

Concentrations and Health Effects of Particulate Matter on the London Underground

Michael Hedges

**Environmental Research Group
School of Public Health / Faculty of Medicine
Imperial College London**

Thesis submitted to fulfil the requirements for the degree of Doctor of Philosophy (PhD)

Declaration of own work

I declare that this PhD thesis, entitled:

'Concentrations and Health Effects of Particulate Matter on the London Underground'

is entirely my own work and that where any material, that could be construed as the work of others, is fully cited and referenced, and/or with appropriate acknowledgement given. The Medical Research Council (MRC) funded health study investigating "Exposure to particulate matter on the London Underground in healthy participants and participants with Chronic Obstructive Pulmonary Disease (COPD)" was undertaken with the assistance of the Clinical Research Fellow. The exposure measurement campaigns were assisted by members of the Environmental Research Group. The omics analysis was undertaken with assistance of members of Professor Marc Chadeau-Hyam's team. This work has not been submitted in whole or in part for any other degree or qualification in this, or at any other, educational institute.

Name of Student: Michael Hedges

Name of Supervisors: Dr David Green, Professor Marc Chadeau-Hyam and Dr Rudy Sinharay

Copyright Declaration

The copyright of this thesis rests with the author. Unless otherwise indicated, its contents are licensed under a [Creative Commons Attribution 4.0 International Licence](#) (CC BY).

Under this licence, you may copy and redistribute the material in any medium or format for both commercial and non-commercial purposes. You may also create and distribute modified versions of the work. This on the condition that you credit the author.

When reusing or sharing this work, ensure you make the licence terms clear to others by naming the licence and linking to the licence text. Where a work has been adapted, you should indicate that the work has been changed and describe those changes.

Please seek permission from the copyright holder for uses of this work that are not included in this licence or permitted under UK Copyright Law.

Abstract

Subway systems provide an important mode of sustainable urban transportation. However, there are increasing concerns over the elevated levels of particulate matter (PM) concentrations found in the subway and the potential health effects to passengers and staff. This thesis aimed to make high quality measurements of the concentrations and composition of PM, and other air pollutants, nitrogen dioxide and ozone (NO₂, O₃), that passengers travelling on the rail networks in London are exposed to. A small, wheeled measurement platform was developed – it made use of smaller, lower power technology which has enabled a long-term, exposure assessment of the spatial and temporal variability of air pollutants. A comprehensive set of laboratory and field experiments were undertaken to ensure the highest quality data from the different transport micro-environments. These measurements were used as part of a panel study examining the health impacts for participants with Cardiovascular Obstructive Pulmonary Disease (COPD) and healthy volunteers travelling on the subway and overground trains.

PM_{2.5} concentrations on the subway journey were 321 µg m⁻³ in the tunnelled sections (198 µg m⁻³ for the complete journey), with concentrations found to be affected by ventilation, tunnel depth and seasonality. These are far higher than the overground journey (4 µg m⁻³) and mean ambient concentrations in London over the same period (8 µg m⁻³). The oxidative potential of subway PM_{2.5} was found to be highly correlated to transition metals generated underground by train-related emission processes. A methodology for a multi-omics assessment of molecular and biochemical pathways affected by subway exposure was developed for use in a further cross-omics subway study. This work will provide a better understanding of the exposure in different transport microenvironments, the potential health impacts and encourage the application of mitigation strategies to reduce exposure in London and other subway systems worldwide.

Table of Contents

DECLARATION OF OWN WORK	2
ABSTRACT	3
TABLE OF CONTENTS	4
TABLE OF FIGURES	9
TABLE OF TABLES	16
ACKNOWLEDGEMENTS	18
PUBLICATIONS AND CONFERENCE PROCEEDINGS	19
LIST OF ABBREVIATIONS.....	20
LIST OF KEY POLLUTANTS.....	21
CHAPTER 1 INTRODUCTION	22
1.1 BACKGROUND.....	22
1.2 INTRODUCTION	23
1.3 THESIS RATIONALE	27
1.4 AIM AND OBJECTIVES.....	31
1.5 THESIS STRUCTURE	32
CHAPTER 2 LITERATURE REVIEW	34
2.1 LITERATURE REVIEW SEARCH STRATEGY	34
2.2 THE SUBWAY MICROENVIRONMENT.....	38
2.3 MEASURING AIR QUALITY	39
2.4 FACTORS AFFECTING CONCENTRATIONS.....	41
2.5 SOURCES OF PARTICULATE MATTER	44
2.6 HEALTH STUDIES.....	46
2.7 CONTRIBUTION TO PERSONAL EXPOSURE	50
2.8 REMEDIAL MEASURES TO REDUCE PM CONCENTRATIONS	50
2.9 CURRENT KNOWLEDGE GAPS	51
CHAPTER 3 MATERIALS AND METHODS.....	53

3.1	INTRODUCTION	53
3.2	ADDRESSING MEASUREMENT CHALLENGES	54
3.3	MOBILE REFERENCE STATION (MoRS)	56
3.3.1	Instrument housing	57
3.3.2	MoRS Measurement Instrumentation	57
3.3.3	Gaseous Measurements	61
3.3.4	Noise	62
3.3.5	MoRS development	62
3.4	DATA COLLECTION	66
3.5	MEASURING PARTICIPANT PERSONAL EXPOSURE	67
3.5.1	Study Route	67
3.5.2	Experimental design	68
3.5.3	Subway and Overground Trial Journeys	69
3.6	RESILIENCE PLANNING	70
3.6.1	Alternative starting stations and lines	70
3.6.2	Instrument Breakdown	70
3.7	QUALITY ASSURANCE AND QUALITY CONTROL	71
3.7.1	Mini-Wras NaCl Aerosol Laboratory Testing	72
3.7.2	Field intercomparison campaigns	73
3.7.3	Field intercomparison background sites	74
3.7.4	Marylebone Road Field intercomparison kerbside site	75
3.7.5	Hampstead Station measurement facility	76
3.8	RESULTS AND DISCUSSION	77
3.8.1	Laboratory intercomparison using a polydisperse NaCl aerosol	77
3.8.2	Urban background and kerbside site field campaigns	79
3.8.3	North Kensington Field Campaign	84
3.8.4	Marylebone Road Kerbside PM _{2.5} Field Campaign	84
3.8.5	Hampstead subway Station PM _{2.5} Field Campaign	86
3.8.6	Summary of derived scaling factors	90
3.9	CONCLUSION	90

CHAPTER 4	CHARACTERISING EXPOSURE IN THE LONDON UNDERGROUND	93
4.1	INTRODUCTION	93
4.2	METHODS	96
4.2.1	Train journeys	96
4.2.2	Exposure measurements	99
4.2.3	Spatial mapping	101
4.2.4	Repeated exposure journeys	101
4.2.5	Train carriage measurement position	103
4.2.6	Calibration factors	104
4.3	RESULTS	105
4.3.1	Subway and overground exposure assessment	105
4.3.2	Face mask effect	113
4.3.3	Outbound and return subway journeys	115
4.3.4	Particle number counts	125
4.3.5	Effect of ventilation on particle size, PM _{2.5} and NO ₂ concentrations	127
4.3.6	Seasonality and PM _{2.5} concentrations	132
4.3.7	Hampstead station platform measurements	134
4.3.8	Size distributions in different locations	138
4.4	CONCLUSION	139
CHAPTER 5	LABORATORY ANALYSIS OF METALS AND OXIDATIVE POTENTIAL	141
5.1	BACKGROUND	141
5.2	INTRODUCTION	141
5.3	METHODOLOGY	144
5.3.1	PM _{2.5} filter collection	144
5.3.2	Filter preparation for toxicological analysis	145
5.3.3	Filter processing for ascorbic acid	146
5.3.4	Filter processing for glutathione	147
5.3.5	Filter preparation for acid digestion for ICP-MS elemental analysis	149
5.3.6	Quantifying AA and GSH depletion	150

5.3.7	Metals analysed by ICP-MS	150
5.4	RESULTS.....	151
5.4.1	Underground and overground antioxidant consumed.....	151
5.4.2	Determination of antioxidant depletion rates	154
5.4.3	PM _{2.5} metal composition	157
5.5	EFFECTS OF SUBWAY PM _{2.5} CHEMICAL COMPOSITION ON OP	158
5.6	CONCLUSION	163
CHAPTER 6 MULTI-OMIC SIGNATURES OF TRAFFIC RELATED AIR POLLUTION		165
6.1	BACKGROUND.....	165
6.2	INTRODUCTION	166
6.3	METHODS.....	167
6.3.1	Oxford Street study design.....	167
6.3.2	Participant exposure measurements	168
6.3.3	Omics data acquisition and pre-processing.....	169
6.3.4	Transcriptomics data	170
6.3.5	Technical confounding correction	170
6.3.6	Statistical analysis.....	171
6.3.7	Pathway analysis	172
6.3.8	Conditional independence network	173
6.4	RESULTS.....	174
6.4.1	Data overview.....	174
6.4.2	Metabolomic and transcriptomic markers of TRAP exposures	174
6.4.3	Pathway enrichment and annotations	178
6.4.4	Metabolomic network analysis	181
6.5	CONCLUSION	183
CHAPTER 7 DISCUSSION AND CONCLUSION.....		186
7.1	SUMMARY.....	186
7.2	STRENGTHS AND LIMITATIONS	191
7.2.1	Strengths	191

