

FINAL REPORT

Mapping, Optimization of Controls, and Reduction of Fenceline Impacts of Fugitive Dust Emissions from DoD Roads, Trails, and Training Areas: Demonstration of Tools in Practical Applications

Dr. J.A. Gillies
Dr. V. Etyemezian
Mr. G. Nikolich
Dr. J. Mejia
Dust-Solve, LLC

December 2021

This report was prepared under contract to the Department of Defense Environmental Security Technology Certification Program (ESTCP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

REPORT DOCUMENTATION PAGE					<i>Form Approved</i> OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YYYY) 31/12/2021		2. REPORT TYPE ESTCP Final Report			3. DATES COVERED (From - To) 6/26/2017 - 12/31/2021	
4. TITLE AND SUBTITLE Mapping, Optimization of Controls, and Reduction of Fenceline Impacts of Fugitive Dust Emissions from DoD Roads, Trails, and Training Areas: Demonstration of Tools in Practical Applications					5a. CONTRACT NUMBER 17-C-0046	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Dr. J.A. Gillies Dr. V. Etyemezian Mr. G. Nikolich Dr. J. Mejia					5d. PROJECT NUMBER RC-201700	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Dust-Solve, LLC 326 Quiet Harbor Drive Henderson, NV 89052					8. PERFORMING ORGANIZATION REPORT NUMBER RC-201700	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program 4800 Mark Center Drive, Suite 16F16 Alexandria, VA 22350-3605					10. SPONSOR/MONITOR'S ACRONYM(S) ESTCP	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) RC-201700	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT Fugitive dust generated by military activity can contribute to local exceedances of the National Ambient Air Quality Standards (NAAQS) for PM10 and/or PM2.5, particulate matter (PM). Geological sources of dust can have health impacts. Fugitive dust emitted into the environment by Department of Defense testing and training activities can adversely affect military personnel in the vicinity of the emissions and impact air quality beyond the boundaries of installations. Unpaved road dust emissions due to vehicle activity is likely the largest category of activity-based fugitive dust emissions on DoD installations located in arid settings. The overall objective of this project was to demonstrate the TRAKER technology for road dust emission measurements for DoD installations. Dust-Solve, LLC using TRAKER can provide technical services to DoD installations in support of developing dust management plans.						
15. SUBJECT TERMS Fenceline Impacts, Fugitive Dust Emissions, DoD Roads, Trails, and Training Areas						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UNCLASS	18. NUMBER OF PAGES 74	19a. NAME OF RESPONSIBLE PERSON John Gillies	
a. REPORT UNCLASS	b. ABSTRACT UNCLASS	c. THIS PAGE UNCLASS			19b. TELEPHONE NUMBER (Include area code) 775-674-7035	

FINAL REPORT

Project: RC-201700

TABLE OF CONTENTS

	Page
ABSTRACT	VII
EXECUTIVE SUMMARY	ES-1
1.0 INTRODUCTION	1
1.1 BACKGROUND	1
1.2 OBJECTIVE OF THE DEMONSTRATION	2
1.3 REGULATORY DRIVERS	3
2.0 TECHNOLOGY	4
2.1 TRAKER MEASUREMENT THEORY	4
2.2 TRAKER TECHNOLOGY	5
2.3 CHRONOLOGICAL SUMMARY OF TRAKER DEVELOPMENT	6
2.4 EXPECTED APPLICATIONS	8
2.5 TECHNOLOGY DEVELOPMENT	9
2.6 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY	9
3.0 PERFORMANCE OBJECTIVES	11
3.1 ENGINEERING UPGRADES	11
3.2 PRECISION OF TRAKER MEASUREMENTS	11
3.3 ENVIRONMENTAL BIAS FOR EMISSION FACTORS	13
3.4 DUST PALLIATIVE CONTROL EFFECTIVENESS	13
3.5 INTEGRATING TRAKER DATA WITH A DISPERSION MODEL	13
4.0 SITE DESCRIPTION	14
4.1 SITE LOCATION AND HISTORY	14
4.2 SITE CHARACTERISTICS	14
5.0 TEST DESIGN	16
5.1 CONCEPTUAL EXPERIMENTAL DESIGN	16
5.2 BASELINE CHARACTERIZATION	16
5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS	17
5.4 FIELD TESTING	18
5.5 SAMPLING METHODS	19
5.6 SAMPLING RESULTS	19
5.6.1 TRAKER Measurements	19
5.6.2 Monitoring Measurements: Meteorology	24
5.6.3 Monitoring Measurements: Vehicle Fleet Characteristics	26
6.0 PERFORMANCE ASSESSMENT	31

TABLE OF CONTENTS (Continued)

	Page
6.1 PRECISION OF TRAKER MEASUREMENTS	31
6.2 ENVIRONMENTAL BIAS EFFECTS ON EMISSIONS	31
6.3 DUST PALLIATIVE CONTROL EFFECTIVENESS	34
6.4 INTEGRATING TRAKER DATA WITH A DISPERSION MODEL.....	34
6.4.1 Emission Inventory	35
6.4.2 Creating Vehicle Inventory, Emission Factor, and Temporal Profiles	36
6.4.3 Meteorological Input.....	38
6.4.4 Model Execution	39
7.0 COST ASSESSMENT	45
7.1 COST MODEL	45
7.1.1 TRAKER Daily Rate	45
7.2 SCALABILITY	45
7.3 COST DRIVERS	45
7.4 COST ANALYSIS.....	46
8.0 IMPLEMENTATION ISSUES	48
8.1 REGULATIONS FOR TRAKER USE	48
8.2 END-USER CONCERNS, RESERVATIONS, AND DECISION-MAKING FACTORS.....	48
8.3 PROCUREMENT	48
8.4 MARKET DEVELOPMENT	49
8.5 LESSON LEARNED.....	49
8.5.1 Responses to IPR Requests 2020.....	49
8.5.2 Responses to IPR Requests 2021	50
9.0 REFERENCES	51
APPENDIX A POINTS OF CONTACT.....	A-1

LIST OF FIGURES

	Page
Figure 1. Components of TRAKER	5
Figure 2. Flow Diagram of the Technology and Measurement Process.....	7
Figure 3. Current Sampling Instrumentation for TRAKER.	7
Figure 4. The Location of MCAGCC, 29 Palms in California.....	15
Figure 5. Baseline Emissions Map and Locations of Ambient and Vehicle Activity Monitoring Stations.....	17
Figure 6. Road Segments ($\approx$ 200 Meters in Length) Used to Aggregate Individual 1-second TRAKER Data.....	18
Figure 7. Relations Between Pairs of Collocated Dust Monitors in the PM ₁₀ and PM _{2.5} Sample Lines.	21
Figure 8. May 1-2, 2019, TRAKER Emission Measurements.	21
Figure 9. July 17-18, 2019, TRAKER Emission Measurements.....	22
Figure 10. November 26-27, 2019, TRAKER Emission Measurements.....	22
Figure 11. February 25, 2020, TRAKER Emission Measurements.	23
Figure 12. September 9-10, 2020, TRAKER Emission Measurements.	23
Figure 13. Wind Rose Diagram for East Meteorological Station.....	24
Figure 14. Average and Maximum Daily Wind Speeds.	25
Figure 15. Daily Minimum, Average, and Maximum Temperatures.	25
Figure 16. Rainfall, Soil Moisture at Depth (Volumetric Water Content), and Periods of TRAKER Measurement (Vertical Lines).....	26
Figure 17. The Relative Composition of Vehicles Observed at the Monitoring Stations at 29 Palms over 2 Years.....	28
Figure 18. The Percentage of Vehicle Activity as a Function of Hour of the Day (Top Panel), Day of the Week (Middle Panel), and Month of the Year (Bottom Panel).	29
Figure 19. The Vehicle Composition of Convoys Expressed as the Relative Percentage of Military and Civilian Vehicles.	30
Figure 20. Distribution of Segment Coefficients of Variation (Total = 1493).	31
Figure 21. Averaged TRAKER Emissions Measurements and Meteorological Measurements.	33
Figure 22. The Model Framework Process that Couples Emission Potential Measurements Made with TRAKER, Environmental Variables (i.e., Meteorological Data), with AERMOD.....	35
Figure 23. (a) Dispersion Model Report Output Based on AERMOD and a Synthetic Vehicle Inventory and Temporal Activity Example <i>Scenario</i>	40
Figure 24. PDF Report Function Produces Maps of PM ₁₀ Concentrations	42

LIST OF TABLES

		Page
Table 1.	Performance Objectives.	12
Table 2.	Progress Schedule for Each Phase of Testing and Relation Between the Various Operational Phases.	18
Table 3.	Total Number and Types of Data Collected.....	20
Table 4.	Types of Vehicles and Categories of Used to Characterize the Vehicle Fleet at 29 Palms.	27
Table 5.	Meters of Dust Control Application Are Required to Detect a Difference Between the Baseline Road Emission and the Dust-controlled Emission Measurement with 95% Confidence.	34
Table 6.	Vehicle Categories, TRAKER Scaling Factors, and Vehicle Represented by the Category.....	36
Table 7.	An Example Vehicle Activity Scenario Representing the Deployment of 51 Vehicles of Different Categories During Late Afternoon Hours.	36
Table 8.	Example of Vehicle Activity Period Scenarios	37
Table 9.	Cost Model	46

ACRONYMS AND ABBREVIATIONS

DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
HEMTT	Heavy Expanded Mobility Tactical Truck
HMMWV	High Mobility Multipurpose Wheeled Vehicle
LLC	Limited Liability Company
LMTV	Light Medium Tactical Vehicle
MAGTFTP	Marine Air Ground Task Force Training Program
MAGTF	Marine Air Ground Task Force
MCAGCC	Marine Corps Air Ground Combat Center
MAGTFTC	Marine Air Ground Task Force Training Command
NAAQS	National Ambient Air Quality Standards
NRCS	Natural Resources Conservation Service
OTM	Other Test Method
PM	Particulate Matter
QA	Quality Assurance
QC	Quality Control
REIR	Request for Environmental Impact Review
RH	Relative Humidity
SERDP	Strategic Environmental Research and Development Program
RHR	Regional Haze Rule
USDA	United States Department of Agriculture
US EPA	US Environmental Protection Agency
vkt	vehicle kilometer travelled

ACKNOWLEDGEMENTS

We gratefully acknowledge ESTCP's and our project manager Dr. Kurt Preston's support of this demonstration project as well as earlier support from SERDP that provided the opportunity to develop TRAKER as a research instrument and enabled its progress towards certification/commercialization. The support of Drs. Robert Holst and John Hall (both formerly of SERDP) was instrumental in developing TRAKER. We also are grateful to MCAGCC 29 Palms that served as our test site and were unfailingly helpful in supporting our efforts, in particular Mr. Eddie Valls and Mr. Mike Ellitt.

ABSTRACT

INTRODUCTION AND OBJECTIVES

Fugitive dust generated by military activity can contribute to local exceedances of the National Ambient Air Quality Standards (NAAQS) for PM₁₀ and/or PM_{2.5}, particulate matter (PM). Geological sources of dust can have health impacts. Fugitive dust emitted into the environment by Department of Defense testing and training activities can adversely affect military personnel in the vicinity of the emissions and impact air quality beyond the boundaries of installations. Unpaved road dust emissions due to vehicle activity is likely the largest category of activity-based fugitive dust emissions on DoD installations located in arid settings. The overall objective of this project was to demonstrate the TRAKER technology for road dust emission measurements for DoD installations. Dust-Solve, LLC using TRAKER can provide technical services to DoD installations in support of developing dust management plans.

TECHNOLOGY DESCRIPTION

TRAKER measures road dust emissivity. The emissivity measurements can be scaled to represent other vehicles based on their weight and travel speed. During measurements a pump draws air through two inlet lines that sample PM in the wake of TRAKER. A portion of this flow is delivered to internal inlet lines within the plenum that are connected to photometers, which are equipped with either PM₁₀ or PM_{2.5} inlets. The concentration measurements are geo-referenced by Global Positioning System (GPS) to a location and travel speed at an acquisition rate of 1 Hz. Additional instrumentation is used to ascertain that ambient wind conditions are acceptable for the measurement to meet minimum quality criteria. Emission data are used as input to a dispersion model (AERMOD) to estimate particulate matter (PM) concentrations at specified receptors for a given testing and training vehicle activity scenario.

PERFORMANCE AND COST ASSESSMENT

The performance target for measurement precision was 20%, which was achieved. More than 87% of road segments measured during the five field measurement periods had a coefficients of variation (CoV) lower than 20%, 95% of segments had a CoV lower than 30%, and 98.5% of segments had a CoV lower than 50%. TRAKER and environmental measurements revealed changes in road emissivity due to seasonal and meteorological influences. TRAKER can provide information to characterize and quantify the emission potential of a DoD facility's road network, vehicle fleet characteristics and activity levels, aid in developing PM₁₀ and PM_{2.5} inventories for permitting, and provide an assessment of the potential impacts of different testing and training activity scenarios on regional air quality. Cost components scale with the requested level of effort and the degree to which the installation takes on the tasks. Basic costs are: Initial Planning/Site Visit, \$25K; TRAKER Daily Rate, \$5K. Dust-Solve, LLC estimates that a typical implementation would be approximately \$260-\$420K, depending on complexity. An evaluation of dust palliative effectiveness would require using the TRAKER for multiple days and the level of effort will depend on the number of palliatives to be tested. The incremental cost for this ranges from \$20 - \$80K in most instances.

IMPLEMENTATION ISSUES

There are no Federal or State regulations that restrict operation of TRAKER other than the requirement to obey roadway rules and safety standards. Operating TRAKER on military installations may require compliance with an Environmental Impact Review, although the instrument has no impacts beyond any other pickup truck driving on the same road network.

PUBLICATIONS

None

EXECUTIVE SUMMARY

INTRODUCTION

This demonstration project to certify TRAKER and associated modeling capabilities to aid installations in quantifying the emissions of dust created by vehicle movement on unpaved roads during testing and training activities, and the potential impact of those emissions on air quality downwind of the source areas was undertaken at Marine Corps Air Ground Combat Center (MCAGCC)/Marine Air Ground Task Force Training Command (MAGTFTC), Twentynine Palms, CA.

Fugitive dust generated by military activity can contribute to local exceedances of the limits allowed by the National Ambient Air Quality Standards (NAAQS) for PM₁₀ and PM_{2.5}, particulate matter (PM) with aerodynamic diameters $\leq 10 \mu\text{m}$ and $\leq 2.5 \mu\text{m}$, respectively. In addition, several Department of Defense (DoD) facilities are located near Class I Areas where views of landscapes are protected through visibility standards imposed by the Regional Haze Rule (RHR). Recognizing the need to curb dust emissions both for compliance with environmental regulations, lower the risk to of exposure to personnel (military and civilian), families living within facilities, and for maintaining good relations with nearby civilian communities, dust control programs can be developed to meet standards for ambient PM or standards for plume opacity due to dust-raising training and testing activities and general base operations.

Recent research suggests that mineral dust can be a cause of health impacts. Therefore, although fugitive dust emissions have been targeted largely to ensure compliance with metrics imposed by external entities, reduction of service personnel exposure to fugitive dust where practicable is itself a desirable end goal.

One contributor to fugitive dust emissions that is known to be large (likely the largest activity-based source) is the dust suspended by the travel of wheeled and tracked vehicles on unpaved roads and paths on DoD facilities. Currently, base-specific knowledge of PM₁₀ and PM_{2.5} emissions is limited and generally does not include accurate estimates of annual contributions, information on how emissions change through time and over space and verified data on the effectiveness and duration of dust controls applied to travel surfaces. Without readily available means to acquire information needed to accurately evaluate the strength of fugitive dust sources and environmental impacts associated with those emissions, DoD installations cannot develop efficient and effective management strategies.

Fugitive dust in the environment generated by DoD testing and training activities at levels exceeding air quality standards (NAAQS and RHR) beyond the boundaries of installations has the potential to impact such activities by curtailing or halting them until favorable conditions are met. In addition, the opportunity to decrease exposure of DoD and civilian personnel to dust is a laudable goal that should be considered as part of a dust-limiting management plan for installations with high-levels of vehicle activity on their unpaved road networks. Reducing dust levels results in a lower probability of adverse health effects from exposure to this State and Federally regulated air pollutant.

The TRAKER[®] system is a vehicle-based road dust emissions measurement system. TRAKER is ideally suited for DoD application at multiple, geographically distant facilities due to its portability and its ease of operation. In addition, the method by which TRAKER quantifies particulate matter emissions is designated by the US EPA as Other Test Method (OTM) 34 and was designated as such in 2014.

The overall objective of the project was to demonstrate the practical utility of the TRAKER technology for road dust emission measurements for DoD installations where fugitive dust is a pollutant of concern for regulators, the public, or installation managers. PM dust emissions at installations in arid areas are generally dominated by tracked and wheeled vehicle travel on unpaved roads and trails. The overall objective was enhanced by combining the emission factor data acquisition capabilities of TRAKER with a dispersion modeling tool (AERMOD) to demonstrate how these data and model results can be used to identify variation in source areas that contribute to exceedances of air quality PM standards, cause public relations conflicts with surrounding communities, and impact air quality in residential portions of military facilities.

TECHNOLOGY DESCRIPTION

TRAKER was designed to facilitate application at multiple, geographically distant facilities. The main measurement apparatus is now configured to use any standard sized pickup truck as the test vehicle (Fig. 1). The combination of the truck, instrument pallet, baffle, data collection system and visualization electronics (laptop in cabin) constitutes the measurement platform. A flow diagram of the technology and measurement process is shown in Fig. 2. During measurements a pump draws air through two inlet lines that sample PM in the wake of TRAKER. The primary inlet line is approximately in the center of and extends 50 cm (20") beyond the wake baffle. The secondary inlet line extends 50 cm (20") beyond the wake baffle but offset from the center by 20 cm (8"). During operation both inlet lines are set to draw air at 16.7 liters per minute (lpm) through inlets that are 2.5 cm (1") in diameter. Each inlet line is connected to an expansion plenum that slows the flow to 0.066 m s^{-1} . A portion of this flow is delivered to internal inlet lines within the plenum that are connected to photometers, which are equipped with either PM₁₀ or PM_{2.5} inlets. There are a total of four photometers in use (two for PM₁₀ and two for PM_{2.5}) that provide a measure of the concentration of PM dust (mg m^{-3}) emitted. The concentration measurements (adjusted in time to account for travel within inlet lines) are geo-referenced by Global Positioning System (GPS) to a location and travel speed at an acquisition rate of 1 Hz. Additional instrumentation is used to ascertain that ambient wind conditions are acceptable for the measurement to meet minimum quality criteria. Pressure sensors upstream and downstream of the filter media provide indicators of leaks or overloaded filter media.

The measured concentrations are converted to grams (g) of PM produced per vehicle kilometer travelled (vkt) by application of the calibration relationship. However, this information is used to calculate total emissions for any combination of vehicles and travel speeds using the speed and mass relationships previously developed for wheeled and tracked vehicles.

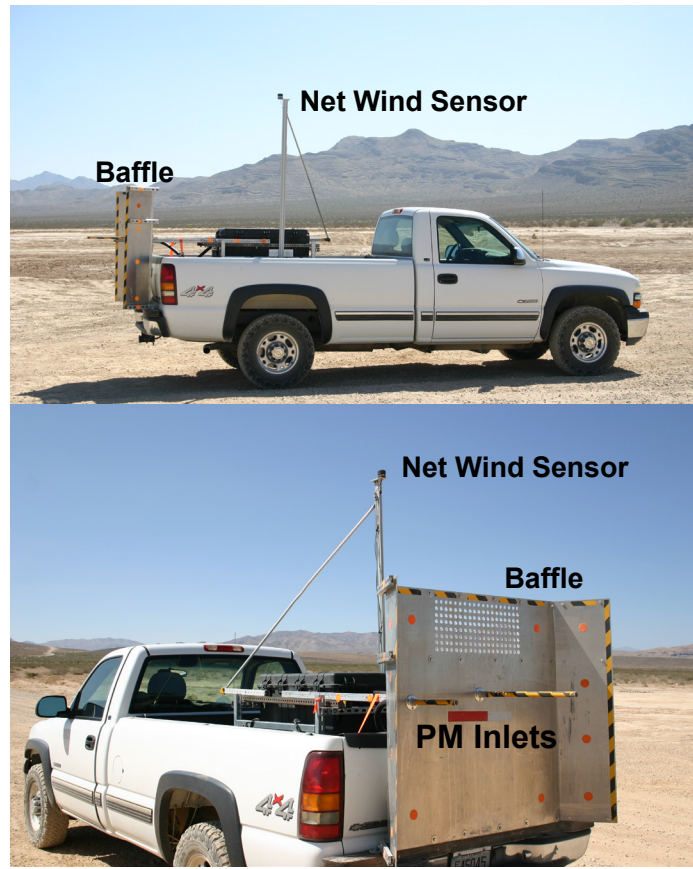


Figure 1. Components of TRAKER Include Instrument Suite in Palletized Enclosure, Rear Baffle with Inlets, and Electronic Data Collection and Visualization Tablet (Not Shown Here).

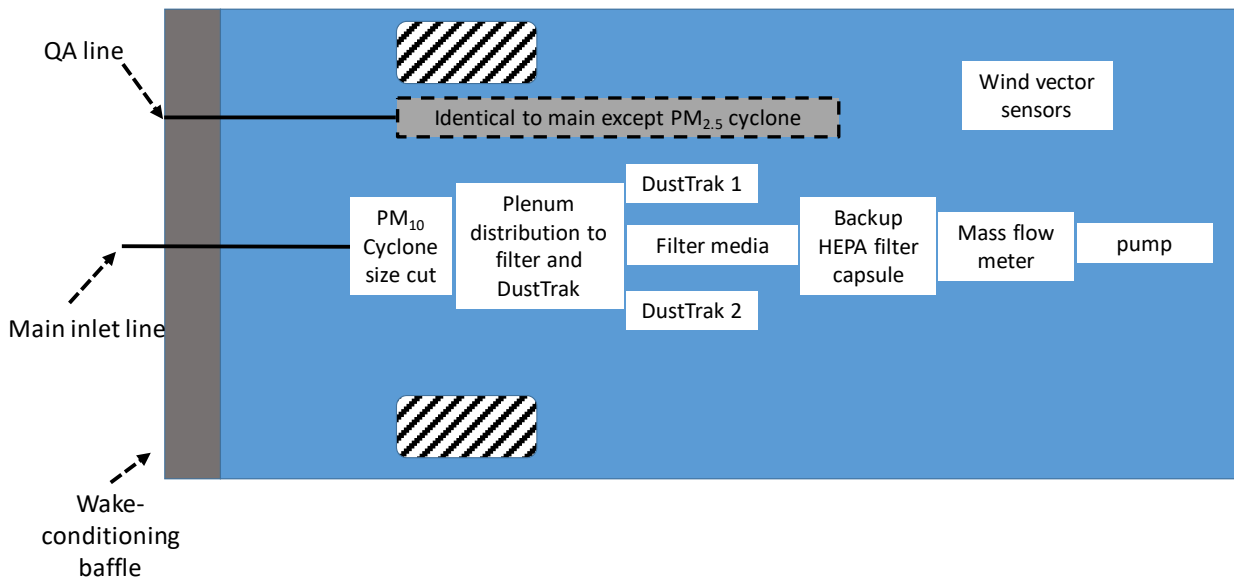


Figure 2. Flow Diagram of the Technology and Measurement Process.

PERFORMANCE ASSESSMENT

Precision of TRAKER measurements was quantified by examining repeated measurements over the same road segment during the same measurement campaign so that seasonal variations and spatial variation do not impact the assessment of measurement repeatability. Where at least two valid measurements (each consisting of a minimum of 10, one-second measurements) were available, a Coefficient of Variation (CoV) was estimated as the ratio of the standard deviation of the segment measurements to the average of the segment measurements. More than 87% of road segments measured during the five field measurement periods had a CoV lower than 20%, 95% of segments had a CoV lower than 30%, and 98.5% of segments had a CoV lower than 50%.

