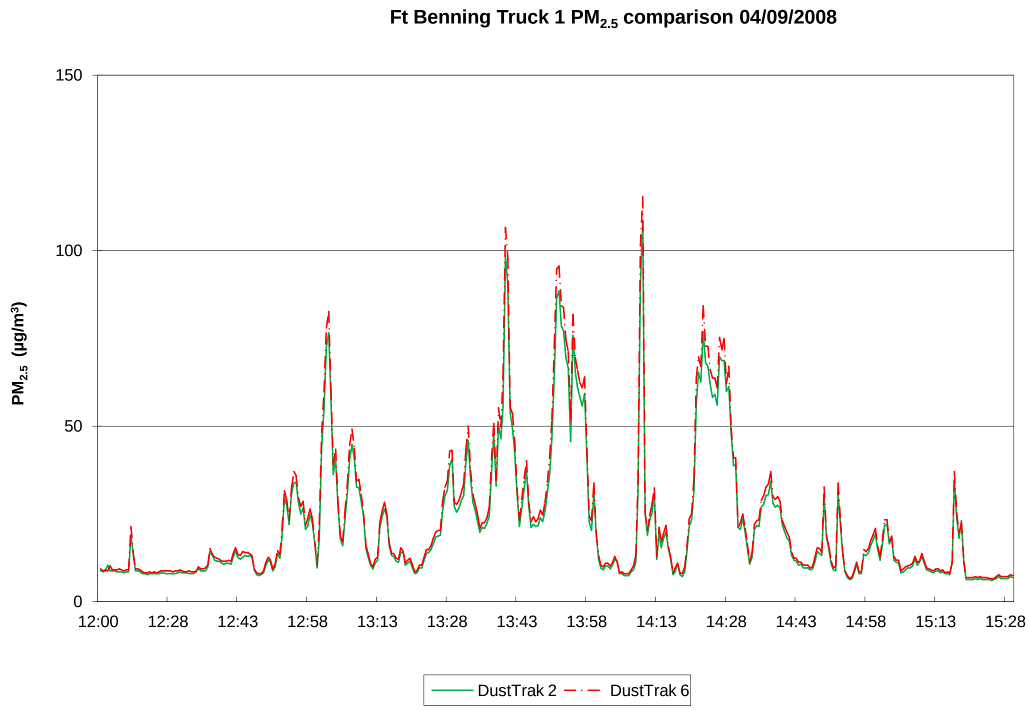
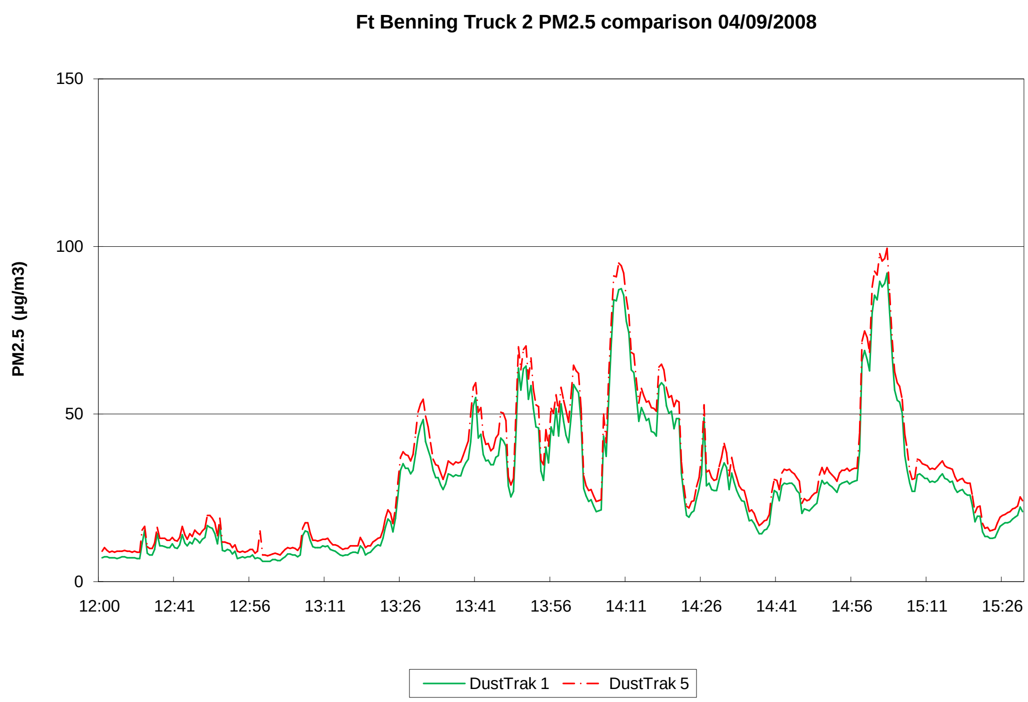
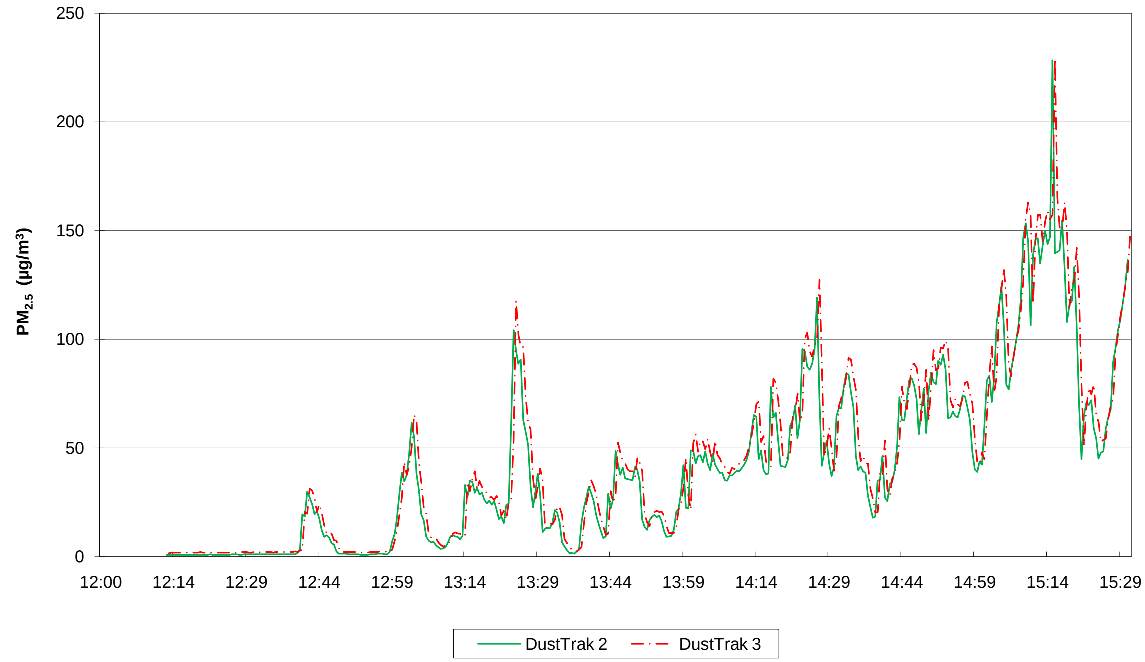
APPENDIX A: REAL-TIME $PM_{2.5}$ DATA MEASURED BY CO-LOCATED AIR SAMPLERS