7.2.2 Limitations	193
7.3 SUBWAY AIR QUALITY IMPLICATIONS.....	193
7.4 FUTURE RESEARCH AND RECOMMENDATIONS	195
REFERENCES.....	198
APPENDIX A: SUPPLEMENTARY FOR CHAPTER 3.....	220
APPENDIX B: SUPPLEMENTARY FOR CHAPTER 4.....	227
APPENDIX C: SUPPLEMENTARY FOR CHAPTER 5	232
APPENDIX D: SUPPLEMENTARY FOR CHAPTER 6	241

Table of Figures

FIGURE 2.1: RESULTS FOR SEARCH STRATEGIES FOR EACH DATABASE.	36
FIGURE 2.2: LITERATURE SEARCH METHODOLOGY. PAPERS WERE SELECTED FOR INCLUSION IN THE REVIEW BY COMBINING EACH OF THE SEARCH BOXES WITH THE BOOLEAN OPERATOR “AND”, ACROSS FIVE DATABASES. THE PAPERS YIELDED BY THIS INITIAL SEARCH WERE REFINED TO ONLY THOSE OF RELEVANCE TO THE SUBWAY AND SUPPLEMENTED BY RELEVANT PAPERS USED IN THE REVIEW OF CHANG ET AL., (2021). THIS YIELDED THE 245 PAPERS FORMING THE CORE BODY OF LITERATURE FOR THIS REVIEW. FURTHER STUDIES HAVE BEEN INCLUDED AND CITED WHERE APPROPRIATE.	37
FIGURE 3.1: MORS V1 (LEFT) AND MORS V2 (CENTRE) AND THE MANNEQUIN HEAD (RIGHT) SHOWING THE FILTER HOLDER SET-UP	64
FIGURE 3.2 THE FINAL DESIGN AND CONFIGURATION OF THE MOBILE REFERENCE STATION (MORS) FOR USE IN THE SUBWAY EXPOSURE ASSESSMENT TO MEASURE PERSONAL EXPOSURES OF THE PARTICIPANTS IN THE MRC STUDY.	65
FIGURE 3.3: MOBILE REFERENCE STATION (MORS) (SCHEMATIC (LEFT), SAMPLING CONFIGURATION (CENTRE) AND PICTURE (RIGHT)).	66
FIGURE 3.4 THE STATION LAYOUT AT WILLESDEN JUNCTION TRAIN STATION SHOWING (A) THE ENTRANCE TO THE STATION AND ACCESS BRIDGE ACROSS THE RAILWAY TRACKS TO THE LIFT. (B) THE LIFT FROM THE STATION CONCOURSE TO THE PLATFORM, (C)) THE WALK FROM THE LIFT TO THE OVERGROUND (X) AND SUBWAY (Y) TRAINS AND (D) THE SUBWAY TRACK IN THE ELEPHANT & CASTLE DIRECTION.	69
FIGURE 3.5: SCHEMATIC REPRESENTATION OF THE NANO-SIZER CALIBRATION FOR THE MINI-WRAS.	73
FIGURE 3.6 LOCATION OF FIXED BACKGROUND AND KERBSIDE MONITORING SITES AND HAMPSTEAD UNDERGROUND STATION USED IN THIS STUDY FOR INTERCOMPARISONS AND CO-LOCATIONS OF THE MOBILE REFERENCE STATION (MORS) INSTRUMENTS AGAINST REFERENCE INSTRUMENTS.	75
FIGURE 3.7: THE MOBILE REFERENCE STATION (MORS) LOCATED AT THE HONOR OAK PARK, URBAN BACKGROUND SITE, FOR INSTRUMENT INTERCOMPARISONS AND CO-LOCATIONS WITH REFERENCE INSTRUMENTS AT THE SITE.....	76
FIGURE 3.8: THE MARYLEBONE ROAD KERBSIDE SITE, WHERE THE MINI-WRAS INTERCOMPARISON AND CO-LOCATION WITH THE REFERENCE INSTRUMENTS TOOK PLACE. THE MINI-WRAS WAS PLACED IN A STEVENSON BOX FOR PROTECTION. ..	76
FIGURE 3.9: THE MOBILE REFERENCE STATION (MORS) IN THE AIR QUALITY FACILITY ON THE NORTHBOUND HAMPSTEAD SUBWAY PLATFORM BEING CO-LOCATED ALONGSIDE A PARTISOL 2025.....	77
FIGURE 3.10: PERFORMANCE OF THE GRIMM MINI WRAS SPECTROMETER 1371 AND SMPS USING A POLYDISPERSE AEROSOL GENERATED FROM A 0.1% NaCl SOLUTION USING AN AEROSOL GENERATOR IN THE LABORATORY. THE SOLID	

LINE SHOWS THE SMPS WITH THE BLACK DOTTED LINES SHOWING THE $\pm 20\%$ RANGE. THE MINI-WRAS IS SHOWN AS A SOLID RED LINE WITH MID POINTS DIAMETERS SHOWN AS WHITE DOTS.	79
FIGURE 3.11 : INTER-COMPARABILITY OF THE GRIMM MINI WRAS SPECTROMETER 1371 AND SMPS SAMPLING AMBIENT AIR AT THE HONOR OAK PARK URBAN BACKGROUND SITE. THE BLUE SOLID LINE SHOWS THE SMPS WITH THE BLACK DOTTED LINES SHOWING THE SMPS $\pm 20\%$ RANGE. THE MINI-WRAS IS SHOWN AS A SOLID RED LINE WITH PARTICLE SIZE MIDPOINT DIAMETERS SHOWN AS WHITE DOTS.	80
FIGURE 3.12: TEMPORAL VARIATION OF PARTICLE NUMBER DISTRIBUTION AND PARTICLE NUMBER COUNTS OF (A) THE MINI-WRAS AND (B) THE SMPS MEASURED AT HONOR OAK PARK FROM 17 JANUARY 2022 TO 20 JANUARY 2022.	81
FIGURE 3.13: DEMING REGRESSION FOR THE MINI-WRAS AT THE HONOR OAK PARK URBAN BACKGROUND SITE ALONGSIDE A FIDAS 200E REFERENCE INSTRUMENT SHOWING (A) THE RAW $PM_{2.5}$ UNCORRECTED VALUES, (B) THE $PM_{2.5}$ DEMING REGRESSION AND (C) THE CORRECTED $PM_{2.5}$ VALUES.	82
FIGURE 3.14: DEMING REGRESSION FOR THE AIRYX ICAD AT THE HONOR OAK PARK URBAN BACKGROUND SITE ALONGSIDE A N500 REFERENCE INSTRUMENT SHOWING (A) THE RAW NO_2 UNCORRECTED VALUES, (B) THE NO_2 DEMING REGRESSION AND (C) THE CORRECTED NO_2 VALUES. (D), (E) AND (F) SHOW THE EQUIVALENT NO_x VALUES.	83
FIGURE 3.15: DEMING REGRESSION FOR THE 2B OZONE MONITOR AT THE NORTH KENSINGTON URBAN BACKGROUND SITE ALONGSIDE A T400 REFERENCE INSTRUMENT SHOWING (A) THE RAW O_3 UNCORRECTED VALUES, (B) THE O_3 DEMING REGRESSION AND (C) THE CORRECTED O_3 VALUES.	84
FIGURE 3.16: INTER-COMPARABILITY OF THE GRIMM MINI WRAS SPECTROMETER 1371 AND SMPS SAMPLING AMBIENT AIR AT THE MARYLEBONE ROAD KERBSIDE SITE. THE BLUE SOLID LINE SHOWS THE SMPS WITH THE BLACK DOTTED LINES SHOWING THE SMPS $\pm 20\%$ RANGE. THE MINI-WRAS IS SHOWN AS A SOLID RED LINE WITH PARTICLE SIZE MID-POINT DIAMETERS SHOWN AS WHITE DOTS.	85
FIGURE 3.17: DEMING REGRESSION FOR THE MINI-WRAS AT THE MARYLEBONE ROAD KERBSIDE SITE ALONGSIDE A BAM 1020 REFERENCE INSTRUMENT SHOWING (A) THE RAW $PM_{2.5}$ UNCORRECTED VALUES, (B) THE $PM_{2.5}$ DEMING REGRESSION AND (C) THE CORRECTED $PM_{2.5}$ VALUES.	86
FIGURE 3.18: INTER-COMPARABILITY OF THE GRIMM MINI WRAS SPECTROMETER 1371 AND A DEKATI ELECTRICAL LOW PRESSURE IMPACTOR (ELPI+) SIMULTANEOUSLY SAMPLING $PM_{2.5}$ ON THE NORTHBOUND PLATFORM AT HAMPSTEAD SUBWAY STATION. THE SOLID BLUE LINE SHOWS THE DEKATI WITH THE BLACK DOTTED LINES SHOWING THE DEKATI $\pm 20\%$ RANGE. THE MINI-WRAS IS SHOWN AS A SOLID RED LINE WITH PARTICLE SIZE MID-POINT DIAMETERS SHOWN AS WHITE DOTS.	87

