COLORADO
Department of Transportation

CDOT Office of Applied Research

Determining the Impact of CDOT Roadway Construction Projects on Air Quality

Evan Coffey, Gabriela Cortez, Madelyn Schmidt, Carlos Rodriguez Amaro, Michael P Hannigan Ph.D., and Ulises D Techera Ph.D.

December, 2025

CDOT-2025-10

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CDOT-2025-10		

4. Title and Subtitle	5. Report Date
Determining the Impact of CDOT Roadway Construction Projects on Air Quality	December 2025
	6. Performing Organization Code
7. Author(s) Evan Coffey, Gabriela Cortez, Madelyn Schmidt, Carlos Rodriguez Amaro, Michael P Hannigan Ph.D., and Ulises D Techera Ph.D.	8. Performing Organization Report No.
9. Performing Organization Name and Address University of Colorado Boulder College of Engineering and Applied Science 1111 Engineering Drive, Boulder, CO 80309	10. Work Unit No. (TRAIS) 11. Contract or Grant No. R123.04
12. Sponsoring Agency Name and Address Colorado Department of Transportation Office of Applied Research 2829 W. Howard Place Denver, CO 80204	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Elevated concentrations of air pollutants can have serious impacts on human health, the environment, and Colorado's ecosystems. The Colorado Department of Transportation (CDOT) has prioritized protecting air quality in accordance with the Colorado Air Pollution Prevention and Control Act (Section 25-7-101 et seq., C.R.S., 2017). This research quantified exposure to air pollutants as a function of construction activity type, distance from the project site, traffic, and weather conditions. A methodology was developed to monitor pollutant concentrations using low-cost, multi-sensor air quality systems ("Pods") strategically positioned along and near CDOT construction sites. Traffic, construction activities, and environmental variables were monitored to identify major pollution sources and the factors influencing dispersion and concentration. The protocol was first implemented as a pilot on a rural highway and later applied to an urban project (CDOT US 6 Clifton Improvements) and a rural project (Passing Lane project on US 40 near Kremmling, CO). Data collected between August 2023 and November 2024 produced an unprecedented, high-quality dataset. The modeling framework—incorporating dynamic background subtraction, Generalized Linear Mixed Models (GLMM), pruned decision trees, and random forests—proved effective in explaining observed concentrations, predicting pollutant levels, and identifying key variables driving them at each site. Asphalt Milling increased PM_{10}, coarse PM, $PM_{2.5}$, and total volatile organic compounds ((t)VOCs); Earthwork elevated NO, NO_x, PM_{10}, coarse PM, and $PM_{2.5}$; and Hot Mix Asphalt (HMA) paving increased CO, NO, NO_x, (t)VOCs, PM_{10}, coarse PM, and $PM_{2.5}$. Concrete saw-cutting, sidewalk and shoulder work, and striping activities also enhanced several pollutants, particularly $PM_{2.5}$, CO, and NO_x. Across all activities, pollutant enhancements were primarily influenced by environmental variables and traffic volumes. Future research in this area is both necessary and promising. This study has established a foundation for collecting, analyzing, and reporting data to better understand how road construction activities influence local air quality. The next steps involve validating the methodology and modeling framework developed here to reliably predict construction-related air quality impacts, and subsequently applying the validated model to evaluate potential mitigation strategies. Advancing these efforts would position CDOT at the forefront of managing air pollution during construction and maintenance activities.

17. Keywords	18. Distribution Statement
Air pollution sources, Air quality, Air Quality Management, Construction, Environmental impacts, Environmental monitoring, Pollution Control, Road Construction, Traffic	This document is available on CDOT's website: https://www.codot.gov/programs/research

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
		211	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgments

The authors gratefully acknowledge the **Colorado Department of Transportation (CDOT)** for sponsoring this research and for its ongoing commitment to improving understanding of construction-related environmental impacts.

CDOT Region 3 Local Team

The authors extend their deepest appreciation to the **CDOT Region 3 Traffic Safety staff**, whose coordination, dedication, and field support were fundamental to the success of this research. In particular, the authors wish to recognize **Mark Bunnell**, Region 3 Traffic Safety Engineer, Research Project Sponsor, and CDOT local project team lead, for his outstanding leadership, continuous engagement, and tireless efforts in organizing field activities and coordinating site access. The authors also thank **Drewe Lee, EIT III**, **Zebulon White, EIT I**, and **Kerry Ribbens, EIT I**, for their invaluable support and many long hours of assistance during field visits and data collection efforts across multiple project sites.

US 6 Urban Project – Clifton, Colorado

The authors sincerely thank the private and public partners who made data collection at the US 6 urban project possible. Their cooperation and flexibility were essential for successful fieldwork. The authors thank **Tony Marsh**, Maintenance and Operations Coordinator for D51 Schools; **Jesse Ellis**, General Manager of Jiffy Lube in Clifton, CO; **Captain Eric Sperber**, Operations Patrol Division; **Jerry Casselberry**, Branch Manager at Recla Metals L.L.L.P.; **Blake Leany**, Manager at Starvin' Arvin's; **Spike Howard**, Owner of Dos Hombres Restaurant; and **Fire Chief Chris Angermuller**, Clifton Fire Department. The authors also thank **Kaity Clark**, CDOT Grand Junction Resident Engineer, for her collaboration and for facilitating project access and coordination during field data collection activities.

The authors further acknowledge **Jim Hatheway**, West Slope Project Manager at **Stantec**, and **Adam Farmer**, Construction Manager at **United Companies**, for granting site access and coordinating efforts during weekly planning meetings. Their professionalism and commitment greatly contributed to the success of this project.

US 40 Rural Project – Kremmling, Colorado

The authors thank the **local CDOT team in Kremmling**, including **Christopher Beebe**, Construction Engineer, Mountain Residency, and **Trey White**, for their cooperation and coordination efforts with **Daniel Macauley**, Sr. Project Manager, Rocky Mountain Region at **CAPITAL** that enabled successful data collection at the US 40 rural project site. Special appreciation is extended to **Grady Pina**, Inspector II, and Materials Technician at **Vivid Engineering Group**, for his detailed documentation, professionalism, and outstanding support in facilitating high-quality data collection efforts.

US 50 Rural Project

The authors extend their gratitude to **Charles McManus**, Project Engineer at **IHC Scott**, and **Andrew Geral**, Chief Ranger of the **Black Canyon of the Gunnison National Park**, for their valuable assistance in field coordination and site access during data collection on the US 50 rural project.

University of Colorado Boulder and Grand Junction Teams

From the **University of Colorado Boulder**, the authors wish to thank the students from the **Hannigan Air Quality Laboratory** for their technical and analytical contributions. **Rylee Beach**, **Percy Smith**, **Sascha Fowler**, **Emma Balevic**, and **Spencer Hoehl** are acknowledged for their contributions to pod design, construction, testing, and implementation. Additionally, the researchers would like to acknowledge Professor **Rajagopalan Balaji Ph.D.** for his invaluable guidance on data analysis.

From the **University of Colorado team in Grand Junction, CO.**, the authors gratefully acknowledge **Benson Wu**, **Andrew Hewett**, and **Felipe Busellini** for their extensive efforts and long hours dedicated to field data collection across multiple project sites and traffic data extraction.

A special acknowledgement is extended to **Associate Professor Karl Castleton**, **Department of Computer Science and Engineering, Colorado Mesa University**, for his exceptional expertise, generosity, and willingness to assist. His deep technical knowledge and hands-on support in repairing and troubleshooting the monitoring pods in Grand Junction were instrumental in ensuring the timely redeployment of the units to the field, minimizing downtime, and maintaining data continuity throughout the study.

Table of Contents

Acknowledgments 1

Table of Contents 3

List of Tables 7

List of Figures 8

List of Abbreviations and Acronyms 12

Executive Summary 15

Chapter 1. Introduction and Literature Review 18

1.1. Introduction 18

1.2. Literature Review 19

1.2.1. Measurement of Roadway Construction Air Pollution 19

1.2.2. Measurement of Traffic Generated Air Pollution by Pollutant 22

1.2.3. Measurement of Air Pollutants Considering Construction Activity and Traffic 26

1.2.4. Point of Departure 27

Chapter 2. Study Design 29

2.1. Project Objectives and Expected Benefits 29

2.2. Overview 29

2.3. Study Phases 30

2.4. Construction Projects Description 31

2.4.1. US 50 Passing Lane Project (Pilot Project, Rural) 31

2.4.2. US 6 Clifton Improvements (Urban Project) 32

2.4.3. US 40 Passing Lane Project (Rural Project) 34

Chapter 3. Materials and Methods 35

3.1. Data Collection 35

3.1.1. Air Quality Sensor Placement Strategy 35

3.1.2. Traffic and Construction Activity Data Collection 39

3.1.3. Data Collection Timeline 42

3.2. Equipment 42

3.2.1. HAQ Lab Air Quality Monitors, XPod and MiniPod Descriptions 42

3.3. Data Extraction, Calibration, and Processing 46

3.3.1. Quantifying Pollutant Concentrations Using Sensor Signals 46

3.3.2. Traffic Data Extraction and Processing 49

3.3.3. Construction Data Extraction and Processing 50

3.4. Data Analysis and Modeling 52

3.4.1. Applying Calibrations to Raw Pod Sensor Signals and Time-Averaging 52

3.4.2. Calculating Pollution Enhancements Through Background Subtraction 52
3.4.3. Merging Data 53
3.4.4. Modeling Pollution Enhancements 53
Chapter 4. Results 56
4.1. Air Quality Measurements Timeline 56
4.2. Air Monitor Sensor Calibrations: Primary Colocations and Harmonizations 56
4.3. Construction Site Air Quality Measurements: Field Deployments 59
4.3.1. Summary of Field Deployment Measurements 59
4.3.2. US 6 Field Deployments 4 and 5 Results 64
4.3.3. US 40 Field Deployments 6 and 7 Results 70
4.4. Modeling Results 75
4.4.1. US 6 Model Results 76
4.4.2. US 40 Model Results 81
Chapter 5. Discussion 87
5.1. Data Collection and Quality 87
5.1.1. Data Completeness 87
5.1.2. Data Calibration Quality 88
5.2. Background Subtraction Approach 89
5.3. Trends in Observed Pollutant Enhancements and Construction Activities 90
5.4. Themes in Modeled Construction Impacts 91
5.4.1. Importance of Environmental Conditions 91
5.4.2. Traffic Impacts on Pollutant Enhancements 93
5.4.3. Construction Activity Impacts on Pollutant Enhancements 93
Chapter 6. Conclusion 101
6.1. Construction Activity Impact on Air Quality and Evidence for Mitigation 101
6.2. Contextualizing Estimated Enhancements using National Ambient Air Quality Standards 103
6.3. Transport of Pollutants 104
6.4. Document, Analyze and Understand Emissions from Road Construction 105
6.5. Data Collection Approaches 106
6.5.1. Field Data Collection 106
Chapter 7. Recommendations 107
7.1. Air Quality Assessment 107
7.1.1. Data Collection 107
7.1.2. Data Extraction, Processing, and Analysis 110
7.2. Air Pollution Mitigation 111

7.3. Future Work ... 112
7.3.1. Modeling Approach External Validation ... 112
7.3.2. Implementation and Validation of New Air Pollution Mitigation Strategies ... 112
References ... 114
Appendix A. Primary Colocation Results, Calibration, and Validation per Pollutant ... 118
Appendix B. Pollutant Enhancements Model Results ... 125
B.1. US6 Measured Pollutant Enhancements ... 125
B.1.1. US 6 NO Enhancements ... 125
B.1.2. US 6 NO_2 Enhancements ... 125
B.1.3. US 6 NO_x Enhancements ... 126
B.1.4. US 6 tVOC Enhancements ... 127
B.1.5. US 6 $PM_{2.5}$ Enhancements ... 127
B.2. US40 Measured Pollutant Enhancements ... 128
B.2.1. US 40 NO Enhancements ... 128
B.2.2. US 40 NO_2 Enhancements ... 129
B.2.3. US 40 NO_x Enhancements ... 130
B.2.4. US 40 tVOC Enhancements ... 130
B.2.5. US 40 $PM_{2.5}$ Enhancements ... 131
B.2.6. US 40 PM_{10} Enhancements ... 132
B.2.7. US 40 Coarse PM Enhancements ... 132
B.3. US6 Modeled Pollutant Enhancements ... 134
B.3.1. US 6 Modeled NO Enhancements ... 134
B.3.2. US 6 Modeled NO_2 Enhancements ... 138
B.3.3. US 6 Modeled NO_x Enhancements ... 143
B.3.4. US 6 Modeled tVOC Enhancements ... 148
B.3.5. US 6 Modeled $PM_{2.5}$ Enhancements ... 153
B.4. US40 Modeled Pollutant Enhancements ... 159
B.4.1. US 40 Modeled NO Enhancements ... 159
B.4.2. US 40 Modeled NO_2 Enhancements ... 163
B.4.3. US 40 Modeled NO_x Enhancements ... 168
B.4.4. US 40 Modeled tVOC Enhancements ... 173
B.4.5. US 40 Modeled $PM_{2.5}$ Enhancements ... 178
B.4.6. US 40 Modeled PM_{10} Enhancements ... 183
B.4.7. US 40 Modeled CoarsePM Enhancements ... 187
Appendix C. Additional Models Characteristics ... 193

C.1. US6 Models 194
C.1.1. CO Models: US 6 194
C.1.2. NO Models: US 6 195
C.1.3. NO_2 Models: US 6 196
C.1.4. NO_x Models: US 6 197
C.1.5. tVOC Models: US 6 198
C.1.6. $PM_{2.5}$ Models: US 6 199
C.2. US 40 Models 200
C.2.1. CO Models: US 40 200
C.2.2. NO Models: US 40 201
C.2.3. NO_2 Models: US 40 202
C.2.4. NO_x Models: US 40 203
C.2.5. tVOC Models: US 40 204
C.2.6. $PM_{2.5}$ Models: US 40 205
C.2.7. PM_{10} Models: US 40 206
C.2.8. CoarsePM Models: US 40 207
Appendix D. Construction Data Form 208
D.1. Proposed Construction Data Form Fundamental Items 208

List of Tables

Table 1. Populated Sensors in the Air Monitors 45

Table 2. Construction Activities Classification 51

Table 3. Hours of Calibrated, Hourly-Averaged Pollutant Observations by Project 60

Table 4. Model 1 (CO_US6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 78

Table 5. Model 1 (CO US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 83

Table 6. Data Completeness Summary 88

Table 7. Random Forest (model 1) Predictor Importance Rankings 92

Table 8. Model 1 Contrasts for US-6 Enhancements: Percent Change in Pollutant Concentrations Relative to “No Construction” 95

Table 9. Model 1 Contrasts for US-40 Enhancements: Percent Change in Pollutant Concentrations Relative to “No Construction” 98

Table 10. National Ambient Air Quality Standards (NAAQS) 104

Table 11. Model 1 (NO_US6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 135

Table 12. Model 1 (NO2_US6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 140

Table 13. Model 1 (NO_x US 6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 145

Table 14. Model 1 (tVOCs US 6): Pairwise Contrasts: Effect sizes, CIs, % Change, and p-values 150

Table 15. Model 1 (PM2.5_US6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 155

Table 16. Model 1 (NO US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 160

Table 17. Model 1 (NO2_US40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 165

Table 18. Model 1 (NO_x US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 170

Table 19. Model 1 (tVOCs US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 175

Table 20. Model 1 ($PM_{2.5}$ US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 180

Table 21. Model 1 (PM_{10} US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values 184

Table 22. Model 1 (coarsePM US 40): Pairwise Contrasts: Effect sizes, CIs, % Change, and p-values 189

List of Figures

Figure 1. Map of Colorado and the Three CDOT Construction Sites 30
Figure 2. Study Phases and a Brief Description of Their Main Activities 31
Figure 3. US 50 Project Area, Approx. 25 Miles West of Gunnison City 32
Figure 4. US 6 Clifton Improvements Project Phases........ 33
Figure 5. US 40 Passing Lane Project Location........ 34
Figure 6. US 6 Project Area, Zones, and Pods' Location for Deployment 4A........ 36
Figure 7. US 6 Project Area, Zones, and Pods' Location for Deployment 4B........ 37
Figure 8. US 6 Project Area, Zones, and Pods' Location for Deployment 5 37
Figure 9. US 40 Project Area, Zones, and Pods' Location for Deployment 6 38
Figure 10. US 40 Project Area, Zones, and Pods' Locations for Deployment 7 39
Figure 11. Traffic Video Camera Configurations........ 40
Figure 12. Pneumatic Road Tube Counters Placed Along US 50 41
Figure 13. Data Collection Timeline Across the Projects 42
Figure 14. XPod (Pod) Hardware Configurations and Sensors Function Description 43
Figure 15. XPod Deployed at the US 40 Site with MET Station, Battery and Solar Panel........ 44
Figure 16. MiniPod Configuration Hosting the OPC-R2 Sensor (Alphasense) 45
Figure 17. Primary Colocation Location Along I-25, Denver........ 46
Figure 18. 1-hop Air Sensor Calibration Scheme 47
Figure 19. Sensors Harmonization at the US 50 Passing Lane Construction Site, October 2023 49
Figure 20. Data Fusion Flowchart 53
Figure 21. Air Quality Measurements Timeline 56
Figure 22. Primary Colocation CO Calibration (orange) and Validation (blue) 58
Figure 23. Senor Harmonization at the US 6 Site at Clifton Elementary School........ 59
Figure 24. Temperatures Measured During Colocation, Harmonization, and Field Deployment 61
Figure 25. Absolute humidity Measured During Colocation, Harmonization, and Field Deployment 62
Figure 26. Pressure Measured During Colocation, Harmonization, and Field Deployment 63
Figure 27. Temperatures (left), Barometric Pressures (middle) and Relative Humidities (right) Observed 64
Figure 28. Wind Roses Showing Speeds and Directions for Diurnal and Nocturnal Patterns (US 6)........ 65
Figure 29. Wind Speeds by Hour of the Day on US 6........ 65
Figure 30. Temperatures, Humidities and Pressures Measured by Pod D2 Throughout the Day on US 6 66

Figure 31. Traffic Volume at US 6, by Hour of Day, Both Directions 66
Figure 32. The Number of Hourly Observations (log scale) of Each Construction Activity at US 6 by Zone 67
Figure 33. Background CO Estimates at US 6 by Hour of the Day 68
Figure 34. Background CO Concentrations (top) at US 6 and the Frequency of Observations (bottom)... 68
Figure 35. CO Enhancements by Zone and Construction Activity on US 6 69
Figure 36. Wind Roses Showing Speeds and Directions for Diurnal and Nocturnal Patterns (US 40)........ 70
Figure 37. US 40 Wind Speeds Measured at Pod D2 by Hour of the Day 71
Figure 38. Environmental Variables Measured by Pod 2 per Hour of the Day at US40 71
Figure 39. Traffic Volume at US 40, by Hour of Day, Both Directions 72
Figure 40. The Number of Hourly Observations of Each Construction Activity at US 40 By Zone 73
Figure 41. Background CO Estimates at US 40 by Hour of the Day 74
Figure 42. Background CO Concentrations (top) at US 40 and the Frequency of Observations (bottom). 74
Figure 43. All CO Enhancements at US 40 by Zone (left) and Construction Activity (right) 75
Figure 44. Model 1 (US 6), Estimated Marginal Mean CO Enhancements by Activity and Distance........ 77
Figure 45. Model 2 (US 6), Estimated Marginal Mean CO Enhancements by Activity and Zones........ 79
Figure 46. Model 1 (CO, US 6) Decision Tree 80
Figure 47. Model 1 (CO US 6) Random Forest Variable Importance (%IncMSE) 81
Figure 48. Model 1 (US 40), Estimated Marginal Mean CO Enhancements by Activity and Distance........ 82
Figure 49. Model 2 (US 40), Estimated Marginal Mean CO Enhancements by Activity and Zones........ 84
Figure 50. Model 1 (CO US 40) Decision Tree 85
Figure 51. Model 1 (CO US 40), Random Forest Variable Importance (%IncMSE) 86
Figure 52. Primary Colocation NO Calibration (orange) and Validation (blue) 118
Figure 53. Primary Colocation NO2 Calibration (orange) and Validation (blue) 119
Figure 54. Primary Colocation NOx Calibration (orange) and Validation (blue)........ 120
Figure 55. Primary Colocation tVOC Calibration (orange) and Validation (blue) 121
Figure 56. Primary Colocation PM2.5 Calibration (orange) and Validation (blue) 122
Figure 57. Primary Colocation PM10 Calibration (orange) and Validation (blue) 123
Figure 58. Primary Colocation Coarse PM Calibration (orange) and Validation (blue) 124
Figure 59. NO Enhancements by Zone and Construction Activity on US 6........ 125
Figure 60. NO2 Enhancements by Zone and Construction Activity on US 6........ 126
Figure 61. NOx Enhancements by Zone and Construction Activity on US 6 126

Figure 62. tVOC Enhancements by Zone and Construction Activity on US 6 127
Figure 63. PM2.5 Enhancements by Zone and Construction Activity on US 6 128
Figure 64. All NO Enhancements at US 40 by Zone (left) and Construction Activity (right) 129
Figure 65. All NO2 Enhancements at US 40 by Zone (left) and Construction Activity (right) 129
Figure 66. All NOx Enhancements at US 40 by Zone (left) and Construction Activity (right) 130
Figure 67. tVOC Enhancements at US 40 by Zone (left) and Construction Activity (right) 131
Figure 68. PM2.5 Enhancements at US 40 by Zone (left) and Construction Activity (right) 131
Figure 69. PM10 Enhancements at US 40 by Zone (left) and Construction Activity (right) 132
Figure 70. Coarse PM Enhancements at US 40 by Zone (left) and Construction Activity (right) 133
Figure 71. Model 1 (US 6), Estimated Marginal Mean NO Enhancements by Activity and Distance 134
Figure 72. Model 2 (US 6), Estimated Marginal Mean NO Enhancements by Activity Across Zones 136
Figure 73. Model 1 (NO US6), Decision Tree 137
Figure 74. Model 1 (NO US 6) Random Forest Variable Importance (%IncMSE) 138
Figure 75. Model 1 (US 6), Estimated Marginal Mean NO_2 Enhancements by Activity and Distance 139
Figure 76. Model 2 (US 6), Estimated Marginal Mean NO_2 Enhancements by Activity and Zones 141
Figure 77. Model 1 (NO2 US 6) Decision Tree 142
Figure 78. Model 1 (NO_2 US 6) Random Forest Variable Importance (%IncMSE) 143
Figure 79. Model 1 (US 6), Estimated Marginal Mean NO_x Enhancements by Activity and Distance 144
Figure 80. Model 2 (US 6), Estimated Marginal Mean NO_x Enhancements by Activity and zones 146
Figure 81. Model 1 (NOx US 6), Decision Tree 147
Figure 82. Model 1 (No_x US 6), Random Forest Variable Importance (%IncMSE) 148
Figure 83. Module 1 (US 6), Estimated Marginal Mean tVOC Enhancements by Activity and Distance .. 149
Figure 84. Model 2 (US 6), Estimated Marginal Mean tVOC Enhancements by Activity and Zones 151
Figure 85. Model 1 (tVOC US 6), Decision Tree 152
Figure 86. Model 1 (tVOCs US 6), Random Forest Variable Importance (%IncMSE) 153
Figure 87. Module 1 (US 6), Estimated Marginal Mean $PM_{2.5}$ Enhancements by Activity and Distance.. 154
Figure 88. Model 2 (US 6), Estimated Marginal Mean $PM_{2.5}$ Enhancements by Activity and Zones 156
Figure 89. Model 1 (PM2.5 US 6), Decision Tree 157
Figure 90. Model 1 ($PM_{2.5}$ US 6), Random Forest Variable Importance (%IncMSE) 158
Figure 91. Model 1 (US 40), Estimated Marginal Mean NO Enhancements by Activity and Distance 159
Figure 92. Model 2 (US 40), Estimated Marginal Mean NO Enhancements by Activity and Zones 161
Figure 93. Model 1 (NO US 40) Decision Tree 162

Figure 94. Model 1 (NO US 40), Random Forest Variable Importance (%IncMSE) 163
Figure 95. Model 1 (US 40), Estimated Marginal Mean NO_2 Enhancements by Activity and Distance 164
Figure 96. Model 2 (US 40), Estimated Marginal Mean NO_2 Enhancements by Activity and Zones 166
Figure 97. Model 1 (NO2 US 40) Decision Tree 167
Figure 98. Model 1 (NO_2 US 40), Random Forest Variable Importance (%IncMSE) 168
Figure 99. Model 1 (US 40), Estimated Marginal Mean NO_x Enhancements by Activity and Distance 169
Figure 100. Model 2 (US 40), Estimated Marginal Mean NO_x Enhancements by Activity and Zones 171
Figure 101. Model 1 (NO_x US 40) Decision Tree 172
Figure 102. Model 1 (NO_x US 40), Random Forest Variable Importance (%IncMSE) 173
Figure 103. Model 1 (US 40), Estimated Marginal Mean tVOC Enhancements by Activity and Distance 174
Figure 104. Model 2 (US 40), Estimated Marginal Mean tVOC Enhancements by Activity and Zones 176
Figure 105. Model 1 (tVOC US 40) Decision Tree 177
Figure 106. Model 1 (tVOC US 40), Random Forest Variable Importance (%IncMSE) 178
Figure 107. Model 1 (US 40), Estimated Marginal Mean $PM_{2.5}$ Enhancements by Activity and Distance 179
Figure 108. Model 2 (US 40), Estimated Marginal Mean $PM_{2.5}$ Enhancements by Activity and Zones 181
Figure 109. Model 1 (PM2.5 US 40) Decision Tree 182
Figure 110. Model 1 ($PM_{2.5}$ US 40), Random Forest Variable Importance (%IncMSE) 182
Figure 111. Model 1 (US 40), Estimated Marginal Mean PM_{10} Enhancements by Activity and Distance 183
Figure 112. Model 2 (US 40), Estimated Marginal Mean PM_{10} Enhancements by Activity and Zones..... 185
Figure 113. Model 1 (PM10 US 40) Decision Tree 186
Figure 114. Model 1 (PM_{10} US 40), Random Forest Variable Importance (%IncMSE) 187
Figure 115. Model 1 (US 40), Estimated Marginal Mean Coarse PM Enhancements by Activity and Distance 188
Figure 116. Model 2 (US 40), Estimated Marginal Mean Coarse PM Enhancements by Activity and Zones 190
Figure 117. Model 1 (Coarse PM US 40) Decision Tree 191
Figure 118. Model 1 (Coarse PM US 40), Random Forest Variable Importance (%IncMSE) 192

List of Abbreviations and Acronyms

AIC - Akaike Information Criterion

AQI – Air Quality Index

AQMS – Air Quality Monitoring Station

BC – Black Carbon

BTS – Base Transceiver Station (used for communication with sensors)

CDOT – Colorado Department of Transportation

CDPHE – Colorado Department of Public Health and Environment

CI – Confidence Interval

CMU – Colorado Mesa University

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

COAQ – Colorado Air Quality

CU – University of Colorado

CU Boulder – University of Colorado Boulder

DT – Decision Tree

EIT – Engineer in Training

EPA – United States Environmental Protection Agency

FHWA – Federal Highway Administration

GLMM – Generalized Linear Mixed Model

GPS – Global Positioning System

HAQ – Hannigan Air Quality (Laboratory)

HC – Hydrocarbon

HMA – Hot Mix Asphalt

HOD – Hour of Day (24-hour format)

I-70b – Interstate 70 Business Loop

IHC – Interstate Highway Construction

LPG – Liquefied Petroleum Gas

LV – Limit Value

MET – Meteorological

MiniPod – Compact version of the XPod used for particulate matter measurements

MLR – Multiple Linear Regression

MP – Mile Point

NAAQS – National Ambient Air Quality Standards

NB – Northbound

NDIR – Nondispersive Infrared

NO – Nitric Oxide

NO_2 – Nitrogen Dioxide

NO_x – Nitrogen Oxides

NTL – National Transportation Library

O_2 – Dioxygen (Molecular Oxygen)

PEMS – Portable Emissions Measurement System

PM – Particulate Matter

PM10 – Particulate Matter less than or equal to 10 micrometers in diameter

PM2.5 – Particulate Matter less than 2.5 micrometers in diameter

PMF – Particulate Matter Fraction

ppb – Parts per Billion

ppm – Parts per Million

QA/QC – Quality Assurance and Quality Control

RF – Random Forest

RMSE – Root Mean Squared Error

ROSA P – Repository & Open Science Access Portal

SB – Southbound

tVOC – Total Volatile Organic Compound

tVOCs – Total Volatile Organic Compounds

US 40 – U.S. Highway 40 (Rural Project in Kremmling, Colorado)

US 50 – U.S. Highway 50 (Pilot Project in Gunnison County, Colorado)

US 6 – U.S. Highway 6 (Urban Project in Clifton, Colorado)

VOC – Volatile Organic Compound

VOCs – Volatile Organic Compounds

WD – Wind Direction

Wks. – Weeks

XPod – Low-Cost Air Quality Monitoring Pod developed by CU Boulder Hannigan Lab

Executive Summary

Background and Purpose

For several decades, the Colorado Department of Transportation (CDOT) has prioritized protection of the state's air quality, consistent with the Colorado Air Pollution Prevention and Control Act (Section 25-7-101 et seq., C.R.S., 2017). Air pollution affects human health—contributing to respiratory and cardiovascular disease, skin inflammation, and premature mortality—as well as plants and ecosystems. Transportation-related activities, including highway construction and maintenance, are recognized sources of air pollutant emissions.

To better understand these impacts, CDOT commissioned this study to examine the contribution of roadway construction activities to local air quality. Advances in low-cost sensor technology now make it possible to deploy compact air quality monitors in small networks, providing spatially resolved data from case studies in different environments. This project focused on three CDOT construction sites—a pilot study on US 50 (rural), a major improvement project on US 6 (urban), and a passing lane project on US 40 (rural)—with the primary results presented here from the US 6 and US 40 deployments.

Project Objectives

The objectives of this study were to:

1. Characterize the impact of construction and maintenance activities in both rural and urban environments with differing meteorology and topography.
2. Improve understanding of pollutant dispersion from case studies in these environments.
3. Identify conditions where mitigation is warranted, including specific construction activities, meteorological conditions, and seasonal factors.
4. Provide CDOT with a methodology to document emissions from construction, traffic, or other sources for future project needs.

Study Design and Methods

Monitoring: Multi-sensor "Pods" (i.e., low-cost air quality monitors built by the University of Colorado Boulder Hannigan Air Quality Lab) measured particulate matter ($PM_{2.5}$, PM_{10}, coarse PM), nitrogen oxides (NO, NO_2, NO_x), carbon monoxide (CO) and total volatile organic compounds (tVOCs). Pods were placed both adjacent to and away from construction activity. Traffic data were collected via counters and video, and construction activities were logged by camera and daily reports. Meteorological data included temperature, relative humidity, barometric pressure, wind speed, and wind direction. Field data collection occurred August 2023–November 2024, beginning with US 50 and concluding with US 40.

Calibration: Pods were colocated with reference-grade instruments to ensure accuracy across varying temperatures, humidity, barometric pressure, and pollution concentrations. Multilinear regressions were used to account for effects environmental variables have on sensor signals as well as signal drift over time. Overall, sensor quantification was strong and moderate underestimation of spikes in certain pollutants (notably NO and tVOCs) was mitigated by analytical design, which focused on pollution enhancements above background.

Analysis: Background subtraction removed some regional influences and reduced boundary layer effects on measurements. Statistical and machine learning models evaluated the role of meteorology, traffic, weekend vs. weekday and proximity to construction activities.

Key Findings

Environmental Conditions: Temperature, humidity, pressure, and wind speed/direction consistently shaped pollutant enhancements.

Traffic Contributions: Vehicle counts influenced CO, NO/NO_2/NO_x, and coarse PM, underscoring the need to account for baseline roadway emissions.

Construction Impacts: Several activities produced measurable increases in pollution levels:

1. Asphalt Milling → Large increases in PM_{10}, coarse particulates (minor increases in fine particulates) and tVOCs.
2. Earthwork → Elevated NO/NO_x and coarse and fine particulates
3. Hot Mix Asphalt (HMA) Application→ Increases in nearly all pollutants.
4. Sidewalk/Shoulder Soil work → Large increases in coarse PM, CO, NO_2/NO_x.
5. Saw Cutting → Increases in fine particulates
6. Striping → Increases in coarse and fine particulates, CO, NO/NO_x and tVOCs

Proximity Effects: Impacts were strongest within the active construction zone and diminished with distance. Coarse PM showed the most pronounced spatial gradients.

Urban vs. Rural: After subtracting local background concentrations, the rural site had less spatial variability of NO and NOx during periods of no construction activity than the urban site suggesting larger baseline variability in urban areas. This was not the case for tVOCs, $PM_{2.5}$ or NO_2. Topography differences could explain differences in the degrees to which the wind impacted measurements between the two settings. Construction activity impacts were mixed between urban and rural settings. More research is warranted.

Implications for CDOT

Air Quality Impact: Construction impacts on air quality varied substantially across proximity to construction activities and pollutants. Asphalt Milling, Earthwork and Shoulder/Soil work, for example, create short-term particulate matter pollution enhancements that could present health concerns affecting nearby residents, workers, and roadway users. However, the air quality impacts are unlikely to surpass relevant National Ambient Air Quality Standards.

Potential Mitigation Strategies for Reducing Pollution Impacts (when needed):

- Enhance dust suppression during earthwork, shoulder soil work, and asphalt milling.
- Strengthen emissions controls on diesel equipment.
- Stage high-emission activities with consideration of wind direction, topography, and sensitive receptors.
- Expand real-time pollution and environmental monitoring during high-impact activities.

Methodological Value: The sensor network, background subtraction, and modeling framework provide CDOT with a replicable method to evaluate future projects and assess mitigation effectiveness. The statistical models used in this study showed reliable to explain pollutant concentration variability by location and construction activity. Future external validation (model performance in other road construction contexts) would expand the applicability of these models to other projects and locations.

Conclusion

This study provides evidence that roadway construction activities contribute measurably to short-term local air quality impacts, with magnitude and pollutant type varying by activity and environment. By leveraging modern sensor networks and advanced analysis, CDOT has established a framework to quantify these impacts, prioritize additional investigations into high-emission activities, and evaluate mitigation measures. The findings will support CDOT in meeting its statutory commitments to promote air quality, safeguard public and worker health, and balance transportation improvements with environmental stewardship.

Chapter 1. Introduction and Literature Review

1.1. Introduction

For several decades, the Colorado Department of Transportation (CDOT) has been conscious of the need for preservation of the air quality of the state. As indicated in the Colorado Air Pollution Prevention and Control Act (Section 25-7-101 et seq., C.R.S.,2017), the state is committed to promoting clean and healthy air for citizens and visitors, protecting the state scenic and natural resources, and promoting statewide greenhouse gas pollution abatement.

Air pollution has been shown to greatly affect human health, causing severe respiratory and cardiovascular conditions (i.e. lung cancer, atherosclerosis, hypertension, etc.), skin conditions such as atopic eczema and inflammation, and other health problems (Bevan et al. 2021; Dijkhoff et al. 2020; Huang et al. 2019; Rajagopalan et al. 2020). Thus, contributing to a lower quality of life and an early mortality rate for humans and animals. Air pollution also affects plants which experience increased defoliation and develop poor crown conditions (Bevan et al. 2021; Bignal et al. 2007).

Transportation-related activities, including highway construction and maintenance, can be a source of atmospheric emissions that contribute to poor air quality and can impact human health as well as the health of nearby ecosystems. There is a need for greater understanding of how specific activities generate emissions, and how the concentration of these emissions varies with distance from the source and height above the ground.

Current research finds that construction activities produce particulate matter and other pollutants, including carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs), and nitrogen oxides (NO_x), which decrease air quality. Several factors play into how much and what category of pollutants are released due to construction, including equipment type, activity, temperature, wind direction, and the experience of equipment operators. Traffic is also a significant emitter of greenhouse gases, including CO, CO_2, and NO_x. Traffic generated pollutants must be considered to understand the actual impact of roadway construction on air quality because traffic is usually present during transportation projects.

The evolution of pollutants' concentrations over time are known to depend on the characteristics of the pollutant (for example, settling time of particulate matter or chemical reactivity of certain other pollutants). It will also depend on meteorological circumstances such as wind speed and direction, and the thickness of the atmospheric mixed layer, as well as presence of sunlight for some chemical reactions. This understanding can be aided with observational case studies that measure the pollutants and meteorological parameters in different environments, such as a rural environment and an urban environment. The differences between these environments may impact the concentration and dispersion of air pollutants. Until recently, such measures were limited because of the cost and complexity of capable instruments. However, recent advances now make this possible with availability of moderately priced sensors that can be packaged to be logistically simple and deployed in small networks.

1.2. Literature Review

1.2.1. Measurement of Roadway Construction Air Pollution

Various approaches have been used to detect air pollution from construction activities, with Portable and Predictive Emissions Monitoring Systems (PEMS) being the most common. PEMS produce accurate emissions data for several common air pollutants (Frey et al. 2010; Lewis et al. 2009, 2011, 2012). According to Lewis et al. (2009), PEMS utilize nondispersive infrared (NDIR) detection technology to measure concentrations of CO, CO_2, and hydrocarbon (HC). Additionally, electrochemical cells are employed to measure nitrogen oxide (NO), nitrogen dioxide (NO_2) and dioxygen (O2) levels during the emissions monitoring process (Lewis et al. 2009).

The study by Frey et al. (2010) utilized an onboard PEMS to directly collect engine, fuel usage, and emissions data from operational construction equipment. Exhaust samples were continuously drawn from the tailpipe to measure concentrations of NO_x, HC, CO, CO_2 , and particulate matter (PM), typically over periods exceeding 3 hours (Frey et al. 2010). Another example of this is seen in Lewis et al. (2009) study where PEMS were used to assess the real-world activity, fuel consumption, and emission rates of the vehicles under examination (Lewis et al. 2009). Based on numerous studies, emissions estimates seem to mainly focus on NO_x, PM, HC, CO, and CO2.

Lewis et al.(2011, 2012) also quantified the emissions released by non-road construction equipment using PEMS. This study used six bulldozers, and emissions data were collected by placing the PEMS onto the equipment itself. The exhaust pipes were also sampled to evaluate for emissions such as NO_x, HC, CO, and PM similar to the method employed by (Frey et al. 2010). Cao et al. (2016) used several different types of equipment including excavators, wheel loaders, backhoes, road graders, and scrapers. The PEMS used to measure emissions for this study were SEMTECH DS PEMS and AVL 493 PEMS which also measured NOx, PM, HC, CO, and CO (Frey et al. 2010; Lewis et al. 2009; Rasdorf et al. 2015).

1.2.1.1. Construction Activity, Equipment Type and Their Effect on Emissions

There are several factors that influence the emissions released during construction, some of the most influential factors were materials being used, whether the equipment was idle or not, and wind direction. Other notable factors were whether the equipment was loaded, the material moved, and activity.

Faber et al. (2015), conducted a series of field studies to determine aerosol emissions from road construction sites in Germany using high-resolution aerosol mass spectrometers and other real time data capture tools. Their studies demonstrate that PM_{10} are mainly caused by earthwork and compacting activities using a plate compactor (emission factors of up to 54 g/l) contributing to 17% of total PM_{10} emissions in Germany, and usually in concentrations greater than 100 $\mu g/m^3$. On the other hand, thermal construction processes such as asphalt paving and internal combustion in engines give place to non-polar hydrocarbons in the submicron range. These studies also showed that all these mineral particles can be easily mitigated by wetting the ground. Muleski et al. (2005) conducted a similar study in the US obtaining comparable results.

Muleski et al. (2005) showed a method of characterizing particulate emissions from construction activities using the time-integrating exposure test in projects from different cities in Kansas and Missouri. The construction equipment used was separated by location, equipment type, surface materials, number of tests, and whether it was controlled or not. Native soil, crushed rock, construction dirt, and soil/sand mixtures were surface materials used. Many of the tests were uncontrolled, and the equipment used in the study included bulldozers, graders, dump trucks, pickup trucks, and urban traffic.

The PM_{10} emissions collected from a John Deere Model 860 scraper showed that on average the emissions released when loading were much higher than during unloading (Muleski et al.2005). Additionally, sensors showed a much larger range of particulate matter when cutting native material than during moving of uncompacted silt and dirt (Muleski et al. 2005). After studying several scrapers, including the John Deere 860, Caterpillar 613, and Caterpillar 621, researchers found that in transit, while loaded, these equipment also produced a larger range of particle sizes, and a larger average size when compared to unloaded (Muleski et al. 2005). Sandanayake et al. (2015) developed a process using the US EPA methodology to calculate emission factors for pollutants. These data were collected from a high-rise construction project in Melbourne and had the emissions compared by activity type and equipment. The study found that excavation was the main source of total emissions from pile foundation construction. Concrete pumping trucks were found to have high emission rates, and excavators were found to be larger producers of CO and PM. As a control measure to reduce emissions, researchers documented that increasing the surface moisture content of the soil instantaneously decrease the amount of PM_{10} produced by the construction activity; the higher the moisture content the smaller the amount of PM_{10}.

Lewis et al. (2011, 2012) showed that the bulldozers spent a significant amount of time in an idle state with the lowest operational efficiency (time spent in non-idle out of total time) (Muleski et al. 2005; Yan et al. 2023) being 34%. When in idle the average emission rate in g/h for NO_x was 130 g/h, and 760 g/h, 700 g/h, and 950 g/h during forward, reverse, and blade respectively. For HC the number was 17 g/h during idle and 32 g/h, 32 g/h, and 33 g/h during the same modes just explained. There was an average of 63 g/h for CO during idle mode and 130 g/h during the other modes. PM emission rates were smaller in g/h but followed a similar pattern of releasing less amounts of pollution during idle mode. Even though the emission rate during idle is much smaller than during the forward, reverse, and blade mode it cannot be ignored because significant levels of emissions were registered from idle equipment.

Yan et al. (2023) collected PM_{10} and fine particulate matter $PM_{2.5}$ in Guangzhou, China using the upwind downwind method during earthmoving operations and measured their concentrations using real-time monitoring over a three-month period. The study measured concentration using a HN-CK3000 Dust On-line monitoring system along with meteorological conditions of the construction sites. This study found that construction PM were negatively correlated with humidity and positively correlated with wind speed. Data was collected for 84 days and an average 12-h upwind PM_{10} and $PM_{2.5}$ concentration of 25.92 $\mu g/m^3$ to 184.60 $\mu g/m^3$ and 24.01 $\mu g/m^3$ to 168.27 $\mu g/m^3$ for $PM_{2.5}$. The average 12-h downwind PM_{10} and $PM_{2.5}$ concentrations were 30.32 $\mu g/m^3$ to 186.72 $\mu g/m^3$ and 28.89 to 176.71 $\mu g/m^3$ respectively. This data resulted in a PM_{10} and $PM_{2.5}$ upwind and PM correlation values of 0.763 and 0.840 respectively. The PM_{10} and $PM_{2.5}$ downwind and PM correlation values were 0.768 and 0.851 respectively. The study measured concentrations for all earthmoving operations as a whole and did not separate them into individual activities.

1.2.1.2. Construction Equipment Engine Tier Effects on Emissions

Engine tier and type of equipment play a vital role in emissions released during earthmoving operations. Many of the studies separated equipment type by its Environmental Protection Agency (EPA) engine tier (the smaller the tier the larger the emissions) making the trend noticeable.

There is variability associated with emissions from different construction activities and equipment used (Muleski et al. 2005). Part of these variabilities can be directly linked to equipment make and model, the engine horsepower, and the age of the equipment. The studies done by Lewis et al.(2011, 2012) quantified emissions released by non-road construction equipment during idle and non-idle periods based on the engine tier. Cao et al. (2016) separated the equipment used in their study into model, horsepower, engine tier, and activity performed.

When Lewis et al. (2009) analyzed varying emissions per gallon of fuel for backhoes, front-end loaders, and motor graders, as engine tier increases, the emission rates from NO, CO, and HC decreased. The largest emissions come from NO, showing more than double the concentrations found among the other pollutants. The emission rates in grams per gallon of petroleum diesel for a tier 1 backhoe for NO, CO, and HC respectively were 104 g/gal, 44 g/gal, and 10.1 g/gal. The same emission rates for a tier 1 front-end loader were 122 g/gal, 14.9 g/gal, and 15.7 g/gal. Finally, the emission rates for tier 1 motor graders were 109 g/gal, 14.6 g/gal, and 16.4 g/gal. for NO, CO, and HC respectively The effect in an increase of engine tier can best be seen in motor graders where the emission rates for tier 3 engines were found to be 68 g/gal for NO, 9 g/gal for CO, and 6.2 g/gal for HC, showing that an increase in two tiers resulted in emission rates that were nearly halved(Lewis et al. 2009). This is a pattern that can be seen throughout studies as with each increase in engine tier, EPA guidelines become stricter to decrease the number of emissions. The largest emission in weight comes from CO_2 by a factor of 1,000 or more and this seemed to be true no matter what the construction activity was (Frey et al. 2010; Rasdorf et al. 2015). The next largest emissions come from NO_x, CO, and then HC (Frey et al. 2010). It is also notable that as the load percentage increased for equipment, fuel consumption and emissions also increased as well (Frey et al. 2010). All these results have been obtained in the field; however, some other studies have investigated the emission of equipment in the laboratory. While the laboratory offers a controlled environment, most studies show that the results obtained in a laboratory setting are less conservative than those obtained in the field.

1.2.2. Measurement of Traffic Generated Air Pollution by Pollutant

1.2.2.1. Carbon Monoxide (CO)

Studies by Kimbrough et al. (2013) and Moutinho et al. (2020) provide critical insights into the contribution of CO from traffic emissions. Kimbrough et al. (2013) reported CO levels at 0.34 ppm near major roadways, highlighting the persistence of this pollutant in traffic-dominated environments.

Similarly, Moutinho et al. (2020) observed significant CO emissions near highways in Atlanta, with values reflecting similar urban air quality challenges. Furthermore, Singer and Harley 1996) emphasized that trucks emit larger amounts of CO per unit of fuel consumed compared to cars, with CO emissions measured at 394 g/gal for trucks versus 342 g/gal for cars. This indicates a higher CO emission intensity for heavy-duty vehicles. Harleman et al. (2023) further underscored the influence of traffic conditions on CO emissions, noting higher levels in areas with heavier traffic congestion. These findings underscore the necessity of considering different vehicle types and traffic patterns when assessing CO emissions and their impact on urban air quality. Effective strategies to manage CO emissions must address both the volume of traffic and the specific contributions of various vehicle categories.

1.2.2.2. Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) emissions from traffic are a critical concern for both air quality and climate change. Kimbrough et al. (2013) and Moutinho et al. 2020) found that CO_2 is one of the largest emissions from traffic, significantly contributing to the atmospheric concentrations near roadways. Kimbrough et al. 2013) noted CO_2 as a primary emission, consistent with Moutinho et al. 2020) findings of substantial CO_2 levels in near-road environments. CO_2 emissions are an indicator of fuel combustion efficiency, and higher traffic volumes correlate with increased CO_2 emissions. For instance, Kimbrough et al. (2013) documented long-term CO_2 monitoring, showing a substantial contribution from traffic, particularly on routes with high volumes of heavy-duty trucks, which are less fuel-efficient. Wang et al. (2022) emphasized the impact of fuel type on CO_2 emissions, revealing significant contributions from different vehicle categories. Diesel vehicles, which typically have lower fuel efficiency than gasoline vehicles, showed higher CO_2 emissions. These findings highlight the considerable effect of traffic-related CO_2 emissions and the need for targeted measures to mitigate their impact. Effective mitigation strategies could include promoting fuel-efficient vehicles, enhancing public transportation, and implementing policies to reduce traffic congestion.

1.2.2.3. Nitrogen Oxides (NO_x)

Nitrogen oxides are among the most significant pollutants emitted from traffic, with substantial implications for air quality. In a year-long study in Las Vegas, NV, Kimbrough et al. (2013) recorded concentrations of NO_2 and NO_x at 20m, 100m, and 300m away from a major highway (206,000 vehicles per day) obtaining average concentrations of 27.32 ppb, 23.81 ppb, and 20.95 ppb for NO_2 downing; 56.08 ppb, 41.16 ppb, and 34.86 ppb respectively for NO_x downwind. These levels are significant and indicate the high impact of traffic emissions on local air quality. Similarly, Moutinho et al. (2020)

reported high NO_x levels in Atlanta, with measurements closely aligning with the findings from Las Vegas, indicating a consistent issue across different urban environments. Panteliadis et al. (2014) supported these findings, showing decreases in NO_x concentrations near roadside monitoring stations following the implementation of low emission zones, suggesting the effectiveness of such interventions. Wang et al. (2022) further emphasized the importance of considering vehicle types and fuel types, with diesel vehicles contributing significantly to NO_x emissions. The study highlighted that diesel vehicles are major NO_x emitters, contributing to poor air quality in urban areas. Collectively, these studies illustrate that NO_x is one of the most prevalent and impactful pollutants from traffic emissions. Effective management of NO_x emissions is crucial for improving urban air quality and can involve strategies such as stricter emission standards, promoting the use of cleaner fuels, and enhancing traffic management systems.

1.2.2.4. Coarse + Fine Particulate Matter (PM_{10})

Traffic-related emissions significantly impact PM_{10} pollution, as indicated by several studies. Harleman et al. (2023) found that roadway improvements could influence PM_{10} levels, with reduced congestion leading to lower concentrations. Kimbrough et al. (2013) reported elevated PM_{10} levels downwind from roadways in Las Vegas, with long-term monitoring showing that PM_{10} concentrations were significantly higher near major traffic routes. This study emphasized the role of traffic emissions in contributing to PM_{10} pollution. Moutinho et al. (2020) also observed significant PM_{10} contributions from highway vehicle emissions in Atlanta, highlighting the pollutant's prevalence in urban settings. Additionally, Panteliadis et al. (2014) showed that implementing low emission zones led to notable decreases in PM_{10} concentrations near roadside monitoring stations, further demonstrating the effectiveness of targeted emission control measures. Wang et al. (2022) underscored the importance of different vehicle types, with diesel vehicles being major contributors to PM_{10} pollution. The study indicated that diesel, gasoline, and Liquefied Petroleum Gas (LPG) vehicles account for 52%, 10%, and 5% of PM_{10} concentrations, respectively.

In addition to particulate matter generated by fuel combustion PM_{10} and $PM_{2.5}$ are generated by tire wear, break wear and road erosion. In Sou10th Korea, Han et al. (2011) collected samples of road suspended dust in front (background) and behind the weal of a moving vehicle in four different locations (port area, land field, residential and major road) finding net concentrations of PM_{10} of 919.3 μg/m³ in the land field, 419.4 μg/m³ in the port area, 263.1 μg/m³ along the major road, and 201.2 μg/m³ in the residential area while driving between 40 and 50 Km/hr. After performing a chemical analysis of these samples, the researchers found high concentrations of organic carbon (OC) and elemental carbon (EC) among both PM_{10} and $PM_{2.5}$ providing evidence that tire wear and brake pads wear significantly contribute to these pollutants. Furthermore, PM_{10} showed two-to-three-time higher concentrations of OC than $PM_{2.5}$, indicating that tire wear and brake pads wear contribute mainly to PM_{10}.

These findings highlight the need for effective measures to control PM_{10} emissions from traffic, including enhancing vehicle emission standards, promoting the use of cleaner fuels, and implementing traffic management policies.

1.2.2.5. Fine Particulate Matter ($PM_{2.5}$)

Fine particulate matter is a critical concern due to its adverse health effects and its presence in traffic emissions. Moutinho et al. 2020) identified significant contributions of $PM_{2.5}$ from highway vehicle emissions, consistent with findings by Kimbrough et al. (2013) and Panteliadis et al. (2014). $PM_{2.5}$ levels were notably high near highways, with concentrations influenced by the volume and type of traffic. Wang et al. 2022) highlighted the substantial contributions of diesel vehicles to $PM_{2.5}$ concentrations, emphasizing the need to address emissions from these sources. The study reported that diesel vehicles contribute significantly to $PM_{2.5}$ pollution, making them a key target for emission reduction strategies. Carr et al. 2014) provided a comprehensive analysis of $PM_{2.5}$ levels in Los Angeles County, illustrating the pollutant's widespread impact. The study documented detailed $PM_{2.5}$ measurements across various urban settings, providing a baseline for assessing the effectiveness of air quality management strategies. These studies collectively show that traffic is a significant source of $PM_{2.5}$, necessitating robust monitoring and mitigation strategies. Effective measures could include implementing low emission zones, promoting the use of electric vehicles, and enhancing public transportation infrastructure.

1.2.2.6. Black Carbon (BC)

Black carbon emissions from traffic are a significant concern due to their impact on climate and health. Kimbrough et al. (2013) found BC levels near roadways in Las Vegas at 1.52 $\mu g/m^3$, indicating significant emissions from traffic sources. Moutinho et al. (2020) reported similar findings in Atlanta, where BC emissions near highways were recorded at 1.6 $\mu g/m^3$, reflecting the impact of traffic emissions on local air quality. Panteliadis et al. 2014) demonstrated reductions in BC concentrations near roadside monitoring stations following the implementation of low emission zones, highlighting the effectiveness of such measures in reducing BC pollution. Wang et al. (2022) emphasized the significant contributions of diesel vehicles to BC emissions, noting the importance of fuel types in emission profiles. Diesel vehicles were identified as major sources of BC, contributing significantly to urban air pollution. Carr et al. (2014) provided valuable data on BC concentrations in Los Angeles County, documenting the levels of BC across different urban areas and providing insights into the effectiveness of current air quality management strategies. These findings illustrate the pervasive nature of BC pollution from traffic and the importance of continued efforts to mitigate its impact. Strategies to reduce BC emissions could include promoting cleaner fuels, enhancing vehicle emission standards, and implementing traffic management measures to reduce congestion and idling.

1.2.3. Measurement of Air Pollutants Considering Construction Activity and Traffic

Previous literature addressing the impact of roadway construction and operations on air pollutants is scarce and mainly based on predictive models with limited measures. Giunta (2020) presented a case study of an 18km-long motorway construction project in Italy encompassing 5 tunnels (13.3 km), 5 bridges (1.4km), and fills and embankments (3.2km). During the construction process and thereafter CO, NO_x and PM_{10} emission were estimated and measured at specific locations, showing that PM_{10} emissions were approximately one order of magnitude greater during the construction phase than during operation, with 85% of PM_{10} during construction arising from the crushing of aggregate, its storage, and transportation over unpaved roads and the remaining 15% arising from the exhaust of equipment and trucks. The rate at which CO and NO_x pollutants were released during both phases were comparable. Additionally, during operation, the ends of tunnels were hotspots through which all the emissions produced inside the tunnel exited, reaching concentrations four times higher than the maximum concentrations for CO and NO_x estimated during construction at other points. However, except for these hotspots, in most places the estimated concentrations of CO and NO_x are higher during construction than during operation. The model also showed that the dispersion of contaminants was largely controlled by the topography of the surrounding area and environmental conditions, which gives an insight into possible mitigation strategies.

Font et al. (2014) Investigated the impact of road construction and the increased traffic during and after a road widening project in South London, particularly investigating concentration changes in particulate matter, NO_x, and NO_2 in the air surrounding the project area. The researchers found that PM_{10} concentrations increased during the construction period up to 15 $\mu g/m^3$ during working hours compared to concentrations before the road works. Furthermore, after the completion of the widening there was an increase in all pollutants when considering rush hour: 2–4 $\mu g/m^3$ for PM_{10}; 1 $\mu g/m^3$ for $PM_{2.5}$; 40 $\mu g/m^3$ for NO_x, and 8 $\mu g/m^3$ for NO_2. NO_2. The EU PM_{10} limit value (LV) was breached during construction and NO_2 EU LV was breached after the road development illustrating a notable deterioration in residential air quality. Lastly, PM_{10}, but not $PM_{2.5}$, glutathione dependent oxidative potential increased after the road was widened consistent with an increase in pro-oxidant components in the coarse particle mode, related to vehicle abrasion.

1.2.4. Point of Departure

Despite Giunta's and Font's case studies, most other studies focus on just one part of our problem. Some researchers have documented the emissions caused by construction equipment in isolation, away from traffic (Cao et al. 2016; Cui et al. 2017; Lim et al. 2009). Others have developed emissions models for different construction off-road equipment under similar circumstances (Cao et al. 2016; Fu et al. 2012). Others still have compared the emissions of equipment in laboratory settings vs project settings discovering that the average emissions are greater in the field than in the laboratory due to periods of acceleration and breaks, thus making manufacturer emission counts less reliable (Pirjola et al. 2017).

Some researchers focused on the variation in air pollutants due to different traffic conditions such as the effects of tolls and intersections. Tolls appear to have a strong influence on transportation modality change from private to mass public such as buses and trains, which in turn would significantly reduce emissions (Miguel et al. 2017). Intersections, on the contrary, due to the accumulation of cars suppose a greater risk of exposure to contaminated air (Wang et al. 2018). Lastly, several researchers investigated levels of air pollution and created dispersion models that apply to specific cities (urban areas) around the world (Antanasijević et al. 2018; Csikós et al. 2015; Gong et al. 2015; Liu et al. 2019) or rural areas where the road grade and local topographic and other conditions will highly affect the level of exposure (Liu et al. 2020; Sentoff et al. 2015; Wyatt et al. 2014).

Research on emissions from construction projects in the United States is very limited. Many of the larger studies were conducted outside the US, in countries that do not have the same equipment and vehicle regulations as the US. Out of the studies done on construction emissions, there are very few that describe the effect of road construction on air quality, especially in combination with traffic emissions. There is limited research investigating the combined effect of road construction and traffic on air quality, and all of them were conducted outside of the US. There is a dearth of knowledge addressing the effect of road construction on air quality in the US. It is well known that construction projects release emissions, however, their quantification has remained elusive in the US due to the difficulty of determining these concentrations in the presence of other competing sources such as traffic. This study was conducted to address such a research gap.

Additionally, previous studies presented several emissions models and their discrepancies with the actual acquired data, which underlines important limitations when trying to apply these models to different locations. Given these limitations, different topographic characteristics, different meteorological characteristics, and the uniqueness of each construction project, the development of emissions and air quality databases for Colorado will provide the most reliable information for CDOT and will contribute to future production of dispersion models, reliable for the state of Colorado.

Chapter 2. Study Design

2.1. Project Objectives and Expected Benefits

- Expand CDOTs air quality research by characterizing the impact of construction and maintenance activities in a rural environment and in a relatively urban environment. These projects encompass different meteorological and topographic characteristics than other CDOT air quality research.
- Provide an improved understanding of the dispersion of each relevant air pollutant based on case studies in these two environments.
- Identify conditions where pollution mitigations may be needed, including the specific construction activity, meteorological condition including seasonality, and topographical situation.
- Provide a potential methodology to understand or document emissions (from construction, traffic, or other sources) for future CDOT needs.

2.2. Overview

The primary aim of this study is to determine the impact of CDOT roadway projects on air quality. To do so the researchers had to assess the extent of air pollutant exposure in relation to multiple factors such as distance from the project site, construction activities, location, traffic, and weather conditions. Measuring traffic, air quality, and construction activities was crucial to determining the effects of construction on air pollution. To accomplish this objective, researchers utilized air quality multi-sensor systems (Pods) strategically positioned along the construction site and surrounding areas (GPS tracked). Construction activities were tracked by video cameras and daily construction activity logs. Traffic was monitored by a combination of traffic counters and video recording. This protocol was implemented at two distinct settings: an urban project (CDOT US 6 Clifton Improvements) and two rural projects (a passing lane project on US highway 50 in Gunnison County, CO. and another passing lane project on US highway 40 just north of Kremmling CO.). The on-site data collection period spanned from August 2023 to November 2024, in a sequential order, starting with US 50 and finishing with US 40. The field deployment on US 50 was mainly used to finalize adjustments to the beta version of the Pods which were then used for data collection on US 6 and US 40. This report will mainly present the results obtained from the data collected in these last two projects. See project locations in Figure 1.

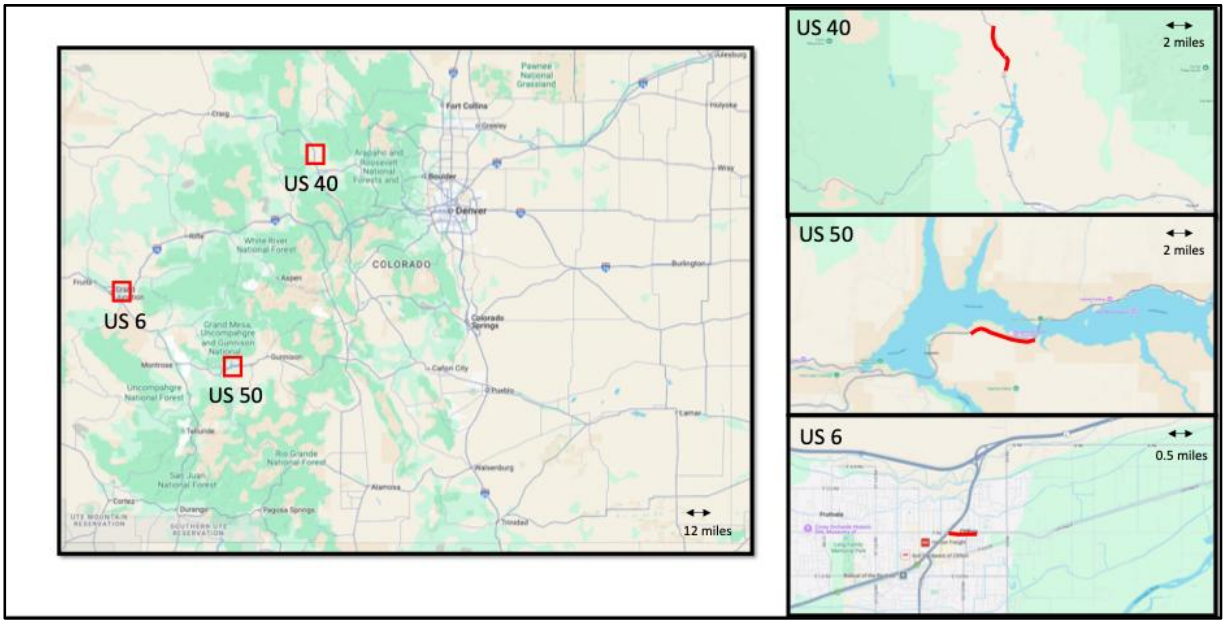


Figure 1. Map of Colorado and the Three CDOT Construction Sites

The evaluation of both types of construction environments was valuable to this project because of the significant difference in the number of sources of pollutants in each construction environment. In the rural construction environment, transportation and construction were expected to be the dominant local sources of pollutants, making it easier to study their effects. In contrast, in the urban construction environment, a variety of other local and regional sources of pollution may exist. The overarching goal of this project was to understand how transportation and construction pollution emissions behave in these environments.

2.3. Study Phases

The project was divided into four main phases. The first phase of the project consisted of a planning phase which encompassed the development and optimization of research tools and the procurement of access to construction sites and locations to install the data collection equipment.

The second phase of the project consisted of collecting data. During this phase the researchers mainly focused on obtaining construction activity data, traffic data, air quality data, and meteorological data. Several construction activities were monitored, mainly (1) earthmoving operations, (2) paving, (3) sidewalk and shoulder construction, and (4) striping. Regarding traffic, the volume and a two-class classification was used to separate gas operated vehicles (sedans and light duty trucks) from diesel operated vehicles (heavy duty trucks and above) considering the FHWA classification categories.

Several pollutants were monitored throughout the project including CO, CO_2, NO_x, PM_{10}, $PM_{2.5}$, and VOCs. Lastly, basic meteorological data was obtained including atmospheric pressure, temperature, wind speed and direction. Our hypothesis was that all these variables would influence air pollution.

The third phase consisted of extracting, calibrating, and analyzing the data to achieve the project objectives. During this phase, the data from several collocations and harmonizations was used to calibrate the data obtained from the pods. Additionally, several statistical models were developed to understand the complex interactions among a high number of variables and thus achieve the project objectives.

The last phase of this project consisted in discussing the results with CDOT project stakeholders and preparing actionable documents to communicate the results of the study. These phases can be seen in Figure 2.

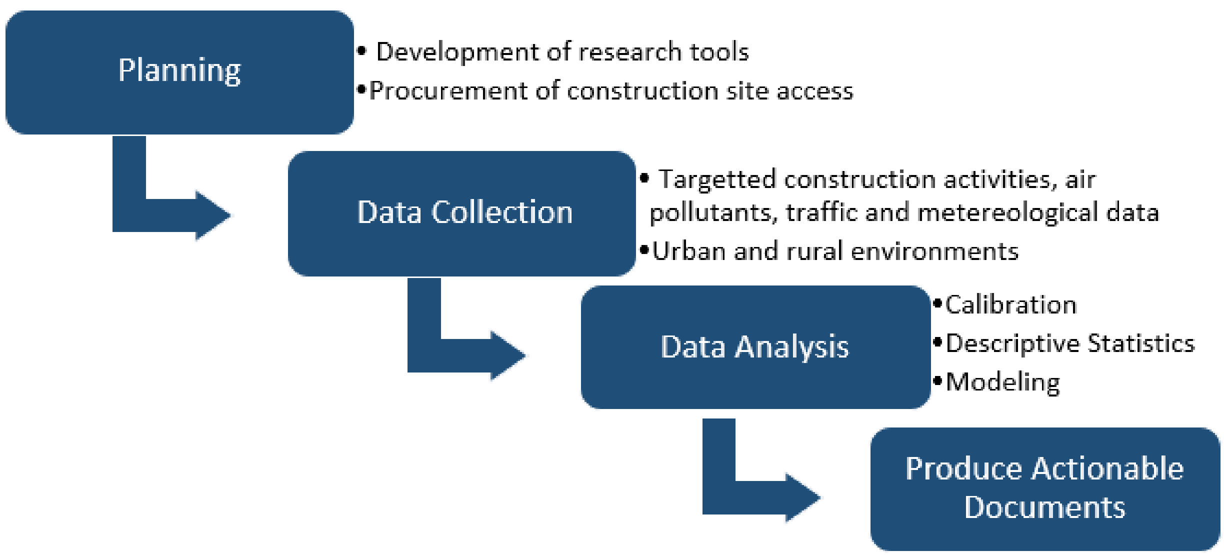


Figure 2. Study Phases and a Brief Description of Their Main Activities

2.4. Construction Projects Description

2.4.1. US 50 Passing Lane Project (Pilot Project, Rural)

2.4.1.1. Project Facts:

- **Construction Cost:** $7,499,484
- **Contractor:** IHC Scott, Inc.
- **Original Timeline:** March - September 2023
- **Location:** US 50 near County Road 26, Gunnison County

2.4.1.2. Project Description:

The US 50 Gunnison County Passing Lane Project was carried out to improve safety on US 50. Safety improvements included the construction of a passing lane along with the removal and replacement of 39 guardrail end anchors. The passing lane construction was located on US 50 from mile point (MP) 134.6 to MP 136. The replacement of guardrail end anchors east and west of the passing lane was to be completed from MP 128.31 to 139.07. These improvements are designed to give motorists wider roads to travel on during inclement weather, higher traffic volumes, and to prevent road erosion. The resurfacing and widening were to create smoother pavement and improved driving conditions, adding chain-up areas would significantly improve safety for travelers when weather conditions suddenly change. Figure 3 shows the location of the project along US 50.

Figure 3. US 50 Project Area, Approx. 25 Miles West of Gunnison City

2.4.2. US 6 Clifton Improvements (Urban Project)

2.4.2.1. Project Facts:

- **Construction Cost:** $16.5 Million
- **Contractor:** United Companies
- **Timeline:** November 2022-Fall 2024
- **Location:** US Highway 6 from the Business Loop (I-70b) to just east of Clifton Elementary School

2.4.2.2. Project Description:

The Colorado Department of Transportation contracted with United Companies to perform several improvements on US Highway 6, see Figure 4. The project took place in Clifton, CO. on US 6 (F Road) from just west of the I-70b intersection to just east of 5th St. and Clifton Elementary School. The objective of the project was to improve safety by realigning and updating traffic patterns on US 6, adding two roundabouts and center medians and an additional eastbound travel lane. Pedestrian and bicycle connections through the corridor would also be improved. The project is part of CDOT's 10-year plan improvements for the US 6 corridor in Mesa County.