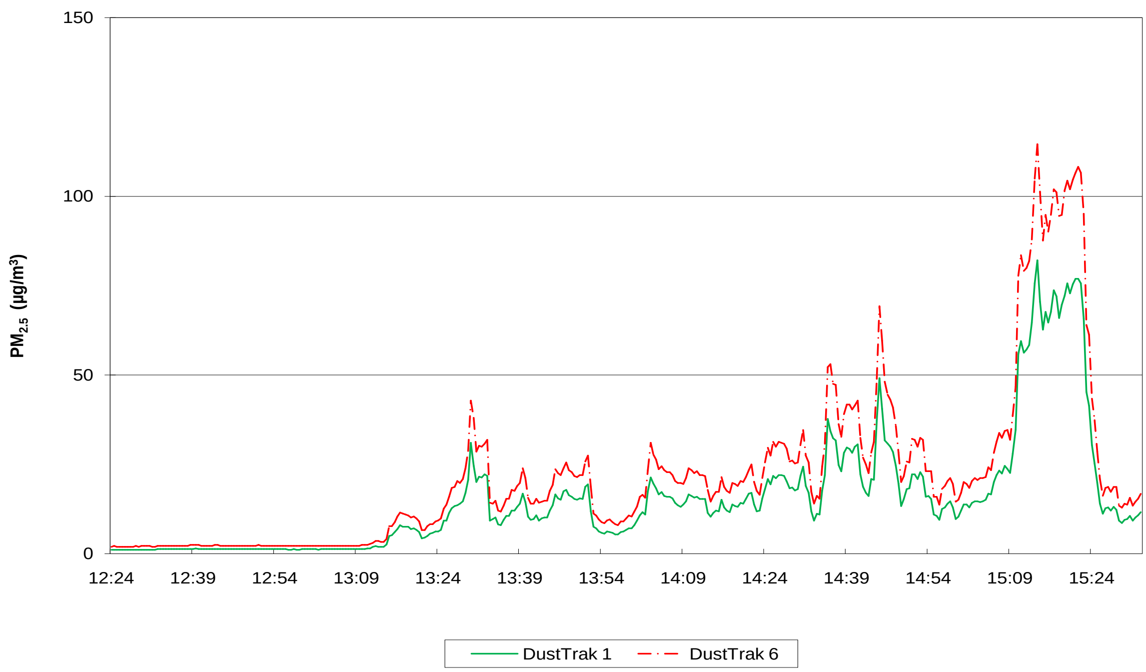


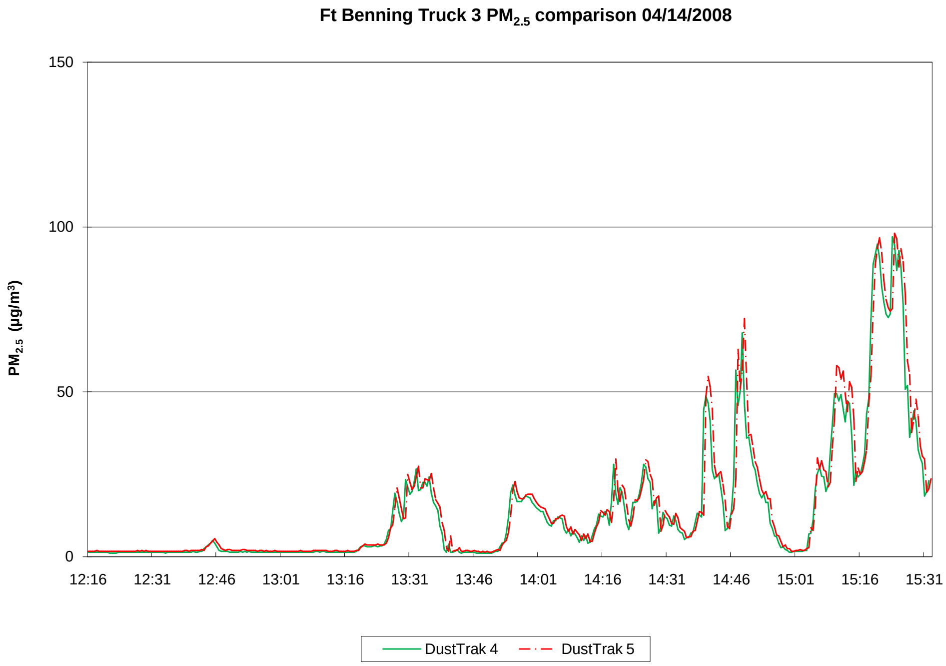


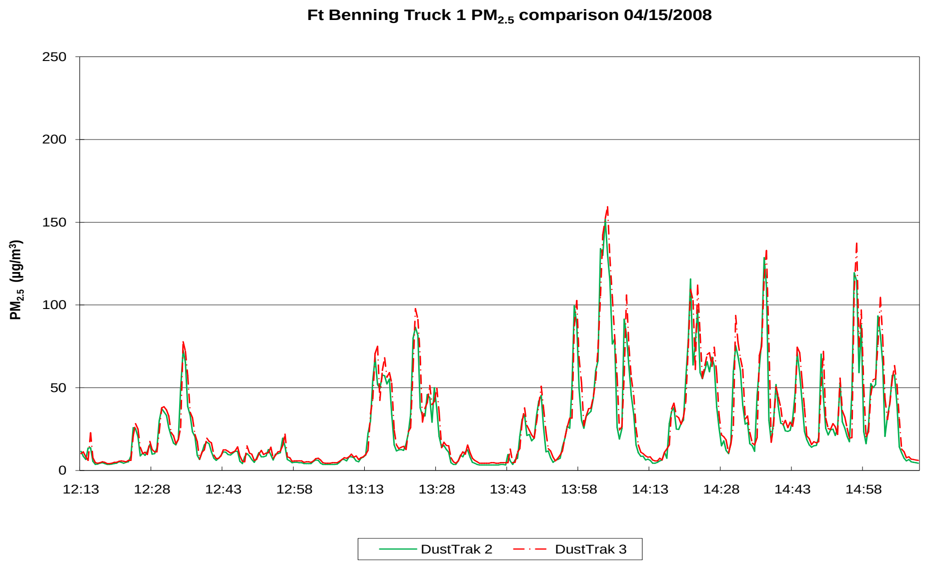
Ft Benning Truck 1 $PM_{2.5}$ comparison 04/14/2008



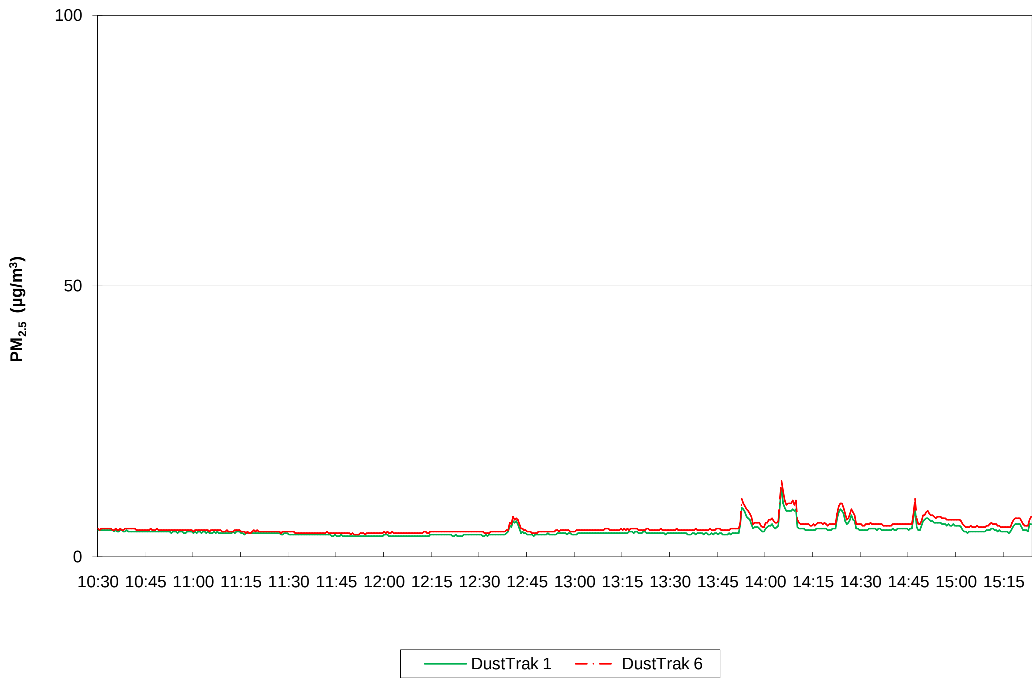
Ft Benning Truck 2 $PM_{2.5}$ comparison 04/14/2008



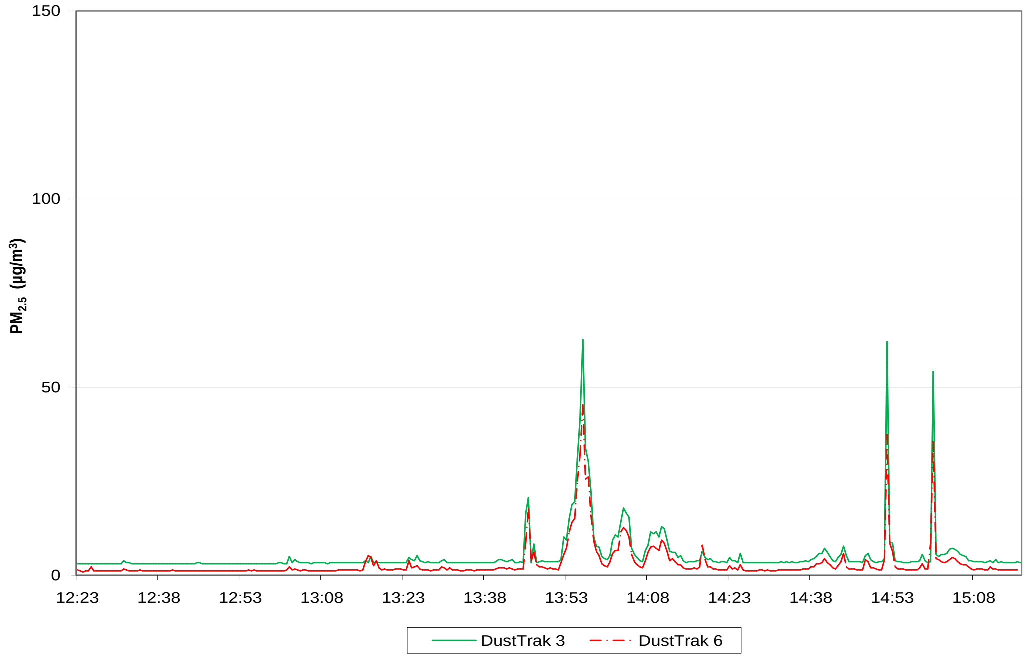

Ft Benning Truck 3 $PM_{2.5}$ comparison 04/14/2008
150
100
50
0
$PM_{2.5}$ (µg/m³)
12:16
12:31
12:46
13:01
13:16
13:31
13:46
14:01
14:16
14:31
14:46
15:01
15:16
15:31
DustTrak 4
DustTrak 5