FIGURE 3.19: DEMING REGRESSION FOR THE MINI-WRAS AT THE HAMSTEAD STATION MEASUREMENT SITE ALONGSIDE A PARTISOL 2025 REFERENCE INSTRUMENT SHOWING (A) THE RAW $PM_{2.5}$ UNCORRECTED VALUES, (B) THE $PM_{2.5}$ DEMING REGRESSION AND (C) THE CORRECTED $PM_{2.5}$ VALUES.....	88
FIGURE 3.20: DEMING REGRESSION FOR THE SIDEPAK ALONGSIDE THE MINI-WRAS ON A BAKERLOO LINE SUBWAY JOURNEY ON 17 OCTOBER 2022 SHOWING (A) THE RAW $PM_{2.5}$ UNCORRECTED VALUES, (B) THE $PM_{2.5}$ DEMING REGRESSION AND (C) THE CORRECTED $PM_{2.5}$ VALUES.....	89
FIGURE 3.21: DEMING REGRESSION FOR THE SIDEPAK ALONGSIDE THE MINI-WRAS ON AN OVERGROUND JOURNEY ON 24 OCTOBER 2022 SHOWING (A) THE RAW $PM_{2.5}$ UNCORRECTED VALUES, (B) THE $PM_{2.5}$ DEMING REGRESSION AND (C) THE CORRECTED $PM_{2.5}$ VALUES.	89
FIGURE 4.1: MAP OF THE LONDON UNDERGROUND SHOWING THE RETURN SUBWAY BAKERLOO LINE FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION (BROWN CIRCLES) AND THE ALTERNATIVE RETURN SUBWAY JUBILEE LINE JOURNEY FROM KILBURN STATION TO CANNING TOWN STATION (SILVER CIRCLES).	95
FIGURE 4.2: MAP OF THE LONDON OVERGROUND SHOWING THE RETURN OVERGROUND LINE JOURNEY FROM WILLESDEN JUNCTION STATION TO WATFORD JUNCTION STATION (RED CIRCLES) AND THE ALTERNATIVE RETURN OVERGROUND LINE JOURNEY FROM KENSAL RISE STATION TO STRATFORD STATION (BLUE CIRCLES).	95
FIGURE 4.3: THE POSITIONING OF MORS BETWEEN THE PARTICIPANTS MEASURING AT THE BREATHING HEIGHT OF THE PARTICIPANTS ON A SUBWAY JOURNEY (LEFT) AND AN OVERGROUND JOURNEY (RIGHT).	100
FIGURE 4.4: DIAGRAM SHOWING THE THREE MEASUREMENT POSITIONS OF THE RESEARCHERS FOR THE THREE BAKERLOO LINE RETURN JOURNEYS FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION IN THE FRONT (A), REAR (B) AND MIDDLE (C) CARRIAGES.	104
FIGURE 4.5: CONCENTRATIONS OF $PM_{2.5}$, NO_2 AND O_3 MEASURED ALONG THE RETURN JOURNEY BETWEEN WILLESDEN JUNCTION STATION AND ELEPHANT & CASTLE STATION ON 09 NOVEMBER 2022 ON A BAKERLOO LINE SUBWAY TRAIN. SHADED GREEN AREAS INDICATED THE TIMES WHEN THE TRAIN REMAINED IN A STATION. THE DOTTED BLACK LINES INDICATE WHEN THE TRAIN ENTERED AND EXITED THE SUBWAY TUNNEL. RED DOTTED LINES INDICATE BACKGROUND CONCENTRATIONS. $PM_{2.5}$ HAS BEEN SCALED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).....	106
FIGURE 4.6: CONCENTRATIONS OF $PM_{2.5}$, NO_2 AND O_3 MEASURED ALONG THE RETURN JOURNEY BETWEEN KILBURN STATION AND CANNING TOWN STATION ON 19 DECEMBER 2022 ON A JUBILEE LINE SUBWAY TRAIN. SHADED GREEN AREAS INDICATED THE TIMES WHEN THE TRAIN REMAINED IN A STATION. THE DOTTED BLACK LINES INDICATE WHEN THE TRAIN ENTERED AND EXITED THE SUBWAY TUNNEL. RED DOTTED LINES INDICATE BACKGROUND CONCENTRATIONS. $PM_{2.5}$ HAS BEEN SCALED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	108

FIGURE 4.7: CONCENTRATIONS OF $PM_{2.5}$, NO_2 AND O_3 MEASURED ALONG THE RETURN JOURNEY BETWEEN WILLESDEN JUNCTION STATION AND WATFORD JUNCTION STATION ON 13 JULY 2022 ON A WILLESDEN JUNCTION OVERGROUND TRAIN AND BETWEEN KENSAL RISE STATION AND STRATFORD STATION ON 14 NOVEMBER 2022 ON A KENSAL RISE OVERGROUND TRAIN. SHADED GREEN AREAS INDICATED THE TIMES WHEN THE TRAIN REMAINED IN A STATION. RED DOTTED LINES INDICATE BACKGROUND CONCENTRATIONS. $PM_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	109
FIGURE 4.8: REPEATED JOURNEYS ON THE BAKERLOO LINE DISPLAYING 35 COMPLETE RETURN JOURNEYS FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION FOR $PM_{2.5}$, NO_2 , NO_x AND O_3 . THE SHADED AREA REPRESENTS THE 95% CONFIDENCE INTERVALS. $PM_{2.5}$ HAS BEEN SCALED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	111
FIGURE 4.9: REPEATED JOURNEYS ON THE JUBILEE LINE DISPLAYING TWO COMPLETE RETURN JOURNEYS FROM KILBURN STATION TO CANNING TOWN STATION FOR $PM_{2.5}$, NO_2 , NO_x AND O_3 . THE SHADED AREA REPRESENTS THE 95% CONFIDENCE INTERVALS. $PM_{2.5}$ HAS BEEN SCALED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020)	113
FIGURE 4.10 REPEAT JOURNEYS ON THE RETURN BAKERLOO LINE JOURNEY FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION WEARING A MASK (BLUE LINE) AND WITHOUT WEARING A MASK (RED LINE). THE SHADED AREAS REPRESENT THE 95% CONFIDENCE INTERVALS. $PM_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	114
FIGURE 4.11: CUMULATIVE $PM_{2.5}$ EXPOSURE OVER THE COMPLETE BAKERLOO LINE RETURN JOURNEY WEARING A MASK (BLUE LINE) AND WITHOUT WEARING A MASK (RED LINE). THE SHADED AREA REPRESENTS THE 95% CONFIDENCE INTERVALS. $PM_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	115
FIGURE 4.12: CONCENTRATIONS OF $PM_{2.5}$, NO_2 , NO_x AND O_3 ON THE OUTBOUND JOURNEY FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION (BLUE LINE) AND THE RETURN JOURNEY FROM ELEPHANT & CASTLE STATION TO WILLESDEN JUNCTION STATION (RED LINE). THE SHADED AREA REPRESENTS THE 95% CONFIDENCE INTERVALS. $PM_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	116
FIGURE 4.13: BAR CHART SHOWING $PM_{2.5}$ CONCENTRATIONS COMPARED TO STATION DEPTH FOR EACH STATION ON THE RETURN BAKERLOO LINE JOURNEY FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION. $PM_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	122
FIGURE 4.14: BAR CHART SHOWING NO_2 CONCENTRATIONS COMPARED TO STATION DEPTH FOR EACH STATION ON THE RETURN BAKERLOO LINE JOURNEY FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION.	123