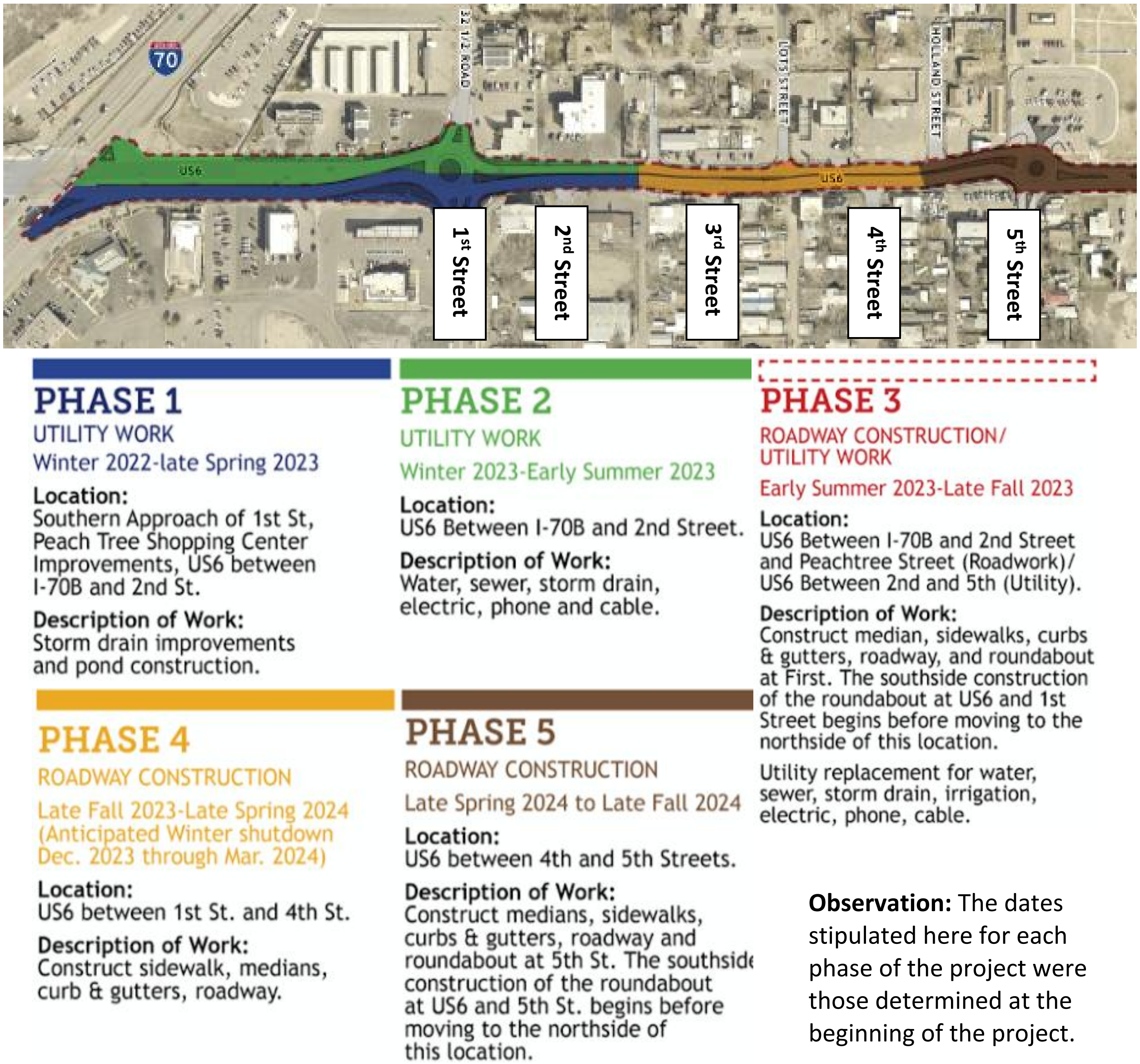


Figure 4. US 6 Clifton Improvements Project Phases

2.4.3. US 40 Passing Lane Project (Rural Project)

2.4.3.1. Project Facts:

Construction Cost: $5.4 Million
Contractor: Capital Paving and Construction
Original Timeline: May - October 2024
Location: US 40 just north of Wolford Mountain Reservoir, Grand County

2.4.3.2. Project Description:

This is a passing lane construction project located on US 40 between Kremmling and Steamboat Springs, MP 171.9 to 173.3. Work included adding passing lanes for both eastbound and westbound US 40, extending culverts, signing, striping and traffic control. The construction of Passing Lanes allows for safer transportation of commercial/freight trucks, motorists and cyclists on this busy corridor by providing a stretch of highway with space and opportunity for faster vehicles to safely pass slower moving traffic. Figure 5 shows the location of the project along US 40.

Figure 5. US 40 Passing Lane Project Location

Chapter 3. Materials and Methods

3.1. Data Collection

3.1.1. Air Quality Sensor Placement Strategy

For each construction project site, the study team met to inspect maps showing important geographical information (existing roadways, proposed areas of construction and staging, topographic information, public and private lands adjacent to the construction area etc.). This data provided preliminary information but would be refined with an in-person visit to the field site where such information could be confirmed and additional information regarding site accessibility, specific placement options and feedback from on-site CDOT personnel/project manager would steer the study team towards a final set of sensor locations.

Generally, the monitor placement strategy consisted of identifying at least one or two background sites distant from the active construction area to serve as a reasonable indicator of background air quality. This method is preferable if making pre- and post-construction measurements is not feasible, which was the case in this study, as the selected construction projects had already begun previous to our data collection. Background sites were chosen based on accessibility and their ability to resemble, as much as possible, the conditions of the other monitoring sites (i.e., distance to roadway, local site environmental parameters etc.) isolating the impacts from construction activity to the activity-proximate monitors. Pollutants can be transported by winds which can cause background sites to be impacted by construction activities. Therefore, a second background site opposite the construction area from the other can help account for transport across the study area as only one background monitor would likely be impacted from transported pollutants from the activities at any one time. The remaining monitors were located based on anticipated construction activities and their location across the study area. In each project site there were between four and ten air quality sensors at any given time.

Early on, it was deduced that creating zones (as layers on a map) within the study area could help associate air quality measurements in specific zones with activities occurring in those zones. The strategy behind creating zones was to incorporate a measure of proximity, or distance between the air monitors and the construction activities. These zones could improve the research team's ability to explore relationships between construction activities happening at various distances from air quality monitors and the pollutant levels. Occasionally, some air monitors were moved during the construction project to better capture impacts from specific construction activities planned for specific locations.

These plans were shared by the construction team based on the schedule. Whenever the locations of the monitors in the sensor network were modified, a new Field Deployment was created to distinguish one network configuration from the next. The air monitoring network configuration for each of the field deployment periods is shown in Figures 6 through 10 for each project.

Figures 6 to 8 depict the US 6 construction site, the five study zones delineated in white and the individual pods placed around the site for field deployments 4-5. Note, pod D4 was moved on June 5th to be a few yards closer to US 6 during field deployment 5 (marked "A" May 2 to June 6 and "B" June 6-17).

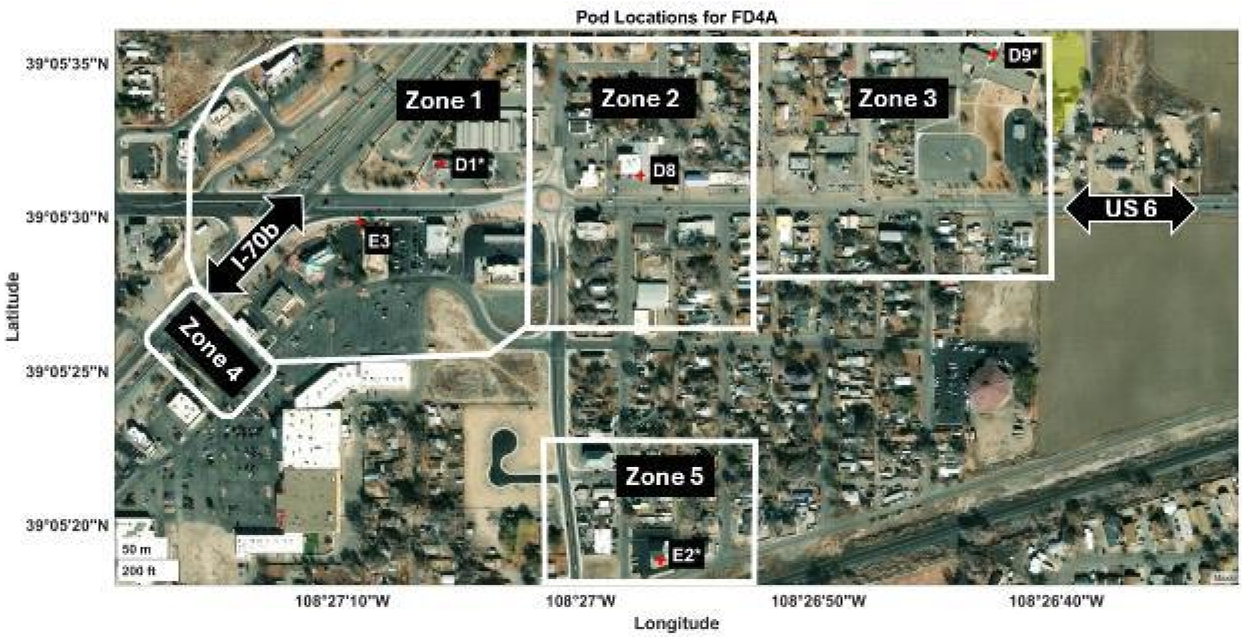


Figure 6. US 6 Project Area, Zones, and Pods' Location for Deployment 4A

Note: Study map showing air sensor locations (red pluses), construction zones, and placement of the meteorological (MET) station for the US 6 field deployment 4A, from October 13 to November 3, 2023. Pods marked with an asterisk were located on roof tops 10 to 15 ft above the ground.

Figure 7. US 6 Project Area, Zones, and Pods' Location for Deployment 4B

Note: Study map showing air sensor locations (red pluses), construction zones, and placement of the meteorological (MET) station for the US 6 field deployment 4B, from November 3, 2023, to January 11, 2024. Pods marked with an asterisk were located on roof tops 10 to 15 ft above the ground.

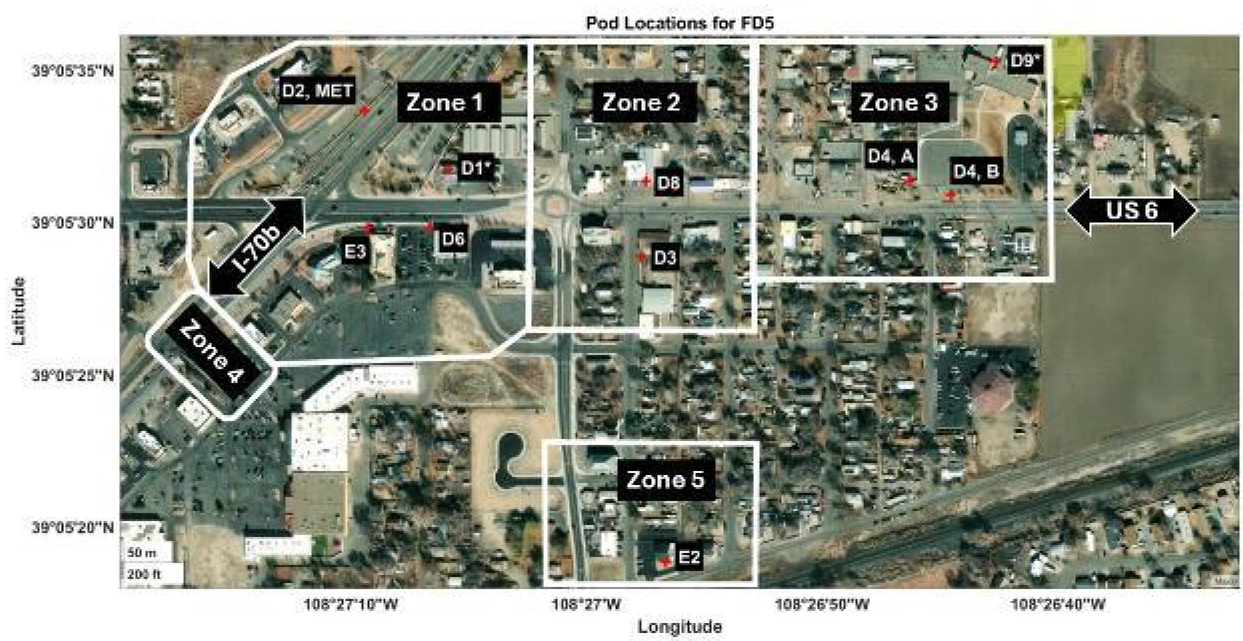


Figure 8. US 6 Project Area, Zones, and Pods' Location for Deployment 5

Note: Study map showing air sensor locations (red pluses), elevations at select sites, construction zones, and placement of the meteorological (MET) station for the US 6 field deployment 5, from

February 8 to June 17, 2024. Pods marked with an asterisk were located on roof tops 10 to 15 ft above the ground.

Figures 9 and 10 depict the US 40 construction site during field deployments 6 and 7, respectively, showing the five discrete study zones and the individual pod locations. Some locations indicate the elevation since this site had the most topographic change amongst pod locations (172ft elevation change) between highest and lowest pod. This site also featured a long river valley paralleling the highway north/south just to the west. Traffic stops for one-way flow through the construction area are shown on the maps for northbound and southbound traffic. The location of the zones and traffic stops were consistent across both field deployment periods and only some pods changed location (yet remained in the same zones).

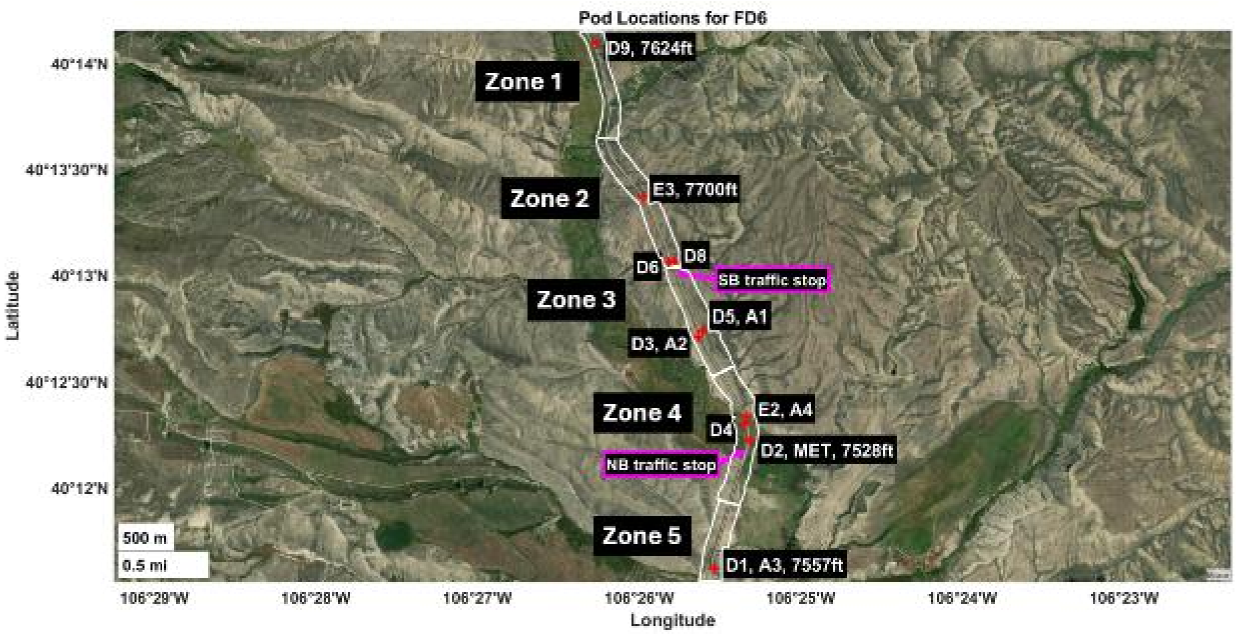


Figure 9. US 40 Project Area, Zones, and Pods' Location for Deployment 6

Note: Study map showing air sensor locations (red pluses), elevations at select sites, construction zones, traffic stop locations for southbound (SB) and northbound (NB) traffic, and placement of the meteorological (MET) station for the US 40 field deployment 6 (June 26 – August 23, 2024).

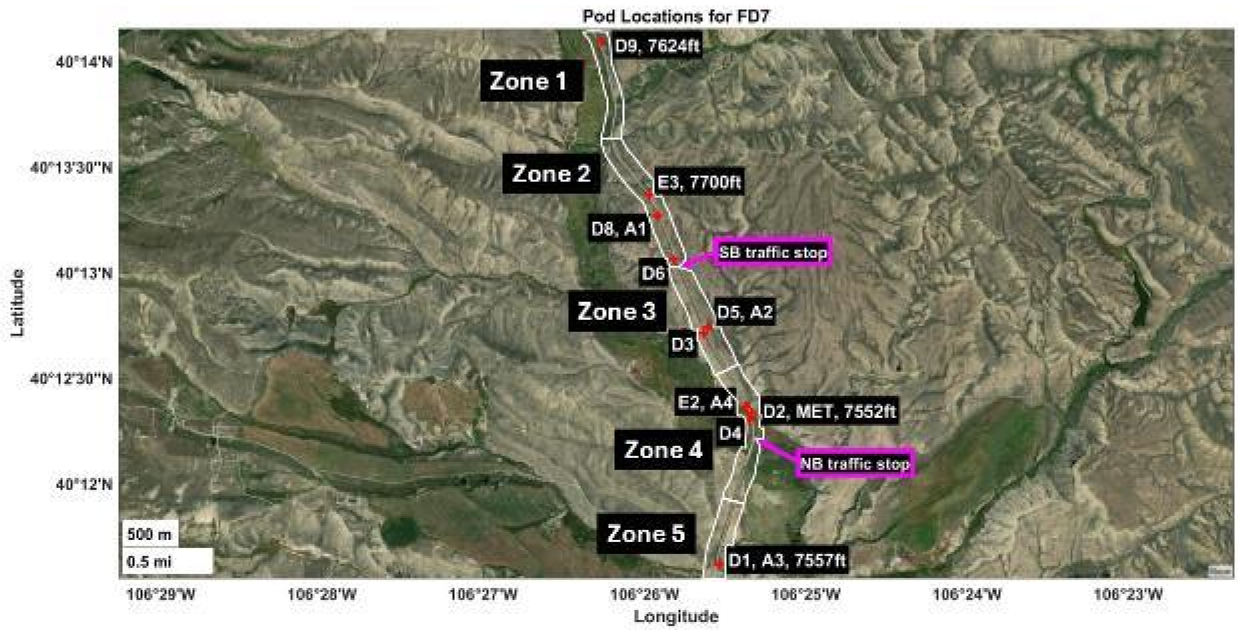


Figure 10. US 40 Project Area, Zones, and Pods' Locations for Deployment 7

Note: Study map showing air sensor locations (red pluses), elevations at select sites, construction zones, traffic stop locations for southbound (SB) and northbound (NB) traffic, and placement of the meteorological (MET) station for the US 40 field deployment 7 (September 6 – November 11, 2024).

3.1.2. Traffic and Construction Activity Data Collection

During the pilot study phase (US 50 rural project) traffic was monitored using both video cameras (street logic Inc. countCAM4) and Pneumatic Road Tube Counters. The video cameras were located to allow for a clear view of the traffic along the road of interest and in a spot able to capture most of the traffic along the road. In this case, US 50 only had one rural road access along the jobsite and the traffic along such access was negligeable. Additionally, the researchers installed dedicated posts to mount the cameras along CDOT's right of way not to interfere with existing infrastructure and signs. Please, see Figure 11 A&B for some examples. The cameras were initially powered by an internal battery plus an external battery pack. This combination allowed for a week of data collection before having to recharge the batteries. For the subsequent rural deployment on US 40, the researchers added a 20W-5V solar panel to each camera unit, which allowed for uninterrupted data collection during the summer months, when most days are sunny. After this implementation the researchers started to retrieve data every two weeks rather than weekly. See Figure 11C for a visual of the second video camera and solar panel configuration.

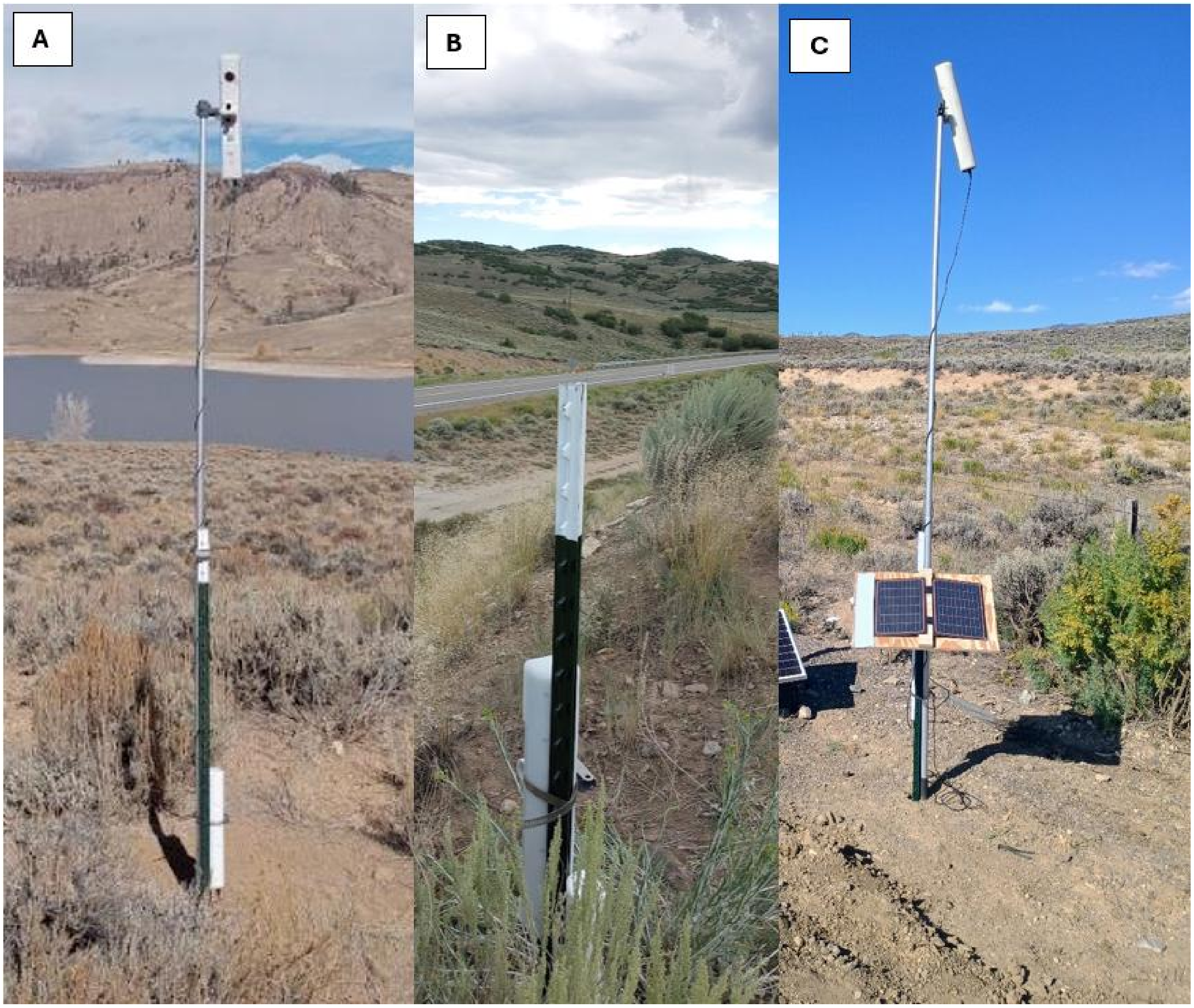


Figure 11. Traffic Video Camera Configurations

The Pneumatic Road Tube Counters were placed at the beginning and the end of the project, over the road, as shown in Figure 12. The tube counters were set up in a configuration that allows for vehicle volume, direction, speed, and classification according to the FHWA 13 class vehicle classification system, which distinguishes between motorcycles (class 1), passenger cars (class 2), Pickup trucks and other light duty four-tire single unit vehicles (class 3), busses (class 4), two-axle, six tire single units (class 5) and heavier duty trucks organized in classes six through 13 according to the number of axels. It is worth mentioning that classes 1 – 3 are mainly gas vehicles, while 4 – 13 are mainly diesel. Initial data processing and analysis showed that watching the traffic videos and coding the traffic into these categories produced a more reliable result than those obtained from the tube counters, therefore for the subsequent deployments only the traffic cameras were used to collect traffic data.

Figure 12. Pneumatic Road Tube Counters Placed Along US 50

The researchers utilized several sources of information to obtain construction activity data. Initially, the researchers obtained the original construction activity schedule. However, this schedule included mainly summary activities, and it was used to evaluate when it was imperative to collect data and when we could perform calibration activities, for example, thus defining the overall data collection schedule.

Additionally, a representative of the research team attended the weekly planning meeting with the project team and obtained the weekly schedule of construction activities. Such a schedule is updated weekly and describes, in detail, the construction activities performed each day during the previous week, as well as the planned construction activities for each day of the following two weeks. This schedule helped determine which construction activities we would monitor each day and when it was optimal to visit the site and collect data. However, while this information was helpful, it did not have the level of accuracy that we needed. We wanted to know what construction activity was taking place each hour of the day, together with its location. To obtain construction activity with this level of detail, the researchers requested access to the construction activity daily logs developed by an on-site inspector. These records provided very good information with the granularity needed. Nonetheless, the accuracy and level of detail of these logs highly depended on the inspector. Some inspectors were more detail-oriented than others, and that introduced variability in the data quality.

In order to improve the construction activity data, the researchers opted for watching the videos obtained from the traffic cameras, which also documented the construction activities taking place on a continuous basis. This approach, while time-consuming, yielded excellent construction activity data minute by minute of the day. In summary, several resources, including quantities takeoff documents for billing, were used to obtain accurate construction activity data for each hour of each day. Such an approach was possible because the cameras were placed and oriented to capture the vast majority of the construction activities taking place, which usually required the repositioning of the cameras on a weekly or biweekly basis. The urban project advanced more slowly than initially anticipated; consequently, most construction activities took place along a street block, which helped document construction activities with a reduced number of cameras for most of the data collection period.

3.1.3. Data Collection Timeline

Each data collection period consisted of deploying air quality monitor sensors, traffic cameras and additional equipment such as power banks, and solar panels. Figure 13 shows the timeline of data collection periods for each project. A more detailed data collection timeline is provided in the Results section, which includes data collection activities withing each data collection period (see Section 4.1).

Figure 13. Data Collection Timeline Across the Projects

3.2. Equipment

3.2.1. HAQ Lab Air Quality Monitors, XPod and MiniPod Descriptions

The CU Boulder HAQ Lab has been developing low-cost air quality monitoring tools for nearly two decades. The most recent version of their air monitoring platform was named the XPod and was being beta-tested in the summer of 2023 as this project began. Briefly, the XPod is an open-sourced, custom environmental monitoring platform that measures temperature, humidity and pressure (BME680, Bosch USA) as well as gas phase compounds and particulate matter via user-populated sensors such as: CO, NO, NO_2, and O_2 (AlphaSense B4 series), CO_2 (S300, ELT), VOCs (including methane, TGS2600 and TGS2602, Figaro USA), and $PM_{2.5}$ (PMS5003, Plantower). A microcontroller (Mega2560, Arduino) processes the raw sensor data (in the form of either analog voltages or digital values) and writes them to a time-stamped row in a text file on a micro SDcard which is loaded onto the XPod printed circuit board (PCB). Raw data were logged every 10-15 seconds, and total continuous power consumption was 6 watts. The electronics were housed in a hard plastic, weather resistant case (S300, Seahorse) with two 1-inch inlets cut into the case of the wall on one end and two DC fans mounted on the opposite wall, exchanging air inside the case. Figure 14 depicts two XPod configurations, which present all the same sensors except for the Plantower PMS5003 to obtain $PM_{2.5}$ concentrations in OPODD1, and the Alphasense OPC-R2, for PM10 and coarse PM monitoring in OPODD2.

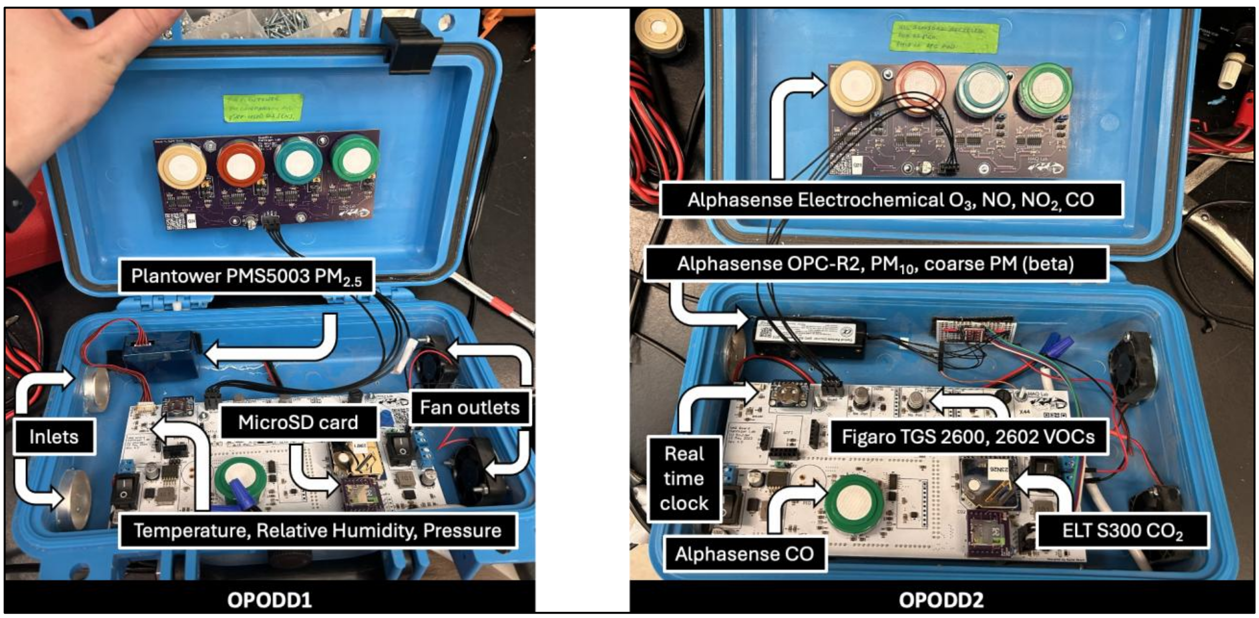


Figure 14. XPod (Pod) Hardware Configurations and Sensors Function Description

Some XPods can be custom-outfitted with cup-and-vane style anemometers (SEN-15901, Sparkfun) to provide wind speed and direction measurements. For deployments in the field, XPods were mounted at the top of a 5 foot long, 1.25-inch diameter schedule 40 PVC pipe which were placed over 1.25-inch T-posts secured into the soil. A 50W solar panel with a built-in charge controller unit (BC-50W-PM-2, SUNER POWER) were mounted to each pipe, below the Xpod, using a bracket (NPB-60P, Newpowa) which connected to a 35 Amp-hour sealed lead acid battery (ML35-12, Mighty Max) housed in a plastic battery case to keep the battery dry. A single XPod monitoring setup at the US 40 site can be seen in Figure 15 and costs roughly $1,200.

Figure 15. XPod Deployed at the US 40 Site with MET Station, Battery and Solar Panel

The beta-testing of the XPod involved the integration of the OPC-R2 sensor (Alphasense) to add PM_{10} and coarse PM measurement capabilities. Due to incompatibilities between the OPC-R2 and the Mega2560 as outfitted in the XPod, a separate monitor called the MiniPod was designed to accommodate a single OPC-R2 sensor which logged raw data to a SD card on a data logging shield (1141, Adafruit) using a Sparkfun Redboard Qwiic (DEV-15123, Sparkfun). See Figure 16 for a description of the MiniPod hardware. All raw data were logged every 2-10 seconds. An overview of each pod's sensor configuration for this project is provided in Table 1. MiniPods have IDs that start with "A" (i.e., A1).

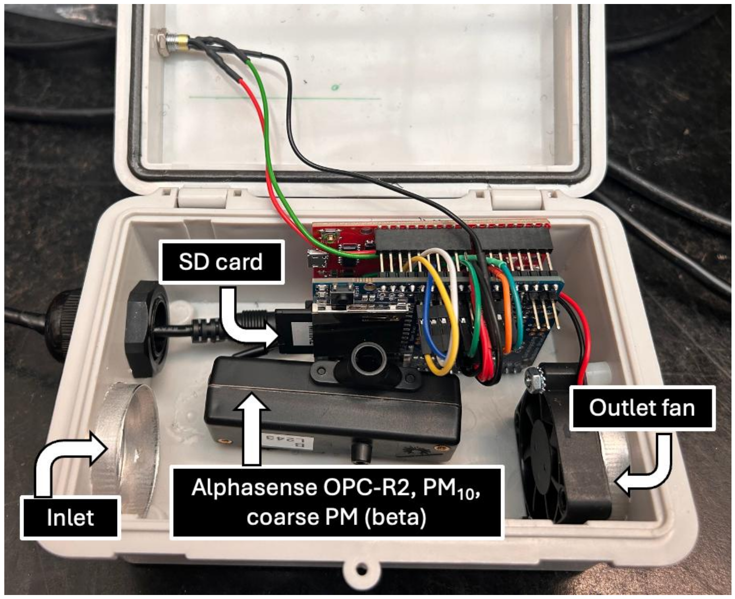


Figure 16. MiniPod Configuration Hosting the OPC-R2 Sensor (Alphasense)

Note: MiniPod was used to collect coarse PM and PM_{10} data

Table 1. Populated Sensors in the Air Monitors

Pod	ELT S300 CO_2	Alpha Sense CO-B4	Alpha Sense NO-B4	Alpha Sense NO_2-B4	Alpha Sense O_3+NO	Figaro TGS2600 tVOCs	Figaro TGS2602 tVOCs	Bosch BME680 Temperature, RH, Pressure	Plantower PMS5003 $PM_{2.5}$	Alpha Sense OPC-R2 Coarse PM, PM_{10}
D1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Beta
D2*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
D3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
D4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
D5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
D6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
D7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
D8	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Beta
D9*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
E2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
E3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
A1	No	No	No	No	No	No	No	No	No	Yes
A2	No	No	No	No	No	No	No	No	No	Yes
A3	No	No	No	No	No	No	No	No	No	Yes
A4	No	No	No	No	No	No	No	No	No	Yes

Note: * indicates pods outfitted with Sparkfun MET station (DEV-15123) for wind speed and wind direction measurements. "Beta" indicates a sensor configured only for the piloting phase. "Yes" indicates the presence of the corresponding sensor in a Pod, and "No" the absence of that sensor.

3.3. Data Extraction, Calibration, and Processing

3.3.1. Quantifying Pollutant Concentrations Using Sensor Signals

The HAQ Lab has developed several novel calibration procedures and models to convert raw sensor signals into volumetric (i.e., molar) or mass concentrations for many pollutant species. These procedures and models have been informed by best practices and balance quality of data against expended project resources. For example, Okorn and Hannigan (2021) devised and validated a calibration procedure that leverages the strong linearity found among sensors of the same make, model and age, allowing for a single XPod, dubbed the “reference pod”, to be calibrated (normalized) against reference-grade gas and particulate analyzer(s) at a Colorado regulatory air quality monitoring station (AQMS, Figure 17), called the primary colocation. Afterwards, the “reference pod” is collected and relocated alongside the remaining XPods (referred to as the deployment pods) in the field for 1-3 weeks allowing for the pods to harmonize while being exposed to the same environment during a process called the harmonization. Following a successful harmonization, the “reference pod” can then be returned to the AQMS to continue calibrating alongside the reference-grade monitor(s) and this process can be repeated many times to account for seasonal changes in temperature, humidity, pollutant concentration ranges and general sensor drift.

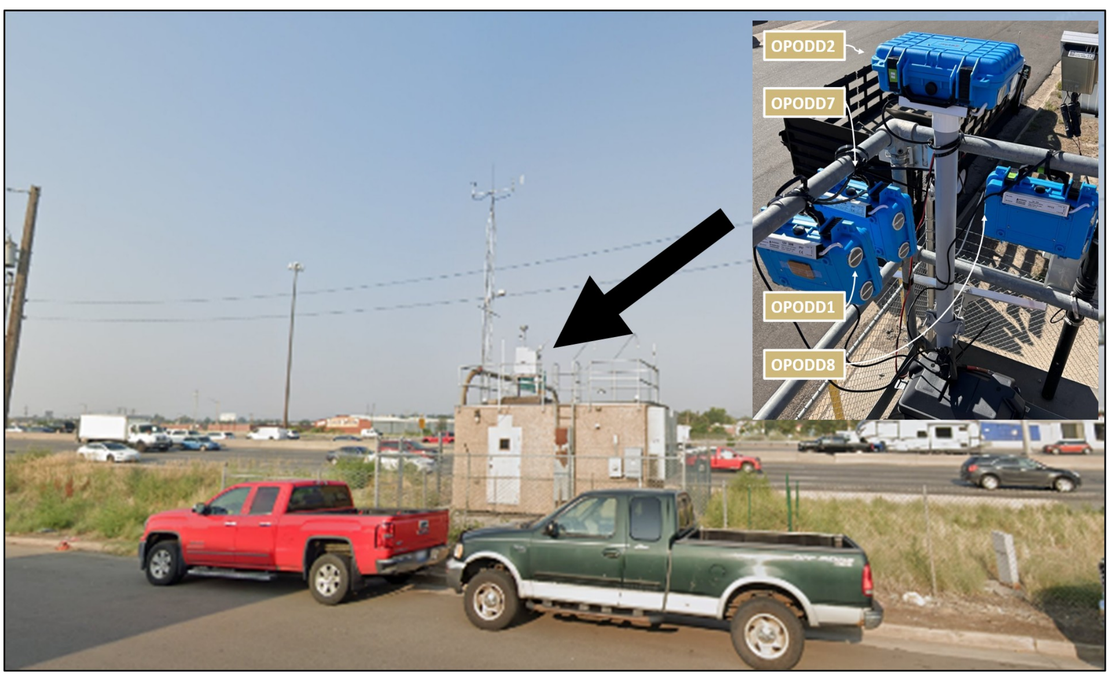


Figure 17. Primary Colocation Location Along I-25, Denver

Note: Colorado Department of Public Health and Environment's (CDPHE) I25 Denver AQMS where primary colocations for CO, $PM_{2.5}$, PM_{10}, coarse PM, NO, NO_2 and NO_x took place. This site uses a Thermo 48i-TL CO gas analyzer, GRIMM EDM 180 PM monitor and Teledyne API T200 gas analyzer for NO_x, (NO + NO_2).

This approach is called the "1-hop" calibration because the relationship(s) found between sensor signals of the "reference pod" and reference-grade concentration measurements is transferred to the other deployment pods during the harmonization. This method assumes all the pods are exposed to the same air mass at the same time and the air mass is well mixed. Individual sensors from one pod are often highly correlated (r>0.9) with their corresponding sensor in the other pods making this approach very useful. This greatly reduces project resources allocated to calibration because the "reference pod" is the only pod required to be colocated at the AQMS, drastically reducing the space and power requests from state AQMS managers. This approach also allows for more robust calibrations (i.e., larger environmental parameter space of temperatures, humidities and concentrations) as the "reference pod" can be colocated at the AQMS for months (across multiple seasons) while the deployment pods can be installed in the field where the target research is being conducted (coined field deployment) and undergo periodic harmonizations with the "reference pod" at sites across the study region. This process is described in Figure 18.

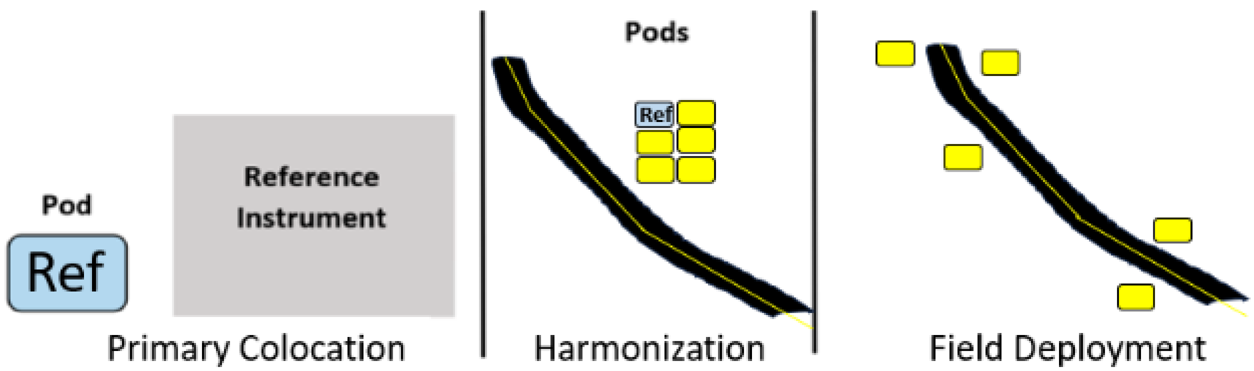


Figure 18. 1-hop Air Sensor Calibration Scheme

Note: The figure indicates the primary colocation between the blue "reference pod" and the reference-grade instrument, the harmonization among the reference pods and the deployment pods (yellow) and the field

Within the "1-hop" calibration approach, several sensor signal quantification models were investigated to normalize XPod sensor data to reference-grade concentration measurements. Multivariable linear regressions (MLR), although simplistic, offer robust quantification of sensor signals and are straightforward to interpret. A generalized form of the MLR used in this work is shown in Eq 1, where the reference monitor pollutant concentration is estimated by temperature, humidity, pressure, and one or more pod sensor signals. Here, reference concentration measurements are regressed on z-scored temperature, humidity (absolute or relative), pressure and pollutant sensor signals. An elapsed time term can be used to account for sensor drift between primary colocations and harmonizations. Optimization of the linear coefficients (betas in Equation 1) in MATLAB R2024a is done through ordinary least squares (OLS). Some reference concentration time series exhibited primarily low baseline levels with few short duration peaks. To better fit these peak levels, weighted regressions were implemented (indicated with a “pw” at the end of the model’s name) to weigh peak observations higher than baseline observations. This often results in better peak estimates at the cost of slight biases at lower levels (Frischmon et al. 2025).

$$Concentration_{reference} \sim \beta_0 + \beta_1 temperature + \beta_2 humidity + \beta_3 pressure + \beta_n signal_{sensor_n} \quad (\boldsymbol{Eq.1})$$

Validation of the models was investigated using k-fold cross validation where a subset of data was held back from the regression and model estimates were made on those data and compared to reference concentrations. For this work, a random 20% of hours (5 folds) were held back for validation for each model. The resulting model diagnostics (i.e., coefficient of determination R^2, root mean squared error RMSE and mean biased error MBE) were used to assess model performance lending to further refinement and quantifying uncertainty. An identical quantification process is implemented during the harmonization phase where MLRs are explored between “reference pod” estimates and z-scored signals from the deployment pods when placed alongside one another in the field. Figure 19 shows the harmonization configuration used for US 50. The last three harmonizations were completed by placing all the pods (blue monitor case only) on a single PVC pole so that the sensors were as close together as they could be.

Figure 19. Sensors Harmonization at the US 50 Passing Lane Construction Site, October 2023

3.3.2. Traffic Data Extraction and Processing

Two modalities were used to obtain traffic data. The first modality consisted in using the volume count feature of the countCAM4. When using this feature, the camera was positioned at a specific distance perpendicular to the road, with the camera lens pointing at the road at a specific height as determined by manufacturer specifications. While using this feature the camera did not collect video data, instead it would detect when a vehicle was passing by, the direction of travel, and the speed of the vehicle as a function of the camera distance from the road centerline. This traffic volume information was downloaded as a workbook into a laptop and then properly stored following CDOT's approved data management plan (DMP). This protocol was followed to collect traffic data from US 40 because being a remote location there was no concern of vandalism, we were able to install the cameras along the right of way, and they remained undisturbed during data collection. This approach yielded traffic data on a continuous basis during the 24 hours of the day. In total, we collected 11 weeks of traffic data with total volume every 15 minutes that we aggregated every hour for analysis. Due to technical challenges with the cameras the researchers were unable to collect traffic data during eight weeks (not consecutive weeks) of the data collection period. The missing data was populated by computing the mean (average) hourly traffic volume for the corresponding hour of the day and day of the week. The Average Daily Traffic determined for US 40 was 3476 vehicles.

The second traffic data collection and processing modality consisted in recording traffic in real time using the countCAM4 cameras and submitting these recordings to the streetlogicpro team (the countCAM4 manufacturing company) for counting and classification. The company offers traffic counting services conducted by actual human beings who watch the traffic videos. The company ensures 95% to 98% data accuracy. In total we submitted 1040hs of traffic videos capturing the traffic along the US 6 project from 7am to 5pm each day. After watching the videos, the company provided traffic volumes and two-class classification every 15 minutes for each hour of video submitted. The researchers aggregated such data by hour of day for posterior analysis. In this case, all data analysis conducted on US 6 (except for harmonization periods) had real traffic count data. Given the urban environment of this project, it was not possible to position the cameras to count traffic volumes following the first modality due to vandalism concerns. In fact, we had vandalism issues at US 6 several times during data collection. The 10-hr-ADT observed from 7am to 5pm on US 6 was of 7,451 vehicles.

During the pilot test on US 50 traffic data was obtained by watching the traffic video footage from the cameras. This modality allowed traffic classification in addition to vehicle volume, at the expense of losing speed data. This modality was extremely time-consuming and required two researchers to guarantee quality assurance and quality control (QA/QC) procedures. QA was sought through training meetings in which members of the research team would watch an hour of video footage together and classify the vehicles together to ensure consistency among the researchers and to address any doubts regarding the classification of the vehicles. QC was conducted by a principal researcher by randomly selecting two or three hours of video footage for each day and comparing the data extracted by a research assistant with the data observed on the footage by the principal investigator. If several mistakes were found on the data provided the entire traffic dataset for that day was corrected. Otherwise, the dataset was accepted for processing. It was more economical to outsource traffic data counting and classification to streetlogicpro for the US 6 project due to a significant increase in traffic volume, compared to US 50 (rural area), which made the data extraction process even more time consuming for the research team.

3.3.3. Construction Data Extraction and Processing

Construction activity was defined and aggregated on an hourly basis for each day. Work typically began around 7:00 a.m. and ended around 5:00 p.m., with occasional variations. For each location, activities were recorded by the hour (e.g., 7:00–8:00 a.m., Hot Mix Asphalt in Zone X). If an activity was interrupted or did not span the full hour, it was still coded as long as it lasted more than 15 minutes within that hour. Using this approach, the researchers classified 38 distinct construction activities into 10 main categories. A complete list of these activities is provided in Table 2.

Table 2. Construction Activities Classification

Group	Number	Acronym	Description	Group Name
1	1.0	ABC	Aggregate base course placement	Earthwork
1	1.1	ABC.PATCHING	Patching soft spots of ABC	Earthwork
1	1.2	SUBBASE	Grading the existing subbase	Earthwork
1	1.3	SUBBASE.STOCKPILE	Stockpile work	Earthwork
1	1.4	TOPSOIL	Applying topsoil	Earthwork
1	1.5	SUBGRADE	Clearing grubbing and preparing subgrade	Earthwork
2	2.0	HMA.B	HMA bottom mat	HMA
2	2.1	HMA.M	HMA mid mat	HMA
2	2.3	HMA.BINDER	Asphalt oil	HMA
2	2.4	HMA.PATCHING	Patching HMA	HMA
2	2.5	HMA.T	HMA top mat	HMA
3	3.0	STRIPING	Striping	Striping
4	4.0	EXC.SW	Excavating sidewalk	Sidewalk/Shoulder Soil
4	4.1	SUBBASE.SW	Grading subbase for sidewalk	Sidewalk/Shoulder Soil
4	4.2	SUBBASE.MEDIAN	Subbase for median	Sidewalk/Shoulder Soil
4	4.3	ABC.SW	Placing ABC for sidewalk	Sidewalk/Shoulder Soil
4	4.4	SAFETY.EDGE	Installing a soil safety edge	Sidewalk/Shoulder Soil
4	4.5	SOIL.MEDIAN	Applying topsoil to the median	Sidewalk/Shoulder Soil
4	4.6	SHOULDER.SOIL	Applying topsoil to the shoulder	Sidewalk/Shoulder Soil
5	5.0	CONCRETE.C&G	Pouring concrete curb and gutter	Sidewalk/C&G Pouring
5	5.1	CONCRETE.SW	Pouring concrete sidewalk	Sidewalk/C&G Pouring
6	6.0	JOINTS.CUT.SW	Cutting concrete joints	Saw Cutting and Other
6	6.1	SHOULDER	Shoulder work	Saw Cutting and Other
6	6.2	SWEEPING	Sweeping with skid steer	Saw Cutting and Other
6	6.3	CONCRETE.SAW.CUT	Concrete saw cutting	Saw Cutting and Other
7	7.0	CONCRETE.PCCP	Concrete road pouring	Rigid Pavement
7	7.1	CONCRETE.F	Concrete Finishing	Rigid Pavement
8	8	SSU	Subsurface Utility	Subsurface Utility
8	8.1	CONCRETE.U	Concrete pouring for utility	Subsurface Utility
8	8.2	MANHOLE	Manhole Installation	Subsurface Utility
9	9.0	MILLING	Asphalt cold milling	Asphalt Milling
9	9.1	ASPHALT.SAW.CUTTING	Asphalt saw cutting	Asphalt Milling
10	10.0	FORMING.SW	Forming Sidewalk	Undefined
10	10.1	WARMUP	Equipment warmup	Undefined
10	10.2	HYDRO.S	Hydro seeding	Undefined
10	10.3	BARRIER	Moving Jersey barriers	Undefined
10	10.4	CLEARING	Clearing site	Undefined
10	10.5	ASPHALT.R	Asphalt removal	Undefined
10	10.6	NaN	No Information	Undefined
11	11.0	NONE	No construction activity	No Construction

Note: Activities were grouped according to expected air pollution impact, and construction activity characteristics.

3.4. Data Analysis and Modeling

3.4.1. Applying Calibrations to Raw Pod Sensor Signals and Time-Averaging

Pollutant-and-pod-specific calibration equations were applied to 5-minute mean raw deployment data collected within each field deployment window. Resulting concentration estimates were quality checked to a) remove sensor warmup periods (within 30 minutes from powering on), and b) filter out unrealistically high (>6*standard deviations of differences between consecutive estimates) or negative estimates. Five-minute estimates were then hourly averaged (to match the resolution of other data streams, i.e., construction activity) to form the observational unit for subsequent analyses. Two pods (D2 and D9) were outfitted with meteorological sensors to measure wind speed and direction (2D anemometers). The raw sensor data was converted to speed in miles per hour and direction in degrees from North (0 degree) using manufacturer conversions. Time-averaging of windspeed was straightforward, akin to averaging pollutant concentrations, but time-averaging of wind direction required converting from Polar coordinates to Cartesian coordinates for averaging in two dimensions and then converting back to Polar coordinates. This avoids the issue of averaging 1 degree and 359 degrees (both almost straight North) as 180 degrees (straight South).

3.4.2. Calculating Pollution Enhancements Through Background Subtraction

Assessing pollutant concentrations across a construction site can be useful when exploring ranges and magnitudes but is limited in addressing the extent to which construction activities impact local air because background concentration levels within a region can fluctuate over time. These fluctuations are often driven by atmospheric mixing, which follows a typical diurnal cycle: a stable and poorly mixed atmosphere in the early morning turning into a well-mixed atmosphere during the daytime when temperatures and pressure gradients cause thermal variations and increased mixing followed by evening cooling and more stable atmospheric conditions lending to a lower boundary layer. These fluctuations can cause daytime concentrations to decrease relative to nighttime concentrations even though emissions are higher during the day. Therefore, the area background concentration was estimated for each hour by finding the lowest mean hourly concentration measured amongst all pods at a site. This background concentration was subtracted from the hourly measurements at all pods to estimate the enhancement above the background at each pod. For each field deployment, a record of the number of instances each pod was determined to be measuring background was logged. Analyses were performed in MATLAB R2024a.

3.4.3. Merging Data

Timeseries data of pollution enhancements, traffic volume (and classifications for US 6), environmental variables and construction activities were fused into one dataset using a custom MATLAB script incorporating key variables such as date and time, field deployment number, and geographic information of the pods (GPS locations and zones) or construction activities (zones), See Figure 20. Specifically, a single fused dataset was created for each pollutant of interest covering all field deployments across the various sites. Additional descriptive variables such as weekend vs. weekday, day (6am to 7pm) vs. night (7pm to 6am), were generated to offer additional explanatory power in modeling air quality impacts.

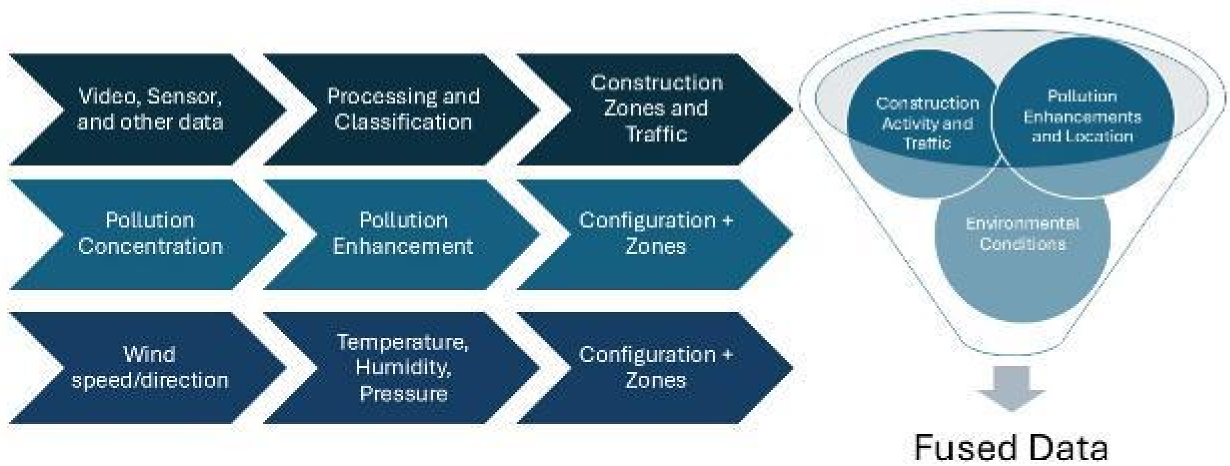


Figure 20. Data Fusion Flowchart

Note: The figure depicts the three main project data sets including construction activity and traffic data, pollution enhancements and location information and environmental conditions as inputs into the models.

3.4.4. Modeling Pollution Enhancements

Several modeling approaches were investigated to understand linkages between construction activities and resulting air pollution enhancements around construction sites. Understanding the degree to which certain factors contribute to increased enhancements at a site can help identify pathways to addressing such factors towards reducing the frequency and magnitudes of those enhancements. The strengths and weaknesses of each modeling approach described here were blended to elicit a well-rounded and complementary set of research outcomes. All modeling was performed in R (v4.4.2). Before models were constructed and run, the fused datasets were first filtered for quality. Observations where classifying construction activity lacked sufficient information resulting in less reliable categorizations, were omitted from analysis. Imbalanced data can also have a significant impact on model predictions and performance (Kuhn and Johnson 2013). This is due to some categories, like "No Construction" occurring most frequently (say >80% of the time) while specific construction activities being seldom (<1-5%). Down-sampling was implemented by removing nighttime (7pm-6am) observations to improve observational balance across construction activities and to remove artifacts of diurnal trends for which the background-subtraction method could not completely account.

3.4.4.1. Generalized Linear Mixed Effects Model

The first model type investigated were generalized linear mixed effect (GLMM) models employing a log linkage to model fixed and random effects with non-normal and skewed observations. Since air pollution enhancements were significantly skewed and all positive (except at the background site, 0 which were omitted from analysis) a Gamma distribution was assumed. Main, or fixed, effects are predictor variables that are assumed to have consistent impacts across space and time and therefore have a systematic influence on pollution enhancements. The random effects account for variability between specified groups. For these models, the grouping variable was pod ID, which was associated with a specific location for the duration of each field deployment period. The random effects help handle repeated measures from a single pod and account for consistent pod-specific differences not accounted for by fixed effects (baseline shifts, elevation effects, distance to road or idling vehicles etc.), allowing fixed effects to focus on shared patterns across space and time. GLMM predictor variable selection was done by iteratively removing predictors, one-by-one, from the complete set and selecting the model with the lowest Akaike Information Criterion (AIC) values. Model diagnostics were assessed and estimated marginal means were calculated, using the emmeans package, to explore the interactions between location (zone) or proximity to construction activities controlling for other variables in the model (Lenth et al. 2018).

3.4.4.2. Decision Trees

The second modeling approach pursued were decision trees. Decision trees (trees) are non-parametric algorithms that classify, focusing on partitioning data based on criteria (or rules). They lack predictive performance yet can succinctly visualize pathways taken to reach large (or small) enhancements and specify criteria (or rules) determining those pathways. The percentage of the total observations are shown at the node (before each split) indicating the relative numbers of data after the splitting criteria is applied. One of the best ways to interpret decision trees is to observe what the splitting criteria are (which variables and at what levels/amounts) and the resulting mean enhancements estimates for the splits which ultimately indicates the conditions in which high and low enhancements occur. Trees can therefore provide information to prioritize specific mitigation strategies to, say, limit the frequency and/or magnitude of enhancements. Trees can also rank the importance of predictor variables in a model by indicating changes in mean squared errors (MSE) when specific predictors are left out of the model. Trees were pruned using a cost complexity (cp) parameter (which penalizes larger trees and finds a balance between reduced sum squared errors (SSE) and complexity. Many machine learning resources exist which contain a wealth of information on Decision Trees, Random Forests and more. Bradley Boehmke created a tutorial of Hands on Machine Learning with R available on GitHub, which was used for this work.

3.4.4.3. Random Forests

The third approach was the decision tree-related random forest models. Random forests are a modification of (bagged) decision trees, or bootstrapped aggregated tree models, that build an ensemble of de-correlated trees to further improve predictive performance. Their strengths are good predictive performance with relatively little hyperparameter tuning. Like trees, they can also rank predictor importance which is a measure of the increased MSE when a predictor is unused when permuted. One way to think about random forests is, if decision tree is considered to be an individual expert's opinion, the random forest represents a large assembly of opinions from experts and the result of the forest is a consensus, the average.

Chapter 4. Results

4.1. Air Quality Measurements Timeline

A full timeline of all XPod and MiniPod air quality measurements are shown in Figure 21. Primary colocation, field harmonization, and field deployment measurement types are indicated by patterned boxes.

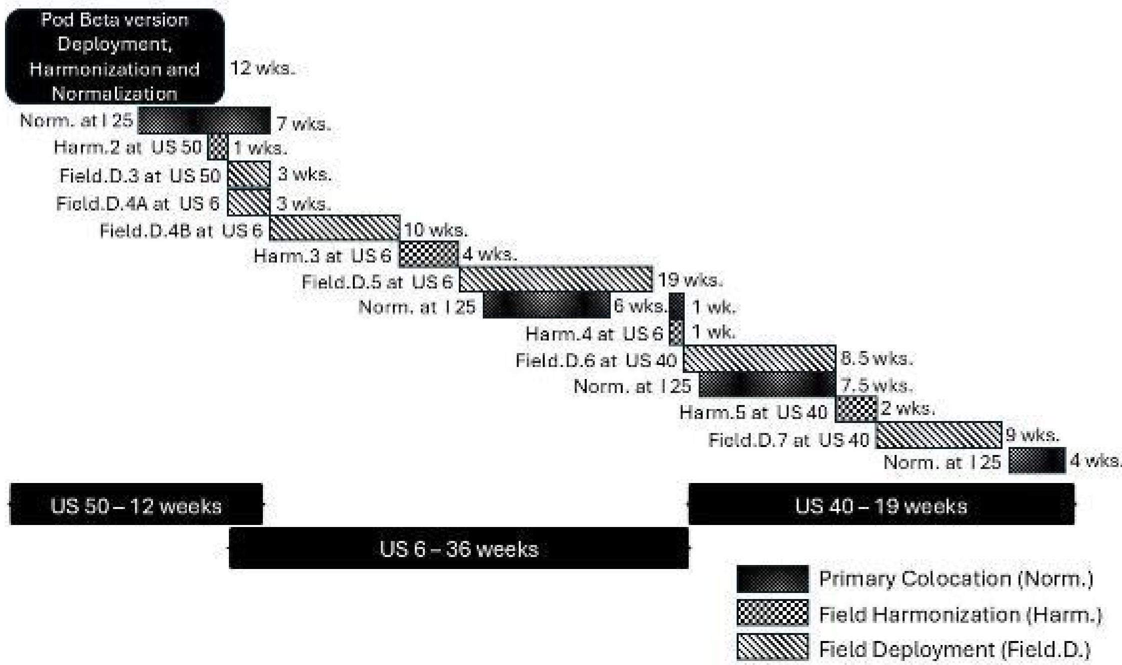


Figure 21. Air Quality Measurements Timeline

Note: The bands near the bottom correspond to the construction site. The textured horizontal bars indicate the phase of measurements (primary colocation, harmonization, or field deployment) and the period over which those measurements took place.

4.2. Air Monitor Sensor Calibrations: Primary Colocations and Harmonizations

The reference pod, D7, spent a total of 145 days at the I25 Denver AQMS from September 2023 to August 2024 for primary colocations for CO, $PM_{2.5}$, NO, NO_2, and NO_x. All 4 MiniPods (IDs, A1-A4) spent a total of 84 days at the I25 Denver AQMS from June 2024 to December 2024 for primary colocations for PM_{10} and coarse PM. Challenges finding a suitable reference tVOC monitor within the state of Colorado nudged the study team to leverage the reference monitoring capabilities and ongoing partnership with the South Coast Air Quality Management District (SCAQMD) in California. Reference pod D7 was sent to the Inner Port AQMS near Long Beach, CA for a total of 82 days from March to June of 2025.

Figure 22 (and Figures 52-58 in Appendix A) depict primary colocation calibration results at the CDPHE I25 Denver AQMS from pod D7 for CO, NO, NO_2, NO_x and $PM_{2.5}$ and pod A2 for PM_{10} and coarse PM as well as pod D7 for tVOCs from the Long Beach, CA Inner Port AQMS. Generally, D7 estimates showed strong linearity with reference grade concentration measurements (R^2 >0.75). Errors (RMSE), relative to the measurement range over which calibrations were generated, ranged from 3.3%-8.8%. Model biases in the calibration and validation folds were quite small for most pollutant models. Quantifying tVOCs is challenging due to the number and variety of volatile species observed in the air samples and the resultant sensitivities in sensor responses (Okorn and Hannigan 2021). For this work, a proxy for tVOCs concentration was measured at the SCAQMD reference site which consisted of a summed propane, butane and octane concentration so tVOCs concentrations reported are likely lower and less varied than actual amounts as they're more species of tVOCs in most air masses than just those three. Given this, the absolute enhancement concentration values for tVOCs should be used more as an indicator of larger or small levels. Moreover, identifying peaks in pollutants concentrations was important so a peak-weighted regression was fit for NO at the cost of a minor bias which would be counteracted during enhancement calculations (i.e., calculating differences between pods with similar biases removes spatial bias). Despite these efforts, high peaks in NO are likely underestimated (at values above 100ppb) as can be seen in Figure 52 (in Appendix A). Ultimately, propagated 5min measurement errors (RMSE) assuming independent errors across the 12, 5-min mean measurements (e.g., 12 x 5min = 60 min) resulted in hourly enhancement uncertainties of 0.03 ppm for CO, 4.3 ppb for NO, 1.5 ppb for NO_2, 4.5 ppb for NO_x, 9.2 ppb for tVOCs, 0.67 μg/m^3 for $PM_{2.5}$, 3.65 μg/m^3 for PM_{10}, and 2.92 μg/m^3 for coarse PM.

The primary colocation model results, calibration, and validation plots for the other pollutants can be found in Appendix A.

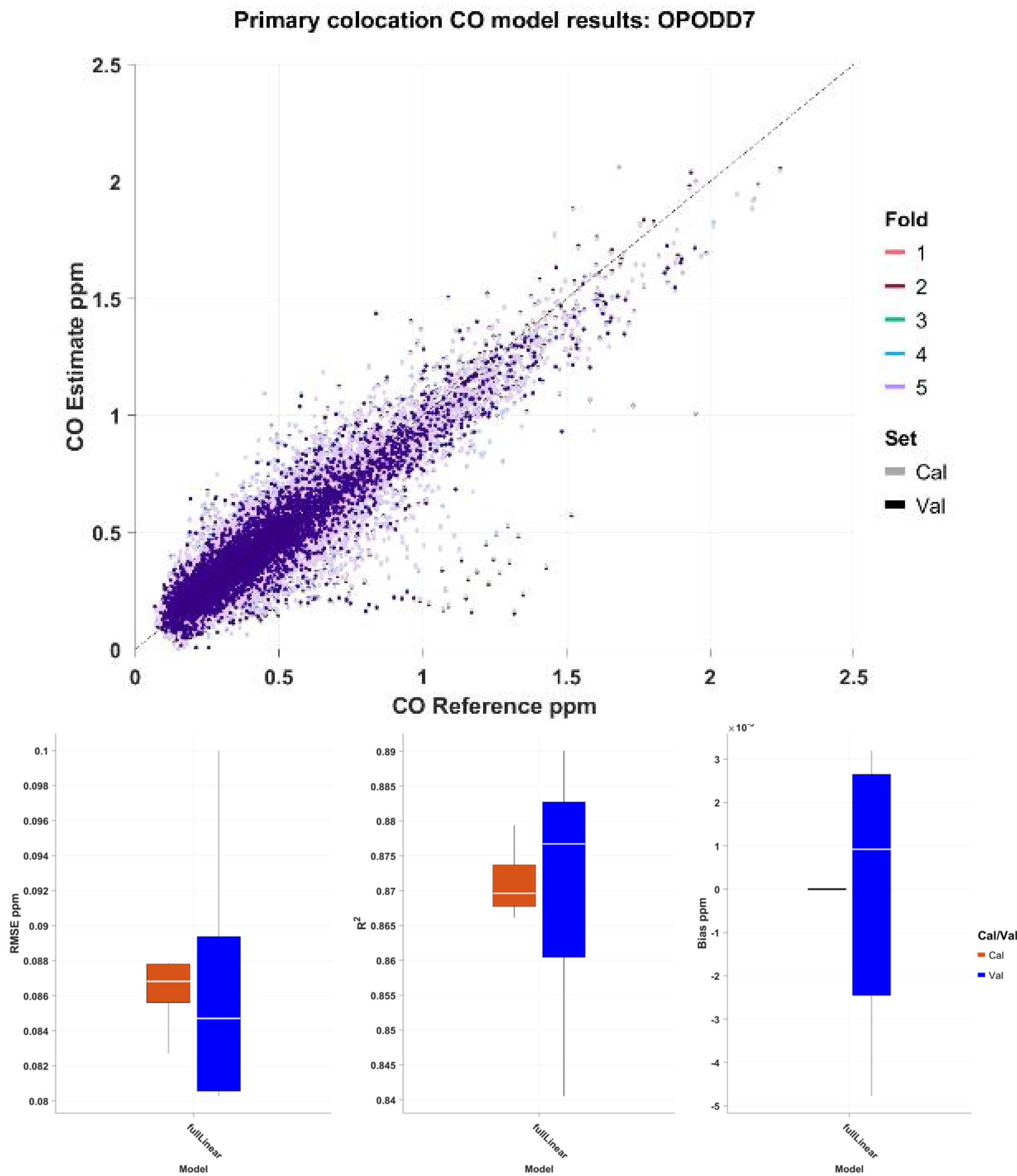


Figure 22. Primary Colocation CO Calibration (orange) and Validation (blue)

Note: Results at 5-minute means for "reference pod" D7. Top plot shows estimated CO against reference measurements across the 5 folds of validation. The dashed line is 1:1. Boxplots (bottom) show the variability in model diagnostics indicating overall performance across the 5 validation folds. Horizontal lines indicate medians.

Harmonizations took place every 2-4 months and there was at least one harmonization at each construction site. A total of 54 days were spent harmonizing the pods in the field. These harmonizations typically took place for 1-2 weeks at a time. Harmonizations required all pods to be located as close to one another as possible and when AC power was accessible, pods could be plugged in, and the batteries and solar panels could be stored (Figure 23A). Figure 23B shows an example of the CO harmonization results between pod D1 and reference pod D7 across all 54 days of harmonization in the field. Outliers (points far from the dashed, 1:1 line) are rare but are presumably the result of the pods being a couple of feet away from one another and the resulting small differences in the air sampled in each pod from perhaps a very near source.

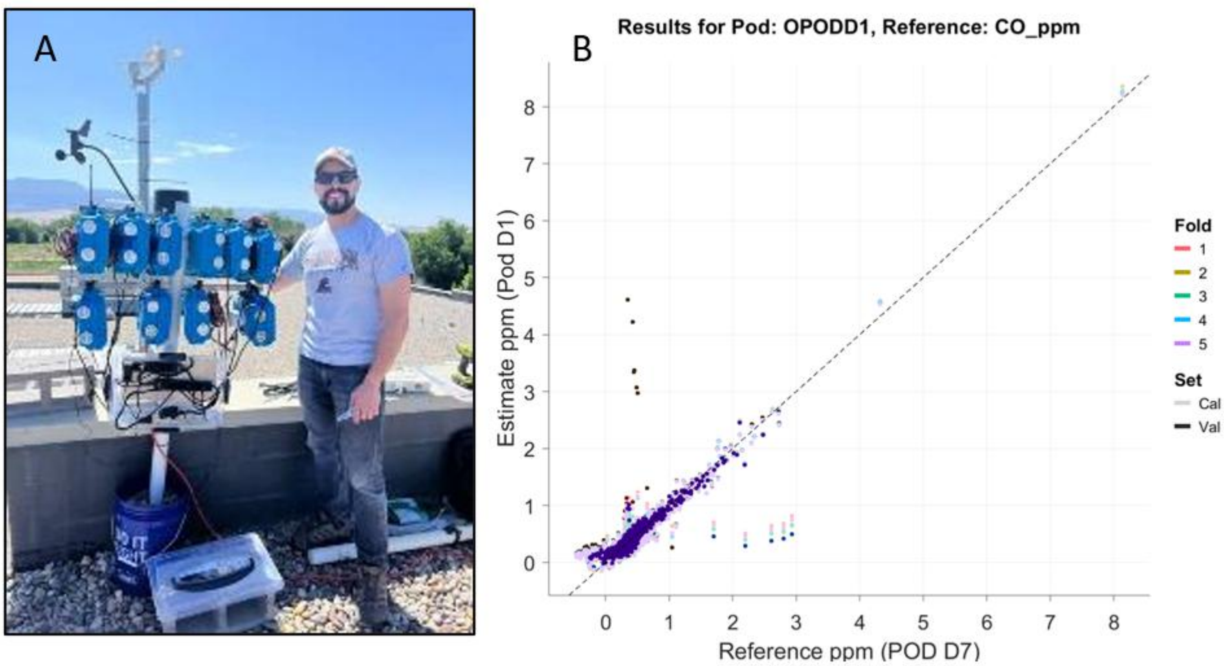


Figure 23. Senor Harmonization at the US 6 Site at Clifton Elementary School

Note: A) Sensor harmonization configuration at the US 6 site, on top of Clifton Elementary School in June 2024 and B) an example of the CO harmonization 1-hop results between pod D1 and reference pod D7 across all 54 days of harmonizing in the field. Units are in ppm and boxplots show the variability in model performance across the 5 folds. Dashed line is the 1:1 line.