TRAKER data provided clear indication that emissions potential of unpaved road dust at 29 Palms are significantly impacted by seasonal scale environmental changes. The average TRAKER emissions measurement across all road segments tested at 29 Palms varied by measurement campaign. The data suggest that in this arid region of the southwest US, there is a clear seasonal signal in the emissions. Generally, emissions are highest in the warmer months and lower in the cooler months. We hypothesize that the tendency towards higher emissions potential in summer than winter is due to the way in which solar radiation dries the top few centimeters of soil in the summer compared to the winter. Road dust emissions are modulated by solar radiation intensity and its effect on the relative humidity in the near surface pores. The impact of environmental factors on road dust emissions is likely to be due to a combination of seasonal changes and discrete precipitation events.

As part of this project, we coupled TRAKER-derived emission data with the US EPA sanctioned dispersion model American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD). AERMOD is EPA's preferred near-field dispersion modeling system, which uses a steady-state plume formulation that incorporates complex terrain and air dispersion based on planetary boundary layer turbulence structure and scaling concepts. We adapted this model to incorporate novel emission factors (i.e., $\text{kg PM}_{10} \text{ vkt}^{-1}$) based on measurements from TRAKER. Together, the model framework presented constitutes a tool for realistic predictions of PM_{10} or $\text{PM}_{2.5}$ concentrations created by observed vehicle activity patterns, with options to simulate user-defined scenarios of vehicle activity that represent known testing and training vehicle activity patterns or for testing hypothetical patterns. This flexibility allows the modeling system to be used as a tool for planning testing and training vehicle movement and evaluate the effects of the vehicle-generated dust emissions on air quality at the source and downwind at receptors of interest (e.g., nearby residential areas or points of specific interest [e.g., schools or hospitals]).

Vehicle inventories that represent, for example, a testing/training activity, the associated emission factors, and the temporal profile of activity (i.e., which vehicles are moving during which hour of the day) are developed within an easy-to-interact with Excel file format. The defined vehicle activity scenario is provided to the dispersion model using the Python script developed as part of this project. The model utilizes surface and upper-air level data preprocessed at hourly time increments, which is available from multiple sources and will be dependent on the data available for any individual installation.

Available historic meteorological data are typically used for air quality assessments after the event of interest has occurred (diagnostic mode), for example after a testing and training activity has taken place. The system developed as part of this demonstration project can use forecast (real-time) data for prognostic operation-planning purposes (i.e., future testing and training activities under forecast meteorological conditions). Our system provides options to automatically download North American Mesoscale Forecast System (NAM) or Global Forecasting System products. This forecast option can be used to simulate vehicle activity scenarios for real-time estimates of impacts on PM₁₀ concentrations anywhere in the domain under the influence of the forecast weather conditions.

The modeling system performs basic post-processing of the simulated output and prepares an easy-to-read report summarizing the input parameters and model results for, for example a 24-hour period (Fig. 3) or in one-hour increments (Fig. 4).

COST ASSESSMENT

The cost model developed is based on the experience of executing the demonstration plan objectives at the 29 Palms test site. The tasks completed and the expenditures to complete those tasks are those that would be expected to occur when an installation contracts with Dust-Solve, LLC to provide them with information to characterize and quantify the emission potential of their road network, their vehicle fleet characteristics and activity levels, aid in developing their PM₁₀ or PM_{2.5} inventories for permitting, and provide an assessment of the potential impacts of different testing and training activity scenarios on regional air quality.

The current daily rate for TRAKER is based on an estimated (annual) labor cost (for the principles and a technician=\$4800), operating expenses include instrument calibration (\$3,600 annually), vehicle maintenance (\$1000), and supplies (\$4,000). No depreciation is considered and the usage days per year is set currently at six. There is an indirect cost rate added of 65% for Federal Contracts and 75% for private as the TRAKER unit is leased to Dust-Solve, LLC under a licensing agreement with the Desert Research Institute, Las Vegas, NV. The daily rate in 2021 is \$5,000 (Federal) and \$5,303 (private).

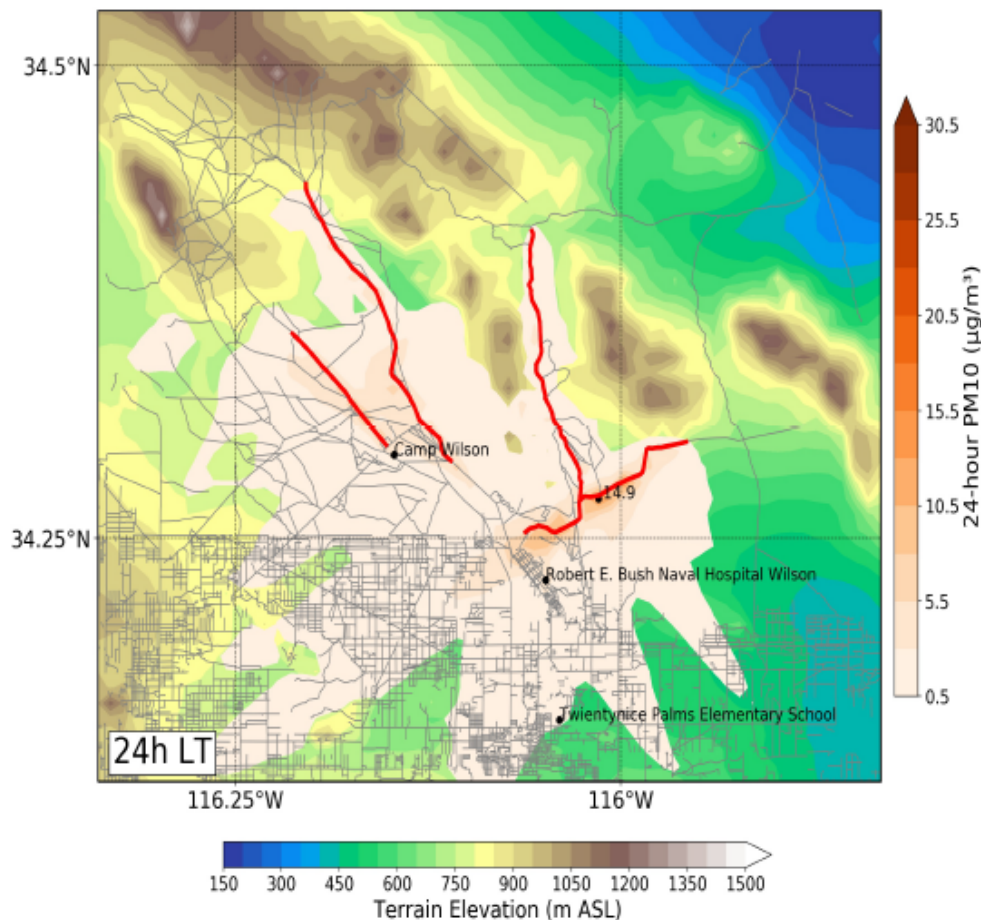
Cost drivers for using TRAKER and the associated modeling system will be dependent on the level of effort proposed by an installation to achieve its management objectives that deal with dust emission created by the activities on the base, and the amount of that effort that Dust-Solve, LLC will be responsible for versus the effort the installation chooses to be responsible for. The basic cost drivers are presented in Table 1.

The cost structure presented in Table 1 is scalable as the client can choose to have personnel become capable in all or part of the Cost Elements listed. At a minimum, the cost would be the Initial Planning/Training/Site Visit (\$25,000) and the daily usage rate (\$5,000/day) for the rental of the TRAKER instrument pallet (plus shipping) for the number of days rented to accomplish the task required. To reach the level of proficiency required by on-site personnel to collect data, QA/QC the data, and carry out analysis components (e.g., emission inventory and being able to run the TRAKER/AERMOD model) an in-depth training session would be recommended with an associated cost of \$35,000.

In general Dust-Solve, LLC estimates that to carry out a level of effort similar to what was accomplished at 29 Palms would be approximately \$260-\$420k (based on Table 1).

Region:	29 Palms	Simulation Type:	NormalObs	Road Segment:	All	Period Start:	2019-07-26H00
Date Report:	09/26/2021	Hour Report:	12:47:39	Performed by:	J. Mejia	Period End:	2019-07-27H00

(I) SURFACE 24-HR PM10 VALUES FOR SOURCE GROUP:



Maximum 1-hour PM10 ($\mu\text{g}/\text{m}^3$): 1.0; Location: 34.388 °S, 116.165 °W

- Terrain Elevations from the NASA's Shuttle Radar Topography Mission (SRTM) 250 m resampled to 1 km grid size

- Primary and secondary roads, highways, streets from the California Highway ArcGIS database.

Figure 3. Dispersion Model Report Output Based on AERMOD and a Synthetic Vehicle Inventory and Temporal Activity Example Scenario.

Report is produced in PDF format and contains statistics and graphics developed to facilitate planning and decision making. This example shows results integrated over 24 hours for PM₁₀ concentrations across the domain.

(IV) HOURLY RECEPTOR MAPS:

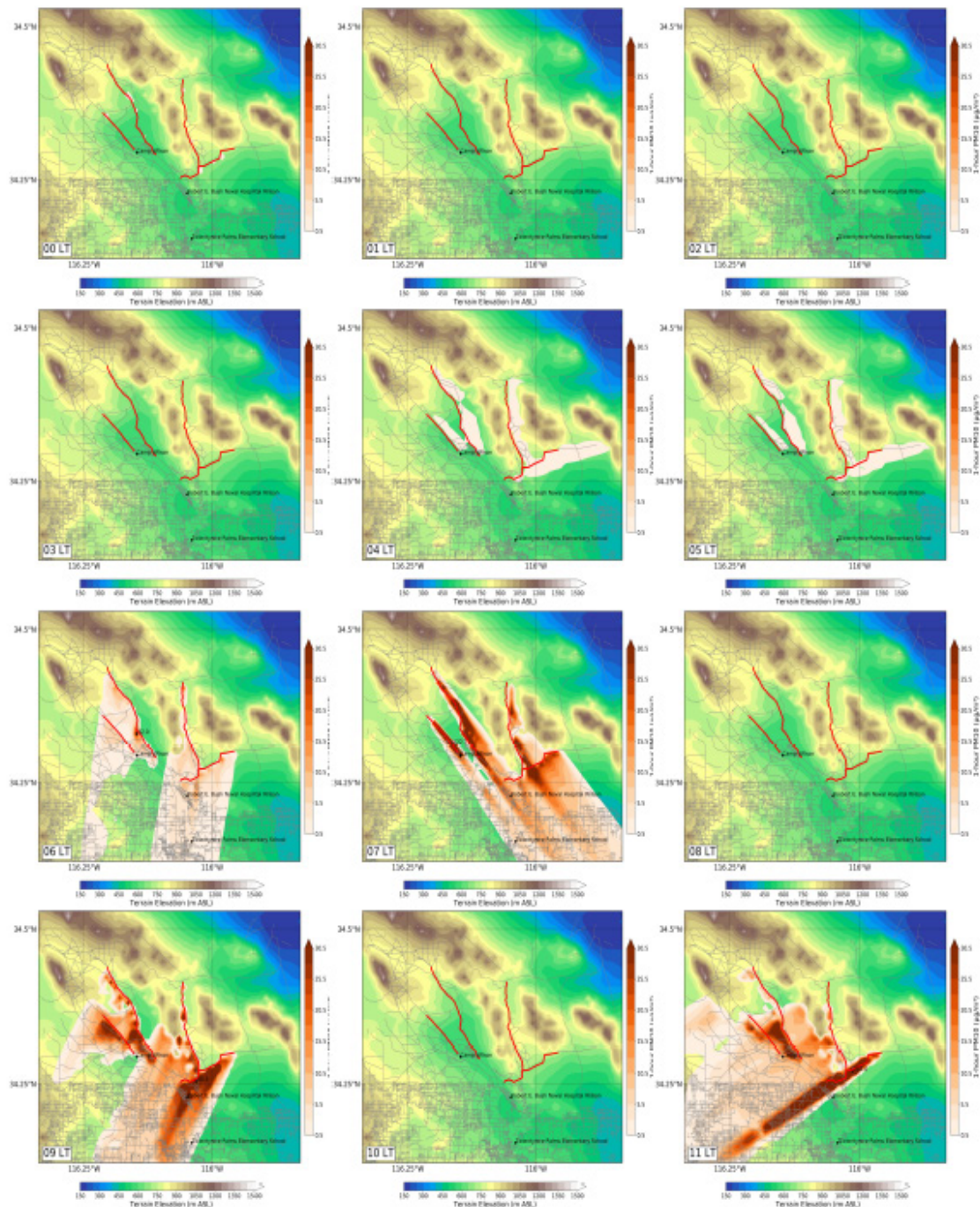


Figure 4. PDF Report Function Produces Maps of PM₁₀ Concentrations for 12 Hours of a Day that Visualize Effects of the Developed *Scenario* Across Space, through Time, and for Receptors of Interest.

Table 1. Cost Model

Cost Element	Cost
Initial Planning/Training/Site Visit	\$25K
Daily Usage Rate (DUR)	\$5K
Meteorological/PM/Vehicle Monitoring (2 years)	\$50K
Vehicle Classification Inventory	\$30-\$50K
Emission Inventory (PM emitted by installation)	\$25K
Model Set Up (estimating effects of emissions)	\$40-\$50K
Modeling runs for requested scenarios	\$20-\$40K
Evaluating dust control effectiveness	\$20-\$80K
Annual support (following initial year) (e.g., update model inputs and runs)	\$15-\$20K
In Depth Training	\$35K

An evaluation of dust palliative effectiveness would require using the TRAKER for multiple days and the level of effort will depend on the number of palliatives to be tested. The cost range is \$20,000 to \$80,000.

IMPLEMENTATION ISSUES

There are no Federal or State regulations that restrict operation of TRAKER in a civilian environment with the exception that when used on public roads the vehicle needs to be operated as guided by traffic regulations that apply to the roads being measured.

Operating TRAKER on military installations may require compliance with an Environmental Impact Review as was necessary for Dust-Solve, LLC to undertake the TRAKER measurements at MCAGCC 29 Palms. The decision in support of allowing measurement at an installation may involve satisfying the National Environmental Policy Act review requirements and qualified as a categorical exclusion (CATEX) in compliance with 32 Code of Federal Regulations Part 775.6(f)(18). CATEX 18 applies to "studies, data, and information gathering that involve no permanent physical change to the environment (e.g., topographic surveys, wetlands mapping, surveys for evaluating environmental damage, and engineering efforts to support environmental analyses)."

1.0 INTRODUCTION

1.1 BACKGROUND

Fugitive dust generated by military activity can contribute to local exceedances of the limits allowed by the National Ambient Air Quality Standards (NAAQS) for PM₁₀ and PM_{2.5}, particulate matter (PM) with aerodynamic diameters $\leq 10 \mu\text{m}$ and $\leq 2.5 \mu\text{m}$, respectively. In addition, several Department of Defense (DoD) facilities are located near Class I Areas where views of landscapes are protected through visibility standards imposed by the Regional Haze Rule (RHR). Recognizing the need to curb dust emissions both for compliance with environmental regulations, lower the risk to of exposure to personnel (military and civilian), families living within facilities, and for maintaining good relations with nearby civilian communities, dust control programs can be developed to meet standards for ambient PM or standards for plume opacity due to dust-raising training and testing activities and general base operations.

Recent research suggests that dust, though derived from naturally occurring geologic material, can be a cause of health impacts, on par with or surpassing PM from other sources such as combustion processes. This has been observed with in-vitro studies of inflammatory response (Halatek et al., 2011; Happo et al., 2010) as well as epigenetic (Miousse et al., 2015) alterations as well as in epidemiological (Rodopoulou et al., 2014) approaches. Therefore, although fugitive dust emissions have been targeted largely to ensure compliance with metrics imposed by external entities, reduction of service personnel exposure to fugitive dust where practicable is itself a desirable end goal.

One contributor to fugitive dust emissions that is known to be large (likely the largest activity-based source) is the dust suspended by the travel of wheeled and tracked vehicles on unpaved roads and paths on DoD facilities (Gillies et al., 2005, 2007, 2010; Kuhns et al., 2010; Moosmüller et al., 2005). Currently, base-specific knowledge of PM₁₀ and PM_{2.5} emissions is limited and generally does not include accurate estimates of annual contributions, information on how emissions change through time and over space and verified data on the effectiveness and duration of dust controls applied to travel surfaces. Without readily available means to acquire information needed to accurately evaluate the strength of fugitive dust sources and environmental impacts associated with those emissions, DoD installations cannot develop efficient and effective management strategies.

Fugitive dust in the environment generated by DoD testing and training activities at levels exceeding air quality standards (NAAQS and RHR) beyond the boundaries of installations has the potential to impact such activities by curtailing or halting them until favorable conditions are met. It is difficult to quantify what these restrictions could entail in terms of dollar equivalence, but the argument could be made based on the amounts of resources in play for large testing or training activities that millions of dollars are at stake. In addition, the opportunity to decrease exposure of DoD and civilian personnel to dust is a laudable goal that should be considered as part of a dust-limiting management plan for installations with high-levels of vehicle activity on their unpaved road networks. Reducing dust levels results in a lower probability of adverse health effects from exposure to this State and Federally regulated air pollutant.

The TRAKER[®] system for vehicle-based road dust emissions measurement was developed at the DRI (Etyemezian et al., 2003a, 2003b, 2006; Kavouras et al., 2016; Kuhns et al., 2001, 2003; 2005; Zhu et al., 2009, 2012, 2014). TRAKER in its current configuration was re-designed as part of this demonstration project to be ideally suited for DoD application at multiple, geographically distant facilities due to its portability and its ease of operation. In addition, the method by which TRAKER quantifies particulate matter emissions is designated by the US EPA as Other Test Method (OTM) 34 (OTM-34, <https://www.epa.gov/sites/default/files/2020-08/documents/otm34.pdf>) and was designated as such in 2014.

The use of TRAKER operating under OTM 34 criteria to quantify fugitive dust emissions from roadways and tracks represents a substantial improvement over previously available methods such as the extremely labor-intensive “Silt Loading” method prescribed in the US EPA AP-42 Guidance Document (4th Edition) (1993), which also suffers from very limited validation. That method infers an emission factor for a road surface based only on the measurement of the amount of silt sized material (4-62.5 μm geometric diameter) that is removed from a known surface area of a road (by sweeping or vacuuming). It fails to incorporate the role of vehicle speed, which was demonstrated by Kuhns et al. (2001), Etyemezian et al. (2003a), and Gillies et al. (2005) to be a first order effect on emission strength. Additionally, Gillies et al. (2005, 2015) and Kuhns et al. (2010) demonstrated that vehicle weight is also an important variable affecting the magnitude of the emissions.

With support from the Environmental Security Technology Certification Program (ESTCP), Dust-Solve, LLC in partnership with the Desert Research Institute (DRI) matured this technology and its associated software analysis tools for evaluating PM impacts at downwind locations. This demonstration project resulted in the improvement of TRAKER operability engineering- and operation-wise, which enabled its transition from a research measurement platform to one that can provide technical services to DoD installations in support of developing effective dust management plans to mitigate impacts related to operations and to human health.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of the project was to demonstrate the practical utility of the TRAKER technology for road dust emission measurements for DoD installations where fugitive dust is a pollutant of concern for regulators, the public, or installation managers. Prior work funded by Strategic Environmental Research and Development Program (SERDP) indicated that PM dust emissions at installations in arid area are generally dominated by tracked and wheeled vehicle travel on unpaved roads and trails. As part of this demonstration project facility-specific TRAKER dust emission data were collected at Marine Corps Air Ground Combat Center (MCAGCC)/ Marine Air Ground Task Force Training Command (MAGTFT), Twentynine Palms, CA.

The overall objective was enhanced by combining the emission factor data acquisition capabilities of TRAKER with a dispersion modeling tool (AERMOD) to demonstrate how these data and model results can be used to identify variation in source areas that contribute to exceedances of air quality PM standards, cause public relations conflicts with surrounding communities, and impact air quality in residential portions of military facilities.

Specific demonstration efforts will include quantifying measurement repeatability for unpaved roads, identifying the impact of temporally variable environmental factors (such as moisture, temperature, etc.) on measurement results, and using the platform to quantify efficacy of surface treatments that are in wide use at DoD facilities. The platform and the data collection practices create a standardized approach to allow for consistent use across all DoD facilities with fugitive dust concerns. Instructional documents and materials have been generated for technology transfer as well as the establishment of the capacity for Dust-Solve, LLC, to offer these services on a contractual basis to DoD installations.

1.3 REGULATORY DRIVERS

The principal federal regulatory driver is the Clean Air Act (amended in 1990), in which Title I effectively specifies that metropolitan planning areas that do not meet NAAQS are to be considered in non-attainment and are required to submit plans to demonstrate a path for reasonable progress towards attainment of the standards in question. Primary (based on human health effects in contrast to “secondary” which are based on welfare effects) NAAQS standards are set for six different air pollutants, several of which apply to PM. The 24-hour standard for PM₁₀, which is not to be exceeded more than 3 times in three years is 150 $\mu\text{g m}^{-3}$; the 24-hour standard for the 98th percentile average PM_{2.5} concentration averaged over a three-year period is 35 $\mu\text{g m}^{-3}$; an annual mean (3-year average) standard of 12 $\mu\text{g m}^{-3}$ applies to PM_{2.5}. In addition to these Federally-regulated standards for PM, individual States have set their own through State legislative processes. For example, the State of California sets a 24-hour mean standard of 50 $\mu\text{g m}^{-3}$ and an annual average of 20 $\mu\text{g m}^{-3}$ for PM₁₀. California has no set standard for 24-hour mean PM_{2.5} concentration and adopts the US EPA’s value of an annual mean value of 12 $\mu\text{g m}^{-3}$. In arid regions, fugitive dust is most likely to contribute to the violation of the PM₁₀ standard but can also be a factor that contributes significantly to the violation of the annual PM_{2.5} standard in regions where significant sources of PM_{2.5} pollution are present from either motor vehicle activity, industrial processes, or natural emissions.

The RHR sets standards for visual impairment in Class I areas (156) of the US, which are principally composed of National Parks, National Forests, and other protected areas. The RHR requires that visibility in Class I areas continually improve towards background levels over a prescribed period of time. The responsibility for demonstrating compliance with the RHR ultimately rests with States, which must develop implementation plans. Fugitive dust from a variety of sources is a major contributor to haze in numerous class I Areas across the western and southwestern United States (e.g., Kavouras et al., 2009).

2.0 TECHNOLOGY

2.1 TRAKER MEASUREMENT THEORY

When wheeled or tracked vehicles travel on a road, the vehicle tires or tracks interact with the road surface through frictional and aerodynamic forces. These interactions result in the emission of PM from the road surface through processes of mechanical and aerodynamic suspension and, to a lesser degree, abrasion of the road materials. On unpaved roads or tracks, vehicle tires/tracks interact directly with loose, erodible soil aggregates and particles.

Following suspension of PM, the PM plume behind each source disperses with distance from the tires (or tracks) and in the wake of the vehicle. The TRAKER measurement platform combined with the OTM 34 method is based on the principle that a vehicle that quantifies only the increase in concentration of PM above ambient background at a known travel speed and a fixed distance from the vehicle tires can provide repeatable measurements and be reliably calibrated (scaled) to an external standard for measurement of road dust PM emissions. The incremental increase in PM concentration due to road dust emission is quantified by subtracting the background PM concentration from the PM concentration at a location that is directly influenced by the road dust plume. The background concentration can be measured at a location that is not influenced by the test vehicle's own road dust plume (e.g., hood of the test vehicle).

The four principal assumptions that are invoked in the application of this measurement method are: 1) that for a given test vehicle, under ambient meteorological conditions that fall within prescribed guidelines, the degree of dispersion (dilution) that occurs with distance from the vehicle's mechanical conveyance method (i.e., tires or tracks) is controlled primarily by the speed of the vehicle; 2) that within certain limits of distance from the vehicle tires, other factors such as the activity of other vehicles on the road, the magnitude of the road dust PM emissions, and the mechanism of road dust PM emission have a negligible effect on the degree of plume dispersion; 3) that the dust emissions are a result solely of the interaction of the vehicle with the road surface and that aerodynamic entrainment of dust from the turbulence created by the vehicle's body is negligible; and 4) that the differences in terms of emissions of road dust between the test vehicle used and other vehicles on the road arising from differences in aerodynamics, and tire/track characteristics are either small or can be accounted for through known or presumed mathematical relationships.