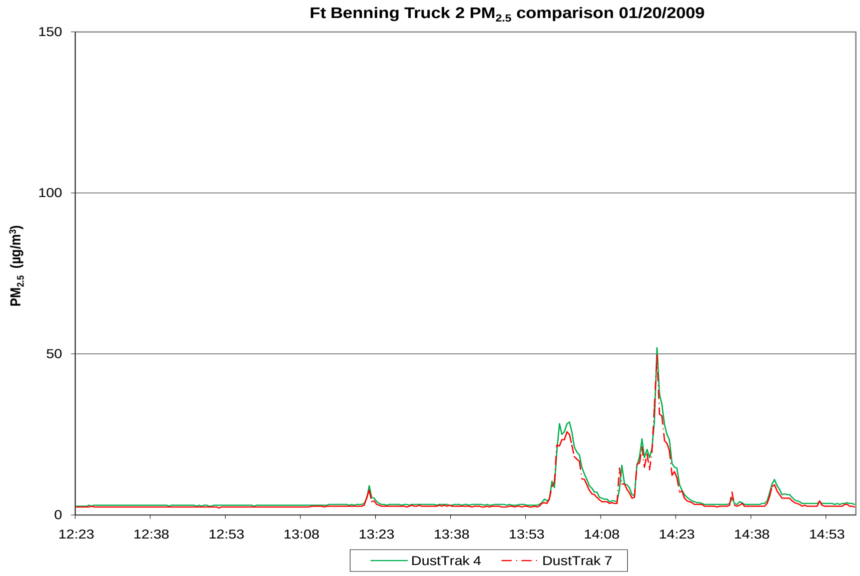

Ft Benning Truck 1 $PM_{2.5}$ comparison 04/15/2008
250
200
150
100
50
0
$PM_{2.5}$ (µg/m³)
12:13
12:28
12:43
12:58
13:13
13:28
13:43
13:58
14:13
14:28
14:43
14:58
DustTrak 2
DustTrak 3

Ft Benning Truck 2 $PM_{2.5}$ comparison 04/15/2008

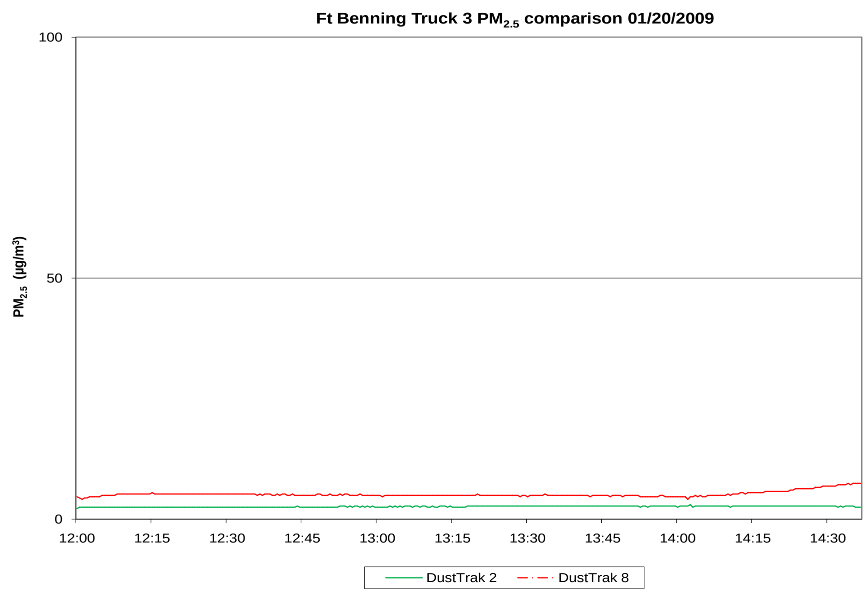


Ft Benning Truck 1 $PM_{2.5}$ comparison 01/20/2009

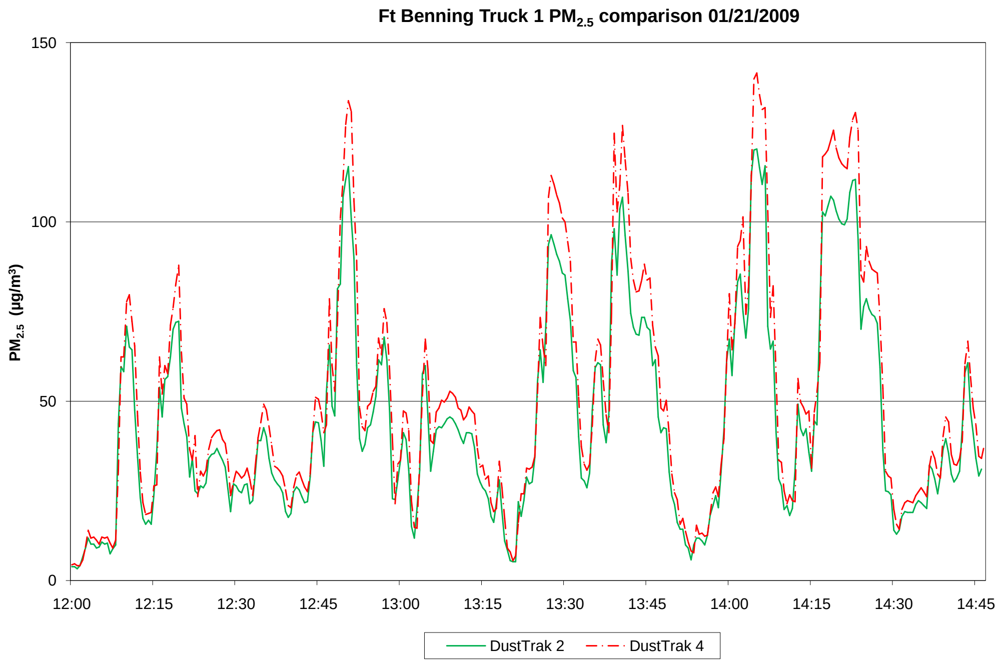




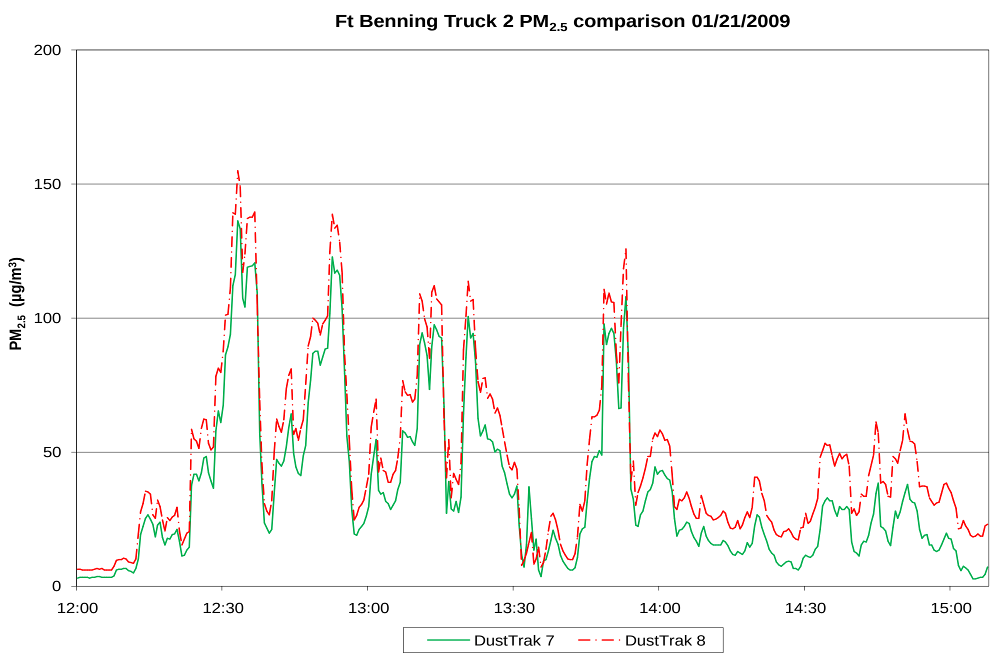
Ft Benning Truck 2 PM2.5 comparison 01/20/2009
PM2.5 (µg/m3)
150
100
50
0
12:23
12:38
12:53
13:08
13:23
13:38
13:53
14:08
14:23
14:38
14:53
DustTrak 4
DustTrak 7



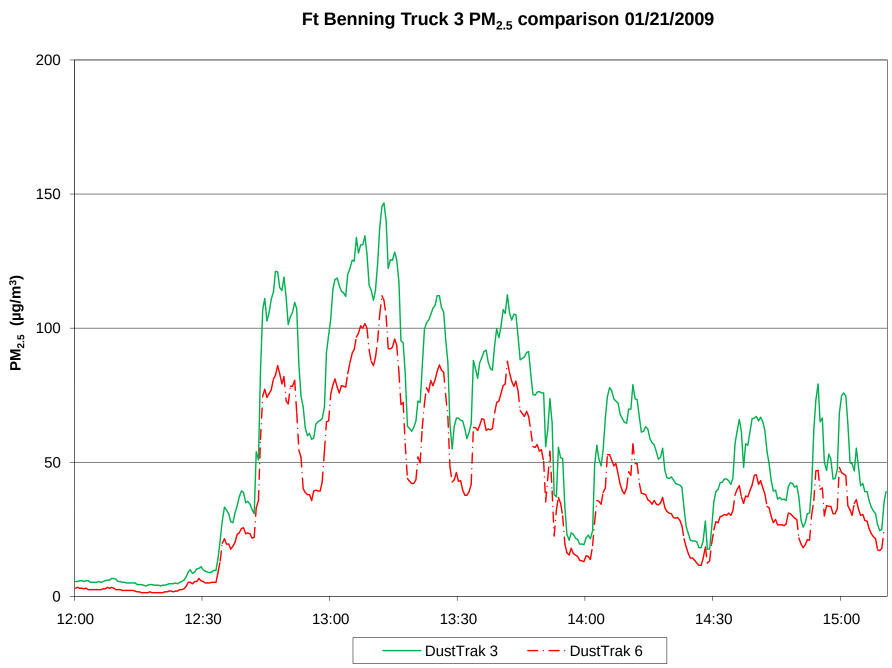
Ft Benning Truck 3 PM2.5 comparison 01/20/2009
PM2.5 (µg/m3)
100
50
0
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
DustTrak 2
DustTrak 8