4.3. Construction Site Air Quality Measurements: Field Deployments

4.3.1. Summary of Field Deployment Measurements

Field deployment air quality measurements took place between August 2023 and November 2024 for a total of more than 335 days of monitoring. The US 50 construction site served as a testbed for our new pod integration in the field. As described in Section 3.1, this phase of the study served as a useful pilot, where we discovered power management and data formatting issues early on as we integrated the OPC PM sensor into the new hardware and software package. As such, data collected from this portion of the study is less informative and the bulk of the analysis presented below focuses on the US 6 and US 40 construction sites. D5 experienced power issues in September 2023 and required significant repair. It did not rejoin the network of pods until harmonization 4 at US 6 in June 2024. An overall summary of the number of hourly-averaged observations for each pollutant are shown in Table 3.

Table 3. Hours of Calibrated, Hourly-Averaged Pollutant Observations by Project

Pollutant	US 50	US 6	US 40
NO	Pilot/beta	33,929	20,313
NO_2	Pilot/beta	34,898	25,402
NO_x	Pilot/beta	34,303	23,367
CO	Pilot/beta	35,092	24,405
$PM_{2.5}$	Pilot/beta	26,983	20,009
Coarse PM	NA	NA	7,004
PM_{10}	NA	NA	8,821
tVOCs	Pilot/beta	35,192	23,429

The one-hop calibration approach, and low-cost sensor quantification generally, excels when the environmental parameters observed during the primary calibration are not exceeded or subceeded in harmonization or field deployment measurement periods. Estimates made outside the calibration parameter space result in extrapolation and can have inherent errors. Figures 24-26 depict the temperatures, humidities and pressures observed during the primary colocation, harmonizations and field deployments showing robust overlap across all parameters except pressure. The elevation difference between the reference site (Denver I25 AQMS, elevation ~5200 feet) and the field sites (US 6, 4700ft and US 40, 7600ft) is the cause. This minor extrapolation could cause a small bias but would likely be consistent across pods and therefore biases in enhancements would become negligible. Absolute humidities were used in all calibration equations (as it is independent of temperature), except for PM where relative humidity was used due to marginally improved fits over absolute humidity. Relative humidities varied between 5-85% and no extrapolation was necessary.

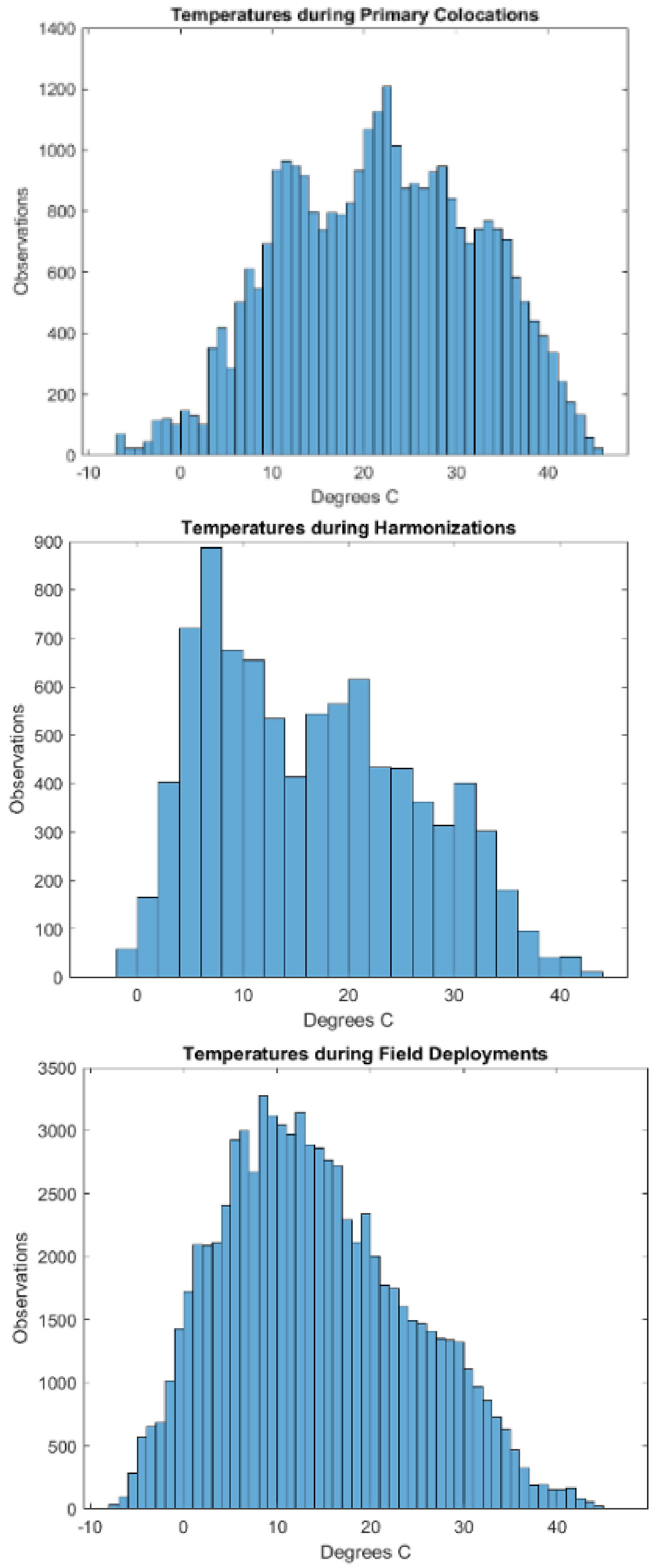


Figure 24. Temperatures Measured During Colocation, Harmonization, and Field Deployment

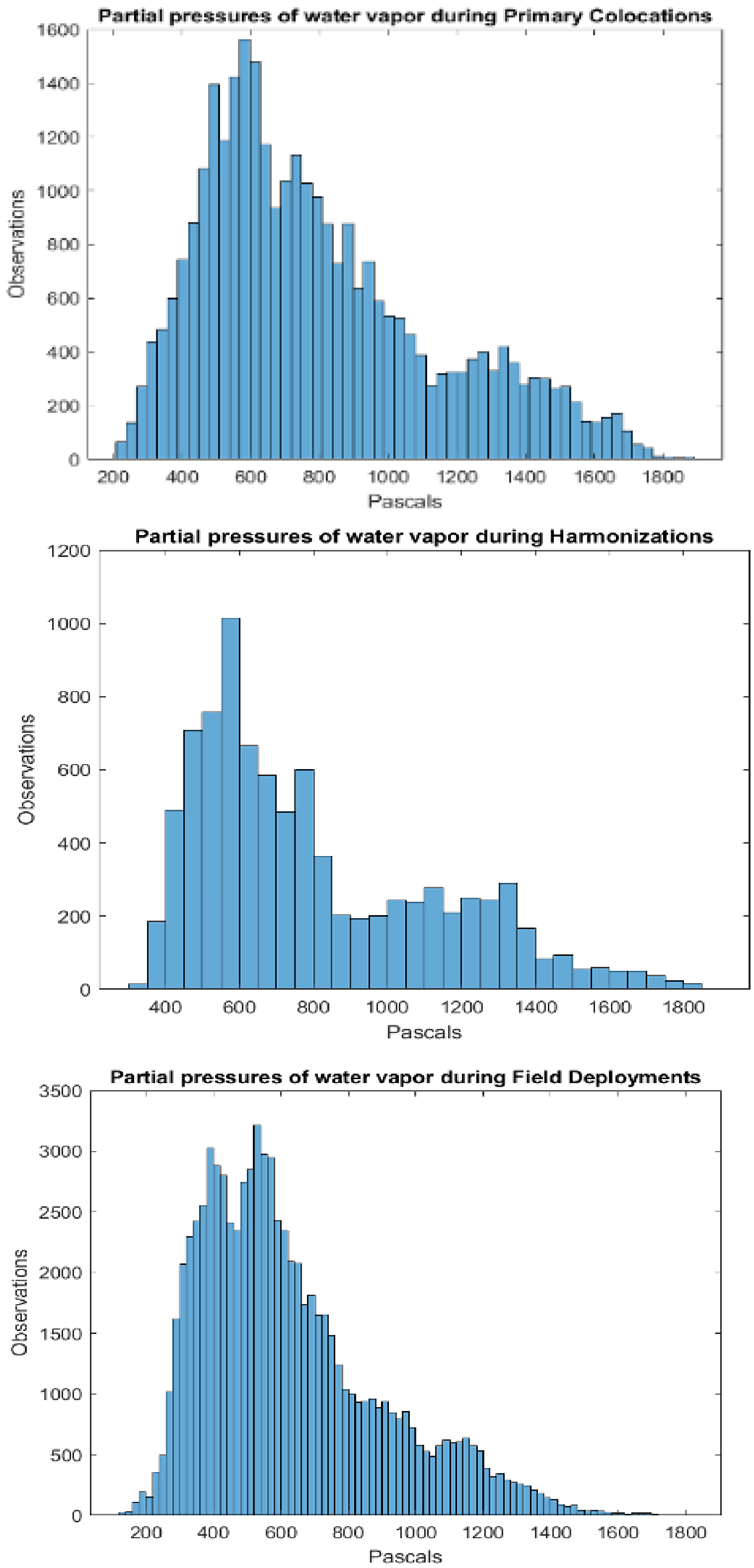


Figure 25. Absolute humidity Measured During Colocation, Harmonization, and Field Deployment

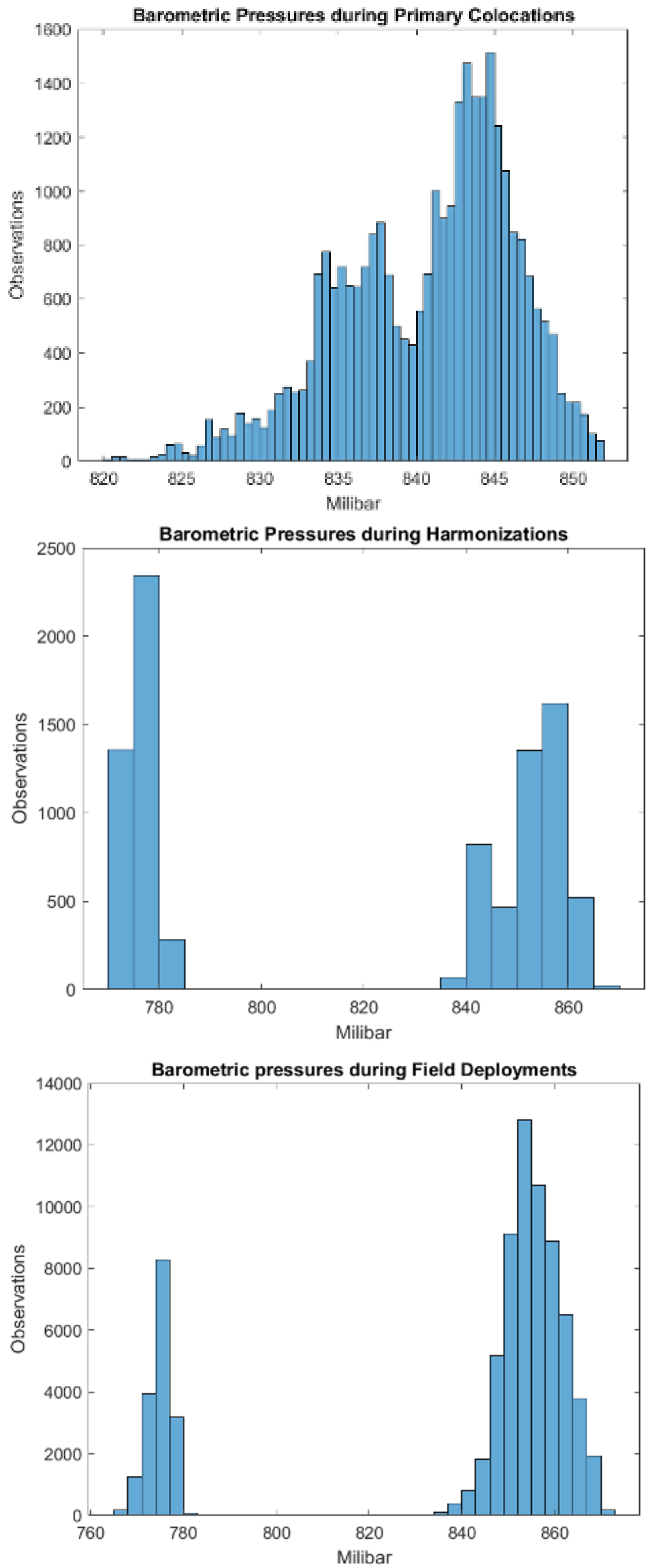


Figure 26. Pressure Measured During Colocation, Harmonization, and Field Deployment

Temperatures, humidities and pressures measured by pod D2 (with MET station) are shown in Figure 27 by hour of day across all field deployments. Strong diurnal patterns for temperature and humidity are evident whereas pressure variations are mainly dominated by construction site location, due to elevation, and dwarf diurnal variations across hours of the day.

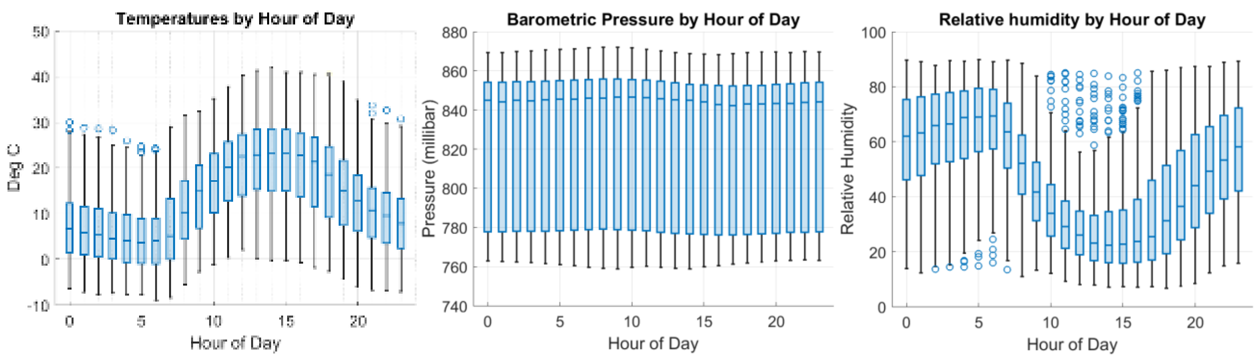


Figure 27. Temperatures (left), Barometric Pressures (middle) and Relative Humidities (right) Observed

Note: Environmental variables measured by D2 by hour of day across all field deployments (October 2023 to November 2024). Each box (interquartile range, IQR) shows the median (horizontal line) and whiskers are 1.5·IQR from the box outline and indicate outliers (circular dots).

4.3.2. US 6 Field Deployments 4 and 5 Results

This section explores the spatial and temporal variations in environmental conditions, construction activities, vehicle volume, and air quality enhancements observed during the US 6 field deployments 4A, 4B and 5 taking place between October 13, 2023, and June 17, 2024.

4.3.2.1. US 6 Environmental Conditions

Wind speeds and directions measured at pod D2 during the US 6 deployments are shown in Figure 28 for all hours as well as daytime (6am-7pm) and nighttime (7pm-6am) hours. The general patterns were gustier winds out of the South and West and East/West winds during the daytime and calmer winds mainly out of the North during the night. Most of the time, wind speeds were under 4mph.

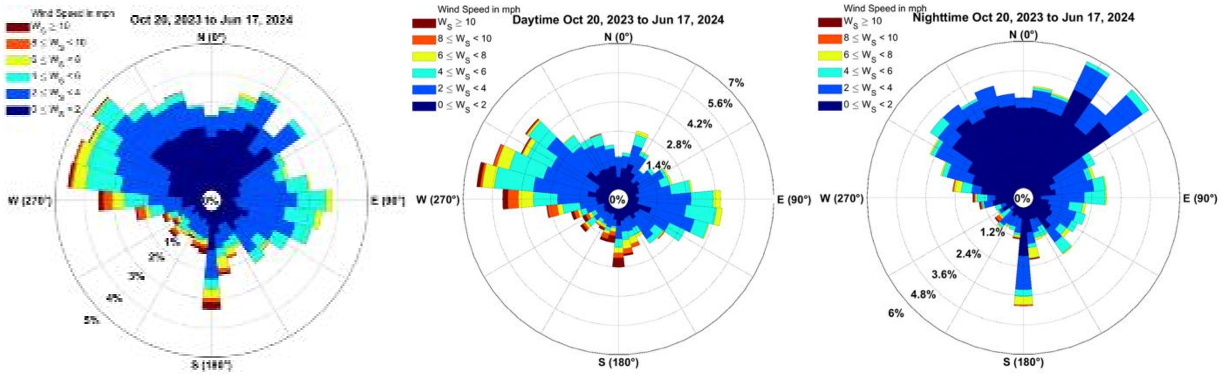


Figure 28. Wind Roses Showing Speeds and Directions for Diurnal and Nocturnal Patterns (US 6)

Note: Wind roses showing wind speeds and directions at US 6 field deployments 4-5 during all hours (left), daytime hours (6am-7pm, middle) and nighttime hours (7pm-6am, right). The warmer the coloring the higher the speed and the longer the radial distance from the center, the more frequent that direction was.

Wind speeds across the hour of the day are shown in Figure 29. Wind speeds peaked in the midafternoon (3-4pm) and were calmest in the early morning (midnight to 4am). The largest variability in windspeeds were observed during the afternoon (noon-6pm).

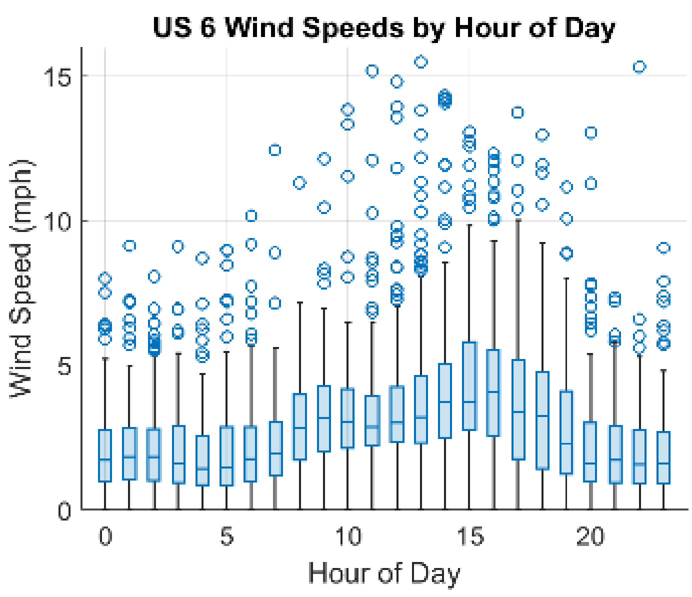


Figure 29. Wind Speeds by Hour of the Day on US 6

Temperatures, humidities and pressures measured by pod D2 are shown in Figure 30 by hour of day. Strong diurnal patterns for temperature, pressure and humidity are evident. Peaks in temperature corresponded with lowest humidity as expected. Barometric pressure dipped in midafternoon when wind speeds were the highest and peaked in the early morning when wind speeds were medium-low.

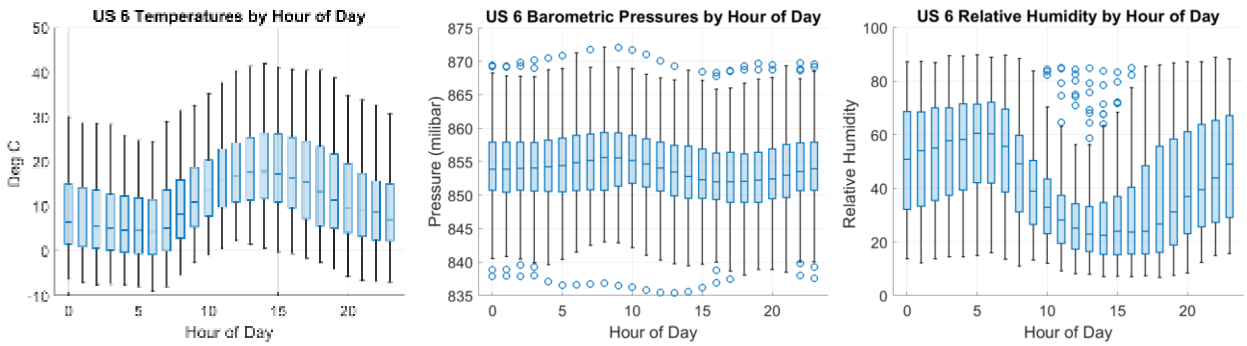


Figure 30. Temperatures, Humidities and Pressures Measured by Pod D2 Throughout the Day on US 6

4.3.2.2. US 6 Traffic

Hourly traffic volume measurements for US 6 (Figure 31) along the construction area were limited to daytime hours only due to lack of camera visibility during low light periods (dusk to dawn). Traffic counts generally increased throughout the day with a peak around 4pm at nearly 1000 vehicles per hour.

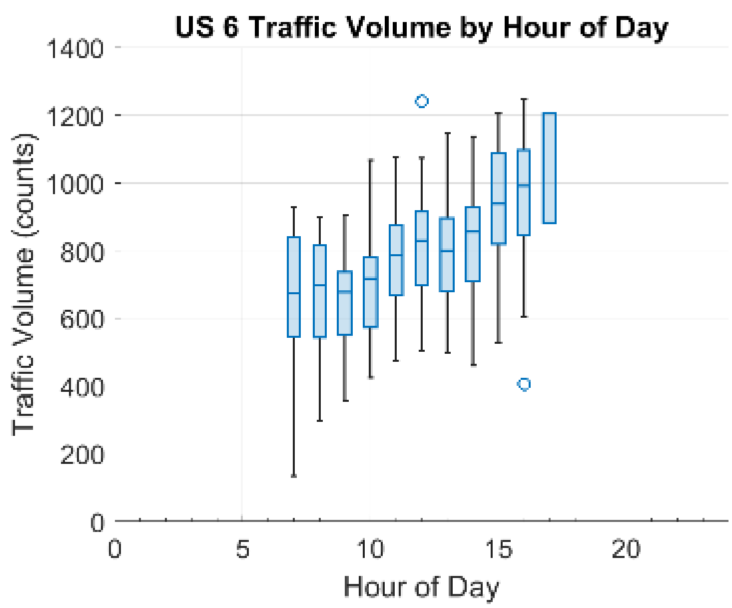


Figure 31. Traffic Volume at US 6, by Hour of Day, Both Directions

4.3.2.3. US 6 Construction Activities

Construction at US 6 consisted primarily of Earthwork and HMA followed by Sidewalk/C&G Pouring, Sidewalk/Shoulder Soil work and Asphalt Milling in zones 1 and 2, mainly. Striping was only conducted in zone 1. Very little (a couple of hours) HMA was conducted in zone 4 (where no pods were located). Nearly 90 hours were classified as Undefined construction activity with no zone assignment, and between 10 and 20 hours of Undefined construction activity in zones 1 and 2, each. Altogether, zone 1 had the most construction hours observed. Notably, No Construction was most common with nearly

4000 hours which was expected given these data were from all hours (24 hours/day). Figure 32 represents the number of hourly observations of each construction activity at US 6 by zone.

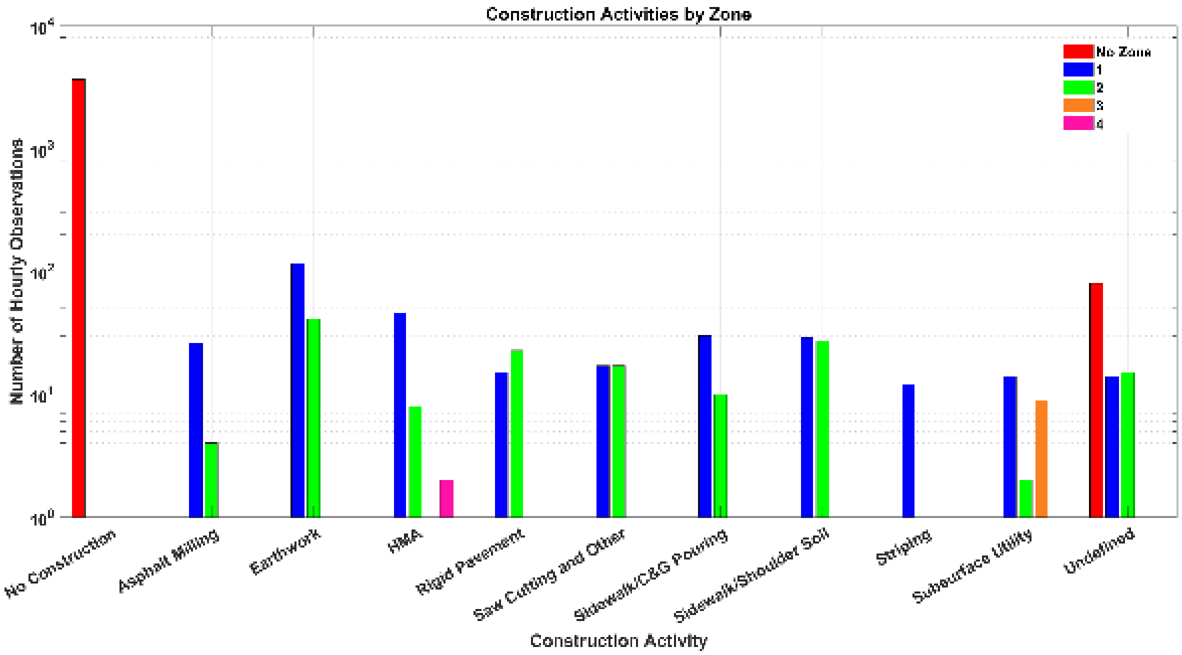


Figure 32. The Number of Hourly Observations (log scale) of Each Construction Activity at US 6 by Zone

Note: Data from field deployments 4A, 4B and 5 (October 2023-June 2024) across all hours (24 hr/day). "No Construction" refers to hours in which no construction was occurring across all zones. Zone 5 had no construction not all zones had every construction activity. The y-axis scale is logarithmic.

4.3.2.4. US 6 Pollution Enhancements

Pollution enhancements were calculated through background subtraction. As an example, background CO concentration estimates are shown by hour of the day in Figure 33. Background levels peaked in the early morning (7-8 am) and were lowest around 1-2 pm attributable to increased atmospheric mixing. Figure 34 depicts the timeseries of background CO levels at US 6 as well as the frequency each pod measured background over field deployments 4A, 4B and 5 (note: some pod locations changed between field deployments). Pod D4 measured background the most often. It is evident that background levels fluctuated on a 24hr cycle and seasonally, most likely due to vertical atmospheric mixing patterns caused by temperature and pressure fluctuations. Cooler air temperatures can lead to more stable (less air mixing) conditions, resulting in higher background concentrations. Analysis of measured enhancements at US6 of the other pollutants (example for CO below) can be found in Appendix B1.

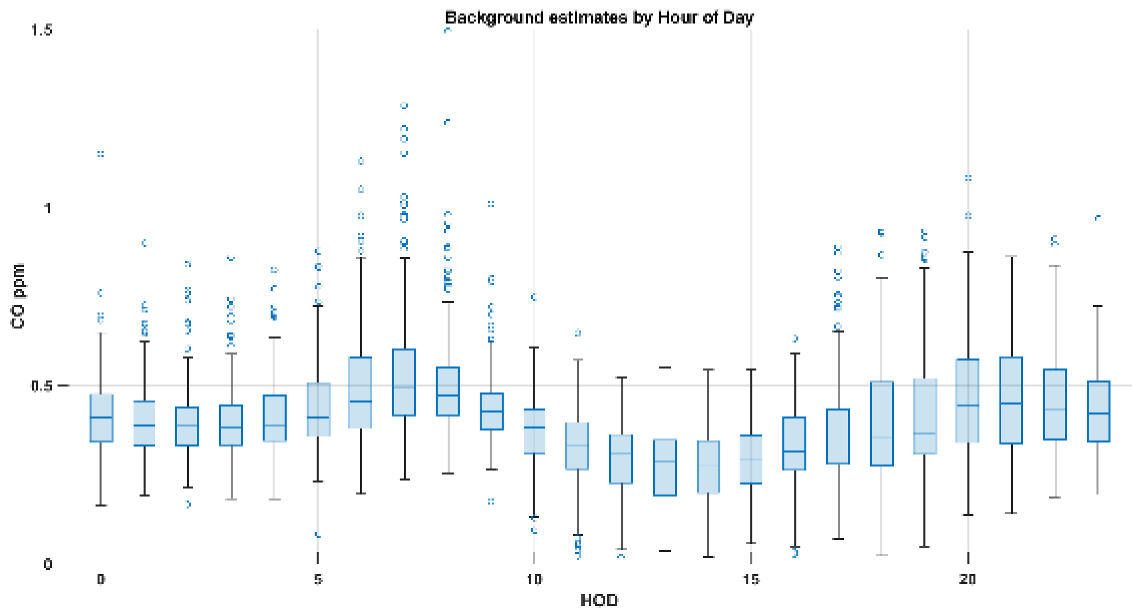


Figure 33. Background CO Estimates at US 6 by Hour of the Day

Note: Each box (interquartile range, IQR) shows the median (horizontal line) and whiskers are 1.5·IQR from the box outline and indicate outliers (circular dots).

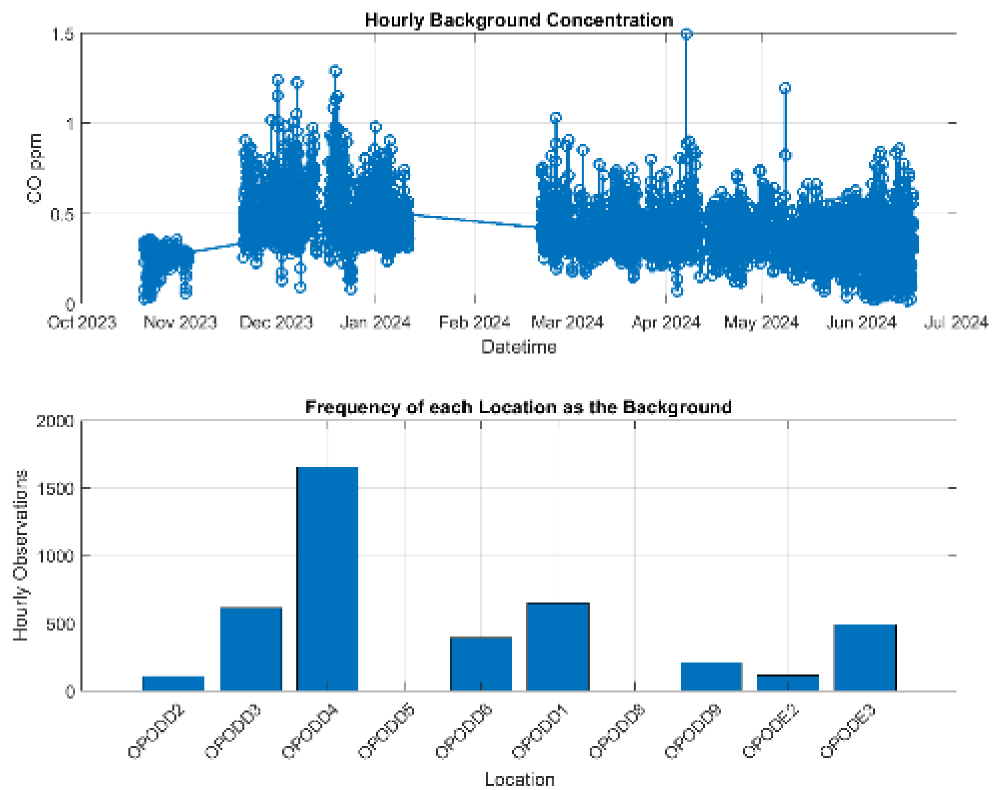


Figure 34. Background CO Concentrations (top) at US 6 and the Frequency of Observations (bottom)

Note: The frequency refers to the number of hours each pod was determined to be measuring CO background across field deployments 4B, 4A and 5 at US 6 (bottom). D4 in zone 3, on the north side of the road, measured background most often.

4.3.2.4.1. US 6 CO Enhancements

Hourly averaged CO enhancements ranged from 0 to 5.98 ppm (Figure 35). Again, mean hourly CO measurement uncertainty was estimated to be 0.03 ppm. Median enhancements for each zone ranged from 0.08ppm for zone 3 to 0.19 ppm for zone 2 (zone 5: 0.17 ppm, zone 1: 0.12 ppm). Zone 1 had the three highest hourly observed CO enhancements (4-6 ppm). When grouped by construction activity, Striping and HMA had the highest median enhancements at 0.16 ppm, followed by Earthwork (0.15 ppm) and Subsurface Utilities (0.14 ppm). Sidewalk/C&G Pouring was associated with two of the top five enhancements. No construction was also associated with dozens of outlier enhancements which could be explained by vehicle traffic emissions or other combustion emissions unrelated to construction.

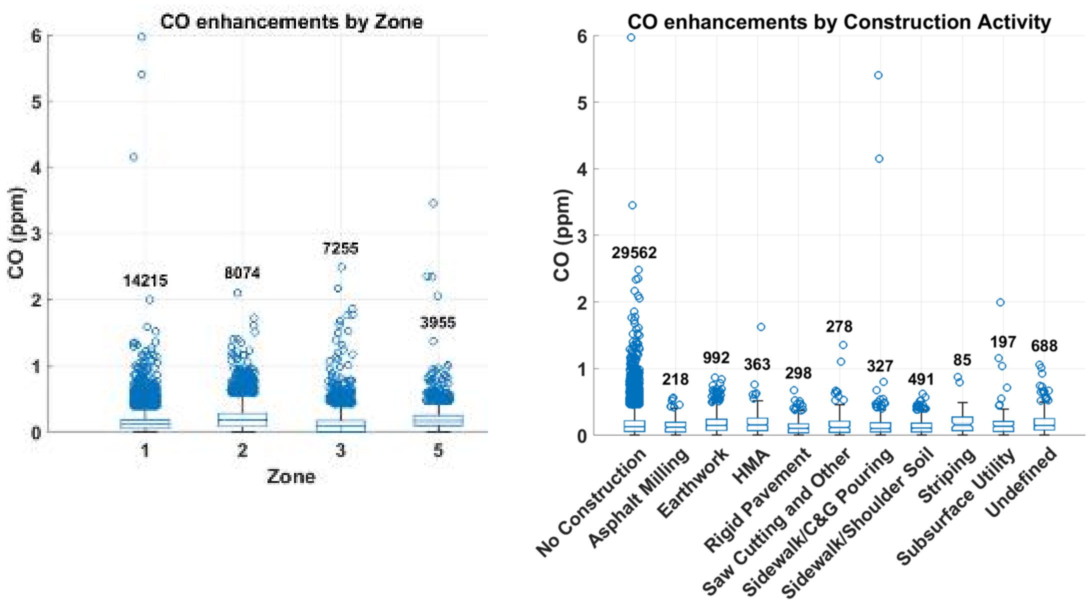


Figure 35. CO Enhancements by Zone and Construction Activity on US 6

Note: Bolded numbers above each group's boxplot indicate the number of hourly observations for that group. Each box (interquartile range, IQR) shows the median (horizontal line) and whiskers are 1.5·IQR from the box outline and indicate outliers (circular dots). The shaded band within each box indicates the uncertainty of the mean of that grouping. The larger the shading the larger the uncertainty.

Analysis of measured enhancements at US6 of the other pollutants can be found in Appendix B1.

4.3.3. US 40 Field Deployments 6 and 7 Results

This section explores the spatial and temporal variations in environmental conditions, construction activities, vehicle volume, and air quality enhancements observed during the US 40 field deployments 6 and 7 taking place between June 26, 2024, and November 11, 2024.

4.3.3.1. US 40 Environmental Conditions

Wind speeds and directions measured at pod D2 during the US 40 deployments are shown in Figure 36 for all hours as well as daytime (6am-7pm) and nighttime (7pm-6am) hours. The general patterns were gustier winds out of the south/southeast during the daytime and calmer winds out of the north/northwest during the night. This corresponded to up-valley winds during the day and down-valley winds during the night. Most of the time, wind speeds were under 4mph.

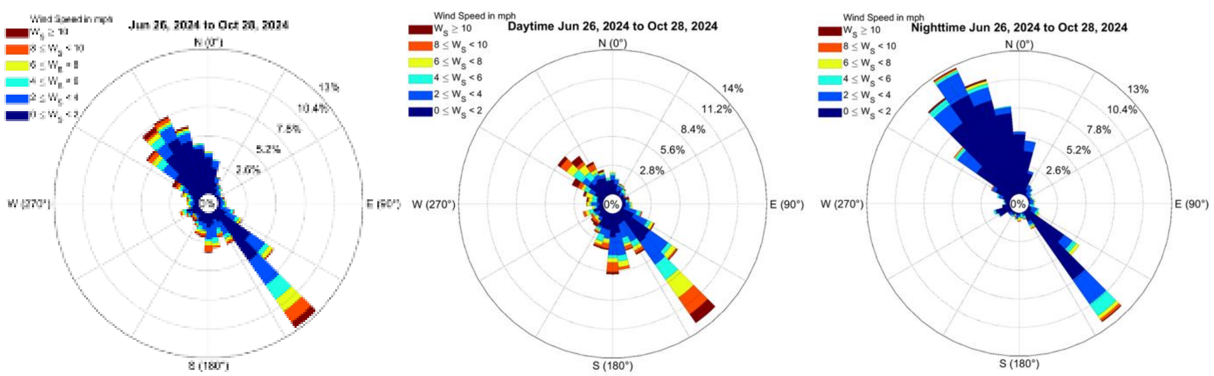


Figure 36. Wind Roses Showing Speeds and Directions for Diurnal and Nocturnal Patterns (US 40)

Note: Wind roses showing wind speeds and directions at US 40 field deployments 6 and 7 during all hours (left), daytime hours (6am-7pm, middle) and nighttime hours (7pm-6am, right). The warmer the coloring the higher the speed and the longer the radial distance from the center, the more frequent that direction was.

Wind speeds across the hour of the day are shown in Figure 37. Wind speeds peaked in the midafternoon (3pm) and were calmest in the early morning (7am). The largest variability in windspeeds were observed during the afternoon/evening (12pm-8pm).

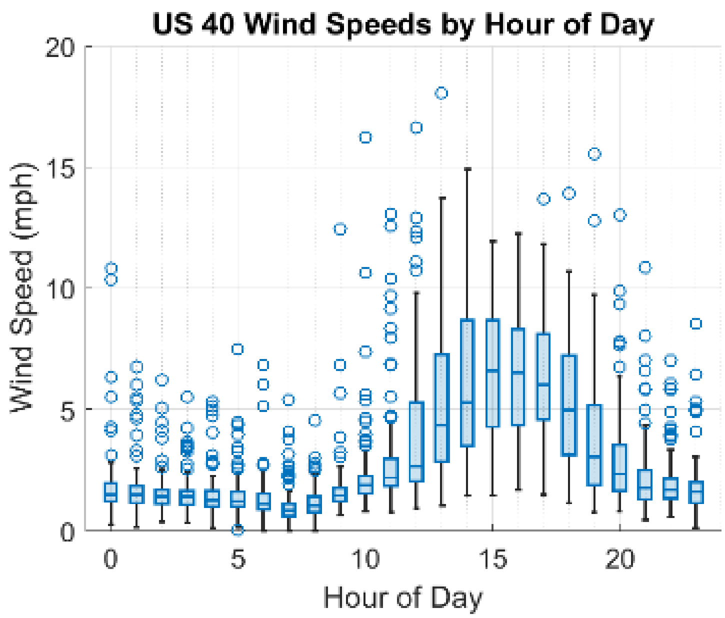


Figure 37. US 40 Wind Speeds Measured at Pod D2 by Hour of the Day

Temperatures, humidities and pressures measured by pod D2 are shown in Figure 38 by hour of day. Strong diurnal patterns for temperature, pressure and humidity were evident. Peaks in temperature corresponded with lowest humidity as expected. Barometric pressure dipped in midafternoon when wind speeds were the highest and peaked in the early morning when wind speeds were low.

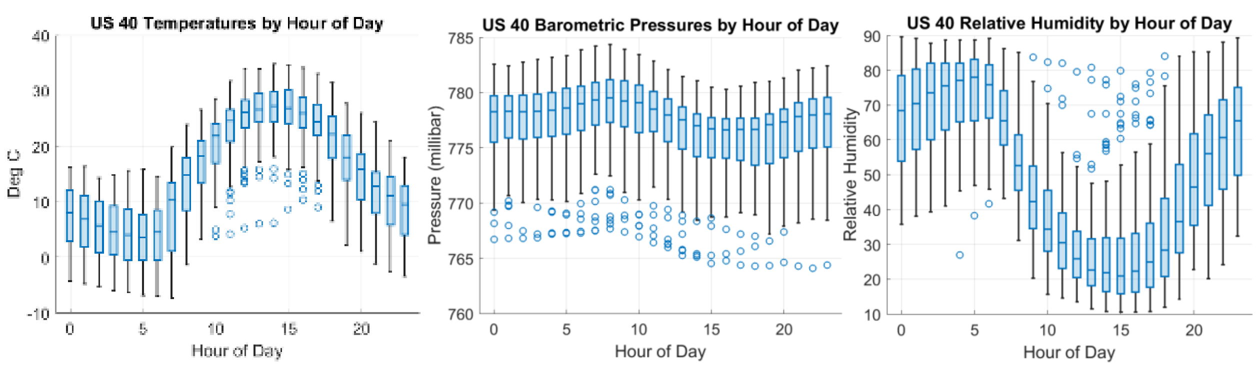


Figure 38. Environmental Variables Measured by Pod 2 per Hour of the Day at US40

Note: Temperatures (left), barometric pressures (middle), and relative humidity (right) measured by pod D2 (with MET) by hour of day at US 40.

4.3.3.2. US 40 Traffic

Traffic at US 40 (Figure 39) followed a strong hourly pattern with traffic peaking midday to early afternoon at nearly 300 vehicles per hour on median. Then traffic counts dwindled to just a couple dozen an hour in the evening and early morning.

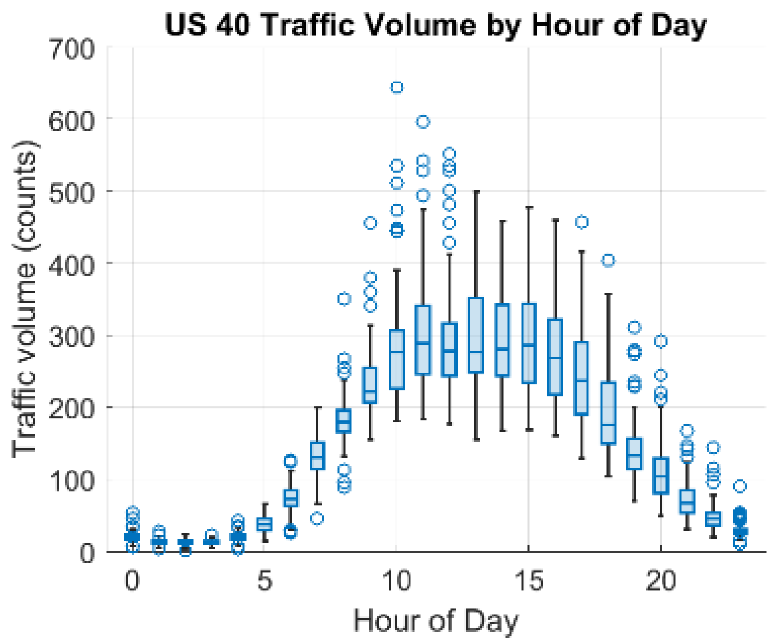


Figure 39. Traffic Volume at US 40, by Hour of Day, Both Directions

4.3.3.3. US 40 Construction Activities

Construction at US 40 (June – November 2024) primarily consisted of earthwork, HMA, sidewalk/shoulder soil and striping. Less than 10 hours of asphalt milling and saw cutting and other were observed. Figure 40 shows the breakdown of construction activities by zone. Earthwork was most common in zones 2 and 3 (>150 hours) with about 50 hours taking pace in zone 4. Zone 3 had the most HMA followed by zone 2 and 4. No construction took place in zones 1 and 5. Notably, No Construction was most common with nearly 2000 hours which is expected given these data are from all hours (24 hours/day).

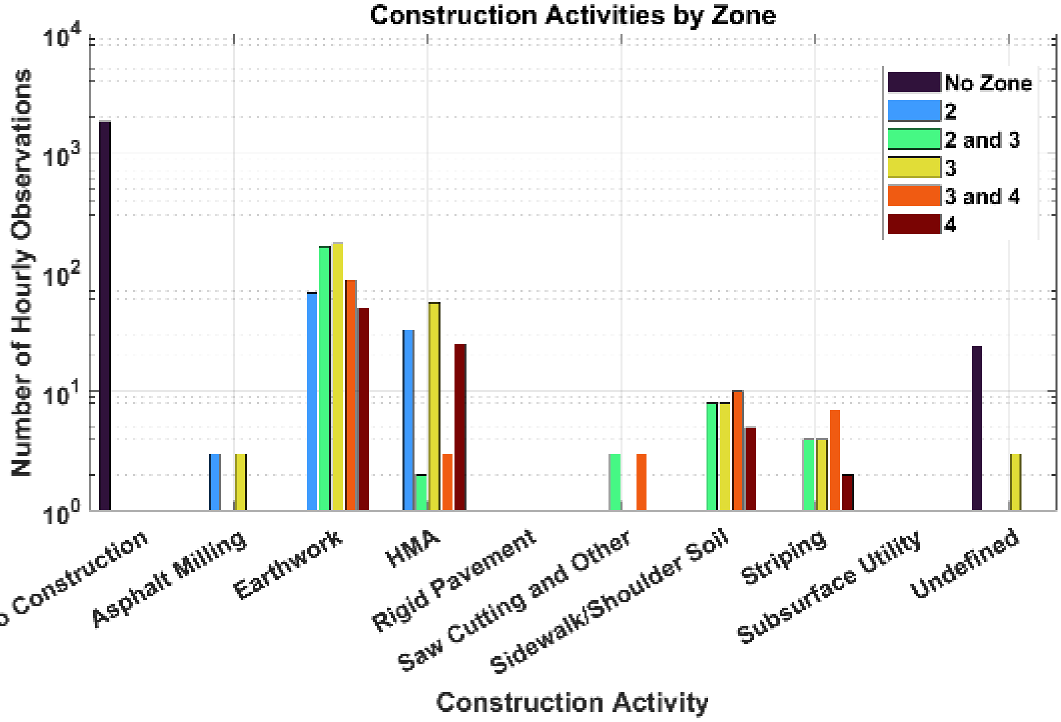


Figure 40. The Number of Hourly Observations of Each Construction Activity at US 40 By Zone

Note: Data for field deployments 6 and 7 (June-November 2024) across all hours (24 hr/day). Construction was observed taking place in more than one zone simultaneously and is indicated with more than one zone ("2 and 3", "3 and 4"). "No Construction" refers to hours in which no construction was occurring across all zones. Zones 1 and 5 had no construction in them.

4.3.3.4. US 40 Pollution Enhancements

Pollution enhancements were calculated through background subtraction. As an example, background CO concentration estimates are shown by hour of the day in Figure 41. Background levels peak in the early morning (7-8 am) and are lowest around 1-2 pm attributable to atmospheric mixing. Figure 42 depicts the time series of background CO levels at US 40 as well as the frequency each pod was measuring background over field deployments 6 and 7 (note: some pod locations change between field deployments 6 and 7). Pod D1 was overwhelmingly measuring background the most often. Resulting enhancements, when the background observations were removed, followed most closely, a Gamma distribution with a modest peak near zero but positive, and a long positive tail. Analysis of measured enhancements at US 40 of the other pollutants (example for CO below) can be found in Appendix B2.

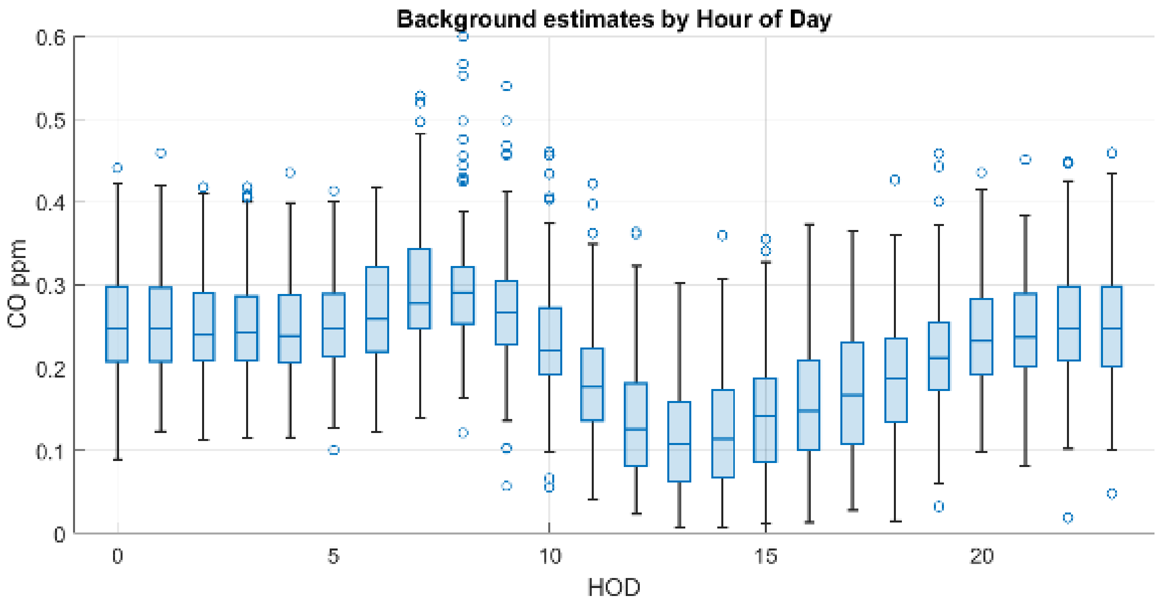


Figure 41. Background CO Estimates at US 40 by Hour of the Day

Note: Each box (interquartile range, IQR) shows the median (horizontal line) and whiskers are 1.5·IQR from the box outline and indicate outliers (circular dots).

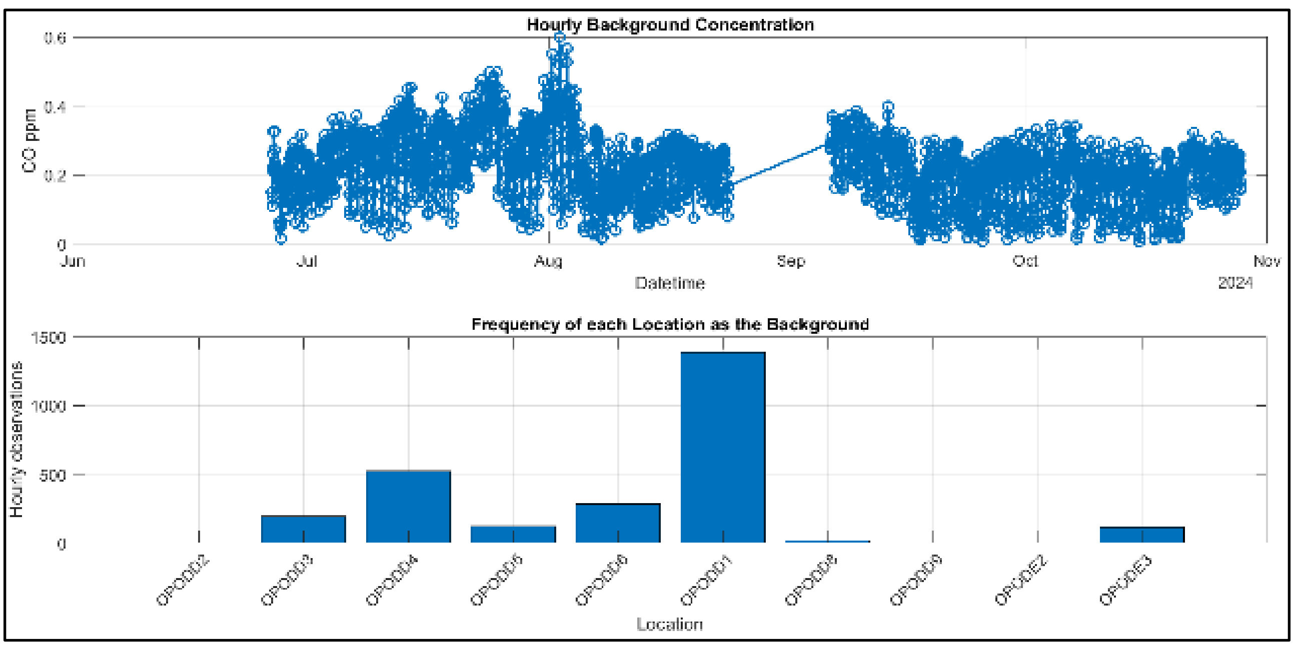


Figure 42. Background CO Concentrations (top) at US 40 and the Frequency of Observations (bottom)

Note: Background CO concentrations (top) at US 40 and the frequency (the number of hours) each pod was determined to be measuring CO background across field deployments 6 and 7 at US 40 (bottom). D1 in zone 5, on the southernmost section of the site, measured background most often.

4.3.3.4.1. US 40 CO Enhancements

Hourly averaged CO enhancements ranged from 0 to 5.98 ppm (Figure 43). Again, mean hourly CO measurement uncertainty was estimated to be 0.03 ppm. Median enhancements for each zone ranged from 0ppm for zone 5 to 0.18 ppm for zone 1 (zone 2: 0.12 ppm, zone 3: 0.10 ppm and zone 4: 0.17 ppm. When grouped by construction activity, Rigid Pavement, Sidewalk/Shoulder Soil, Saw Cutting and Other, and HMA had median enhancements of 0.20 ppm, 0.19 ppm, 0.18 ppm and 0.18 ppm, respectively. No Construction had a median enhancement of 0.12 ppm. Notably, outliers (beyond the whiskers of 1.5 x IQR) of hourly enhancements were associated with Sidewalk/Shoulder Soil, No Construction, HMA and Earthwork.

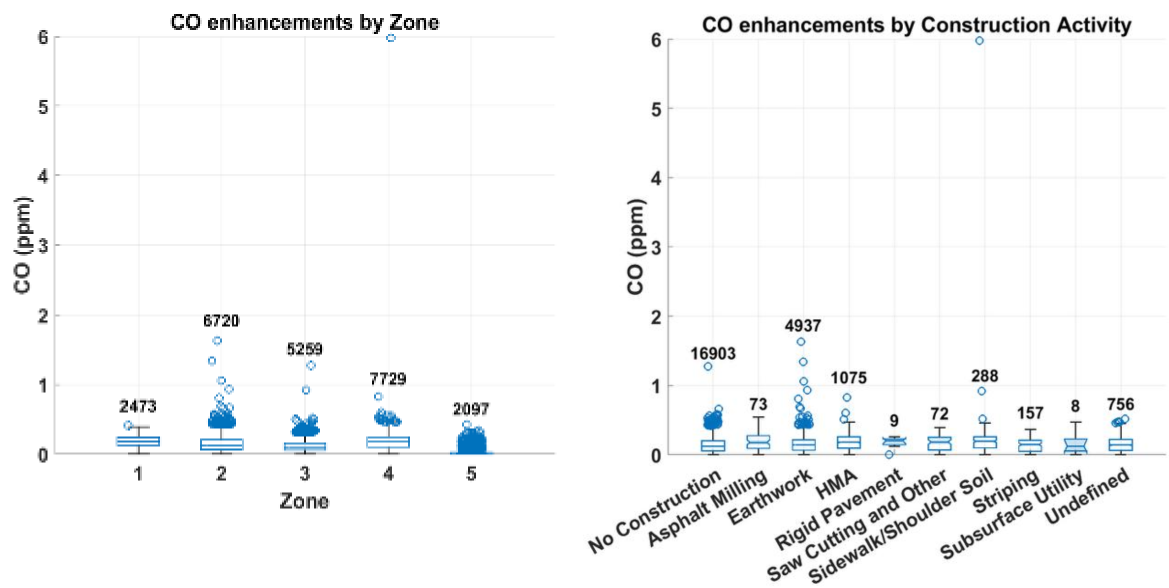


Figure 43. All CO Enhancements at US 40 by Zone (left) and Construction Activity (right)

Note: Bolded numbers above each group's boxplot indicate the number of hourly observations for that group. Each box (interquartile range, IQR) shows the median (horizontal line) and whiskers are 1.5·IQR from the box outline and indicate outliers (circular dots). The shaded band within each box indicates the uncertainty of the mean of that grouping. The larger the shading the larger the uncertainty.

Analysis of measured enhancements at US40 of the other pollutants can be found in Appendix B2.

4.4. Modeling Results

Of the 26+ GLMM models explored, the model form which struck the best balance between interpretability and highest performance (i.e., lowest AIC) took the form shown in Equation 2, named Model 1. Specifically, hourly mean enhancements were modeled by the distance an observation was from specific construction activities (Activity_dist, which is a combination of construction activity and proximity classifications of “samezone” as construction, “adjacent” zone to construction or “far” zone from construction), temperature, pressure, humidity, windspeed, vehicle counts (volume), weekday or weekend, wind direction (WD) and a random intercept at the location or pod ID grouping. “Far” refers to distances of two or more zones between pollutant measurements and activity while “adjacent” refers to one zone away and “samezone” is within the same zone as construction. Therefore, Activity_dist provided a proximity-to-construction-activity parameter in the model. “No Construction” served as the baseline Activity_dist category which was when no construction was taking place in any zone. Model 1 reference groups were “No Construction”, “Weekday” and “East” for Activity_dist, WeekdayWeekend and WD, respectively, unless otherwise stated.

Model 1:

$$\text{Enhancement} \sim \text{Activity\_dist} + \text{temperature} + \text{humidity} + \text{pressure} + \text{windspeed} + \text{VehicleVolume} + \text{WeekdayWeekend} + \text{WD} + (1 \mid \text{Location}) \qquad \textbf{(Eq2)}$$

The second-best performing model, Model 2, specified zone as an independent predictor variable which allowed comparisons to take place across zones. It also included an interaction term between construction activity category (Activity1) and zone to elucidate pollutant impacts from activities across space, by zone, rather than proximity or means over the entire site. See Equation 3.

Model 2:

$$\text{Enhancement} \sim \text{Activity1 x zone} + \text{temperature} + \text{humidity} + \text{pressure} + \text{windspeed} + \text{VehicleVolume} + \text{WeekdayWeekend} + \text{WD} + (1 \mid \text{Location}). \qquad \textbf{(Eq3)}$$

The decision tree and random forest model results are presented through 1) visualization of a single decision tree pruned to be an appropriate size for presentation in this report and 2) the random forest variable importance plot which ranks the most influential predictor variables in explaining enhancements and minimizing error.

Results of the three unique modeling approaches are presented for each project site and pollutant of interest in the sections below.

4.4.1. US 6 Model Results

Analysis of modeled enhancements at US6 of the other pollutants (example for CO below) can be found in Appendix B3.

4.4.1.1. US 6 Modeled CO Enhancements

Model 1 estimated marginal mean CO enhancements grouped by activity_dist, construction activity and proximity to construction, are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 44. The whiskers on each bar represent the 95% CI of the estimate. Mean hourly estimated enhancements by activity_dist ranged from 0.09 ppm to 0.18 ppm. Generally, there does appear to be a relationship between closer proximity and higher enhancements indicating a source attributable to the activities. This trend is not consistent across all activities (i.e., Sidewalk/C&G Pouring and Striping) suggesting pollutant transport, blending of impacts between zones or other sources of pollution.

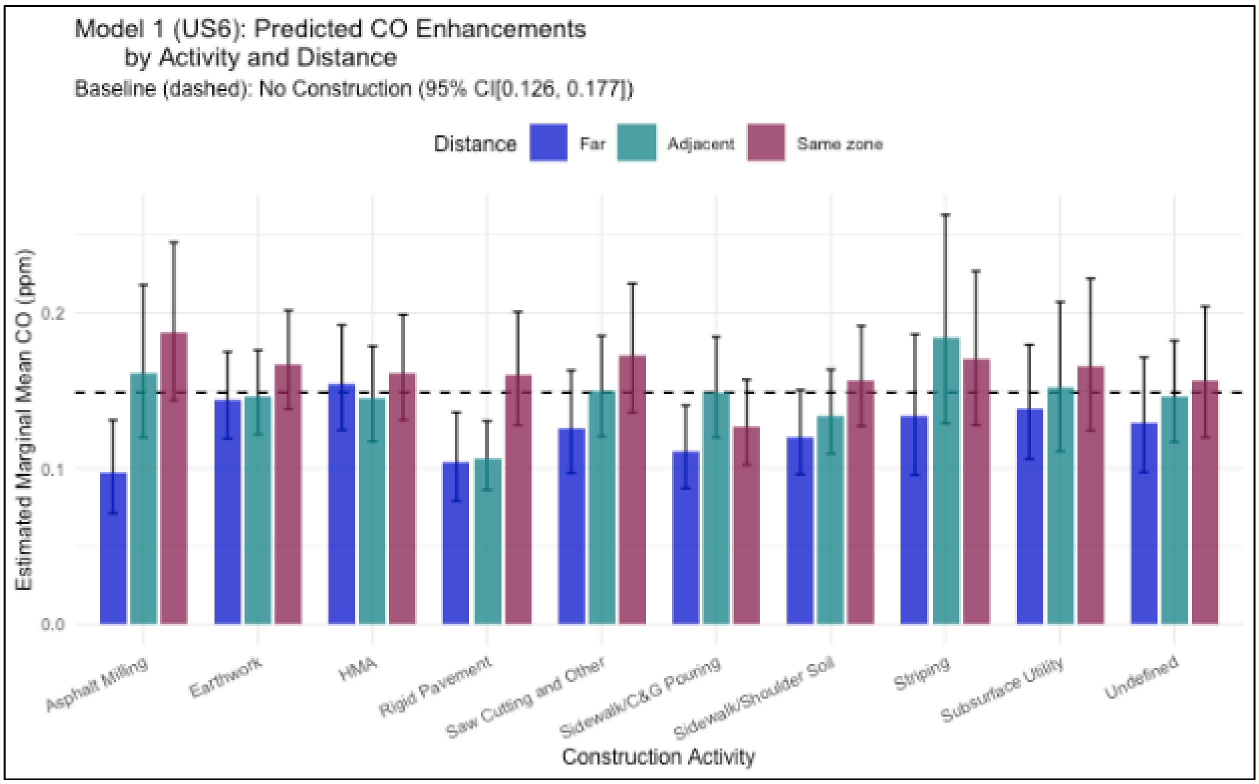


Figure 44. Model 1 (US 6), Estimated Marginal Mean CO Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 4 in addition to lower and upper confidence limits (CL), percent change and p-values. P-values help determine if there is a significant difference (ex. as opposed to no difference) between the means of two distributions by establishing a confidence interval (e.g., 1-p-value). The rule of thumb is, if the p-value is less than or equal to 0.05 for a given comparison, the difference between the two is significant (as opposed to no different). The lower the p-value the more confidence there can be that the two means being compared are different. Ratios below 1 represented a decrease relative to No Construction while ratios above 1 indicated increases. Some activities which occurred "far" from where the measurements were made had ratios significantly lower ($p<0.05$) than 1. That said, the background sites, at zone 5 and D9 in zone 3, were always "far" or "adjacent" from any place construction ever occurred.

Table 4. Model 1 (CO_US6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	LowerCL	UpperCL	%change	p-value
Asphalt Milling_far / No Construction	0.65	0.43	0.97	-35.00	0.03
Rigid Pavement_far / No Construction	0.70	0.50	0.98	-30.23	0.03
Rigid Pavement_adjacent / No Construction	0.71	0.58	0.87	-28.72	0.00
Asphalt Milling_samezone / No Construction	1.26	0.91	1.75	26.11	0.39
Sidewalk/C&G Pouring_far / No Construction	0.74	0.57	0.98	-25.62	0.02
Striping_adjacent / No Construction	1.24	0.76	2.02	23.62	0.91
Sidewalk/Shoulder Soil_far / No Construction	0.81	0.64	1.02	-19.13	0.11
Saw Cutting and Other_samezone / No Construction	1.16	0.89	1.51	15.84	0.72
Saw Cutting and Other_far / No Construction	0.85	0.62	1.16	-15.44	0.76
Sidewalk/C&G Pouring_samezone / No Construction	0.85	0.69	1.06	-14.74	0.34
Striping_samezone / No Construction	1.14	0.79	1.65	14.39	0.96
Undefined_far / No Construction	0.87	0.61	1.24	-13.11	0.94
Earthwork_samezone / No Construction	1.12	0.97	1.30	12.19	0.26
Subsurface Utility_samezone / No Construction	1.12	0.77	1.62	11.59	0.99
Striping_far / No Construction	0.90	0.57	1.41	-10.17	1.00
Sidewalk/Shoulder Soil_adjacent / No Construction	0.90	0.75	1.07	-10.05	0.63
Asphalt Milling_adjacent / No Construction	1.09	0.74	1.60	8.56	1.00
HMA_samezone / No Construction	1.09	0.88	1.33	8.54	0.94
Rigid Pavement_samezone / No Construction	1.08	0.84	1.38	7.67	0.99
Subsurface Utility_far / No Construction	0.93	0.67	1.28	-7.23	1.00

Results from Model 2 illustrate the difference in estimated marginal mean enhancements by zone for the various construction activities performed at the site while covariates were kept constant at parameter means or baseline levels Figure 45. Estimated mean hourly enhancements by construction activity and zone ranged from 0.07 ppm to 0.2 ppm. A clear trend is shown of increased enhancements in zones 1 and 2, the most popular zones for active construction which are more pronounced during specific construction activities than when no construction happened. This finding suggests larger spatial heterogeneity in enhancements when activities occurred than when no activities did. Zones 5 and 3 showed less change by construction activity as they are the furthest from activity.

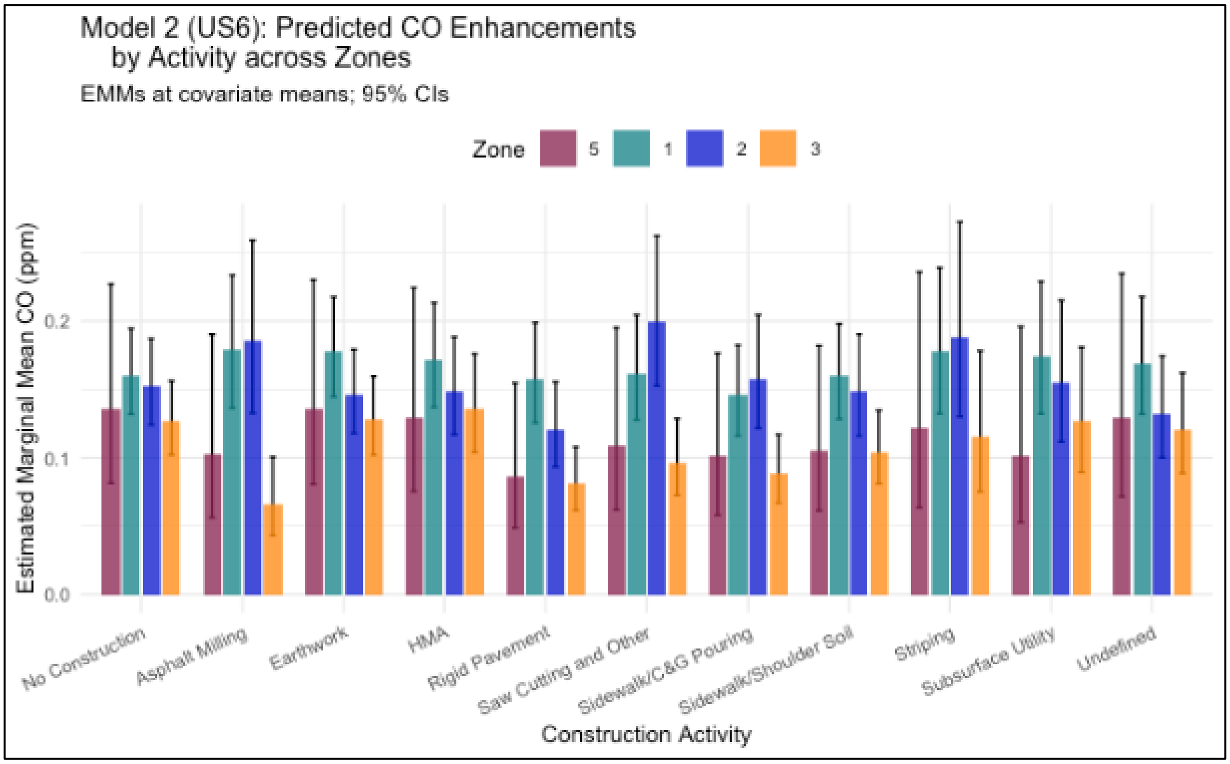


Figure 45. Model 2 (US 6), Estimated Marginal Mean CO Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 46. Here the criteria used to most efficiently split observed enhancements into 5 bins is first determined by humidity, then activity_dist and pressure and lastly temperature. If one follows the path to the largest enhancements (0.59 ppm), it is during periods of high humidity (>72% RH) and high barometric pressure (>857 millibar). The lowest mean enhancements (0.13 ppm) take place during drier conditions (<72% RH, 0.17 ppm) when activity_dist falls under the categories in group A (see figure), and it is cooler (<84F, 0.17 ppm) else the enhancements are on average 0.22 ppm.