These assumptions are used to construct the fundamental relationship (Kuhns et al., 2001):

$$EF_{ps} = MSC_{i,v,ps} \times K_i \quad (1)$$

where EF_{ps} is the emission factor of PM road dust in grams of PM per vehicle kilometer traveled (g vkt^{-1}), $MSC_{i,v,ps}$ is the concentration of PM (mg m^{-3}) as measured by a specific mobile measurement system i (in our case TRAKER) operating at speed v , and K_i may be a function of the mobile measurement system travel speed and is specific to mobile measurement system i . The subscript ps refers to a specific particle size range (e.g., PM_{10} , $\text{PM}_{2.5}$).

2.2 TRAKER TECHNOLOGY

TRAKER was re-designed as part of this demonstration project to facilitate application at multiple, geographically distant facilities. The main measurement apparatus is now configured to use any standard sized pickup truck as the test vehicle (Fig. 1). The combination of the truck, instrument pallet, baffle, data collection system and visualization electronics (laptop in cabin) constitutes the measurement platform known as TRAKER.

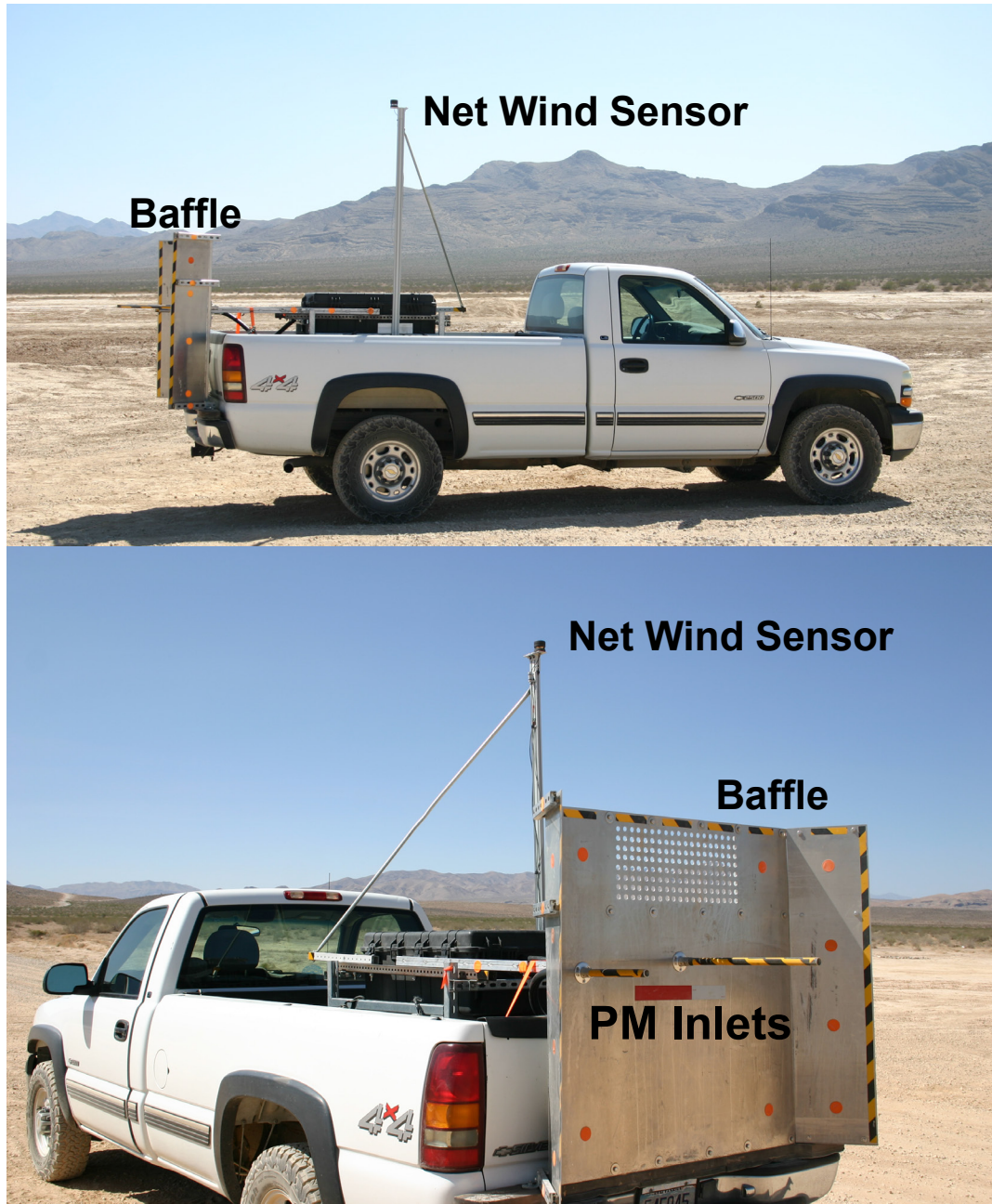


Figure 1. Components of TRAKER Include Instrument Suite in Palletized Enclosure, Rear Baffle with Inlets, and Electronic Data Collection and Visualization Tablet (in cabin, not shown here).

A flow diagram of the technology and measurement process is shown in Fig. 2 and the instrument package in Fig. 3. During measurements a pump draws air through two inlet lines that sample PM in the wake of TRAKER. The primary inlet line is approximately in the center of and extends 50 cm (20") beyond the wake baffle. The secondary inlet line extends 50 cm (20") beyond the wake baffle but offset from the center by 20 cm (8"). During operation both inlet lines are set to draw air at 16.7 liters per minute (lpm) through inlets that are 2.5 cm (1") in diameter developing a face velocity of 0.567 m s^{-1} . Each inlet line is connected to an expansion plenum that slows the flow to 0.066 m s^{-1} . A portion of this flow is delivered near isokinetically to internal inlet lines within the plenum that are connected to photometers (DustTrak, TSI, Inc.), which are equipped with either PM₁₀ or PM_{2.5} inlets. There are a total of four photometers in use (two for PM₁₀ and two for PM_{2.5}) that provide a measure of the concentration of PM dust (mg m^{-3}) emitted. The concentration measurements (adjusted in time to account for travel within inlet lines) are geo-referenced by Global Positioning System (GPS) to a location and travel speed at an acquisition rate of 1 Hz. Additional instrumentation is used to ascertain that ambient wind conditions are acceptable for the measurement to meet minimum quality criteria. Pressure sensors upstream and downstream of the filter media provide indicators of leaks or overloaded filter media.

The measured concentrations are converted to grams (g) of PM produced per vehicle kilometer travelled (vkt) by application of the calibration relationship (where K in Equation 1 is a multiplier of 14 g PM vkt^{-1} for every 1 mg m^{-3} of concentration measured in the primary inlet) developed using a flux-tower method (e.g., Gillies et al., 2015). The resolved per kilometer emission rate calculated in this manner is for a pickup truck that is traveling at the same speed that the TRAKER vehicle was traveling at the time of the measurement. However, this information is used to calculate total emissions for any combination of vehicles and travel speeds using the speed and mass relationships developed for both wheeled (Gillies et al., 2005) and tracked vehicles (Kuhns et al., 2010).

2.3 CHRONOLOGICAL SUMMARY OF TRAKER DEVELOPMENT

1999

- Proof of concept measurements made by H.D. Kuhns and V. Etyemezian of the DRI supported by internal funding from DRI.

2001

- Testing Re-entrained Aerosol Kinetic Emissions from Roads, i.e., TRAKER, system introduced in the peer-reviewed literature (Kuhns et al., 2001).

2003

- Extensive and performance testing carried out at multiple locations and on paved and unpaved road surfaces through funding support from SERDP (CP-1191) and the Idaho Department of Environmental Quality, Boise, ID. TRAKER road dust emission measurement, methods and calibration, and effect of environmental conditions on the measurements published in a series of papers in the peer-reviewed literature (Etyemezian et al., 2003a, 2003b; Kuhns et al., 2003).

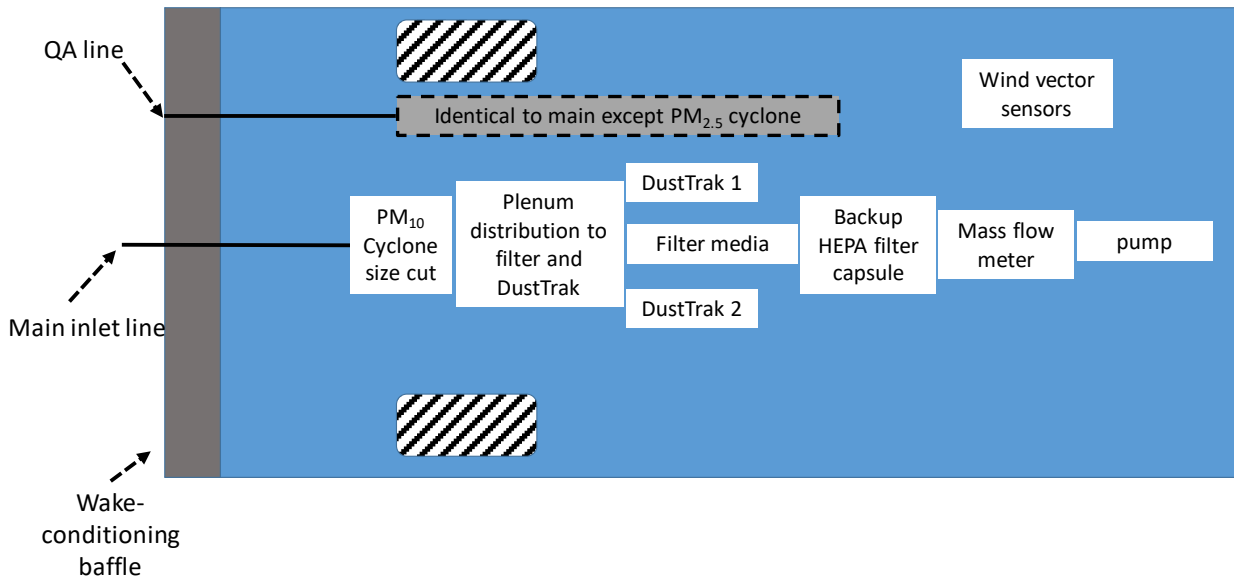


Figure 2. Flow Diagram of the Technology and Measurement Process.

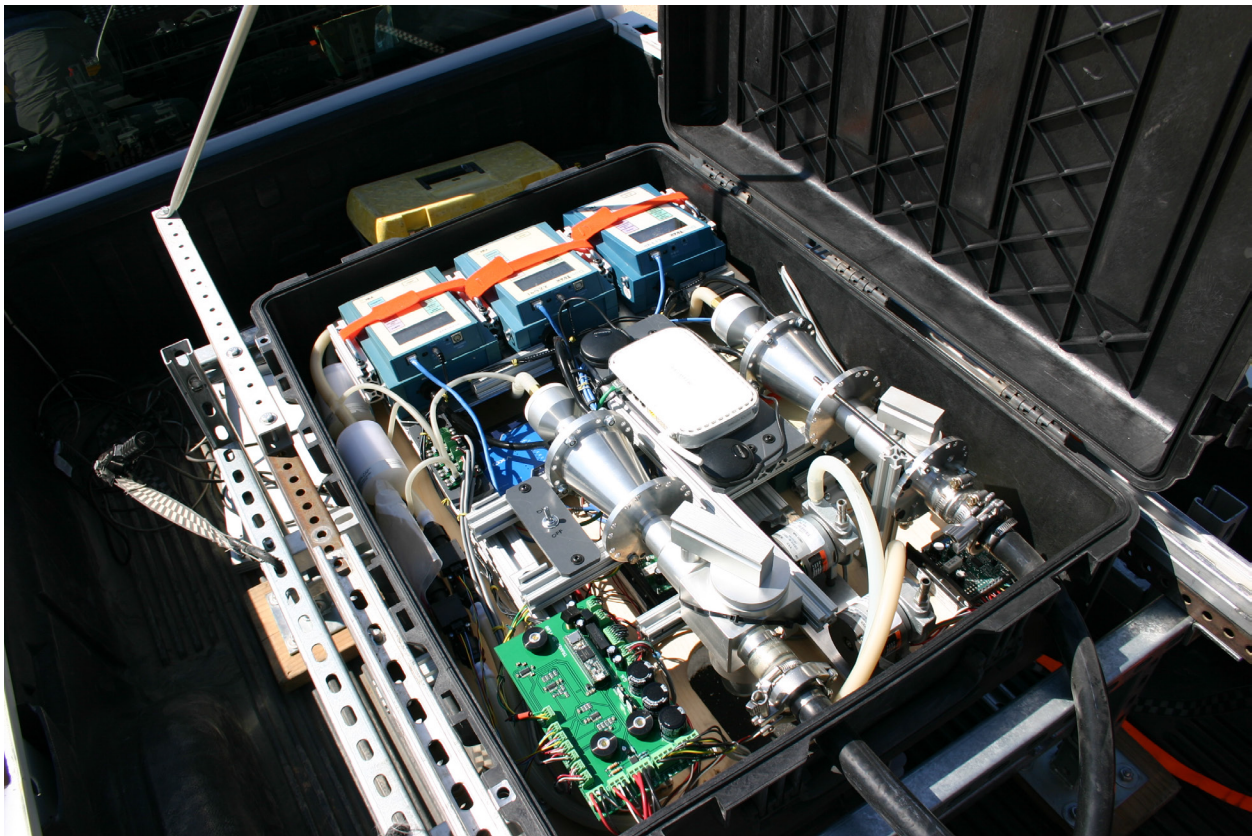


Figure 3. Current Sampling Instrumentation for TRAKER.

2005-2009

- TRAKER is used to characterize road dust emission potential in a number of studies including road networks near El Paso, TX (Kuhns et al., 2005) and around Lake Tahoe, NV and CA (Zhu et al., 2009).
- TRAKER further developed using SERDP funding support (SI-1399) and calibration with flux-tower method carried out at multiple locations (Gillies et al., 2009; Langston et al., 2008).

2010-2018

- TRAKER used to collect data to analyze effectiveness of control measures for road dust emission, Lake Tahoe NV and CA (Zhu et al., 2012).
- TRAKER method designated as OTM-34 by US EPA.
- TRAKER used to characterize the spatial distribution of unpaved road dust emissions in the US-Mexico border region (Las Cruces, NM, El Paso, TX and Ciudad Juarez, CH, Mexico) (Kavouras et al., 2016).
- TRAKER converted to a modular format for mounting in the bed of a pick-up truck using SERDP funding support (RC-1729) and calibrated with flux-tower method (Gillies et al., 2015).
- TRAKER used to measure emissions from unpaved roads at Ft. Riley KS (Gillies et al., 2015).
- TRAKER behind-front-wheel measurement version and in-truck version configurations comparability evaluated through simultaneous measurements of emissions from unpaved roads, Dugway Proving Ground, UT, as well as cross-calibration with flux-tower method (Gillies et al., 2015).
- TRAKER used to quantify PM emissions from convoy track and assess effectiveness of magnesium chloride as a dust palliative at Ft. Irwin, CA for US Army Environmental Command, Ft. Sam Houston, TX (Gillies et al., 2015).
- TRAKER used to assess effectiveness of dust suppressants on trails at the Ocotillo Wells State Vehicular Recreation Area, Borrego Springs, CA (Etyemezian et al., 2016).
- TRAKER used to collect filter samples of resuspended road dust to determine content of the fungal pathogen *Coccidioides* as part of SERDP project RC-2650 (Etyemezian et al., 2018).

2018-2020

- TRAKER compared with flux tower measurements and with SCAMPER (a trailer-based road dust measurement system, Fitz et al., 2020) (Fitz et al., 2021).
- TRAKER (with latest modifications) performance tested at MCAGCC/MAGTFT, Twentynine Palms, CA (This project).

2.4 EXPECTED APPLICATIONS

TRAKER and the dispersion modeling system can be used for the following applications:

- Develop robust PM₁₀ and PM_{2.5} emission inventories for vehicle testing and training activities to provide key information for permitting purposes.

- Provide an effective and efficient tool for evaluating how testing/training activities impact key receptor sites in terms of time resolved concentrations of PM₁₀ or PM_{2.5}, both diagnostically (i.e., for completed activities), or prognostically (i.e., for planned activities under forecast meteorological conditions).
- Provide an effective and efficient tool for evaluating how testing/training activities could be modified to lessen their impact on fence line concentrations of PM₁₀ or PM_{2.5}.
- Provide an effective and efficient tool for evaluating the efficacy of applied dust palliatives to assure performance specifications have been achieved and inform the selection process to ensure benefits of application are achieved or to inform when reapplication is required.
- TRAKER remains an effective technology for addressing outstanding research questions related to understanding how the environment (e.g., regional climatology) and the surface conditions (e.g., regional soil characteristics) effect vehicle-generated emissions of dust across space and through time.

2.5 TECHNOLOGY DEVELOPMENT

The TRAKER system development and design are described in a series of peer-reviewed papers that document its conception through to its use as a measurement platform for research related to quantifying road dust emissions. Key publications are: Kuhns et al., 2001, 2003, 2005, 2010; Etyemezian et al., 2003a, 2003b, 2006; Langston et al., 2007; Zhu et al., 2016; Kavouras et al., 2016; and Fitz et al., 2021. US EPA categorized TRAKER as OTM-34 for measuring road dust emissions in 2014 following evaluation of documentation describing field and laboratory validation studies; results of collaborative testing; articles from peer-reviewed journals; peer-review comments; and quality assurance (QA) and quality control (QC) procedures in the method itself.

2.6 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages:

The advantages of TRAKER over the silt loading method, plume profiling method, and other mobile monitoring systems for measuring PM emissions from paved and unpaved surfaces are enumerated as follows:

Safety: Generally during use TRAKER follows the rules-of-the-road, there is no need for lane closures, and does not require personnel to control traffic.

Provides a known repeatability/uncertainty on emission measurements.

Has improved spatial representativeness due to its ability to characterize kilometers of road surface.

Ease of Use/Time needed/Area Covered.

Has documented Quality Assurance (QA) and Quality Control (QC) protocols to ensure high quality data are acquired.

Has US EPA, Other Test Method (OTM-34) designation, providing confidence that measurements and PM inventories derived from the measurements will be given a high degree of credibility.

TRAKER system has been integrated with dispersion model (AERMOD) interface to efficiently allow projection of PM air quality impacts of vehicle emission inventories that have traveled or will travel across a TRAKER-measured road network.

Limitations:

Cannot operate in conditions with ambient wind speeds in excess of 7 m s^{-1} .

Can only collect emission data on relatively straight sections of road $\geq 100 \text{ m}$ in length.

3.0 PERFORMANCE OBJECTIVES

The performance objectives of this project were defined in the Demonstration Plan and are based on technical performance specifications for TRAKER, evaluating the role of environmental conditions to affect TRAKER measurements, the ability of TRAKER to resolve differences in emissivity due to dust palliative application to roads, bring TRAKER operability to a user-friendly state (hardware and software), and integrate TRAKER derived emissivity data with a dispersion model that can be used to evaluate effects of road dust emissions on air quality on a scale up to tens of kilometers in distance from the source areas. The performance objectives, the data required to assess the objectives and the outcomes of the assessment are provided in Table 1.

3.1 ENGINEERING UPGRADES

By 2017 TRAKER had been developed to serve as an instrument for research related to understanding the spatial and temporal controls on road dust emissivity and defining the scaling relation for emissivity between TRAKER and other vehicle types. To reach a usability level that would enable commercialization, the suite of instruments and its ease of operation required substantial re-engineering of the hardware and software that comprise the TRAKER system.

The re-engineered TRAKER as shown in Figs. 1 and 3 has reached a level of operability from the engineering upgrades that make it easy to transport, setup, and use with a modest degree of training. TRAKER and the associated services offered by Dust-Solve, LLC to enable management of vehicle-generated road dust for DoD installations and across the public and private sector are available through contractual arrangements.

3.2 PRECISION OF TRAKER MEASUREMENTS

In order to provide confidence to potential users of the TRAKER system, an assessment of the TRAKER's ability to repeatedly measure road dust emissivity was deemed crucial for this project. Quantifying measurement precision is necessary for developing management strategies for road dust emissions that incorporates an understanding of uncertainty. Quantification of uncertainty enables development of a dust management plan that can incorporate some degree of a factor of safety to ensure the desired outcome is achieved. Repeated measurements of emissivity using TRAKER across the test road network provided the data necessary to examine the precision of TRAKER to quantify emissivity and define the associated uncertainty.

Based on previous measurements with TRAKER (Etyemezian et al., 2006) it was known that emission factors from unpaved roads can vary over several orders of magnitude. Similarly, the effect of dust abatement treatments is usually a reduction of emissions by several fold or more.

Our performance objective target for measurement precision (i.e., measurement of emissivity of the same segment of road for the same environmental conditions) was set at 20%. While in some fields of science a precision of 20% seems very high, in the field of road dust emissions, a measurement with such precision can provide extremely useful information. The TRAKER measurements repeated on the test road network at 29 Palms provided data that indicated that for >87% of the paired data, precision of <20% was achieved.

Table 1. Performance Objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
20% repeatability of TRAKER measurements	Repeated TRAKER dust emission factor measurements of a specific length of test surface within a time span of minutes at a given vehicle speed.	Calculated emission factor for a designated length of test surface show $\leq 20\%$ difference in magnitude with the established level of uncertainty	TRAKER repeatability confirmed to be $\leq 20\%$ for $>87\%$ of paired measurements (i.e., same location, same time).
Determine if environmental parameters cause identifiable biases on TRAKER emission factor measurements	Repeated TRAKER dust emission factor measurements along an established test surface route (i.e., unpave road) and continuous (10 min. mean) environmental data (e.g., wind speed, wind direction, precipitation, etc.) over at least a one-year period	Determination if environmental factors do or do not play a significant role in affecting dust emission potential of the test site roads. If observed changes were in excess of repeatability criteria (assume 20%) the environmental conditions could be considered a source of quantifiable bias.	Seasonal bias in emission factors observed at test site and quantified.
Dust palliative control effectiveness	Repeated (quarterly) TRAKER dust emission factor measurements of treated and untreated surfaces.	TRAKER measurements within their repeatability criterion showing time series data defining the delta change in emissions through time referenced to the uncontrolled surface emission factor.	TRAKER able to detect difference between the baseline road emissions and a dust-controlled section with 95% confidence.
Qualitative Performance Objectives			
TRAKER engineering modifications		Successful switch to battery power source. Less than one hour to operation. Filter system incorporated into PM sampling train.	System is powered by DC battery system. Assembly is approximately one hour. US EPA approved cyclone filter sampler is integrated into the system.
Ease of use		Enhances on-board, real time data quality control algorithms in place to identify valid data collection. Novice operator trained in one day.	Algorithms executed and operable. Remains untested.
Integrating TRAKER data with a dispersion model	TRAKER road dust emissivity survey Regional meteorological data. Topography data in selected domain.	Dispersion model accepts spatially resolved TRAKER dust emission data.	AERMOD with custom designed Python interface successfully accepts TRAKER dust emission data and links with user/ installation relevant meteorological data to generate PM concentration estimates through time and across space.

3.3 ENVIRONMENTAL BIAS FOR EMISSION FACTORS

Measurements of dust emissivity, whether for unpaved roads or desert surfaces susceptible to wind erosion, are often made under very restricted timeframes due to logistical and budgetary constraints. Environmental conditions such as precipitation, temperature, relative humidity, etc., are known to modulate emissivity and typically have seasonal patterns linked to geographic location. As part of this demonstration project, demonstrating that emissivity of the test road network exhibited change linked to differences in the environmental conditions across seasons was an important objective. Equally important was that if differences in emissivity could be demonstrated to be linked to seasonal changes in the environment, emission factors could be adjusted to reflect the quantified bias. To acquire environmental data at 29 Palms and evaluate its influence on emissivity through time, two monitoring stations in close proximity to the test road network were emplaced that continually collected wind speed, wind direction, temperature, relative humidity, soil moisture, and particulate matter concentrations on an hourly basis for a period of two years. The environmental monitoring data and TRAKER-derived emissivity data clearly demonstrated that there were short-term fluctuations in emissivity related to rainfall as well as longer term variations due, most likely to temperature and solar radiation effects. These effects on emissivity of the test road network across the seasons were quantified for 29 Palms.