FIGURE 4.15: BAR CHART SHOWING NO_x CONCENTRATIONS COMPARED TO STATION DEPTH FOR EACH STATION ON THE RETURN BAKERLOO LINE JOURNEY FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION.	124
FIGURE 4.16: PARTICLE NUMBER COUNTS (PNC's) FOR THE RETURN BAKERLOO LINE JOURNEY FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION. THE SHADED AREA REPRESENTS THE 95% CONFIDENCE INTERVALS.	125
FIGURE 4.17: IDEALISED PARTICLE SIZE DISTRIBUTION DISPLAYING THE FOUR MODES: NUCLEATION, AITKEN, ACCUMULATION AND COARSE MODES. ALSO SHOWN ARE THE MAJOR FORMATION AND GROWTH MECHANISMS OF THE FOUR MODES OF AMBIENT PARTICLES. V = VOLUME, DP = PARTICLE DIAMETER.	128
FIGURE 4.18: $\text{PM}_{2.5}$ AND NO_2 CONCENTRATIONS COMPARED TO THE NUCLEATION, AITKEN, ACCUMULATION AND COARSE MODE PARTICLE CONCENTRATIONS FOR THE RETURN BAKERLOO LINE JOURNEY FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION. THE SHADED AREA REPRESENTS THE 95% CONFIDENCE INTERVALS. $\text{PM}_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	131
FIGURE 4.19: LONG-TERM VARIATION OF $\text{PM}_{2.5}$ CONCENTRATIONS FOR EACH RETURN JOURNEY FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION IN THE TUNNELLED SECTIONS OF THE BAKERLOO LINE (WINTER = PURPLE, SPRING = BLUE, SUMMER = GREEN AND AUTUMN = RED). THE LOWER AND UPPER HINGES CORRESPOND TO THE 25 TH AND 75 TH PERCENTILES, THE HORIZONTAL LINE TO THE MEDIAN AND THE WHISKERS TO $1.55 \times$ THE IQR (APPROX. 95% PERCENTILE). $\text{PM}_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	133
FIGURE 4.20: $\text{PM}_{2.5}$ CONCENTRATIONS IN THE TUNNELLED SECTIONS OF THE BAKERLOO LINE SHOWING SEASONAL VARIATION BETWEEN AUTUMN/WINTER (RED) AND SPRING/SUMMER (BLUE) (LEFT). $\text{PM}_{2.5}$ CONCENTRATIONS IN THE OVERGROUND SHOWING SEASONAL VARIATION BETWEEN AUTUMN/WINTER (RED) AND SPRING/SUMMER (BLUE) (RIGHT). THE LOWER AND UPPER HINGES CORRESPOND TO THE 25 TH AND 75 TH PERCENTILES, THE HORIZONTAL LINE TO THE MEDIAN, AND THE WHISKERS TO $1.5 \times$ THE IQR (APPROX. 95% PERCENTILE). $\text{PM}_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	134
FIGURE 4.21: TIME-SERIES OF $\text{PM}_{2.5}$ CONCENTRATIONS (RED LINE) AND PM_{10} CONCENTRATIONS (BLUE LINE) MEASURED AT HAMSTEAD NORTHBOUND PLATFORM. $\text{PM}_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	135
FIGURE 4.22: A CONTOUR PLOT DISPLAYING NUMBER CONCENTRATIONS FOR EACH PARTICLE SIZE AT HAMPSTEAD STATION PLATFORM OVER FOUR MEASUREMENT DAYS FROM 14 JANUARY TO 17 JANUARY 2022.	137
FIGURE 4.23: A COMPARISON OF PARTICLE SIZE CONCENTRATIONS, CUMULATIVE PARTICLE NUMBER CONCENTRATIONS AND PARTICLE MASS CONCENTRATIONS AT HAMPSTEAD STATION PLATFORM, MARYLEBONE ROAD KERBSIDE SITE AND HONOR OAK PARK URBAN BACKGROUND SITE.	138

FIGURE 5.1: INDUCED OP^{AA} AND OP^{GSH} DEPLETION OF ANTIOXIDANT TREATMENT ON $PM_{2.5}$. FOR OP^{AA} DEPLETION ANTIOXIDANT REMAINING AFTER 2 HOURS INCUBATION FOR ALL FILTERS. C0 BEFORE THE INCUBATION PERIOD, C2 PARTICLE FREE CONTROL, M120 NEGATIVE CONTROL, NIST1648A POSITIVE CONTROL, BAKERLOO, JUBILEE, WILLESDEN AND KENSAL RISE LINES, FIELD BLANKS AND LAB BLANK. FOR OP^{GSH} DEPLETION ANTIOXIDANT REMAINING AFTER 4 HOURS INCUBATION FOR ALL FILTERS. C0 BEFORE THE INCUBATION PERIOD, C4 PARTICLE FREE CONTROL, M120 NEGATIVE CONTROL, NIST1648A POSITIVE CONTROL, BAKERLOO, JUBILEE, WILLESDEN AND KENSAL RISE LINES, FIELD BLANKS AND LAB BLANK.	153
FIGURE 5.2: OP^{AA} ANTIOXIDANT % C2 DEPLETION PER UNIT MASS OF $PM_{2.5}$ FOR THE BAKERLOO LINE (BROWN) AND JUBILEE LINE (SILVER) AND OP^{GSH} ANTIOXIDANT % C4 DEPLETION PER UNIT MASS OF $PM_{2.5}$ FOR THE BAKERLOO LINE (BROWN) AND JUBILEE LINE (SILVER).....	154
FIGURE 5.3: OP^{AA} ANTIOXIDANT % C2 DEPLETION PER UNIT VOLUME OF $PM_{2.5}$ FOR THE BAKERLOO LINE (BROWN) AND JUBILEE LINE (SILVER) AND OP^{GSH} ANTIOXIDANT % C4 DEPLETION PER UNIT VOLUME OF $PM_{2.5}$ FOR THE BAKERLOO LINE (BROWN) AND JUBILEE LINE (SILVER).	156
FIGURE 5.4: METAL CONCENTRATIONS PER UNIT MASS OF $PM_{2.5}$ ($NG\ M^{-3}\ \mu G^{-1}\ PM$) IN THE BAKERLOO LINE (BROWN) AND JUBILEE LINE (SILVER). NOTE THE DIFFERING Y-AXIS AS METAL CONCENTRATIONS DECREASE. STATISTICALLY SIGNIFICANT DIFFERENCES ARE ACCORDING TO THE MANN WHITNEY TEST, * * $p<0.05$, ** $p<0.01$ AND *** $p<0.001$	158
FIGURE 5.5: CORRELATION PLOTS OF OP^{AA} AND OP^{GSH} PER UNIT OF MASS ($OP\ \mu G^{-1}$) AND METAL CONCENTRATIONS PER UNIT OF MASS ($NG\ M^{-3}\ \mu G^{-1}$) ON THE BAKERLOO AND JUBILEE LINES.	160
FIGURE 5.6: CORRELATION PLOTS OF OP^{AA} AND OP^{GSH} PER UNIT OF VOLUME ($OP\ M^{-3}$) AND METAL CONCENTRATIONS PER UNIT VOLUME ($NG\ M^{-3}\ M^{-3}$) ON THE BAKERLOO AND JUBILEE LINES.	161
FIGURE 6.1: SCORE PLOTS OF THE FIRST (X-AXIS) AND SECOND (Y-AXIS) PRINCIPAL COMPONENTS FROM PRINCIPAL COMPONENT ANALYSIS (PCA) APPLIED TO THE 300 METABOLIC PROFILES COLLECTED FOR THE 50 PARTICIPANTS. THE 5 OUTLYING OBSERVATIONS ARE 1511, 6011, 7623, 9721 AND 10123	172
FIGURE 6.2: BOXPLOT SUMMARY OF TRAFFIC RELATED AIR POLLUTANTS (TRAP's) CONCENTRATIONS FOR BC , NO_2 , PM_{10} , $PM_{2.5}$ AND PARTICLE NUMBER COUNT (PNCT) FOR THE PARTICIPANT EXPOSURE WALKS IN OXFORD STREET (RED) AND HYDE PARK (BLUE). THE LOWER AND UPPER HINGES CORRESPOND TO THE 25TH AND 75TH PERCENTILES, THE HORIZONTAL LINE TO THE MEDIAN, AND THE WHISKERS TO $1.5 \times$ THE IQR (APPROX. 95% PERCENTILE).	176
FIGURE 6.3: MANHATTAN PLOTS ILLUSTRATING THE ASSOCIATION BETWEEN METABOLIC FEATURES AND EACH INDIVIDUAL TRAP FROM THE MVN UNIVARIATE ANALYSIS. DISTINCTIVE PLOTS ARE SHOWN HERE FOR ASSOCIATIONS WITH BC , NO_2 , PCNT, PM_{10} AND $PM_{2.5}$ FROM TOP TO BOTTOM. METABOLIC FEATURES ARE PLOTTED BY THEIR RETENTION TIME	

(MIN) AND $-\log_{10}$ P-VALUES FROM THE MVN MODEL. FEATURES IN RED ARE SIGNIFICANTLY ASSOCIATED WITH TRAP EXPOSURE AFTER BONFERRONI CORRECTION, FEATURES IN BLUE AFTER BONFERRONI CORRECTION (N=78) AND USING THE ENT (N=299). 177

FIGURE 6.4: UPSET PLOTS INDICATING THE NUMBER OF UNIQUE METABOLIC FEATURES AND MRNA SIGNIFICANTLY ASSOCIATED WITH AT LEAST ONE TRAP EXPOSURE IN OXFORD STREET. PANEL A. ILLUSTRATES THE 78 METABOLIC FEATURES ASSOCIATED WITH AT LEAST ONE TRAP OR COMBINATION OF TRAPS FROM THE MVN MODEL AND AFTER BONFERRONI CORRECTION. PANEL B. SUMMARISES THE 53 SIGNIFICANT MRNA ASSOCIATED TO EACH INDIVIDUAL TRAP FROM THE MVN MODEL AND AFTER BONFERRONI CORRECTION USING THE ENT (N=202)..... 178

FIGURE 6.5: FUNCTIONAL ANALYSIS INDICATING THE PATHWAYS ASSOCIATED WITH EACH TRAP EXPOSURE. COLOURS INDICATE THE STRENGTH OF THE ASSOCIATION (ORANGE FOR P-VALUE <0.5 AND BLUE FOR P-VALUE <0.1). EACH PATHWAY REPORTED THE NUMBER OF FEATURES IDENTIFIED BY THE MUMMICHOG IN THE DATASET FOR EACH PATHWAY AND THE NUMBER OF FEATURES INCLUDED IN THE PATHWAY AS PART OF THE MUMMICHOG DATABASE. 179