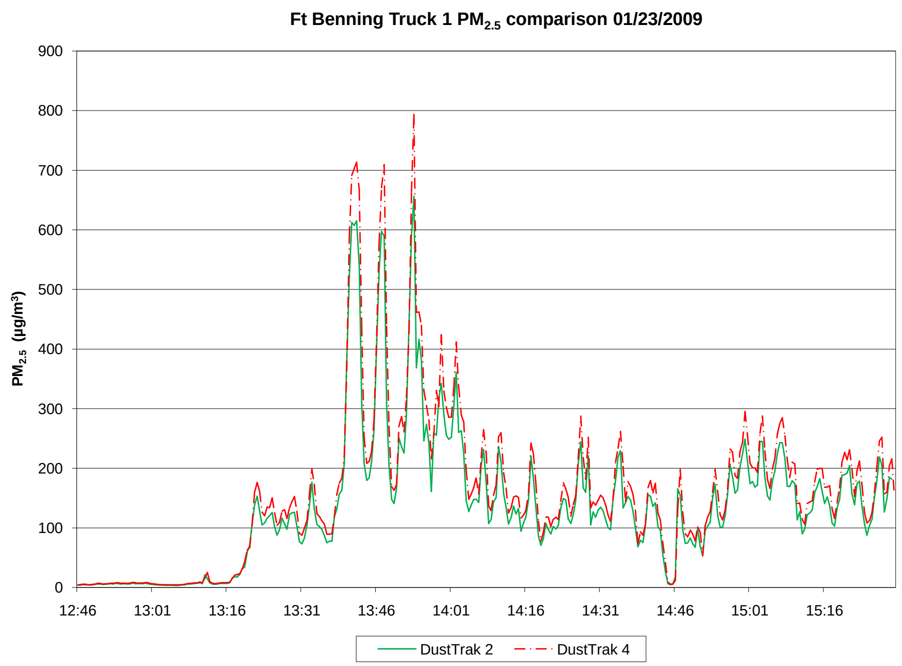


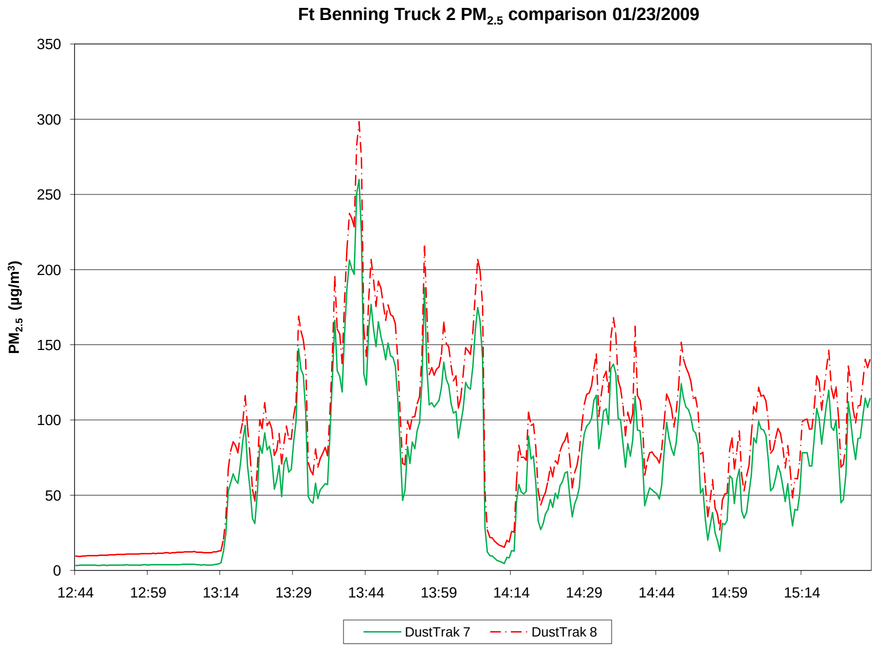
Ft Benning Truck 1 PM2.5 comparison 01/21/2009
PM2.5 (µg/m³)
150
100
50
0
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
DustTrak 2
DustTrak 4

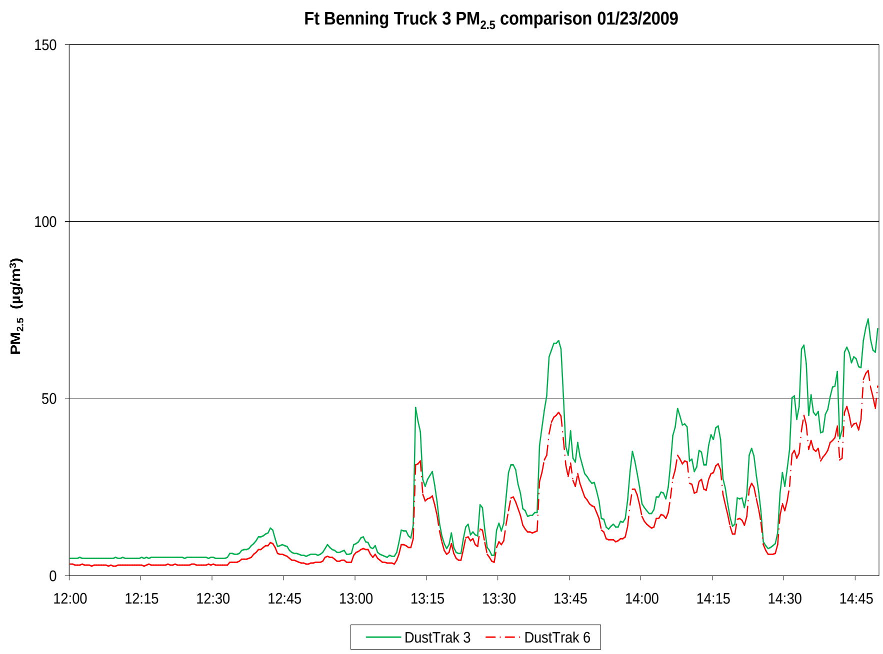


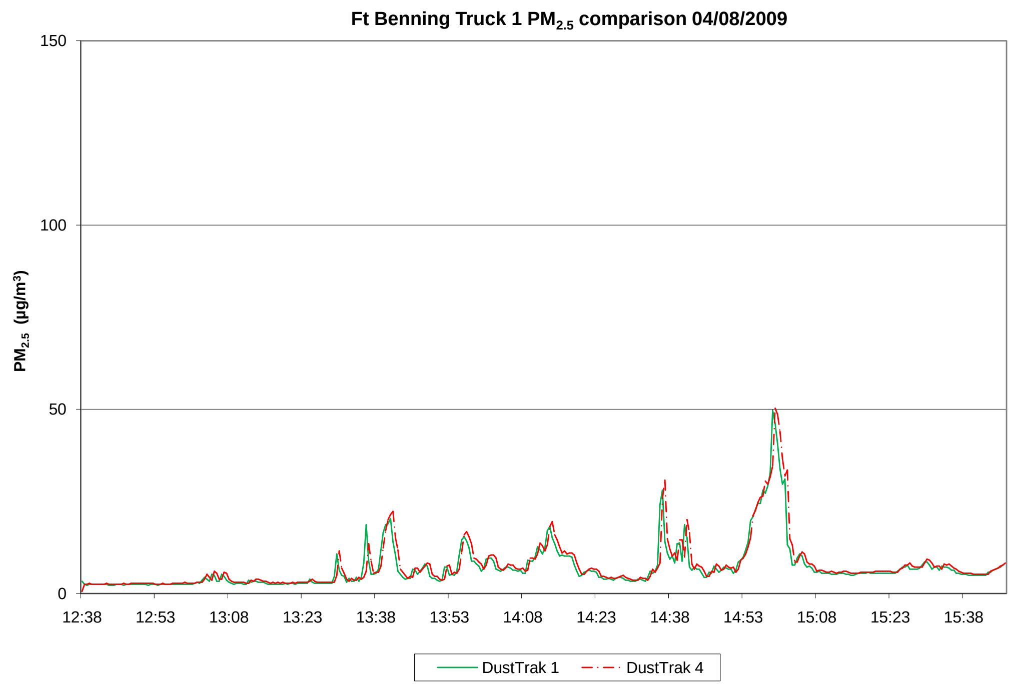
Ft Benning Truck 2 PM2.5 comparison 01/21/2009
PM2.5 (µg/m³)
200
150
100
50
0
12:00
12:30
13:00
13:30
14:00
14:30
15:00
DustTrak 7
DustTrak 8