3.4 DUST PALLIATIVE CONTROL EFFECTIVENESS

To reduce the amount of dust created by vehicles as they travel on unpaved roads dust palliatives are often applied. Palliatives span a spectrum of methods, but all are applied to essentially bind road materials together such that the mechanical action of a vehicle driving on the road that creates the forces that entrain and suspend dust are resisted. TRAKER is an effective and efficient measurement method for quantifying the effectiveness of a dust palliative. By comparing emissivity pre- and post-application, TRAKER measurements can be used to evaluate the effectiveness of the palliative to decrease emissions and repeated measurements can define palliative performance through time and its rate of degradation that may be due to environmental (e.g., precipitation) or mechanical (e.g., vehicle use rate). During the demonstration project 29 Palms did not apply any dust palliatives that could have been tested by TRAKER. However, establishing that TRAKER can achieve repeatability measurements with precision of <20% difference between paired measurements, provides confidence that the method can be used to define dust palliative effectiveness relations through time.

3.5 INTEGRATING TRAKER DATA WITH A DISPERSION MODEL

TRAKER data quantifying the emissivity of road networks is critical for defining the potential for that road network to degrade air quality when used by vehicles performing testing/training activities or even by vehicles moving in support of day-to-day activities related to base operations. To make effective use of this information requires a means to link the emission data with a modeling system that can estimate the impacts of the emitted particulate matter at local and regional scales. As part of this demonstration project the emission factor data derived from TRAKER was successfully linked with the US EPA-approved dispersion model AERMOD. This was achieved using a Python script developed to organize the emission and meteorological data inputs into the formats required by AERMOD and then organizes the model outputs and creates reports based on user-defined needs, for example, time-resolved PM₁₀ concentrations at specified receptor sites.

4.0 SITE DESCRIPTION

4.1 SITE LOCATION AND HISTORY

MCAGCC/MAGTFT, Twentynine Palms reported to Dust-Solve, LLC in 2017 that it has the potential to exceed its established emissions thresholds for particulate matter (PM) due, in large part, to mobile equipment travelling on its unpaved road network. Exceeding these thresholds would require modification or a reduction of operations and requirements to keep emissions within the NAAQS limits. The recognized potential to exceed PM limits, largely due to vehicle-based dust emissions, offer information to better quantify their PM emissions and aid in developing mitigation efforts if needed, made this base our choice for carrying out our test plan to achieve certification of TRAKER.

MCAGCC/MAGTFT is located within the Morongo Basin, which is in the high desert region of the Mojave Desert in San Bernardino County, California (Fig. 4). The main cantonment on the base is approximately 1.4 mi² (3.7 km²). The entire installation is approximately 935 mi² (2,412 km²) in area and is the largest Marine Corps base in terms of landmass. The mission of this base is to manage the Marine Air Ground Task Force Training Program (MAGTFTP) and conduct service level Marine Air Ground Task Force (MAGTF) combined arms training to enhance the combat readiness of the operating forces and support the Marine Corps' responsibilities to national security.

The high level of use of the extensive unpaved road network within the base by testing and training activities had sufficient kilometers of roads on which to operate TRAKER to allow for the measurements to be acquired to evaluate our performance objective goals and meet the certification requirements. In addition, the active testing and training activities provided the conditions needed to obtain data to characterize the effect of changing environmental conditions on the emission of dust from the road network related to seasonal changes in meteorology and vehicle use patterns.

4.2 SITE CHARACTERISTICS

The terrain outside the cantonment consists of steeply-sloped mountain sides and flat valleys running generally northwest-southeast, with elevations ranging from 1,800 to 4,500 feet (1,400 m) above sea level. Overlain on the valleys and extending partially up many of the mountain sides is an extensive network of unpaved roads and trails, even taking into account restricted access areas there is sufficient kilometers of road that can be traversed by TRAKER to obtain a robust data set to evaluate performance metrics.

The climate is upland desert with an average rainfall of 112 mm (4.4"), which most often occurs in the fall and winter months. Summer temperatures can peak near 50 °C (≈120 °F) and reach a low of -9 °C (≈15 °F) in the winter, with an annual average of 20 °C (≈69 °F). Weather is generally clear most days and nights, with low relative humidity.

The physical and climatic settings at MCAGCC/MAGTFT provided an environment wherein the road network remained in a dust-producing condition during an entire year providing the opportunity to carry out measurements during any month with only short periods of time immediately following a rain event that would curtail measurements

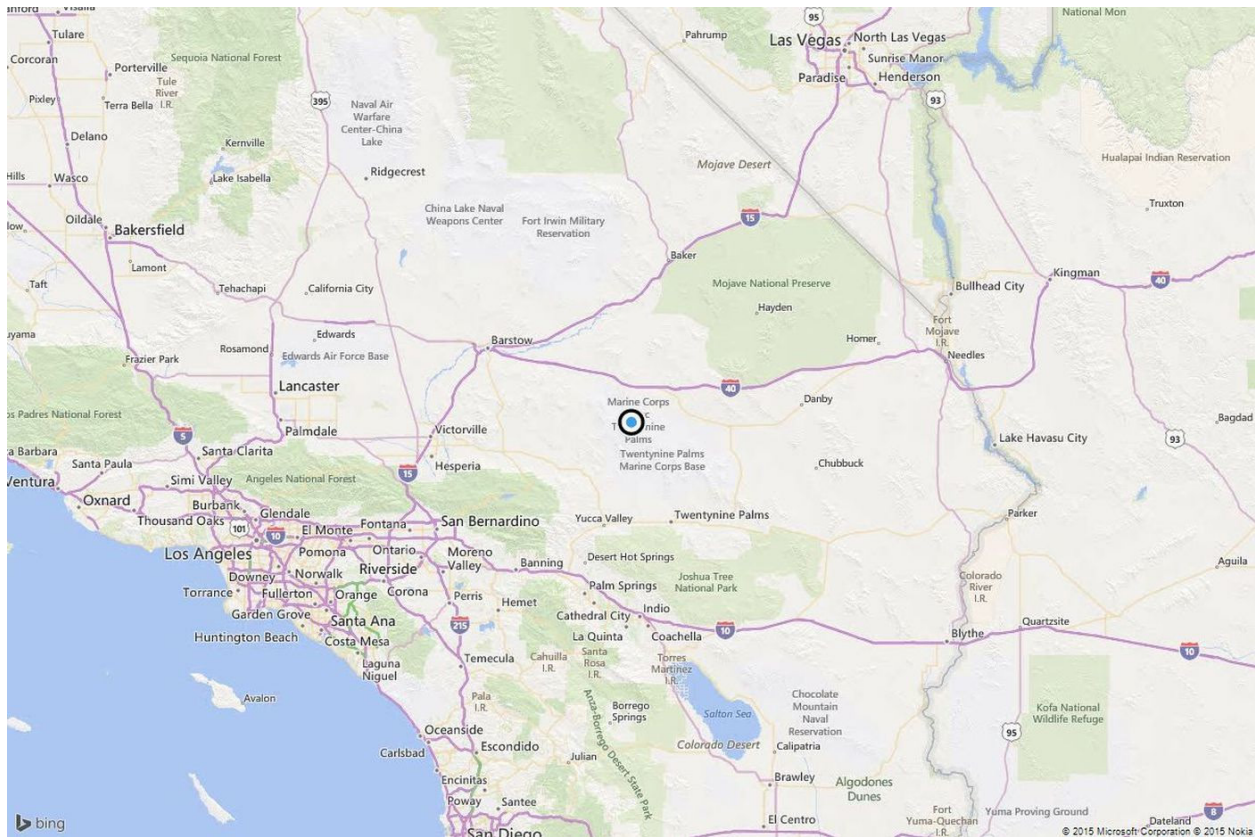


Figure 4. The Location of MCAGCC, 29 Palms in California.

Soils and unconsolidated sediments at MCAGCC Twentynine Palms consist of well-drained sands on the basin floor and excessively drained sandy loams in the mountain valleys. Along the basin floor, a thin veneer of very poorly drained clayey loam (playa soils) covers the playas. Low rainfall combined with high summer temperatures results in accumulation of carbonates, alkali, and other soluble salts from the root zone of desert soils (USDA NRCS, 1999).

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The test design was developed to demonstrate that TRAKER can be used to assemble a facility-wide road dust emission inventory. This was accomplished by conducting repeated TRAKER measurements at the Test Facility over the course of two years. The TRAKER measurements were also related to meteorological and vehicle activity data measured at two monitoring stations placed in proximity to the roadway test route. The environmental monitoring was designed to uncover any temporal or environmental dependencies in the TRAKER emission data to determine if there was a need for empirical corrections due to effects related to seasonal environmental changes.

To demonstrate TRAKER's ability to quantify dust control effectiveness we compared the differences and variations in TRAKER emission data with the repeatability of the measurements. Dust controls have been applied at MCAGCC Twenty-Nine Palms primarily in the form of aggregate (gravel) spreading over highly traveled surfaces. The dates of application and reapplication were not available, but the aggregate material is present to varying degrees on all roads that were tested by TRAKER. Therefore, it is reasonable to assume that there is also wide variability in how long the aggregate has been in place and what environmental and traffic parameters have acted on the aggregate to modify its ability to ameliorate road dust over time. Although it would have been preferable to conduct controlled studies where baseline measurements were obtained for a road segment, the segment was subsequently treated with dust control(s), and the segment was repeatedly re-measured with TRAKER, in practice this activity was not aligned with the other resource obligations and priorities of the base. Recognizing that the performance objective to be met was directed at whether or not TRAKER can be used to accurately monitor dust control effectiveness and was not to quantify efficacy of specific dust suppressants, we can use the repeatability of measurements in conjunction with the distribution of the measured values of emissions to ascertain that dust control effectiveness could be efficiently quantified with the TRAKER. In this construct, performance is judged based on the absolute measurement uncertainty and what is equivalent to a signal to noise ratio.

5.2 BASELINE CHARACTERIZATION

The development of the emission inventory at our selected site began with an initial survey using TRAKER to define the baseline emissions map (Fig. 5). The baseline data are comprised of the g-PM vkt^{-1} for ≈ 200 m long segments of road where valid data are acquired. Subsequent to this, measurements for the same geo-reference positions were compared to determine if there had been a change from the baseline.

A second baseline characterization was the ambient monitoring of meteorological (wind speed, wind direction, RH, temperature, solar radiation, precipitation, and soil moisture), ambient PM (1-minute averaged estimates of the suspended particle concentration for particles nominally between $0.5 \mu\text{m}$ and $20 \mu\text{m}$ in diameter), and vehicle activity (number of vehicles and vehicle type per unit time). The data from this monitoring was used to determine if there was an observable in the TRAKER measured emission potential of the road network due to seasonal changes in environmental conditions.

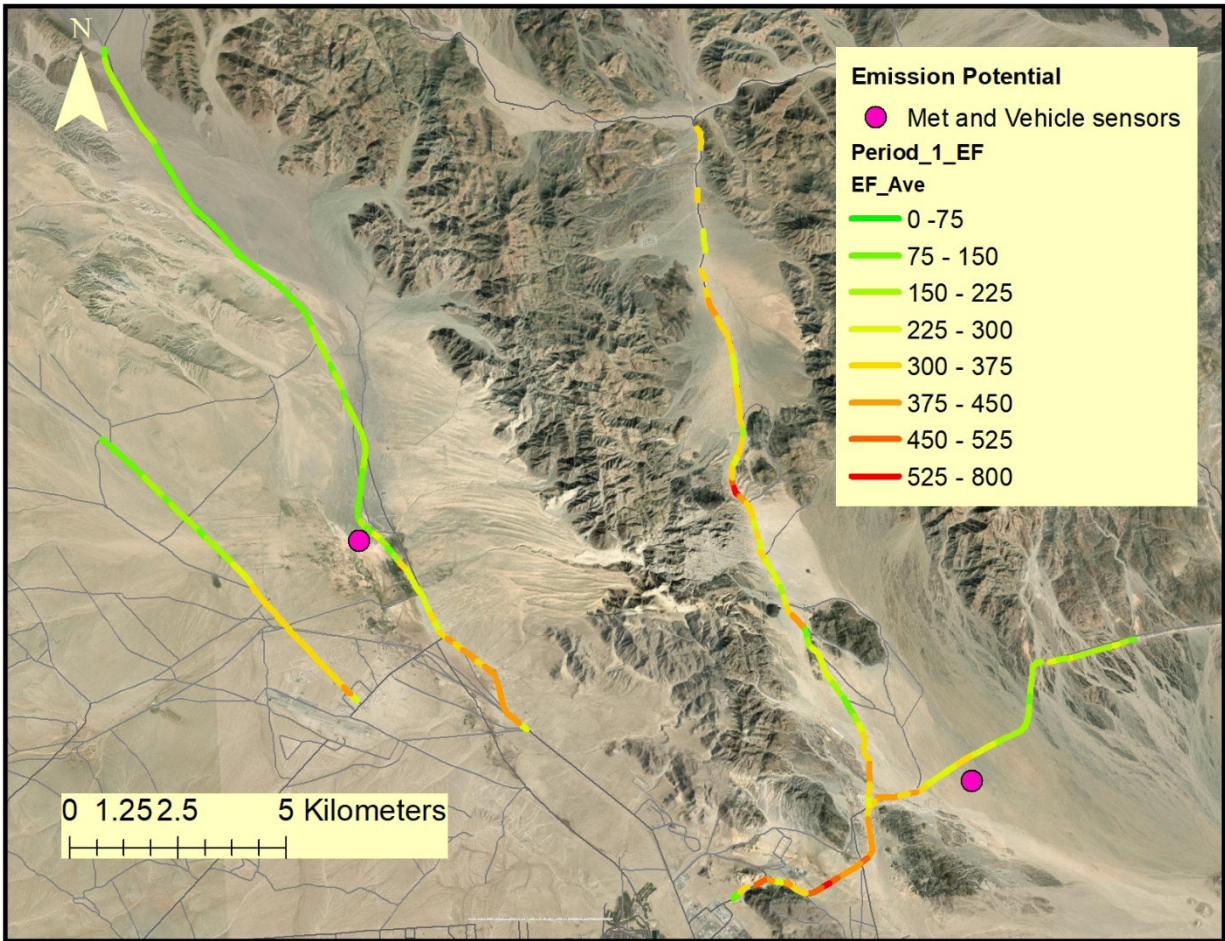


Figure 5. Baseline Emissions Map and Locations of Ambient and Vehicle Activity Monitoring Stations.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The route that was used for repeated traversal with the TRAKER was divided into segments ranging in length between 201 and 242 m (Fig. 6). Individual, one-second TRAKER data points were each associated with a road segment. Averages of TRAKER data over these road segments provided consistent basis of comparison of emissions over space and time.

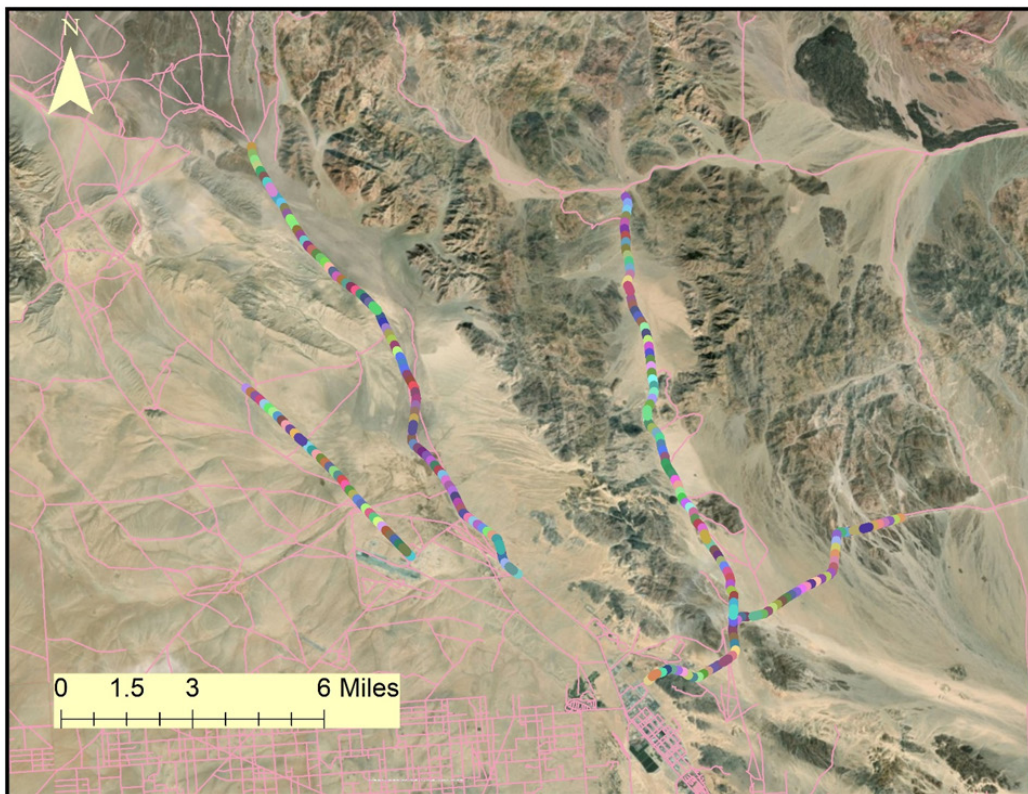


Figure 6. Road Segments (≈200 Meters in Length) Used to Aggregate Individual 1-second TRAKER Data.

5.4 FIELD TESTING

There were two operational phases of field testing for this project. To monitor ambient PM conditions nearby roadways affected by on-base vehicle activity, two self-contained meteorological and PM sampling systems were installed at selected locations. Monitoring of data was accomplished using dataloggers with collection of these data made during site visits on a quarterly interval. The lack of connection to a cellular network at the sites did not allow for remote access to the stored data. The monitoring stations were removed following the completion of the ambient monitoring phase and there was no residual effect on the environment.

The second operational phase was the deployment of the TRAKER system to characterize the PM emission potential of the unpaved road network on the base. The system was fully functional on arrival and required no system start-up beyond assembly of the component parts. There was no phase of shutdown or demobilization for this field component.

The progress schedule for each phase of testing and relation between the various operational phases is shown in Table 2.

Table 2. Progress Schedule for Each Phase of Testing and Relation Between the Various Operational Phases.

Milestone/Deliverable*	Q1 July-Sept, 2017	Q2 Oct-Dec, 2017	Q3 Jan-March, 2018	Q4 April-June, 2018	Q5 July-Sept, 2018	Q6 Oct-Dec, 2018	Q7 Jan-March, 2019	Q8 April-June, 2019	Q9 July-Sept, 2019	Q10 Oct-Dec, 2019	Q11 Jan-March, 2020	Q12 April-June, 2020	Q13 July-Sept, 2020	Q14 Oct-Dec, 2020	Q15 Jan-March, 2021	Q16 April-June, 2021	Q17 July-Sept, 2021	Q18 Oct-Dec, 2021
Demonstration Plan																		
Complete TRAKER upgrades																		
Install/Remove Monitoring Stations																		
TRAKER field measurements for emissions inventory																		
Install/Remove Monitoring Stations for treatment effectiveness																		
TRAKER field measurements for treatment effectiveness																		
Modeling (DUSTRAN and resource																		
On-site demonstrations for environmental																		
Assemble e-media file for web publishing																		
Final Report																		
*Grey color indicates period of activity to complete Milestone/Deliverable																		

5.5 SAMPLING METHODS

No physical samples were collected for analysis as part of this project. Table 3 lists the data capture for the five collection periods for TRAKER and the meteorological, PM₁₀, and vehicle activity. The project relied exclusively on the collection of real-time data from the instruments that comprise the TRAKER system and from the monitoring stations that we placed near sections of the test road network to monitor ambient meteorological conditions and the near-roadway PM concentrations that resulted from the passage of vehicles and high wind events that entrained sediment and lofted PM into the air.

Air flows through the TRAKER inlet lines were checked against a reference standard mass flow meter at the beginning of each sampling day, each time a filter sample was changed (collected but not meant to be analyzed in this project), and prior to shutting down the system for the day. These checks served as opportunities to make minor adjustments over the course of the day to ensure that the flow through the cyclone separators, one each in the PM_{2.5} and PM₁₀ lines, were operating at their design flow rates (16.7 lpm).

While data collection was in progress, data quality was assessed and flagged as appropriate based on two threshold criteria with respect to cross winds and absolute ambient wind speeds. These were imposed as: 1. Minimum acceptable net wind speed (vector sum of vehicle speed and ambient wind speed) is at least 5 m s⁻¹ (11 mph), 2. Maximum acceptable deviation of net wind direction from the direction of vehicle travel is 30°. Measurements collected outside of these criteria are not considered valid because a uniform wake shape cannot be maintained behind the baffle. In most cases, this translates into a requirement that ambient wind speeds be <7 m s⁻¹ (16 mph).

Duplication of real-time PM concentration measurements in each of the sample lines was used to ensure that the two instruments were providing measurements in consistent proportions over time (Fig. 7). As a secondary indicator of data quality, the ratio of PM concentrations measured with the primary inlet to that measured with the secondary inlet is examined over the course of measurement. When the wake of the TRAKER is being conditioned and sampled as designed, this ratio is nearly constant (2:3). Large or prolonged deviations from this ratio can be used as indicators of problems with one of the sampling lines or as an independent check on the acceptability of wind conditions. The two inlet lines also provide a degree of redundancy in case of malfunction in one of them.

5.6 SAMPLING RESULTS

5.6.1 TRAKER Measurements

Average Emission potential measured by TRAKER for the five sampling campaigns are shown in Figs. 8 through 12. In order for a pass on a segment to have a valid value, a minimum of 10 individual TRAKER measurements associated with the segment during that pass must meet the basic data quality criteria. A pass refers to a traverse of the segment in either direction of travel. Averages assigned to segments are averages of all available and valid passes during the sampling interval. Data recovery during the February 2020 measurement campaign (Fig. 11) was poor due to adverse wind conditions.