FIGURE 6.6: CONDITIONAL INDEPENDENCE NETWORK ON CLUSTERS OF METABOLIC FEATURES SIGNIFICANTLY ASSOCIATED WITH TRAP EXPOSURE, AT 2 HOURS BEFORE VISITS AND -2 HOURS (BASELINE) 2 AND +24 HOURS AFTER VISITS. EACH NODE REPRESENTS A FEATURE OR CLUSTER OF FEATURES AND EACH EDGE REPRESENTS A CORRELATION BETWEEN TWO FEATURES CONDITIONAL ON ALL OTHER FEATURES. PANEL A SHOWS NODES COLOURED BY ASSOCIATION TO EACH TRAP EXPOSURE. PANEL B SHOWS NODES COLOURED BY ASSOCIATION TO ONE OR MULTIPLE PATHWAYS ENRICHED WITH THE MUMMICHOG TOOL. 182

FIGURE 6.7: CONDITIONAL INDEPENDENCE NETWORK OF 63 CLUSTERS OF METABOLIC FEATURES AND 38 MRNA FEATURES SIGNIFICANTLY ASSOCIATED WITH TRAP EXPOSURE, AT BASELINE -2 HOURS (BASELINE) BEFORE EXPOSURE WALK, 2 HOURS AND +24 HOURS AFTER THE EXPOSURE WALK. EACH NODE REPRESENTS A FEATURE OR CLUSTER OF FEATURES AND EACH EDGE REPRESENTS A CORRELATION BETWEEN TWO FEATURES CONDITIONAL ON ALL OTHER FEATURES. 183

Table of Tables

TABLE 1.1: TIME COURSE OF PHYSIOLOGICAL AND HEALTH OUTCOME MEASUREMENTS.	31
TABLE 2.1: COMPARISON OF $PM_{2.5}$ CONCENTRATIONS MEASURED ON PLATFORMS, INSIDE TRAIN CARRIAGES AND DRIVERS' CAB IN DIFFERENT SUBWAY SYSTEMS WORLDWIDE.....	43
TABLE 3.1: INSTRUMENTS AND CONFIGURATION SETTINGS AND TYPICAL RUNTIMES BETWEEN CHARGES OF EQUIPMENT USED IN THE MOBILE REFERENCE STATION (MoRS) FOR THE MRC STUDY.	67
TABLE 3.2: STATIONS WITH STEP-FREE ACCESS WITHIN A 20-MINUTE TAXI JOURNEY OF IMPERIAL COLLEGE WHITE CITY CAMPUS SHOWING $PM_{2.5}$ CONCENTRATIONS FROM SMITH ET AL., (2020) FOR THE LU LINES.	68
TABLE 3.3: THE QA/QC PROGRAMME TO ENSURE INSTRUMENTS WERE MAINTAINED FOR HIGH-QUALITY DATA COLLECTION.	72
TABLE 3.4: FIELD CO-LOCATION COMPARISONS BETWEEN THE MoRS AND REFERENCE INSTRUMENTATION AT HAMPSTEAD SUBWAY STATION, AN URBAN KERBSIDE SITE AND URBAN BACKGROUND SITES (MEAN, MEDIAN, RANGE AND INTERCEPT ARE DISPLAYED AS $\mu G M^{-3}$).	92
TABLE 4.1: TUNNEL DEPTHS (M) BELOW GROUND-LEVEL AND THE NUMBER OF INTERCHANGES AT EACH STATION ON THE BAKERLOO LINE.....	97
TABLE 4.2: TUNNEL DEPTHS (M) BELOW GROUND-LEVEL AND THE NUMBER OF INTERCHANGES AT EACH STATION ON THE JUBILEE LINE.	98
TABLE 4.3: RETURN DISTANCES AND RETURN TRAVEL TIME FOR EACH LINE USED IN THE MRC STUDY.....	102
TABLE 4.4: MEAN $PM_{2.5}$ ($\mu G M^{-3}$) CONCENTRATIONS IN THE BAKERLOO LINE ON THE OUTWARD JOURNEY (WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION) AND THE RETURN JOURNEY (ELEPHANT & CASTLE STATION TO WILLESDEN JUNCTION STATION). $PM_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	118
TABLE 4.5: CONCENTRATION OF $PM_{2.5}$ IN THE THREE MEASUREMENT POSITIONS DURING THE RETURN BAKERLOO LINE JOURNEY FROM WILLESDEN JUNCTION STATION TO ELEPHANT & CASTLE STATION WITH THE COMPARATIVE P-VALUE FOR EACH POSITION. $PM_{2.5}$ HAS BEEN ADJUSTED USING THE FORMULA PROPOSED BY SMITH ET AL., (2020).	120
TABLE 5.1: METALS ANALYSED BY ICP-MS ANALYSIS FROM FILTER SAMPLES COLLECTED ON SUBWAY AND OVERGROUND TRAINS DURING THE MRC STUDY.	152

TABLE 6.1: CHARACTERISTICS OF THE STUDY POPULATION WITH FULL EXPOSURE DATA IN THE OXFORD STREET II STUDY

(COPD: CHRONIC OBSTRUCTIVE PULMONARY DISEASE, IHD: ISCHEMIC HEART DISEASE. P-VALUES WERE CALCULATED
USING A PAIRED T-TEST..... 175

Acknowledgements

Firstly, I would like to thank my primary supervisor, Dr David Green, for his guidance and constant support and encouragement during the four years of this thesis. Dave entrusted me to undertake the measurement campaign for such an important public health project which has been the basis for this thesis. His enthusiasm and willingness to provide advice and expert feedback is unsurpassed and I could not have wished for a better supervisor. I am extremely lucky to have two other brilliant supervisors, Professor Marc Chadeau-Hyam and Dr Rudy Sinharay, who provided me with fresh insights and pushed me in new directions. Together my supervisors have been a superb team always approachable and enthusiastic. Without their expertise and support the completion of this thesis would not have been possible.

I wish to extend my warmest gratitude to my colleagues in the Aerosol Science team, who are always there to help and provide support and have made my time so enjoyable. I am extremely fortunate to be part of such an inspiring group of people. I am also indebted to the support of the Environmental Research Group who have encouraged and helped me throughout this completely unexpected journey. I want to thank Dr Alison Kent who was so easy to work with, committed to the project and good company during the 100 train journeys we undertook. Thanks also to Dr Max Priestman and Dr Yiqun Han who covered for me so brilliantly on the train journeys, wheeling MoRS around. I want to thank Amber Vaughan who was so patient and instructive throughout the laboratory work that was essential to my completion of this thesis. She always being available to get me out of trouble. Special thanks go to Angela Lewis and Valentina Lotti who have been fantastic to work with.

It has been a pleasure to be part of Marc's team and to have worked with so many of them. I particularly want to thank Sibó Lucas Cheng and Professor Sonia Dagnino who I have collaborated closely with over the last three years.

Finally, I want to thank my partner Jayne Fisher, who has always encouraged and supported me through the last four years. Thank you so much for your understanding, support, patience and unwavering love over these years.

Publications and Conference Proceedings

Parts of this thesis have been published in peer-review journals and presented at national and international conferences.

Publications

Michael Hedges, Max Priestman, Marc Chadeau-Hyam, Rudy Sinharay, Frank J Kelly and David C. Green. Characterising a mobile reference station (MoRS) to quantify personal exposure to air quality. *Atmospheric Environment*, 315, 120160, doi.org/10.1016/j.atmosenv.2023.120160, 2023

Sibo Cheng⁺, **Michael Hedges**⁺, Pekka Keski-Rahkonen, Chorioallantois Chatziioannou, Augustin Scalbert, Kian Fan Chung, Rudy Sinharay, David C Green, Theo de Kok, Jelle Vlaanderen, Soterios Kyrtopoulos, Frank J Kelly, Lützen Portengen, Paolo Vineis, Roel Vermeulen, Marc Chadeau-Hyam^{*}, Sonia Dagnino^{*}. Multi-omic signatures of traffic related air pollution in London reveal short-term perturbations in gut microbiome-related pathways. *Environment Science & Technology*, 58 (20), 8771-8782, 10.1021/acs.est.3c09148, 2024.