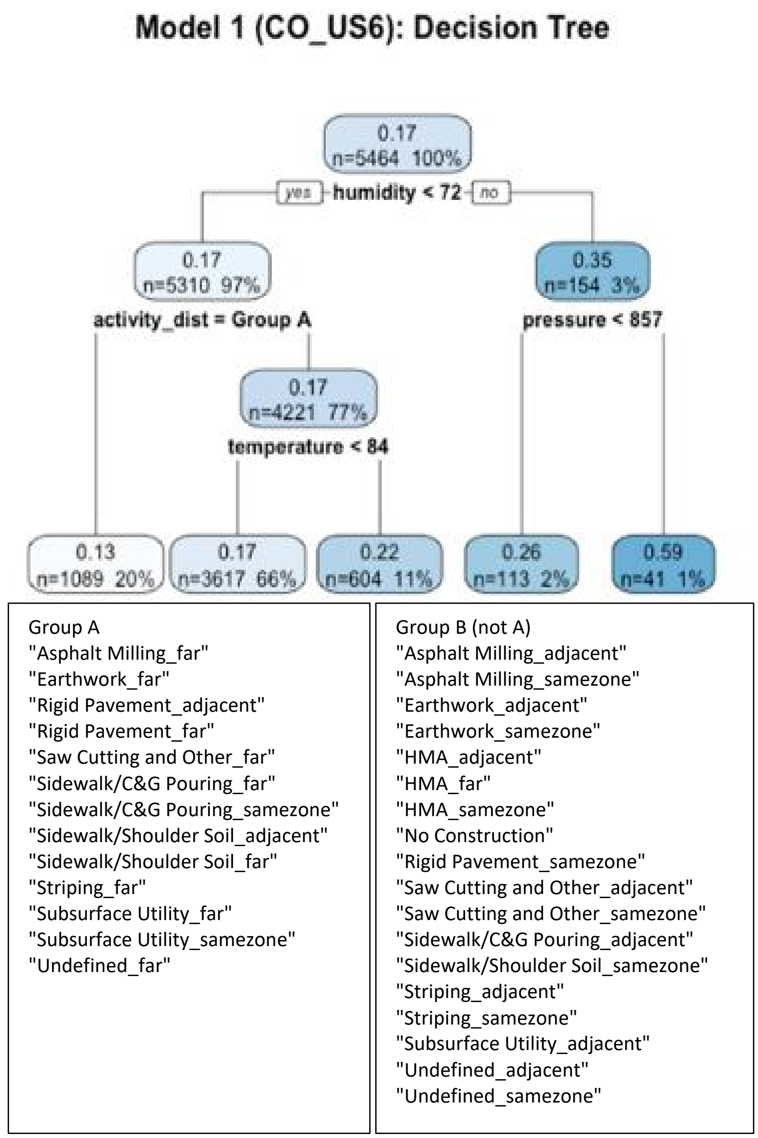


Figure 46. Model 1 (CO, US 6) Decision Tree

Note: The center-top number in each box represents the mean enhancement estimate of the data in that section of the tree before each split (e.g., mean of 0.17 ppm for n=5464 observations which is 100% of data). At the bottom of the tree are the final nodes (5 for this tree) which split the data into 5 groups with different n observations and different mean enhancement estimates. The highest mean grouping is on the far right (0.59 ppm) which has 41 observations, which is 1% of the dataset.

The random forest of Model 1, see Figure 47, ranks activity_dist followed by temperature and then humidity as the most important variables in reducing overall model error.

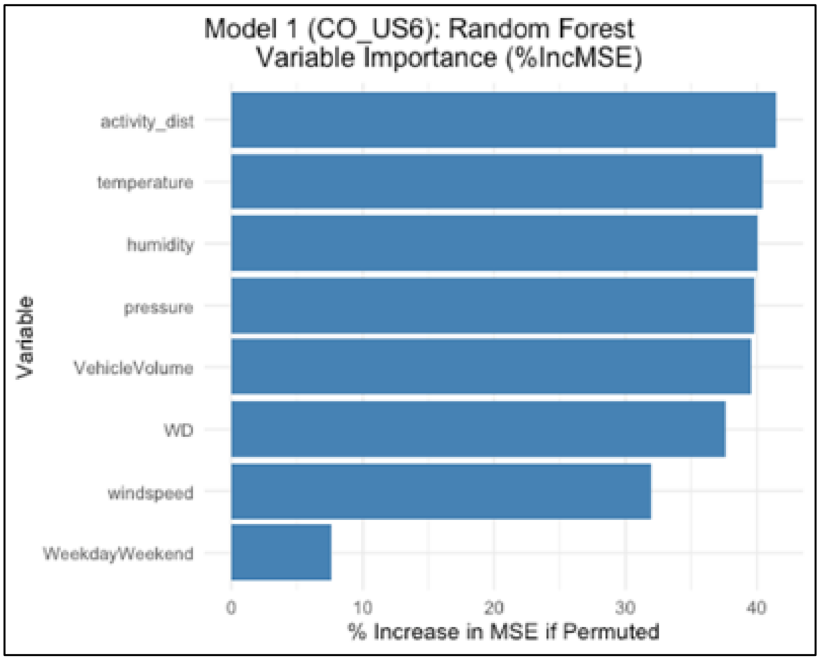


Figure 47. Model 1 (CO US 6) Random Forest Variable Importance (%IncMSE)

Analysis of modeled enhancements at US6 of the other pollutants can be found in Appendix B3.

4.4.2. US 40 Model Results

Analysis of modeled enhancements at US40 of the other pollutants (example for CO below) can be found in Appendix B4.

4.4.2.1. US 40 Modeled CO Enhancements

Model 1 estimated marginal mean CO enhancements grouped by activity_dist (construction activity by proximity-to-construction) are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 48. The whiskers on each bar represent the 95% CI of the estimate. Mean hourly estimated enhancements by activity_dist ranged from 0.09 ppm to 0.26 ppm. Generally, there does appear to be a relationship between closer proximity and higher enhancements indicating a source attributable to the activities. This trend is not consistent across all activities (i.e., Saw Cutting and Other, Sidewalk/Shoulder Soil) suggesting pollutant transport, blending of impacts between zones or other sources of pollution.

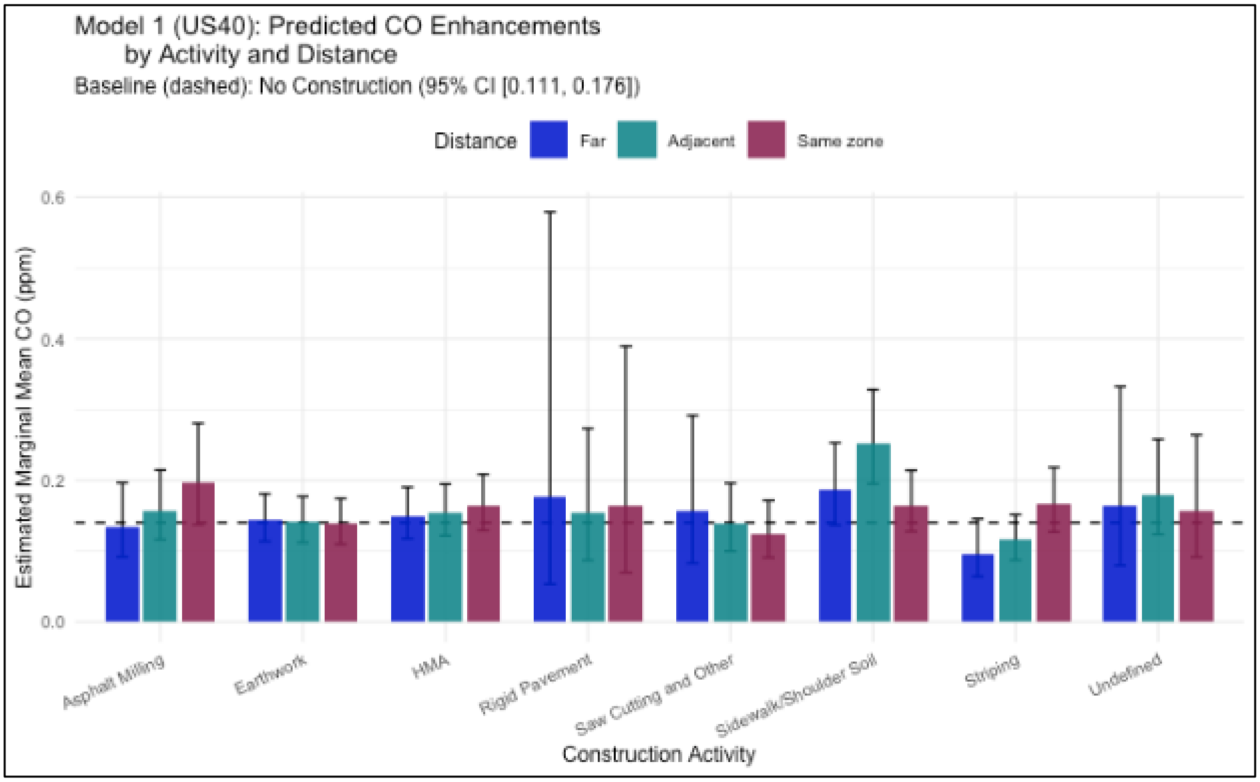


Figure 48. Model 1 (US 40), Estimated Marginal Mean CO Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 5 in addition to lower and upper confidence limits (CL), percent change and p-values. Ratios below 1 represented a decrease relative to No Construction while ratios above 1 indicated increases. Sidewalk/Shoulder Soil in an adjacent zone as the measurement and HMA in the same zone had 80% and 17% higher enhancements, respectively, than No Construction ($p<0.01$).

Table 5. Model 1 (CO US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	LowerCL	UpperCL	% Change	p-value
Sidewalk/Shoulder Soil_adjacent / No Construction	**1.80**	**1.49**	**2.18**	**80.49**	**0.00**
Asphalt Milling_samezone / No Construction	1.40	0.92	2.14	40.21	0.23
Sidewalk/Shoulder Soil_far / No Construction	1.33	0.96	1.83	32.75	0.13
Striping_far / No Construction	0.69	0.41	1.16	-30.98	0.36
Undefined_adjacent / No Construction	1.27	0.81	2.00	27.39	0.72
Rigid Pavement_far / No Construction	1.26	0.21	7.48	25.57	1.00
Striping_samezone / No Construction	1.19	0.95	1.49	18.72	0.28
Rigid Pavement_samezone / No Construction	1.18	0.33	4.17	17.94	1.00
Sidewalk/Shoulder Soil_samezone / No Construction	1.18	0.97	1.43	17.87	0.16
Striping_adjacent / No Construction	0.82	0.65	1.03	-17.8	0.15
HMA_samezone / No Construction	**1.17**	**1.04**	**1.32**	**17.07**	**0.00**
Undefined_far / No Construction	1.16	0.41	3.27	16.34	1.00
Asphalt Milling_adjacent / No Construction	1.13	0.82	1.55	12.64	0.94
Undefined_samezone / No Construction	1.11	0.54	2.31	11.27	1.00
Saw Cutting and Other_far / No Construction	1.11	0.45	2.72	11.14	1.00
Saw Cutting and Other_samezone / No Construction	0.89	0.64	1.25	-10.82	0.96
Rigid Pavement_adjacent / No Construction	1.10	0.50	2.46	10.32	1.00
HMA_adjacent / No Construction	1.10	1.00	1.21	9.75	0.07
HMA_far / No Construction	1.07	0.94	1.21	6.76	0.74
Asphalt Milling_far / No Construction	0.96	0.60	1.53	-3.81	1.00

Note: Bolded activity-distance categories had ratios which were significantly ($p \leq 0.05$) greater than 1.0 indicating higher levels than No Construction.

Results from Model 2 illustrate the difference in estimated marginal mean enhancements by zone for the various construction activities performed at the site while covariates were kept constant at parameter means or baseline levels (Figure 49). Estimated mean hourly enhancements by construction activity and zone ranged from 0.03 ppm to 0.31 ppm. Zone 5 is consistently lower than the other zones and this zone never had construction. Zone 1, which also never had construction taking place, had some of the higher enhancements on average suggesting pollutant transport or hyper-local sources (other than construction) or unique site/monitor characteristics.

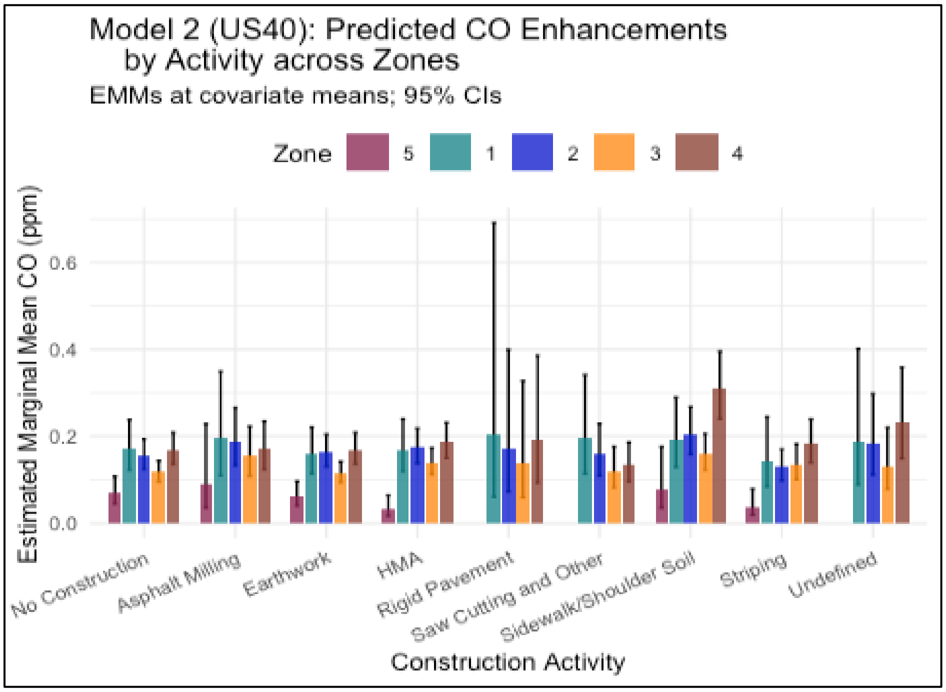
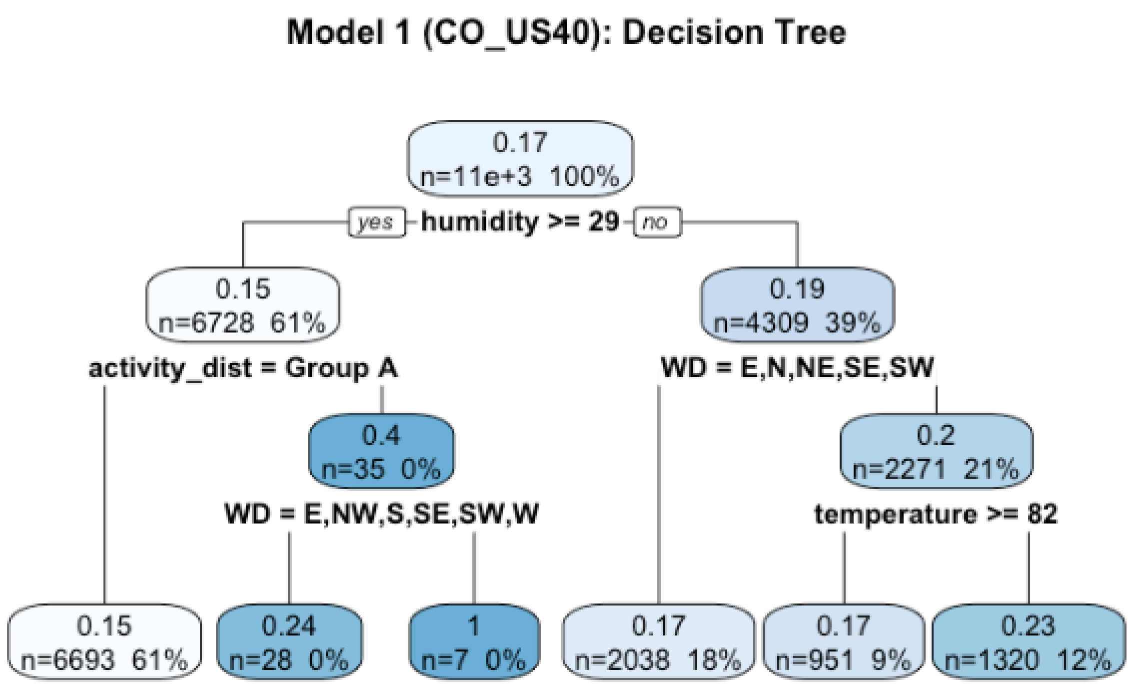


Figure 49. Model 2 (US 40), Estimated Marginal Mean CO Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 50. Here the criteria used to most efficiently split observed enhancements into 6 bins was first determined by humidity, then activity_dist and wind direction. If one follows the path to the largest enhancements, it was during periods of higher humidity (>29% RH, 0.15 ppm) and activity_dist categories in group B (0.4 ppm), and winds from the N/NE (1.0 ppm). The lowest mean enhancements took place during higher humidity (>29% RH, 0.15 ppm) when activity_dist fell under the categories in group A (0.15 ppm).



Group A
"Asphalt Milling_adjacent"
"Asphalt Milling_far"
"Asphalt Milling_samezone"
"Earthwork_adjacent"
"Earthwork_far"
"Earthwork_samezone"
"HMA_adjacent"
"HMA_far"
"HMA_samezone"
"No Construction"
"Saw Cutting and Other_adjacent"
"Saw Cutting and Other_samezone"
"Sidewalk/Shoulder Soil_far"
"Sidewalk/Shoulder Soil_samezone"
"Striping_adjacent"
"Striping_far"
"Striping_samezone"
"Undefined_adjacent"
"Undefined_far"
"Undefined_samezone"

Group B
"Rigid Pavement_adjacent"
"Rigid Pavement_far"
"Rigid Pavement_samezone"
"Saw Cutting and Other_far"
"Sidewalk/Shoulder Soil_adjacent"

Figure 50. Model 1 (CO US 40) Decision Tree

The random forest of Model 1 ranks windspeed followed by temperature, pressure and humidity as the most important variables in reducing overall model error, see Figure 51.

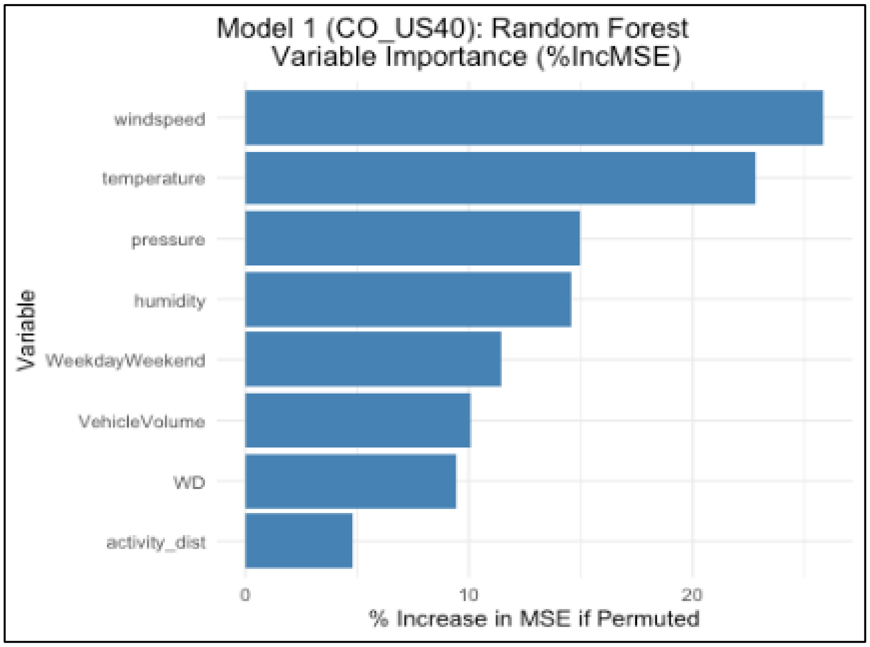


Figure 51. Model 1 (CO US 40), Random Forest Variable Importance (%IncMSE)

Analysis of modeled enhancements at US40 of the other pollutants can be found in Appendix B4. Additional models' characteristics can be found in Appendix C.

Chapter 5. Discussion

5.1. Data Collection and Quality

5.1.1. Data Completeness

Obtaining high-quality data was paramount in this study, and the research team spared no effort to achieve this objective. In practice, this required a sustained and meticulous commitment to closely monitoring the data collection process. The primary challenges included weather conditions, power supply limitations, and intrinsic hardware constraints. To address these, the researchers implemented strict data collection protocols and QA/QC procedures. These protocols required frequent inspection of the equipment to ensure proper operation, necessitating regular site visits—often weekly, and at times bi-weekly. For the rural projects, this represented a particularly significant effort, as project sites were located approximately three to five hours from the research team's base.

In the rural projects, each traffic camera operated on a 20-Watt, 5-Volt solar panel, supported by an external battery pack and an internal manufacturer-provided battery. The pod units were powered by a 50-Watt, 12-Volt solar panel and a 12-Volt battery. Despite these backup systems, some equipment occasionally failed due to insufficient power, typically caused by extended cloudy periods, snow, or dirt accumulation on solar panel surfaces. As a result, continuous data collection in rural settings proved feasible during the summer months but substantially more challenging during fall and winter.

While four pod units in the urban project were able to use AC power, all other pods and traffic cameras relied on the solar-battery configuration described above. Urban deployment also introduced the risk of vandalism; on several occasions, solar panels and batteries were stolen, interrupting data collection. Fortunately, the thieves appeared unfamiliar with the pods and cameras and did not tamper with the devices themselves, allowing researchers to preserve the collected data up until the power was cut. In response, the team installed decoy surveillance cameras, chains, and warning signs, which proved effective deterrents.

The arduous efforts to collect data yielded an extensive and powerful dataset that enabled multiple insightful data analysis approaches. See Table 6 for a description of data completeness.

Table 6. Data Completeness Summary

Highway	Air Quality (Pod)	Construction Activity	Traffic
US 6	79.3 %	98.1%	98.7%
US 40	83.4 %	99.7%	59.4%

Note: Data completeness percentages for Air Quality and Construction Activity were calculated considering the hours of the day for which the researchers were able to collect data as a percentage of the total hours in a day (24hs). Data completeness for Traffic were calculated considering just the hours of traffic data collected during the days included in modeling, from 7 am to 5 pm (10hr days).

5.1.2. Data Calibration Quality

Quality sensor calibrations were achieved through a) the opportunities to collocate pods next to reference grade analyzers in similar environmental contexts as the project sites and across seasons b) the one-hop quantification approach c) and leveraging the knowledge gained from years of sensor quantification and modeling in the HAQ lab. It was critical that the primary colocation variable space represented the deployment variable space as much as possible to reduce extrapolations. This objective was met as combinations of temperature, humidity and to a slightly lesser extent pressure, were well covered in the primary colocations at the I25 Denver CDPHE site. This air quality monitoring station, being proximate to a vast array of diverse vehicle traffic, nearby industry and other sources, allowed for sensor quantification in a complex, real-world environment with confounding species which ultimately strengthened the calibration and reduced uncertainty. Generally speaking, the sensor model fits were quite robust across air pollutants. There was strong linearity among pod estimates and reference grade measurements and low to no bias (across validation folds).

It is worth noting that calibration results presented were reported at the 5min averaging time whereas hourly averaged data were used in analyses and modeling. This averaging difference resulted in even smaller measurement uncertainties (RMSE) at the hourly level than those reported at the 5min level (i.e., by the inverse of the square root of 12). That said, it is worth remarking on some of the limitations of the quantification reported. Specifically, spikes (often short) of NO, and to a lesser extent NO_x, were often underestimated despite the peak weighting strategies. The peak weighting did improve the fits for higher concentrations, but relative to other pollutants, absolute levels of NO were likely to be underestimated throughout this study. However, one of the advantages of using the background subtraction method was investigating differences between pod measurements not absolute values, moderating the limitations of the underestimated NO peaks. In addition, although the environmental variable space was well represented in the primary colocations, the range of pollutant concentrations were not always. Specifically, PM_{10}, coarse PM and tVOC concentrations estimated during the field deployments were significantly higher than those measured at the reference sites which could introduce some uncertainties and presents space for future improvements. On a similar note, incorporating relative humidity rather than absolute humidity in regression models using OPC and Plantower sensor signals did show minor improvements (R^2 values marginally increased).

Lastly, major efforts were expended by the research team to identify and execute a robust primary colocation for tVOCs. The initial attempt to collocate pods with CDPHE's mid-cost sensor platforms near oil and gas operations was not successful due to accuracy and precision limitations of reference instrumentation. The research team pivoted by sending the reference pod to Los Angeles where it could be positioned next to a SCAQMD high-end, Fourier Transform Infrared Spectroscopy (FTIR) continuous optical multi-pollutant analyzer (FluxSense Inc., San Diego, CA) for high temporal resolution measurements in a complex environment with traffic and nearby heavy industries. Calibration results for tVOCs were the weakest of all the pollutants, yet, given the challenges presented in quantifying a large and diverse mixture of volatile species with significant confounders, the results are promising for low-cost sensors and offer a robust relative measure of higher or lower levels of tVOCs. The low-cost sensor research field is prioritizing tVOC quantification and significant advances in calibration methodology are in progress and likely to be available for use in subsequent research.

5.2. Background Subtraction Approach

As mentioned in the section above, the background subtraction approach explored in this work provided a path to more comprehensively investigate linkages between construction activities and pollution measurements. The challenge with using ambient concentration measurements of pollution was accounting for the large, systematic impact atmospheric mixing and changing boundary layer heights have on pollution concentrations which follow a strong diurnal pattern. This phenomenon results in much lower concentrations during the daytime when the boundary layer expands and increased concentrations at night and into the early morning as the boundary layer is compressed. The background subtraction method use in this work reduces the impacts of these trends on measurements by dynamically subtracting the lowest measurement across space at each timepoint. This method may be introducing small amounts of error as the researchers assume the lowest measurement at each hour is characteristic of local background. Given the spatial extent of the sensor networks, this assumption is likely valid but unconfirmed. The other major benefit to subtracting background and analyzing enhancements is the capability to compare enhancements across varying project sites with different background conditions. Specifically, results from US 6 and US 40 can now be more directly compared as background levels, as different as they may be, have been subtracted.

5.3. Trends in Observed Pollutant Enhancements and Construction Activities

At both the US 6 Clifton improvements and US 40 passing lane projects, the most common construction classification for all hours of monitoring was “No Construction” which established a clear baseline category with which to group observations and compare across space (zones) and construction activities. Median enhancements for most pollutants were quite small in part due to the numerous hours of no construction and lower traffic volumes at night with fewer emitting activities. Because the observed enhancements were reported for all hours of the day, there were significantly more samples in the observed data than the modeled data (which included daytime hours only). That said, some of the hourly averaged enhancements were very high (>5ppm CO, >400 ppb NO, >120ppb NO_2, >100 µg/m^3 $PM_{2.5}$, >600 µg/m^3 PM_{10} and >500 µg/m^3 for coarse PM). These were extreme values but there were many extreme enhancements observed at these sites. Overall, the air quality at the construction sites was characterized by low to modest pollution enhancements punctuated by periods of substantially elevated pollution levels.

Grouping observations of enhancements by zone and construction activity presented the first glimpses into the spatial and activity-driven differences of pollution across the sites. At US 40, the PM_{10} and Coarse PM enhancements by zone showed some of the clearest spatial gradients of large enhancements (many extremes/outliers) with the lowest levels in zone 5 with increased levels moving North into zones 4, 3 and 2. This finding supports evidence to the effect construction activities and prevailing wind may have on pollution emissions and transport. More discussion on wind effects and other environmental conditions can be found below. Enhancements in zone 5, an area void of construction activities, saw some of the lowest median enhancements of CO, NO, NO_2 and NO_x at the study site. At the same time, zone 1 (another background site) experienced the highest medians of CO, NO, NO_2 and NO_x enhancements further suggesting pollution transport as an important factor. Patterns revealed in enhancements grouped by construction activity spurred the research team to investigate other analytical methods because quantifying the impacts attributable to construction and teasing out the influences from traffic and environmental conditions were going to be crucial. Findings from those modeling efforts are discussed in the next section.

5.4. Themes in Modeled Construction Impacts

5.4.1. Importance of Environmental Conditions

A consistent finding at both construction project sites and across pollutants was the importance of temperature, humidity, pressure, and wind conditions when modeling enhancements. It is worth noting that these predictors were often the top three (or within the top five) most important variables in reducing errors in the random forest models (see Table 7) and occurred most frequently as splitting criteria at nodes throughout decision trees. The objective of ranking the importance of model variables was to provide some quantitative evidence as to which variables warrant additional investigation as to their impact on observed enhancements. Moreover, all the sensor calibration models included temperature, pressure, and humidity terms in the regressions accounting for influences from these variables on sensor signals. Therefore, there was significant evidence that these environmental conditions played a large role in explaining variation in enhancements around the construction sites. Although these parameters were consistently important in the modeling, they were not consistent in the direction of their effect across sites and pollutants perhaps due to site-specific patterns and covariates. Temperature and relative humidity were found to be moderately/highly correlated (R=0.81) and therefore the most appropriate way to interpret their impact in many of the random forest models is to consider them jointly as approximating some atmospheric phenomenon, such as atmospheric mixing or boundary layer, rather than independently. As seen in Table 7, humidity and temperature often share the same effect direction (color of cell indicating positive or negative coefficient) for a given pollutant. This supports the claim that they jointly represent an atmospheric phenomenon.

Wind speed and direction were also important predictors in most models. Wind speed effects on enhancements were almost exclusively negative (inversely related) suggesting dilution or dispersion with some exceptions (NO_2). Specific wind directions predicted higher or lower enhancements suggesting spatial gradients due to pollutant transport. For example, the prevailing wind patterns at the US 40 site were S/SE winds blowing up valley during the daytime and N/NW winds blowing down valley during the night. Since the modeling was confined to daytime hours, the south-to-north winds resulted in a clear concentration gradient, with on median, higher enhancements occurring in the northern-most zone (zone 1) compared to zone 5 (south of the construction project). At US 6, the composite daytime winds were mainly from the E and W in almost equal frequency. The wind blew from the W/NW slightly more often than it did from the East. This directionality of transport would have likely manifested in higher pollutant enhancements downwind at zones 3 and 1. Zone 1 did have some of the highest mean enhancements but zone 3, on the Eastern edge of the construction area with some pods further from the roadway (e.g., D9), tended to have lower levels like zone 5, the background site, to the south. $PM_{2.5}$ enhancements, for example, were higher when winds were originating from the W and NW compared to winds out of the E. This finding could be explained by the I-70 business loop (I-70b) running N/S directly W of the main construction corridor and $PM_{2.5}$ emissions from this busy roadway may have been transported E to pods located along the construction area. However, this trend was opposite for NO_x which had lower enhancements for winds originating out of the S and SW compared to E. This brings up the importance of siting air monitors across gradients of prevailing winds to increase the probability of having an upwind and downwind measurement at the same time. Ideally, a background monitor would be set up in each of the four cardinal directions from the construction site.

Table 7. Random Forest (model 1) Predictor Importance Rankings

Predictor Importance Ranking	#1	#2	#3	#4	#5
US 40 CO	Windspeed (p)	Temperature (p)	Pressure (p)	Humidity (p)	W/W
US 40 NO	Windspeed (n)	Temperature (n)	Pressure (p)	Humidity (n)	VehicleVolume (p)
US 40 NO_2	VehicleVolume (n)	Pressure (p)	Temperature (n)	Humidity (n)	Windspeed (p)
US 40 NO_x	Windspeed (n)	WD	Temperature (n)	Humidity (n)	Pressure (p)
US 40 tVOCs	Windspeed (n)	Temperature (p)	Wind direction	VehicleVolume (p)	Pressure (n)
US 40 $PM_{2.5}$	Pressure (p)	WD	Temperature (n)	Windspeed (n)	VehicleVolume (n)
US 40 PM_{10}	Humidity (n)	Activity_dist	Temperature (n)	WD	VehicleVolume (n)
US 40 CoarsePM	VehicleVolume (n)	WD	Activity_dist	Humidity (n)	Temperature (n)
US 6 CO	Activity_dist	Temperature (p)	Humidity (p)	Pressure (n)	VehicleVolume (p)
US 6 NO	Temperature (p)	Humidity (p)	Pressure (n)	Activity_dist	VehicleVolume (p)
US 6 NO_2	Pressure (n)	Temperature (p)	Humidity (p)	Activity_dist	VehicleVolume (p)
US 6 NO_x	Pressure (n)	Temperature (p)	VehicleVolume (p)	WD	Windspeed (n)
US 6 tVOCs	Temperature (p)	VehicleVolume (n)	Humidity (p)	W/W	Pressure (n)
US 6 $PM_{2.5}$	Windspeed (n)	WD	VehicleVolume (n)	Activity_dist	Temperature (p)

Note: #1 refers to the most important predictor term in the model and #2 the second, and so on. Variables with "(p)" indicate a positive correlation with enhancements and are colored red, whereas

variables with "(n)" indicate a negative correlation with enhancements and are colored green. "WD" is wind direction. "W/W" indicates Weekend/Weekday.

5.4.2. Traffic Impacts on Pollutant Enhancements

Hourly vehicle counts at both US 6 and US 40 were useful predictors of pollutant enhancements and appeared in the top 5 most important variables in reducing errors in the random forest models for nearly all pollutants (see Table 7). Vehicle volume was the most important predictor variable for NO_2 and CoarsePM at US 40. At US 40, higher vehicle volume was associated with higher NO and tVOC enhancements. As a primary emission from internal combustion engines and most pronounced in diesel vehicles, it would make sense that NO enhancements would increase with higher vehicles counts. This was the case for NO, but increased NO_2 enhancements were tied to decreased vehicle volume. Oxidation of NO to form NO_2 occurs in the order of minutes in the presence of sufficient ozone and on a much slower timescale in the presence of molecular O_2. Perhaps there was a lag between NO_2 formation and increased vehicle volume. At US 6, increased vehicle volumes were associated with increased enhancements of CO, NO, NO_2 and NO_x. There, traffic counts took place in zone 1, a zone which included I-70b and the area directly East. When comparing enhancements during periods of no construction across the 4 zones with pods, there was a trend of higher values in zones 1 and 2 which were the main zones of construction and closest in proximity to the I-70b. In fact, zone 1 included the intersection of I-70b and US 6 and tended to have the largest enhancements. From Model 2 results, which showed estimated mean enhancements by zone and activity, NO values were higher in zone 1 than zone 2, whether there was construction or not. However, NO_2 was similar if not slightly higher in zone 2 compared to zone 1. This also suggests reaction chemistry taking place forming NO_2 as the distance from the large traffic volumes on the I-70b increased. At US 6, fine particulates and tVOC enhancements were correlated with lower traffic volumes, a surprising finding but one which may be better understood regarding boundary layer fluctuations. Further research into this phenomenon is warranted. Although useful in the modeling efforts, the vehicle volume parameter informed by US 6 traffic alone may not have characterized the local traffic in the general area as well as a composite of traffic volumes from multiple nearby roadways, an objective recommended for future work.

5.4.3. Construction Activity Impacts on Pollutant Enhancements

Results from the measurement campaigns at both the US 6 and US 40 construction sites provided qualitative and quantitative evidence that some construction activities were associated with higher pollution levels for some pollutants. This evidence came in the form of three general findings 1) proximity-based gradients of enhancements associated with specific construction activities informed by Model 1, 2) zonal patterns of increased enhancements in zones that had active construction informed by Model 2 and 3) the importance of construction activity proximity predictor terms in modeling enhancements with decision tree and random forest models.

Starting with findings from Model 1 across pollutants and study sites, there was a general pattern of increased enhancements the closer an air quality measurement was to a construction activity whilst considering traffic volume, weekend/weekday, and environmental variables. Tables 8 and 9 depict the percent changes (relative to No Construction) of modeled enhancements for a given construction activity at varying proximities ("S" = same zone, "A" = adjacent, "F" = far) for US 6 and US 40, respectively. Positive values represent increases, and negative values decreases in modeled enhancements relative to No Construction (estimates of which are shown on the bottom row for average conditions, i.e., mean environmental conditions on a weekday etc.). One important takeaway from this table is that estimated enhancements in the same zone (S) as most activities were either no different from or larger than No Construction enhancements (red) while estimates "far" (F) from most activities were either no different from or lower than No Construction enhancements (green).

Table 8. Model 1 Contrasts for US-6 Enhancements: Percent Change in Pollutant Concentrations Relative to "No Construction"

US 6 Model 1	D	CO	NO	NO_2	NO_x	tVOCs	$PM_{2.5}$
Asphalt Milling	S	26	30	6	25	110 *	59 *
	A	9	11	2	11	40	19
	F	-35 *	-34	-13	-4	19	-2
Earthwork	S	13	16 *	11	2	-4	26 *
	A	NA	-11	-3	-12 *	-1	11
	F	NA	-19 *	-15 *	-26 *	-1	-20 *
HMA	S	9	17	8	2	23 *	109 *
	A	NA	6	-11	-2	6	29 *
	F	NA	-3	-28 *	-12	-7	-1
Rigid Pavement	S	8	-4	16	5	-2	21
	A	-29 *	-13	8	-4	-13	-12
	F	-30 *	-35 *	-33 *	-34 *	-17	-28 *
Saw Cutting and Other	S	16	4	9	0	14	75 *
	A	NA	14	11	11	7	31 *
	F	-15	-28 *	-21	-23	-4	29
Sidewalk C&G Pouring	S	-15	-4	-7	-8	-13	31
	A	NA	18	4	6	-11	21
	F	-26 *	-19	-44 *	-20	-7	-20
Sidewalk Shoulder Soil	S	NA	22 *	8	23 *	-30 *	7
	A	-10	17	2	14	-27 *	12
	F	-19	-7	-13	-2	-9	-3
Striping	S	14	44	35	24	46 *	147 *
	A	24	38	10	25	58 *	80 *
	F	-10	-9	-13	-14	9	50
Subsurface Utility	S	12	16	-9	-4	20	31
	A	NA	0	-7	-14	-14	28
	F	-7	-10	-9	-12	10	17
Undefined	S	NA	-4	7	-12	-23	4
	A	NA	0	16	-3	-8	-7
	F	-13	-22	-30 *	-32 *	-16	-8
No Construction	--	0.14 ppm	16.5 ppb	5.6 ppb	22.1 ppb	8.6 ppb	1.2 ug/m3

Note: Construction activities at varying distances (D) from the measurements (S = same zone, A = adjacent, F = far). P-values ≤ 0.1 indicated with an asterisk. Estimated mean enhancements for "No Construction" at covariate means in the last row and percent differences are relative to these values. Cells showing a statistically significant increase in pollution concentration enhancements are colored red, whereas cells showing a significant decrease in enhancements are colored green.

At US 6, noteworthy associations between closer proximity and increased enhancements of $PM_{2.5}$ were found for **Asphalt Milling** (Same zone, S: +59%), **Earthwork** (S: +26%), **HMA** (S: +109%), **Saw Cutting and Other** (S: +75%) and **Striping** (S: +147%). These are substantial and significant increases, but these differences are in relation to a relatively small mean enhancement of 1.2 µg/m^3 during No Construction.

The researchers presume that activities such as Asphalt Milling, Earthwork, and Saw Cutting and Other produce many particles across a wide size distribution due to mechanical means with a significant tail in the fine particle range. On the other hand, HMA and Striping likely produced organic vapors, oil mist, and fumes (e.g., formed from condensing) emitting fine particles. During the HMA pavement process the paving machine receives the HMA from a dump truck unto the hopper, then the asphalt is placed on the road with the help of the auger assembly, which spreads the mix from the hopper point of exit on to the entire width of the machine. At this point, the mix is flattened against the road by the screed plate, which is heated to approximately 350 degrees Fahrenheit. Behind the machine, a white vapor is visible to the human eye, and the smell of tar is strong. Some research has shown warm mix asphalt (WMA) , 20 to 120 degrees Fahrenheit cooler than HMA, reduced levels of airborne respirable particulate matter, organic carbon, and asphalt vapor compared to paving with HMA (Olsen et al. 2021). Striping has been tied to emissions of VOCs which can in time form particulates (Burghardt and Pashkevich 2018). These emissions depend on the type of base-layer used in the striping process. In addition to secondary particle formation, some particles may be emitted during the application of the retroreflective materials, commonly glass beads, intended to become embedded in the paint, yet those beads are typically 100-2000µm in diameter and unlikely to become airborne (Burghardt and Pashkevich 2018).

In a similar vein, **Asphalt Milling** (S: +110%), **HMA** (S: +23%) and to some extent, **Striping** (Adjacent, A: +58%), resulted in higher tVOC enhancements compared to No Construction (8.6 ppb). The milling of asphalt involves the mechanical grinding of binders and petroleum-based materials impregnated with hydrocarbons. The heat and friction generated from this abrasive process may be enough to volatilize these hydrocarbons (Kriech et al. 2022).

NO_x enhancements were elevated closer to **Sidewalk/Shoulder Soil** work (S: +23%) and generally lower than the 22.1 ppb mean enhancement associated with No Construction the further away the pods were from most activities.

NO_2 was not found to have significantly higher enhancements than No Construction (5.6 ppb) the closer measurements were to activities but rather was found to have significantly lower enhancements the further away measurements were from many construction activities (Far, F: -15% to -33%).

For NO, **Earthwork** (S: +16%) and **Sidewalk/Shoulder Soil** (S: +22%) had higher enhancements than No Construction (16.5 ppb). This could be due to the higher emissions of NO attributed to the types of heavy equipment used and/or the proximity, within a zone, this activity was to the pods. Shoulder work, as the name states, occurs on the shoulder of the roadways - regions of the project in which the pods were located.

Interestingly, CO followed a similar trend to NO_2 and had moderate associations with reduced enhancements relative to No Construction (0.14 ppm) when measured far from many activities (F: -26% to -35%).

At US 40, CO enhancements were higher for **HMA** (S: +17%) and **Sidewalk/Shoulder Soil** (A: +80%) relative to No Construction (0.14 ppm).

Earthwork (S: +12%), **HMA** (S: +22%) and **Striping** (S: 39%) had significantly higher NO enhancements than No Construction (10.2 ppb) while NO_2 only had significant differences for **Sidewalk/Shoulder Soil** (A: +28%) relative to No Construction levels (6.5 ppb).

Accordingly, NO_x enhancements followed the additive patterns of NO and NO_2 and were estimated to be higher for **Earthwork** (S: +12%), **HMA** (S: +30%) and **Striping** (S: +32%) relative to No Construction levels (16.6 ppb).

For tVOCs, no construction activity had significantly different estimated enhancements from No Construction levels (9.2 ppb) except, unexpectedly, slightly lower levels associated with Earthwork (S: -9%) and Undefined activities (S: -59%).

$PM_{2.5}$ enhancements were slightly higher during **Earthwork** (S: +25%) and slightly lower for some activities compared to No Construction levels of 3.9 $\mu g/m^3$.

Most pronounced were the extremely elevated enhancements of PM_{10} and coarse PM. PM_{10} enhancements for **Asphalt Milling** (S: +255%), **Earthwork** (S: +179%), **HMA** (+49%) and **Sidewalk/Shoulder Soil** (A: +252%) were significantly and substantially higher compared to baseline, No Construction enhancements of 11.2 µg/m3. Expectantly, all these activities involve the mechanical generation or suspension of dust and large particles.

Coarse PM was similar with **Asphalt Milling** (S: +310%), **Earthwork** (S: +284%), **HMA** (S: +82%), **Sidewalk/Shoulder Soil** (A: +336%) and **Striping** (S: +181%) as activities with significantly and substantially higher enhancements compared to the 9.8 µg/m3 associated with No Construction. Unsurprisingly, coarse PM was also elevated for the same four categories as PM_{10} above, plus Striping, perhaps related to road surface cleaning before paint was applied. Upon further exploration, one of the first steps of the striping process is to prepare the roadway surface for application of the paint. This process can involve industrial blowers to remove debris. This debris was likely in the coarse PM mode.

Both PM_{10} and coarse PM had prominent enhancement gradients. In other words, not only were enhancements significantly higher in the same zone for some activities, but levels were significantly lower in zones far away from many of those same activities suggesting an immediate, proximate impact of those larger emitted or suspended particles and less transport.

Table 9. Model 1 Contrasts for US-40 Enhancements: Percent Change in Pollutant Concentrations Relative to "No Construction"

US 40 Model 1	D	CO	NO	NO_2	NO_x	tVOCs	$PM_{2.5}$	PM_{10}	Coarse PM
Asphalt Milling	S	40	17	12	5	-36	-31	255 *	310 *
	A	13	NA	-5	12	0	-27	-75 *	-69
	F	-4	-15	-17	-10	11	-35	-34	-12
Earthwork	S	NA	12 *	6	12 *	-9 *	25 *	179 *	284 *
	A	NA	10 *	0	12 *	2	7 *	22	51 *
	F	NA	6	5	12 *	-2	-7	-30 *	-39 *
HMA	S	17 *	22 *	11	30 *	12	-13 *	49 *	82 *
	A	10 *	8	-2	18 *	1	-20 *	47 *	80 *
	F	7	7	-1	18 *	15	3	-8	18
Rigid Pavement	S	18	NA	95	98	-61	-52	-77	-62
	A	10	-41	13	51	-40	-11	-93 *	-87
	F	26	NA	30	88	-11	49	NA	NA
Saw Cutting and Other	S	-11	-29	4	-11	-27	-11	-38	-31
	A	NA	-21	26	-19	-29	-10	-47	-35
	F	11	9	43	26	36	1	98	240
Sidewalk Shoulder Soil	S	18	NA	8	2	-6	-25 *	33	61
	A	80 *	9	28 *	9	-5	-10	252 *	336 *
	F	33	-14	12	-8	8	14	-54	-23
Striping	S	19	39 *	25	32 *	-7	-35 *	110	181 *
	A	-18	-13	-19	-7	16	-22 *	-33	-7
	F	-31	-40	6	-12	-2	-17	-65	-54
Undefined	S	11	NA	-26	-9	-59 *	-37	228	360
	A	27	-20	25	-4	-30	-20	-71	-53
	F	16	9	29	23	-9	-8	-60	-59
No Construction	--	0.14 ppm	10.2 ppb	6.5 ppb	16.6 ppb	9.2 ppb	3.9 ug/m3	11.2 ug/m3	9.8 ug/m3

Note: Construction activities at varying distances (D) from the measurements (S = same zone, A = adjacent, F = far). P-values ≤ 0.1 indicated with an asterisk. Estimated mean enhancements for "No Construction" at covariate means in the last row and percent differences are relative to these values. Cells showing a statistically significant increase in pollution concentration enhancements are colored red, whereas cells showing a significant decrease in enhancements are colored green.

In addition to the results discussed above, the findings from Model 2 corroborated the proximity-to-activity impacts quantified in Model 1, through the analysis of modeled enhancements by activities across zones.

For US 6, the general patterns which emerged in the analysis were differences in estimated enhancements between zones (spatial variability) a) during No Construction were often minimal, if at all and b) often increased during construction activities compared to No Construction. These findings suggest spatial variability of enhancements were more uniform during periods of no construction than when construction was occurring (corroborating Model 1 takeaways) and specific activities were related to increased pollution primarily in construction zones (1 and 2) and less so in zones further from construction (zone 3 and 5).

For US 40, similar patterns emerged. However, due to the stronger directional wind behaviors from the S to the N, the background site in zone 5 had the lowest enhancements while zone 1, the background site to the north of the construction zone, had some of the highest enhancements. Still, enhancements in the active construction zones (2,3,4) did show elevated levels during specific activities.

Lastly, the random forest implementations of model 1 resulted in predictor rankings with activity_dist (proximity-to-construction activities) appearing in the top five predictors for 6 of the pollutant models across both sites. Models from US 6 comprised most of this subset.

Due to the background subtraction method employed in this work, the differing background levels between the urban and rural sites was removed from the analysis which provided a more direct way to compare enhancements across the two settings. That said, the environmental parameters and traffic volumes accounted for in the models had slightly different mean values but the same baseline categories of weekday and winds from the E (used in Model 1 contrasts). No significance testing was performed to compare the two construction sites' estimated-marginal-mean-enhancements due to varying model inputs. However, when comparing mean pollutant enhancements across the two settings during No Construction (see bottom rows of Tables 8 and 9), CO values were identical (0.14 ppm), US 6 NO levels were higher (+6.3 ppb), NO_2 levels were slightly lower (-0.9 ppb) and therefore NO_x levels were higher (+5.5 ppb). Estimated tVOC enhancements were similar at both sites but slightly lower at US 6 as were $PM_{2.5}$ enhancements (-2.7 µg/m3).

Another way of interpreting this finding is the average spatial variability across the US 6 construction site compared to US 40 when no construction was occurring, was equal for CO, higher for NO, and NO_x and smaller for tVOCs, NO_2 and $PM_{2.5}$ not accounting for differences in average traffic and environmental conditions. The larger spatial variability in enhancements at US 6 for primary combustion emissions (CO, NO, NO_x) is unsurprising given the diversity of emitting sources, large traffic volumes and general activities present in the urban environment that the rural setting lacked. Importantly, the placement of pods varied more at the US 6 site (i.e., height above ground, roof-top installations, proximity to roadways) due to the nature of finding participating partners to place pods which may have played a role. Moreover, the wind patterns at US 40 created strong pollution gradients which may be responsible for the larger spatial variability for some pollutants (tVOCs, NO_2 and $PM_{2.5}$).

Interestingly, the modeled impacts at the urban and rural sites for the same proximity-to-construction activity category had mixed agreement. Earthwork, for example, had similar magnitudes of modeled impacts at both sites for $PM_{2.5}$ and NO, relative to No Construction. Yet, HMA was associated with higher enhancements of $PM_{2.5}$ at US 6 and lower enhancements at US 40 for example. The differences in the spatial scale of the zones, types and durations of each construction activity and layout of pods at each site may explain why some of the impacts of construction results are mixed.

Chapter 6. Conclusion

6.1. Construction Activity Impact on Air Quality and Evidence for Mitigation

Below is a summary of the construction activities that were linked to increased enhancements (significantly higher than the "No Construction" baseline model condition) at measurement locations several meters to up to ~400 meters away and warrant addition investigation into mitigation efforts. The highest averaged enhancements were often found to be in the same zone as the construction activity, which could be anywhere between a few meters away to up to two or three hundred meters (depending where in the zone the construction was happening). That said, some high enhancements were found to be in an adjacent zone to the zone with the construction activity (~300 meters to ~500 meters away).

The following activities were estimated to have the corresponding **hourly averaged** enhancements (with accompanying 95% confidence interval of the mean):

Asphalt Milling

39.8 $\mu g/m^3$ (95% CI: 10.2, 155) of PM_{10}

38.5 $\mu g/m^3$ (95% CI: 9.1, 176) of coarse PM

1.9 $\mu g/m^3$ (95% CI: 1.2, 4.6) of $PM_{2.5}$

18.1 ppb (95% CI: 12.0, 27.2) of tVOCs

These enhancements were likely due to the mechanical abrasion of the asphalt during the milling process which also generated heat from friction which in turn emitted VOCs.

Earthwork

19.1 ppb (95% CI: 16.5, 22.1) of NO

18.6 ppb (95% CI: 17.3, 19.9) of NOx

31.2 $\mu g/m^3$ (95% CI: 24.4, 40.0) of PM_{10}

37.6 $\mu g/m^3$ (95% CI: 28.2, 50.1) of coarse PM

4.9 $\mu g/m^3$ (95% CI: 4.5, 5.3) of $PM_{2.5}$

Most likely, the increases in PM from dust generated by this activity were mainly in the coarse mode with a tail in the fine mode. NO, and in turn NO_x, (and possibly $PM_{2.5}$) were elevated perhaps due to increased combustion emissions related to the large engine loads on heavy equipment such as dump trucks, dozers and front-end loaders used during Earthwork activities.

HMA

0.16 ppm (95% CI: 0.15, 0.19) for CO

12.4 ppb (95% CI: 10.4, 14.8) of NO

21.6 ppb (95% CI: 18.8, 24.7) of NOx

10.6 ppb (95% CI: 8.4, 13.2) tVOCs

16.7 μg/m^3 (95% CI: 10.8, 25.9) of PM_{10}

17.8 μg/m^3 (95% CI: 11.1, 28.9) of coarse PM

2.5 μg/m^3 (95% CI: 1.9, 3.4) of $PM_{2.5}$

HMA was linked to elevations in the most pollutants. Typical combustion products (CO, NO, NO_x, tVOCs) could be accounted for from the increased engine loads of equipment using during the preparation of the surface to be paved and pouring of the mix. VOC emissions in the form of hydrocarbons released or driven off the mixture is likely. Fumes and vapors produced from the hot petroleum-based mixtures could form fine particulates especially when condensing during cooling

Saw Cutting and Other

2.1 μg/m^3 (95% CI: 1.2, 3.2) of $PM_{2.5}$

Concrete saws, hand operated or machine operated, could be producing small particles through the cutting process directly or via emissions from two-stroke engines under load.

Sidewalk/Shoulder Soil

0.25 ppm (95% CI: 0.21, 0.31) for CO

20.1 ppb (95% CI: 16.7, 24.2) of NO

8.3 ppb (95% CI: 6.9, 10.1) of NO_2

27.2 ppb (95% CI : 22.8, 33.7) NO_x

39.4 μg/m^3 (95% CI: 19.1, 80.1) of PM_{10}

42.7 μg/m^3 (95% CI: 19.2, 95.0) of coarse PM

Similar to Earthwork, Sidewalk/Shoulder Soil work increased PM from dust generated by the moving of soils. Combustion products (CO, NO_2, NO_x) may have been elevated due to increased combustion emissions related to the large engine loads on slightly smaller equipment than Earthwork-related machinery, including skid steers, loaders etc. Additionally, the magnitude of the enhancements may be partially attributable to the closer proximity this shoulder work was to the pods.

Striping

14.2 ppb (95% CI: 10.4, 19.5) of NO

21.9 ppb (95% CI: 17.1, 28.0) NO_x

3.0 μg/m^3 (95% CI: 1.7, 5.1) of $PM_{2.5}$

21.5 μg/m^3 (95% CI: 9.7, 78.3) of coarse PM

13.6 ppb (95% CI: 8.4, 21.8) of tVOCs

Striping is an activity that can produce large amounts of dust when the road surface is cleaned immediately prior to the application of the striping material, which is often comprised of paint and glass beads for retroreflectivity. Combustion byproducts, like many other activities, were elevated and tVOCs emissions from the volatilizing paint fumes was possible. Fine particles may also have been emitted or formed from the aerosolized paint.

6.2. Contextualizing Estimated Enhancements using National Ambient Air Quality Standards

The estimated 1hr average pollution enhancements attributed to construction activities reported above would alone, likely not surpass relevant NAAQS (National Ambient Air Quality Standards) shown in Table 10. Direct comparisons to the NAAQS are not possible because of time averaging differences (e.g., 8hr or 24hr means) and the NAAQS are total concentrations not enhancements above background. Background pollutant concentrations are variable, and the enhancements reported from the modeling must be added to background concentrations which could be elevated in urban or generally more polluted areas. Additionally, baseline model conditions (traffic volume, wind speeds etc.) will vary which would contribute to even higher enhancements (e.g., on top of the values predicted above because those are at variable means - average traffic, average wind speed etc). Out of all the pollutant enhancements modeled, PM_{10} pollution measured within ~200 meters of Asphalt Milling, Sidewalk/Shoulder Soil and

Earthwork present the conditions to be most concerned about contributing to a situation where NAAQS standards are surpassed (24hr, 150 µg/m^3).

Table 10. National Ambient Air Quality Standards (NAAQS)

Pollutant [links to historical tables of NAAQS reviews]		Primary/ Secondary	Averaging Time	Level	Form
Carbon Monoxide (CO)		primary	8 hours	9 ppm	Not to be exceeded more than once per year
			1 hour	35 ppm	
Lead (Pb)		primary and secondary	Rolling 3 month average	0.15 µg/m^3 [1]	maximum arithmetic mean of 3 consecutive monthly means in a 3-year period
Nitrogen Dioxide (NO_2)		primary	1 hour	100 ppb	Annual 98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
		primary and secondary	1 year	53 ppb [2]	Annual Mean
Ozone (O_3)		primary and secondary	8 hours	0.070 ppm [3]	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years
Particle Pollution (PM)	$PM_{2.5}$	primary	1 year	9.0 µg/m^3	annual mean, averaged over 3 years
		secondary	1 year	15.0 µg/m^3	annual mean, averaged over 3 years
		primary and secondary	24 hours	35 µg/m^3	98th percentile, averaged over 3 years
	PM_{10}	primary and secondary	24 hours	150 µg/m^3	Not to be exceeded more than once per year on average over 3 years

Note: Table adapted from the United States Environmental Protection Agency, National Ambient Air Quality Standards (NAAQS) Table. Retrieved from https://www.epa.gov/criteria-air-pollutants/naaqs-table

6.3. Transport of Pollutants

Wind was an important factor to include in an assessment of construction impacts on air quality. Measurements of wind speed and direction improved modeling results by addressing the phenomenon of transport. When modeling, wind patterns should be representative of the timeframe over which observations in the model were made. For example, the wind roses for all hours at both sites indicated a different pattern than the wind roses for daytime hours only. Since only daytime hours were used in the models, the wind patterns over those timeframes were important to emphasize. Wind speed is also critical to measure. Increased wind speeds were associated with decreased enhancements for many pollutants (especially at the windier US 40 site) suggesting wind dispersion as a key process leading to either dilution or missed plumes of emissions. Topography is likely playing a key role in the wind patterns at each site and therefore the resulting direction of pollutant transport and/or dispersion. Varying topography between urban (perhaps flatter) and rural sites may be responsible for some of the differences between findings at these settings.

6.4. Document, Analyze and Understand Emissions from Road Construction

A goal, and significant percentage of this work, was dedicated to developing a robust methodology to collect, categorize and analyze data and report findings in a systematic manner with the objective of better understanding relationships between road construction and air quality impacts. This goal was reached.

The researchers established an improved field data collection methodology through use of novel air sensors (pods), traffic cameras/counters, construction activity cameras, and strong partnerships with CDOT personnel and construction staff.

Traffic cameras offered a cost-effective and systematic way of counting vehicles while the cameras pointed to construction areas were perhaps the most accurate way to classify construction activities. Nonetheless, this process was extremely time consuming. This method was used only because accurate data was not consistently available in another format, however, this methodology may not be practical for continuous construction data monitoring in future projects.

Moreover, the research team developed data processing scripts to automate air sensor calibration and harmonization, a conventionally time consuming and arduous process. Scripts to fuse construction activity, air quality and traffic data were generated. These software products were built to compile a database structure from which modeling could take place. Analytical methods were homed by focusing on enhancements above background and using several statistical and supervised learning modeling approaches.

A multipollutant measurement approach opens analysis avenues that single pollutant measurement analyses lack. For example, increases in combustion products like CO, NO_x and $PM_{2.5}$ point to specific sources (e.g., internal combustion engines) while coarse PM enhancements suggest mechanically generated or re-suspended particles from processes common to construction.

6.5. Data Collection Approaches

6.5.1. Field Data Collection

Standalone low-cost air quality sensors, built to be autonomous in operation, are suitable options for this type of research. Collecting real-world observations of complex systems is challenging and low-cost sensors provide a cost-effective alternative to high-end instrumentation which has constraints. Perhaps the most apparent is scale. Low-cost sensors can be deployed for long periods of time, in large numbers to provide a dense spatial network of time-resolved measurements a) increasing the chances of detecting plumes from point and mobile sources, b) yielding pollution gradients which in turn provide evidence of sources c) offer multi-pollutant sensing capabilities d) provide quantities of data necessary to perform more complex analyses including mixed statistical models and supervised learning. The generalized linear mixed effects modeling proved to be a rather challenging yet powerful approach to disentangle the effects of construction on air pollution enhancements. Considerable effort was invested in this modeling approach to determine applicability, interpretability, and overall usefulness in addressing research questions.

Challenges presented in this work were numerous yet manageable. Remote field sites often generate challenges with power, security, and access. That was the case for the two rural sites. However, the research team overcame the power concerns early on by developing solar-battery-powered units which could be deployed in the field for months at a time. The researchers encountered vandalism and theft which should be considered in future work especially if sensor placement strategies cannot guarantee security (common in this work). In urban settings, involving community members in the placement and operation of sensors is critical. Public land and property are not always sufficient for the tasks at hand.

Chapter 7. Recommendations

Given the results presented here, CDOT should consider additional monitoring and potentially mitigation efforts focused on the activities reported above which were shown to have impacts on pollution levels. These activities may not come as a surprise given the existing literature on this research topic and one's firsthand experience visiting a road construction site with these activities occurring. That said, this report has quantified what these impacts can be at the distances, environmental settings and conditions at the US 6 and US 40 study sites. Larger scale construction projects or sites exhibiting different activity patterns (e.g., night construction only, bridge construction etc.) warrant additional investigation.

Several lessons learned and themes for improvement to be considered for the monitoring and management of air quality during CDOT construction projects and in future research are conveyed in the next sections. The research team has identified several themes of improvement that could be incorporated into future studies focused on addressing similar objectives. The themes include enhanced data collection and analysis approaches, validation efforts, enriched study design, improvements in sensor quantification and functionality, and potential pollutant mitigation strategies.

7.1. Air Quality Assessment

7.1.1. Data Collection

- Standalone, low-cost air quality sensors designed for autonomous operation represent a practical solution for air quality monitoring. Capturing real-world data from complex systems is inherently challenging, and these sensors provide a cost-effective alternative to high-end instrumentation, which often comes with significant constraints. Mid-cost commercial air quality sensors/monitors with accompanying data services (which often include data calibration or quality assurances) are also good options since research-grade tools are not directly compatible for commercial use.
- Low-cost sensors can be deployed over extended periods and in large quantities, enabling the creation of dense spatial networks with time-resolved measurements. This approach can facilitate a more cost-effective, more accurate characterization of air quality within a study area than many alternatives (e.g., high-end reference monitors).
- The use of low-cost, multi-sensor portable devices equipped with real-time, cloud-based data transfer capabilities enables remote monitoring of data collection systems. This approach eliminates

the need for on-site data retrieval and allows for the immediate detection of sensor malfunctions, thereby minimizing potential data loss that might otherwise occur between site visits.

- In urban settings, involving community members in the placement and operation of sensors is critical. Public land and property are not always sufficient for the tasks at hand.
- Consider solutions to provide mounting options for air sensors for continuous monitoring. Solutions could include the ability to provide AC power (which is a challenge) or mounting locations such as poles or existing CDOT infrastructure (signposts etc.) While AC connections should be used whenever available to ensure uninterrupted data collection and reduce maintenance needs, AC power access is often limited or impractical in many CDOT project locations. Therefore, CDOT should scrutinize the design and reliability of battery- and solar-powered sensor systems when considering them for long-term deployments.
- Secure and safeguard data collection equipment to minimize the risk of vandalism, particularly in urban environments.
- Ensure that the primary colocation variable space closely reflects the deployment variable space to minimize the need for extrapolation. This consideration should account for both environmental factors and pollutant concentration levels.
- Certain pollutants, such as tVOCs, may require additional measures to ensure proper calibration. Collaboration with environmental regulatory and public health agencies can be essential to achieving accurate results. In this study, the research team addressed this need by sending the reference pod to Los Angeles, where it was colocated with a South Coast Air Quality Management District (SCAQMD) high-end Fourier Transform Infrared Spectroscopy (FTIR) continuous optical multi-pollutant analyzer (FluxSense Inc., San Diego, CA). This setup provided high temporal resolution measurements in a complex environment influenced by traffic and nearby heavy industries, yet quantification was nevertheless limited to a few VOC species.
- Train CDOT local teams on the proper handling and operation of data collection equipment to reduce the need for frequent site visits.
- For traffic counts, the commercially available COUNTCam4 proved to be a useful tool, though not without software and hardware challenges. When operated in “Traffic Count” mode, these cameras successfully captured vehicle volume, direction, and speed, which are later downloaded from the camera into a spreadsheet (no video file is produced in this modality). The cameras can also record

traffic videos that, once processed, provide vehicle volume and classification data. However, this video processing is an add-on service offered by StreetLogic, requiring the purchase of video analysis hours. In comparison, pneumatic tube counters demonstrated lower performance and required more intensive maintenance than the cameras. It should also be noted that data from the cameras must be manually extracted on a weekly or bi-weekly basis, as no online data retrieval option is currently available.

- Collect air quality and traffic data prior to the start of each construction project to establish baseline conditions and accurately document preexisting environmental factors. This allows for a clearer characterization of construction-related impacts. This approach could unpack the difference in air quality between "No Construction" taking place at an established construction site and "No Construction" taking place with no established construction site present. This distinction could reveal unforeseen impacts or elucidate effects from static or intrinsic construction site characteristics (material piles, disturbed ground, equipment staging areas, traffic pattern changes etc.). Similarly, it would be convenient to collect data for at least one month after the culmination of the construction project to determine if the baseline has changed and the impact that this could have on the analysis of the data obtained during the construction process.
- Deploy monitors across gradients of prevailing winds to increase the probability of having an upwind and downwind measurement at the same time. Ideally, a background monitor would be set up in each of the four cardinal directions from the construction site.
- To ensure construction activities are documented at the required level of detail, a standardized data collection sheet should be developed. Construction inspectors should be trained on its proper use to ensure consistency and accuracy. Ideally, this tool would be implemented as an online platform that both secures the data in its original format and enables seamless export to a spreadsheet for subsequent analysis. See Appendix D for a tentative list of required items for this form. Obtaining data with the required level of detail through this mean would eliminate the need for video analysis to extract construction activity data.
- Additional strategies could be employed to either more accurately delineate zones or approximate distances between sources (i.e., construction equipment) and receptors (pods) in such a way as to provide a more precise and/or dynamic spatial relation between the two to further isolate sources of pollution at a site. Although not fully tested, mounting GPS-enabled pods on construction equipment in the field could accomplish this by revealing deeper relationships between activities

and pollution with a higher signal-to-noise ratio than ambient monitors and short-cut the confounding of pollutant transport and chemistry observed at larger distances from sources.

- Advances made during the span of this research project include the integration of additional pollutant measures. Specifically, the research team successfully piloted, deployed, and assessed a useful PM_{10} and Coarse PM sensor into their research tool. Not only does this sensor show promise for measuring these modes of PM, unlike other popular sensors like the PlantowerPMS5003, the research team developed regressions to enhance the performance and utility of signals recorded by this sensor opening the door to future work focusing on these important modes of air pollution. On the topic of improved monitoring, the HAQ Lab has recently field-tested wireless communication capabilities in their next generation of the pod. These capabilities could transform data collection efficiencies which are still a major hurdle for this type of work.

7.1.2. Data Extraction, Processing, and Analysis

- The analytical approach pursued in the work was challenging but the difficult work of constructing the framework, fusing the rich datasets, and establishing the models has been done. Within this framework, significant additions to the modeling could yield insights beyond those captured in this report. Namely, a model incorporating not only the construction activities, but the equipment used (e.g., D5 dozer, paver, front-end loader etc.) for given tasks could provide more examinational nuance and target specific tasks (within activity categories) for directed mitigation and closer observation.
- Additionally, the modeling approach developed in this work was limited to a single construction activity classification at a given time. Often, two or three construction activities were happening simultaneously at a site, ultimately obfuscating the linkages between specific activities and pollution outcomes. Future modeling would benefit from devising tactics to account for simultaneous activities.
- The unit of observation used in the modeling analyses was a 1 hour mean. Future investigations could benefit from exploring the effects of a) varying observational averaging times (i.e., 15 min) and b) percentiles of observational data (i.e., rather than a mean, a 75th or 95th percentile could produce more insights, especially for short, high polluting events).

7.2. Air Pollution Mitigation

- To assess the potential impact of construction activities on air pollution, closely monitor key environmental variables—such as wind, temperature, humidity, and pressure—as they significantly influence pollutant concentrations.
- To more accurately predict the impact of gaseous pollutants such as CO, CO_2, NO, NO_2, and NO_x, it is essential to account for wind patterns during construction, as pollutant concentrations are strongly influenced by atmospheric transport. As a result, the highest concentrations may not occur near the emission source. In this study, wind speed was generally found to be inversely related to pollutant enhancements—indicating dilution or dispersion—though some exceptions were observed, particularly for NO_2.
- Particulate pollution typically exhibits a decreasing concentration gradient with increasing distance from the source. While transport processes also influence particulate levels, their effect is generally less pronounced compared to gaseous pollutants.
- Pay close attention to vehicle traffic, as it has been shown to increase concentrations of many monitored pollutants, particularly $PM_{2.5}$, coarse PM, tVOCs, and NO. Enhancements in NO_2 concentrations are expected to lag due to the oxidation process required for NO to convert into NO_2, which may take several minutes. However, NO_2 was observed to be less sensitive to traffic patterns compared to NO.
- Urban projects are expected to exhibit greater spatial variability in primary combustion emissions (CO, NO, NO_x) due to the diversity of emission sources, higher traffic volumes, and the wide range of activities characteristic of urban environments, as compared to rural settings.
- Rural environments with a predominant wind direction and localized sources are likely to exhibit spatial variability in pollutants.
- During **Asphalt Milling** the project area will likely experience significant (significantly different from No Construction) enhancements in PM_{10} coarse PM, $PM_{2.5}$, and tVOCs concentrations.
- During **Earthwork** the project area will likely experience significant enhancements in NO, NO_x, PM_{10}, coarse PM, and $PM_{2.5}$ concentrations.
- During **HMA paving** the project area will likely experience significant enhancements in CO, NO, NO_x, tVOCs, PM_{10}, coarse PM, and $PM_{2.5}$ concentrations.