Table 3. Total Number and Types of Data Collected

Component	Matrix	Number of Samples	Valid Data/Valid Segment (253 max.)	Date
Baseline road test network emissions. Valid points for TRAKER include meeting net wind vector, vehicle speed, vehicle acceleration, wheel angle, and GPS coordinate quality criteria.	TRAKER 1 s valid data - period 1	21,248	13,437/242	5/1/2019 – 5/2/2019
	TRAKER 1 s valid data - period 2	21,233	13,622/247	7/17/2019 – 7/18/2019
	TRAKER 1 s valid data - period 3	26,478	16,004/250	11/26/2019 – 11/27/2019
	TRAKER 1 s valid data - period 4	21,793	9,456/151	2/25/2020 – 2/26/2020
	TRAKER 1 s valid data - period 5	23,902	16,431/252	9/9/2020 – 9/10/2020
			% Data Capture	
Near-road ambient monitoring – meteorology and PM	Wind speed (hourly mean)	16632	100%	10/09/2018 – 09/31/2020
	Wind direction (hourly mean)	16632	100%	10/09/2018 – 09/31/2020
	RH (hourly mean)	16632	100%	10/09/2018 – 09/31/2020
	Temperature (hourly mean)	16632	100%	10/09/2018 – 09/31/2020
	Soil moisture (hourly mean)	16632	100%	10/09/2018 – 09/31/2020
	PM ₁₀ and PM _{2.5} concentrations (hourly mean)	16632	100%	10/09/2018 – 09/31/2020
Vehicle Activity	Counts		88% (±3%)*	10/09/2018 – 09/31/2020

*Mean and Std. Deviation for 2 cameras

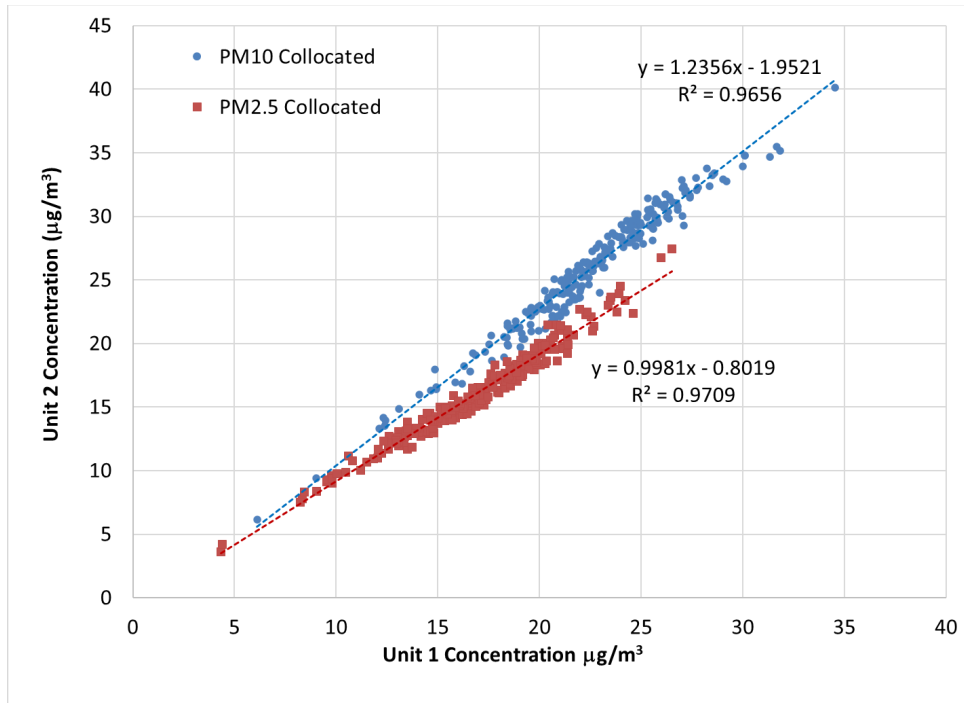


Figure 7. Relations Between Pairs of Collocated Dust Monitors in the PM₁₀ and PM_{2.5} Sample Lines.

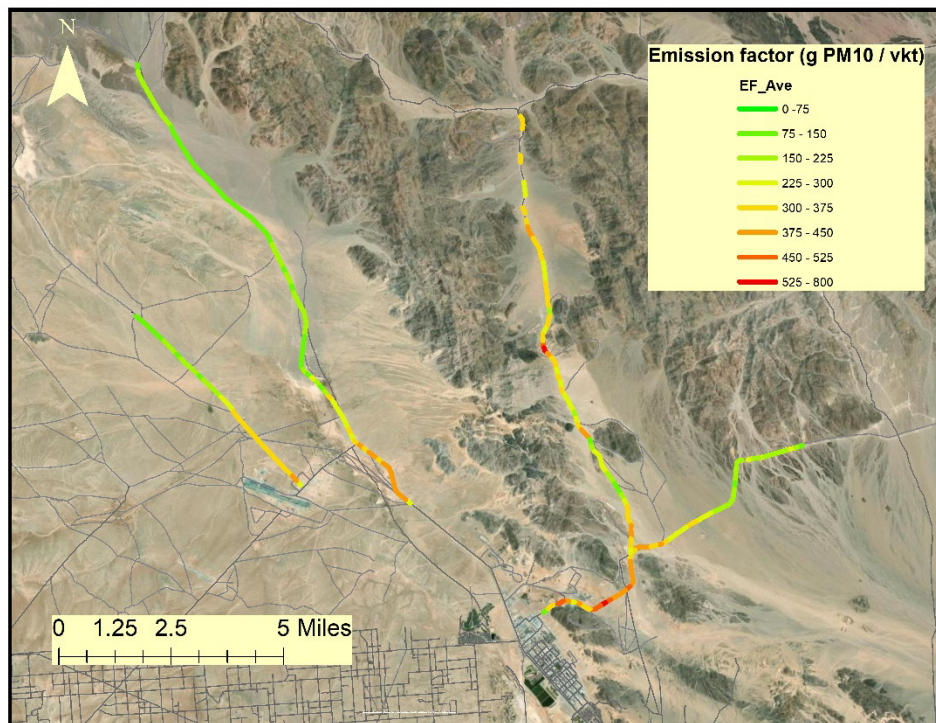


Figure 8. May 1-2, 2019, TRAKER Emission Measurements.

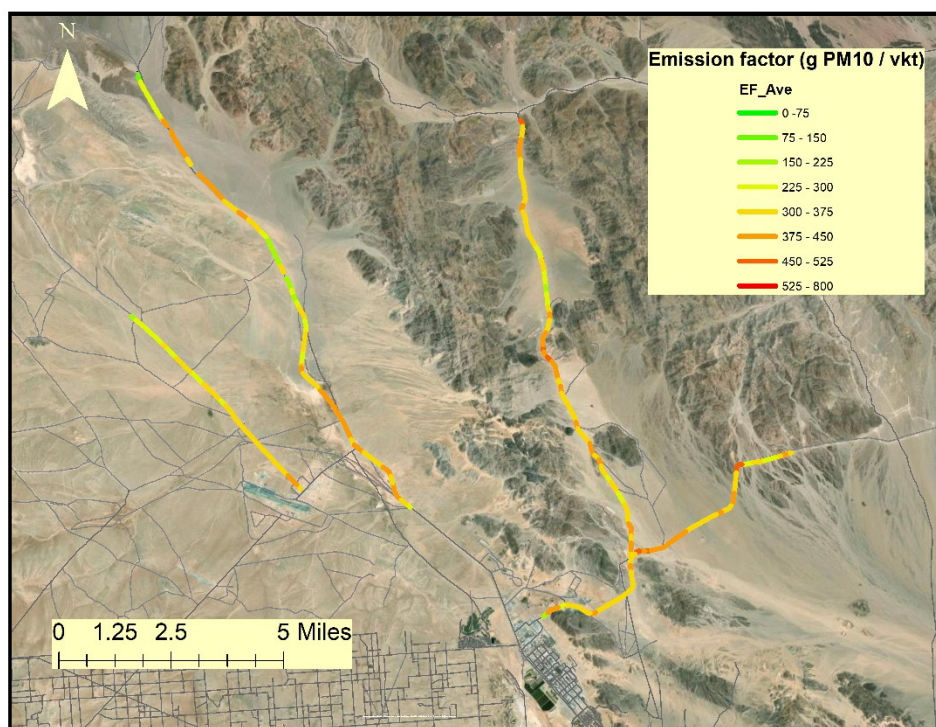


Figure 9. July 17-18, 2019, TRAKER Emission Measurements.

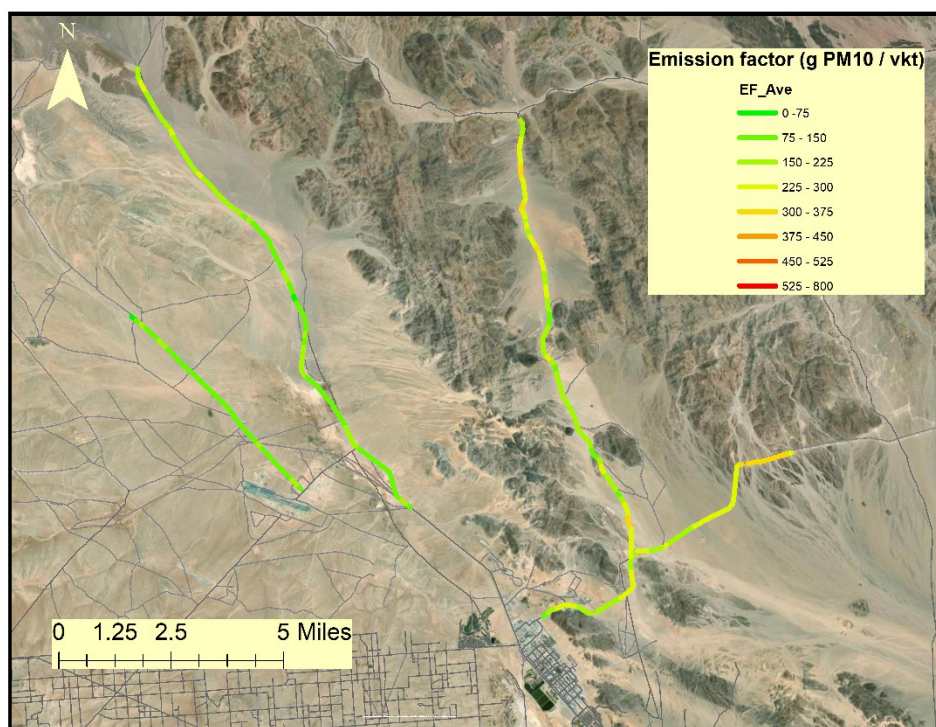


Figure 10. November 26-27, 2019, TRAKER Emission Measurements

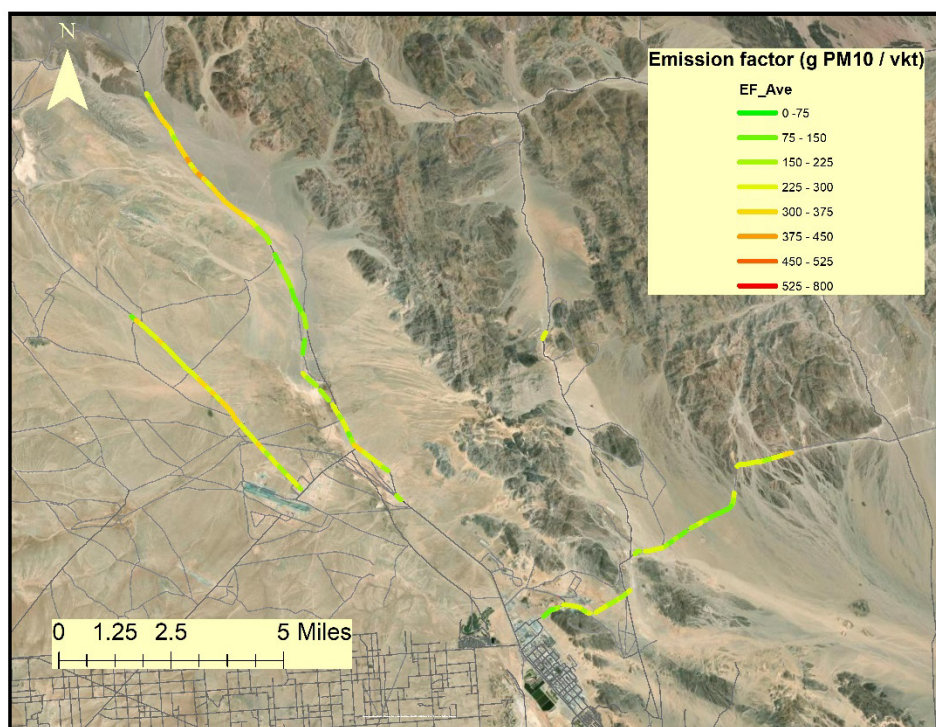


Figure 11. February 25, 2020, TRAKER Emission Measurements.

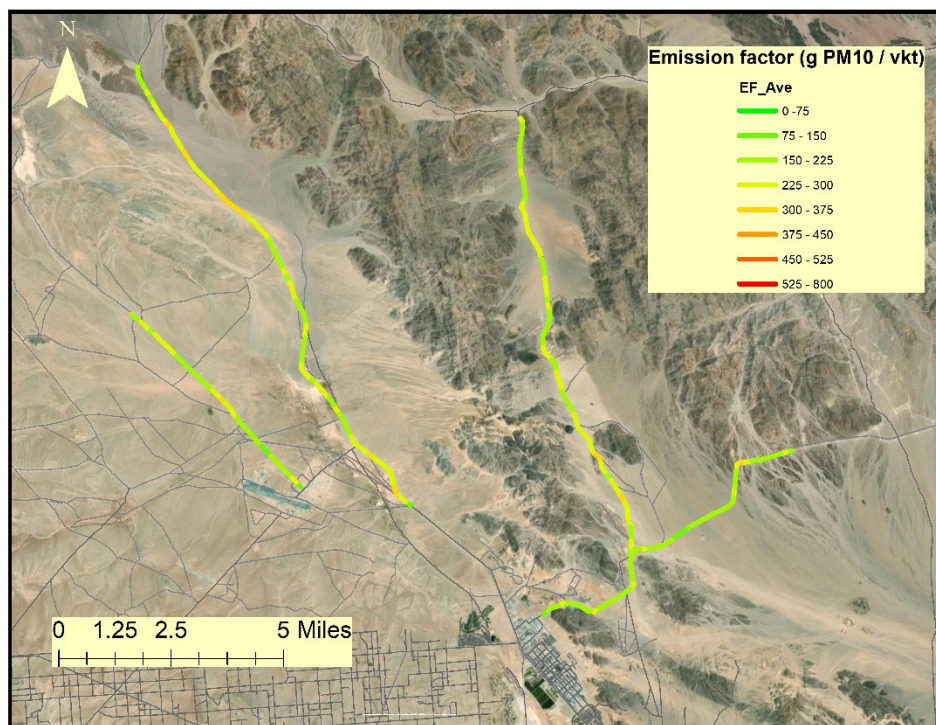


Figure 12. September 9-10, 2020, TRAKER Emission Measurements.

5.6.2 Monitoring Measurements: Meteorology

Meteorological conditions over the course of the project are summarized in Fig. 13 through Fig 16. These figures summarize the data from the East station only for brevity. On aggregate, meteorological conditions were very similar between the two meteorological stations. Temperature patterns are typical for the region with very hot summers and overnight lows approaching freezing at times. Winds increase and decrease as well as change directions over the course of a typical day in response to the diurnal cycle and the hilly terrain. On most days these are highly variable. High winds on consecutive days are typically associated with a frontal passage. Precipitation measured over the period is somewhat typical with most rainfall occurring in the cooler months and some summer rainfall that is likely associated with monsoonal conditions. It is noteworthy that following a significant rainfall event, the soil moisture at depth increases sharply and then decreases slowly over time. Because the measurement is made over an integrated depth of 10 cm, this measure of soil moisture is not a good gauge of the wetness of the near surface soil, which tends to dry much more quickly. Following a heavy rain in summer, an unpaved road surface may return to being dusty in a matter of days. In winter, it may take a week or so, but generally less than two weeks.

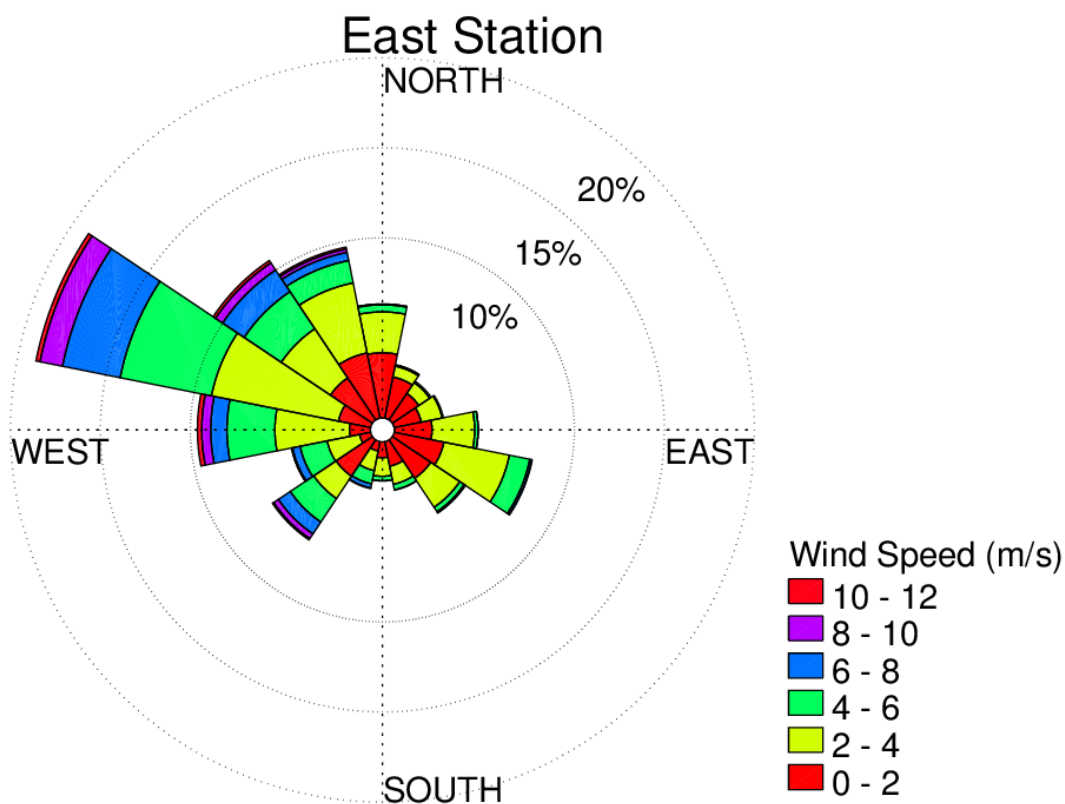


Figure 13. Wind Rose Diagram for East Meteorological Station.

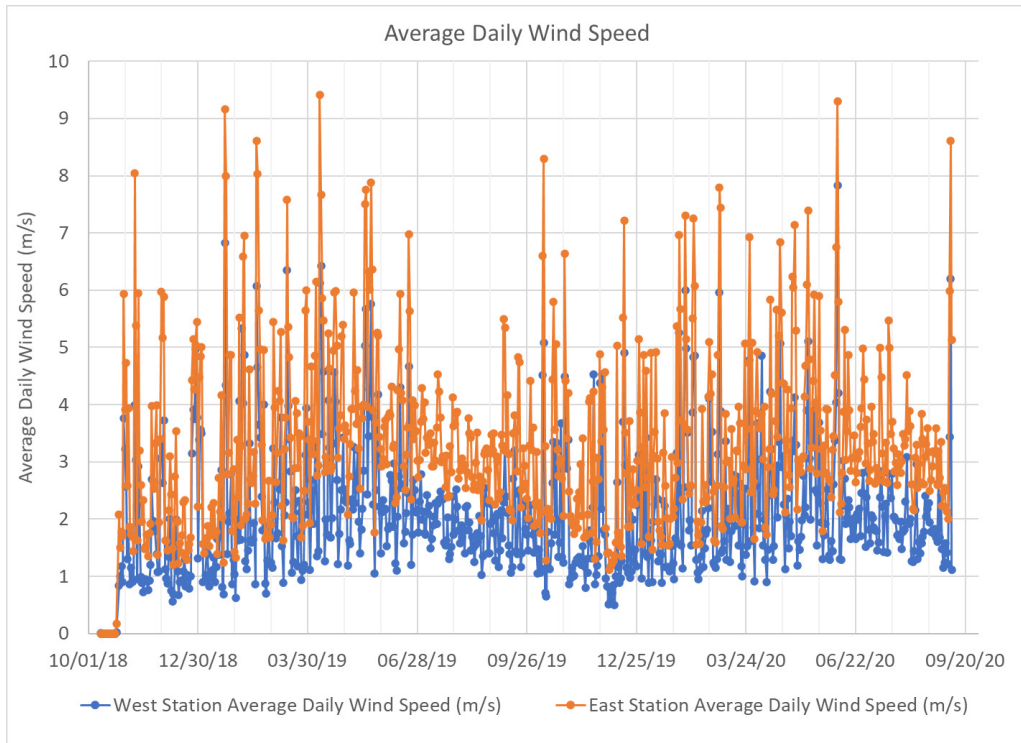


Figure 14. Average and Maximum Daily Wind Speeds.

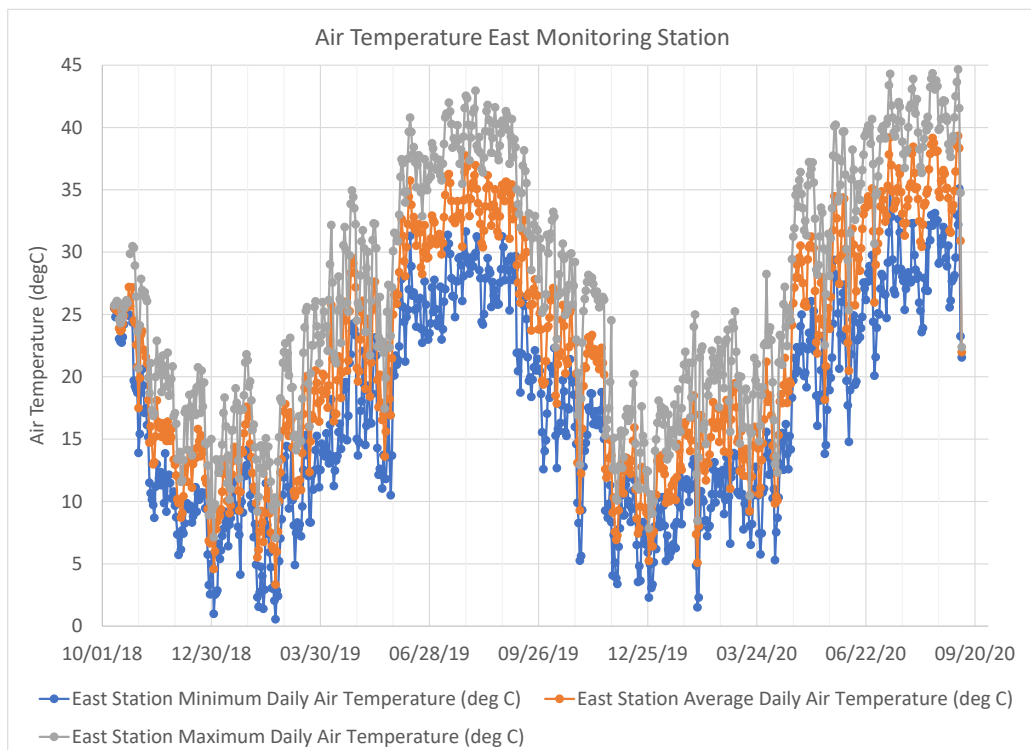


Figure 15. Daily Minimum, Average, and Maximum Temperatures.

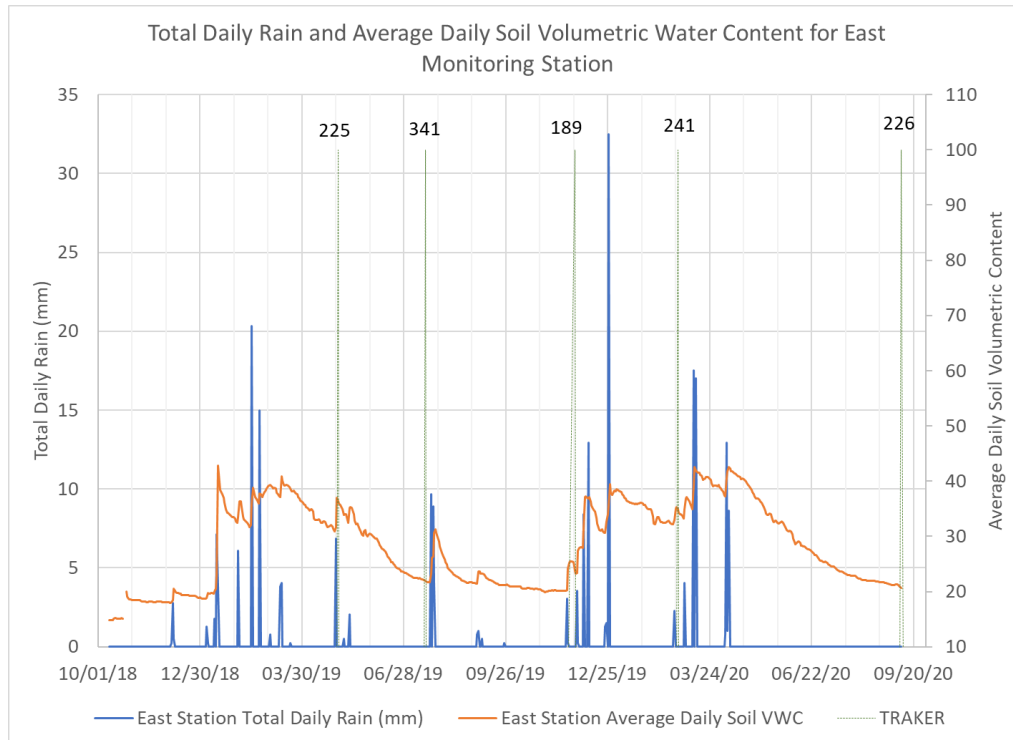


Figure 16. Rainfall, Soil Moisture at Depth (Volumetric Water Content), and Periods of TRAKER Measurement (Vertical Lines).