+ Joint first authors

Conference Proceedings

The results of this Thesis have been presented at:

- *European Aerosol Conference (Virtual, 2021): Poster.*
- *Joint Annual ISAB Meeting (2021, 2022): Oral.*
- *School of Public Health annual PhD symposium (2022). Poster and oral.*
- *Inaugural Annual Meeting of the Joint Training Programme for the MRC Centre and HPRUs (2022): Oral – won best presentation.*
- *Network for Excellence in Aerosols and Health seminar: Airway biological toxicological responses (2022): Oral.*
- *The International Society of Exposure Science (Lisbon, 2022): Oral.*
- *The Aerosol Society Annual Conference (York, 2022): Oral.*

List of Abbreviations

Abbreviation	Meaning
AA	Ascorbate Acid
AURN	Automatic Urban and Rural Network
COMEAP	Committee on the Medical Effects of Air Pollutants
COPD	Chronic Obstructive Pulmonary Disease
ELPI ⁺	Electrical Low Pressure Impactor
ENT	Effective Number of Tests
FEV1	Forced expiratory volume in 1 second
FVC	Forced vital capacity
GOLD	Global Initiative for Chronic Obstructive Lung Disease
GSH	Reduced Glutathione
HOP	Honor Oak Park Urban Background Supersite
ICAD	Iterative CAvity enhanced DOAS
ICP-MS	Plasma Mass Coupled Spectrometry
IHD	Ischaemic Heart Disease
IOM	Institute of Occupational Medicine
ITA	International Tunnelling and Underground Space Association
LHEM	London Hybrid Exposure Model
LU	London Underground
MRC	Medical Research Council
MoRS	Mobile Reference Station
MY	Marylebone Road Roadside Supersite
NIST	National Institute of Standards and Technology
NK	North Kensington Urban Background Supersite
OP	Oxidative Potential
PSD	Platform Screen Doors
QA	Quality Assurance
QC	Quality Control
RSSB	Rail, Safety and Standards Board
SMPS	Scanning Mobility Particle Sizer
TfL	Transport for London
TRAP	Traffic-Related Air Pollution
WHO	World Health Organisation

List of Key Pollutants

Abbreviation	Meaning
BC	Black Carbon
NO ₂	Nitrogen Oxides
NO _x	Nitrogen Oxides
O ₃	Ozone
PM	Particulate Matter
PM ₁	Particulate matter with an aerodynamic diameter of less than 1 micrometre
PM ₁₀	Particulate matter with an aerodynamic diameter of less than 10 micrometres
PM _{10-2.5}	Particulate matter with an aerodynamic diameter of less than 10 micrometres but above 2.5 micrometres (PM coarse)
PM _{2.5}	Particulate matter with an aerodynamic diameter of less than 2.5 micrometres (fine PM)
PM _{4.3}	Particulate matter with an aerodynamic diameter of less than 4.3 micrometres (fine PM) also known as Respirable Dust
PM ₉	Particulate matter with an aerodynamic diameter of less than 9 micrometres
PNC	Particle Number Count
PNSD	Particle Number Size Distributions
UFP	Ultrafine particulate matter (PM with a diameter of 0.1 µm or less)

Chapter 1 Introduction

1.1 Background

My PhD formed part of an existing Medical Research Council (MRC) funded health study investigating “Exposure to particulate matter on the London Underground in healthy subjects and participants with Chronic Obstructive Pulmonary Disease (COPD)”. There were elements of the methodology of my PhD that were defined by the protocol of the MRC study. These were the days and the time of day that the measurements took place, the pollutants that were measured, namely PM_{2.5}, NO₂ and O₃, as well as collecting PM_{2.5} mass onto filters for oxidative potential (OP) and elemental analysis. In addition, temperature, relative humidity and noise were required to be recorded. Similar journey time lengths on a London Underground deep tunnelled line and London Overground line were required, although the lines were not defined. I researched the most suitable lines (with my supervisor), and replacement lines if required, for this PhD and the MRC study. The Bakerloo line from Willesden Junction to Elephant & Castle and the London Overground line from Willesden Junction to Watford Junction were selected in conjunction with my supervisor, with the Jubilee line from Kilburn to Canning Town as the replacement subway line and the line from Kensal Rise to Stratford as the replacement overground line.

The MRC study used an open, crossover experimental design whereby each participant was randomly assigned a 90 min exposure on a London Underground Bakerloo line journey and as a control, a similar overground journey. Both journeys started at Willesden Junction station. The study population comprised participants with at least GOLD stage 2 COPD (GOLD 2023) (n=36) and healthy volunteers (n=47) with no evidence of airflow obstruction. All participants were required to have ceased smoking for at least 12 months. The first train journey was randomised with the participants undertaking the second journey 3-6 weeks later.

I was required to measure the personal exposure of all participants during all the train journeys on the subway and overground (n=108). To measure personal exposures on the journeys, in conjunction with my supervisor, I conceptualised and designed a Mobile Reference Station (MoRS) that I took on each train journey and used MoRS to measure personal exposure at the breathing height of the participants. In a similar way, all instrumentation contained within MoRS was selected by me in conjunction with my supervisor.

Apart from the clinical aspects associated with the MRC study and those outlined above, I conceptualised and carried out all the study design methodology discussed in this thesis. This included designing MoRS, personal exposure data collection, study routes, trial journeys, all quality assurance and quality control, resilience planning, laboratory and fields intercomparisons of all MoRS instrumentation against reference instrumentation and the derivation of scaling factors for all MoRS instrumentation.

I carried out all filter weighing and the laboratory work and data analysis required to understand the oxidative potential of subway PM_{2.5} as well as the filter acid digestions for ICP-MS elemental analysis of subway PM_{2.5}. I carried out all data analysis using the opensource data analysis software 'R' (R_Core_Team 2021). This thesis resulted from my individual intellectual and technical contributions that were derived in addition to the requirements of the MRC study in order to fulfil the aims and objectives of this PhD.

1.2 Introduction

Air pollution is one of the leading contributors to non-communicable diseases globally. It is estimated that air pollution is attributable for 4.2 million premature deaths worldwide every year (Cohen et al., 2017, World Health Organisation 2021). The health risks of air pollution exposure have been well documented with toxicological, epidemiological and clinical studies linking it to adverse respiratory, pulmonary and cardiovascular health outcomes (Pope III et al., 2002, Atkinson et al., 2010, Brook et al., 2010, Hoek et al., 2013) and increased morbidity and mortality (Dockery et al., 1993, Burnett et al., 2018, Yang et al., 2018, Joshi, Miller and Newby 2022).

Road traffic vehicle emissions are a key contributor to air pollution responsible for most of the urban air pollution in cities (Cames and Helmers 2013, Boogaard et al., 2022, Health Effects Institute 2022). Increasingly, people are moving to cities as the world's population grows. As a result of which it is estimated that cities currently contain 55% of the world's population and this is expected to increase to 68% by 2050 (Landrigan et al., 2018, United Nations 2019). This growth in urban population has been accompanied by an increase in vehicle ownership, resulting in increased traffic-related air pollution (TRAP) from vehicle exhaust (Health Effects Institute 2022).

Traffic-related air pollutants comprise a complex mixture of gases and particles including oxides of nitrogen, particulate matter, PM₁₀ and PM_{2.5} (particles with diameters of 10µm or smaller or 2.5µm or smaller), ultrafine particles (particles with diameters of 100 nm or smaller) and black

carbon (Greenbaum 2018, Health Effects Institute 2022). Traffic-related air pollutants are a major source of urban air pollution which has led the International Agency for Research on Cancer (IARC) to declare air pollution from vehicle exhaust carcinogenic to humans (International Agency for Research on Cancer 2012).

Due to the known health risks from vehicle emissions, there is clear need to reduce atmospheric emissions from motor vehicles (Barnes, Chatterton and Longhurst 2019). To reduce vehicle emissions and traffic congestion urban planners are increasingly incentivising public transportation systems (ITA 1987, Beaudoin, Farzin and Lin Lawell 2015, Carroll, Caulfield and Ahern 2019) as public transport accessibility, with fast and reliable services are a key consideration for commuters (Gascon et al., 2020). This has led to a focus on subway systems becoming the major public transportation mode in most cities. As a result now almost every city possesses its own subway system (UTIP 2021). Subway systems have the greatest capacity, amongst urban transport systems, for moving millions of people rapidly around cities (ITA 1987, Midander et al., 2012, Ji, Li and Wang 2021). The use of subway electric trains promotes environmentally efficient travel by moving people through a network of underground tunnels incentivising the use of a public transport system with high daily capacity (Nieuwenhuijsen, Gomez-Perales and Colvile 2007, Martins et al., 2016). Subways are the arteries and veins of cities flowing under the surface providing a rapid, efficient and affordable alternative to private vehicular transport (Shakya, Saad and Aharonian 2020, Luglio et al., 2021, Yang et al., 2021). At the same time, they promote increased public mobility without adding to traffic congestion and traffic emissions (Xu and Hao 2017, Moreno and de Miguel 2018).

Given the urban community benefits of subway systems, they are anticipated to expand rapidly, including being introduced into new cities. This expansion in new subway lines leads to a decrease in air pollution due to reduced traffic congestion (Wang et al., 2020). In addition, there is a substantial health benefit due to reduced mortality and morbidity. (Lu et al., 2018, Yang et al., 2018, Li et al., 2019). This expansion of subways has been impressive, with the ridership on global subways increasing to over 58 billion journeys in 2019 through increased capacity worldwide (UTIP 2021). In London, which is the focus of this thesis, over 5 million passenger journeys per day were taken in 2023 and is likely to increase with the new Elizabeth Line (Transport for London 2023, Transport for London 2023).

As the use of subways have increased worldwide, researchers have identified exposure to elevated concentrations of dust as a major environmental disadvantage of subway travel. Subways operate in a confined space, often with poor ventilation, that can promote the accumulation of dust in tunnels and stations (Cheng, Lin and Liu 2008, Abadie et al., 2014, Hwang et al., 2017). Investigations have raised concerns (Mendes et al., 2018) after PM was shown to be present throughout the subway environment with particularly elevated concentrations of particulate matter (PM) observed in many subway systems (Branis 2004, Ripanucci et al., 2006, Luglio et al., 2021). Research has shown that the elevated concentrations of PM in subways can be significantly higher than outdoor air (Aarnio et al., 2005, Cusack et al., 2015, Bolourchi et al., 2018). Given the time people spend commuting in the subway, (in London this is between 44 and 57 mins), (Smith et al., 2020) this has raised increasing concerns that elevated PM concentrations may pose potential adverse health risks for commuters and workers (Salma et al., 2009, Grass et al., 2010, Zheng et al., 2017).