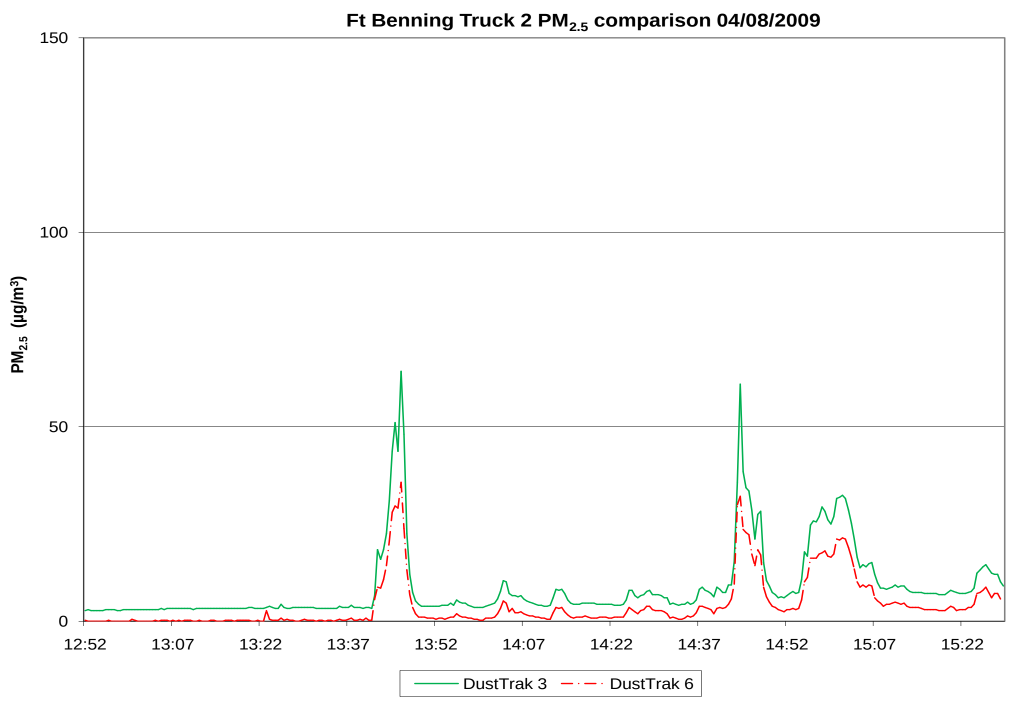

Ft Benning Truck 3 PM2.5 comparison 01/21/2009
PM2.5 (µg/m³)
200
150
100
50
0
12:00
12:30
13:00
13:30
14:00
14:30
15:00
DustTrak 3
DustTrak 6


Ft Benning Truck 1 PM2.5 comparison 01/23/2009
PM2.5 (µg/m³)
900
800
700
600
500
400
300
200
100
0
12:46
13:01
13:16
13:31
13:46
14:01
14:16
14:31
14:46
15:01
15:16
DustTrak 2
DustTrak 4

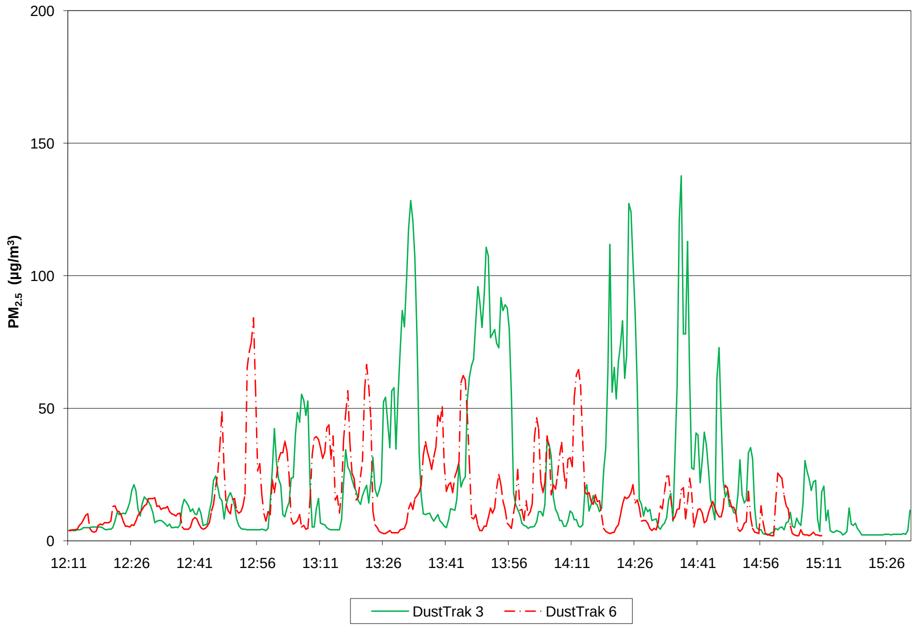

Ft Benning Truck 2 PM2.5 comparison 01/23/2009
PM2.5 (µg/m³)
350
300
250
200
150
100
50
0
12:44
12:59
13:14
13:29
13:44
13:59
14:14
14:29
14:44
14:59
15:14
DustTrak 7
DustTrak 8


Ft Benning Truck 3 PM2.5 comparison 01/23/2009
PM2.5 (µg/m³)
150
100
50
0
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
DustTrak 3
DustTrak 6

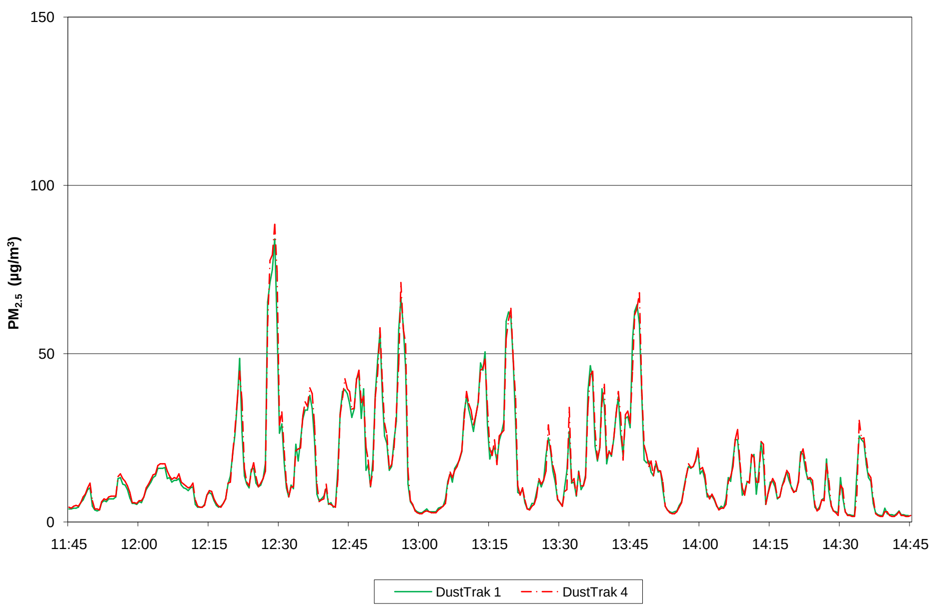

Ft Benning Truck 1 PM2.5 comparison 04/08/2009
PM2.5 (µg/m³)
150
100
50
0
12:38
12:53
13:08
13:23
13:38
13:53
14:08
14:23
14:38
14:53
15:08
15:23
15:38
DustTrak 1
DustTrak 4

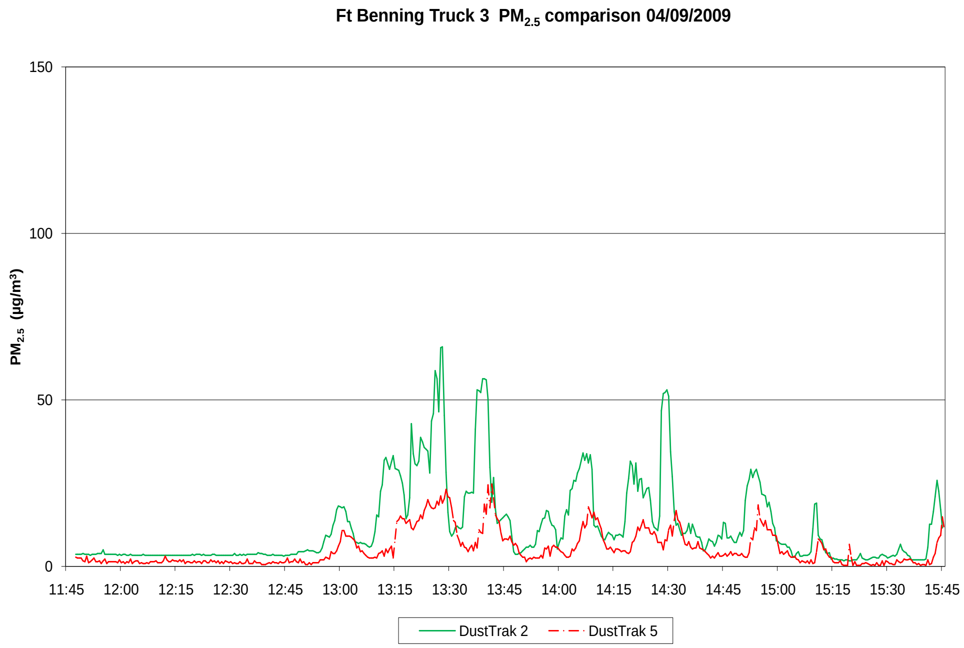

Ft Benning Truck 2 PM2.5 comparison 04/08/2009
PM2.5 (µg/m³)
150
100
50
0
12:52
13:07
13:22
13:37
13:52
14:07
14:22
14:37
14:52
15:07
15:22
DustTrak 3
DustTrak 6