5.6.3 Monitoring Measurements: Vehicle Fleet Characteristics

The motion triggered cameras on the environmental monitoring stations allowed for the characterization of the vehicles that travelled adjacent to the monitoring stations. The cameras recorded single and multivehicle passes that were used to define the vehicle fleet characteristics. The video files were imported into a custom-designed LabView program (NI, Austin TX) where a single person used the program to compile a database of the date and time of occurrence, the type of vehicle observed, and whether it was a single vehicle or multi-vehicle pass. For multi-vehicle passes (labelled as convoys), the make-up of the vehicle group was also identified as all military, military-dominated (>50%), 50% military/50% civilian, or civilian-dominated (>50%). Table 4 lists the type of vehicles identified and convoys that were defined following initial viewings of video files.

Data recovery for vehicle information was sporadic due to several equipment failures and data storage communication issues. Therefore, the distribution of vehicle counts over the course of the two years of monitoring is subject to error. The composition of the fleet of vehicles that were recorded during the environmental monitoring period are shown in Fig. 17. The percent composition of the vehicles observed was dominated by civilian cars/pickup trucks/SUVs (47%) and military HMMWVs (21.6%). The timing of vehicle activity can be characterized for the hour of the day, day of the week, and month of the year as shown in Fig. 18. The passage of vehicles occurred frequently as a series following each other that are defined as convoys. These convoys were denoted by the relative percentage of military and civilian vehicles. The percent occurrence of convoy composition is shown in Fig. 19.

Table 4. Types of Vehicles and Categories of Used to Characterize the Vehicle Fleet at 29 Palms.

Vehicle Name	Vehicle Database ID#
Mil HMMWV	1
Mil LMTV	4
Mil Semi	5
Mil Tracked Vehicle	6
Mil Other	8
Mil HEMTT	9
TRACKER	-1
Car/Pickup/SUV	0
Box Truck	10
Semi Truck	11
Road Grader	12
Road Grader ON	13
Mil Convoy	14
Side by Side ATV	15
Civilian Convoy	16
DRI Service	17
Mil 5-ton	18
Heavy Duty Truck	19
Construction Equipment	20
Mixed Convoy Mil-dominated	21
Mixed Convoy Civ-dominated	22
Mixed Convoy 50-50	23
Other 1	25
False Trigger	2
Night Pass	3

Despite data loss the pattern of increased activity in fall and spring compared with decreased activity in summer and during the winter holiday months is consistent with expectation. The time of day and day of week (Fig. 18) distributions are also consistent with expectation, showing a pattern of reduced activity on weekends and during nighttime hours. The observed distribution of vehicles was reclassified into a simpler mix of the purpose of estimating emissions as discussed in the next section.

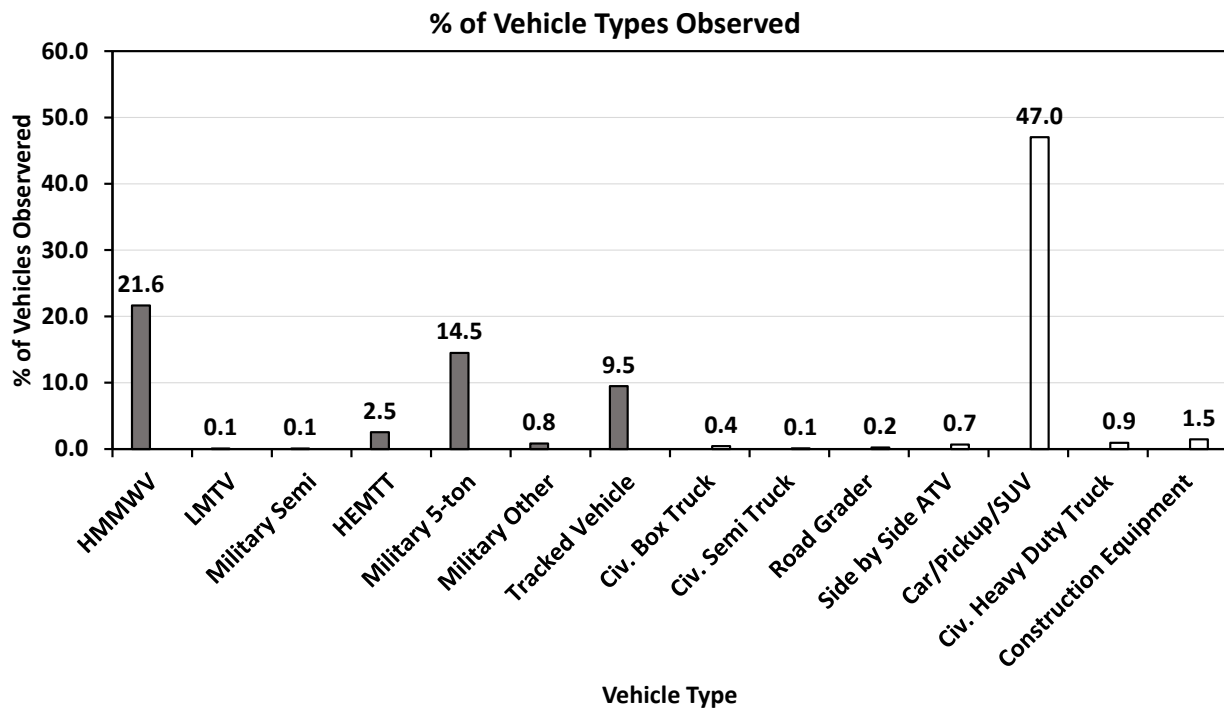


Figure 17. The Relative Composition of Vehicles Observed at the Monitoring Stations at 29 Palms over 2 Years.

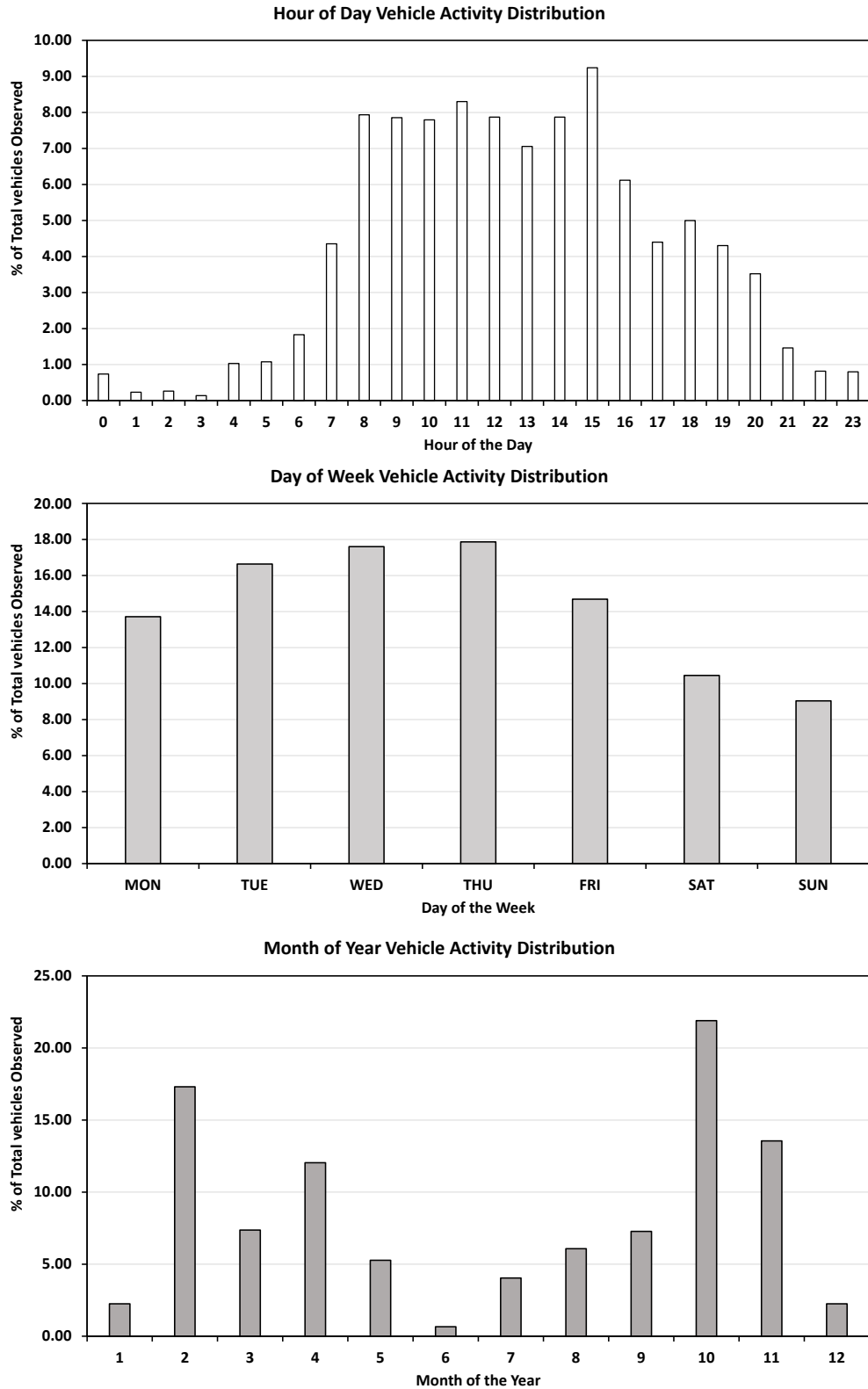


Figure 18. The Percentage of Vehicle Activity as a Function of Hour of the Day (Top Panel), Day of the Week (Middle Panel), and Month of the Year (Bottom Panel).

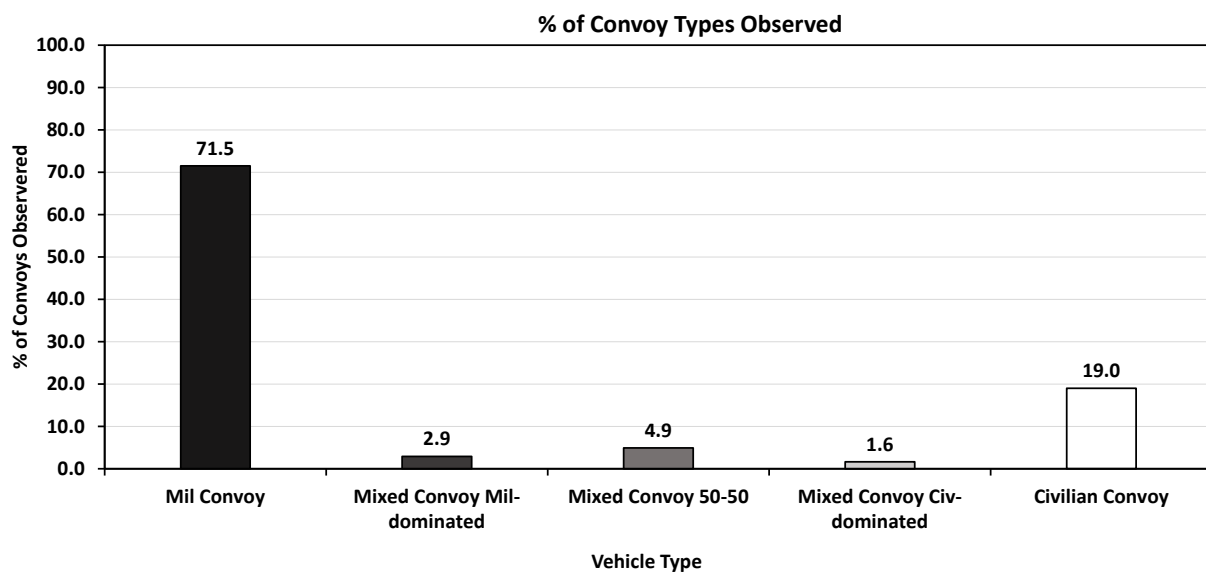


Figure 19. The Vehicle Composition of Convoys Expressed as the Relative Percentage of Military and Civilian Vehicles.

6.0 PERFORMANCE ASSESSMENT

The performance of TRAKER is based on an assessment of achieving its measurement precision target of 20%, ability to quantify seasonal bias in emissivity measurements, quantify dust palliative effectiveness, and to link the TRAKER emissivity data with an operational dispersion model to evaluate the impact of emissions on air quality.

6.1 PRECISION OF TRAKER MEASUREMENTS

Precision of TRAKER measurements was quantified by examining repeated measurements over the same road segment during the same measurement campaign so that seasonal variations and spatial variation do not impact the assessment of measurement repeatability. Where at least two valid measurements (each consisting of a minimum of 10, one-second measurements) were available, a Coefficient of Variation (CoV) was estimated as the ratio of the standard deviation of the segment measurements to the average of the segment measurements. The distribution of CoV is shown in Fig. 20. More than 87% of road segments measured during the five field measurement periods had a CoV lower than 20%, 95% of segments had a CoV lower than 30%, and 98.5% of segments had a CoV lower than 50%.

6.2 ENVIRONMENTAL BIAS EFFECTS ON EMISSIONS

Figures 8 through 12 provide clear indication that emissions potential of unpaved road dust at 29 Palms are significantly impacted by seasonal scale environmental changes. Figure 21 shows how the average TRAKER emissions measurement across all road segments tested at 29 Palms varied by measurement campaign. Also shown are continuous records of the ambient temperature, solar radiation, and rainfall. Although five data points are too few to provide a definitive assessment, taken in conjunction with anecdotal information as well as prior experience with measuring road dust, the weight of evidence suggests that in this arid region of the southwest US, there is a clear seasonal signal in the emissions. Generally, emissions are highest in the warmer months and lower in the cooler months.

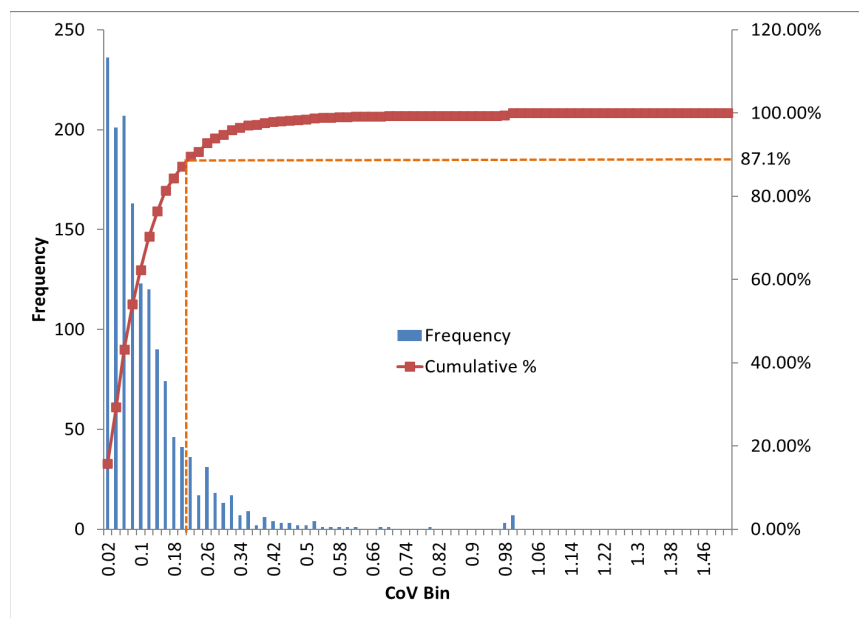


Figure 20. Distribution of Segment Coefficients of Variation (Total = 1493).

It is difficult to verify with direct measurement, but we hypothesize that the tendency towards higher emissions potential in summer than winter is due to the way in which solar radiation dries the top few centimeters of soil in the summer compared to the winter. Regardless of how low the moisture content of a soil, the pore spaces between soil grains below a few centimeters of depth are almost always near saturated with respect to water vapor (i.e., relative humidity [RH] >95%). This can be understood by recognizing that even in desert environments, rainfall results in the presence of liquid water at some depth in the soil, generally within 50 centimeters of the surface. The pore spaces near the liquid water are necessarily saturated with respect to water vapor. At depths below a few centimeters, the temperature profile within the soil column is constant, with changes over time occurring very slowly. Thus, saturated air near the liquid water remains saturated as it moves up through the soil layer, so that the span of pore spaces between where the liquid water is found and the near-surface are essentially saturated.

The region very close to the surface is an exception because it undergoes daily heating by ambient air temperatures and solar radiation, with the latter contributing to a much greater extent. This heating has two effects. First, it causes the air in the pore spaces between the soil grains to expand, so that some fraction must be expelled through the surface. This reduces the overall water vapor content in the pores. Second, when the soil temperature increases, the saturation vapor pressure of water also increases, so that the air in the pores is no longer near saturation. Effectively, this reduces the RH in the pore spaces. We hypothesize that with everything else held constant, road dust emissions would be modulated by solar radiation intensity, and this proposed mechanism by which pore RH is controlled, which is consistent with observations.

Seasonal changes in solar radiation could explain longer term trends in emissions potentials. There is no doubt, however, that rainfall has a more immediate, and sometimes absolute (i.e., reduces to zero) reductive effect on emissions. Thus, the true impact of environmental factors on road dust emissions is likely to be due to a combination of seasonal changes and discrete precipitation events. A hypothetical reconstruction of the road dust emission potential is shown as the dashed purple line in Fig. 21. Since we specifically targeted dry periods for conducting TRAKER field measurements, it is not possible to precisely estimate how quickly following rainfall emissions return to dry season values that are better represented by the solar radiation curve. The purple line in Fig. 21 represents a best approximation of the rainfall effect. The actual form of the relation can be defined if sufficient data were collected. Likely, the duration of impact of rain on emissions will depend on the rainfall amount, season in which it occurs, how well the soil is drained, and wind conditions. In practice, observation suggests that light rainfall in the summer has an impact that lasts as little as a few hours, while heavy rains in cooler months can impact emissions for two weeks or more. It is noteworthy that soil moisture measured at depth, remains elevated following a heavy rain for many weeks and generally has no predictive power with respect to road dust emissions. This is consistent with the hypothesis that the sun is effective at drying out the top few centimeters of soil and that soil moisture below this layer has minimal impact on the dryness of the soil at the surface, and therefore the potential for road dust emissions.

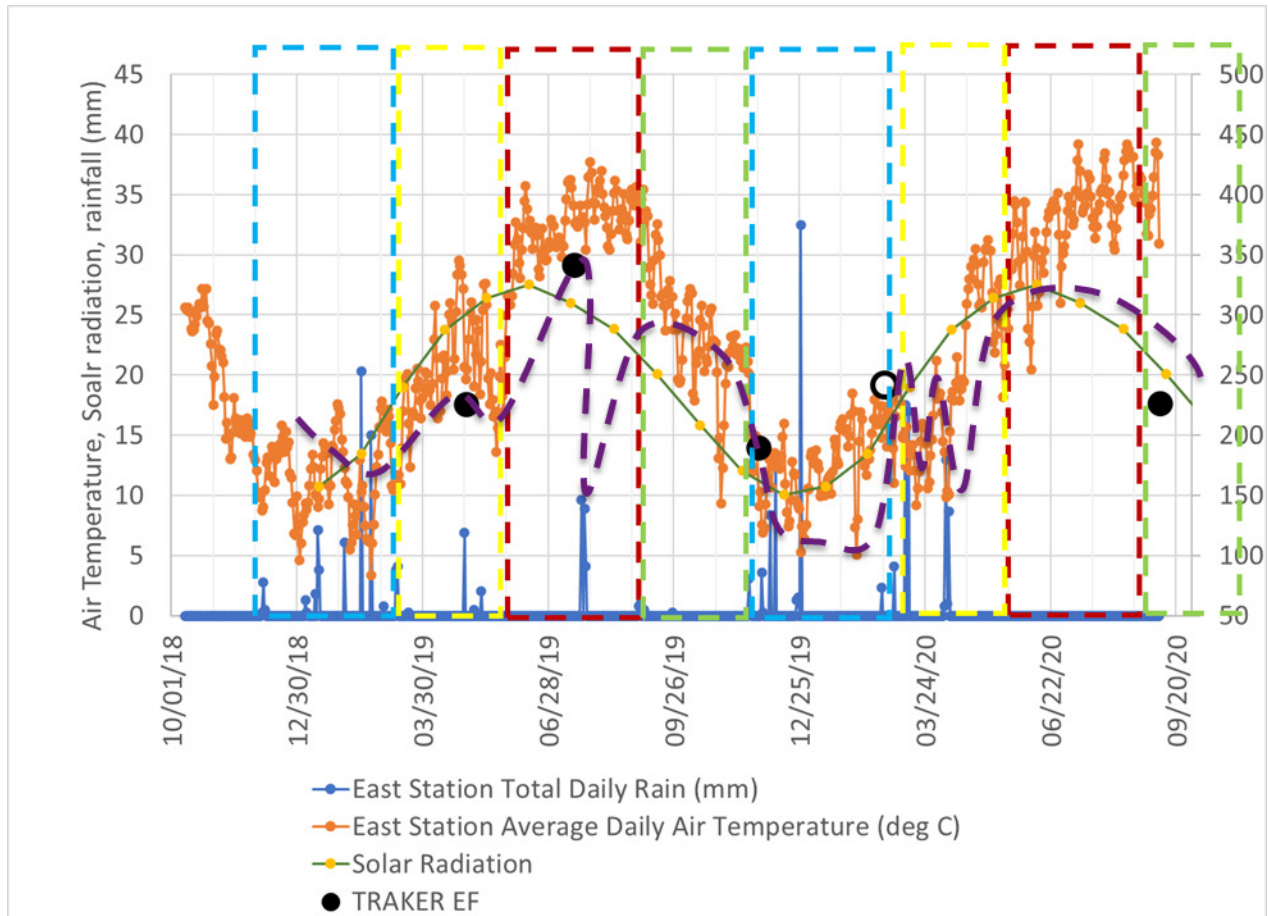


Figure 21. Averaged TRAKER Emissions Measurements and Meteorological Measurements.

Given that additional information is needed to assess the effect of rainfall on emissions and four data points may be too few to fit an equation to differentiate seasonal regimes, a simplified approach for applying environmental corrections is warranted for representing seasonality effects in the modeling of emissions from vehicle activities at 29 Palms. For this purpose, we define seasons based on clear shifts in weather regimes as reflected by the ambient temperature (see Fig. 21). “Summer” (dashed red line) representing the highest potential for emissions is the period near and following the solstice that is characterized by relatively unchanging daily temperatures. This corresponds to the period from May 25 – August 31. Similarly, “Winter” (blue dashed line) represents the lowest potential for emissions and starts shortly before the solstice on December 21, ends on February 28, and is characterized by relatively constant temperatures. “Spring” (yellow dashed lines) and “Fall” (green dashed lines) are the periods in between when changes in ambient conditions can be rapid. These two seasons are assumed to exhibit similar potentials for road dust emissions and are therefore combined into one category. Figure 21 shows which TRAKER data sets were used to estimate the emissions potentials for the respective seasons. For modeling, it was assumed that emission potentials were static over an entire season. This assumption can be modified in future implementations where there is specific knowledge about rainfall amounts and the resultant effects on emissions for specific installations.

6.3 DUST PALLIATIVE CONTROL EFFECTIVENESS

Since it was not possible to directly measure the dust control afforded by a palliative specifically applied for this demonstration project, we instead estimate how many meters of dust control application are required to detect a difference between the baseline road emission and the dust-controlled emission measurement with 95% confidence (Table 5). Note that the entries in the table indicate the minimum difference in emission potential that can be detected with confidence. This difference cannot be solely ascribed to the efficacy of any applied dust controls since there are also environmental factors that can lead to changes in emission potential from one point in time to another. In practice, any assessment of dust control effectiveness will require that measurements conducted over varying environmental conditions be adjusted for an observed effect. This can be accomplished by application of correction factors as discussed in Section 6.2 or by applying empirical corrections derived from road segments where no treatment was applied and that were sampled at the same times as the road segments where treatment was applied. The road segments without any treatment can serve as experimental controls.