- During **concrete Saw Cutting** the project area will likely experience significant enhancements in $PM_{2.5}$ concentrations.
- During **Sidewalk and Shoulder work** the project area will likely experience significant enhancements in CO, NO_2, NO_x, PM_{10}, and coarse PM concentrations.
- During **Striping** the project area will likely experience significant enhancements in CO, NO, NO_x, tVOCs, coarse PM, and $PM_{2.5}$ concentrations.

7.3. Future Work

Future research in this area is both necessary and promising. This study has established a foundation for collecting, analyzing, and reporting data to better understand how road construction activities influence local air quality. The next steps involve validating the methodology and modeling framework developed here to reliably predict construction-related air quality impacts, and subsequently applying the validated model to evaluate potential mitigation strategies. Advancing these efforts would position CDOT at the forefront of managing air pollution during construction and maintenance activities.

7.3.1. Modeling Approach External Validation

The modeling framework developed in this study—incorporating dynamic background subtraction, GLMM, pruned decision trees, and random forests—proved effective in explaining observed pollutant concentrations, predicting concentration levels, and identifying the key variables influencing these concentrations at each site. Applying this framework to new urban and rural projects, using the predictors identified here, would allow for a rigorous assessment of its external validity. If the model demonstrates strong predictive power, it would suggest that accounting for the primary construction activity at a given time is sufficient to forecast air quality impacts. Conversely, if predictions diverge significantly from observed concentrations, this would indicate that concurrent activities or unaccounted confounding variables exert a greater influence than initially anticipated. In such cases, the modeling framework would need to be refined and revalidated through successive iterations until an accurate and robust predictive model is achieved.

7.3.2. Implementation and Validation of New Air Pollution Mitigation Strategies

During data collection, the research team noted that construction activities were executed with the standard level of care and workmanship typical of heavy civil projects. Thus, the observed enhancements present opportunities to explore new air pollution mitigation strategies and innovative construction practices aimed at reducing air quality impacts. The predictive variables identified in this study highlight which factors must be influenced to control emissions associated with specific construction activities—an insight that is central to developing effective mitigation measures and revised construction procedures. With a validated predictive model in place, researchers would then be positioned to test and validate mitigation strategies that affect the variables incorporated in the model.

References

Antanasijević, D., V. Pocajt, A. Perić-Grujić, and M. Ristić. 2018. “Multiple-input–multiple-output general regression neural networks model for the simultaneous estimation of traffic-related air pollutant emissions.” Atmospheric Pollution Research, 9 (2): 388–397. https://doi.org/10.1016/j.apr.2017.10.011.

Bevan, G. H., S. G. Al-Kindi, R. Brook, and S. Rajagopalan. 2021. “Ambient Air Pollution and Atherosclerosis: Recent Updates.” Current Atherosclerosis Reports, 23 (10): 63. https://doi.org/10.1007/s11883-021-00958-9.

Bignal, K., M. Ashmore, A. Headley, K. Stewart, and K. Weigert. 2007. “Ecological impacts of air pollution from road transport on local vegetation.” Applied Geochemistry, 22: 1265–1271. https://doi.org/10.1016/j.apgeochem.2007.03.017.

Burghardt, T. E., and A. Pashkevich. 2018. “Emissions of volatile organic compounds from road marking paints.” Atmospheric Environment, 193: 153–157. Elsevier.

Cao, T. n.d. “Evaluations of in-use emission factors from off-road construction equipment - ScienceDirect.” Accessed March 4, 2024. https://www.sciencedirect.com/science/article/pii/S1352231016307506.

Cao, T., T. D. Durbin, R. L. Russell, D. R. Cocker, G. Scora, H. Maldonado, and K. C. Johnson. 2016. “Evaluations of in-use emission factors from off-road construction equipment.” Atmospheric Environment, 147: 234–245. https://doi.org/10.1016/j.atmosenv.2016.09.042.

Carr, E., J. Ang-Olson, and A. Rosenbaum. 2014. “Effects of Transportation Emissions on Air Quality in Southeast Los Angeles County.” Transportation Research Record, 13: 14.

Csikós, A., I. Varga, and K. M. Hangos. 2015. “Modeling of the dispersion of motorway traffic emission for control purposes.” Transportation Research Part C: Emerging Technologies, Special Issue: Advanced Road Traffic Control, 58: 598–616. https://doi.org/10.1016/j.trc.2015.03.027.

Cui, M., Y. Chen, Y. Feng, C. Li, J. Zheng, C. Tian, C. Yan, and M. Zheng. 2017. “Measurement of PM and its chemical composition in real-world emissions from non-road and on-road diesel vehicles.” Atmospheric Chemistry and Physics, 17 (11): 6779–6795. https://doi.org/10.5194/acp-17-6779-2017.

Dijkhoff, I. M., B. Drasler, B. B. Karakocak, A. Petri-Fink, G. Valacchi, M. Eeman, and B. Rothen-Rutishauser. 2020. “Impact of airborne particulate matter on skin: a systematic review from epidemiology to in vitro studies.” Particle and Fibre Toxicology, 17 (1): 35. https://doi.org/10.1186/s12989-020-00366-y.

Faber, P., F. Drewnick, and S. Borrmann. 2015. “Aerosol particle and trace gas emissions from earthworks, road construction, and asphalt paving in Germany: Emission factors and influence on local air quality.” Atmospheric Environment, 122: 662–671. https://doi.org/10.1016/j.atmosenv.2015.10.036.

Font, A., T. Baker, I. S. Mudway, E. Purdie, C. Dunster, and G. W. Fuller. 2014. “Degradation in urban air quality from construction activity and increased traffic arising from a road widening scheme.” Science of The Total Environment, 497–498: 123–132. https://doi.org/10.1016/j.scitotenv.2014.07.060.

Frey, H. C., W. Rasdorf, and P. Lewis. 2010. “Comprehensive Field Study of Fuel Use and Emissions of Nonroad Diesel Construction Equipment.” Transportation Research Record: Journal of the Transportation Research Board, 2158 (1): 69–76. https://doi.org/10.3141/2158-09.

Frischmon, C., J. Silberstein, A. Guth, E. Mattson, J. Porter, and M. Hannigan. 2025. “Improving the quantification of peak concentrations for air quality sensors via data weighting.” Atmospheric Measurement Techniques, 18 (13): 3147–3159. Copernicus Publications Göttingen, Germany.

Fu, M., Y. Ge, J. Tan, T. Zeng, and B. Liang. 2012. "Characteristics of typical non-road machinery emissions in China by using portable emission measurement system." Science of the Total Environment, 437: 255–261. Elsevier.

Giunta, M. 2020. "Assessment of the environmental impact of road construction: Modelling and prediction of fine particulate matter emissions." Building and Environment, 176: 106865. Elsevier.

Gong, W., T. Zhang, Z. Zhu, Y. Ma, X. Ma, and W. Wang. 2015. "Characteristics of PM1.0, PM2.5, and PM10, and Their Relation to Black Carbon in Wuhan, Central China." Atmosphere, 6 (9): 1377–1387. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/atmos6091377.

Han, S., J.-S. Youn, and Y.-W. Jung. 2011. "Characterization of PM10 and PM2.5 source profiles for resuspended road dust collected using mobile sampling methodology." Atmospheric Environment, 45 (20): 3343–3351. https://doi.org/10.1016/j.atmosenv.2011.04.015.

Harleman, M., L. Harris, M. D. Willis, B. Ritz, P. Hystad, and E. L. Hill. 2023. "Changes in traffic congestion and air pollution due to major roadway infrastructure improvements in Texas." Science of the Total Environment, 898: 165463. Elsevier.

Huang, K., X. Yang, F. Liang, F. Liu, J. Li, Q. Xiao, J. Chen, X. Liu, J. Cao, C. Shen, L. Yu, F. Lu, X. Wu, L. Zhao, X. Wu, Y. Li, D. Hu, J. Huang, Y. Liu, X. Lu, and D. Gu. 2019. "Long-Term Exposure to Fine Particulate Matter and Hypertension Incidence in China." Hypertension, 73 (6): 1195–1201. American Heart Association. https://doi.org/10.1161/HYPERTENSIONAHA.119.12666.

Kimbrough, S., R. W. Baldauf, G. S. W. Hagler, R. C. Shores, W. Mitchell, D. A. Whitaker, C. W. Croghan, and D. A. Vallero. 2013. "Long-term continuous measurement of near-road air pollution in Las Vegas: seasonal variability in traffic emissions impact on local air quality." Air Quality, Atmosphere & Health, 6 (1): 295–305. https://doi.org/10.1007/s11869-012-0171-x.

Kriech, D. M., A. C. Crawford, L. A. Smith, L. V. Osborn, and A. J. Kriech. 2022. "Characterizing asphalt emissions under in-service conditions." Atmospheric Environment: X, 16: 100196. Elsevier.

Kuhn, M., and K. Johnson. 2013. Applied Predictive Modeling. New York, NY: Springer New York.

Lenth, R., H. Singmann, J. Love, P. Buerkner, and M. Herve. 2018. "Estimated marginal means, aka Least-Squares Means. R package version 1.2." Https://CRAN. R-Project. Org/Package= emmeans.

Lewis, P., H. C. Frey, and W. Rasdorf. 2009. "Development and Use of Emissions Inventories for Construction Vehicles." Transportation Research Record: Journal of the Transportation Research Board, 2123 (1): 46–53. https://doi.org/10.3141/2123-06.

Lewis, P., M. Leming, H. C. Frey, and W. Rasdorf. 2011. "Assessing Effects of Operational Efficiency on Pollutant Emissions of Nonroad Diesel Construction Equipment." Transportation Research Record: Journal of the Transportation Research Board, 2233 (1): 11–18. https://doi.org/10.3141/2233-02.

Lewis, P., W. Rasdorf, H. C. Frey, and M. Leming. 2012. "Effects of Engine Idling on National Ambient Air Quality Standards Criteria Pollutant Emissions from Nonroad Diesel Construction Equipment." Transportation Research Record: Journal of the Transportation Research Board, 2270 (1): 67–75. https://doi.org/10.3141/2270-09 ?casa_token=7xh3ruz-8WkAAAAA:n-ciH1XxXcMrX0q5Sb88TYRYvZfE_g4T1hwzE20lYJaWgegBD46VfL0LXEh8JEoayyrwJZIrLwSO.

Lim, J.-H., S.-W. Jung, T.-W. Lee, J.-C. Kim, C.-Y. Seo, J.-H. Ryu, J.-W. Hwang, S.-M. Kim, and D.-S. Eom. 2009. "A Study on Calculation of Air Pollutants Emission Factors for Construction Equipment." Journal of Korean Society for Atmospheric Environment, 25 (3): 188–195. Korean Society for Atmospheric Environment. https://doi.org/10.5572/KOSAE.2009.25.3.188.

Liu, H., M. O. Rodgers, and R. Guensler. 2019. "Impact of road grade on vehicle speed-acceleration distribution, emissions and dispersion modeling on freeways." Transportation research part D: transport and environment, 69: 107–122. Elsevier.

Liu, X., J. Schnelle-Kreis, X. Zhang, J. Bendl, M. Khedr, G. Jakobi, B. Schloter-Hai, J. Hovorka, and R. Zimmermann. 2020. “Integration of air pollution data collected by mobile measurement to derive a preliminary spatiotemporal air pollution profile from two neighboring German-Czech border villages.” Science of The Total Environment, 722: 137632. https://doi.org/10.1016/j.scitotenv.2020.137632.

Miguel, J. P. M., C. S. de Blas, and A. E. G. Sipols. 2017. “A forecast air pollution model applied to a hypothetical urban road pricing scheme: An empirical study in Madrid.” Transportation Research Part D: Transport and Environment, 55: 21–38. Elsevier.

Moutinho, J. L., D. Liang, R. Golan, S. E. Sarnat, R. Weber, J. A. Sarnat, and A. G. Russell. 2020. “Near-road vehicle emissions air quality monitoring for exposure modeling.” Atmospheric Environment, 224: 117318. Elsevier.

Muleski, G. E., C. Cowherd, and J. S. Kinsey. 2005. “Particulate Emissions from Construction Activities.” Journal of the Air & Waste Management Association, 55 (6): 772–783. https://doi.org/10.1080/10473289.2005.10464669.

Okorn, K., and M. Hannigan. 2021. “Improving air pollutant metal oxide sensor quantification practices through: An exploration of sensor signal normalization, multi-sensor and universal calibration model generation, and physical factors such as co-location duration and sensor age.” Atmosphere, 12 (5): 645. MDPI.

Olsen, R., P. Graff, H. L. Daae, I.-L. Bryngelsson, P. Molander, and D. G. Ellingsen. 2021. “Occupational exposure during asphalt paving—comparison of hot and warm Mix asphalt in field experiments.” Annals of Work Exposures and Health, 65 (4): 446–457. Oxford University Press UK.

Panteliadis, P., M. Strak, G. Hoek, E. Weijers, S. van der Zee, and M. Dijkema. 2014. “Implementation of a low emission zone and evaluation of effects on air quality by long-term monitoring.” Atmospheric environment, 86: 113–119. Elsevier.

Pirjola, L., T. Rönkkö, E. Saukko, H. Parviainen, A. Malinen, J. Alanen, and H. Saveljeff. 2017. “Exhaust emissions of non-road mobile machine: Real-world and laboratory studies with diesel and HVO fuels.” Fuel, 202: 154–164. Elsevier.

Rajagopalan, S., M. Brauer, A. Bhatnagar, D. L. Bhatt, J. R. Brook, W. Huang, T. Münzel, D. Newby, J. Siegel, R. D. Brook, and null null. 2020. “Personal-Level Protective Actions Against Particulate Matter Air Pollution Exposure: A Scientific Statement From the American Heart Association.” Circulation, 142 (23): e411–e431. American Heart Association. https://doi.org/10.1161/CIR.0000000000000931.

Rasdorf, W., P. Lewis, I. Arocho, and J. Hummer. 2015. “Characterizing air pollutant emissions for highway construction projects.” Smart and Sustainable Built Environment, 4 (3): 315–328. https://doi.org/10.1108/SASBE-03-2015-0005.

Sandanayake, M., G. Zhang, S. Setunge, and C. M. Thomas. 2015. “Environmental Emissions of Construction Equipment Usage in Pile Foundation Construction Process—A Case Study.” Proceedings of the 19th International Symposium on Advancement of Construction Management and Real Estate, edited by L. Shen, K. Ye, and C. Mao, 327–339. Berlin, Heidelberg: Springer Berlin Heidelberg.

Sentoff, K. M., L. Aultman-Hall, and B. A. Holmén. 2015. “Implications of driving style and road grade for accurate vehicle activity data and emissions estimates.” Transportation Research Part D: Transport and Environment, 35: 175–188. https://doi.org/10.1016/j.trd.2014.11.021.

Singer, B. C., and R. A. Harley. 1996. “A Fuel-Based Motor Vehicle Emission Inventory.” Journal of the Air & Waste Management Association, 46 (6): 581–593. https://doi.org/10.1080/10473289.1996.10467492.

Wang, X., L.-W. A. Chen, M. Lu, K.-F. Ho, S.-C. Lee, S. S. H. Ho, J. C. Chow, and J. G. Watson. 2022. "Apportionment of vehicle fleet emissions by linear regression, positive matrix factorization, and emission modeling." Atmosphere, 13 (7): 1066. MDPI.
Wang, Z., S. Zhong, H. He, Z.-R. Peng, and M. Cai. 2018. "Fine-scale variations in PM2.5 and black carbon concentrations and corresponding influential factors at an urban road intersection." Building and Environment, 141: 215–225. https://doi.org/10.1016/j.buildenv.2018.04.042.
Wyatt, D. W., H. Li, and J. E. Tate. 2014. "The impact of road grade on carbon dioxide (CO2) emission of a passenger vehicle in real-world driving." Transportation Research Part D: Transport and Environment, 32: 160–170. Elsevier.
Yan, H., Q. Li, K. Feng, and L. Zhang. 2023. "The characteristics of PM emissions from construction sites during the earthwork and foundation stages: an empirical study evidence." Environmental Science and Pollution Research, 30 (22): 62716–62732. https://doi.org/10.1007/s11356-023-26494-4.

Appendix A. Primary Colocation Results, Calibration, and Validation per Pollutant

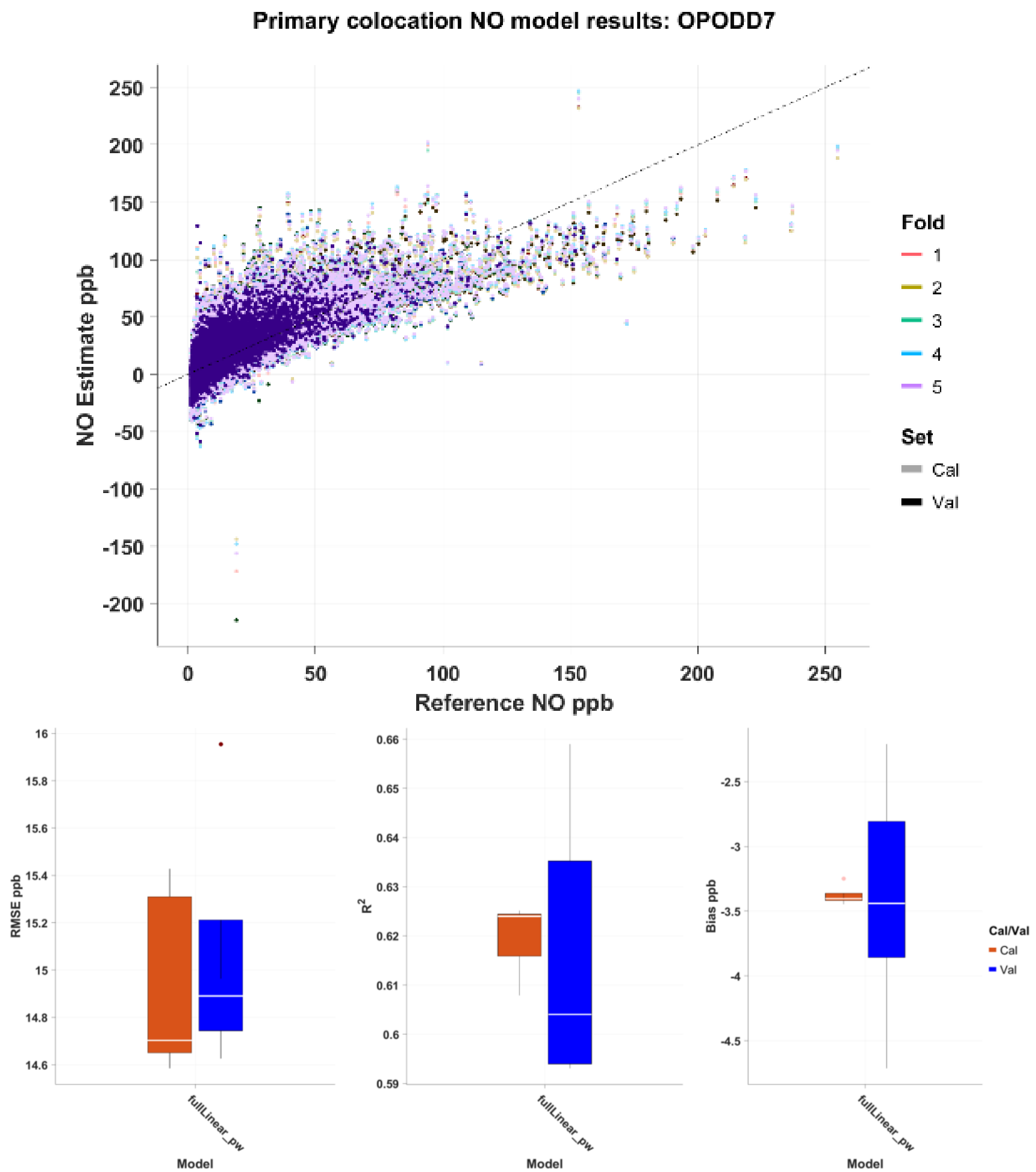


Figure 52. Primary Colocation NO Calibration (orange) and Validation (blue)

Note: Results at 5-minute means for "reference pod" D7. Top plot shows estimated NO against reference measurements across the 5 folds of validation. The dashed line is 1:1. Boxplots (bottom) show the variability in model diagnostics indicating overall performance across the 5 validation folds. Horizontal lines indicate medians.

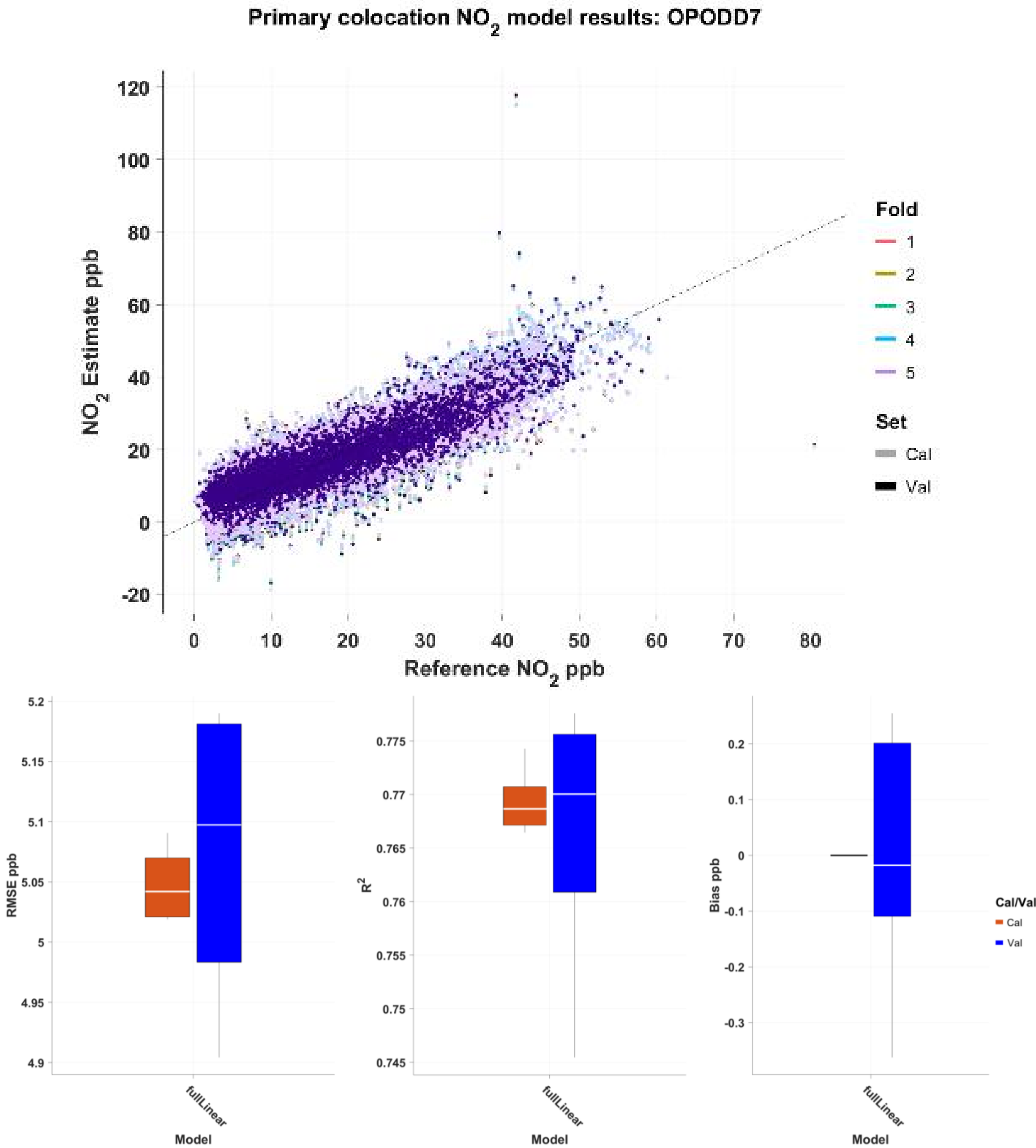


Figure 53. Primary Colocation NO2 Calibration (orange) and Validation (blue)

Note: Results at 5-minute means for "reference pod" D7. Top plot shows estimated NO_2 against reference measurements across the 5 folds of validation. The dashed line is 1:1. Boxplots (bottom) show the variability in model diagnostics indicating overall performance across the 5 validation folds. Horizontal lines indicate medians.

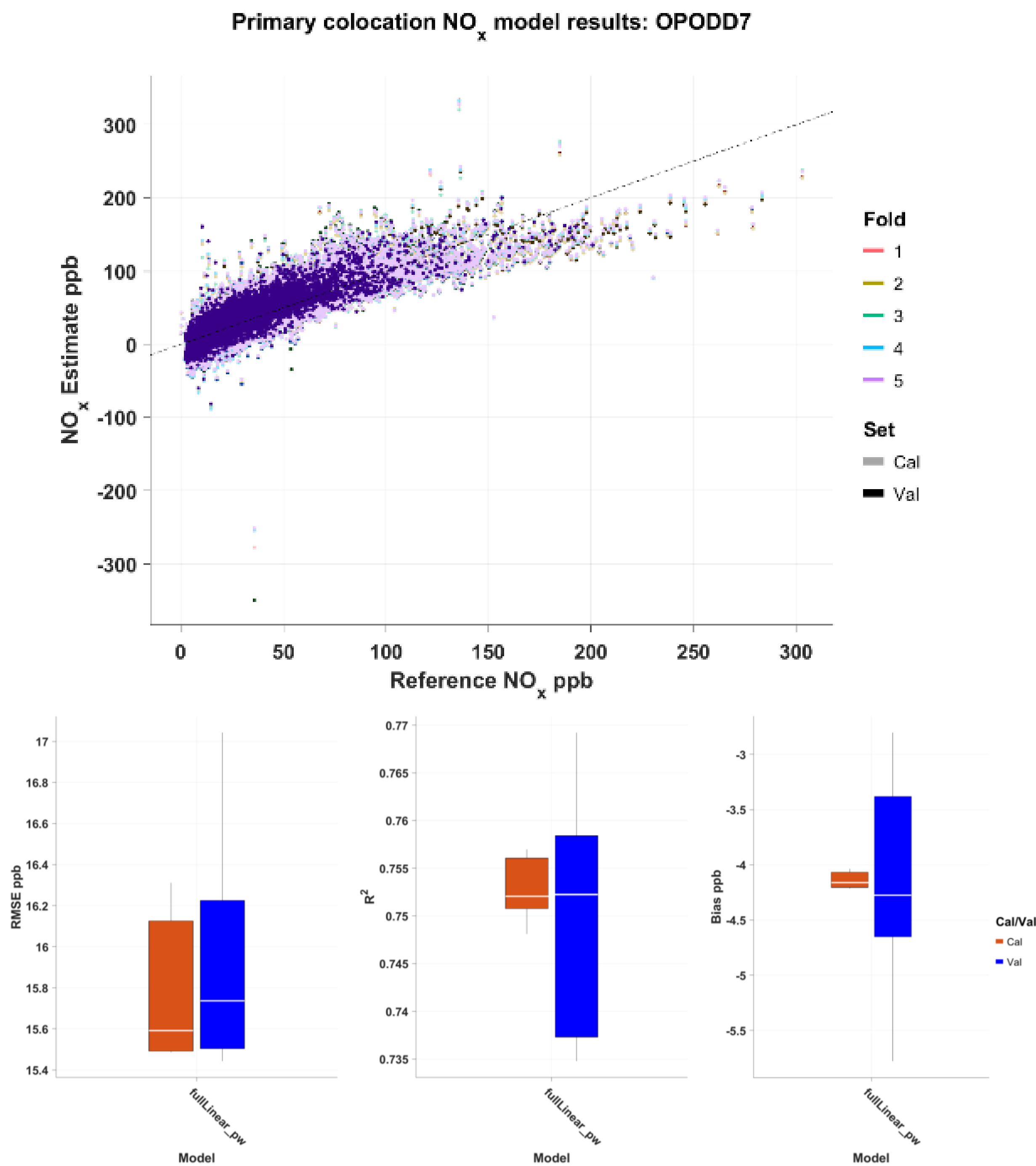


Figure 54. Primary Colocation NOx Calibration (orange) and Validation (blue)

Note: Results at 5-minute means for "reference pod" D7. Top plot shows estimated NO_x against reference measurements across the 5 folds of validation. The dashed line is 1:1. Boxplots (bottom) show the variability in model diagnostics indicating overall performance across the 5 validation folds. Horizontal lines indicate medians.

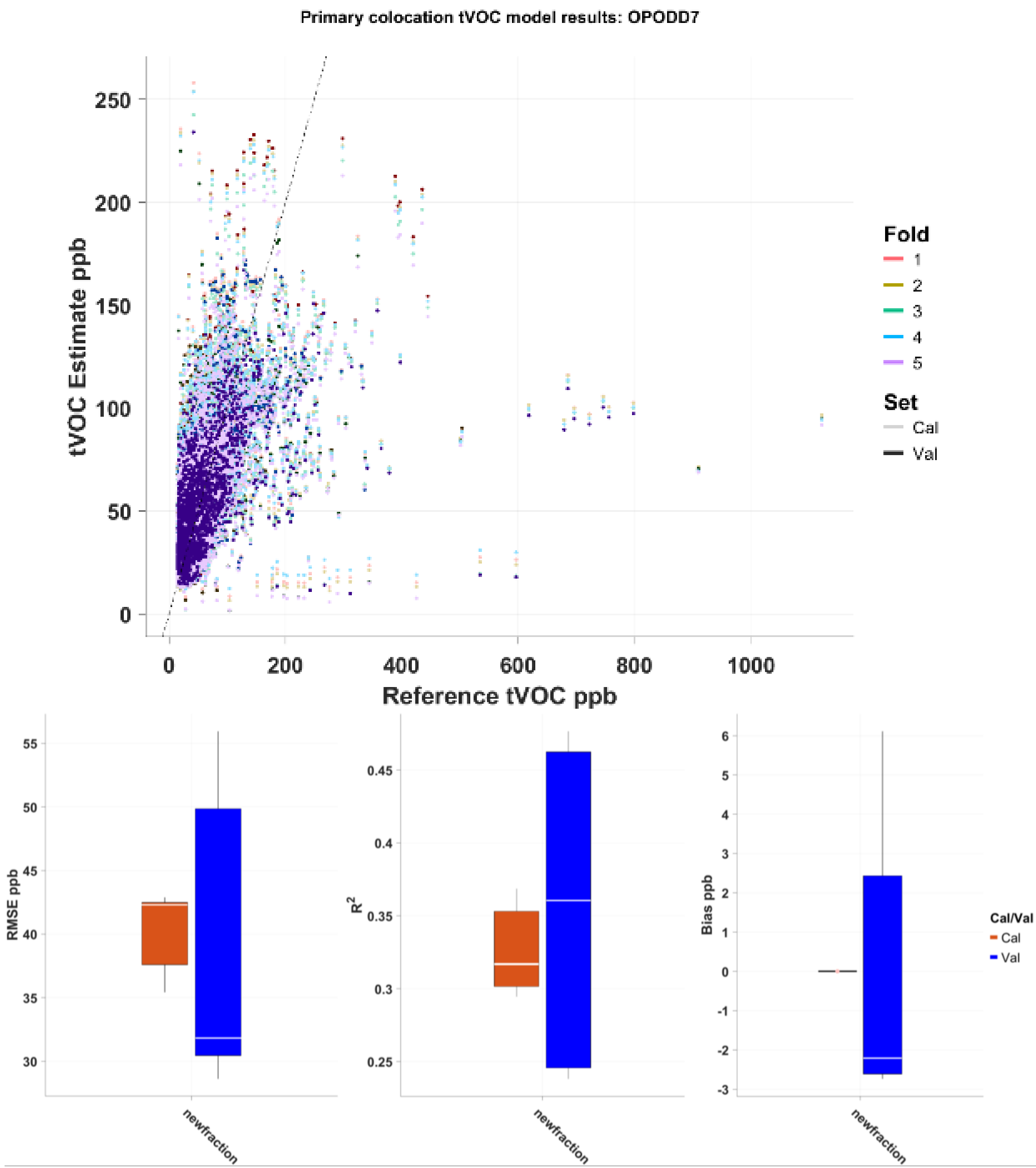


Figure 55. Primary Colocation tVOC Calibration (orange) and Validation (blue)

Note: Results at 5-minute means for "reference pod" D7. Top plot shows estimated tVOC against reference measurements across the 5 folds of validation. The dashed line is 1:1. Boxplots (bottom) show the variability in model diagnostics indicating overall performance across the 5 validation folds. Horizontal lines indicate medians.

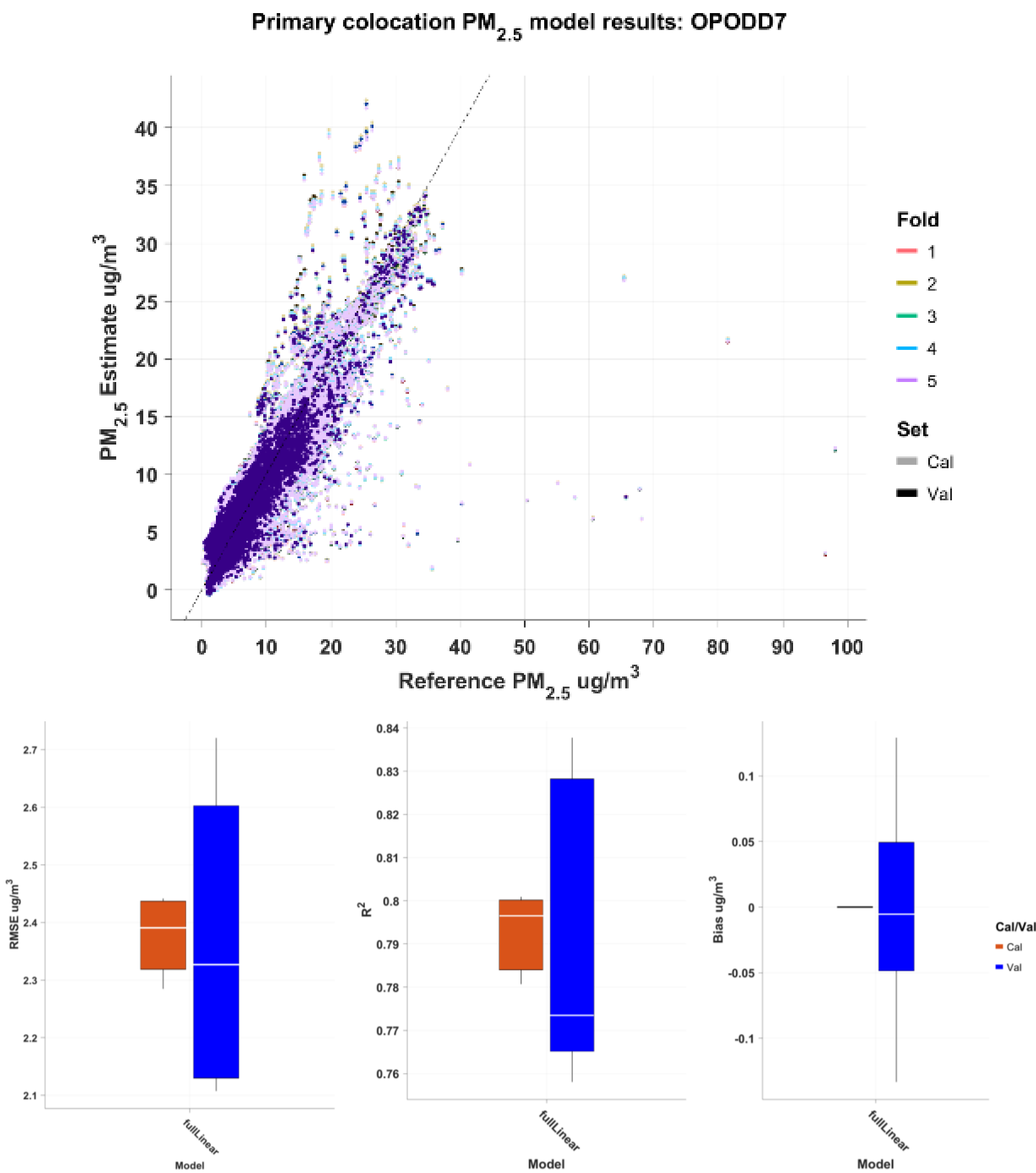


Figure 56. Primary Colocation PM2.5 Calibration (orange) and Validation (blue)

Note: Results at 5-minute means for "reference pod" D7. Top plot shows estimated $PM_{2.5}$ against reference measurements across the 5 folds of validation. The dashed line is 1:1. Boxplots (bottom) show the variability in model diagnostics indicating overall performance across the 5 validation folds. Horizontal lines indicate medians.

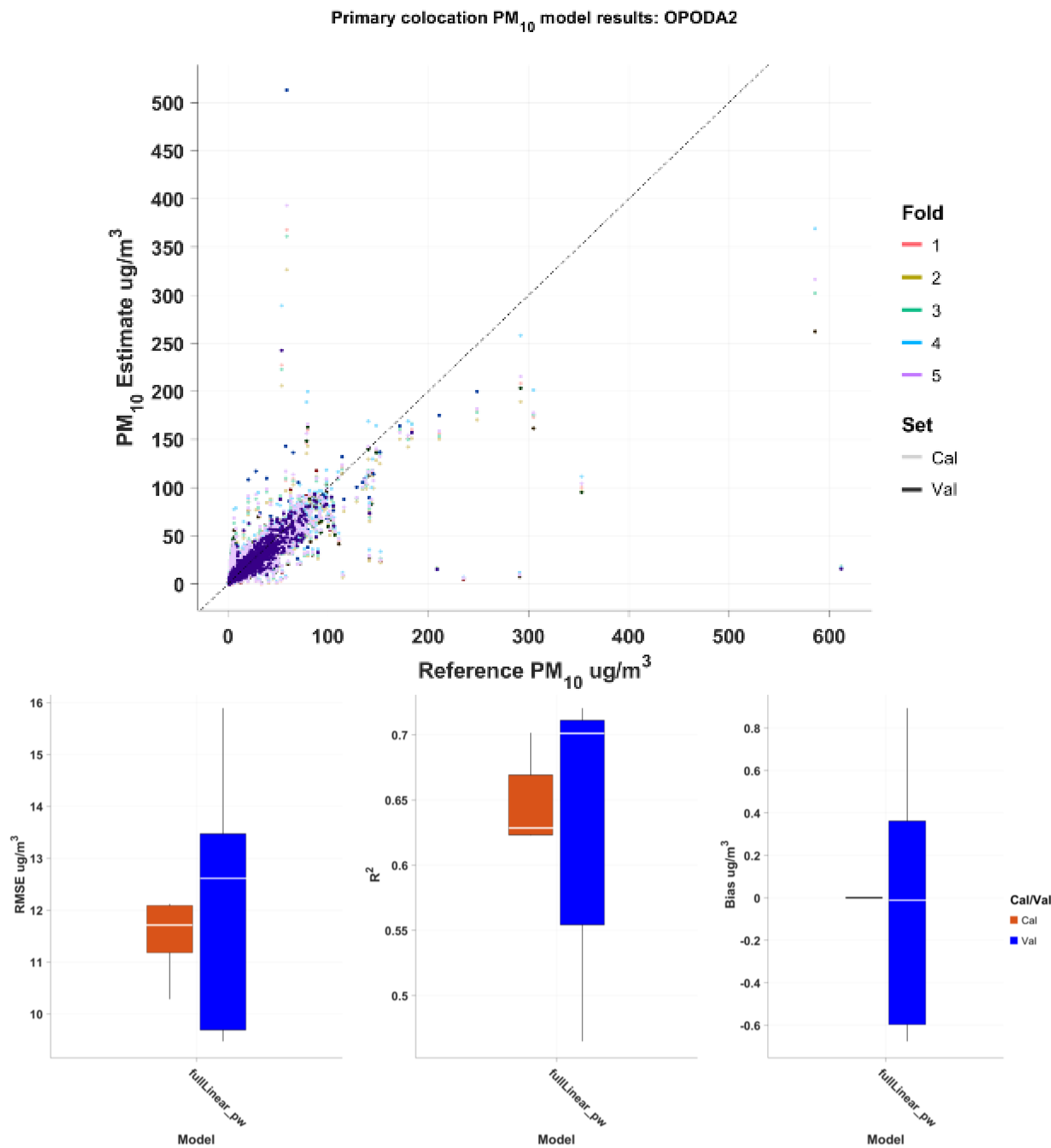


Figure 57. Primary Colocation PM10 Calibration (orange) and Validation (blue)

Note: Results at 5-minute means for "reference pod" D7. Top plot shows estimated PM_{10} against reference measurements across the 5 folds of validation. The dashed line is 1:1. Boxplots (bottom) show the variability in model diagnostics indicating overall performance across the 5 validation folds. Horizontal lines indicate medians.

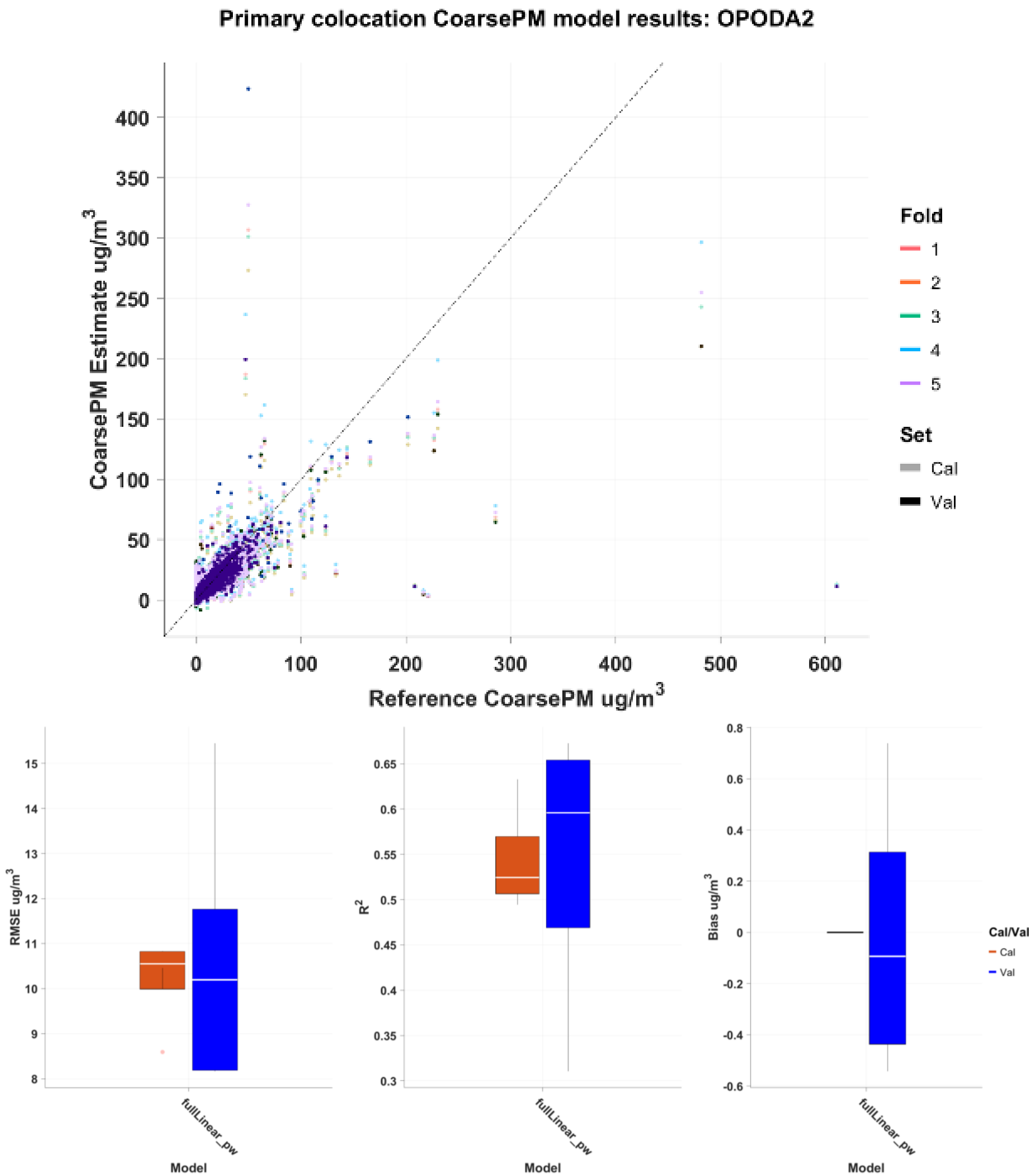


Figure 58. Primary Colocation Coarse PM Calibration (orange) and Validation (blue)

Note: Results at 5-minute means for "reference pod" D7. Top plot shows estimated coarse PM against reference measurements across the 5 folds of validation. The dashed line is 1:1. Boxplots (bottom) show the variability in model diagnostics indicating overall performance across the 5 validation folds. Horizontal lines indicate medians.

Appendix B. Pollutant Enhancements Model Results

B.1. US6 Measured Pollutant Enhancements

B.1.1. US 6 NO Enhancements

Hourly averaged NO enhancements ranged from 0 to 442 ppb (Figure 59). Again, mean hourly NO measurement uncertainty was estimated to be 4.3 ppb. Median enhancements for each zone ranged from 13.4 ppb for zone 3 to 17.6 ppb for zone 5 (zone 1: 14.4 ppb, zone 2: 16.5 ppb). Zone 1 had the three highest hourly observed NO enhancements (300-450 ppb). When grouped by construction activity, Striping and HMA had the highest median enhancements at 17.7 ppb, followed by No construction (15.3 ppb).

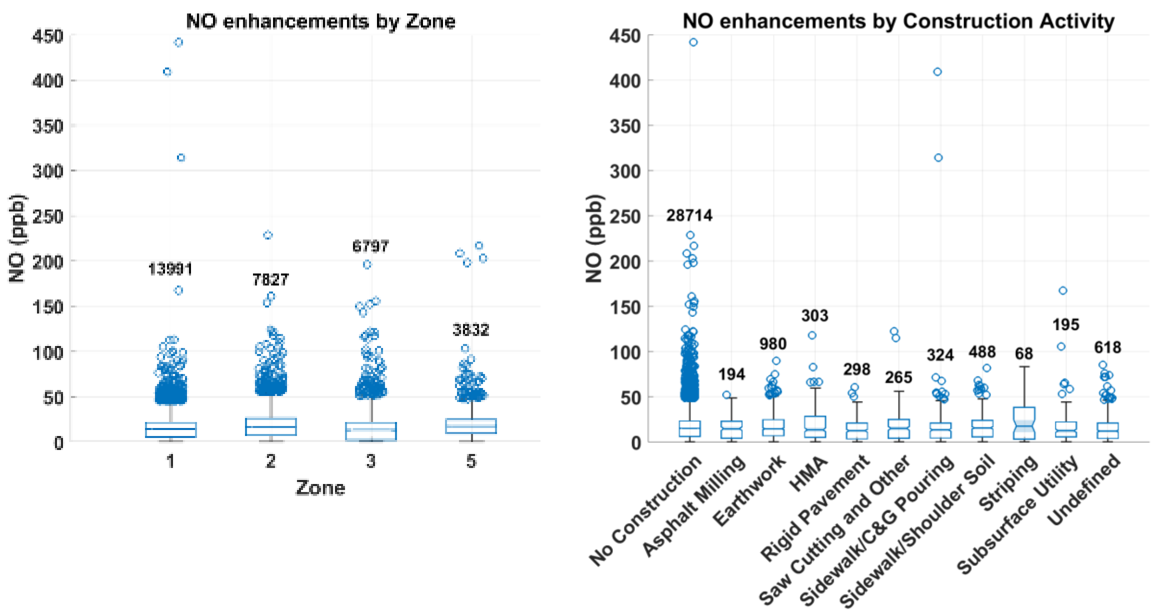


Figure 59. NO Enhancements by Zone and Construction Activity on US 6

B.1.2. US 6 NO_2 Enhancements

Hourly averaged NO_2 enhancements ranged from 0 to 123 ppb (Figure 60). Again, mean hourly NO_2 measurement uncertainty was estimated to be 1.5 ppb. Median enhancements for each zone ranged from 3.2 ppb for zone 3 to 6.6 ppb for zone 2 (zone 5: 4.9 ppb, zone 1: 5.1 ppb). When grouped by construction activity, Striping had the highest median enhancements at 6.4 ppb, followed by Asphalt Milling (5.8 ppb) and Saw Cutting and Other (5.5 ppb).

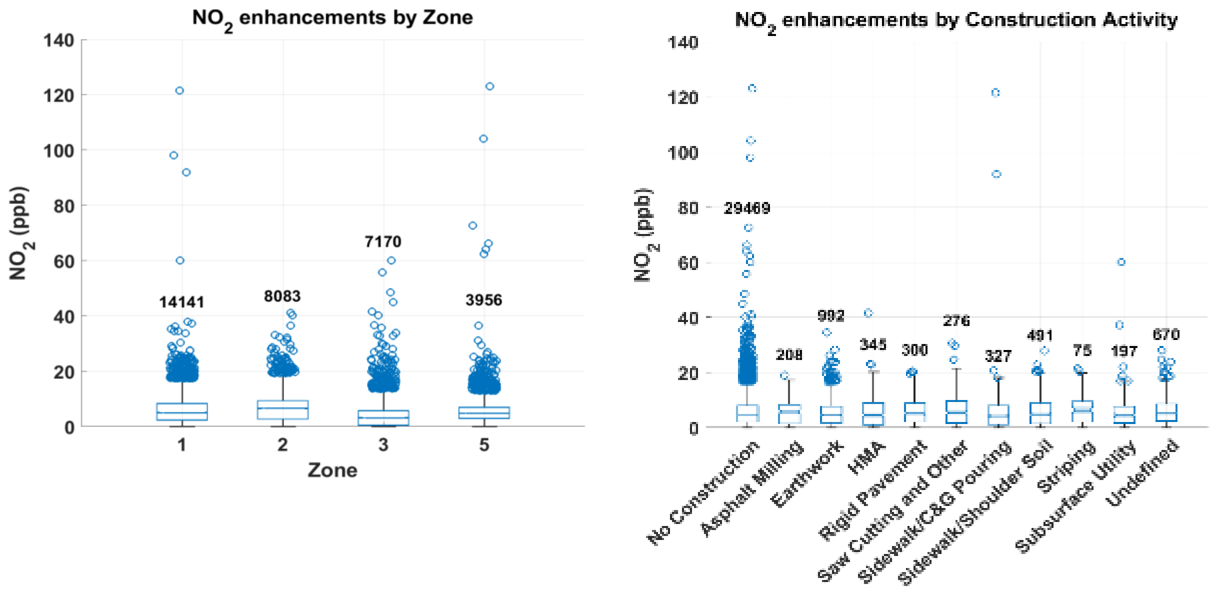


Figure 60. NO2 Enhancements by Zone and Construction Activity on US 6

B.1.3. US 6 NO_x Enhancements

Hourly averaged NO_x enhancements ranged from 0 to 474 ppb (Figure 61). Again, mean hourly NO_x measurement uncertainty was estimated to be 4.5 ppb. Median enhancements for each zone ranged from 14.7 ppb for zone 3 to 19.7 ppb for zone 2 (zone 5: 18.1 ppb, zone 1: 16.3 ppb). When grouped by construction activity, Asphalt Milling had the highest median enhancements at 22 ppb, followed by Sidewalk/Shoulder Soil (20.3 ppb) and Saw Cutting and Other (19.7 ppb). More than 50 hourly mean enhancements surpassed 100 ppb.

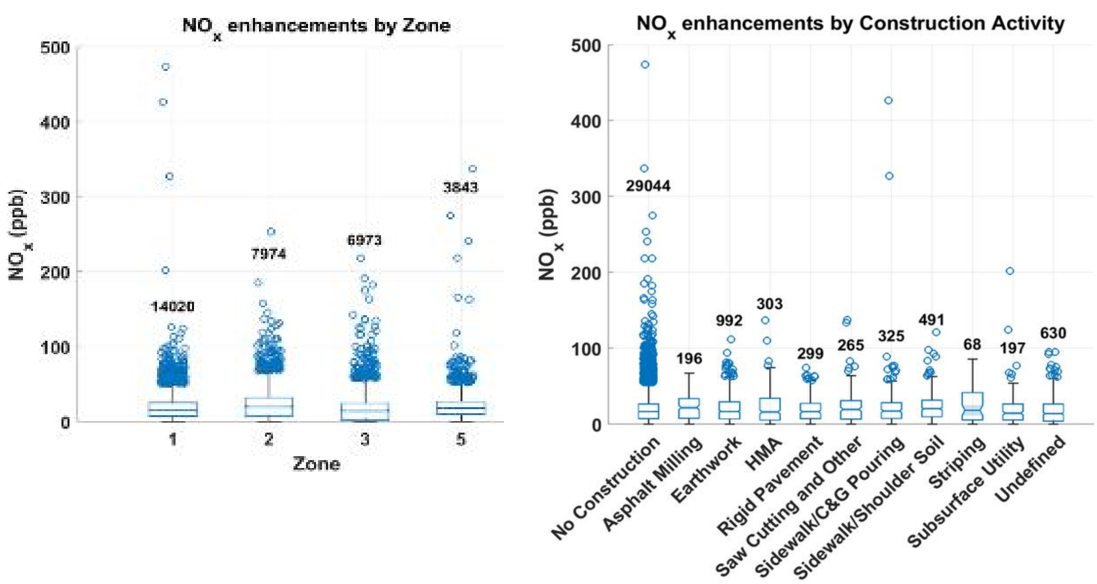


Figure 61. NOx Enhancements by Zone and Construction Activity on US 6

B.1.4. US 6 tVOC Enhancements

Hourly averaged tVOC enhancements ranged from 0 to 300 ppb (Figure 62). Again, mean hourly tVOC measurement uncertainty was estimated to be 9.2 ppb. Median enhancements for each zone ranged from 5.6 ppb for zone 5 to 8.4 ppb for zone 3 (zone 1: 7.1ppb, zone 2: 7.5ppb). When grouped by construction activity, Striping had the highest median enhancements at 8.5 ppb, followed by Asphalt Milling (7.8 ppb) and No Construction (7.6 ppb).

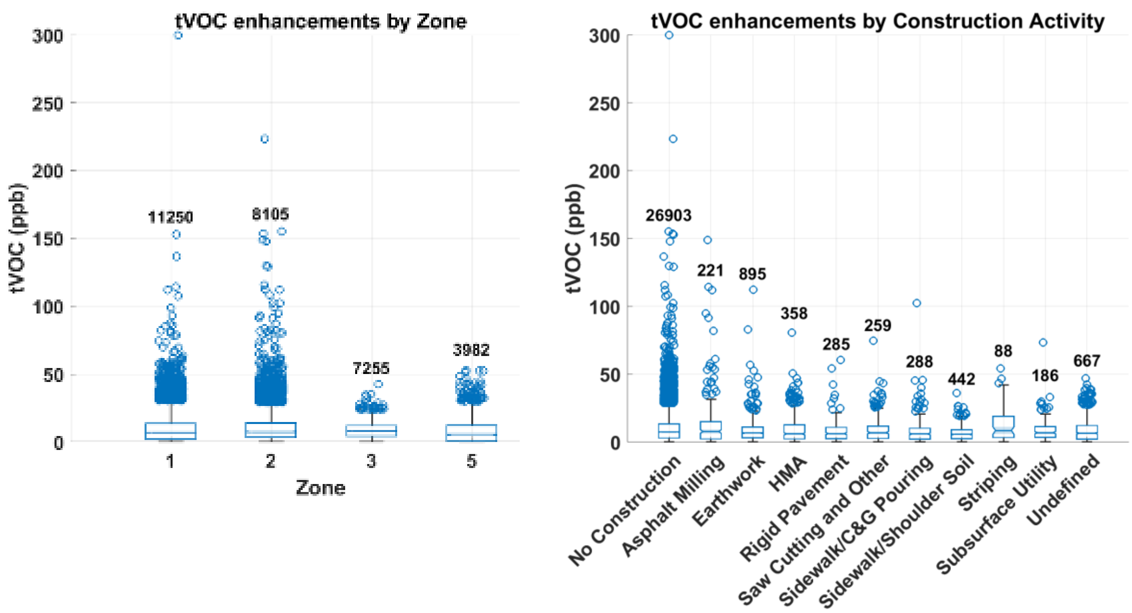


Figure 62. tVOC Enhancements by Zone and Construction Activity on US 6

B.1.5. US 6 $PM_{2.5}$ Enhancements

Hourly averaged PM2.5 enhancements ranged from 0 to 51.0 µg/m^3 (Figure 63). Again, mean hourly $PM_{2.5}$ measurement uncertainty was estimated to be 0.67 µg/m^3. Median enhancements for each zone ranged from 0.4 µg/m^3 for zone 2 to 1.3 µg/m^3 for zone 3 (zone 5: 1.1 µg/m3, zone 1: 0.8 µg/m^3). When grouped by construction activity, Striping had the highest median enhancements at 1.7 µg/m^3, followed by HMA (1.5 µg/m^3) and Asphalt Milling (1.1 µg/m^3). No Construction was associated with the largest variability in $PM_{2.5}$ enhancements.

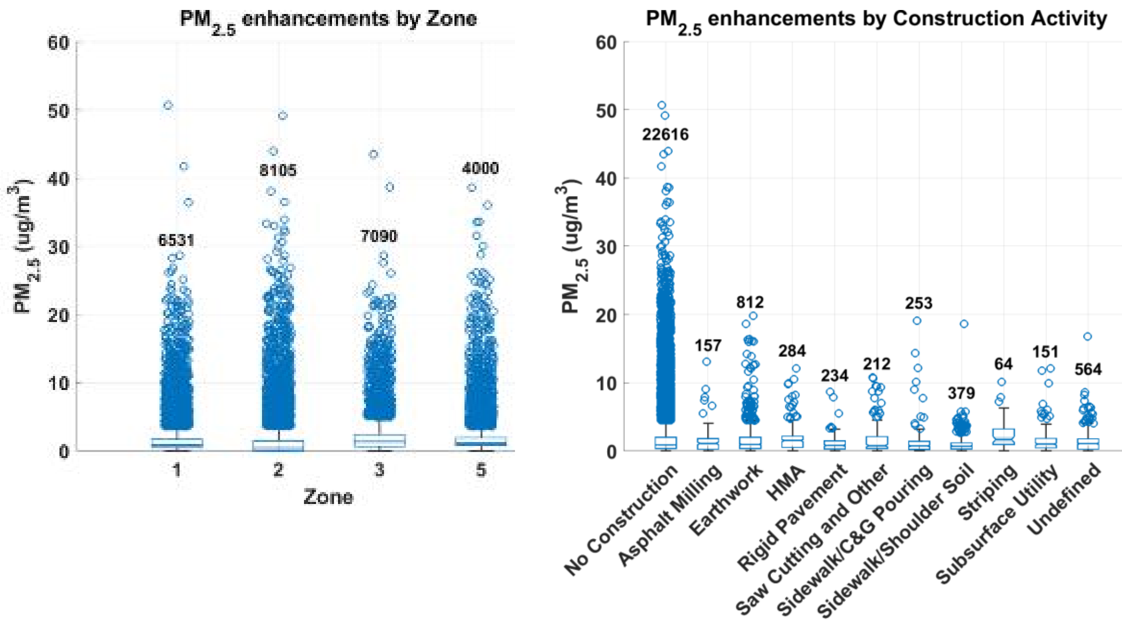


Figure 63. PM2.5 Enhancements by Zone and Construction Activity on US 6

B.2. US40 Measured Pollutant Enhancements

B.2.1. US 40 NO Enhancements

Hourly averaged NO enhancements ranged from 0 to 157ppb (Figure 64). Again, mean hourly NO measurement uncertainty was estimated to be 4.3 ppb. Median enhancements for each zone ranged from 0ppb for zone 5 to 17.9 ppb for zone 1 (zone 2: 6.8 ppb, zone 3: 4.8 ppb and zone 4: 15.5 ppb. When grouped by construction activity, Subsurface Utility had the highest median enhancement at 14.3 ppb but only 4 observations made up that category. The second highest median enhancement was Undefined at 10.5 ppb followed by No Construction at 9.8 ppb. Notably, outlier enhancements were associated with Earthwork.

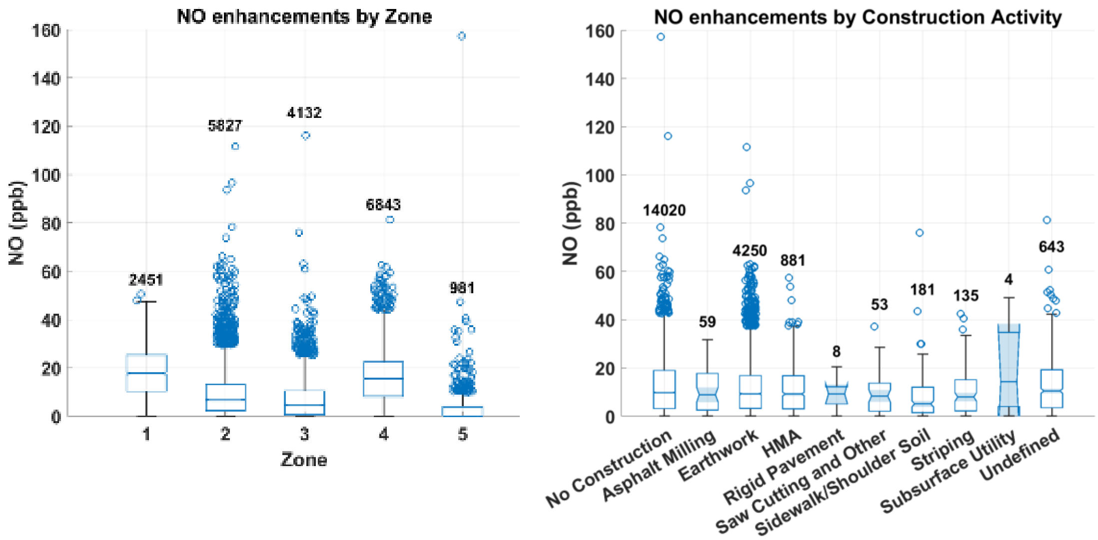


Figure 64. All NO Enhancements at US 40 by Zone (left) and Construction Activity (right)

B.2.2. US 40 NO_2 Enhancements

Hourly averaged NO_2 enhancements ranged from 0 to 135 ppb (Figure 65). Again, mean hourly NO_2 measurement uncertainty was estimated to be 1.5 ppb. Median enhancements for each zone ranged from 3.6 ppb for zone 3 to 7.5 ppb for zone 1 (zone 2: 6.6 ppb, zone 4: 4.4 ppb and zone 5: 4.3 ppb. When grouped by construction activity, Saw Cutting and Other had the highest median enhancement (6.9 ppb) followed by Sidewalk/Shoulder Soil (6.2 ppb). Notably, outlier enhancements were associated with Earthwork, Sidewalk/Shoulder Soil and No Construction.

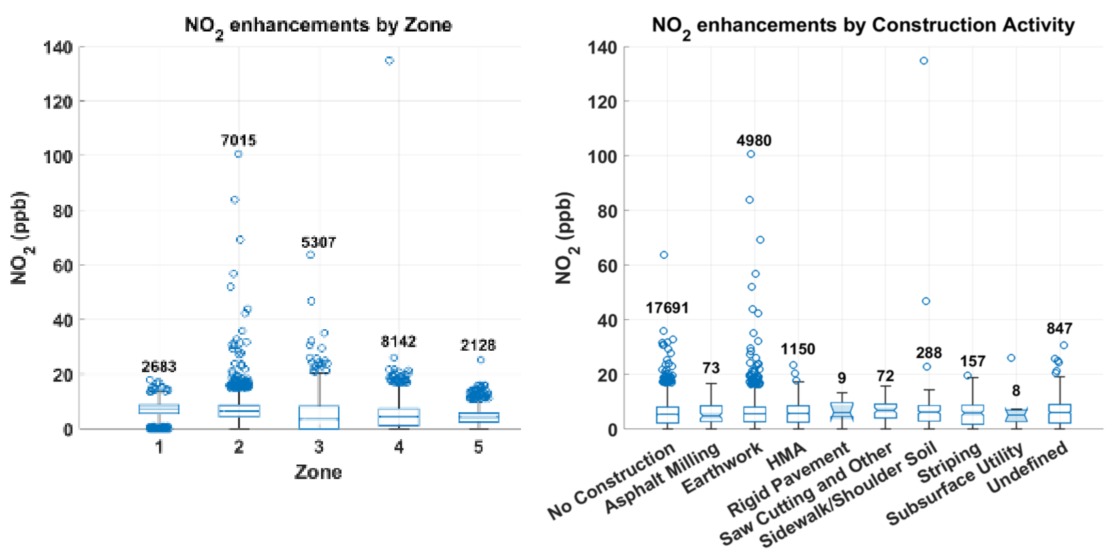


Figure 65. All NO2 Enhancements at US 40 by Zone (left) and Construction Activity (right)

B.2.3. US 40 NO_x Enhancements

Hourly averaged NO_x enhancements ranged from 0 to 184 ppb (Figure 66). Again, mean hourly NO_x measurement uncertainty was estimated to be 4.5 ppb. Median enhancements for each zone ranged from 0.5 ppb for zone 5 to 27.3 ppb for zone 1 (zone 2: 15.4 ppb, zone 3: 9.9 ppb and zone 4: 21.4 ppb. When grouped by construction activity, Rigid Pavement had the highest median enhancement at 34.4 ppb (but only has 9 observations) followed by HMA at 19.0 ppb. Notably, many outlier enhancements were associated with Earthwork, Sidewalk/Shoulder Soil and No Construction.

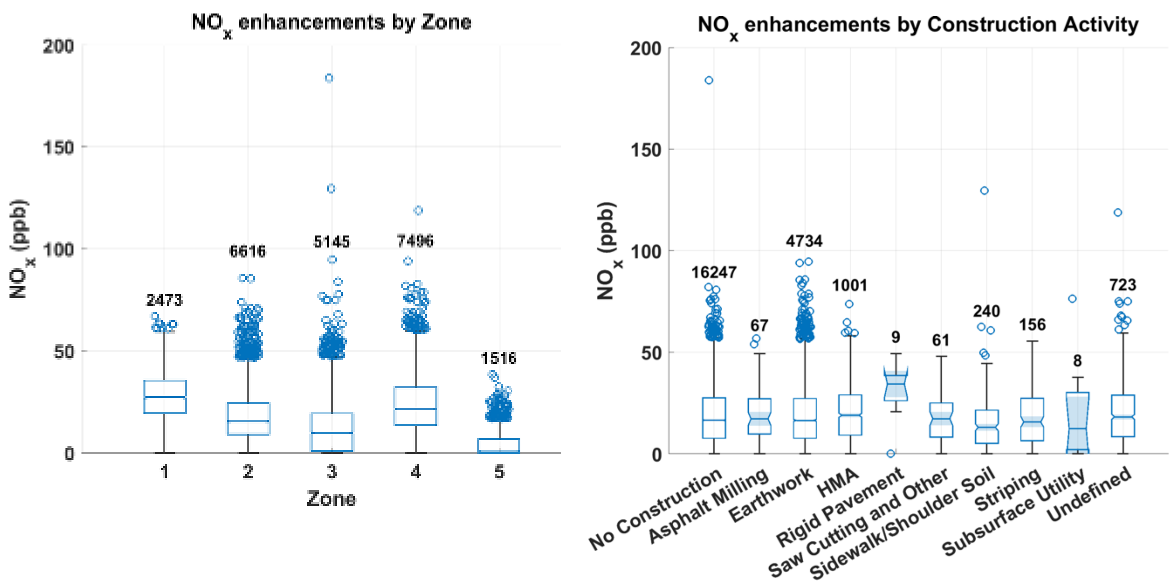


Figure 66. All NOx Enhancements at US 40 by Zone (left) and Construction Activity (right)

B.2.4. US 40 tVOC Enhancements

Hourly averaged tVOC enhancements ranged from 0 to 115 ppb (Figure 67). Again, mean hourly tVOC measurement uncertainty was estimated to be 9.2 ppb. Median enhancements for each zone ranged from 6.3 ppb for zone 5 to 12.3 ppb for zone 1 (zone 2: 6.4 ppb, zone 3: 6.5 ppb, zone 4: 7.4 ppb). When grouped by construction activity, HMA had the highest median enhancement at 8.7 ppb followed by Striping at 8.2 ppb. Notably, many outlier enhancements were associated with Earthwork, No Construction and Undefined.