Ft Benning Truck 1 $PM_{2.5}$ comparison 04/09/2009

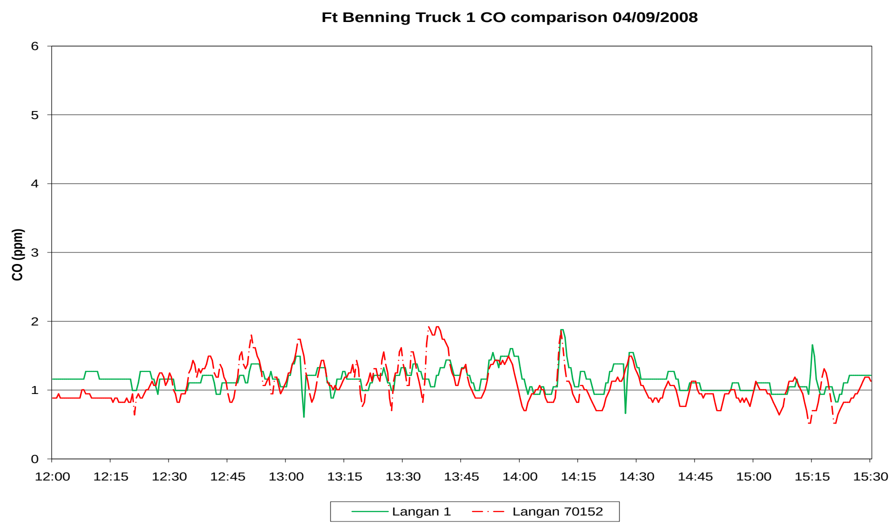


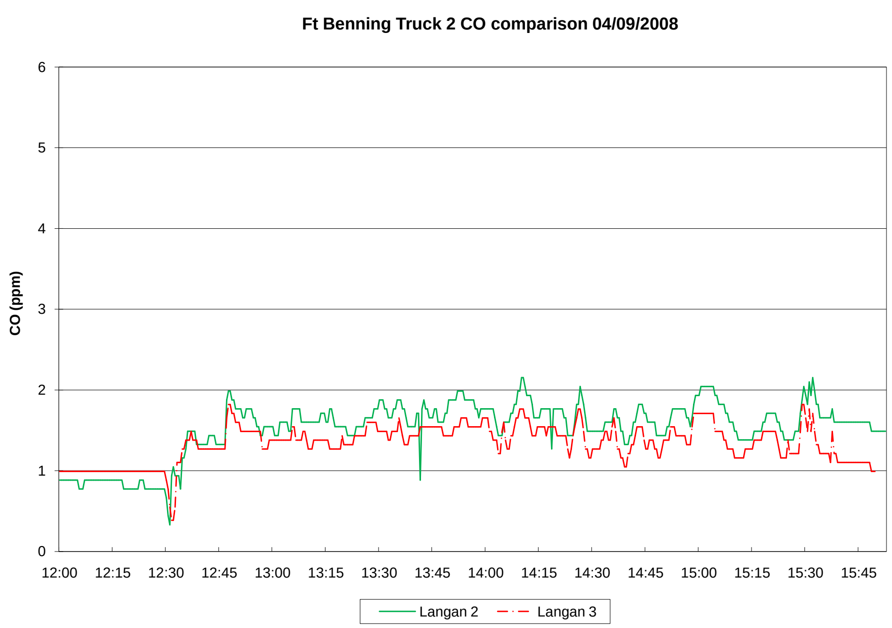
Ft Benning Truck 2 $PM_{2.5}$ comparison 04/09/2009

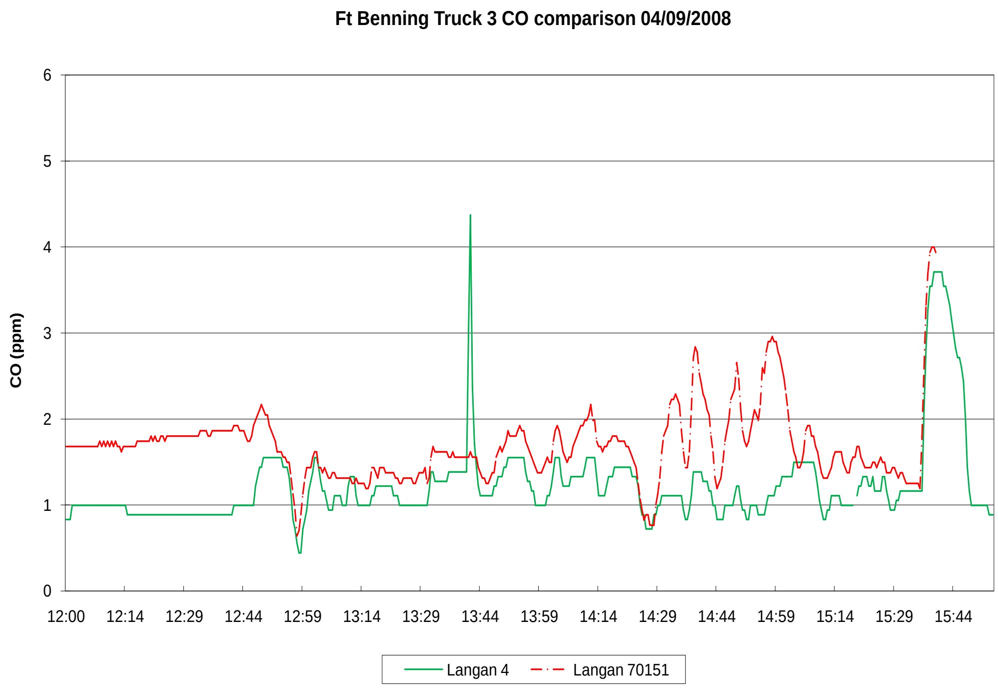


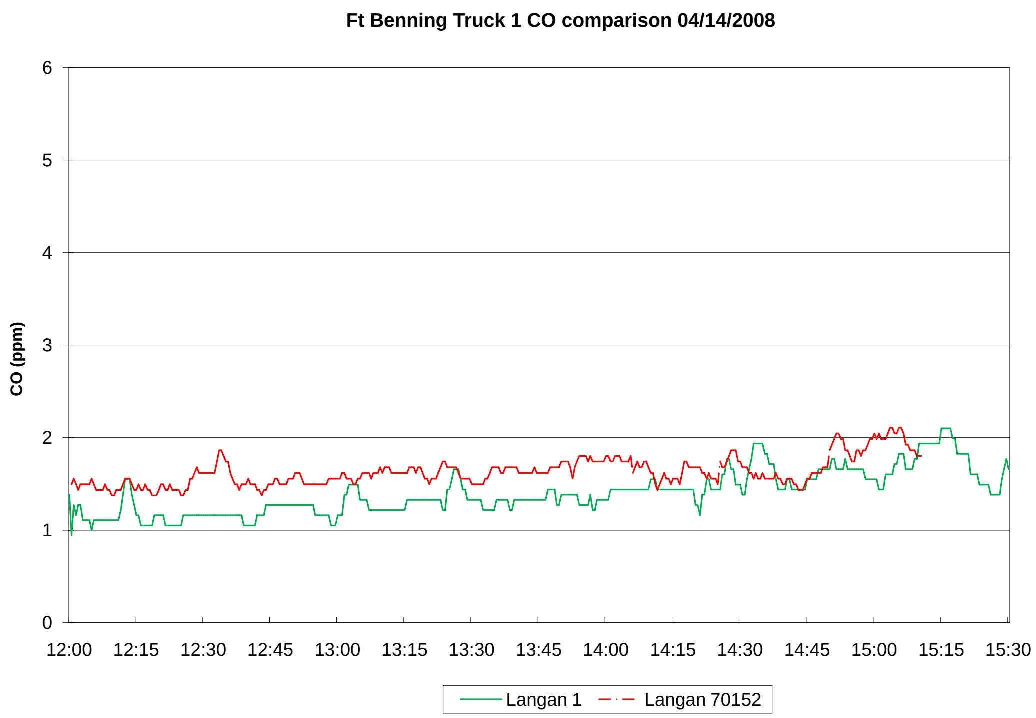

Ft Benning Truck 3 PM$_{2.5}$ comparison 04/09/2009
PM$_{2.5}$ (µg/m^3)
150
100
50
0
11:45
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:30
15:45
DustTrak 2
DustTrak 5