Elevated PM concentrations occur in the subway due to the very distinctive microenvironment of the subway. The subway has its own unique specific PM sources which affect air quality (Kamani et al., 2014, Chang et al., 2021). These PM sources originate from train and subway source materials and generation methods specific to subway systems (Cha et al., 2018, Loxham and Nieuwenhuijsen 2019).

Train-specific sources from the wear of train components occur from the movement of trains, principally at the wheel-rail interface and brakes due to friction and abrasion processes (Ma et al., 2012, Querol et al., 2012, Colombi et al., 2013). Particulate matter in the subway is particularly rich in transition metals, especially iron (Fe), but also barium (Ba), copper (Cu), Chromium (Cr) and Manganese (Mn) (Kang et al., 2008, Murrini et al., 2009). These metal particles from subway PM emission sources are very different from ambient particles due to their very different physicochemical properties (Lu et al., 2015, Martins et al., 2016, Kumar et al., 2023). Particles generated in the subway environment are mainly metallic with a small contribution from organic and elemental carbon, whereas organic carbon and secondary inorganic aerosols are most abundant in ambient particles (Smith et al., 2020).

Particulate matter in the subway accumulates in tunnels due to restricted air flow, often with little air exchange with the outside environment (Jung et al., 2010, Babu, Khare and Goyal 2015).

Together with the continual resuspension of PM from the piston effect of moving trains (Pan et al., 2013), this maintains concentrations above those on roads in many cities (Johansson and Johansson 2003, Raut, Chazette and Fortain 2009, Ma 2015, Xu and Hao 2017). Despite the health effects from PM_{2.5} and PM₁₀ exposure to traffic-related air pollution being well established (Cames and Helmers 2013, Samoli et al., 2016, Boogaard et al., 2022, Health Effects Institute 2022) management of air quality regulations is restricted to outdoor ambient environments (World Health Organisation 2021) with no guidelines being issued for subway railway systems (Carteni, Cascetta and Campana 2015). Instead, in the UK, occupational exposure standard (HSE 2020) guidelines have been used to assess safety limits.

Although PM concentrations are generally elevated in the subway environment, evidence of increased adverse health effects from PM exposure in this environment are less well understood compared to outdoor ambient environments (Pan et al., 2019, Azad et al., 2023). Health studies investigating potential adverse health effects from subway PM exposure have provided little clarity on whether subway PM is more toxic than ambient PM (Midander et al., 2012, Chang et al., 2021).

There are a number of clear reasons why exposure to subway air may be hypothesised to pose a risk to health through increased genotoxicity (Karlsson, Nilsson and Moller 2005, Bergvall and Westerholm 2007), inflammatory processes (Seaton et al., 2005, Wang et al., 2023), reactive oxygen species activity (Kam et al., 2011, Jung et al., 2012), oxidative stress (Janssen et al., 2015, Cooper and Loxham 2019), cytotoxicity (Vallabani et al., 2023) and susceptibility to bacterial respiratory infection (Miyashita et al., 2022). Overall, health research on the subway has been inconsistent (Loxham and Nieuwenhuijsen 2019), including finding no evidence of chronic effects from subway exposure (Bigert et al., 2007, Gustavsson, Bigert and Pollan 2008).

Given this contradictory evidence there is an urgent need to better understand if there are potential adverse health effects from subway PM exposure (Kam et al., 2011). This is especially important given the number of people potentially exposed through regularly commuting or working in subway systems (Jung et al., 2010, Chang et al., 2021). Although the known health effects of ambient air are not fully transferable to the subway, the possibility that there is a health risk from exposure to subway PM cannot be ruled out (Abbasi et al., 2013, COMEAP 2018).

1.3 Thesis rationale

One of the earliest measured assessments of personal $PM_{2.5}$ exposure on the London Underground (Pfeifer, Harrison and Lynam 1999) evaluated the health effects of a fuel additive MMT (methylcyclopentadienyl manganese tricarbonyl) high in manganese (Mn) on taxi drivers. Office workers were used as a control in this study and, surprisingly to the researchers, it was discovered that office workers had the highest Mn exposure. Further investigations concluded this was due to the high Mn concentration's office workers experienced whilst travelling on the London Underground.

A further report on the London Underground observed elevated concentrations of PM_{10} in the London Underground (Priest, Burns and Gorbunov 1998). This prompted London Underground to ask the Committee on the Medical Effects of Air Pollutants (COMEAP) to investigate any adverse health effects that could arise from exposure to dust on the London Underground (COMEAP 1998). COMEAP concluded that using published epidemiological studies based on outdoor ambient aerosol may not apply to the subway environment and called for a study into the health effects of exposure to subway dust to be undertaken.

No studies were undertaken until 2003 when Transport for London (TfL) requested the Institute of Occupational Medicine (IOM) to investigate whether exposure to subway dust in the London Underground presented a health risk to commuters and workers (Seaton et al., 2005). The authors conducted a series of toxicological studies using subway $PM_{2.5}$. This confirmed that type II human alveolar-like epithelial cells when stimulated by tunnel dust had cytotoxic and inflammatory potential through increased levels of LDH and IL-8 as well as inducing DNA damage. This led Seaton et al., (2005) to state that although subway dust is not without toxicity users of the London Underground should not be seriously concerned and should continue to use the subway based on convenience not health risks. These conclusions were reached in accordance with UK occupational exposure standards (HSE 2020). These standards are based on PM respirable dust equivalent to $PM_{4.3}$, in comparison to the WHO guidelines which are based on the much smaller size fraction of $PM_{2.5}$. UK occupational exposure limit values are magnitudes of order higher than the WHO guideline limits ($PM_{4.3}$ should not exceed 4 mg m^{-3} averaged over eight hours compared to annual average concentrations of $PM_{2.5}$ not exceeding $5 \text{ } \mu\text{g m}^{-3}$, while 24-hour average exposures should not exceed $15 \text{ } \mu\text{g m}^{-3}$ more than 3 - 4 days per year). It is

questionable whether workplace exposure limits should be applied to subway commuter exposure to PM_{2.5}. In addition, there is also the question of the innate bias of occupational exposure standards due to the healthy worker effect (Chowdhury, Shah and Payal 2017).

In 2017 COMEAP was again asked by TfL to re-assess the health risks of subway travel connected with PM exposure (COMEAP 2018). This followed new research investigating subway concentrations and composition throughout the London Underground network (Smith et al., 2020) and worldwide subway systems (Salma, Weidinger and Maenhaut 2007, Kam et al., 2011, Guo et al., 2014, Onat and Stakeeva 2014) including toxicological studies (Karlsson, Holgersson and Moller 2008, Lundstrom et al., 2011, Loxham et al., 2015).

To assist with the report, COMEAP commissioned six working parties to produce reports for COMEAP to consider as evidence for the review. A literature review was commissioned as working party 1 (COMEAP 2018) identifying and summarising relevant studies and evidence from previous subway studies. Working party 2 (COMEAP 2018) summarised concentrations and components of PM in the London Underground based on the paper by Smith et al., (2020). This measured PM_{2.5} concentrations in train carriages over two to five journeys on all lines in the London Underground network. They found the highest concentrations on the Victoria Line, which had a median PM_{2.5} concentration of 361 µg m⁻³ with the deep tunnel lines having the highest PM_{2.5} concentrations. Mean PM_{2.5} concentrations in the LU were 88 µg m⁻³ compared to mean ambient background concentrations of 19 µg m⁻³.

The authors found a great deal of variability between different lines and between locations within lines, which they concluded was influenced by station depth and distance from an above-ground station. PM_{2.5} mass and composition were measured on Hampstead station platform with PM_{2.5} concentrations found to be highly correlated with train movements through the station ($r^2 = 0.96$). Mean PM_{2.5} concentrations at Hampstead station ranged from 97 to 658 µg m⁻³ with the lowest concentrations occurring between 03:00 and 06:00 when there were no train movements following the last train. The chemical composition of LU PM_{2.5} at Hampstead station was found to comprise 47% iron oxide, 7% elemental carbon, 11% organic carbon, and 14% metallic and mineral oxides.

COMEAP working party 3 (COMEAP 2018) investigated workers exposure to respirable dust: from 2005-2017. Information from TfL on routine London Underground worker dust-exposure

levels and PM sampling results, pre- and post-clean-up were discussed showing cleaning the LU was more successful when tunnels and platforms were cleaned compared to solely cleaning platforms. Occupational exposure in terms of respirable dust by workers in the LU were within occupational exposure limits. Working Party 4 (COMEAP 2018) investigated the mechanistic evidence for health effects of particulate matter in the London Underground assessing the evidence for risks to health posed by exposure to PM in underground railway systems, analysing evidence from in vivo and in vitro studies performed in underground railway systems around the world. This concluded that currently there is little in-vivo and in-vitro evidence to suggest that underground PM poses a significantly increased risk to health compared to ambient PM.