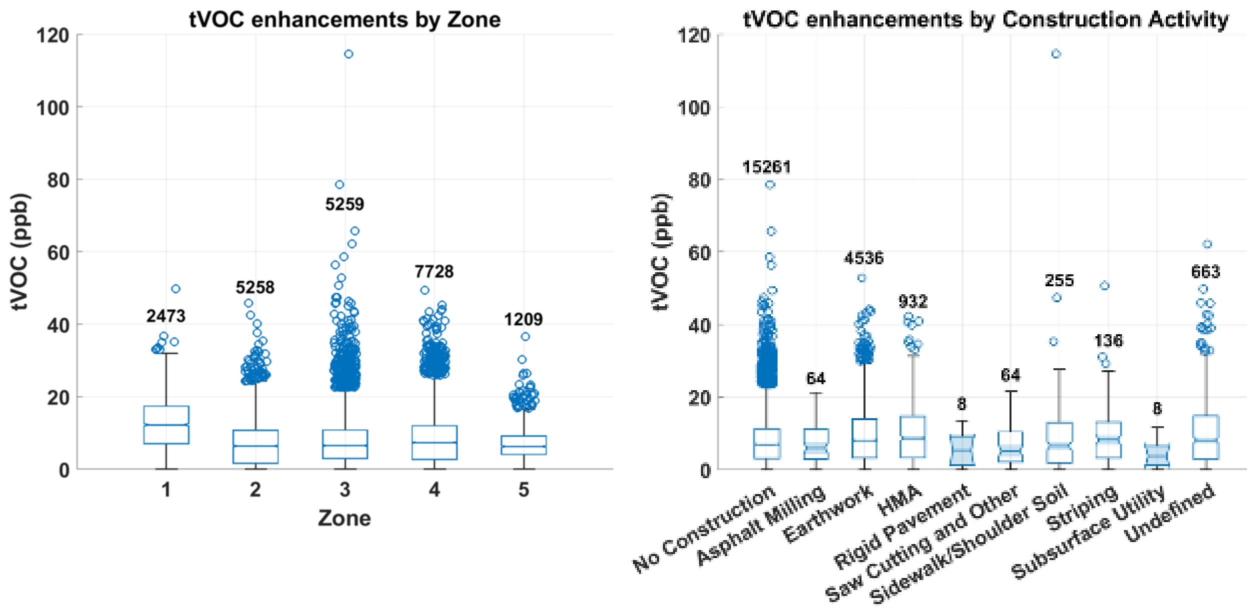


Figure 67. tVOC Enhancements at US 40 by Zone (left) and Construction Activity (right)

B.2.5. US 40 $PM_{2.5}$ Enhancements

Hourly averaged $PM_{2.5}$ enhancements ranged from 0 to 106 µg/m^3 (Figure 68). Again, mean hourly $PM_{2.5}$ measurement uncertainty was estimated to be 0.67 µg/m^3. Median enhancements for each zone ranged from 1.78 µg/m^3 for zone 3 to 3.75 µg/m^3 for zone 1 (zone 2: 2.15 µg/m^3 and zone 4: 3.18 µg/m^3. When grouped by construction activity, Saw Cutting and Other had the highest median enhancement at 2.78 µg/m^3 followed by Earthwork at 2.75 µg/m^3. Notably, many outlier enhancements were associated with Earthwork and No Construction.

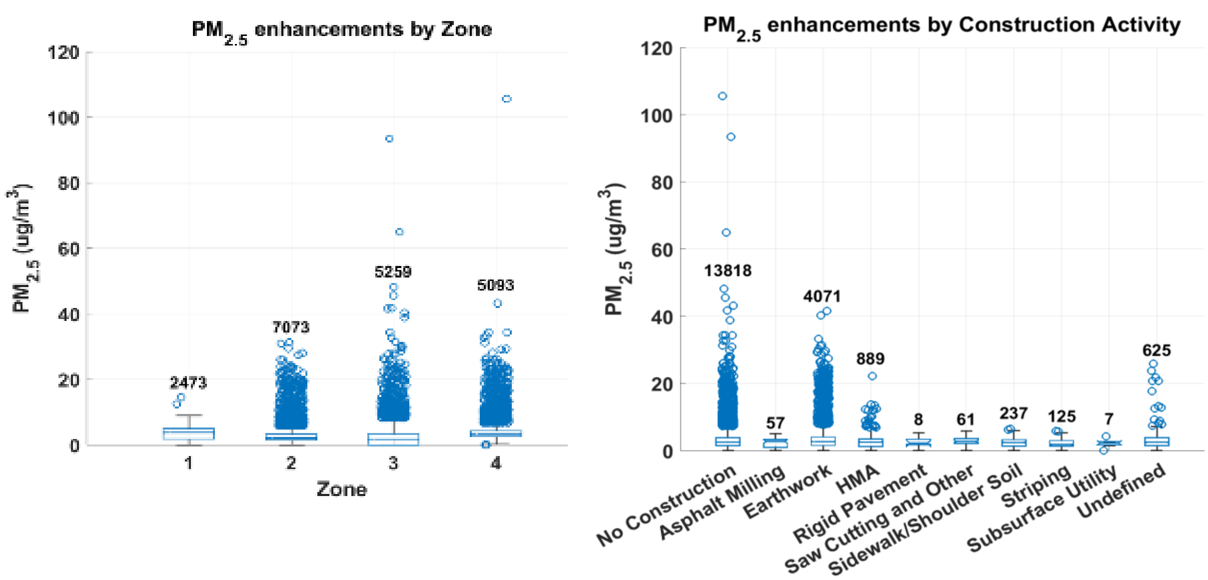


Figure 68. PM2.5 Enhancements at US 40 by Zone (left) and Construction Activity (right)

B.2.6. US 40 PM_{10} Enhancements

Hourly averaged $PM_{2.5}$ enhancements ranged from 0 to 688 µg/m^3 (Figure 69). Again, mean hourly PM_{10} measurement uncertainty was estimated to be 3.65 µg/m^3. Median enhancements for each zone ranged from 0 µg/m^3 for zone 4 to 2.75 µg/m^3 for zone 5 (zone 2: 0.98 µg/m^3 and zone 3: 1.58 µg/m^3. These data are highly skewed positive, so means are larger than medians. When grouped by construction activity, Earthwork had the highest median enhancement at 2.16 µg/m^3 followed by HMA at 1.90 µg/m^3. Notably, many outlier enhancements were associated with Earthwork, HMA, Sidewalk/Shoulder Soil, Undefined and No Construction.

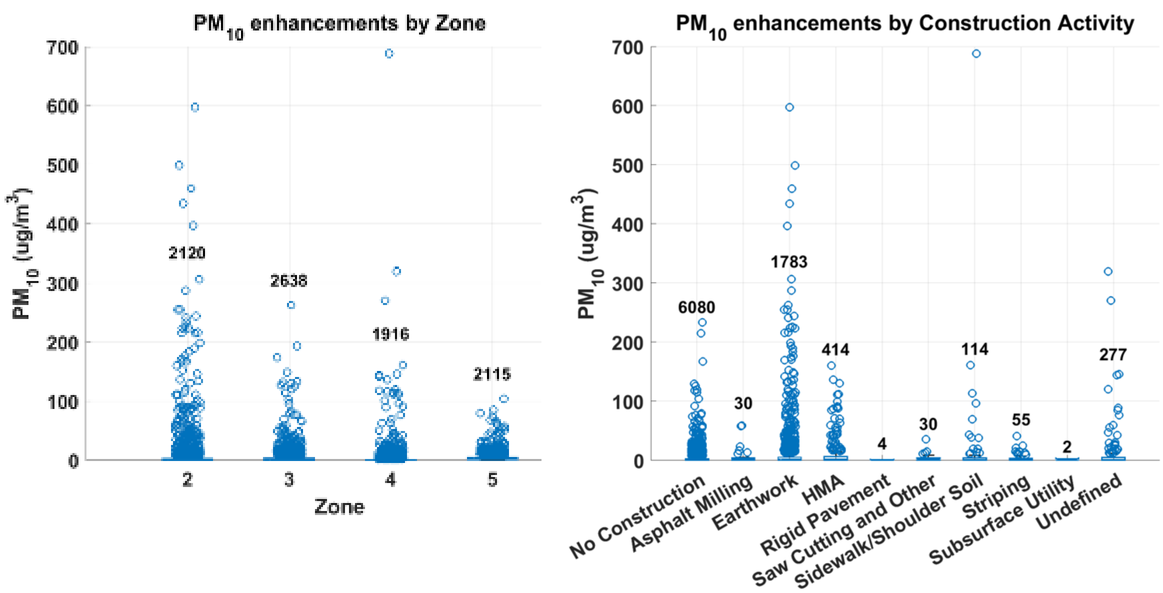


Figure 69. PM10 Enhancements at US 40 by Zone (left) and Construction Activity (right)

B.2.7. US 40 Coarse PM Enhancements

Hourly averaged $PM_{2.5}$ enhancements ranged from 0 to 560 µg/m^3 (Figure 70). Again, mean hourly coarse PM measurement uncertainty was estimated to be 2.92 µg/m^3. Median enhancements for each zone ranged from 0.31 µg/m^3 for zone 4 to 0.89 µg/m^3 for zone 5 (zone 2: 0.47 µg/m^3 and zone 3: 0.52 µg/m^3. These distributions are highly skewed positive, so means are larger than medians. When grouped by construction activity, Asphalt Milling had the highest median enhancement at 1.49 µg/m^3 followed by HMA at 1.20 µg/m^3. Notably, many outlier enhancements were associated with Earthwork, HMA, Sidewalk/Shoulder Soil, Undefined and No Construction.

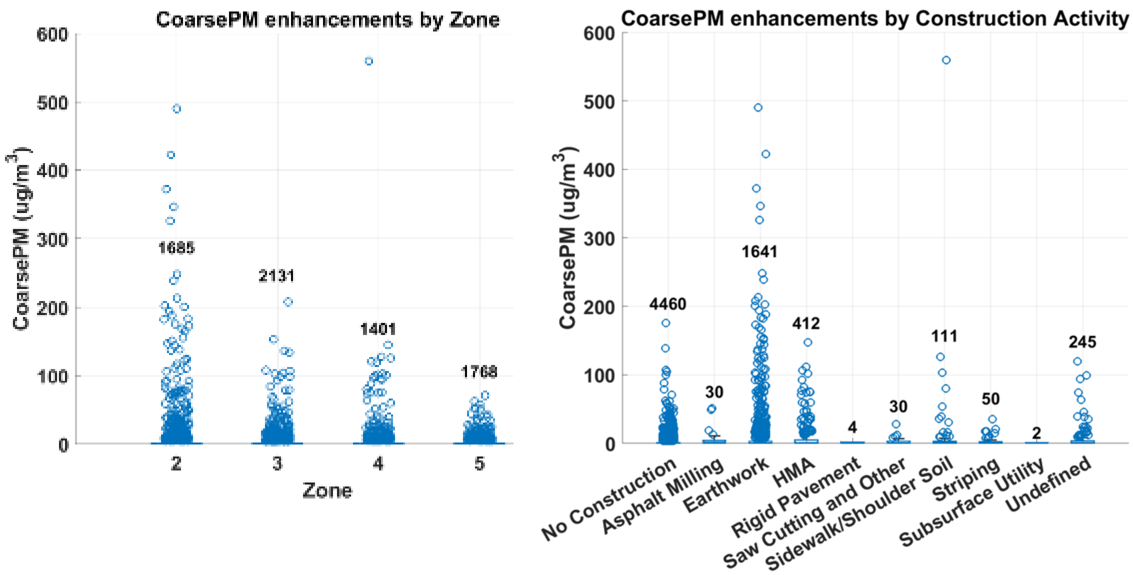


Figure 70. Coarse PM Enhancements at US 40 by Zone (left) and Construction Activity (right)

B.3. US6 Modeled Pollutant Enhancements

B.3.1. US 6 Modeled NO Enhancements

Model 1 estimated marginal mean NO enhancements grouped by construction activity and proximity to construction are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 71. The whiskers on each bar represent the 95% CI of the estimate. Hourly estimated mean enhancements by activity_dist ranged from about 11 ppb to 27 ppb. Again, there does appear to be a relationship between closer proximity and higher enhancements indicating a source attributable to the activities.

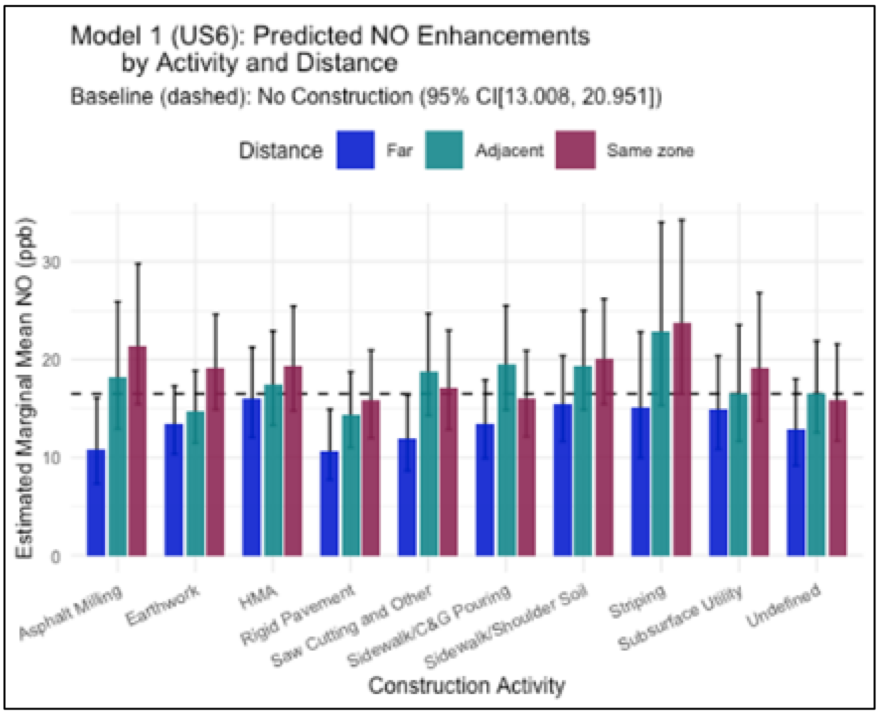


Figure 71. Model 1 (US 6), Estimated Marginal Mean NO Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 11 in addition to percent change and p-values. Ratios below 1 represent decreases relative to No Construction while ratios above 1 indicate increases. On average, Sidewalk/Shoulder Soil occurring in the same zone as the observation is associated with 22% higher enhancements than No Construction (p=0.04) and Earthwork in the same zone is associated with a 16% higher enhancement (p=0.05).

Table 11. Model 1 (NO_US6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	Lower CL	Upper CL	% Change	p-value
Striping_samezone / No Construction	1.44	0.92	2.24	43.91	0.20
Striping_adjacent / No Construction	1.38	0.83	2.29	38.19	0.54
Rigid Pavement_far / No Construction	0.65	0.45	0.93	-34.97	0.01
Asphalt Milling_far / No Construction	0.66	0.40	1.08	-34.22	0.17
Asphalt Milling_samezone / No Construction	1.30	0.90	1.86	29.80	0.37
Saw Cutting and Other_far / No Construction	0.72	0.51	1.01	-27.96	0.07
Undefined_far / No Construction	0.78	0.53	1.14	-22.11	0.50
Sidewalk/Shoulder Soil_samezone / No Construction	**1.22**	**1.01**	**1.47**	**21.80**	**0.04**
Sidewalk/C&G Pouring_far / No Construction	0.81	0.61	1.07	-19.20	0.31
Earthwork_far / No Construction	0.81	0.69	0.96	-18.81	0.00
Sidewalk/C&G Pouring_adjacent / No Construction	1.18	0.95	1.46	17.84	0.31
HMA_samezone / No Construction	1.17	0.94	1.47	17.41	0.39
Sidewalk/Shoulder Soil_adjacent / No Construction	1.17	0.98	1.39	16.78	0.13
Subsurface Utility_samezone / No Construction	1.16	0.80	1.69	16.16	0.94
Earthwork_samezone / No Construction	**1.16**	**1.00**	**1.34**	**15.95**	**0.05**
Saw Cutting and Other_adjacent / No Construction	1.14	0.91	1.43	13.77	0.68
Rigid Pavement_adjacent / No Construction	0.87	0.71	1.06	-12.89	0.43
Earthwork_adjacent / No Construction	0.89	0.78	1.02	-10.80	0.16
Asphalt Milling_adjacent / No Construction	1.11	0.74	1.66	10.78	1.00
Subsurface Utility_far / No Construction	0.90	0.65	1.25	-9.75	0.98
Striping_far / No Construction	0.91	0.54	1.56	-8.63	1.00
Sidewalk/Shoulder Soil_far / No Construction	0.93	0.74	1.18	-6.60	0.99
HMA_adjacent / No Construction	1.06	0.85	1.31	5.66	1.00
Saw Cutting and Other_samezone / No Construction	1.04	0.80	1.36	4.05	1.00
Rigid Pavement_samezone / No Construction	0.96	0.76	1.22	-3.98	1.00
Undefined_samezone / No Construction	0.96	0.71	1.31	-3.77	1.00
Sidewalk/C&G Pouring_samezone / No Construction	0.96	0.78	1.20	-3.53	1.00
HMA_far / No Construction	0.97	0.75	1.25	-3.08	1.00
Subsurface Utility_adjacent / No Construction	1.00	0.67	1.51	0.43	1.00
Undefined_adjacent / No Construction	1.00	0.80	1.27	0.40	1.00

Note: Activity-distance categories with ratios significantly ($p \leq 0.05$) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the difference in estimated marginal mean enhancements by zone for the various construction activities performed at the site. Mean hourly estimated enhancements by construction activity and zone ranged from 5 to 29 ppb. Again, Figure 72. shows the clear trend in increased enhancements in zones 1 and 2, the most popular zones for active construction. Zone 5 and zone 3 were furthest from construction and have lower estimates indicating spatial differences, yet, relative to No Construction, the differences within zone are less pronounced. High traffic volumes on I-70 business loop could be impacting the overall spatial gradient of NO as zone 1 encompasses a stretch of that interstate, zone 2 is adjacent and zones 3 and 5 are furthest.

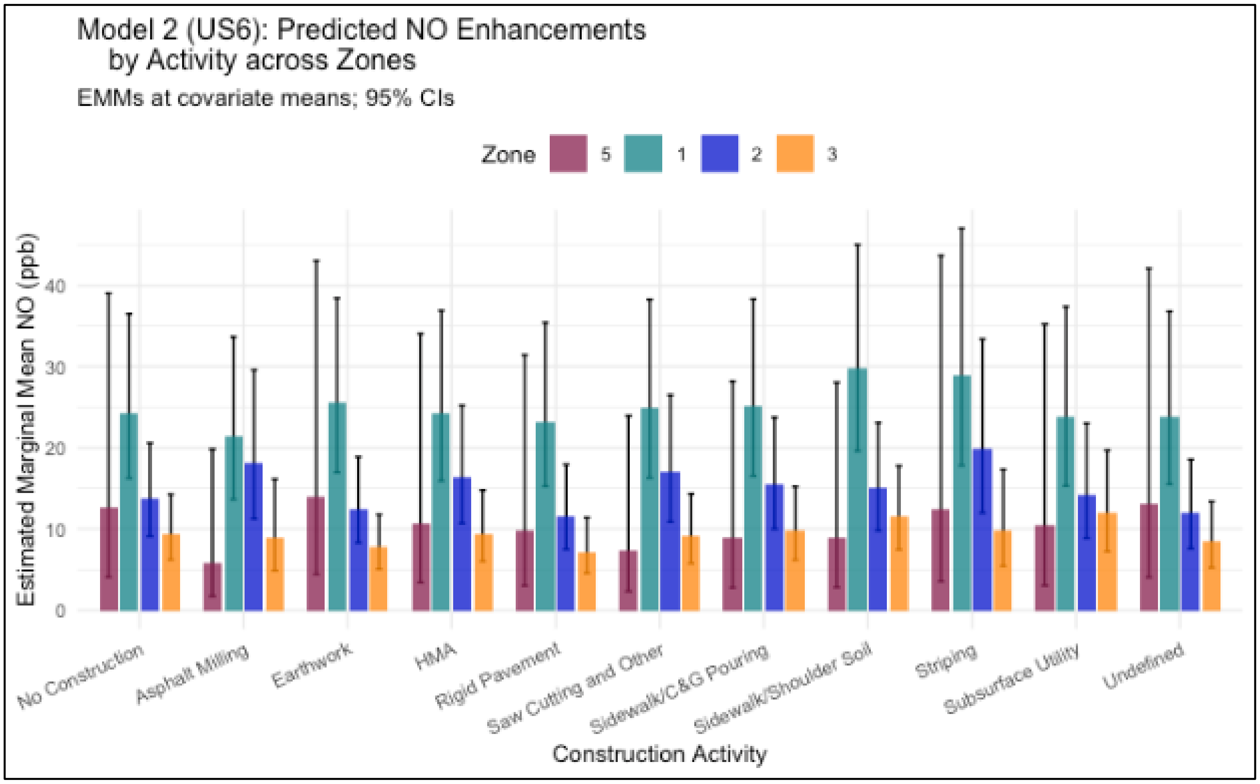
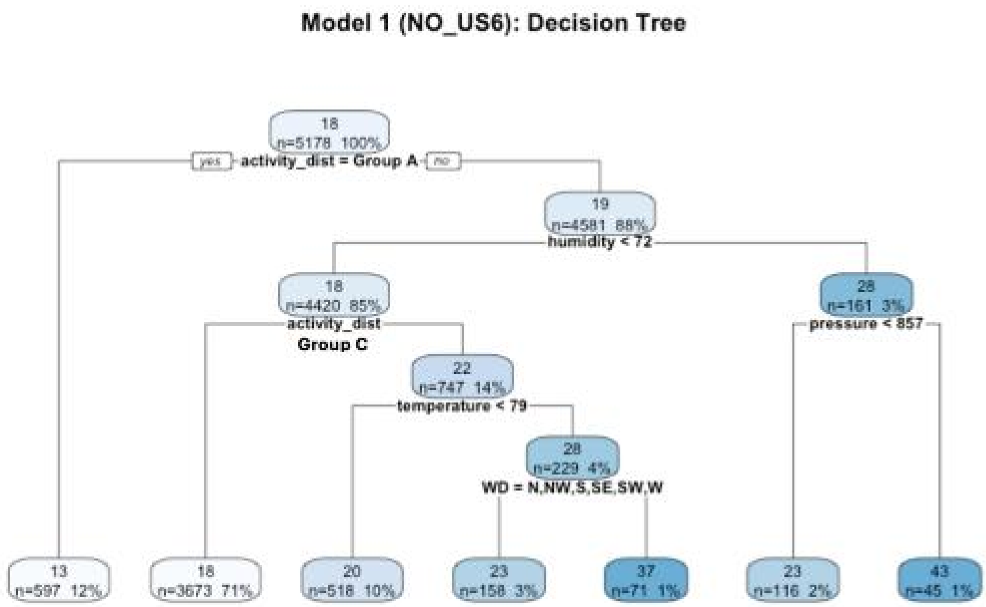


Figure 72. Model 2 (US 6), Estimated Marginal Mean NO Enhancements by Activity Across Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 73. Here the criteria used to most efficiently split observed enhancements into 7 bins was first determined by activity_dist, then humidity, pressure, temperature, and wind direction. The path to the largest enhancements was activity_dist from group B (19 ppb), high humidity (>72% RH, 28 ppb) and higher pressure (>857 millibar) resulting in mean estimated enhancements of 43 ppb. The path to the lowest enhancements was activity_dist categories in group A (which were all far from any construction).



Group A
"Asphalt Milling_far"
"Earthwork_far"
"Rigid Pavement_far"
"Saw Cutting and Other_far"
"Sidewalk/C&G Pouring_far"
"Sidewalk/Shoulder Soil_far"
"Subsurface Utility_far"
"Undefined_far"

Group B
"Asphalt Milling_adjacent"
"Asphalt Milling_samezone"
"Earthwork_adjacent"
"Earthwork_samezone"
"HMA_adjacent"
"HMA_far"
"HMA_samezone"
"No Construction"
"Rigid Pavement_adjacent"
"Rigid Pavement_samezone"
"Saw Cutting and Other_adjacent"
"Saw Cutting and Other_samezone"
"Sidewalk/C&G Pouring_adjacent"
"Sidewalk/C&G Pouring_samezone"
"Sidewalk/Shoulder Soil_adjacent"
"Sidewalk/Shoulder Soil_samezone"
"Striping_adjacent"
"Striping_far"
"Striping_samezone"
"Subsurface Utility_adjacent"
"Subsurface Utility_samezone"
"Undefined_adjacent"
"Undefined_samezone"

Group C
"Asphalt Milling_adjacent"
"Asphalt Milling_samezone"
"Earthwork_adjacent"
"Earthwork_samezone"
"HMA_adjacent"
"HMA_far"
"HMA_samezone"
"No Construction"
"Rigid Pavement_adjacent"
"Rigid Pavement_samezone"
"Saw Cutting and Other_adjacent"
"Saw Cutting and Other_samezone"
"Sidewalk/C&G Pouring_adjacent"
"Sidewalk/C&G Pouring_samezone"
"Sidewalk/Shoulder Soil_adjacent"
"Sidewalk/Shoulder Soil_samezone"
"Striping_adjacent"
"Striping_far"
"Striping_samezone"
"Subsurface Utility_adjacent"
"Subsurface Utility_samezone"
"Undefined_adjacent"
"Undefined_samezone"

Figure 73. Model 1 (NO US6), Decision Tree

The random forest of Model 1 (Figure 74) ranks temperature followed by humidity and pressure as the most important variables in reducing overall model error.

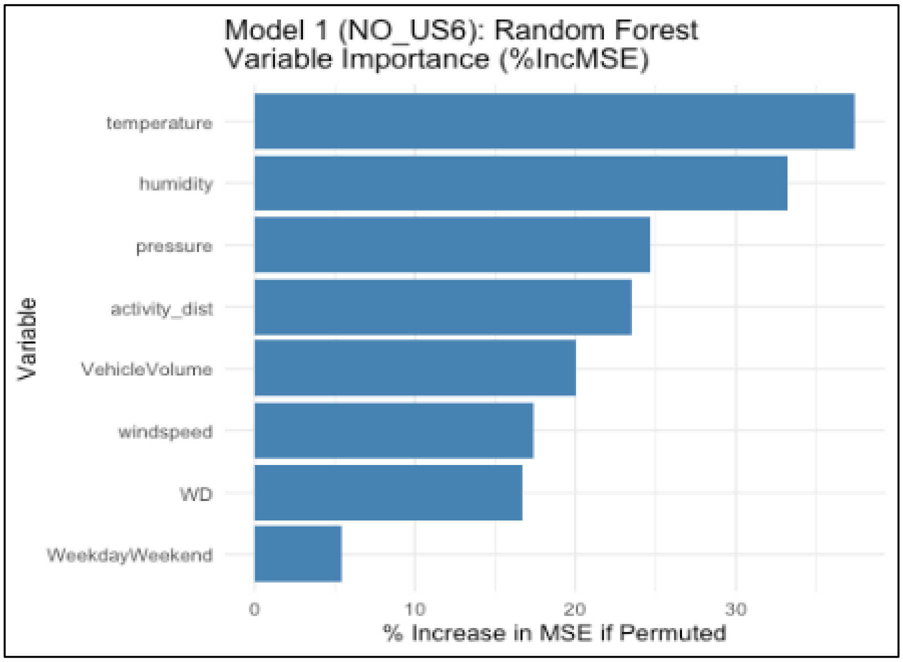


Figure 74. Model 1 (NO US 6) Random Forest Variable Importance (%IncMSE)

B.3.2. US 6 Modeled NO_2 Enhancements

Model 1estimated marginal mean NO_2 enhancements grouped by construction activity and proximity to construction are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 75. The whiskers on each bar represent the 95% CI of the estimate. Hourly estimated mean enhancements by activity_dist ranged from about 3 ppb to 7.5 ppb. Again, there does appear to be a relationship between closer proximity and higher enhancements indicating a source attributable to the activities.

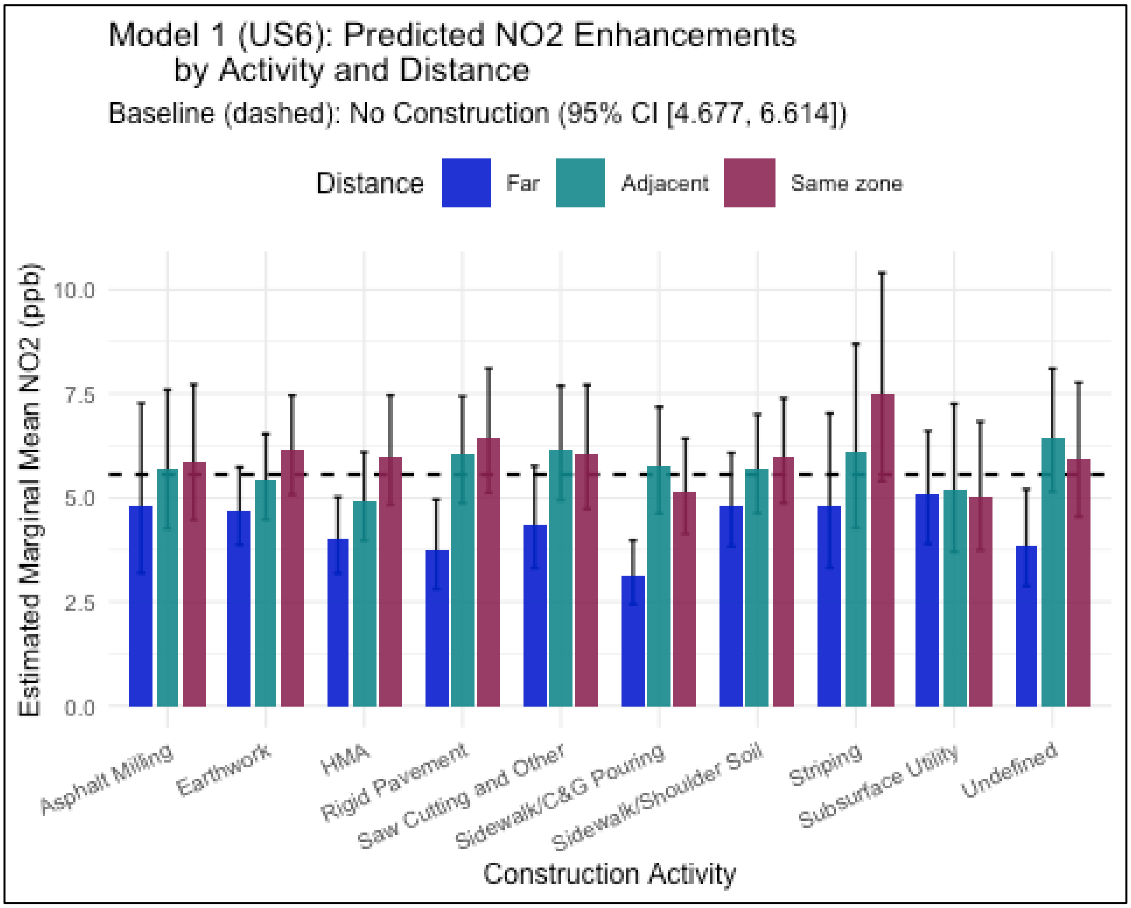


Figure 75. Model 1 (US 6), Estimated Marginal Mean NO_2 Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 12. in addition to percent change and p-values. Ratios below 1 represent decreases relative to No Construction while ratios above 1 indicate increases. Some activity_dist categories which happened “far” from activities were significantly lower than No Construction, but other categories were no different.

Table 12. Model 1 (NO2_US6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	LowerCL	UpperCL	% Change	p-value
Sidewalk/C&G Pouring_far / No Construction	0.56	0.42	0.74	-44.00	0.00
Striping_samezone / No Construction	1.35	0.87	2.10	34.86	0.46
Rigid Pavement_far / No Construction	0.67	0.47	0.96	-32.86	0.02
Undefined_far / No Construction	0.70	0.48	1.02	-30.35	0.08
HMA_far / No Construction	0.72	0.56	0.92	-28.11	0.00
Saw Cutting and Other_far / No Construction	0.79	0.56	1.11	-21.38	0.42
Undefined_adjacent / No Construction	1.16	0.91	1.48	16.09	0.58
Rigid Pavement_samezone / No Construction	1.16	0.90	1.49	15.84	0.65
Earthwork_far / No Construction	0.85	0.72	1.00	-15.24	0.04
Asphalt Milling_far / No Construction	0.87	0.48	1.56	-13.33	1.00
Sidewalk/Shoulder Soil_far / No Construction	0.87	0.68	1.11	-13.27	0.67
Striping_far / No Construction	0.87	0.51	1.47	-13.19	0.99
HMA_adjacent / No Construction	0.89	0.72	1.09	-11.48	0.68
Saw Cutting and Other_adjacent / No Construction	1.11	0.88	1.39	10.85	0.88
Earthwork_samezone / No Construction	1.11	0.95	1.29	10.69	0.47
Striping_adjacent / No Construction	1.10	0.67	1.79	9.65	1.00
Subsurface Utility_samezone / No Construction	0.91	0.61	1.34	-9.11	1.00
Subsurface Utility_far / No Construction	0.91	0.66	1.26	-8.81	0.99
Saw Cutting and Other_samezone / No Construction	1.09	0.82	1.43	8.62	0.99
Rigid Pavement_adjacent / No Construction	1.08	0.88	1.33	8.25	0.95
HMA_samezone / No Construction	1.08	0.86	1.35	8.01	0.97
Sidewalk/Shoulder Soil_samezone / No Construction	1.08	0.89	1.31	7.94	0.94
Sidewalk/C&G Pouring_samezone / No Construction	0.93	0.74	1.16	-7.36	0.97
Undefined_samezone / No Construction	1.07	0.77	1.48	6.86	1.00
Subsurface Utility_adjacent / No Construction	0.93	0.59	1.47	-6.83	1.00
Asphalt Milling_samezone / No Construction	1.06	0.75	1.48	5.63	1.00
Sidewalk/C&G Pouring_adjacent / No Construction	1.04	0.83	1.30	3.57	1.00
Earthwork_adjacent / No Construction	0.97	0.85	1.12	-2.75	1.00
Sidewalk/Shoulder Soil_adjacent / No Construction	1.02	0.85	1.23	2.36	1.00
Asphalt Milling_adjacent / No Construction	1.02	0.71	1.48	2.30	1.00

Results from Model 2 illustrate the difference in estimated marginal mean enhancements by zone for the various construction activities performed at the site. Mean hourly estimated enhancements by construction activity and zone ranged from 1.8 to 7.5 ppb. Again, Figure 76. shows the clear trend in increased enhancements in zones 1 and 2, the most popular zones for active construction. Zone 5 and zone 3 were furthest from construction and have lower estimates indicating spatial differences, yet, relative to No Construction, the differences within zone are less pronounced. Similar to NO results, the nearby interstate may be contributing to the spatial gradient of enhancements seen across zones after accounting for construction activity.

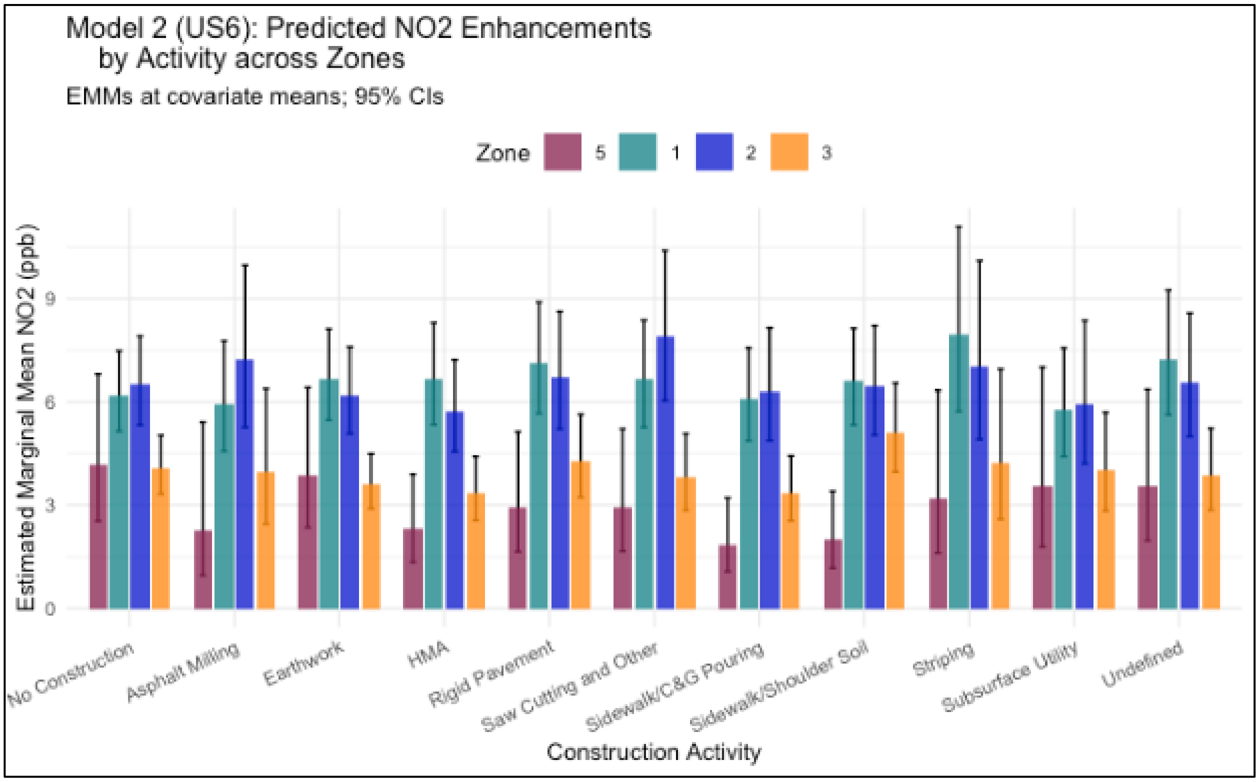


Figure 76. Model 2 (US 6), Estimated Marginal Mean NO_2 Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 77. Here the criteria used to most efficiently split observed enhancements into 5 bins was first determined by temperature, then humidity, activity_dist and pressure. The path to the largest enhancements (13 ppb) was cooler weather (<72F), higher humidity (>67% RH) and higher pressure (>857 millibar). The path to the lowest enhancements (3.9 ppb) was cooler weather (<72F), drier conditions (<67% RH), and activity_dist categories in group A (many of which were far from or adjacent to any construction).

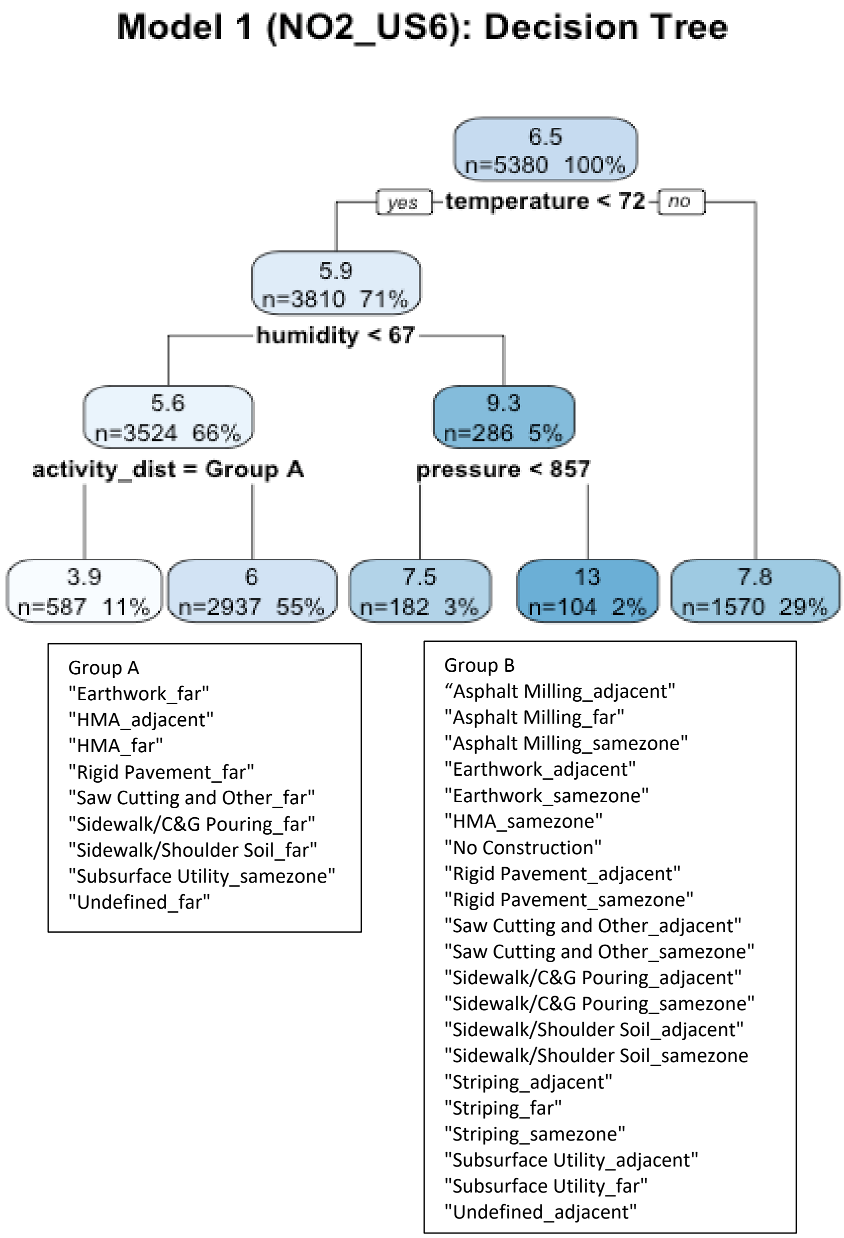


Figure 77. Model 1 (NO2 US 6) Decision Tree

The random forest of Model 1 ranks pressure, followed by temperature, humidity and activity_dist as the most important variables in reducing overall model error (Figure 78.).

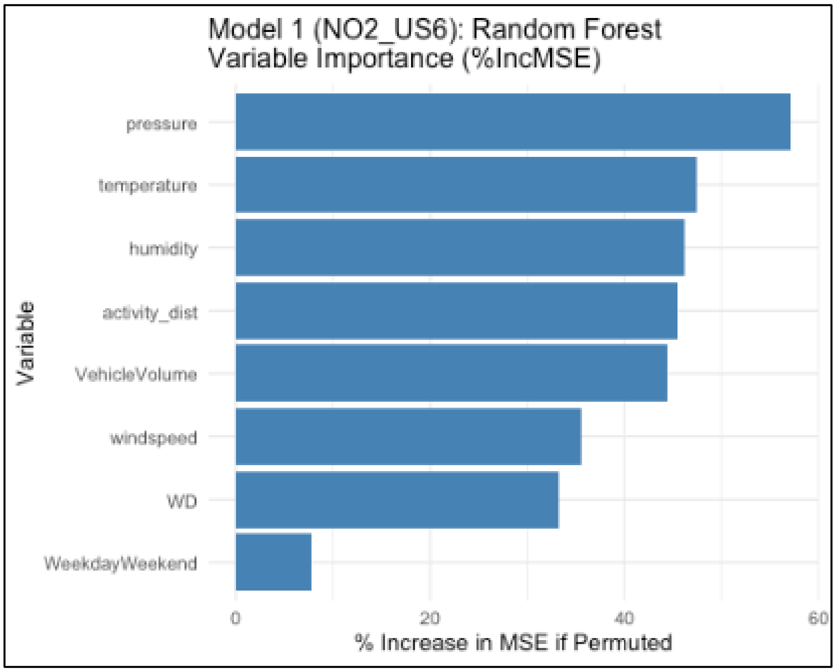


Figure 78. Model 1 (NO_2 US 6) Random Forest Variable Importance (%IncMSE)

B.3.3. US 6 Modeled NO_x Enhancements

Model 1 estimated marginal mean NO_x enhancements grouped by construction activity and proximity to construction are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 79. The whiskers on each bar represent the 95% CI of the estimate. Hourly estimated mean enhancements by activity_dist ranged from about 15 ppb to 28 ppb. Again, there does appear to be a relationship between closer proximity and higher enhancements indicating a source attributable to the activities.

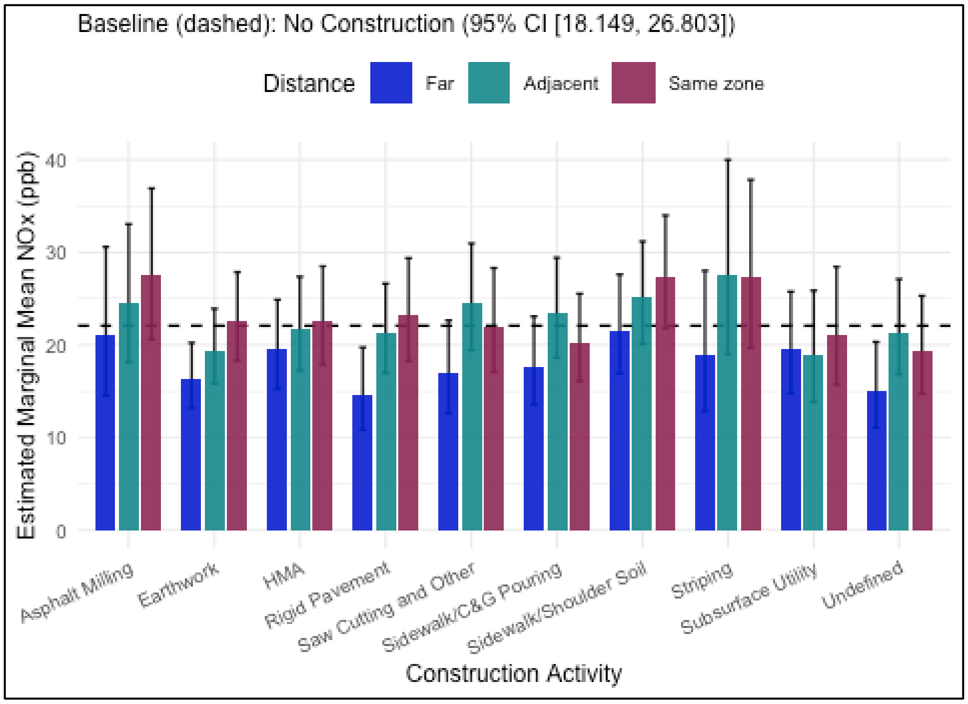


Figure 79. Model 1 (US 6), Estimated Marginal Mean NO_x Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone the activity was occurring in. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 13. in addition to percent change and p-values. Ratios below 1 represent decreases relative to No Construction while ratios above 1 indicate increases. Modeled enhancements in the same zone as Sidewalk/Shoulder Soil work were 23% higher than No Construction (p=0.01). Some activity_dist categories which happened “far” from activities were significantly lower than No Construction.

Table 13. Model 1 (NO_x US 6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	LowerCL	UpperCL	% Change	p-value
Rigid Pavement_far / No Construction	0.66	0.46	0.95	-33.68	0.01
Undefined_far / No Construction	0.68	0.47	0.98	-32.05	0.03
Earthwork_far / No Construction	0.74	0.63	0.86	-26.04	0.00
Asphalt Milling_samezone / No Construction	1.25	0.88	1.77	24.92	0.54
Striping_adjacent / No Construction	1.25	0.76	2.06	24.88	0.89
Striping_samezone / No Construction	1.24	0.81	1.88	23.64	0.80
Saw Cutting and Other_far / No Construction	0.77	0.54	1.08	-23.42	0.29
Sidewalk/Shoulder Soil_samezone / No Construction	**1.23**	**1.03**	**1.48**	**23.37**	**0.01**
Sidewalk/C&G Pouring_far / No Construction	0.80	0.60	1.07	-19.86	0.30
Subsurface Utility_adjacent / No Construction	0.86	0.58	1.27	-14.26	0.94
Striping_far / No Construction	0.86	0.51	1.46	-14.00	0.99
Sidewalk/Shoulder Soil_adjacent / No Construction	1.14	0.96	1.34	13.55	0.31
Undefined_samezone / No Construction	0.88	0.65	1.18	-12.45	0.89
Earthwork_adjacent / No Construction	0.88	0.78	1.00	-11.87	0.05
HMA_far / No Construction	0.88	0.69	1.12	-11.68	0.79
Subsurface Utility_far / No Construction	0.88	0.64	1.22	-11.59	0.95
Saw Cutting and Other_adjacent / No Construction	1.11	0.90	1.38	11.18	0.82
Asphalt Milling_adjacent / No Construction	1.11	0.77	1.60	10.90	0.99
Sidewalk/C&G Pouring_samezone / No Construction	0.92	0.75	1.13	-8.18	0.92
Sidewalk/C&G Pouring_adjacent / No Construction	1.06	0.86	1.30	6.06	0.99
Rigid Pavement_samezone / No Construction	1.05	0.83	1.32	4.95	1.00
Asphalt Milling_far / No Construction	0.96	0.58	1.58	-4.38	1.00
Subsurface Utility_samezone / No Construction	0.96	0.67	1.37	-4.21	1.00
Rigid Pavement_adjacent / No Construction	0.96	0.79	1.17	-3.70	1.00
Undefined_adjacent / No Construction	0.97	0.77	1.21	-3.23	1.00
Earthwork_samezone / No Construction	1.02	0.89	1.18	2.33	1.00
HMA_samezone / No Construction	1.02	0.82	1.27	2.26	1.00
Sidewalk/Shoulder Soil_far / No Construction	0.98	0.77	1.24	-2.10	1.00
HMA_adjacent / No Construction	0.98	0.80	1.21	-1.66	1.00
Saw Cutting and Other_samezone / No Construction	1.00	0.77	1.29	-0.37	1.00

Note: Activity-distance categories with ratios significantly ($p \leq 0.05$) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the difference in estimated marginal mean enhancements by zone for the various construction activities performed at the site. Mean hourly estimated enhancements by construction activity and zone ranged from 8 to 34 ppb. Again, Figure 80. shows the clear trend in increased enhancements in zones 1 and 2, the most popular zones for active construction. Zone 5 and zone 3 were furthest from construction and have lower estimates indicating spatial differences, yet, relative to No Construction, the differences within zone are less pronounced.

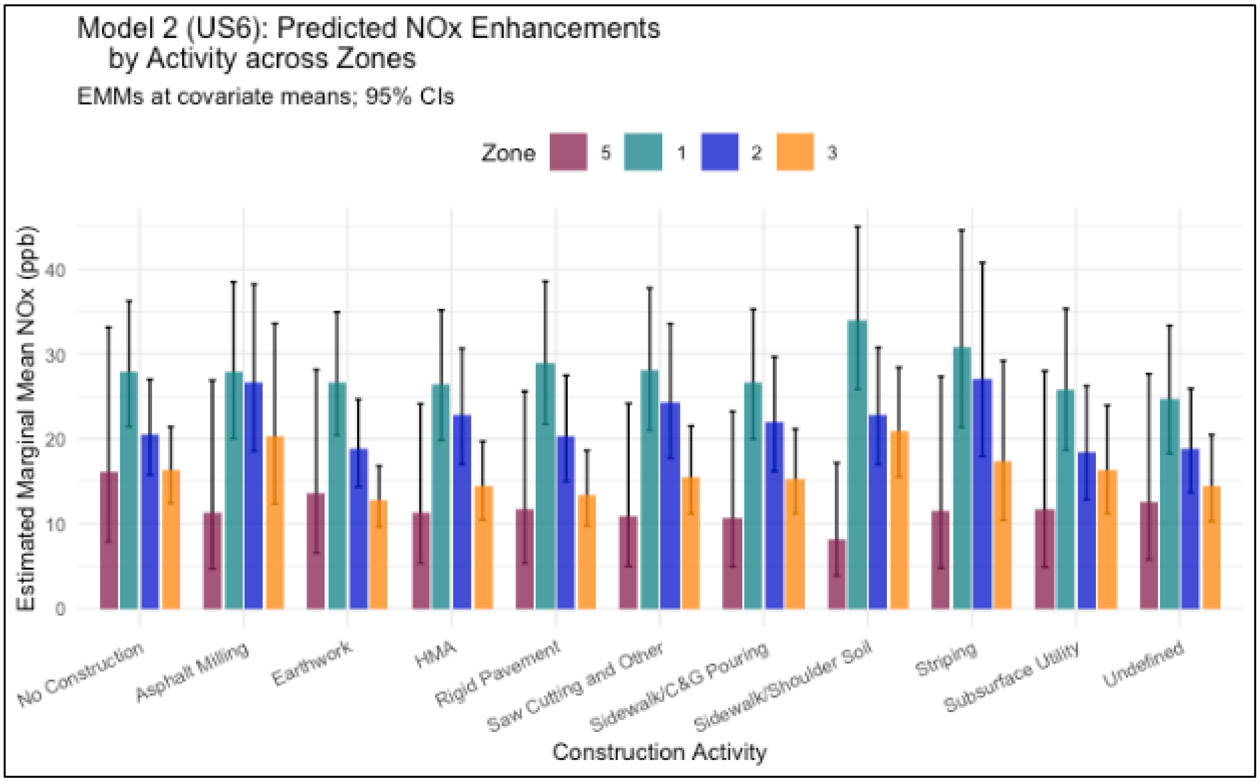


Figure 80. Model 2 (US 6), Estimated Marginal Mean NO_x Enhancements by Activity and zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 81. Similar to NO and NO_2, the criteria used to most efficiently split observed enhancements into 5 bins was first determined by temperature, then humidity and pressure and then activity_dist. The path to the largest enhancements (34 ppb) was cooler weather (<71F) and higher humidity (>72% RH). The path to the lowest enhancements (14 ppb) was cooler (<71F) and drier (<72% RH) weather, and activity_dist categories in group A (all of which were far from any construction).

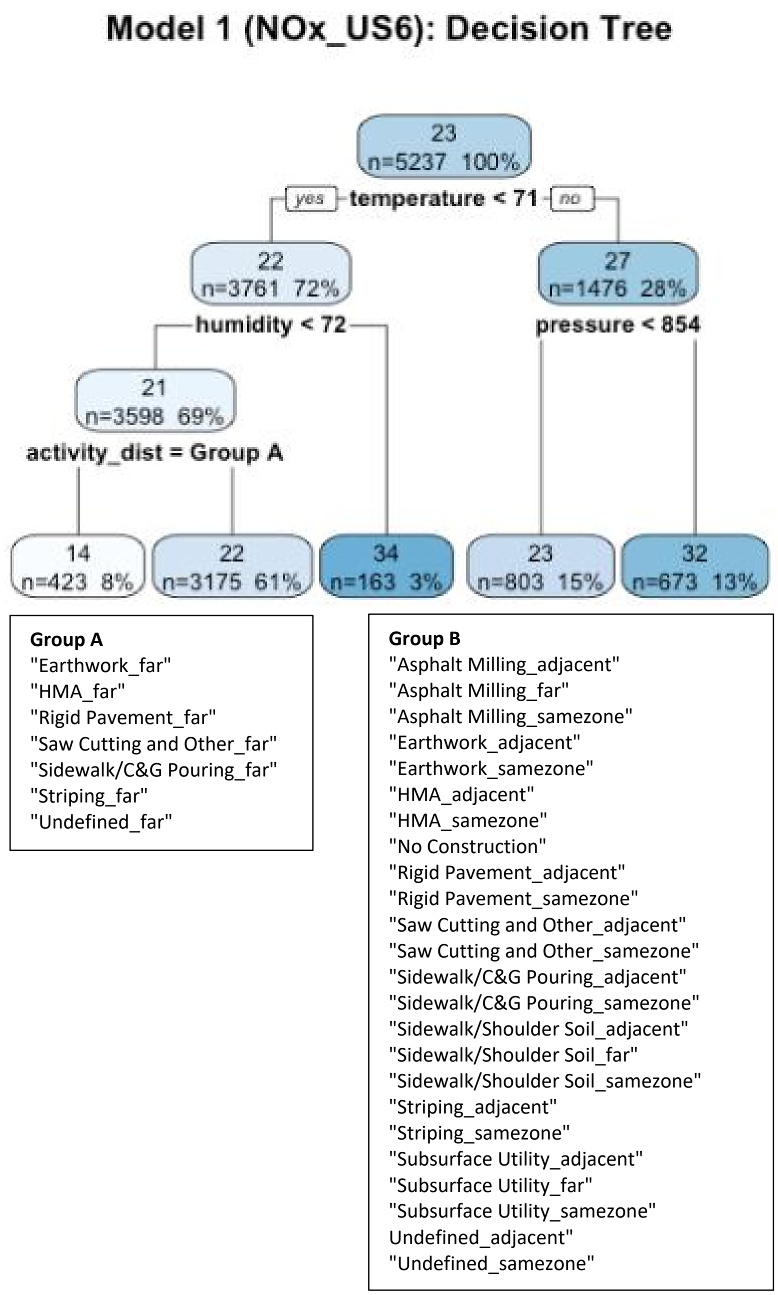


Figure 81. Model 1 (NOx US 6), Decision Tree

The random forest of Model 1 ranks pressure, followed by temperature and vehicle volume as the most important variables in reducing overall model error (Figure 82).

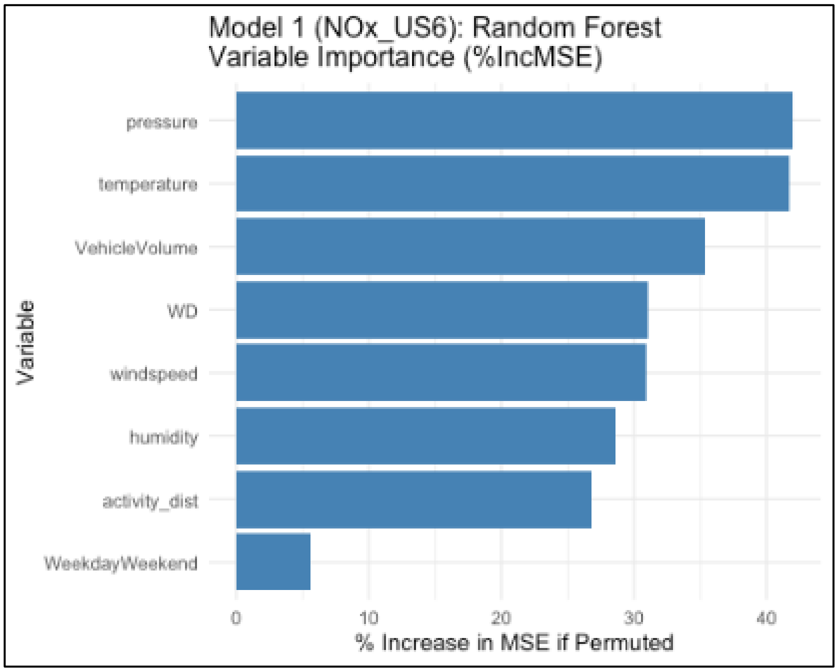


Figure 82. Model 1 (No_x US 6), Random Forest Variable Importance (%IncMSE)

B.3.4. US 6 Modeled tVOC Enhancements

Model 1 estimated marginal mean tVOC enhancements grouped by construction activity and proximity to construction are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 83. The whiskers on each bar represent the 95% CI of the estimate. Hourly estimated mean enhancements by activity_dist ranged from about 12 ppb to 23 ppb. Asphalt Milling and Striping stand out as having increased enhancements relative to No Construction. The trend of larger enhancements with closer proximity to activity is less clear for some activities than others.

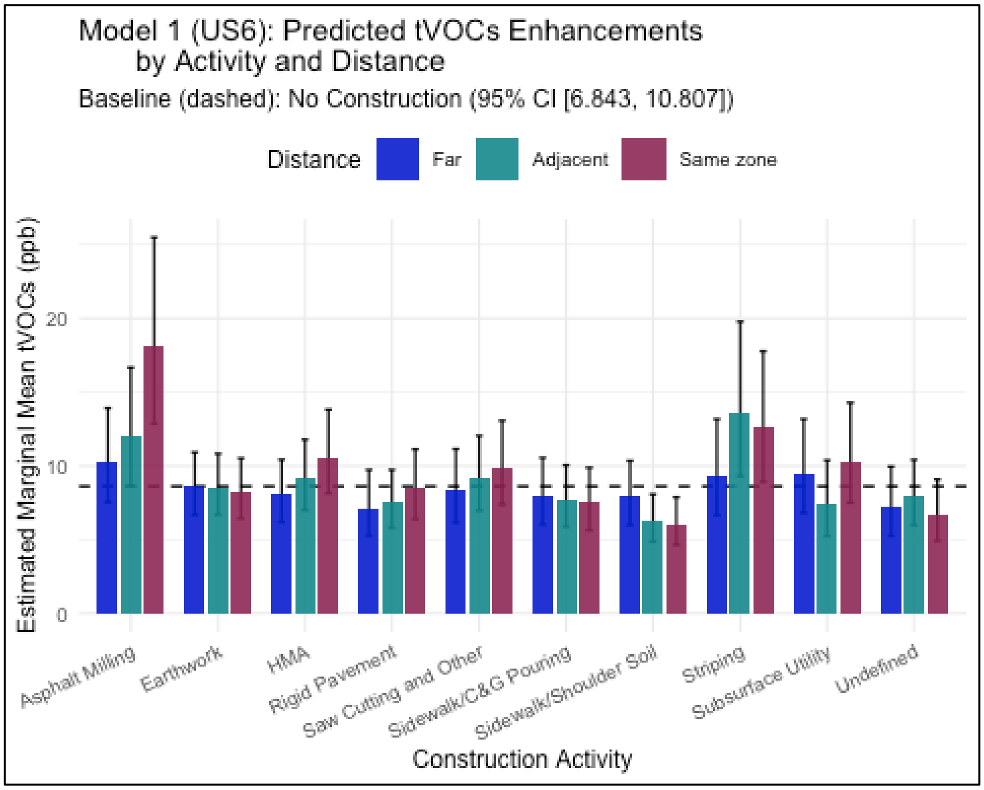


Figure 83. Module 1 (US 6), Estimated Marginal Mean tVOC Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 14. in addition to percent change and p-values. Ratios below 1 represent decreases relative to No Construction while ratios above 1 indicate increases. Asphalt Milling in the same zone as measurements had 110% higher enhancements relative to No Construction. Some activity_dist categories which happened "far" from activities were significantly lower than No Construction and many others were no different.

Table 14. Model 1 (tVOCs US 6): Pairwise Contrasts: Effect sizes, CIs, % Change, and p-values

Contrast	Effect	Lower CL	Upper CL	% Change	p-value
Asphalt Milling_samezone / No Construction	**2.10**	**1.40**	**3.16**	**110.34**	**0.00**
Striping_adjacent / No Construction	1.58	0.98	2.54	57.58	0.08
Striping_samezone / No Construction	1.46	0.97	2.20	46.19	0.09
Asphalt Milling_adjacent / No Construction	1.40	0.96	2.04	39.62	0.13
Sidewalk/Shoulder Soil_samezone / No Construction	0.70	0.57	0.87	-29.89	0.00
Sidewalk/Shoulder Soil_adjacent / No Construction	0.73	0.61	0.87	-27.35	0.00
HMA_samezone / No Construction	1.23	0.98	1.54	23.10	0.10
Undefined_samezone / No Construction	0.78	0.56	1.07	-22.49	0.27
Subsurface Utility_samezone / No Construction	1.20	0.83	1.74	19.95	0.83
Asphalt Milling_far / No Construction	1.19	0.85	1.66	18.84	0.79
Rigid Pavement_far / No Construction	0.83	0.59	1.16	-16.85	0.72
Undefined_far / No Construction	0.84	0.59	1.20	-16.03	0.84
Subsurface Utility_adjacent / No Construction	0.86	0.57	1.29	-14.31	0.95
Saw Cutting and Other_samezone / No Construction	1.14	0.87	1.50	14.01	0.85
Sidewalk/C&G Pouring_samezone / No Construction	0.87	0.67	1.13	-13.18	0.75
Rigid Pavement_adjacent / No Construction	0.87	0.71	1.07	-12.64	0.51
Sidewalk/C&G Pouring_adjacent / No Construction	0.89	0.71	1.13	-10.61	0.83
Subsurface Utility_far / No Construction	1.10	0.76	1.60	10.22	1.00
Striping_far / No Construction	1.09	0.73	1.63	8.88	1.00
Sidewalk/Shoulder Soil_far / No Construction	0.92	0.72	1.17	-8.43	0.96
Undefined_adjacent / No Construction	0.92	0.71	1.18	-8.19	0.98
Sidewalk/C&G Pouring_far / No Construction	0.93	0.71	1.21	-7.18	0.99
Saw Cutting and Other_adjacent / No Construction	1.07	0.84	1.37	6.84	0.99
HMA_far / No Construction	0.94	0.76	1.16	-6.46	0.98
HMA_adjacent / No Construction	1.06	0.86	1.31	5.88	0.99
Earthwork_samezone / No Construction	0.96	0.81	1.13	-4.30	0.99
Saw Cutting and Other_far / No Construction	0.96	0.71	1.31	-3.51	1.00
Rigid Pavement_samezone / No Construction	0.98	0.76	1.28	-1.83	1.00
Earthwork_adjacent / No Construction	0.99	0.86	1.14	-0.86	1.00
Earthwork_far / No Construction	0.99	0.85	1.17	-0.55	1.00

Activity-distance categories with ratios significantly ($p \leq 0.05$) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the difference in estimated marginal mean enhancements by zone for the various construction activities performed at the site. Mean hourly estimated enhancements by construction activity and zone ranged from 7 to 24 ppb. Relative to other pollutants, the spatial differences in tVOC enhancements are not as correlated to zone Figure 84. Zones 5 and zone 3 were furthest from construction and are often associated with some of the highest mean estimates. Significant deviations from this trend are associated with Asphalt Milling and Striping.

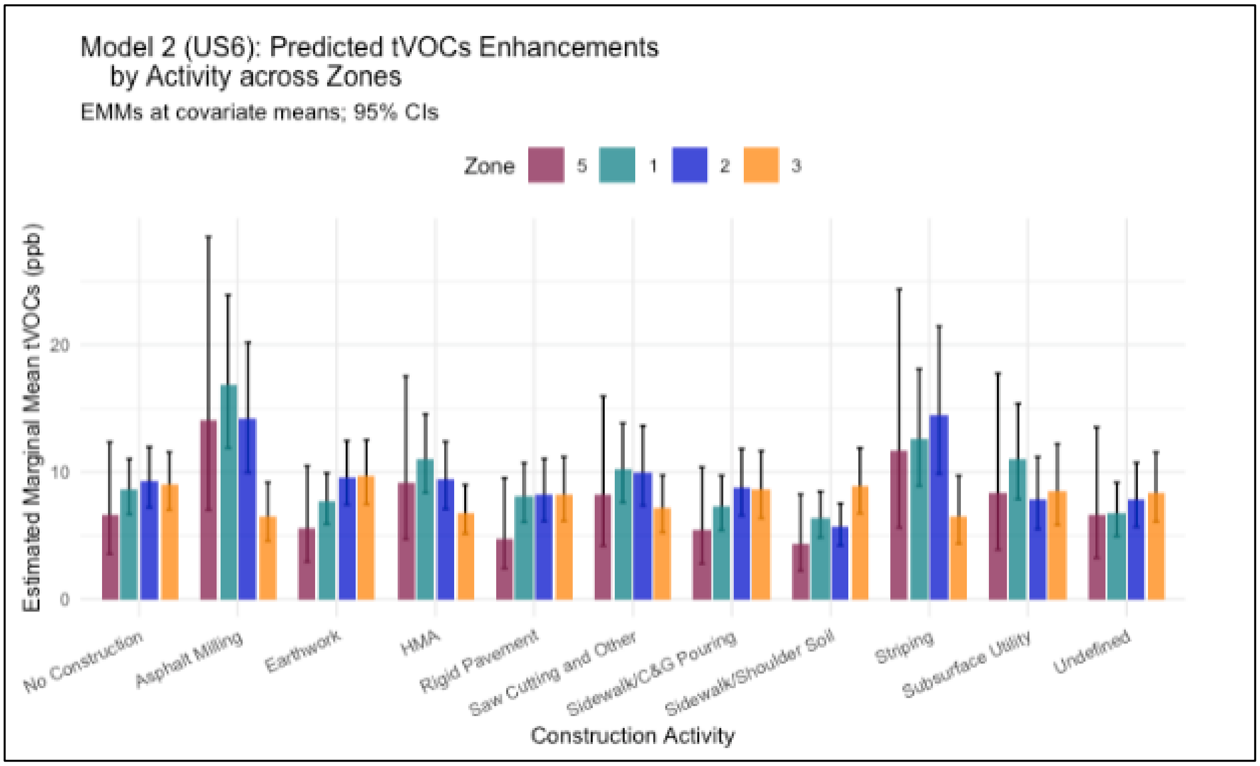
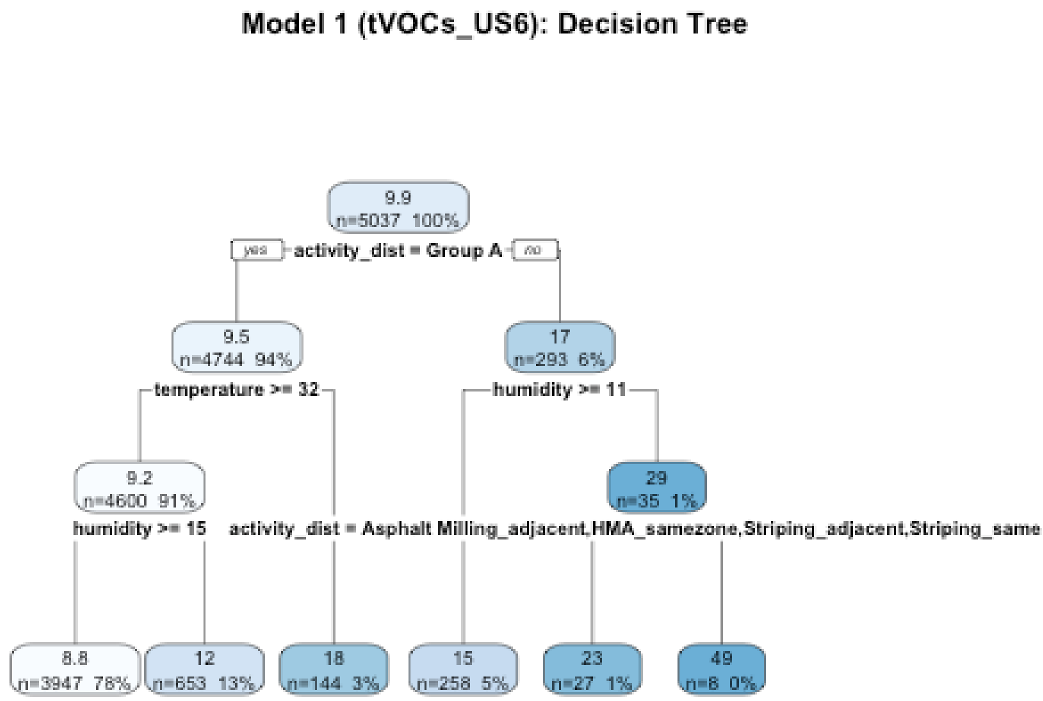


Figure 84. Model 2 (US 6), Estimated Marginal Mean tVOC Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 85. The criteria used to most efficiently split observed enhancements into 6 bins was first determined by activity_dist, then humidity and temperature. The path to the largest enhancements (49 ppb) was activity_dist categories in group B, and very dry conditions (<11% RH) and specifically during Asphalt Milling (samezone) and Saw Cutting and Other (samezone). The path to the lowest enhancements (8.8 ppb) was activity_dist categories in group A, warmer temperatures (≥32F) and higher humidities (≥15% RH).