6.4 INTEGRATING TRAKER DATA WITH A DISPERSION MODEL

This section describes the coupling of TRAKER-derived emission data with the US EPA sanctioned dispersion model American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD; <https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models#aermod>). AERMOD is EPA's preferred near-field dispersion modeling system, which uses a steady-state plume formulation that incorporates complex terrain and air dispersion based on planetary boundary layer turbulence structure and scaling concepts. We adapted this model to incorporate novel emission factors (i.e., kg PM₁₀ vkt⁻¹) based on measurements from TRAKER. Together, the model framework presented constitutes

Table 5. Meters of Dust Control Application Are Required to Detect a Difference Between the Baseline Road Emission and the Dust-controlled Emission Measurement with 95% Confidence.

Segment length	Difference detectable with one pass	Difference detectable with 3 passes	Difference detectable with 5 passes
200 m	42%	14%	8.5%
400 m	30%	10%	6.0%
600 m	24%	8.2%	4.9%
800 m	21%	7.1%	4.2%
1,000 m	19%	6.3%	3.8%
2,000 m	13%	4.5%	2.7%

a tool for realistic predictions of PM₁₀ or PM_{2.5} concentrations created by observed vehicle activity patterns, with options to simulate user-defined scenarios of vehicle activity that represent known testing and training vehicle activity patterns or for testing hypothetical patterns. This flexibility allows the modeling system to be used as a tool for planning testing and training vehicle movement and evaluate the effects of the vehicle-generated dust emissions on air quality at the source and downwind at receptors of interest (e.g., nearby residential areas or points of specific interest [e.g., schools or hospitals]). A schematic of the process is illustrated in Fig. 22.

Emission
potential
(TRAKER)

Emission
potential
(TRAKER) + Vehicle
Activity = Emissions
Inventory

Emission
potential
(TRAKER) + Vehicle
Activity + Meteorology + AERMOD
Dispersion Model-
(EPA Approved;
DRI interface) = Air Quality
Impacts and
Planning

Figure 22. The Model Framework Process that Couples Emission Potential Measurements Made with TRAKER, Environmental Variables (i.e., Meteorological Data), with AERMOD to Estimate Impacts on Air Quality.

6.4.1 Emission Inventory

To create an emission inventory from the TRAKER measurements requires that they be scaled to represent the emission potential of other vehicles and the seasonal bias factor (if available). The scaling factors for vehicles are based on Gillies et al. (2005) and Kuhns et al. (2010) that examined how vehicle weight and speed influenced emissions from unpaved roads. Table 6 presents the scaling factors for combined categories of vehicles representative of those observed at 29 Palms. The number of categories has been reduced from those in Table 4 and Fig. 17 to simplify specification of vehicle mixes for the purpose of modeling. These values can be adjusted to provide better representation for different installations.

TRAKER measured Emission Factors (EF, kg vkt⁻¹) for the different seasons and road segments are multiplied by the emissivity of each individual vehicle; recall that each vehicle has an emissivity multiplier relative to TRAKER measurements. AERMOD, however, requires that emissions be in units of g s⁻¹ m⁻². This conversion is completed in the pre-processing stage and the vehicle activity and related emissions (or emissions inventory in) varying in space (each road segment) and time (hourly) are provided to AERMOD. The total emissions inventory is the summation of emission contributions from each individual vehicle.

The observed vehicle activity was used to develop realistic emissions as a function of time (hour of the day, day of the week, and season; hereafter *Normal*) for 29 Palms (Figs. 17, 18, 19). Alternatively, different scenarios (hereafter *Scenarios*) can be created by prescribing vehicle activity for a given hour of the day, vehicle type, and vehicle count, which can represent planned or hypothetical vehicle activities. Table 7 shows an example of a hypothetical late afternoon activity consisting of 51 vehicles of different categories. Contrasting model results of dust dispersion related to *Normal* against those from different *Scenarios* offers the capability to assess whether the designed *Scenario* could result in detrimental air quality impacts compared to those defined by *Normal* vehicle activity.

Table 6. Vehicle Categories, TRAKER Scaling Factors, and Vehicle Represented by the Category.

Category	TRAKER Multiplier	Vehicles in Category	Gross Vehicle Weight Class (kg)
Civilian	0.8	Car/pickup/SUV	<4000
Heavy Payload	11.5	Semi-trucks, HEMMT	35000-55000
Medium Payload	4.2	LMTV, 5-ton, road construction	19000-35000
Light Payload	1.2	HMMVW, heavy duty service truck, box truck	4000-10000
Heavy Tracked	19	M1 Abrams	>50000
Medium Tracked	9.5	Tracked	<50000
Side-by-Side	0.33	ATV	<2000

Table 7. An Example Vehicle Activity Scenario Representing the Deployment of 51 Vehicles of Different Categories During Late Afternoon Hours.

		Over-night 1	Over-night 2	Over-night 3	Morning 1	Morning 2	Mid-day 1	After-noon 1	After-noon 2
		21:00-23:00	00:00-02:00	03:00-05:00	06:00-08:00	09:00-11:00	11:00-13:00	14:00-16:00	17:00-19:00
Category (#Vehicles)	Activity Times (Local)								
	Civilian	0	0	0	0	0	0	0	14
	Heavy Payload	0	0	0	0	0	0	0	12
	Medium Payload	0	0	0	0	0	0	0	4
	Light Payload	0	0	0	0	0	0	0	6
	Heavy Tracked	0	0	0	0	0	0	0	2
	Medium Tracked	0	0	0	0	0	0	0	8
	Side-by-Side	0	0	0	0	0	0	0	5

6.4.2 Creating Vehicle Inventory, Emission Factor, and Temporal Profiles

Vehicle inventories that represent, for example, a testing/training activity, the associated emission factors, and the temporal profile of activity (i.e., which vehicles are moving during which hour of the day) are developed within an easy-to-interact with Excel file format (EmissionFactors_x_t.xlsx). The defined vehicle activity scenario is provided to the dispersion model using the Python script developed as part of this project. The spreadsheets contain information that represents the annual vehicle inventory for an installation (e.g., Fig. 17 for 29 Palms) and other user-defined time and vehicle activity profiles that represent scenarios of interest or of planned testing and training activities. The spreadsheets are distributed as follows:

- Vehicle_distribution (Normal): Contains vehicle categories and their emission factors relative to TRAKER for the installation based on the annual vehicle activity patterns.
- RoadSegments (Normal): Contains the lookup table that relates the road segment information with the TRAKER Emission Factors for every season (to account for the defined seasonal biases).
- Diurnal_distribution, Weekday_distribution, Monthly_distribution (Normal): Time profiles of the vehicle activity as a fraction of the total number of observed vehicles.
- Diurnal_distribution, Weekday_distribution, Monthly_distribution (Normal): Time profiles of the vehicle activity as a fraction of the total number of observed vehicles.
- Vehicle_categories (Scenario): Used for *Scenario* development. Vehicle categories and their respective emission factors relative to TRAKER are provided (Table 6).
- ScenarioDiurnalProfiles (Scenario): Hourly vehicle activity profiles (i.e., fraction of vehicles in motion) for different periods during the day. Several periods can be implemented but temporal profile factors need to be modified accordingly (Table 8). Note that the sum of factors for the period to be implemented must add to 1.
- ScenarioVehicleDistribution (Scenario): this table relates the Scenario vehicle activity by providing the number of vehicles for any vehicle category and period during the day (see Table 7). Note that the number of rows must correspond to the entries in the Vehicle_categories spreadsheet (Table 6) and the number of columns must correspond to the entries in the ScenarioDiurnalProfiles spreadsheet (Table 8).

Table 8. Example of Vehicle Activity Period Scenarios to Facilitate Specifying Windows of Activity.

Hour	Overnight 1	Overnight 2	Overnight 3	Morning 1	Morning 2	Midday 1	Afternoon 1	Afternoon 2
0	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00
1	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.33	0.33	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
23	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

6.4.3 Meteorological Input

The model utilizes surface and upper-air level data preprocessed at hourly time increments, which is available from multiple sources and will be dependent on the data available for any individual installation. For this demonstration project observations from the 29 Palms Airport surface station site (KNXP; 34.29401 °N, 116.14717 °W) were available. This source of observations is located in the middle of the defined modeling domain and contains records with relatively good quality observations.

Significant efforts are needed to preprocess and adapt meteorological data, such as those available from 29 Palms Airport, to create an input data file for AERMOD. As a first step the Python script carries out basic quality control and quality assurance procedures to treat missing data and remove outliers. Hourly upper-air vertical profiles of temperature, wind, and turbulence parameters were retrieved for the nearest grid point closest to the surface station using the ERA5 modern reanalysis products (available at hourly time increments and 0.25° grid size). This was a necessary step due to the lack of upper-air radiosonde observations (National Weather Service operational soundings) near 29 Palms. Surface and upper-air observations generally conformed well in time, despite some reanalysis scale issues; of note is that the surface site implemented here has been assimilated into the reanalysis products. All necessary input parameters were estimated following AERMET procedures (AERMOD meteorology preprocessor; EPA, 2018c) and input meteorology data were created conforming the input files using the default format for AERMOD (aermet2.sfc and aermet2.plt for surface and upper-air profiles, respectively).

For this demonstration project, hourly meteorology data for the full year 2019 were prepared using the Python script. The current model setup for 29 Palms can be executed for any day and period during that year. The ERA5 reanalysis product allows for the estimation of hourly upper-air sounding data that are typically measured only twice a day (00 and 12 UTC), which improves the forecast. Although the use of hourly reanalysis profiles can help reduce major underlying assumptions of the mixing layer in space and time there are intrinsic limitations with ERA5 reanalysis due to issues of scale and underlying assumptions in the data assimilation procedure and relevant parameterization schemes.

Available historic meteorological data are typically used for air quality assessments after the event of interest has occurred (diagnostic mode), for example after a testing and training activity has taken place. The system developed as part of this demonstration project can use forecast (real-time) data for prognostic operation-planning purposes (i.e., future testing and training activities under forecast meteorological conditions). Our system provides options to automatically download North American Mesoscale Forecast System (NAM) or Global Forecasting System products. This forecast option can be used to simulate the *Normal* or a *Scenario* vehicle activity condition for real-time estimates of impacts on PM₁₀ concentrations anywhere in the domain under the influence of the forecast weather conditions.

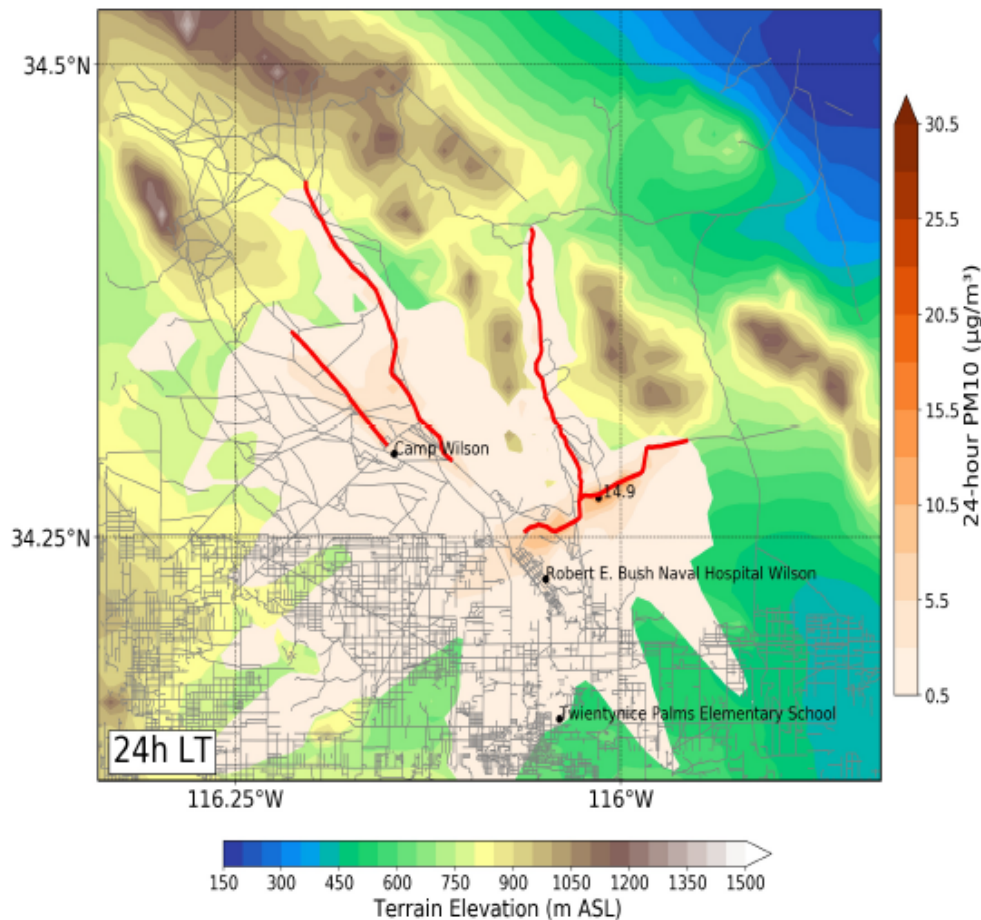
6.4.4 Model Execution

The developed model framework uses Python language as the model driver, which is defined here as the “wrapper”, as it wraps around AERMOD organizing the input and output data. The wrapper adapts the model domain, prepares the meteorology for diagnostic or prognostic time frames, and estimates emissions based on the input activity scenario. The wrapper and AERMOD have been compiled so that it can be used on Windows, Mac, and Linux operating systems (OS). The user is required to use executable scripts according to their OS systems. If warranted by future demand, the system could be executed via a web portal at Dust-Solve, LLC, which would divorce it from a local OS used at an installation.

The model has been tailored and adapted to operate in both diagnostic and prognostic modes for a variety of surveyed mobile emissions distribution (and design scenarios) such as: vehicle types, hour, day of week and month. Users are required to interact with several input parameters, including simulation period (diagnostic or prognostic), vehicle activity type (*Normal* or *Scenario*), receptor information, and the TRAKER derived data on emissivity and position on the road network. Meteorology parameters and emissions inventory are then estimated and adapted to run automatically by AERMOD. The model is very efficient and can be executed on a normal desktop PC. One simulated day scenario can be executed in approximately 2-3 minutes. Currently, the model can simulate any day of 2019 or perform simulations for periods extending from weeks, seasons, or the full year for 29 Palms. The model framework performs basic post-processing of the simulated output and prepares an easy-to-read report summarizing the input parameters and model results (Figs. 23a, b and 24a, b).

Region:	29 Palms	Simulation Type:	NormalObs	Road Segment:	All	Period Start:	2019-07-26H00
Date Report:	09/26/2021	Hour Report:	12:47:39	Performed by:	J. Mejia	Period End:	2019-07-27H00

(I) SURFACE 24-HR PM10 VALUES FOR SOURCE GROUP:



Maximum 1-hour PM10 ($\mu\text{g}/\text{m}^3$): 1.0; Location: 34.388 °S, 116.165 °W

- Terrain Elevations from the NASA's Shuttle Radar Topography Mission (SRTM) 250 m resampled to 1 km grid size

- Primary and secondary roads, highways, streets from the California Highway ArcGIS database.

Figure 23. (a) Dispersion Model Report Output Based on AERMOD and a Synthetic Vehicle Inventory and Temporal Activity Example *Scenario*. Report is Produced in PDF Format and Contains Statistics and Graphics Developed to Facilitate Planning and Decision Making. This Example Shows Results Integrated Over 24 Hours for PM₁₀ Concentrations Across the Domain. (b) The Meteorology (Bottom Left Panel), and the PM₁₀ Concentrations at Three Selected Receptor Sites.

(II) SURFACE METEOROLOGY:

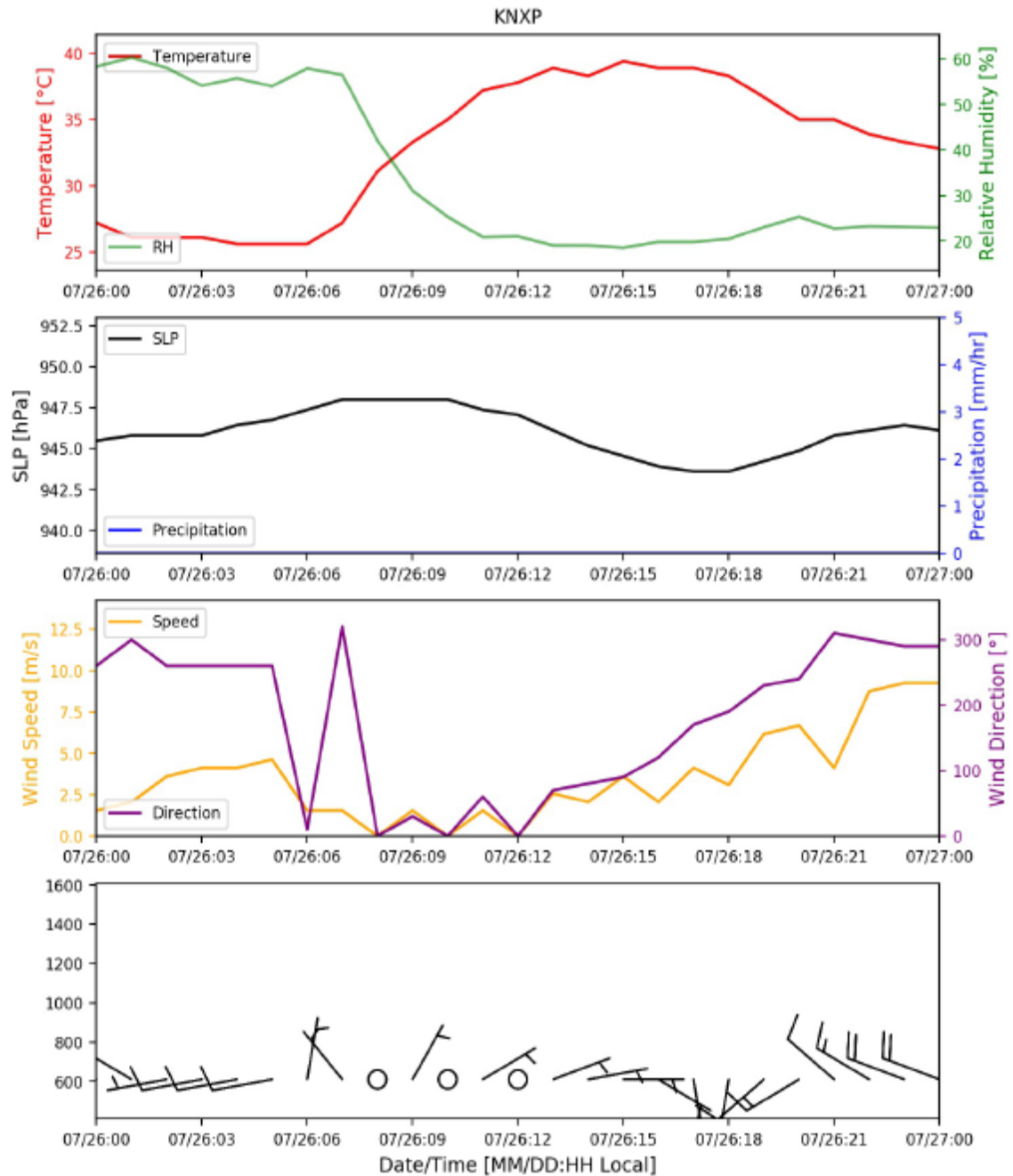


Figure 23b. The Meteorology and the PM₁₀ Concentrations at Three Selected Receptor Sites.

(IV) HOURLY RECEPTOR MAPS:

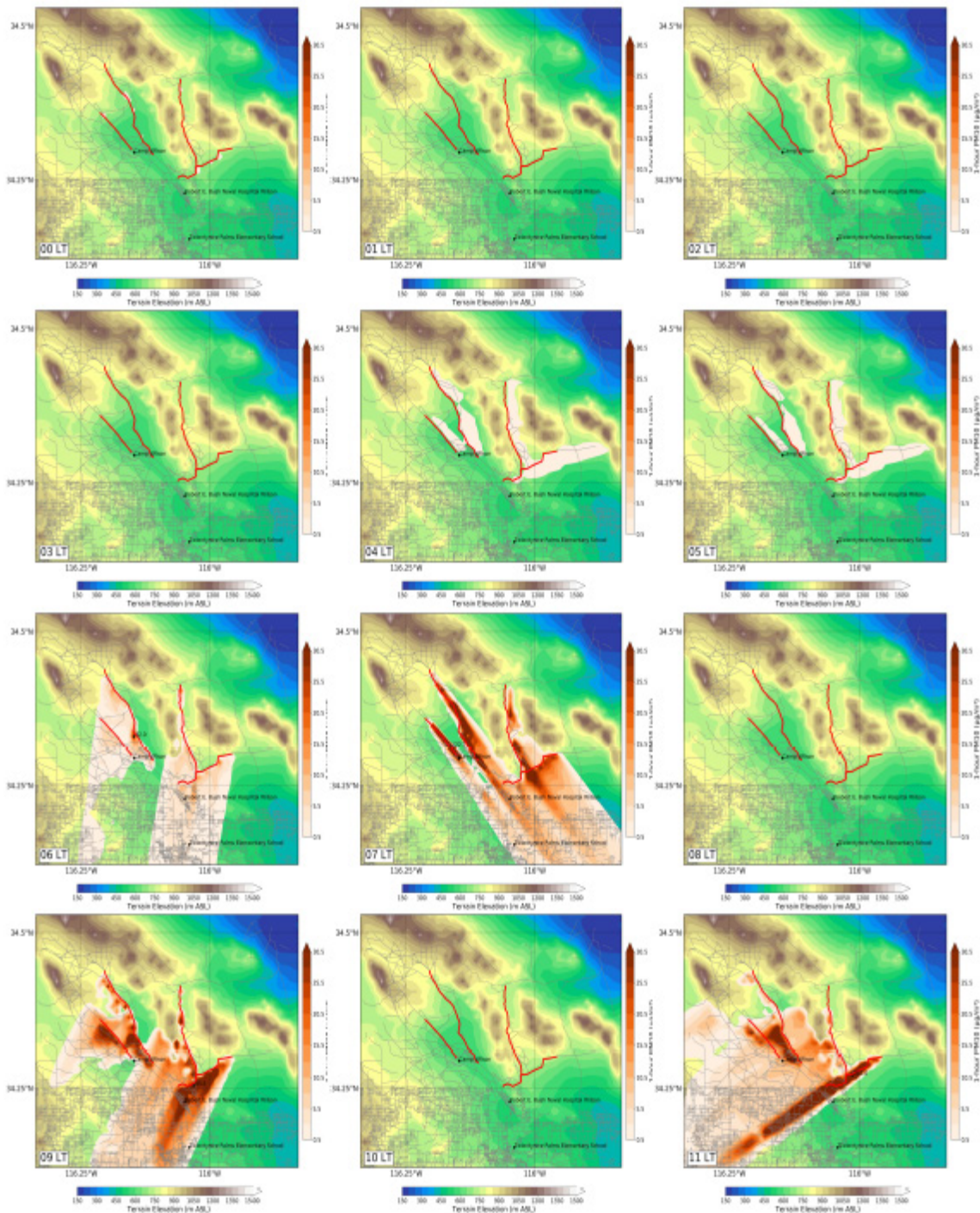


Figure 24. PDF Report Function Produces Maps of PM₁₀ Concentrations for Each Hour of the Day that Visualize Effects of the Developed *Scenario* Across Space, Through Time, and for Receptors of Interest. (a) Hours 00:00 to 12:00, (b) 13:00 to 12:00

(IV) HOURLY RECEPTOR MAPS (cont...):