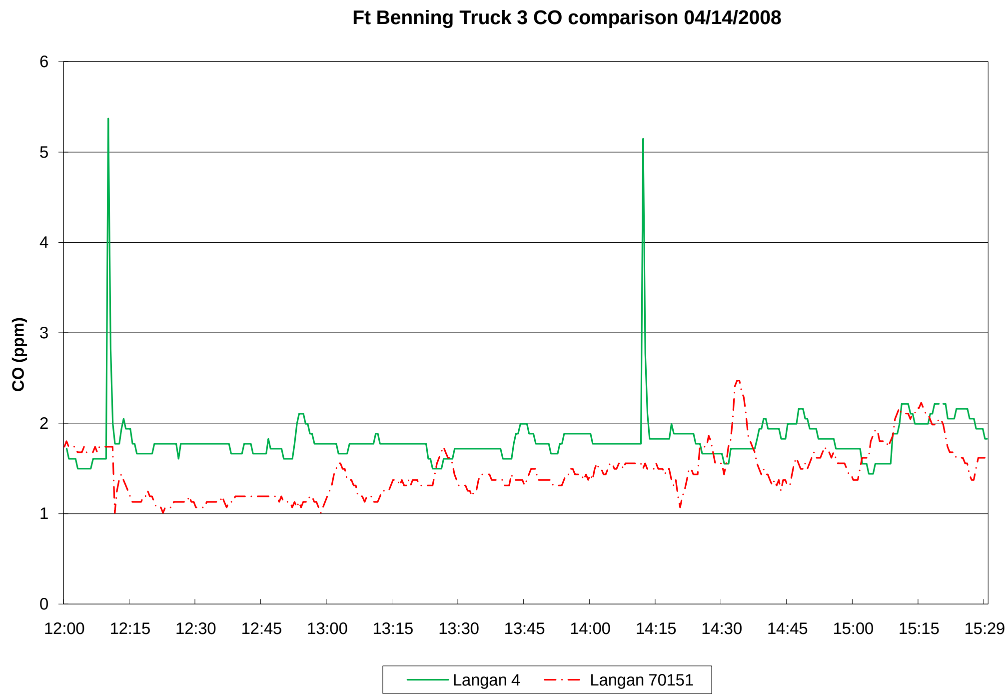
APPENDIX B: REAL-TIME CO DATA MEASURED BY CO-LOCATED AIR SAMPLERS

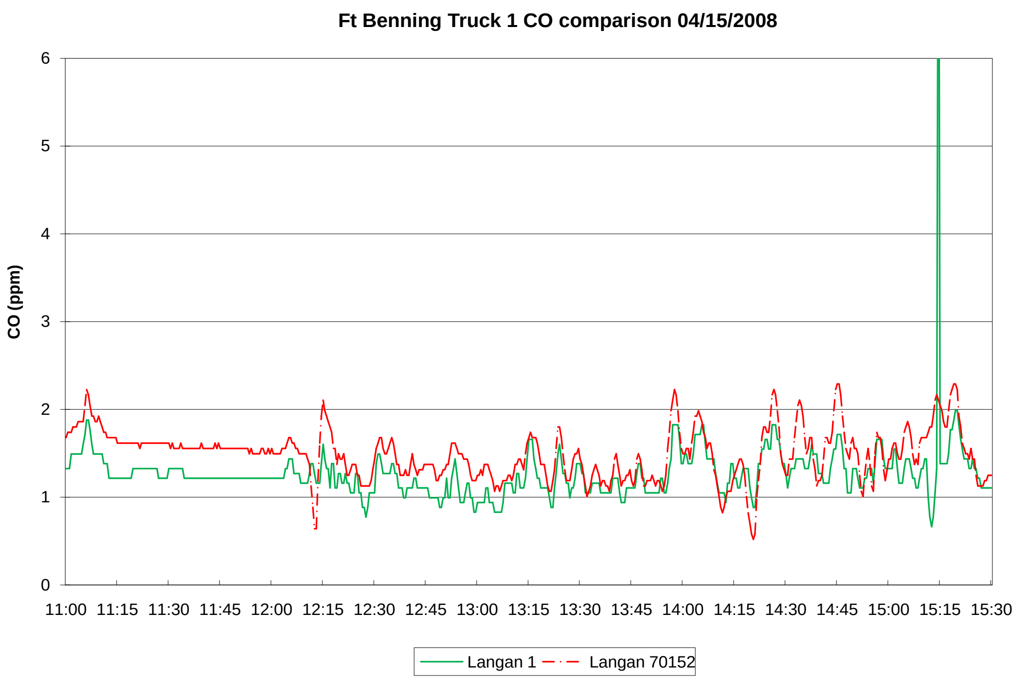


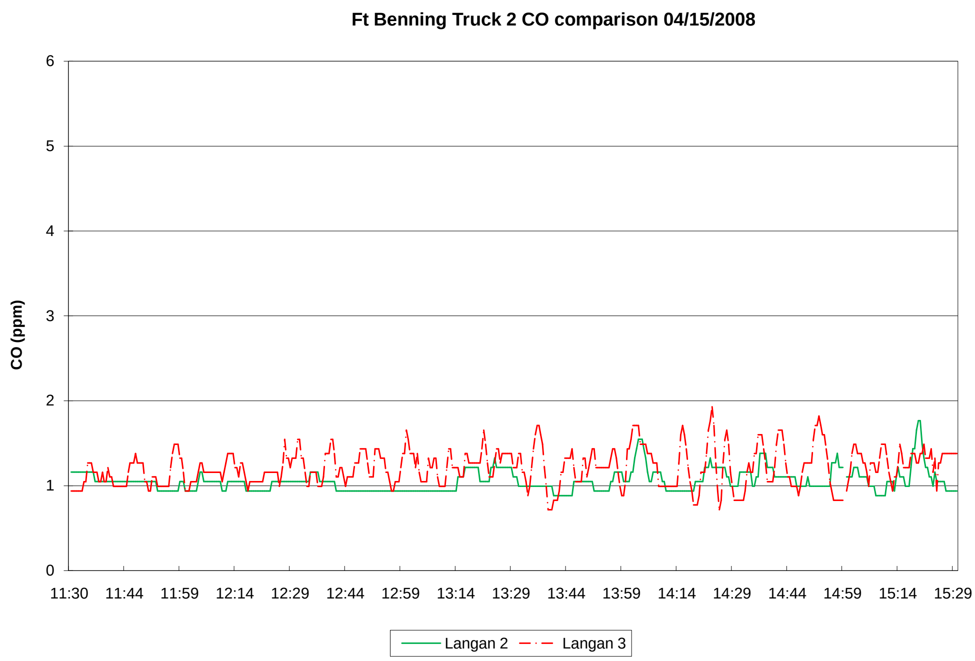


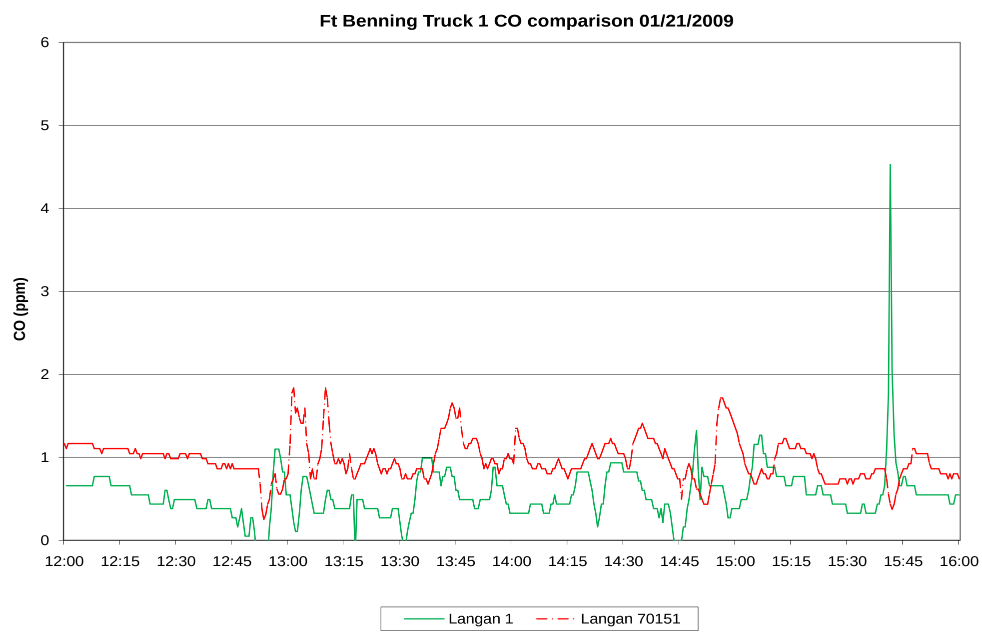

Ft Benning Truck 3 CO comparison 04/09/2008
CO (ppm)
6
5
4
3
2
1
0
12:00
12:14
12:29
12:44
12:59
13:14
13:29
13:44
13:59
14:14
14:29
14:44
14:59
15:14
15:29
15:44
Langan 4
Langan 70151