Group A
"Asphalt Milling_far"
"Earthwork_adjacent"
"Earthwork_far"
"Earthwork_samezone"
"HMA_adjacent"
"HMA_far"
"No Construction"
"Rigid Pavement_adjacent"
"Rigid Pavement_far"
"Rigid Pavement_samezone"
"Saw Cutting and Other_adjacent"
"Saw Cutting and Other_far"
"Sidewalk/C&G Pouring_adjacent"
"Sidewalk/C&G Pouring_far"
"Sidewalk/C&G Pouring_samezone"
"Sidewalk/Shoulder Soil_adjacent"
"Sidewalk/Shoulder Soil_far"
"Sidewalk/Shoulder Soil_samezone"
"Striping_far"
"Subsurface Utility_adjacent"
"Subsurface Utility_far"
"Subsurface Utility_samezone"
"Undefined_adjacent"
"Undefined_far"
"Undefined_samezone"

Group B
"Asphalt Milling_adjacent"
"Asphalt Milling_samezone"
"HMA_samezone"
"Saw Cutting and Other_samezone"
"Striping_adjacent"
"Striping_samezone"

Figure 85. Model 1 (tVOC US 6), Decision Tree

The random forest of Model 1 ranks temperature followed by vehicle volume and humidity as the most important variables in reducing overall model error (Figure 87).

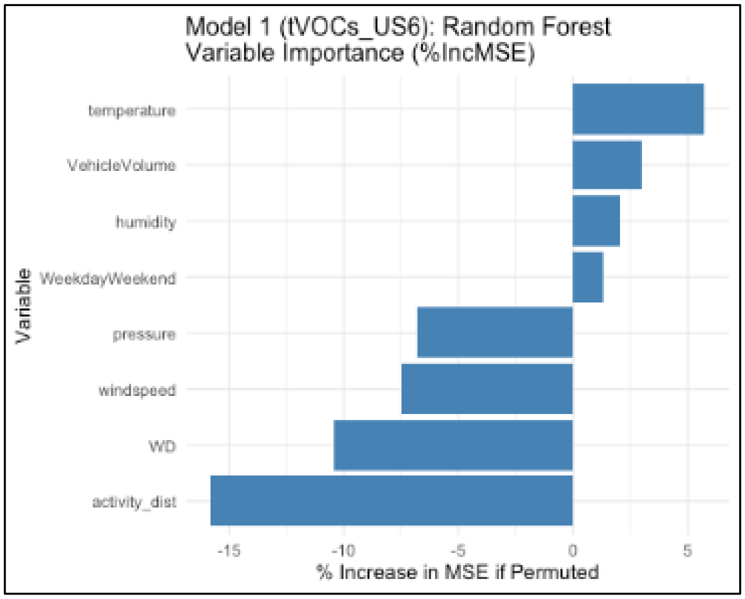


Figure 86. Model 1 (tVOCs US 6), Random Forest Variable Importance (%IncMSE)

B.3.5. US 6 Modeled $PM_{2.5}$ Enhancements

Model 1 estimated marginal mean $PM_{2.5}$ enhancements grouped by construction activity and proximity to construction are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 87. The whiskers on each bar represent the 95% CI of the estimate. Hourly estimated mean enhancements by activity_dist ranged from about 0.75 µg/m^3 to 2.85 µg/m^3. A clear relationship between closer proximity to activities and higher enhancements, indicating a source attributable to the activities, is evident.

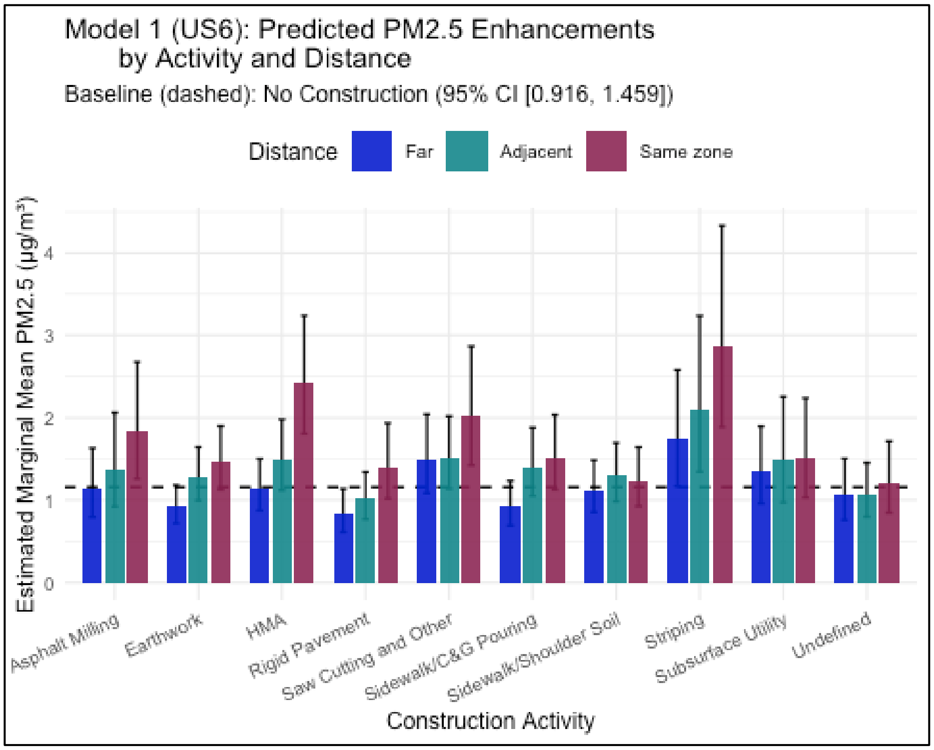


Figure 87. Module 1 (US 6), Estimated Marginal Mean $PM_{2.5}$ Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 15. in addition to percent change and p-values. Ratios below 1 represent decreases relative to No Construction while ratios above 1 indicate increases. Striping, HMA, Saw Cutting and Other and Earthwork which occurred in the same zone as the measurements had 147%, 109% ,75% and 26% higher enhancements, respectively, relative to No Construction ($p \leqq 0.01$). Striping which happened adjacent to measurements had 80% higher enhancements than No Construction ($p=0.05$). Some activity_dist categories which happened “far” from activities were significantly lower than No Construction and many others were no different.

Table 15. Model 1 (PM2.5_US6): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	LowerCL	UpperCL	% Change	p-value
Striping_samezone / No Construction	**2.47**	**1.43**	**4.27**	**147.33**	**0.00**
HMA_samezone / No Construction	**2.09**	**1.56**	**2.81**	**109.16**	**0.00**
Striping_adjacent / No Construction	**1.80**	**1.00**	**3.26**	**80.38**	**0.05**
Saw Cutting and Other_samezone / No Construction	**1.75**	**1.15**	**2.65**	**74.62**	**0.00**
Asphalt Milling_samezone / No Construction	1.59	0.99	2.55	58.72	0.06
Striping_far / No Construction	1.50	0.90	2.49	50.06	0.24
Subsurface Utility_samezone / No Construction	1.31	0.80	2.15	31.30	0.72
Sidewalk/C&G Pouring_samezone / No Construction	1.31	0.96	1.78	31.03	0.13
Saw Cutting and Other_adjacent / No Construction	1.31	0.99	1.73	31.02	0.07
HMA_adjacent / No Construction	1.29	0.98	1.70	28.75	0.10
Saw Cutting and Other_far / No Construction	1.29	0.91	1.82	28.67	0.35
Subsurface Utility_adjacent / No Construction	1.28	0.73	2.23	27.93	0.89
Rigid Pavement_far / No Construction	0.72	0.52	1.01	-27.91	0.06
Earthwork_samezone / No Construction	**1.26**	**1.03**	**1.55**	**26.48**	**0.01**
Sidewalk/C&G Pouring_adjacent / No Construction	1.21	0.90	1.64	21.49	0.51
Rigid Pavement_samezone / No Construction	1.21	0.84	1.75	21.22	0.77
Earthwork_far / No Construction	0.80	0.68	0.94	-20.32	0.00
Sidewalk/C&G Pouring_far / No Construction	0.80	0.59	1.07	-20.27	0.28
Asphalt Milling_adjacent / No Construction	1.19	0.71	2.01	19.24	0.97
Subsurface Utility_far / No Construction	1.17	0.78	1.74	16.65	0.95
Rigid Pavement_adjacent / No Construction	0.88	0.68	1.14	-12.22	0.81
Sidewalk/Shoulder Soil_adjacent / No Construction	1.12	0.89	1.41	11.73	0.85
Earthwork_adjacent / No Construction	1.10	0.93	1.32	10.50	0.69
Undefined_far / No Construction	0.92	0.62	1.38	-7.60	1.00
Undefined_adjacent / No Construction	0.93	0.69	1.26	-6.98	1.00
Sidewalk/Shoulder Soil_samezone / No Construction	1.07	0.81	1.40	6.68	1.00
Undefined_samezone / No Construction	1.04	0.68	1.59	4.09	1.00
Sidewalk/Shoulder Soil_far / No Construction	0.97	0.76	1.25	-2.84	1.00
Asphalt Milling_far / No Construction	0.98	0.63	1.53	-1.63	1.00
HMA_far / No Construction	0.99	0.78	1.26	-1.15	1.00

Activity-distance categories with ratios significantly (p≤0.05) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the difference in estimated marginal mean enhancements by zone for the various construction activities performed at the site at covariate means and baseline categories. Mean hourly estimated enhancements by construction activity and zone ranged from 0.75 μg/m^3 to 2.85

µg/m³. Relative to No Construction, spatial differences (across zones) were more pronounced during construction activities Figure 88. Zones 5 and zone 3 were furthest from construction and are often associated with some of the lowest mean estimates whereas zones 1 and 2, the most active zones, had some of the highest mean enhancement estimates.

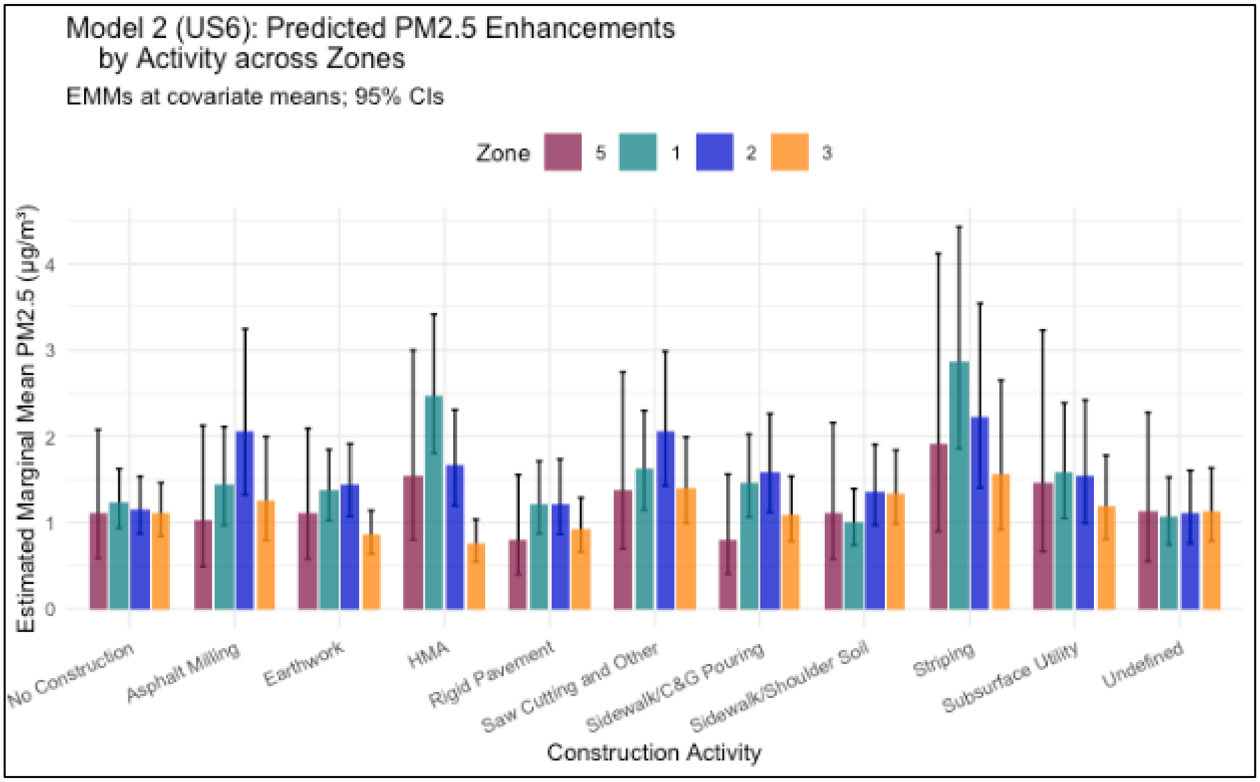
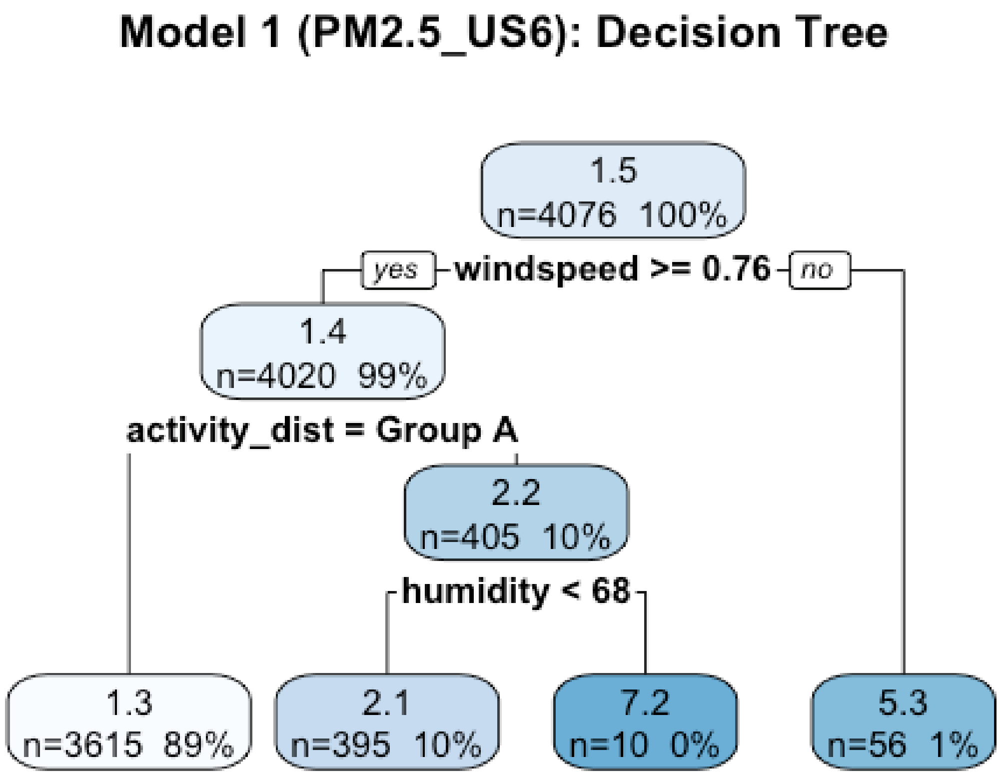


Figure 88. Model 2 (US 6), Estimated Marginal Mean $PM_{2.5}$ Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 89. The criteria used to most efficiently split observed enhancements into 4 bins was first determined by windspeed, then activity_dist and humidity. The path to the largest enhancements (7.2 µg/m³) was windier conditions (>0.76 mph) activity_dist categories in group B and humid conditions (>68% RH). The path to the lowest enhancements (1.3 µg/m³) was windier conditions (>0.76 mph) and activity_dist categories in group A.



Group A
"Asphalt Milling_adjacent"
"Asphalt Milling_far"
"Earthwork_adjacent"
"Earthwork_far"
"Earthwork_samezone"
"HMA_far"
"No Construction"
"Rigid Pavement_adjacent"
"Rigid Pavement_far"
"Rigid Pavement_samezone"
"Sidewalk/C&G Pouring_adjacent"
"Sidewalk/C&G Pouring_far"
"Sidewalk/C&G Pouring_samezone"
"Sidewalk/Shoulder Soil_adjacent"
"Sidewalk/Shoulder Soil_far"
"Sidewalk/Shoulder Soil_samezone"
"Subsurface Utility_adjacent"
"Subsurface Utility_far"
"Subsurface Utility_samezone"
"Undefined_adjacent"
"Undefined_far"
"Undefined_samezone"

Group B
"Asphalt Milling_samezone"
"HMA_adjacent"
"HMA_samezone"
"Saw Cutting and Other_adjacent"
"Saw Cutting and Other_far"
"Saw Cutting and Other_samezone"

Figure 89. Model 1 (PM2.5 US 6), Decision Tree

The random forest of Model 1 ranks windspeed followed by wind direction (WD) and vehicle volume as the most important variables in reducing overall model error (Figure 90.).

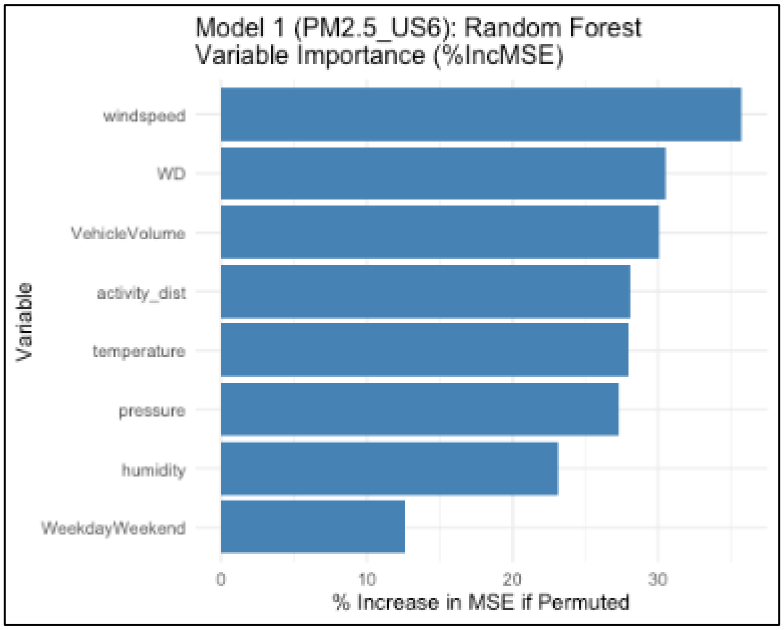


Figure 90. Model 1 ($PM_{2.5}$ US 6), Random Forest Variable Importance (%IncMSE)

B.4. US40 Modeled Pollutant Enhancements

B.4.1. US 40 Modeled NO Enhancements

Model 1 estimated marginal mean NO enhancements grouped by activity_dist (construction activity by proximity-to-construction) are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 91. The whiskers on each bar represent the 95% CI of the estimate. Mean hourly estimated enhancements by activity_dist ranged from 5 ppb to 15 ppb. Generally, there does appear to be a relationship between closer proximity and higher enhancements indicating a source attributable to the activities. This trend is not consistent across all activities (i.e., Saw Cutting and Other, Sidewalk/Shoulder Soil) suggesting pollutant transport, blending of impacts between zones or other sources of pollution.

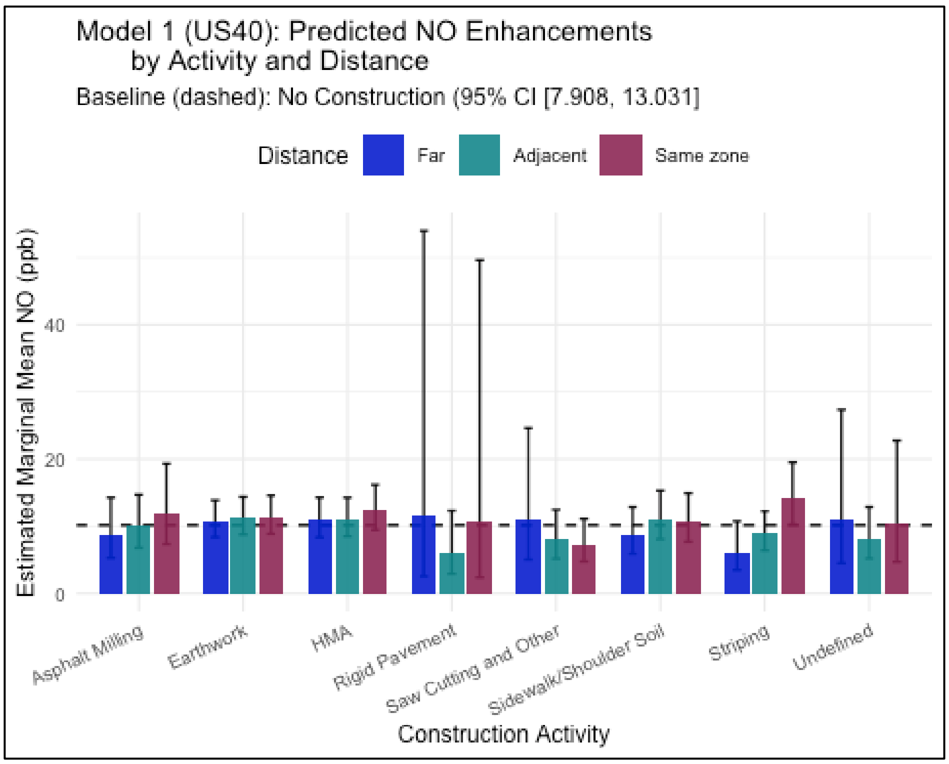


Figure 91. Model 1 (US 40), Estimated Marginal Mean NO Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 16 in addition to lower and upper confidence limits (CL), percent change and p-values. Ratios below 1 represented a decrease relative to No Construction while ratios above 1 indicated increases. Striping, HMA and Earthwork which occurred in the same zone as the measurements had 39%, 21% and 12% higher enhancements, respectively, than No Construction (p<0.03). Earthwork which happened in adjacent zones were found to have 10% higher enhancements than No Construction (p=0.01).

Table 16. Model 1 (NO US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	LowerCL	UpperCL	% Change	p-value
Rigid Pavement_adjacent / No Construction	0.59	0.21	1.66	-41.04	0.77
Striping_far / No Construction	0.60	0.28	1.30	-39.72	0.48
Striping_samezone / No Construction	**1.39**	**1.02**	**1.91**	**39.36**	**0.03**
Saw Cutting and Other_samezone / No Construction	0.71	0.42	1.21	-28.76	0.52
HMA_samezone / No Construction	**1.22**	**1.02**	**1.45**	**21.88**	**0.01**
Saw Cutting and Other_adjacent / No Construction	0.79	0.45	1.38	-21.30	0.89
Undefined_adjacent / No Construction	0.80	0.44	1.47	-19.71	0.95
Asphalt Milling_samezone / No Construction	1.17	0.61	2.23	17.19	0.99
Rigid Pavement_far / No Construction	1.15	0.11	11.56	15.17	1.00
Asphalt Milling_far / No Construction	0.85	0.44	1.66	-14.80	0.99
Sidewalk/Shoulder Soil_far / No Construction	0.86	0.53	1.37	-14.39	0.97
Striping_adjacent / No Construction	0.87	0.63	1.20	-12.83	0.88
Earthwork_samezone / No Construction	**1.12**	**1.02**	**1.22**	**11.66**	**0.01**
Earthwork_adjacent / No Construction	**1.10**	**1.01**	**1.20**	**10.20**	**0.01**
Sidewalk/Shoulder Soil_adjacent / No Construction	1.09	0.79	1.50	9.27	0.99
Saw Cutting and Other_far / No Construction	1.09	0.34	3.47	9.24	1.00
Undefined_far / No Construction	1.09	0.29	4.13	8.83	1.00
HMA_adjacent / No Construction	1.08	0.94	1.25	8.10	0.70
HMA_far / No Construction	1.07	0.90	1.28	7.19	0.93
Earthwork_far / No Construction	1.06	0.94	1.19	5.86	0.80

Activity-distance categories with ratios significantly (p≤0.05) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the estimated marginal mean enhancements by zone for the various construction activities performed at the site while covariates were kept constant at parameter means or baseline levels (Figure 92). Estimated mean hourly enhancements by construction activity and zone ranged from 3 ppb to 15 ppb. Like CO, zone 5 was consistently lower than the other zones and this zone never had construction. Zone 1, which also never had construction taking place, and zone 4 (which did) had some of the higher enhancements on average suggesting pollutant transport or hyper-local sources (other than construction) or unique site/monitor characteristics.

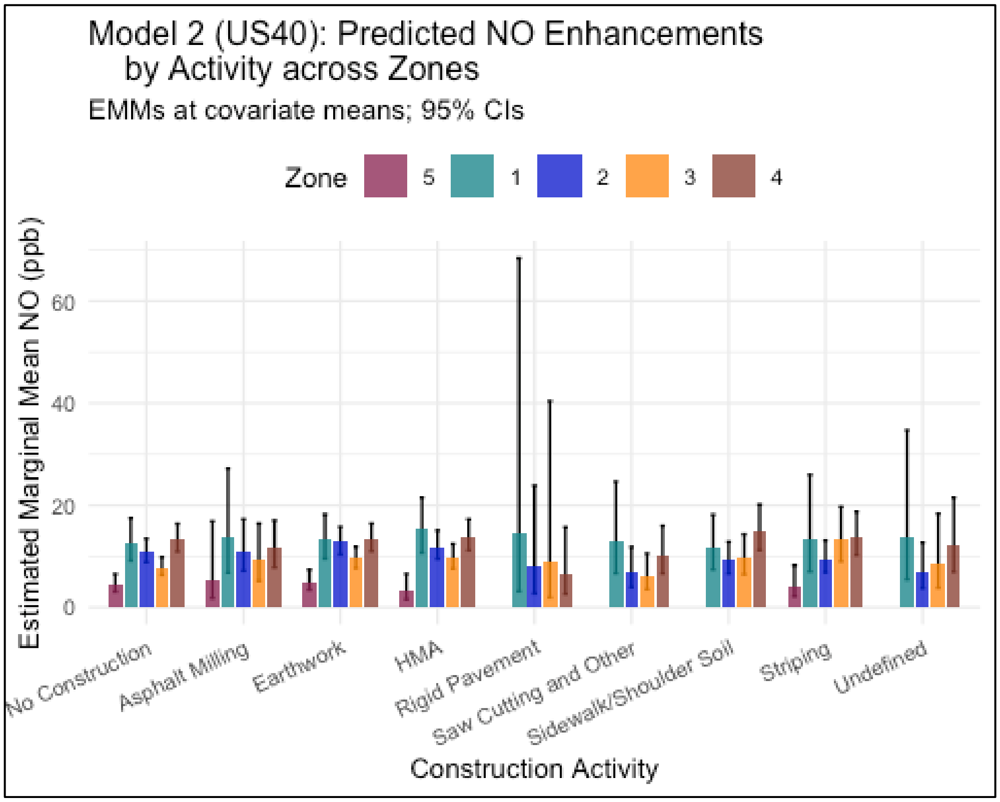
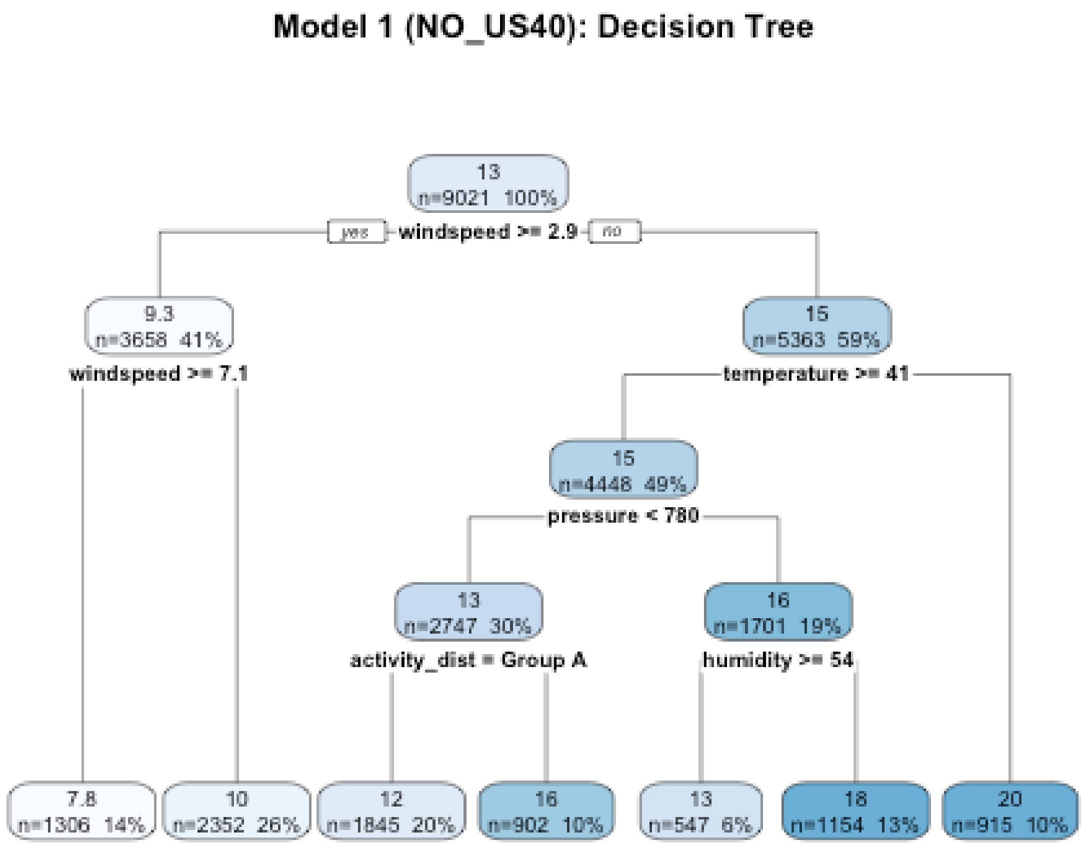


Figure 92. Model 2 (US 40), Estimated Marginal Mean NO Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 93. Here the criteria used to most efficiently split observed enhancements into 7 bins was first determined by humidity, then activity_dist and wind direction. If one follows the path to the largest enhancements, it was during periods of low wind speeds (<2.9% mph, 15 ppb) and temperatures greater than 41F (20 ppb). The path to the lowest mean enhancements took place during windy (>2.9 mph, 9.3 ppb) and even windier conditions (>7.1ppb, 7.8 ppb).



Group A
"Earthwork_samezone"
"HMA_adjacent"
"HMA_samezone"
"No Construction"
"Rigid Pavement_adjacent"
"Rigid Pavement_samezone"
"Saw Cutting and Other_adjacent"
"Saw Cutting and Other_samezone"
"Sidewalk/Shoulder Soil_adjacent"
"Sidewalk/Shoulder Soil_far"
"Striping_adjacent"
"Striping_far"
"Striping_samezone"
"Undefined_samezone"

Group B
"Asphalt Milling_adjacent"
"Asphalt Milling_far"
"Asphalt Milling_samezone"
"Earthwork_adjacent"
"Earthwork_far"
"HMA_far"
"Rigid Pavement_far"
"Saw Cutting and Other_far"
"Sidewalk/Shoulder Soil_samezone"
"Undefined_adjacent"
"Undefined_far"

Figure 93. Model 1 (NO US 40) Decision Tree

The random forest of Model 1 ranks windspeed followed by temperature, pressure and humidity as the most important variables in reducing overall model error, see Figure 94.

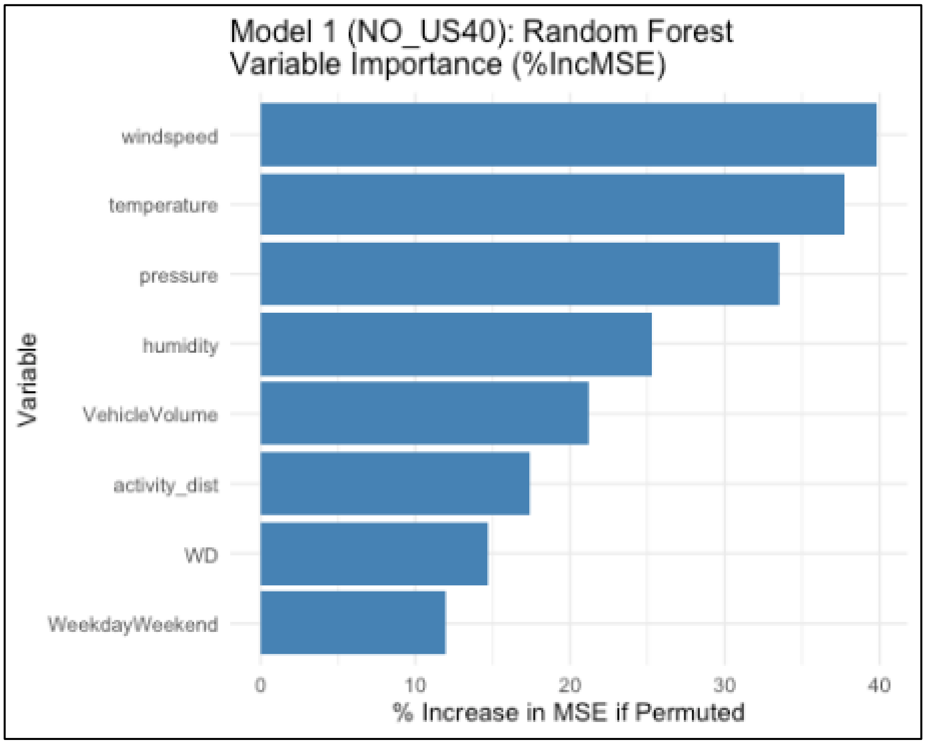


Figure 94. Model 1 (NO US 40), Random Forest Variable Importance (%IncMSE)

B.4.2. US 40 Modeled NO_2 Enhancements

Model 1 estimated marginal mean NO_2 enhancements grouped by activity_dist (construction activity by proximity-to-construction) are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 95. The whiskers on each bar represent the 95% CI of the estimate. Mean hourly estimated enhancements by activity_dist ranged from 5 ppb to 13 ppb. The general trend between closer proximity and higher enhancements was not as strong for this model, again indicating other sources, chemical aging and or significant transport across zones.

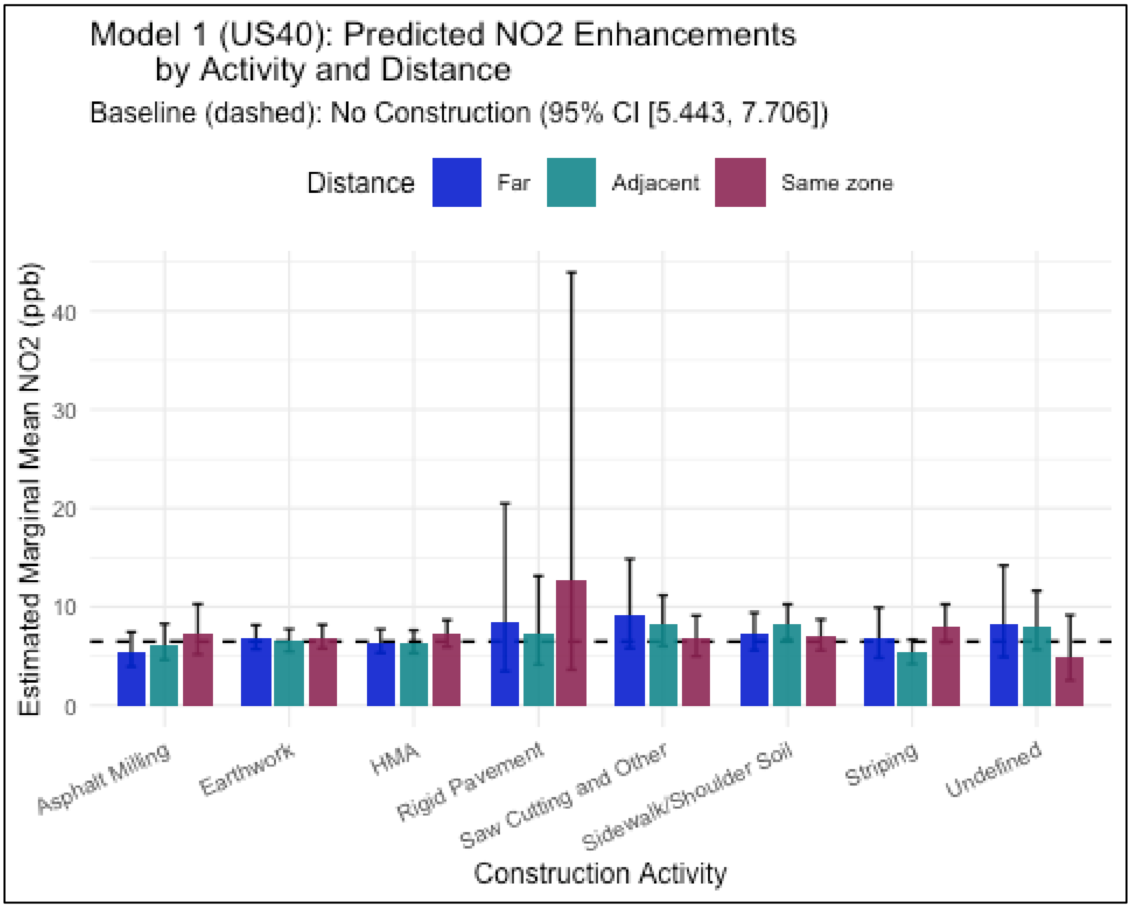


Figure 95. Model 1 (US 40), Estimated Marginal Mean NO_2 Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 17. in addition to lower and upper confidence limits (CL), percent change and p-values. Ratios below 1 represented a decrease relative to No Construction while ratios above 1 indicated increases. Modeled enhancements which occurred adjacent to Sidewalk/Shoulder Soil work were 28% higher than No Construction ($p<0.01$). No other categories had significant differences from No Construction.

Table 17. Model 1 (NO2_US40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	LowerCL	UpperCL	% Change	p-value
Rigid Pavement_samezone / No Construction	1.95	0.29	12.86	94.63	0.96
Saw Cutting and Other_far / No Construction	1.43	0.73	2.80	43.18	0.72
Rigid Pavement_far / No Construction	1.30	0.34	4.93	29.73	1.00
Undefined_far / No Construction	1.29	0.59	2.79	28.62	0.97
Sidewalk/Shoulder Soil_adjacent / No Construction	**1.28**	**1.06**	**1.55**	**28.00**	**0.00**
Saw Cutting and Other_adjacent / No Construction	1.26	0.85	1.88	26.29	0.62
Undefined_samezone / No Construction	0.74	0.29	1.92	-25.58	0.98
Undefined_adjacent / No Construction	1.25	0.76	2.04	24.98	0.86
Striping_samezone / No Construction	1.25	0.98	1.60	24.98	0.11
Striping_adjacent / No Construction	0.81	0.64	1.03	-18.59	0.14
Asphalt Milling_far / No Construction	0.83	0.55	1.26	-16.61	0.88
Rigid Pavement_adjacent / No Construction	1.13	0.49	2.64	13.45	1.00
Asphalt Milling_samezone / No Construction	1.12	0.71	1.78	12.39	0.99
Sidewalk/Shoulder Soil_far / No Construction	1.12	0.82	1.51	11.67	0.95
HMA_samezone / No Construction	1.11	0.97	1.26	10.61	0.26
Sidewalk/Shoulder Soil_samezone / No Construction	1.07	0.86	1.34	7.50	0.97
Striping_far / No Construction	1.06	0.65	1.74	6.49	1.00
Earthwork_samezone / No Construction	1.06	0.99	1.13	6.09	0.12
Earthwork_far / No Construction	1.05	0.97	1.14	5.17	0.54
Asphalt Milling_adjacent / No Construction	0.95	0.66	1.38	-4.59	1.00
Saw Cutting and Other_samezone / No Construction	1.04	0.71	1.52	3.91	1.00
HMA_adjacent / No Construction	0.98	0.89	1.08	-2.05	1.00
HMA_far / No Construction	0.99	0.88	1.11	-1.03	1.00
Earthwork_adjacent / No Construction	1.00	0.94	1.07	0.31	1.00

Activity-distance categories with ratios significantly ($p \leq 0.05$) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the estimated marginal mean enhancements by zone for the various construction activities performed at the site while covariates were kept constant at parameter means or baseline levels (Figure 96). Estimated mean hourly enhancements by construction activity and zone ranged from 3.5 ppb to13 ppb. Enhancement estimates were generally lowest in zone 5 and higher in zone 1, both zones without construction activity, indicating a gradient which may be explained by transport.

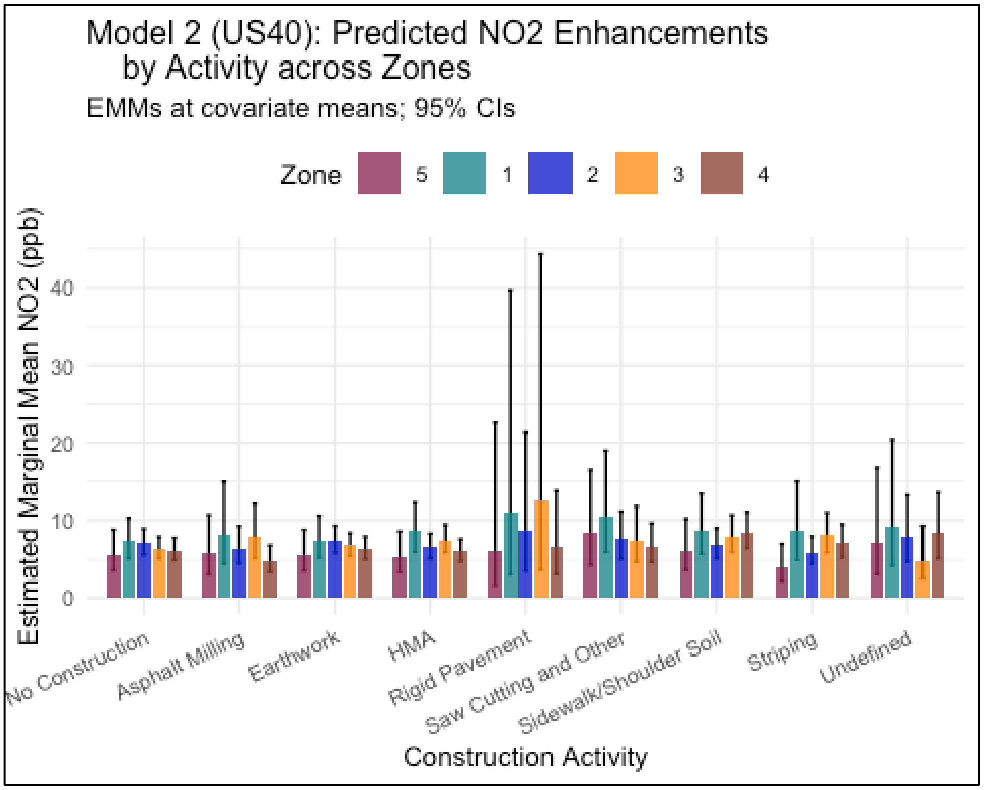
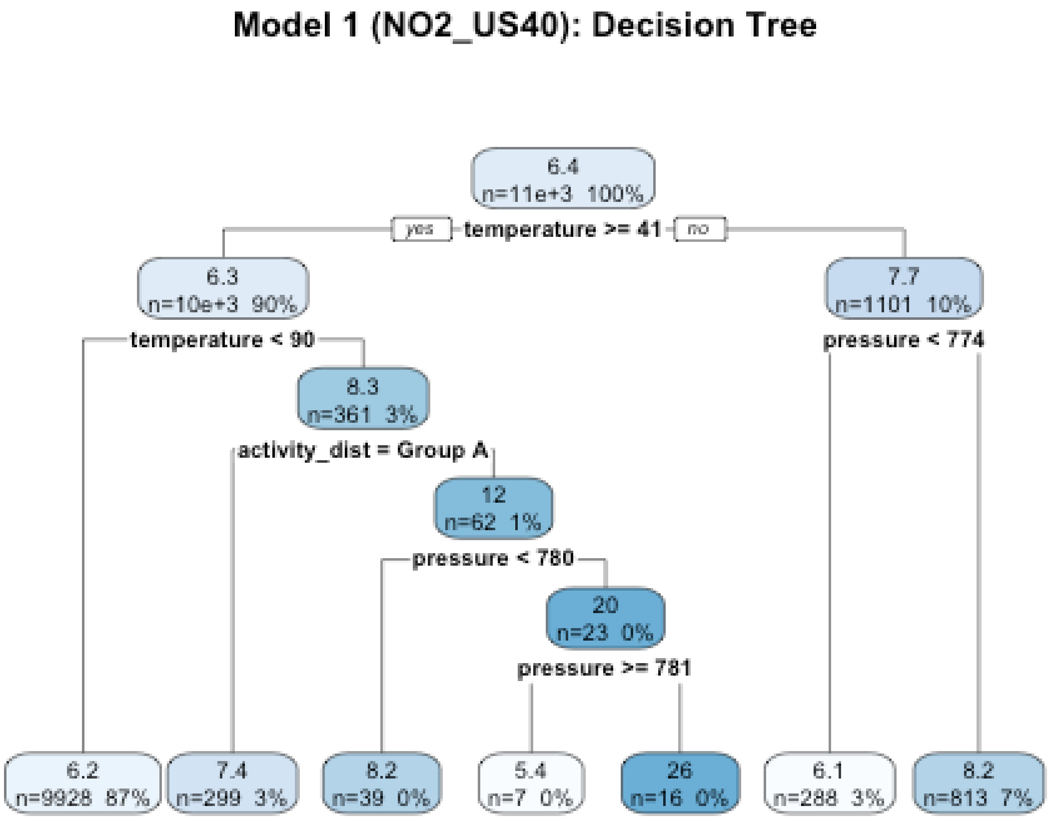


Figure 96. Model 2 (US 40), Estimated Marginal Mean NO_2 Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 97. Here the criteria used to most efficiently split observed enhancements into 7 bins was first determined by temperature, then pressure and activity_dist. If one follows the path to the largest enhancements, it was during periods of not only warm temperatures (>41F, 6.3 ppb) but hot (>90F, 8.3 ppb) and when activity_dist categories on group B happened (12ppb) and pressures were equal to or over 780millibar (20 ppb) but highest when at 780 millibar (26 ppb). The path to the lowest mean enhancements took place during warm (>41F, 6.3 ppb) but not hot (<90F 6.2 ppb) conditions.



Group A
"Earthwork_adjacent"
"Earthwork_far"
"HMA_adjacent"
"HMA_far"
"No Construction"
"Sidewalk/Shoulder Soil_adjacent"
"Sidewalk/Shoulder Soil_far"
"Sidewalk/Shoulder

Group B
"Asphalt Milling_adjacent"
"Asphalt Milling_far"
"Asphalt Milling_samezone"
"Earthwork_samezone"
"HMA_samezone"
"Rigid Pavement_adjacent"
"Rigid Pavement_far"
"Rigid Pavement_samezone"
"Saw Cutting and Other_adjacent"
"Saw Cutting and Other_far"
"Saw Cutting and Other_samezone"
"Striping_adjacent"
"Striping_far"
"Striping_samezone"
"Undefined_adjacent"
"Undefined_far"
"Undefined_samezone"

Figure 97. Model 1 (NO2 US 40) Decision Tree

The random forest of Model 1 ranks vehicle volume followed by pressure and temperature as the most important variables in reducing overall model error., see Figure 98.

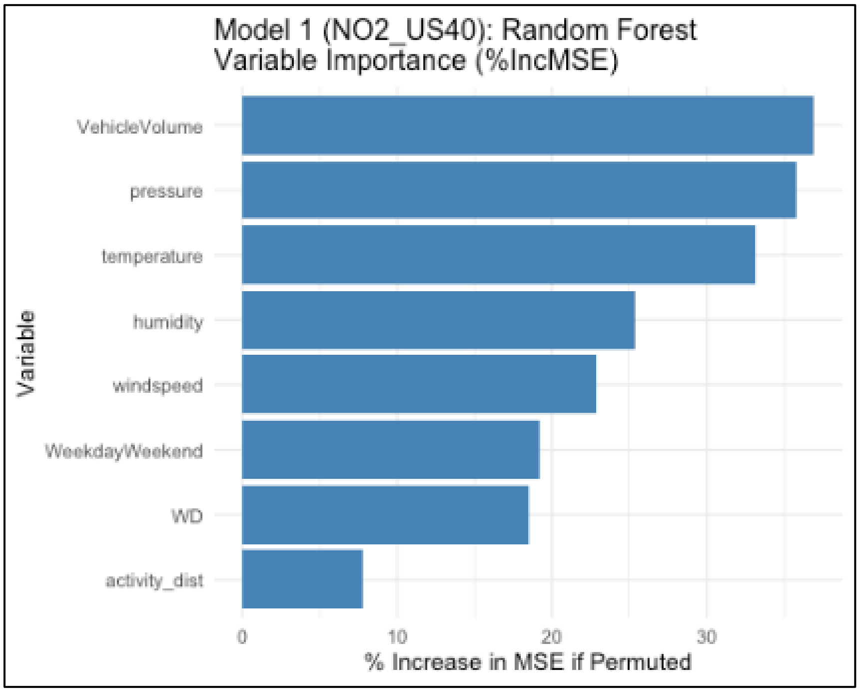


Figure 98. Model 1 (NO_2 US 40), Random Forest Variable Importance (%IncMSE)

B.4.3. US 40 Modeled NO_x Enhancements

Model 1 estimated marginal mean NO_x enhancements grouped by activity_dist (construction activity by proximity-to-construction) are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 99. The whiskers on each bar represent the 95% CI of the estimate. Mean hourly estimated enhancements by activity_dist ranged from 13 ppb to 33 ppb. The general trend between closer proximity and higher enhancements was not as strong for this model, again indicating other sources, chemical aging and or significant transport across zones.

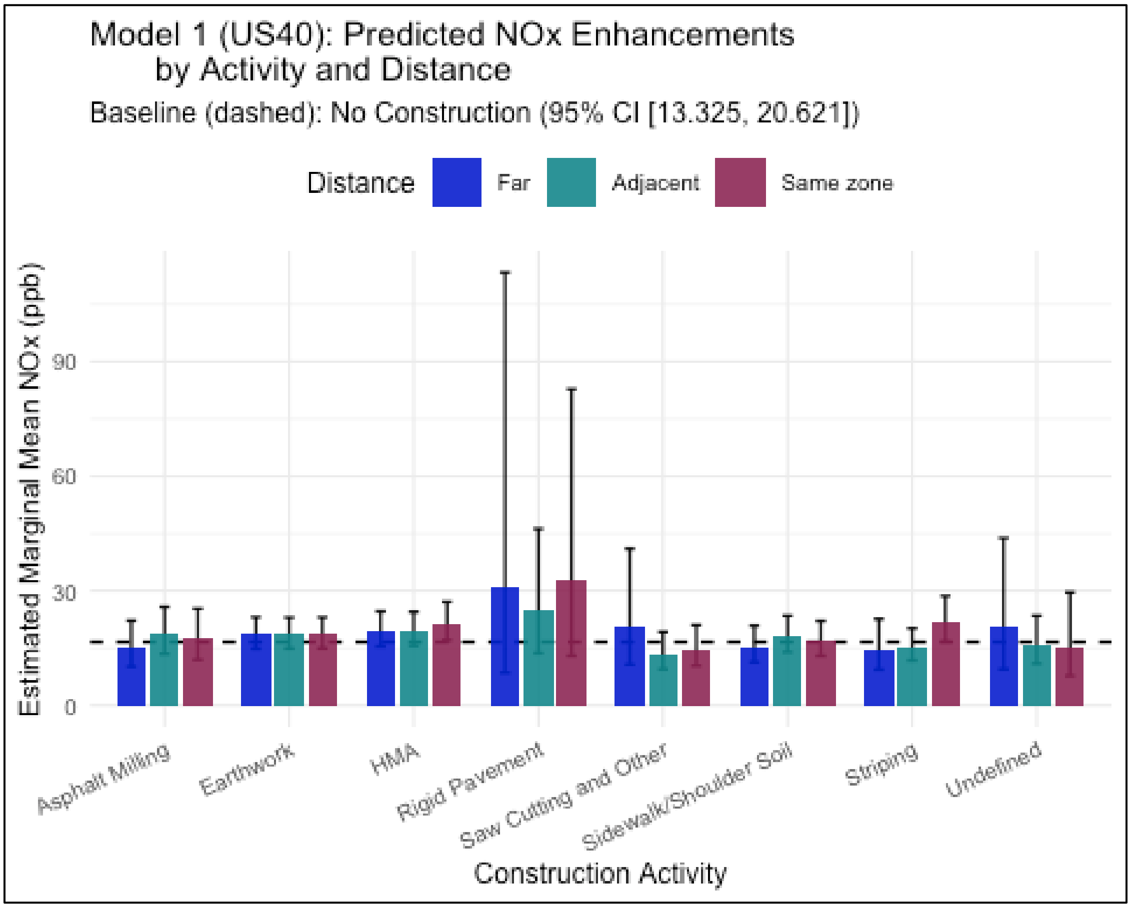


Figure 99. Model 1 (US 40), Estimated Marginal Mean NO_x Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 18. in addition to lower and upper confidence limits (CL), percent change and p-values. Ratios below 1 represented a decrease relative to No Construction while ratios above 1 indicated increases. Modeled enhancements which occurred in the same zone, adjacent to and far from HMA were 30%, 18% and 18% higher than No Construction ($p \leq 0.01$). Striping in the same zone had 32% higher enhancements than No Construction ($p=0.02$) and Earthwork in the same zone, adjacent to or far from the measurements were all associated with 12% higher enhancements ($p \leq 0.01$).

Table 18. Model 1 (NO_x US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	LowerCL	UpperCL	% Change	p-value
Rigid Pavement_samezone / No Construction	1.98	0.50	7.83	97.54	0.80
Rigid Pavement_far / No Construction	1.88	0.27	13.15	87.59	0.97
Rigid Pavement_adjacent / No Construction	1.51	0.63	3.62	51.43	0.82
Striping_samezone / No Construction	**1.32**	**1.03**	**1.69**	**31.81**	**0.02**
HMA_samezone / No Construction	**1.30**	**1.13**	**1.49**	**29.60**	**0.00**
Saw Cutting and Other_far / No Construction	1.26	0.47	3.35	26.04	0.99
Undefined_far / No Construction	1.23	0.40	3.78	22.67	1.00
Saw Cutting and Other_adjacent / No Construction	0.81	0.53	1.25	-18.68	0.81
HMA_adjacent / No Construction	**1.18**	**1.05**	**1.32**	**17.77**	**0.00**
HMA_far / No Construction	**1.18**	**1.02**	**1.35**	**17.58**	**0.01**
Striping_far / No Construction	0.88	0.49	1.58	-12.39	1.00
Asphalt Milling_adjacent / No Construction	1.12	0.77	1.64	12.20	0.98
Earthwork_samezone / No Construction	**1.12**	**1.04**	**1.20**	**11.78**	**0.00**
Earthwork_far / No Construction	**1.12**	**1.02**	**1.22**	**11.60**	**0.01**
Earthwork_adjacent / No Construction	**1.12**	**1.04**	**1.19**	**11.55**	**0.00**
Saw Cutting and Other_samezone / No Construction	0.89	0.58	1.36	-11.08	0.99
Asphalt Milling_far / No Construction	0.90	0.55	1.50	-9.60	1.00
Sidewalk/Shoulder Soil_adjacent / No Construction	1.09	0.87	1.37	8.98	0.94
Undefined_samezone / No Construction	0.91	0.34	2.42	-8.89	1.00
Sidewalk/Shoulder Soil_far / No Construction	0.92	0.66	1.29	-7.52	1.00
Striping_adjacent / No Construction	0.93	0.72	1.19	-7.24	0.98
Asphalt Milling_samezone / No Construction	1.05	0.65	1.69	4.79	1.00
Undefined_adjacent / No Construction	0.96	0.59	1.58	-3.55	1.00
Sidewalk/Shoulder Soil_samezone / No Construction	1.02	0.80	1.30	1.99	1.00

Activity-distance categories with ratios significantly ($p \leq 0.05$) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the estimated marginal mean enhancements by zone for the various construction activities performed at the site while covariates were kept constant at parameter means or baseline levels (Figure 100). Estimated mean hourly enhancements by construction activity and zone ranged from 4 ppb to 39 ppb. Similar to NO and NO_2 enhancement estimates were generally lowest in zone 5 and higher in zone 1, both zones without construction activity, indicating a gradient which may be explained by transport.

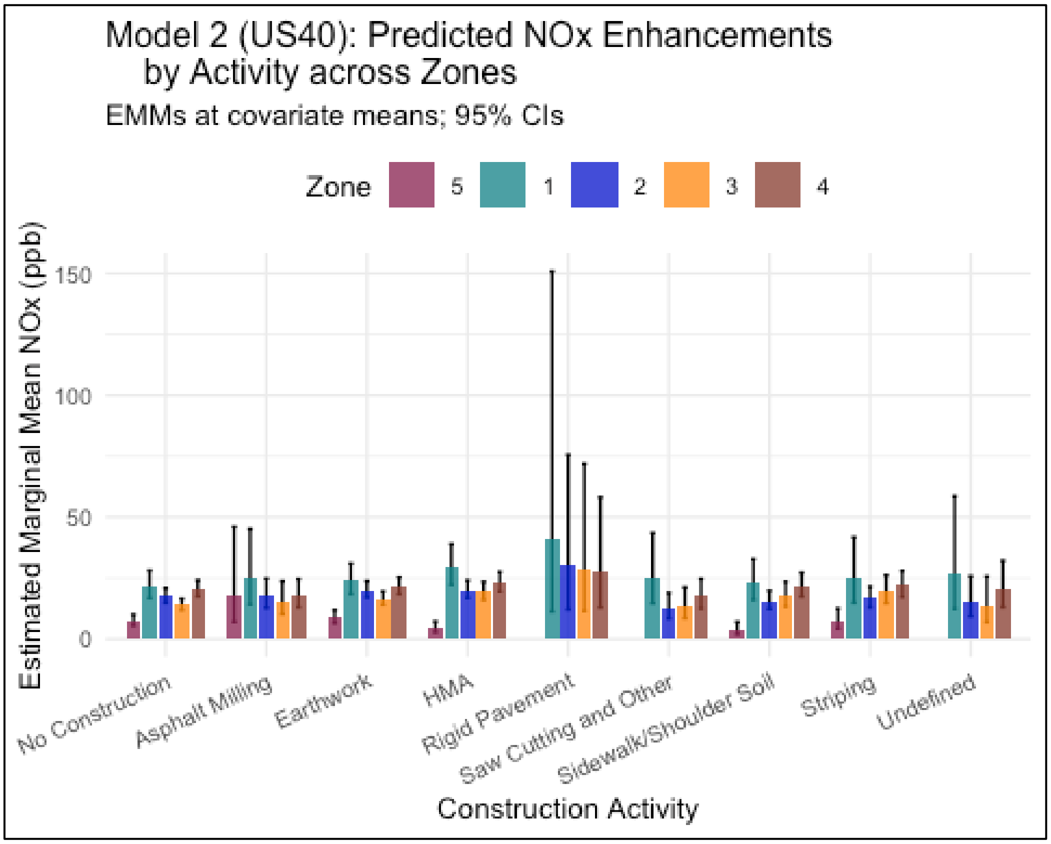


Figure 100. Model 2 (US 40), Estimated Marginal Mean NO_x Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 101. Here the criteria used to most efficiently split observed enhancements into 8 bins was first determined by windspeed, then temperature and humidity and wind direction. If one follows the path to the largest enhancements, it was during periods of calm winds (<2.7mph, 24 ppb) warm (≥38F, 23 ppb), winds out of the west, southwest and south (26 ppb), temperature above 65F (23 ppb) and pressure above 783 millibar (42 ppb). The path to the lowest mean enhancements took place during windy conditions (≥2.7mph, 17 ppb).

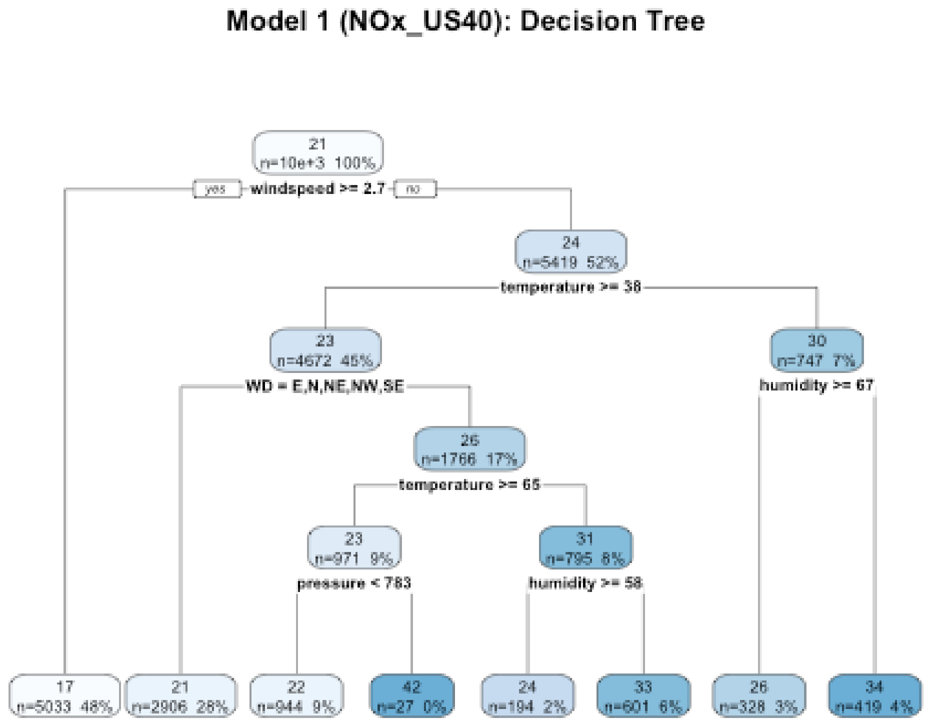


Figure 101. Model 1 (NO_x US 40) Decision Tree

The random forest of Model 1 ranks windspeed followed wind direction and temperature as the most important variables in reducing overall model error, see Figure 102.

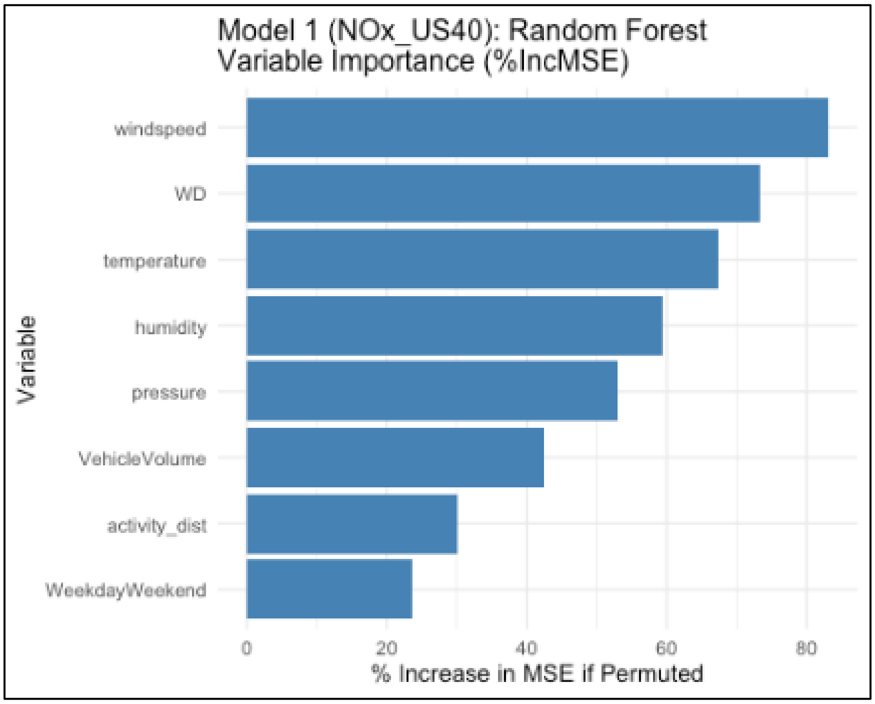


Figure 102. Model 1 (NO_x US 40), Random Forest Variable Importance (%IncMSE)

B.4.4. US 40 Modeled tVOC Enhancements

Model 1 estimated marginal mean tVOC enhancements grouped by activity_dist (construction activity by proximity-to-construction) are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 103. The whiskers on each bar represent the 95% CI of the estimate. Mean hourly estimated enhancements by activity_dist ranged from 3.5 ppb to 12.5 ppb. The trend between closer proximity and higher enhancements was not clear for this model, again indicating other sources, chemical aging and or significant transport across zones.

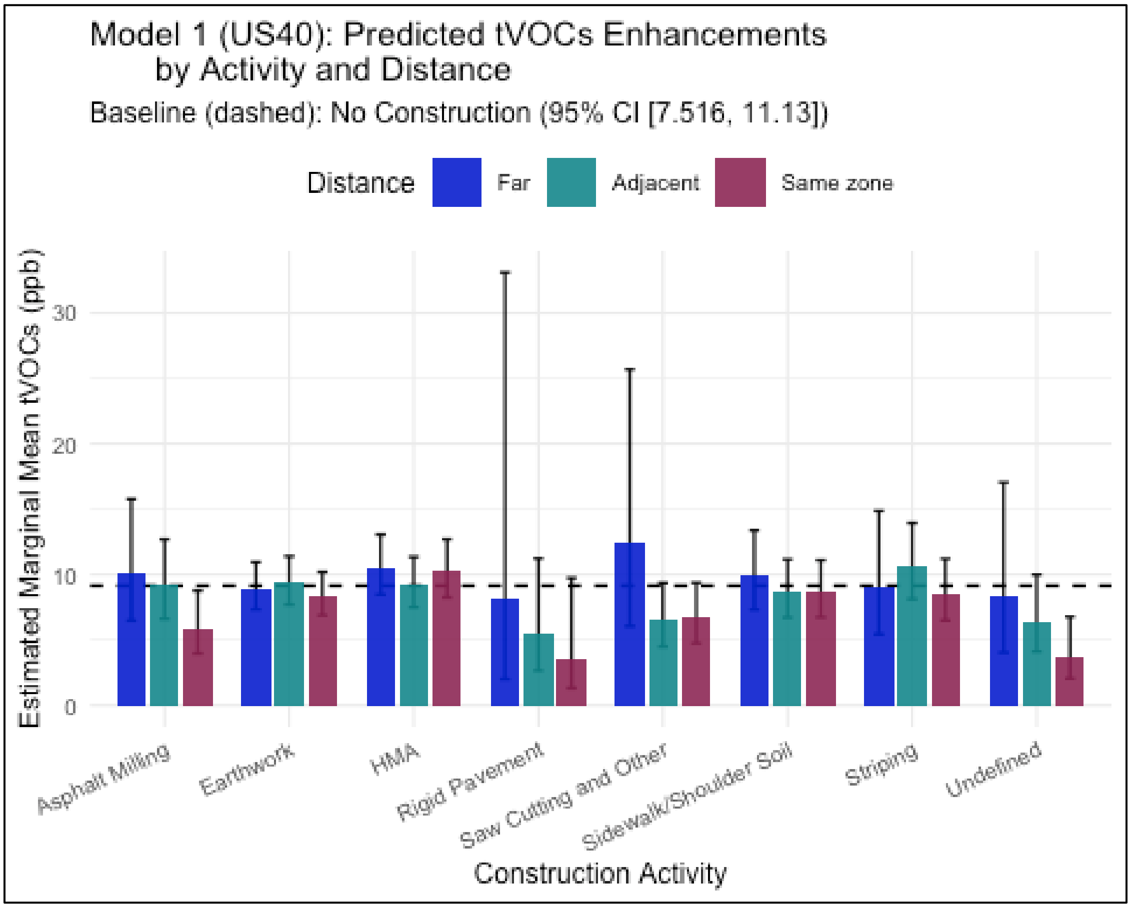


Figure 103. Model 1 (US 40), Estimated Marginal Mean tVOC Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 19 in addition to lower and upper confidence limits (CL), percent change and p-values. Ratios below 1 represented a decrease relative to No Construction while ratios above 1 indicated increases. No modeled enhancements contrasted by activity_dist were significantly higher than No Construction.