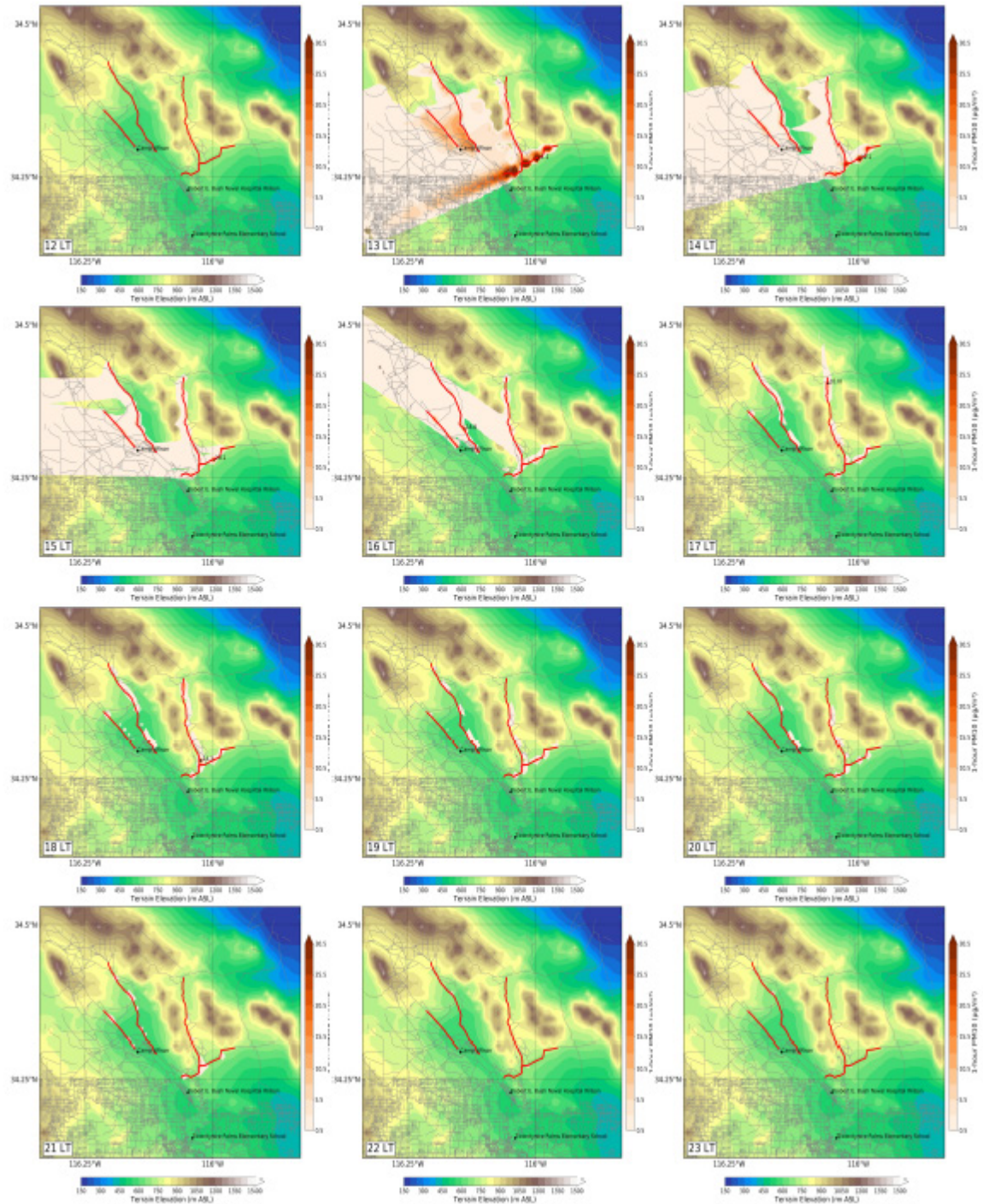


Figure 24. (b) Hours 13:00 to 12:00.

The model output as shown in Figs. 23 and 24 do not account for the background concentrations of PM₁₀ during the time frame of interest. Only PM₁₀ dust related to vehicle activity and its subsequent dispersion are considered. If observations of background PM₁₀ are available from nearby monitors, the user can add those values to the model generated values to estimate the total PM₁₀, but care must be taken in the consideration of the timing and averaging (e.g., 24-hour mean or hourly mean values) of available air quality monitoring data.

The model values are simulated independently for each hour and do not accumulate from all previous hours. This is a reasonable assumption for near field dispersion modeling formulations that extend up to distances of tens of kilometers.

7.0 COST ASSESSMENT

7.1 COST MODEL

The cost model presented is based on the experience of executing the demonstration plan objectives at the 29 Palms test site. The tasks completed and the expenditures to complete those tasks are those that would be expected to occur when an installation contracts with Dust-Solve, LLC to provide them with information to characterize and quantify the emission potential of their road network, their vehicle fleet characteristics and activity levels, aid in developing their PM₁₀ or PM_{2.5} inventories for permitting, and provide an assessment of the potential impacts of different testing and training activity scenarios on regional air quality. The cost of a standalone assessment of the effectiveness of dust palliatives is also provided in Table 9, which will be largely dependent upon the number of palliatives to be tested.

The analyses to arrive at the TRAKER daily rate is provided below.

7.1.1 TRAKER Daily Rate

The current daily rate for TRAKER is based on an estimated (annual) labor cost (for the principles and a technician=\$4800), operating expenses include instrument calibration (\$3,600 annually), vehicle maintenance (\$1000), and supplies (\$4,000). No depreciation is considered and the usage days per year is set currently at six. There is an indirect cost rate added of 65% for Federal Contracts and 75% for private as the TRAKER unit is leased to Dust-Solve, LLC under a licensing agreement with the Desert Research Institute, Las Vegas, NV. The daily rate in 2021 is \$5,000 (Federal) and \$5,303 (private).

7.2 SCALABILITY

The TRAKER system does not require the consideration of scalability as it relates to the hardware and software components as it is at full scale. A perceivable scaling factor would be that at a certain demand level, additional TRAKER instrument pallets would need to be constructed.

7.3 COST DRIVERS

Cost drivers for using TRAKER and the associated modeling system will be dependent on the level of effort proposed by an installation to achieve its management objectives that deal with dust emission created by the activities on the base, and the amount of that effort that Dust-Solve, LLC will be responsible for versus the effort the installation chooses to be responsible for.

Basic cost drivers are:

- The frequency of TRAKER usage and the desired degree of uncertainty bounding
- Availability of on-site meteorological data
- Availability of on-site vehicle distribution/activity data
- The motivation for the contracted effort that could include:
 - Emission inventory only
 - One time or multiple model runs to assess impacts of testing and training activities

- Continued modeling support to support decision making and inform management strategies
- Dust control effectiveness testing

A minimum broad characterization of the emissivity of an installation's unpaved road network would require 3-4 days of use (2 days of measurements and 1-2 days of assembly, shipping, traveling). This would provide a point-in-time snapshot of the road network emission potential. If seasonal effects are not known and deemed to be important, then the usage days ranges between 9 – 24 days (i.e., 1-2 days per trip, 3-4 trips per year, over 1-3 years). If a special study was to be carried out, e.g., palliative performance tests, that would require additional usage days (open-ended, but 12 days would be our upper limit estimate). We note that approximately half the cost is incurred in the setup, planning, and reporting. The number of usage days is not deemed to be the most significant cost driver.

Table 9. Cost Model

Cost Element	Cost
Initial Planning/Training/Site Visit	\$25K
Daily Usage Rate (DUR)	\$5K
Meteorological/PM/Vehicle Monitoring (2 Years)	\$50K
Vehicle Classification Inventory	\$30-\$50K
Emission Inventory (PM emitted by installation)	\$25K
Model Set Up (estimating effects of emissions)	\$40-\$50K
Modeling runs for requested scenarios	\$20-\$40K
Evaluating dust control effectiveness	\$20-\$80K
Annual support (following initial year) (e.g., update model inputs and runs)	\$15-\$20K
In Depth Training	\$35K

7.4 COST ANALYSIS

The cost structure presented in Table 9 is scalable as the client can choose to have personnel become capable in all or part of the Cost Elements listed. At a minimum, the cost would be the Initial Planning/Training/Site Visit (\$25,000) and the daily usage rate (\$5,000/day) for the rental of the TRAKER instrument pallet (plus shipping) for the number of days rented to accomplish the task required. To reach the level of proficiency required by on-site personnel to collect data, QA/QC the data, and carry out analysis components (e.g., emission inventory and being able to run the TRAKER/AERMOD model) an in-depth training session would be recommended with an associated cost of \$35,000.

In general Dust-Solve, LLC estimates that to carry out a level of effort similar to what was accomplished at 29 Palms and an effort that demanded a greater effort would be approximately \$260-\$420k (based on Table 9).

An evaluation of dust palliative effectiveness would require using the TRAKER for multiple days and the level of effort will depend on the number of palliatives to be tested. The cost range is \$20,000 to \$80,000.

To the best of our knowledge a technology and modeling system similar as described in this demonstration project is not commercially available.

8.0 IMPLEMENTATION ISSUES

8.1 REGULATIONS FOR TRAKER USE

There are no Federal or State regulations that restrict operation of TRAKER in a civilian environment with the exception that when used on public roads the vehicle needs to be operated as guided by traffic regulations that apply to the roads being measured.

Operating TRAKER on military installations may require compliance with an Environmental Impact Review as was necessary for Dust-Solve, LLC to undertake the TRAKER measurements at MCAGCC 29 Palms. The decision in support of allowing measurement at MCAGCC 29 Palms was based on the activities undertaken as part of this demonstration project satisfying the National Environmental Policy Act review requirements and qualified as a categorical exclusion (CATEX) in compliance with 32 Code of Federal Regulations Part 775.6(f)(18). CATEX 18 applies to "studies, data, and information gathering that involve no permanent physical change to the environment (e.g., topographic surveys, wetlands mapping, surveys for evaluating environmental damage, and engineering efforts to support environmental analyses)."

8.2 END-USER CONCERNS, RESERVATIONS, AND DECISION-MAKING FACTORS

- It is important to review data as it is being collected to ensure that all instruments are operating correctly
- Use of cell modems is encouraged to enable downloading and data review for monitoring stations in the field
- If possible, plan the study with contingency data collection methods if the initial optimal conditions change such as heavy rain that washes dust suppressants from part of road network
- Plan to collect the data under realistic conditions even if it may show high emissions
- Use the collected data to optimize management decisions to ameliorate PM emission from testing and training activities

8.3 PROCUREMENT

Equipment to maintain or construct additional TRAKER instrument pallets are all commercial off-the-shelf products. The baffle at the rear of TRAKER is fabricated to specifications at a machine shop, but the materials are readily available, and procurement of additional baffles is easily assured.

A new TRAKER platform would need some redesign as it would need to be modified to integrate the new model TSI DustTrak 8530 instead of the outdated DustTrak 8520. The cost of a new TRAKER platform is approximately \$75K in supplies and materials. Labor costs are not considered.

8.4 MARKET DEVELOPMENT

The SARS-CoV-2 pandemic affected Dust-Solve, LLC's ability to market TRAKER's capabilities in 2020 and in 2021 due primarily to travel restrictions and the change from in-person conferences and meetings to virtual platforms.

As of October 14, 2021, Dust-Solve, LLC has produced a video that provides an account of this demonstration project framed to provide potential clients an understanding of TRAKER development, its capabilities, and its utility along with the integrated AERMOD dispersion model to meet their needs for developing vehicle generated PM₁₀ and PM_{2.5} for inventories. This highlights the system as being an effective a tool for managing testing and training activities that generate dust, which can impact local and regional air quality. This video is available for viewing at the Dust-Solve, LLC website (<http://www.dustsolve.com/>) and on these social media platforms: https://www.youtube.com/channel/UC4C0jIJaZWveAv_X-9Zru0w, <https://www.instagram.com/dustsolve/>, twitter: @dustsolve.

Dust-Solve, LLC presented the results of this demonstration project and an overview presentation of the TRAKER and AERMOD system to personnel at MCAGCC, 29 Palms, November 16, 2021.

Dust-Solve, LLC team presented an overview of the results of this demonstration project and the capabilities of the TRAKER/AERMOD system as part of the DoD Natural Resources Program Webinar series, November 18, 2021.

Dust-Solve, LLC will continue to market our capabilities at meetings and trade shows.

8.5 LESSON LEARNED

- TRAKER DC battery packs provide efficient and reliable power sources
- Wireless network between control tablet and TRAKER WiFi router operated reliably and can be used in future versions
- Motion triggered cameras for detection of traffic by the meteorological stations need to be upgraded to a more reliable model for field operations
- MetOne Profiler instruments for characterizing near road PM need to be collocated before field deployment with a known PM₁₀ standard instrument
- Replace MetOne profilers after approximately 12 months of continuous field monitoring
- Develop AI video processing tool for identifying vehicles passing by the monitoring stations

8.5.1 Responses to IPR Requests 2020

These requests were posed at the 2020 IPR for discussion in this Final Report:

- The emission factors from the different soil types

- Consider mapping out the different dust generation processes that are relevant and see how much progress has been made with the characterization, what do we know and what do we not know at this point

TRAKER measures emissivity of roads across space and through time, which provides data to allow estimation of PM emission inventories and to inform AERMOD such that, along with the developed Python code, the combined system can provide estimates of impacts of PM emitted by vehicles operating on DoD facilities at the local and regional scale. We observed and quantified the bias in emission factors that are related to short- and longer-term environmental variables, but we could not filter out a bias that could be related to the sedimentary characteristics of the road. The roadbed is in many instances a complex mixture of the native soil in the vicinity of the road as well as soil material that may have been brought from other areas and mixed with this material, amended with gravel material from yet another area, and then subsequently graded. Disentangling the relative effects of the various road components on vehicle-generated dust emissions would increase our understanding of the controls on those emissions and TRAKER could provide a well-characterized measurement of the emissions, but those measurements would need to be combined with detailed sediment characterization measurements of the roadbed. This level of effort for this type of research was beyond the scope and budgetary constraints of this demonstration project.

The second request, we respectfully suggest, was also beyond the scope of this project to undertake within the confines of the need to complete the deliverables within the budget of the project. The evaluation of dust generating activities beyond those associated with wheeled/tracked vehicles characterized as part of this demonstration project was not feasible given the goals and objectives of this demonstration project.

8.5.2 Responses to IPR Requests 2021

This request was posed at the 202 IPR for discussion in this Final Report:

- Within the cost assessment portion, consider determining the cost savings, or mission relief, that TRAKER may provide to an installation when considering air permitting requirements and costs over current approaches.

As we investigated this following the 2021 IPR, we found that installations often contract this activity to private companies, and we were unable to formulate how cost savings could be realized using TRAKER. We note, however, that using TRAKER and the associated modeling components developed for this Demonstration Project, to develop emission inventories required for permitting would be much more accurate and defensible based on TRAKER methodology being an EPA-approved Other Test Method (OTM-34) designation. The data generated for emission inventories and used in permitting will be given a high degree of credibility, compared to less robust methods that use assumptions regarding emissivity that are not based on current knowledge of dust emission physics and the influence of environmental parameters.

9.0 REFERENCES

- Etyemezian, V., Kuhns, H., Gillies, J.A., Chow, J.C., Green, M., Hendrickson, K., McGowan, M., Pitchford, M., 2003a. Vehicle based road dust emissions measurement (III): effect of speed, traffic volume, location, and season on PM₁₀ road dust emissions. *Atmospheric Environment* 37, 4583-4593.
- Etyemezian, V., Kuhns, H., Gillies, J.A., Green, M., Pitchford, M., Watson, J.G., 2003b. Vehicle based road dust emissions measurement (I): methods and calibration. *Atmospheric Environment* 37, 4559-4571.
- Etyemezian, V., Kuhns, H.D., Nikolich, G., 2006. Precision and repeatability of the TRAKER vehicle-based paved road dust emission potential. *Atmospheric Environment* 40, 2953-2958.
- Etyemezian, V., Nikolich, G., Lauer, A., Azate, A.F., Batcha, F.S., Kaur, M., Mander, J., Passaglia, A.K., Garcia, E. (2018). *Assessing the Impacts of Climate and Land Use/Land Cover Change on Valley Fever Incidence*. Final Report prepared for SERDP, Alexandria, VA, Jan. 2018.
- Fitz, D.R., Bumiller, K., Bufalino, C., James, D.E., 2020. Real-time PM₁₀ emission rates from paved roads by measurement of concentrations in the vehicle's wake using on-board sensors part 1. SCAMPER method characterization. *Atmospheric Environment* 230, 117483.
- Fitz, D.R., Bumiller, K., Etyemezian, V., Kuhns, H.D., Gillies, J.A., Nikolich, G., James, D.E., Langston, R., Merle, R.S., 2021. Real-time PM₁₀ emission rates from paved roads by measurement of concentrations in the vehicle's wake using on-board sensors Part 2. Comparison of SCAMPER, TRAKER™, flux measurements, and AP-42 silt sampling under controlled conditions. *Atmospheric Environment* 256, 118453.
- Gillies, J.A., Arnott, P., Etyemezian, V., Gillette, D.A., Kuhns, H., McDonald, E., Moosmüller, H., Nickling, W.G., Schwemmer, G., Wilkerson T. (2005). *Characterizing and Quantifying Local and Regional Particulate Matter Emissions from Department of Defense Installations: Final Report*. Prepared for Strategic Environmental Research and Development (SERDP), Arlington, VA, 22203-1821, March 2005.
- Gillies, J.A., Etyemezian, V., Kuhns, H., Nikolic, D., Gillette, D.A., 2005. Effect of vehicle characteristics on unpaved road dust emissions. *Atmospheric Environment* 39, 2341–2347.
- Gillies, J.A., Etyemezian, V., Kuhns, H., Moosmüller, H., Engelbrecht, J.P., King, J., Uppapalli, S., Nikolich, G., McAlpine, J.D., Gillette, D.A., Allwine, K.J. (2007). *Particulate Matter Emission for Dust from Unique Military Activities*. Annual Report Prepared for Strategic Environmental Research and Development (SERDP), Arlington, VA, 22203-1821, December 2007.
- Gillies, J.A., Etyemezian, V., Kuhns, H., Moosmüller, H., Engelbrecht, J.P., King, J., Uppapalli, S., Nikolich, G., McAlpine, J.D., Zhu, D., Skiba, M., Gillette, D.A., Shaw, W., Hashmonay R. (2010). *Particulate Matter Emission for Dust from Unique Military Activities*. Final Report Prepared for Strategic Environmental Research and Development (SERDP), Arlington, VA, 22203-1821, December 2009.

- Gillies, J.A., Etyemezian, V., Zhu, D., Nikolich, G., Engelbrecht, J.P., Shaw, W., Berg, L., Chapman, E., Clapton, S., Pekour, M., Rishell, J., Rutz F.C. (2015). *Characterizing and Quantifying Emissions and Transport of Fugitive Dust Emissions due to Department of Defense Activities*. Final Report prepared for SERDP, Alexandria, VA, Jan. 2015.
- Halatek, T., Stepnik, M., Stetkiewicz, J., Krajnow, A., Szymczak, W., 2011. The inflammatory response in lungs of rats exposed on the airborne particles collected during different seasons in four European cities. *Journal of Environmental Science and Health, Part A* 46 (13), 1469-1481.
- Happo, M.S., Salonen, R.O., Hälinen, A.I., Jalava, O.I., Pennanen, A.S., Dormans, J.A.M.A., Gerlofs-Nijland, Cassee, F.R., Kosma, V.-M., Silanpää, M., Hillamo, R., Hirvonen, M.-R., 2010. *Inhalation Toxicology* 22 (5), 402-416.
- Kavouras, I.G., DuBois, D.W., Nikolich, G., Corral Avittia, A.Y., Etyemezian, V., 2016. Particulate dust emission factors from unpaved roads in the US-Mexico border semi-arid region. *Journal of Arid Environments* 124, 189-192.
- Kavouras, I.G., Etyemezian, V., DuBois, D.W., 2009. Development of a geospatial screening tool to identify source areas of windblown dust. *Environmental Modelling & Software* 24, 1003-1011.
- Kuhns, H., Etyemezian, V., Gillies, J.A., Ahonen, S., Durham, C., Nikolic, D. (2005). Spatial variability of unpaved road dust emissions factors near El Paso, Texas. *Journal of the Air and Waste Management Association* 55, 3-12.
- Kuhns, H., Etyemezian, E., Green, M., Hendrickson, K., McGown, M., Barton, K., Pitchford, M., 2003. Vehicle-based road dust emissions measurement (II): effect of precipitation, wintertime road sanding, and street sweepers on PM₁₀ fugitive dust emissions from paved and unpaved roads. *Atmospheric Environment* 37, 4573-4593.
- Kuhns, H., Etyemezian, V., Landwehr, D., MacDougall, C., Pitchford, M., Green, M., 2001. Testing Re-entrained Aerosol Kinetic Emissions from Roads (TRAKER): a new approach to infer silt loading on roadways. *Atmospheric Environment* 35, 2815-2825.
- Kuhns, H., Gillies, J.A., Etyemezian, V., Nikolich, G., King, J., Zhu, D., Uppapalli, S., Engelbrecht, J., Kohl, S., 2010. Effect of soil types and momentum on unpaved road particulate matter emissions from wheeled and tracked vehicles. *Aerosol Science and Technology* 44, 193-202.
- Langston, R., Merle Jr., R.S., Hart, D., Etyemezian, V., Kuhns, H., Gillies, J., Fitz, F., Bumiller, K., James, D.E. (2008). *The Preferred Alternative Method for Measuring Paved Road Dust Emissions for Emissions Inventories: Mobile Technologies vs. the Traditional AP-42 Methodology*. Report prepared for U.S. EPA, Research Triangle Park, NC, <https://www3.epa.gov/ttnchie1/conference/ei16/session11/langston.pdf>
- Miousse, I.R. et al. (2015). *In vitro* toxicity and epigenotoxicity of different types of ambient particulate matter. *Toxicological Science* 148 (2), 473-487.
- Moosmüller, H., Varma, R., Arnott, W.P., Kuhns, H.D., Etyemezian, V., Gillies, J.A., 2005. Scattering cross section emission factors for visibility and radiative transfer applications: military vehicles traveling on unpaved roads. *Journal of the Air and Waste Management Association* 55, 1743-1750.

- Rodopoulo, S., et al. (2014). Air pollution and hospital emergency room and admissions for cardiovascular and respiratory diseases in Doña Ana County, New Mexico. *Environmental Research*, 129, 39-46.
- United States Department of Agriculture, National Resources Soil Survey (1999). *Soil Survey of Marine Corps Air Ground Combat Center, Twentynine Palms, California*.
- Zhu, D., Kuhns, H.D., Brown, S., Gillies, J.A., Etyemezian, E., Gertler, A.W., 2009. Fugitive dust emissions from paved road travel in the LakeTahoe Basin. *Journal of the Air & Waste Management Association* 59, 1219-1229.
- Zhu, D., Kuhns, H.D., Gillies, J.A., Etyemezian, E., Brown, S., Gertler, A.W., 2012. Analysis of the effectiveness of control measures to mitigate road dust emissions in a regional network. *Transportation Research Part D: Transport and Environment* 17, 332-340.
- Zhu, D., Kuhns, H.D., Gillies, J.A., Gertler, A.W., 2014. Evaluating vehicle re-entrained road dust and its potential to deposit to Lake Tahoe: A bottom-up inventory approach. *Science of the Total Environment* 466, 277-286.

APPENDIX A POINTS OF CONTACT

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
John Gillies	Dust-Solve, LLC 326 Quiet Harbor Dr. Henderson NV 89052-2346	775-530-4350 Jack.Gillies@dri.edu	PI
Vic Etyemezian	Dust-Solve, LLC 326 Quiet Harbor Dr. Henderson NV 89052-2346	702-862-1952 Vic.Etyemezian@dri.edu	Co-PI
George Nikolich	Dust-Solve, LLC 326 Quiet Harbor Dr. Henderson NV 89052-2346	702-739-4439 George.Nikolich@dri.edu	Co-PI
John Mejia	Desert Research Institute 2215 Raggio Parkway, Reno NV 89512	405-863-2842 John.Mejia@dri.edu	TRAKER/AERMOD Python model development