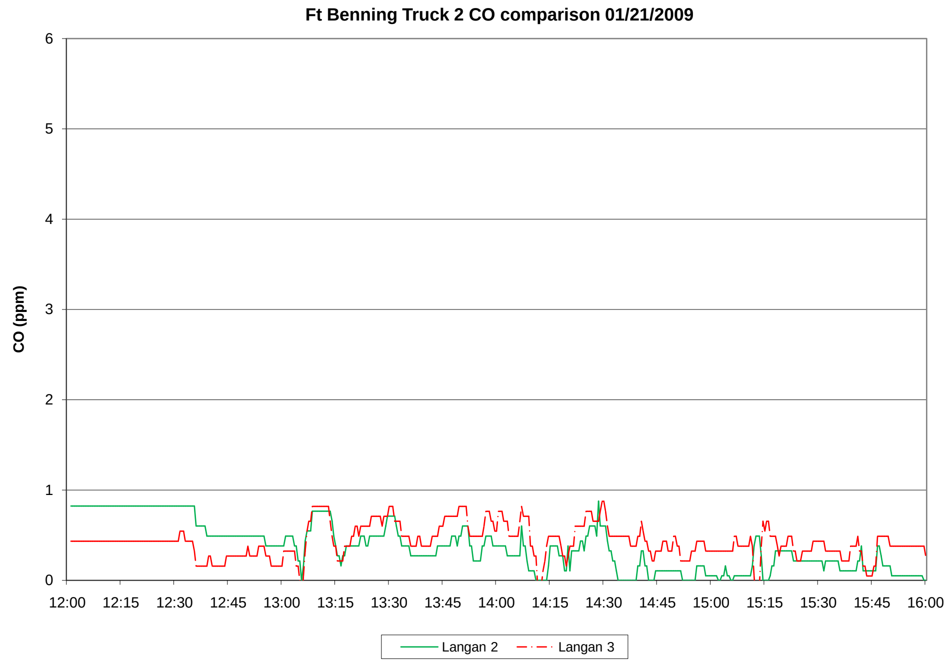

Ft Benning Truck 1 CO comparison 04/14/2008
CO (ppm)
6
5
4
3
2
1
0
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:30
Langan 1
Langan 70152


Ft Benning Truck 3 CO comparison 04/14/2008
CO (ppm)
0
1
2
3
4
5
6
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:29
Langan 4
Langan 70151

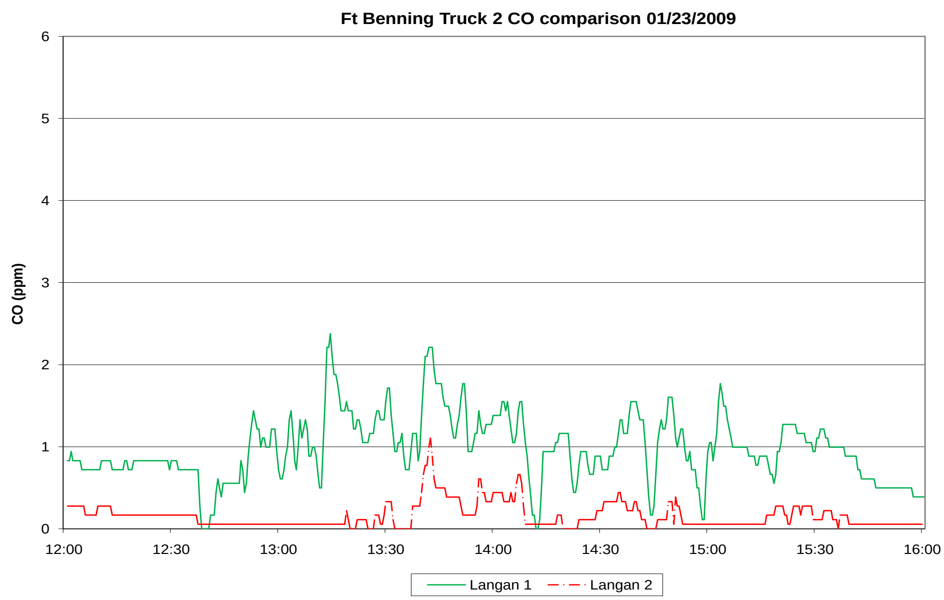

Ft Benning Truck 1 CO comparison 04/15/2008
CO (ppm)
0
1
2
3
4
5
6
11:00
11:15
11:30
11:45
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:30
Langan 1
Langan 70152


Ft Benning Truck 2 CO comparison 04/15/2008
CO (ppm)
0
1
2
3
4
5
6
11:30
11:44
11:59
12:14
12:29
12:44
12:59
13:14
13:29
13:44
13:59
14:14
14:29
14:44
14:59
15:14
15:29
Langan 2
Langan 3

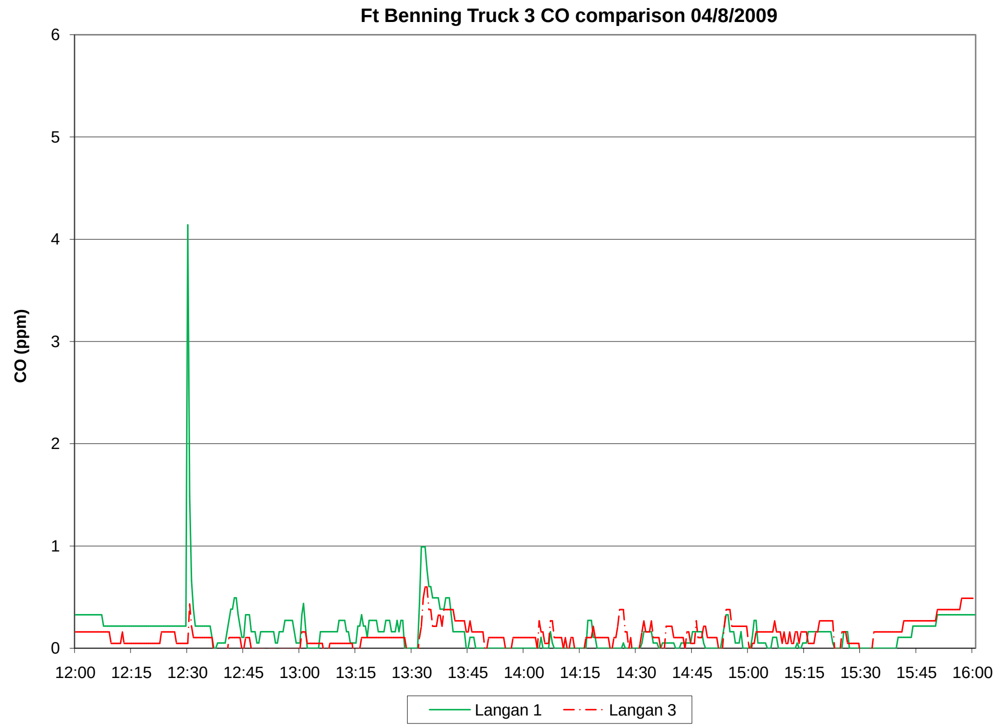

Ft Benning Truck 1 CO comparison 01/21/2009
CO (ppm)
0
1
2
3
4
5
6
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:30
15:45
16:00
Langan 1
Langan 70151

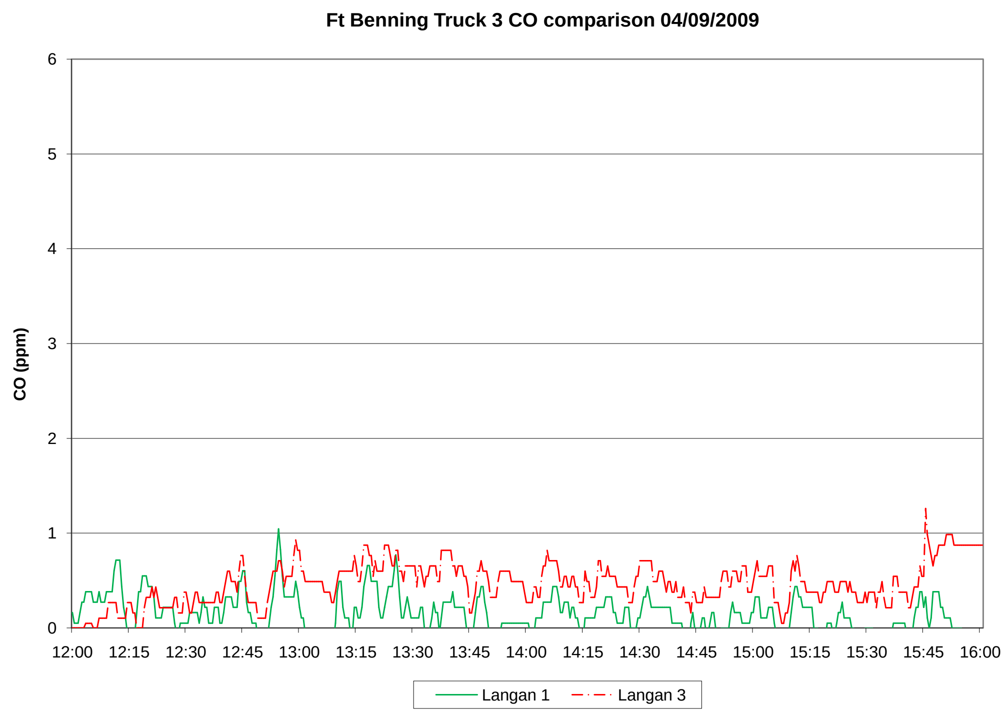


Ft Benning Truck 2 CO comparison 01/21/2009
CO (ppm)
6
5
4
3
2
1
0
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:30
15:45
16:00
Langan 2
Langan 3



Ft Benning Truck 2 CO comparison 01/23/2009
CO (ppm)
6
5
4
3
2
1
0
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
Langan 1
Langan 2


Ft Benning Truck 3 CO comparison 04/8/2009
CO (ppm)
0
1
2
3
4
5
6
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:30
15:45
16:00
Langan 1
Langan 3


Ft Benning Truck 3 CO comparison 04/09/2009
CO (ppm)
0
1
2
3
4
5
6
12:00
12:15
12:30
12:45
13:00
13:15
13:30
13:45
14:00
14:15
14:30
14:45
15:00
15:15
15:30
15:45
16:00
Langan 1
Langan 3