Table 19. Model 1 (tVOCs US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	Lower CL	Upper CL	% Change	p-value
Rigid Pavement_samezone / No Construction	0.39	0.09	1.76	-60.95	0.54
Undefined_samezone / No Construction	0.41	0.17	0.97	-59.34	0.04
Rigid Pavement_adjacent / No Construction	0.60	0.21	1.73	-40.41	0.81
Saw Cutting and Other_far / No Construction	1.36	0.47	3.95	36.26	0.98
Asphalt Milling_samezone / No Construction	0.64	0.38	1.10	-35.60	0.19
Undefined_adjacent / No Construction	0.70	0.38	1.30	-29.96	0.64
Saw Cutting and Other_adjacent / No Construction	0.71	0.44	1.14	-29.19	0.35
Saw Cutting and Other_samezone / No Construction	0.73	0.47	1.12	-27.16	0.32
Striping_adjacent / No Construction	1.16	0.87	1.55	16.36	0.74
HMA_far / No Construction	1.15	0.98	1.35	14.89	0.14
HMA_samezone / No Construction	1.12	0.96	1.31	11.89	0.35
Rigid Pavement_far / No Construction	0.89	0.11	7.43	-11.15	1.00
Asphalt Milling_far / No Construction	1.11	0.60	2.05	10.53	1.00
Undefined_far / No Construction	0.91	0.31	2.63	-9.34	1.00
Earthwork_samezone / No Construction	0.92	0.84	0.99	-8.45	0.02
Sidewalk/Shoulder Soil_far / No Construction	1.08	0.76	1.55	8.22	1.00
Striping_samezone / No Construction	0.93	0.69	1.25	-6.76	0.99
Sidewalk/Shoulder Soil_samezone / No Construction	0.95	0.74	1.21	-5.48	1.00
Sidewalk/Shoulder Soil_adjacent / No Construction	0.95	0.73	1.22	-5.36	1.00
Earthwork_adjacent / No Construction	1.02	0.95	1.10	2.35	0.98
Earthwork_far / No Construction	0.98	0.89	1.08	-2.09	1.00
Striping_far / No Construction	0.98	0.48	2.00	-1.76	1.00
HMA_adjacent / No Construction	1.01	0.89	1.14	0.86	1.00
Asphalt Milling_adjacent / No Construction	1.00	0.67	1.50	0.13	1.00

Results from Model 2 illustrate the estimated marginal mean enhancements by zone for the various construction activities performed at the site while covariates were kept constant at parameter means or baseline levels (Figure 104). Estimated mean hourly enhancements by construction activity and zone ranged from 2.8 ppb to 18.5 ppb. Enhancements in zone 1 were notably higher than other zones. This could be due to site specific characteristics or indicative of transport north along the highway or more likely along the drainage since zone 2 is not elevated.

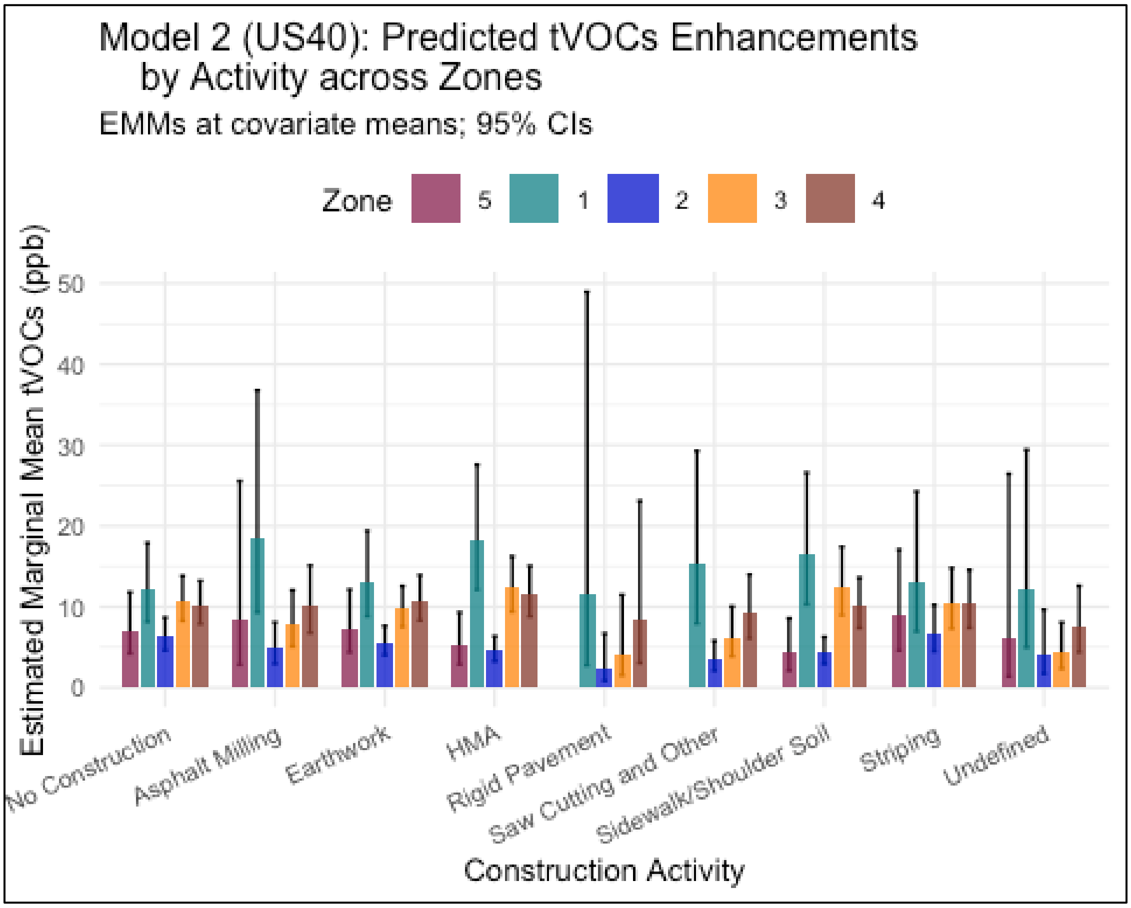


Figure 104. Model 2 (US 40), Estimated Marginal Mean tVOC Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 105. Here the criteria used to most efficiently split observed enhancements into 4 bins was determined by temperature, wind speed and activity_dist. If one follows the path to the largest enhancements, it was during warm (>80F, 13 ppb) and calm winds (<2.5 mph, 17 ppb). The path to the lowest mean enhancements took place during warm (>80F, 13 ppb) breezy (≥ 2.5 mph, 12ppb) and in activity_dist group A conditions (7.8 ppb).

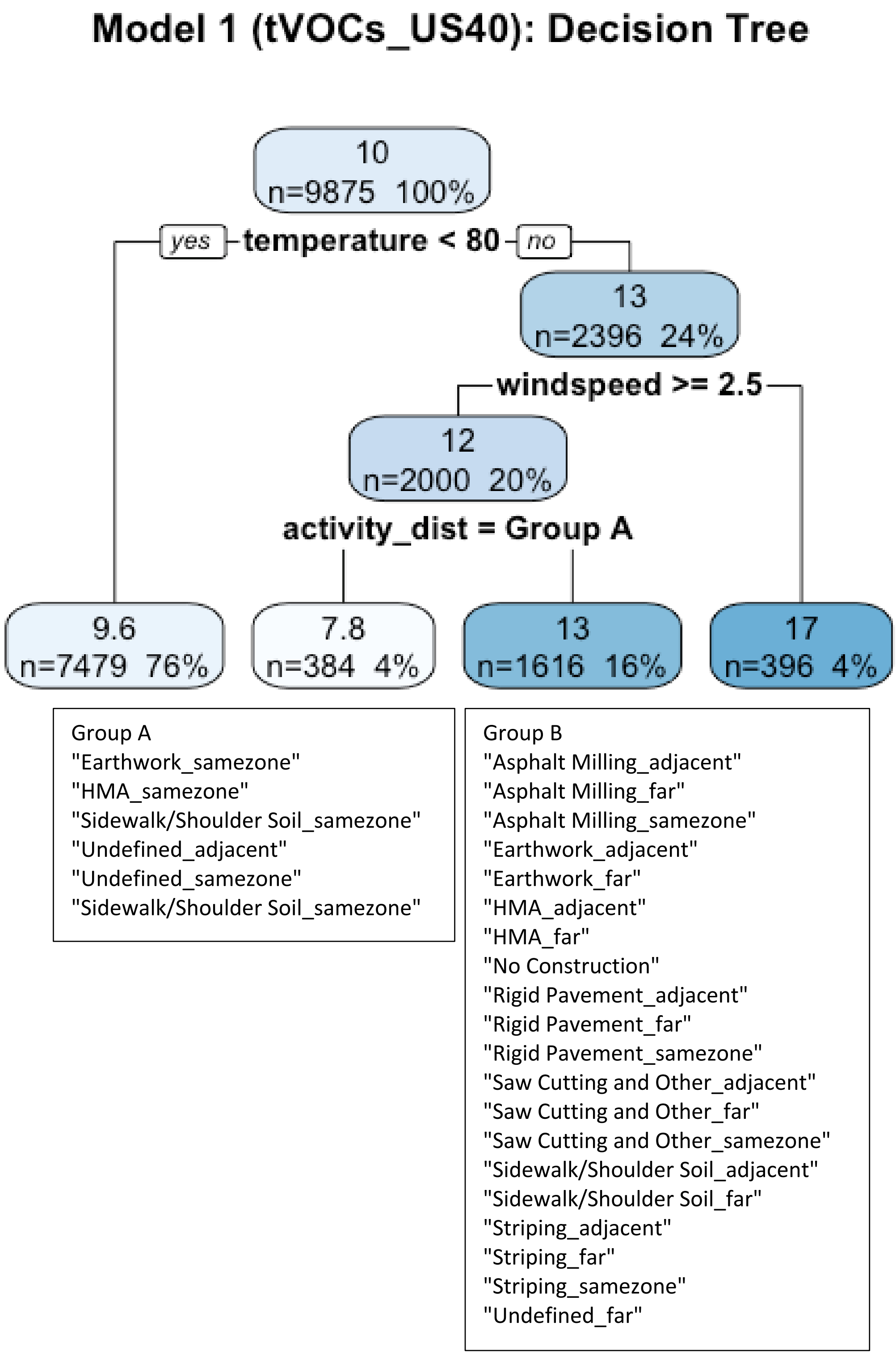


Figure 105. Model 1 (tVOC US 40) Decision Tree

The random forest of Model 1 ranks wind speed, temperature and wind direction as the most important variables in reducing overall model error, see Figure 106.

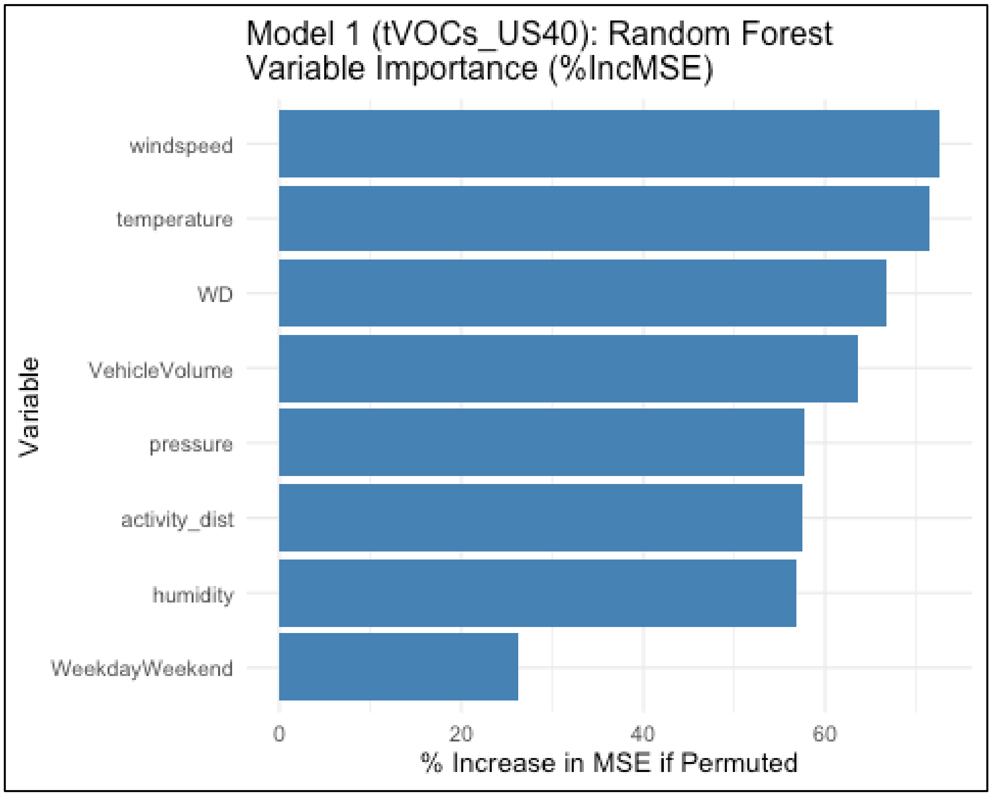


Figure 106. Model 1 (tVOC US 40), Random Forest Variable Importance (%IncMSE)

B.4.5. US 40 Modeled $PM_{2.5}$ Enhancements

Model 1 estimated marginal mean $PM_{2.5}$ enhancements grouped by activity_dist (construction activity by proximity-to-construction) are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 107. The whiskers on each bar represent the 95% CI of the estimate. Mean hourly estimated enhancements by activity_dist ranged from 1.5 µg/m^3 to 6.0 µg/m^3. The trend between closer proximity and higher enhancements was apparent for some activities (i.e., Earthwork) but not for others, and even reversed for some (i.e., Sidewalk/Shoulder Soil and Rigid Pavement although there were very few observations of this activity).

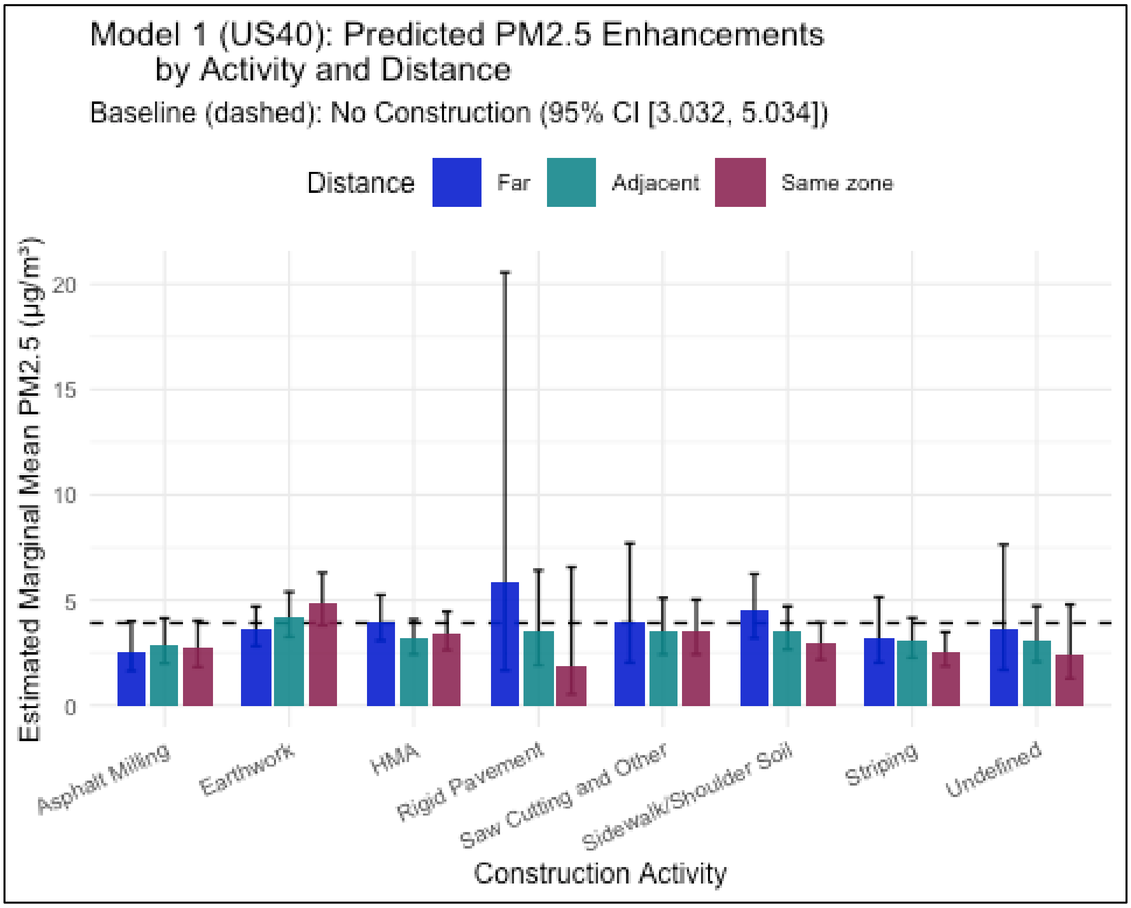


Figure 107. Model 1 (US 40), Estimated Marginal Mean $PM_{2.5}$ Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 20 in addition to lower and upper confidence limits (CL), percent change and p-values. Ratios below 1 represented a decrease relative to No Construction while ratios above 1 indicated increases. Eathwork which occurred in the same zone as the measurements had 25% higher enhancements compared to No Construction ($p<0.01$).

Table 20. Model 1 ($PM_{2.5}$ US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	Lower CL	Upper CL	% Change	p-value
Rigid Pavement_samezone / No Construction	0.48	0.07	3.14	-52.33	0.92
Rigid Pavement_far / No Construction	1.49	0.23	9.83	49.31	1.00
Undefined_samezone / No Construction	0.63	0.24	1.62	-37.00	0.80
Striping_samezone / No Construction	0.65	0.49	0.86	-34.94	0.00
Asphalt Milling_far / No Construction	0.65	0.37	1.16	-34.75	0.31
Asphalt Milling_samezone / No Construction	0.69	0.43	1.11	-30.93	0.26
Asphalt Milling_adjacent / No Construction	0.73	0.49	1.10	-26.60	0.29
Sidewalk/Shoulder Soil_samezone / No Construction	0.75	0.58	0.96	-25.37	0.01
Earthwork_samezone / No Construction	**1.25**	**1.16**	**1.35**	**25.18**	**0.00**
Striping_adjacent / No Construction	0.78	0.60	1.02	-21.65	0.10
Undefined_adjacent / No Construction	0.80	0.48	1.33	-20.17	0.87
HMA_adjacent / No Construction	0.80	0.72	0.90	-19.61	0.00
Striping_far / No Construction	0.83	0.45	1.50	-17.44	0.97
Sidewalk/Shoulder Soil_far / No Construction	1.14	0.81	1.61	14.31	0.92
HMA_samezone / No Construction	0.87	0.76	1.00	-12.69	0.07
Saw Cutting and Other_samezone / No Construction	0.89	0.59	1.34	-10.83	0.99
Rigid Pavement_adjacent / No Construction	0.89	0.38	2.08	-10.62	1.00
Saw Cutting and Other_adjacent / No Construction	0.90	0.59	1.37	-10.33	0.99
Sidewalk/Shoulder Soil_adjacent/ No Construction	0.90	0.73	1.12	-9.57	0.83
Undefined_far / No Construction	0.92	0.31	2.73	-8.24	1.00
Earthwork_far / No Construction	0.93	0.84	1.03	-7.14	0.33
Earthwork_adjacent / No Construction	1.07	1.00	1.15	7.05	0.07
HMA_far / No Construction	1.03	0.89	1.19	2.69	1.00
Saw Cutting and Other_far / No Construction	1.01	0.39	2.60	1.04	1.00

Activity-distance categories with ratios significantly ($p \leq 0.05$) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the estimated marginal mean enhancements by zone for the various construction activities performed at the site while covariates were kept constant at parameter means or baseline levels (Figure 108). Estimated mean hourly enhancements by construction activity and zone ranged from 2 μg/m^3 to 7 μg/m^3. Differences across zones were more pronounced during construction than during no construction but estimates have significant overlap.

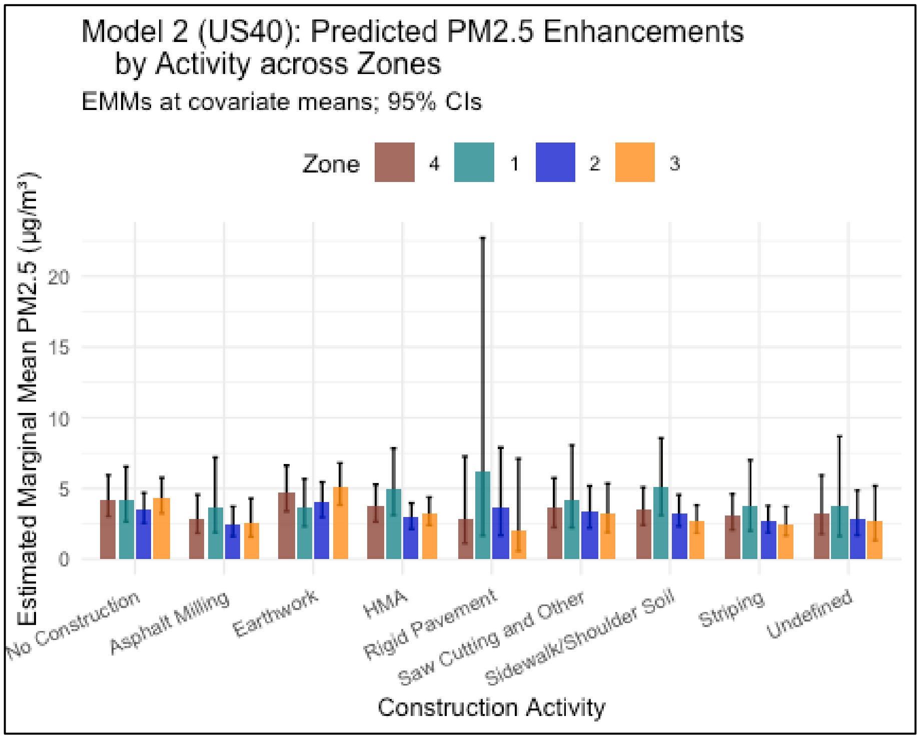


Figure 108. Model 2 (US 40), Estimated Marginal Mean $PM_{2.5}$ Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 109. Here the criteria used to most efficiently split observed enhancements into 5 bins was determined by pressure and humidity alone. The path to the largest enhancements involves mixtures of specific pressures and lower humidities (21 µg/m^3), while the path to the lowest enhancements is low pressures (<778 millibar, 3 µg/m^3).

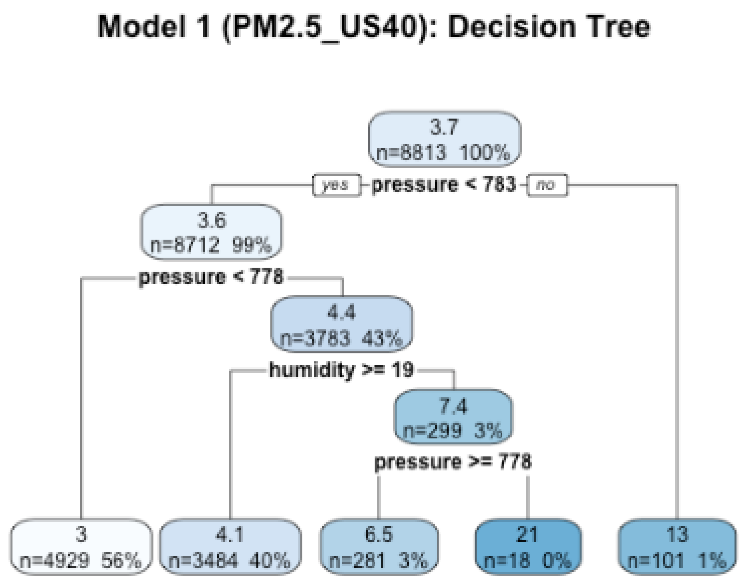


Figure 109. Model 1 (PM2.5 US 40) Decision Tree

The random forest of Model 1 ranks pressure, wind direction and as the top 3 most important variables in reducing overall model error, see Figure 110.

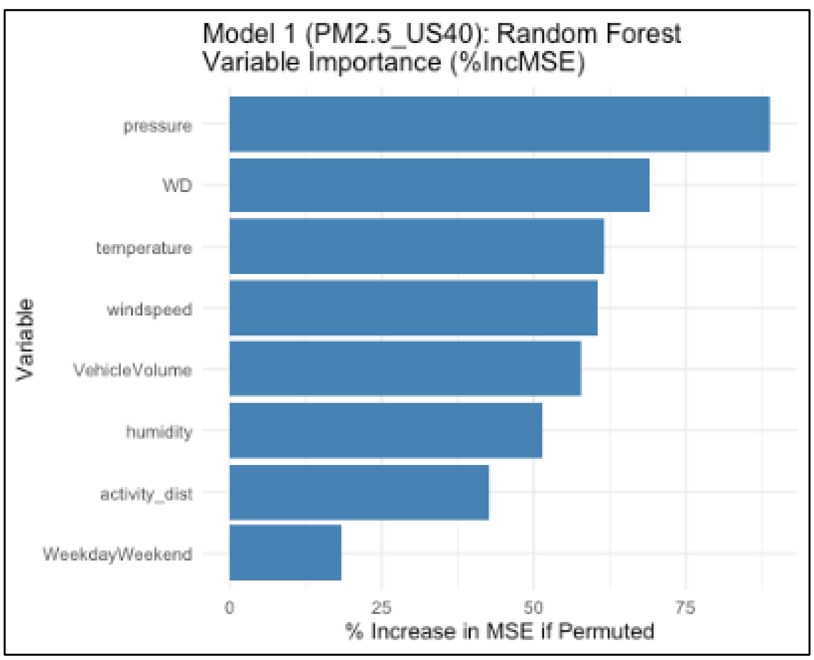


Figure 110. Model 1 ($PM_{2.5}$ US 40), Random Forest Variable Importance (%IncMSE)

B.4.6. US 40 Modeled PM_{10} Enhancements

Model 1 estimated marginal mean PM_{10} enhancements grouped by activity_dist (construction activity by proximity-to-construction) are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 111. The whiskers on each bar represent the 95% CI of the estimate. Mean hourly estimated enhancements by activity_dist ranged from 1.3 µg/m^3 to 41 µg/m^3. Generally, the highest enhancements were modeled to take place during Earthwork, Asphalt Milling, Striping and Undefined activities and most pronounced when measured in the same zone as the activity. Measurements made "far" from activities were modeled to have lower enhancements than adjacent and same zone (sometimes even lower than No Construction).

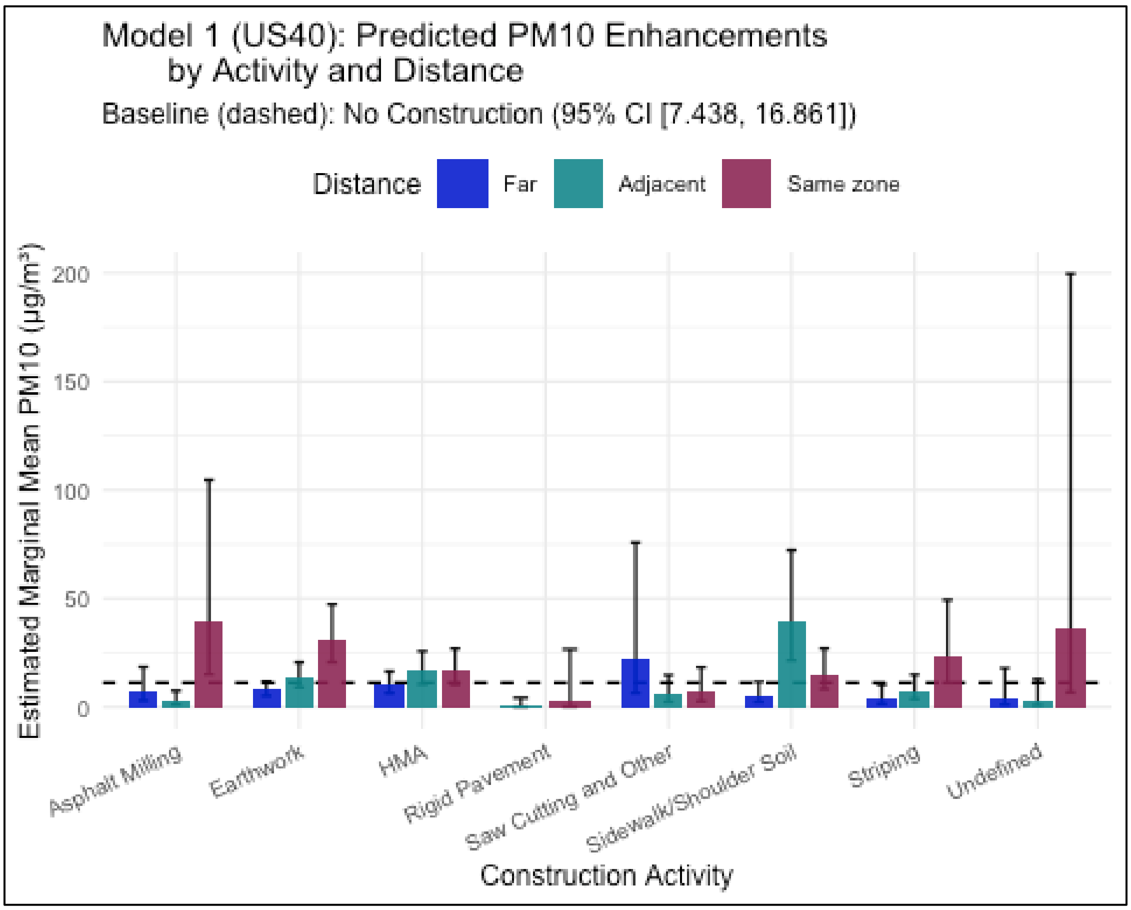


Figure 111. Model 1 (US 40), Estimated Marginal Mean PM_{10} Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 21 in addition to lower and upper confidence limits (CL), percent change and p-values. Ratios below 1 represented a decrease relative to No Construction while ratios above 1 indicated increases. Sidewalk/Shoulder Soil activities which occurred adjacent to measurements had 252% higher enhancements than No Construction (p<0.01). Eathwork which occurred in the same zone as the measurements had 179% higher enhancements compared to No Construction (p<0.01) and enhancements modeled adjacent to HMA were 47% larger than No Construction (p=0.03).

Table 21. Model 1 (PM_{10} US 40): Pairwise Contrasts: Effect Sizes, CIs, % Change, and p-values

Contrast	Effect	Lower CL	Upper CL	% Change	p-value
Asphalt Milling_samezone / No Construction	3.55	0.91	13.80	254.74	0.09
Sidewalk/Shoulder Soil_adjacent / No Construction	**3.52**	**1.71**	**7.23**	**252.02**	**0.00**
Undefined_samezone / No Construction	3.28	0.27	40.14	228.03	0.82
Earthwork_samezone / No Construction	**2.79**	**2.18**	**3.57**	**179.11**	**0.00**
Striping_samezone / No Construction	2.10	0.81	5.43	109.55	0.26
Saw Cutting and Other_far / No Construction	1.98	0.34	11.67	98.41	0.93
Rigid Pavement_adjacent / No Construction	0.07	0.01	0.85	-93.07	0.03
Rigid Pavement_samezone / No Construction	0.23	0.01	7.69	-77.38	0.89
Asphalt Milling_adjacent / No Construction	0.25	0.07	0.98	-74.58	0.04
Undefined_adjacent / No Construction	0.29	0.04	2.20	-71.48	0.56
Striping_far / No Construction	0.35	0.09	1.34	-64.93	0.25
Undefined_far / No Construction	0.40	0.05	3.08	-60.13	0.86
Sidewalk/Shoulder Soil_far / No Construction	0.46	0.16	1.37	-53.56	0.38
HMA_samezone / No Construction	1.49	0.96	2.31	49.10	0.10
Saw Cutting and Other_adjacent / No Construction	0.53	0.15	1.87	-47.07	0.77
HMA_adjacent / No Construction	**1.47**	**1.02**	**2.12**	**46.86**	**0.03**
Saw Cutting and Other_samezone / No Construction	0.62	0.16	2.40	-37.94	0.95
Asphalt Milling_far / No Construction	0.66	0.19	2.36	-33.86	0.97
Sidewalk/Shoulder Soil_samezone / No Construction	1.33	0.67	2.65	33.32	0.89
Striping_adjacent / No Construction	0.67	0.28	1.60	-33.24	0.84
Earthwork_far / No Construction	0.70	0.53	0.92	-30.18	0.00
Earthwork_adjacent / No Construction	1.22	0.95	1.57	21.74	0.25
HMA_far / No Construction	0.92	0.61	1.39	-8.17	1.00

Activity-distance categories with ratios significantly (p≤0.05) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the estimated marginal mean enhancements by zone for the various construction activities performed at the site while covariates were kept constant at parameter means or baseline levels (Figure 112). Estimated mean hourly enhancements by construction activity and zone ranged from <1 μg/m^3 to 85 μg/m^3. Differences across zones were much more pronounced during construction than during periods of no construction. Large, estimated enhancements are evident for zones 2, 3 and 4 especially during Earthwork, Asphalt Milling, HMA and Sidewalk/Shoulder Soil work.

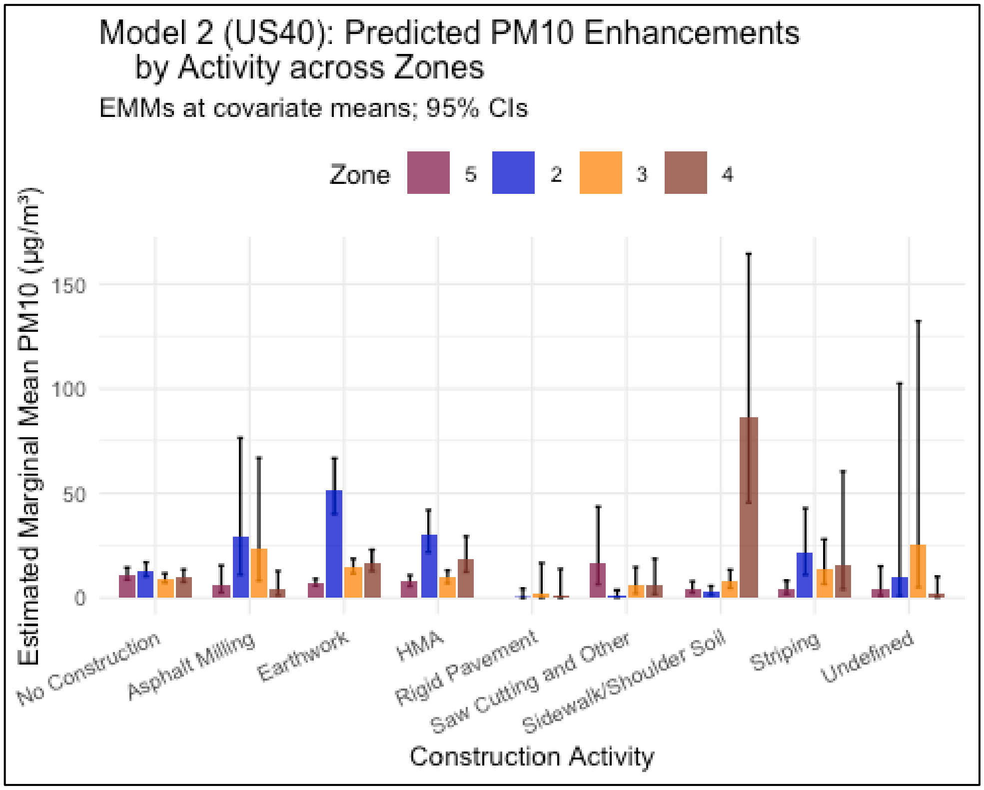


Figure 112. Model 2 (US 40), Estimated Marginal Mean PM_{10} Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 113. Here the criteria used to most efficiently split observed enhancements into 5 bins was determined by activity_dist, humidity and vehicle volume. The path to the largest enhancements were associated with activity_dist categories from group B (26 μg/m^3), very dry conditions (<13 % RH, 100 μg/m^3) and when vehicle volume was below 258 counts/hour (225 μg/m^3). The path to the lowest enhancements was associated with activity_dist categories in group A (7.4 μg/m^3).

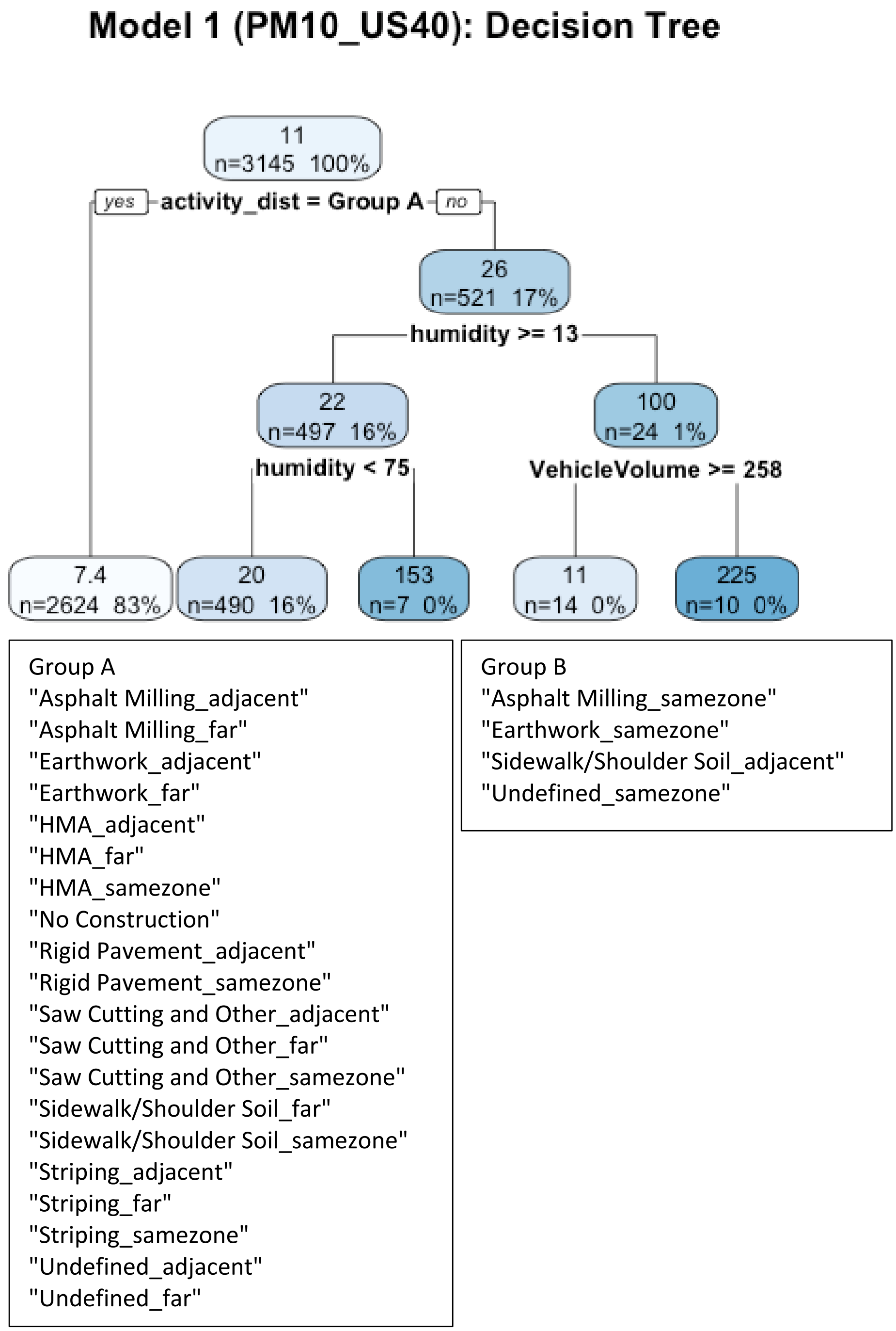


Figure 113. Model 1 (PM10 US 40) Decision Tree

The random forest of Model 1 ranks humidity, activity_dist and temperature as the top 3 most important variables in reducing overall model error, see Figure 114.

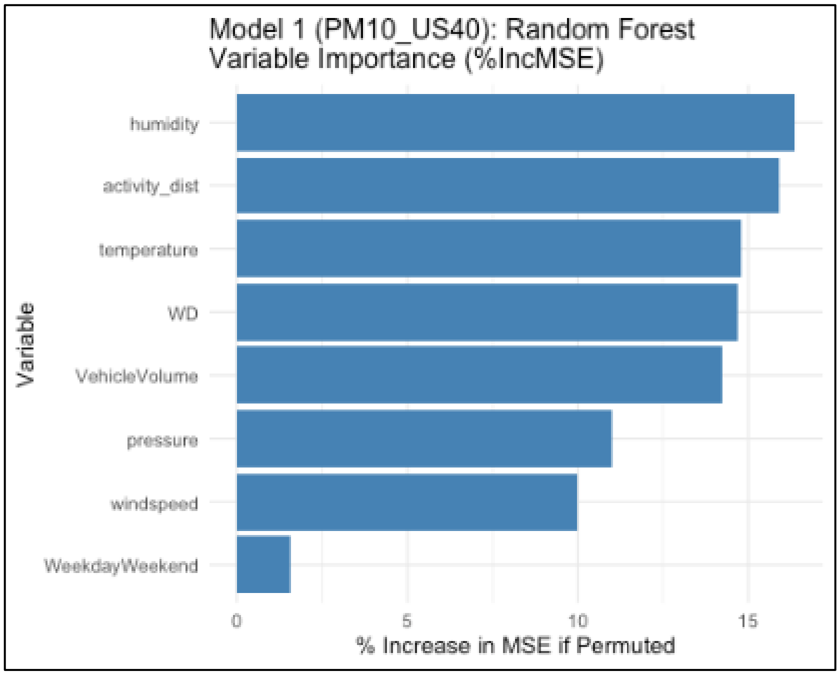


Figure 114. Model 1 (PM_{10} US 40), Random Forest Variable Importance (%IncMSE)

B.4.7. US 40 Modeled CoarsePM Enhancements

Model 1 estimated marginal mean coarsePM enhancements grouped by activity_dist (construction activity by proximity-to-construction) are shown relative to the baseline case of No Construction (horizontal dashed line) in Figure 115. The whiskers on each bar represent the 95% CI of the estimate. Mean hourly estimated enhancements by activity_dist ranged from about 2 μg/m^3 to 46 μg/m^3. Generally, the highest enhancements were modeled to take place during Earthwork, Asphalt Milling, Striping and Undefined activities and most pronounced when measured in the same zone as the activity. Measurements made “far” from activities were often modeled to have lower enhancements than adjacent (except Sidewalk/Shoulder Soil) and same zone.

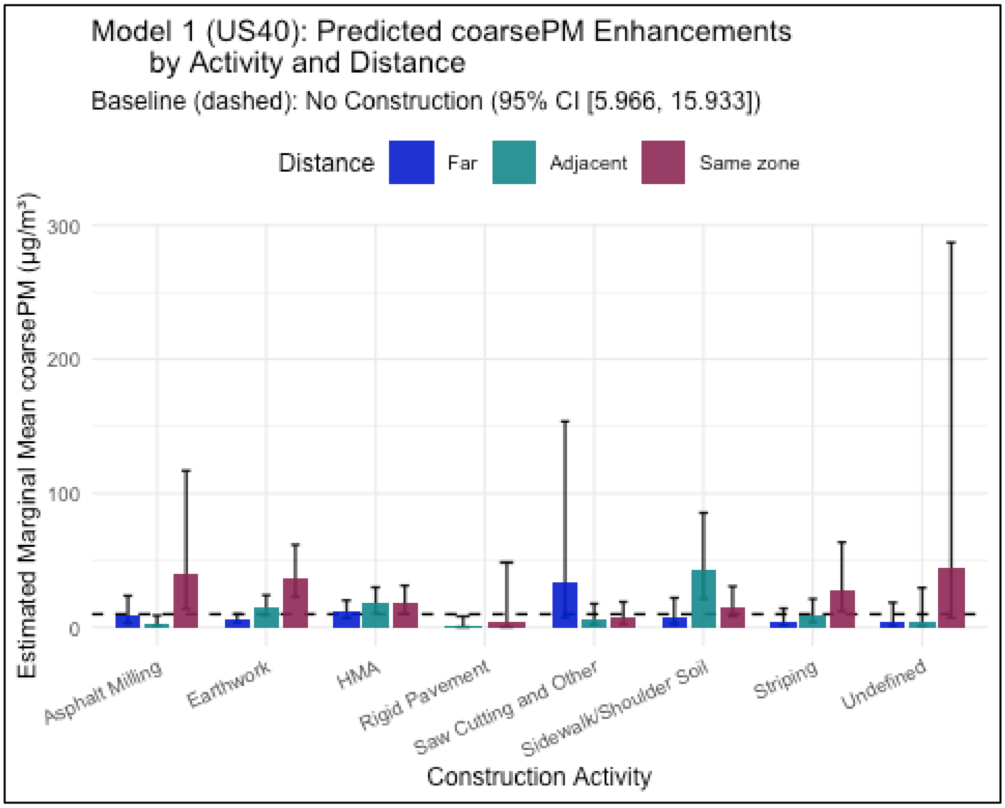


Figure 115. Model 1 (US 40), Estimated Marginal Mean Coarse PM Enhancements by Activity and Distance

Note: Distance is categorized as same zone, adjacent, and far relative to the zone in which the activity was occurring. The horizontal dashed line represents the baseline case of No Construction at covariate means. Whiskers on the bars indicate the 95% confidence interval on the mean.

Ratios of pairwise contrasts of estimated enhancements by activity_dist relative to No Construction are shown in Table 22 in addition to lower and upper confidence limits (CL), percent change and p-values. Ratios (effects) below 1 represented a decrease relative to No Construction while ratios above 1 indicated increases. Sidewalk/Shoulder Soil activities which occurred adjacent to measurements had 336% higher enhancements than No Construction ($p<0.01$). Eathwork which occurred in the same zone as and adjacent to the measurements had 283% and 50% higher enhancements, respectively, compared to No Construction ($p<0.01$) and enhancements modeled adjacent to and in the same zone as HMA activities were 82% and 80% larger, respectively, than No Construction ($p<0.01$). Modeled enhancements in the same zone as Striping were 181% larger compared to No Construction ($p=0.05$).

Table 22. Model 1 (coarsePM US 40): Pairwise Contrasts: Effect sizes, CIs, % Change, and p-values

Contrast	Effect	Lower CL	Upper CL	% Change	p-value
Undefined_samezone / No Construction	4.60	0.30	70.55	360.19	0.67
Sidewalk/Shoulder Soil_adjacent / No Construction	**4.36**	**1.96**	**9.69**	**335.79**	**0.00**
Asphalt Milling_samezone / No Construction	4.10	0.93	18.00	309.85	0.07
Earthwork_samezone / No Construction	**3.83**	**2.88**	**5.11**	**283.50**	**0.00**
Saw Cutting and Other_far / No Construction	3.40	0.37	31.55	239.97	0.69
Striping_samezone / No Construction	**2.81**	**0.99**	**7.99**	**181.15**	**0.05**
Rigid Pavement_adjacent / No Construction	0.13	0.01	1.99	-86.95	0.30
HMA_samezone / No Construction	**1.82**	**1.13**	**2.95**	**82.43**	**0.00**
HMA_adjacent / No Construction	**1.80**	**1.20**	**2.70**	**80.44**	**0.00**
Asphalt Milling_adjacent / No Construction	0.31	0.07	1.36	-68.83	0.24
Rigid Pavement_samezone / No Construction	0.38	0.01	17.68	-62.08	0.99
Sidewalk/Shoulder Soil_samezone / No Construction	1.61	0.78	3.32	60.51	0.49
Undefined_far / No Construction	0.41	0.04	3.77	-59.42	0.91
Striping_far / No Construction	0.46	0.10	2.24	-53.70	0.80
Undefined_adjacent / No Construction	0.47	0.03	7.22	-52.53	0.99
Earthwork_adjacent / No Construction	**1.51**	**1.13**	**2.01**	**50.99**	**0.00**
Earthwork_far / No Construction	0.61	0.44	0.85	-39.27	0.00
Saw Cutting and Other_adjacent / No Construction	0.65	0.16	2.57	-35.15	0.97
Saw Cutting and Other_samezone / No Construction	0.69	0.17	2.77	-30.60	0.99
Sidewalk/Shoulder Soil_far / No Construction	0.77	0.18	3.38	-22.69	1.00
HMA_far / No Construction	1.18	0.74	1.90	18.41	0.95
Asphalt Milling_far / No Construction	0.88	0.22	3.51	-12.24	1.00
Striping_adjacent / No Construction	0.93	0.31	2.75	-7.05	1.00

Activity-distance categories with ratios significantly ($p \leq 0.05$) greater than 1.0 indicate higher levels than No Construction and are displayed in bold font.

Results from Model 2 illustrate the estimated marginal mean enhancements by zone for the various construction activities performed at the site while covariates were kept constant at parameter means or baseline levels (Figure 116). Estimated mean hourly enhancements by construction activity and zone ranged from <3 $\mu g/m^3$ to 92 $\mu g/m^3$. Like PM_{10}, differences across zones were much more pronounced during construction than during periods of no construction. Large, estimated enhancements are evident for zones 2, 3 and 4 especially during Earthwork, Asphalt Milling, HMA and Sidewalk/Shoulder Soil work.

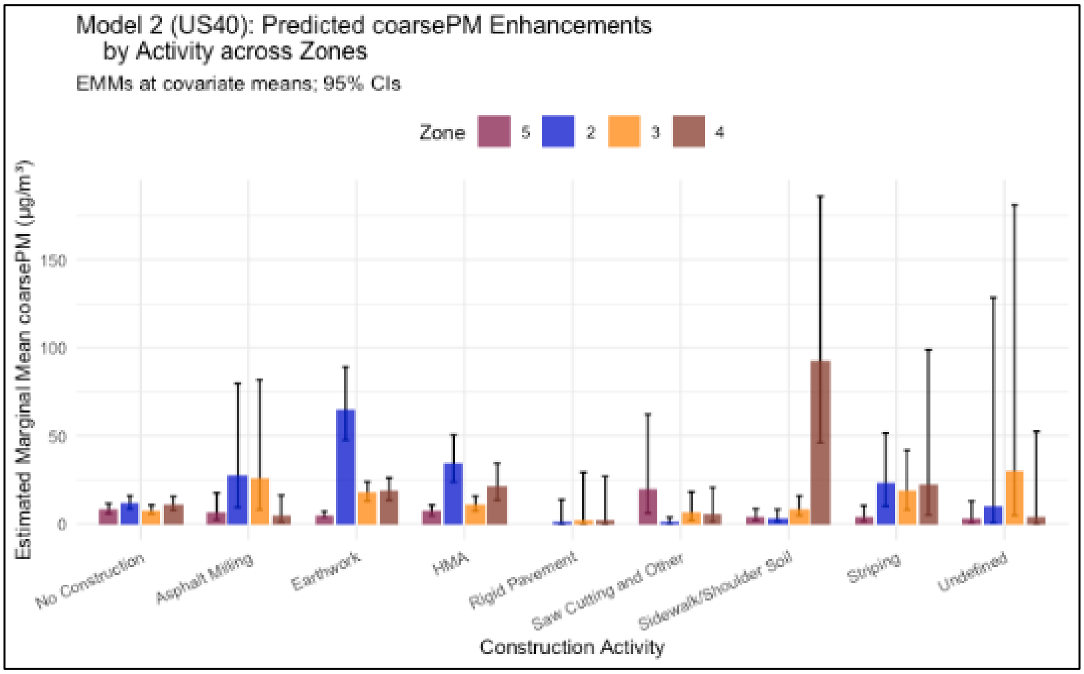
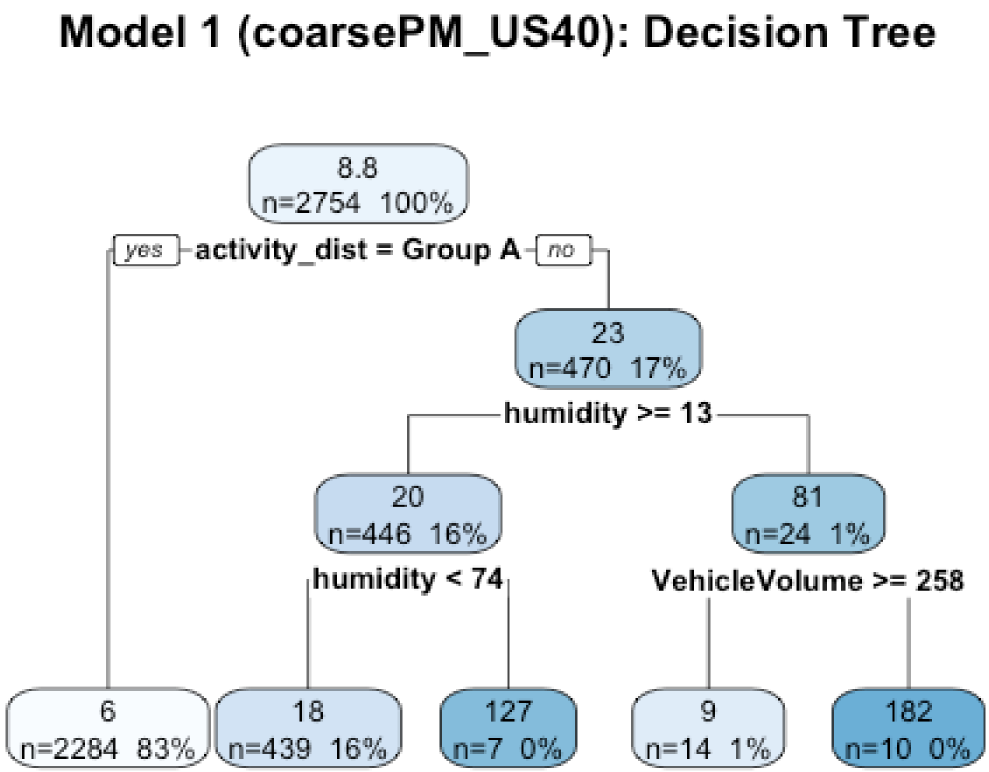


Figure 116. Model 2 (US 40), Estimated Marginal Mean Coarse PM Enhancements by Activity and Zones

Note: Whiskers indicate 95% confidence interval on mean.

A pruned decision tree using Model 1 is shown in Figure 117. Here the criteria used to most efficiently split observed enhancements into 5 bins was determined by activity_dist, humidity and vehicle volume. The pathways to the largest and smallest enhancements were almost identical to PM_{10} decision tree results. The path to the largest enhancements were associated with activity_dist categories from group B (23 µg/m^3), very dry conditions (<13 % RH, 81 µg/m^3) and when vehicle volume was below 258 counts/hour (182 µg/m^3). The path to the lowest enhancements was associated with activity_dist categories in group A (6 µg/m^3).



Group A
"Asphalt Milling_adjacent"
"Asphalt Milling_far"
"Earthwork_adjacent"
"Earthwork_far"
"HMA_adjacent"
"HMA_far"
"HMA_samezone"
"No Construction"
"Rigid Pavement_adjacent"
"Rigid Pavement_samezone"
"Saw Cutting and Other_adjacent"
"Saw Cutting and Other_far"
"Saw Cutting and Other_samezone"
"Sidewalk/Shoulder Soil_far"
"Sidewalk/Shoulder Soil_samezone"
"Striping_adjacent"
"Striping_far"
"Striping_samezone"
"Undefined_adjacent"
"Undefined_far"
"Undefined_samezone"

Group B
"Asphalt Milling_samezone"
"Earthwork_samezone"
"Sidewalk/Shoulder Soil_adjacent"

Figure 117. Model 1 (Coarse PM US 40) Decision Tree

The random forest of Model 1 ranks vehicle volume, WD and activity_dist as the top 3 most important variables in reducing overall model error, see Figure 118.

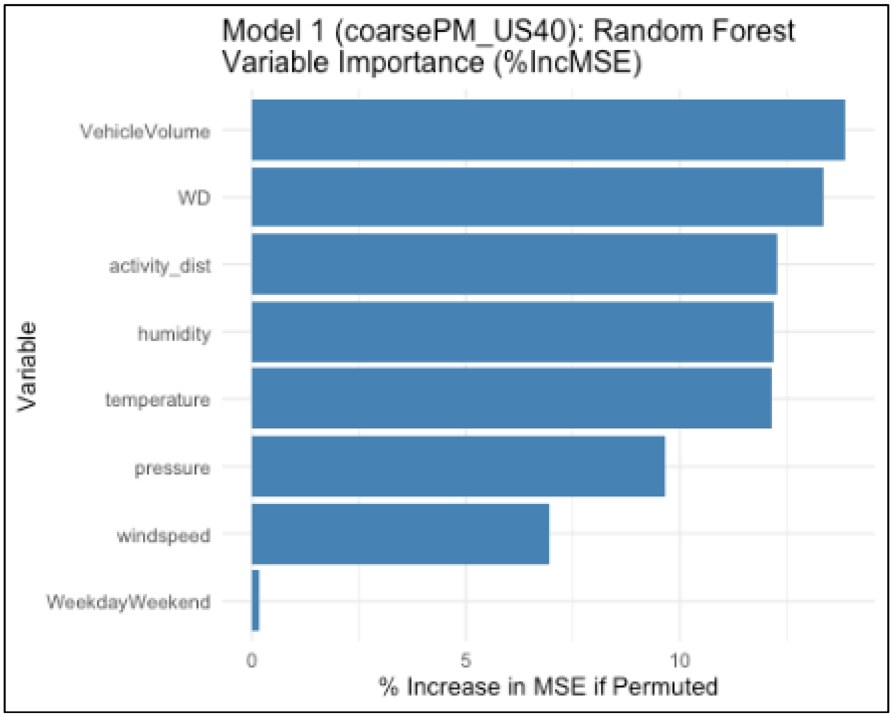


Figure 118. Model 1 (Coarse PM US 40), Random Forest Variable Importance (%IncMSE)

Appendix C. Additional Models Characteristics

The following section presents additional details of modeling results. R2 (R-squared) and ICC (interclass correlation coefficients) results are reported for each model for each pollutant. ICC values closer to one represent strong spatial variability while lower ICC values, closer to 0, indicate high temporal variability and more spatial likeness (homogeneity). These results also indicate a mix of correlation, R2, between model predictions and observed values. These are lower R2 values (weaker correlations) than pod sensor signal models (e.g. Equation 1) because unlike the pod sensor signal models, these models estimate hourly pollutant enhancements using the descriptive variables in Equation 2 with the expressed goal of elucidating the impacts of construction activities on air quality. Combining air sensor measurements (Equation 1) with statistical models like these (Equation 2) can not only characterize local air quality but aid in detecting and quantifying impacts of specific activities and sources to ambient air quality.

C.1. US6 Models

C.1.1. CO Models: US 6

Model 1:

GLMM

Number of obs: 5464, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.499

R2 for Mixed Models

Conditional R2: 0.191

Marginal R2: 0.068

Intraclass Correlation Coefficient

Adjusted ICC: 0.133

Unadjusted ICC: 0.124

R-squared (Decision Tree, Model 1): 0.117

R-squared (Random Forest, Model 1): 0.474

Model 2:

GLMM

Number of obs: 5464, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.496

R2 for Mixed Models

Conditional R2: 0.224

Marginal R2: 0.096

Intraclass Correlation Coefficient

Adjusted ICC: 0.142

Unadjusted ICC: 0.129

R-squared (Decision Tree, Model 2): 0.145

R-squared (Random Forest, Model 2): 0.59

C.1.2. NO Models: US 6

Model 1:

GLMM

Number of obs: 5178, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.499

R2 for Mixed Models

Conditional R2: 0.277

Marginal R2: 0.051

Intraclass Correlation Coefficient

Adjusted ICC: 0.238

Unadjusted ICC: 0.226

R-squared (Decision Tree, Model 1): 0.085

R-squared (Random Forest, Model 1): 0.391

Model 2

GLMM

Number of obs: 5178, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.477

R2 for Mixed Models

Conditional R2: 0.568

Marginal R2: 0.204

Intraclass Correlation Coefficient

Adjusted ICC: 0.457

Unadjusted ICC: 0.364

R-squared (Decision Tree, Model 2): 0.068

R-squared (Random Forest, Model 2): 0.512

C.1.3. NO_2 Models: US 6

Model 1:

GLMM:

Number of obs: 5380, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.54

R2 for Mixed Models

Conditional R2: 0.191

Marginal R2: 0.072

Intraclass Correlation Coefficient

Adjusted ICC: 0.128

Unadjusted ICC: 0.119

R-squared (Decision Tree, Model 1): 0.101

R-squared (Random Forest, Model 1): 0.466

Model 2:

GLMM:

Number of obs: 5380, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.532

R2 for Mixed Models

Conditional R2: 0.276

Marginal R2: 0.173

Intraclass Correlation Coefficient

Adjusted ICC: 0.125

Unadjusted ICC: 0.104

R-squared (Decision Tree, Model 2): 0.125

R-squared (Random Forest, Model 2): 0.562

C.1.4. NO_x Models: US 6

Model 1:

GLMM:

Number of obs: 5237, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.467

R2 for Mixed Models

Conditional R2: 0.222

Marginal R2: 0.054

Intraclass Correlation Coefficient

Adjusted ICC: 0.178

Unadjusted ICC: 0.168

R-squared (Decision Tree, Model 1): 0.08

R-squared (Random Forest, Model 1): 0.432

Model 2:

GLMM

Number of obs: 5237, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.456

R2 for Mixed Models

Conditional R2: 0.379

Marginal R2: 0.160

Intraclass Correlation Coefficient

Adjusted ICC: 0.261

Unadjusted ICC: 0.219

R-squared (Decision Tree, Model 2): 0.084

R-squared (Random Forest, Model 2): 0.537

C.1.5. tVOC Models: US 6

Model 1:

GLMM:

Number of obs: 5499, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.422

R2 for Mixed Models

Conditional R2: 0.219

Marginal R2: 0.030

Intraclass Correlation Coefficient

Adjusted ICC: 0.195

Unadjusted ICC: 0.189

R-squared (Decision Tree, Model 1): 0.072

R-squared (Random Forest, Model 1): 0.331

Model 2:

GLMM:

Number of obs: 5499, groups: Location, 9

Dispersion estimate for Gamma family (sigma^2): 0.414

R2 for Mixed Models

Conditional R2: 0.277

Marginal R2: 0.067

Intraclass Correlation Coefficient

Adjusted ICC: 0.226

Unadjusted ICC: 0.211

R-squared (Decision Tree, Model 2): 0.111

R-squared (Random Forest, Model 2): 0.456

C.1.6. $PM_{2.5}$ Models: US 6

Model 1:

GLMM:

Number of obs: 4076, groups: Location, 7

Dispersion estimate for Gamma family (sigma^2): 0.604

R2 for Mixed Models

Conditional R2: 0.287

Marginal R2: 0.150

Intraclass Correlation Coefficient

Adjusted ICC: 0.161

Unadjusted ICC: 0.137

R-squared (Decision Tree, Model 1): 0.139

R-squared (Random Forest, Model 1): 0.623

Model 2:

GLMM:

Number of obs: 4076, groups: Location, 7

Dispersion estimate for Gamma family (sigma^2): 0.597

R2 for Mixed Models

Conditional R2: 0.313

Marginal R2: 0.165

Intraclass Correlation Coefficient

Adjusted ICC: 0.177

Unadjusted ICC: 0.148

R-squared (Decision Tree, Model 2): 0.276

R-squared (Random Forest, Model 2): 0.703

C.2. US 40 Models

C.2.1. CO Models: US 40

Model 1:

GLMM

Number of obs: 11037, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.355

R2 for Mixed Models

Conditional R2: 0.334

Marginal R2: 0.052

Intraclass Correlation Coefficient

Adjusted ICC: 0.298

Unadjusted ICC: 0.282

R-squared (Decision Tree, Model 1 predictors): 0.088

R-squared (Random Forest, Model 1 predictors): 0.359

Model 2:

GLMM:

Number of obs: 11037, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.355

R2 for Mixed Models

Conditional R2: 0.270

Marginal R2: 0.162

Intraclass Correlation Coefficient

Adjusted ICC: 0.129

Unadjusted ICC: 0.108

R-squared (Decision Tree, Model 2 predictors): 0.1

R-squared (Random Forest, Model 2 predictors): 0.505

C.2.2. NO Models: US 40

Model 1:

GLMM:

Number of obs: 9021, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.593

R2 for Mixed Models

Conditional R2: 0.327

Marginal R2: 0.119

Intraclass Correlation Coefficient

Adjusted ICC: 0.236

Unadjusted ICC: 0.208

R-squared (Decision Tree, Model 1): 0.135

R-squared (Random Forest, Model 1): 0.386

Model 2:

GLMM:

Number of obs: 9021, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.592

R2 for Mixed Models

Conditional R2: 0.249

Marginal R2: 0.200

Intraclass Correlation Coefficient

Adjusted ICC: 0.062

Unadjusted ICC: 0.050

R-squared (Decision Tree, Model 2 predictors): 0.225

R-squared (Random Forest, Model 2 predictors): 0.63

C.2.3. NO_2 Models: US 40

Model 1:

GLMM:

Number of obs: 11390, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.398

R2 for Mixed Models

Conditional R2: 0.189

Marginal R2: 0.021

Intraclass Correlation Coefficient

Adjusted ICC: 0.172

Unadjusted ICC: 0.168

R-squared (Decision Tree, Model 1): 0.049

R-squared (Random Forest, Model 1): 0.332

Model 2:

GLMM:

Number of obs: 11390, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.397

R2 for Mixed Models

Conditional R2: 0.172

Marginal R2: 0.041

Intraclass Correlation Coefficient

Adjusted ICC: 0.136

Unadjusted ICC: 0.131

R-squared (Decision Tree, Model 2): 0.117

R-squared (Random Forest, Model 2): 0.541

C.2.4. NO_x Models: US 40

Model 1:

GLMM:

Number of obs: 10452, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.423

R2 for Mixed Models

Conditional R2: 0.303

Marginal R2: 0.079

Intraclass Correlation Coefficient

Adjusted ICC: 0.243

Unadjusted ICC: 0.224

R-squared (Decision Tree, Model 1): 0.135

R-squared (Random Forest, Model 1): 0.426

Model 2:

GLMM:

Number of obs: 10452, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.421

R2 for Mixed Models

Conditional R2: 0.247

Marginal R2: 0.203

Intraclass Correlation Coefficient

Adjusted ICC: 0.055

Unadjusted ICC: 0.044

R-squared (Decision Tree, Model 2): 0.163

R-squared (Random Forest, Model 2): 0.63

C.2.5. tVOC Models: US 40

Model 1:

GLMM:

Number of obs: 10621, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.455

R2 for Mixed Models

Conditional R2: 0.241

Marginal R2: 0.050

Intraclass Correlation Coefficient Adjusted ICC: 0.201

Unadjusted ICC: 0.191

R-squared (Decision Tree, Model 1): 0.034

R-squared (Random Forest, Model 1): 0.341

Model 2:

GLMM:

Number of obs: 10621, groups: Location, 10

Dispersion estimate for Gamma family (sigma^2): 0.452

R2 for Mixed Models

Conditional R2: 0.298

Marginal R2: 0.183

Intraclass Correlation Coefficient

Adjusted ICC: 0.142

Unadjusted ICC: 0.116

R-squared (Decision Tree, Model 2): 0.16

R-squared (Random Forest, Model 2): 0.559

C.2.6. $PM_{2.5}$ Models: US 40

Model 1:

GLMM:

Number of obs: 8813, groups: Location, 8

Dispersion estimate for Gamma family (sigma^2): 0.396

R2 for Mixed Models

Conditional R2: 0.364

Marginal R2: 0.128

Intraclass Correlation Coefficient

Adjusted ICC: 0.271

Unadjusted ICC: 0.236

R-squared (Decision Tree, Model 1): 0.172

R-squared (Random Forest, Model 1): 0.71

Model 2:

GLMM:

Number of obs: 8813, groups: Location, 8

Dispersion estimate for Gamma family (sigma^2): 0.396

R2 for Mixed Models

Conditional R2: 0.357

Marginal R2: 0.150

Intraclass Correlation Coefficient

Adjusted ICC: 0.244

Unadjusted ICC: 0.207

R-squared (Decision Tree, Model 2): 0.172

R-squared (Random Forest, Model 2): 0.79

C.2.7. PM_{10} Models: US 40

Model 1:

GLMM:

Number of obs: 3145, groups: Location, 4

Dispersion estimate for Gamma family (sigma^2): 1.39

R2 for Mixed Models

Conditional R2: 0.382

Marginal R2: 0.301

Intraclass Correlation Coefficient

Adjusted ICC: 0.117

Unadjusted ICC: 0.082

R-squared (Decision Tree, Model 1): 0.191

R-squared (Random Forest, Model 1): 0.783

Model 2:

GLMM:

Number of obs: 3145, groups: Location, 4

Dispersion estimate for Gamma family (sigma^2): 1.37

R2 for Mixed Models

Conditional R2: NA

Marginal R2: 0.411

R-squared (Decision Tree, Model 2): 0.164

R-squared (Random Forest, Model 2): 0.861

C.2.8. CoarsePM Models: US 40

Model 1:

GLMM:

Number of obs: 2754, groups: Location, 4

Dispersion estimate for Gamma family (sigma^2): 1.65

R2 for Mixed Models

Conditional R2: 0.450

Marginal R2: 0.360

Intraclass Correlation Coefficient

Adjusted ICC: 0.140

Unadjusted ICC: 0.090

R-squared (Decision Tree, Model 1): 0.191

R-squared (Random Forest, Model 1): 0.779

Model 2:

GLMM:

Number of obs: 2754, groups: Location, 4

Dispersion estimate for Gamma family (sigma^2): 1.64

R2 for Mixed Models

Conditional R2: NA

Marginal R2: 0.481

R-squared (Decision Tree, Model 2): 0.256

R-squared (Random Forest, Model 2): 0.865

Appendix D. Construction Data Form

D.1. Proposed Construction Data Form Fundamental Items

- Construction activities start time
- Construction activities interruption period
- Construction activities finish time
- Precise construction activity's location
- Equipment used
- Materials used
- Quantities
- Pollution mitigation strategies (PMS) employed
- Frequency and duration of PMS applied
- Timeline of weather conditions throughout the project