Working party 5 (COMEAP 2018) used statistical estimates and time-activity patterns from the London Hybrid Exposure Model (LHEM) (Smith et al., 2016) to estimate exposure to PM_{2.5} for the population of London and while traveling by the London Underground and bus. Finally, working party 6 (COMEAP 2018) looked at the comparison of published health-based exposure limits (occupational and population) with PM metal concentrations in the London Underground, from measurements made by Smith et al., (2020) on the platform at Hampstead underground station.

After gathering evidence from the six working party reports, COMEAP made three research recommendations to further the understanding of the relationship between adverse health effects and exposure to subway PM. These were:

- 1) Investigation of ways to increase the usefulness of employment health records of those working in the underground to assess potential adverse health effects of underground exposures.
- 2) Well-conducted human exposure studies in volunteers, similar to the studies investigating the health effects of Oxford Street air pollution (Sinharay et al., 2018) and epidemiological studies, if power calculations suggest these could provide valuable additional understanding.
- 3) Well-designed mechanistic studies (in vivo and in vitro) to better understand the relative toxicity of subway particle components and the molecular pathways involved.

This thesis primarily focused on the second research recommendation of the COMEAP (2018) report by providing high-quality reference grade exposure data from the London Underground in support of a Medical Research Council (MRC) funded epidemiology study. This improved exposure estimates by undertaking a spatial and temporal monitoring campaign which

characterised PM_{2.5} in the London Underground and how PM_{2.5} varied with time and distance identifying environmental and other influencing factors. These exposure measurements were used with a series of respiratory and cardiovascular clinical outcomes measured in COPD participants and healthy volunteers with normal lung function before, during and after exposure on London Underground and London Overground train journeys. This was the first panel study to be undertaken in the subway and addressed the existing knowledge gap in understanding any adverse health effects of subway travel.

The MRC study utilised a similar approach to the Oxford Street study (Sinharay et al., 2018) to address the possible health impacts of subway air in the London Underground. Using the same protocols as in the Oxford Street study the health impacts of using the London Underground network in healthy volunteers and subjects with cardio-respiratory problems was investigated. The MRC study used an open, crossover experimental design whereby each participant was randomly assigned a 90 min exposure on a London Underground Bakerloo line journey and as a control, a similar overground journey. Both journeys started at Willesden Junction station. The study population comprised participants with at least GOLD stage 2 COPD (GOLD 2023) (n=36) and healthy volunteers (n=47) with no evidence of airflow obstruction. All participants were required to have ceased smoking for at least 12 months. The first train journey was randomised with the participants undertaking the second journey 3-6 weeks later.

On the morning of the participant train journeys, baseline measurements were taken of physiological and health metrics at Hammersmith Hospital, before participants were driven to and from Willesden Junction station in an electric taxi to undertake an exposure train journey. On return the physiological and health metrics were repeated at scheduled time points (Table 1.1). Participant personal exposures to PM, nitrogen dioxide (NO₂) and ozone (O₃) were characterised throughout each train journey to allow their effects on health to be disentangled to understand which pollutants were most responsible for any observed health effects arising from subway exposure. The exposure measurements were used to identify if travelling on the London Underground caused any changes to the participants measured physiological and health metrics relative to the overground. All health data was collected by the Clinical Research Fellow employed by the MRC study.

Table 1.1: Time course of physiological and health outcome measurements.

	Schedule of measurements								
Time (from start of subway exposure)	-2hr	0hr	+90mins	+2hr	+4hr	+5hr	+6hr	+7hr	+24hr
Place	lab	site	site	lab	lab	lab	lab	lab	lab
Time (24hr)	8am	10am	11.30am	12pm	2pm	3pm	4pm	5pm	10am
Symptoms	X	X	X		X	X	X		X
Arterial stiffness	X			X		X	X		X
Venesection	X							X	X
Diffusion capacity	X							X	X
Urine collection	X								X
Spirometry	X	X	X	X	X		X		X
Induced sputum	X							X	X

1.4 Aim and objectives

The aim of this research was to provide high-quality reference grade exposure data from the London Underground and London Overground for use in a MRC funded study investigating “Exposure to particulate matter on the London Underground in healthy subjects and participants with Chronic Obstructive Pulmonary Disease (COPD)”.

To deliver this there were five objectives:

- Develop a mobile measurement system to measure PM_{2.5}, nitrogen dioxide and ozone in subway and overground railway carriages.
- Conduct a well-characterised exposure assessment of PM_{2.5}, particle number count (PNC), particle size distribution, NO₂ and O₃ in the London Underground.
- Measure the chemical composition and oxidative potential (OP) of PM_{2.5} in the London Underground.
- Develop a cross-omics approach to understand molecular responses to exposures for use on the London Underground.
- To provide evidence-based recommendations to Transport for London on reducing subway exposure for commuters.

1.5 Thesis structure

Chapter 2 provides an in-depth literature review of the subway microenvironment, concentrations, factors affecting concentrations and sources of PM to provide a better understanding of PM variability within the subway microenvironment. An evaluation of subway health studies, personal exposure estimates and current methodology for deciding on safe exposure levels in the subway offers an insight into current knowledge of the health effects of subway travel. It then highlights remedial measures and air quality mitigation strategies that have been developed worldwide.

Chapter 3 sets out how the aim to provide high-quality reference grade exposure data from the London Underground and London Overground for use in a MRC study was achieved. The methodology and instrumentation used to measure participant personal exposures is discussed and how measurement difficulties were overcome are described. An overview of the study locations, rationale of location choice, sampling strategy employed and the evolution and challenges of the study are outlined. It is shown how laboratory and field intercomparisons and co-locations and the derivation of scaling factors were employed to ensure accurate measurements.

Chapter 4 outlines an exposure assessment of the London Underground, focusing on the Bakerloo line. This evaluates the spatial and temporal resolution of all fractions of PM, NO₂ and O₃ in the subway. The methodology of obtaining repeated measurements over an 18-month measurement period are discussed. PM_{2.5}, NO₂, particle number concentrations and particle size distributions found in the subway are compared to worldwide findings in the literature in understanding and identifying possible sources and influencing factors. Seasonal effects and the effect of tunnel depth on PM_{2.5} and NO₂ concentrations are investigated.

In **Chapter 5** the methodology describes how particle mass was collected during the exposure trials onto two types of filter material for oxidative potential and chemical analysis. The composition of PM_{2.5} influences its toxicology, and it is important to gain knowledge about which chemical components could be causing particle toxicity. It explains the methodology of the laboratory work required for the assessment of PM_{2.5} oxidative potential and chemical composition in the subway. ICP-MS analyses conducted on those metals known to affect health and OP

analysis results are correlated and compared against previous research of OP analysis in Barcelona and London background and roadside sites.

Chapter 6, outlines work on a multi-omic study carried out on metabolomics and transcriptomics data from the Oxford Street study (Sinharay et al., 2018) to be included in future work recommendations to investigate potential multi-omic signatures arising from exposure in the subway.

The concluding chapter, **Chapter 7**, summarises and discusses the key points and conclusions of the PhD, including revisiting the aims and objectives of the thesis and the strengths and limitations of the study. The final section provides evidenced-based recommendations on reducing exposures in the London Underground, including any suggested remedial work and future directions for research.

Chapter 2 Literature Review

2.1 Literature review search strategy

To identify the relevant literature on all aspects of subway air quality a search strategy was developed for this PhD project with the title “Concentrations and Health Effects of particulate matter on the London Underground”. The literature search was used to identify relevant literature relating to subway air quality, subway health studies, particulate matter sources in the subway, transport microenvironment comparisons and interventions to improve air quality in the subway. The literature search was conducted across Ovid MEDLINE, Ovid EMBASE, Ovid Global, CINAHL and Google Scholar databases.

The searches included all published papers, conference proceedings and thesis’ from inception to 20 January 2022 with no language criteria being specified. The search strategy was developed to find all papers relevant to this PhD project. The databases were searched for all entries containing the search headings (1) EITHER “underground” OR “London Underground” OR “subway” OR “Metro” OR “railroads”, AND (2) EITHER “air pollution” OR “air pollutants” OR “particulate matter” OR “pm2.5” OR “pm10”. In the Ovid databases “air pollutant*” and “pm2*” were searched. The terms “air pollution” and “air pollutants” were included to capture references to nitrogen dioxide and ozone. No results were excluded from each of the databases. The results are shown in Figure 2.1. The search strategy for this review is shown in Figure 2.2.

Ovid MEDLINE

Search Heading	Number of Results
1. underground.mp	7415
2. London Underground	50
3. subway.mp or Railroads/	3685
4. metro.mp	2017
5. 1 OR 2 OR 3 OR 4	12087
6. air pollution.mp	65970
7. air pollutant*	73834
8. particulate matter.mp	34578
9. pm2*.mp	15959
10. pm10.mp	7814
11. 6 OR 7 OR 8 OR 9 OR 10	127359
12. 5 AND 11	943

Ovid EMBASE

Search Heading	Number of Results
1. underground.mp	9643
2. London Underground	61
3. subway.mp	1040
4. railroads.mp	221
5. metro.mp	3388
6. 1 OR 2 OR 3 OR 4 OR 5	13944
7. air pollution.mp	106801
8. air pollutant*	43257
9. particulate matter.mp	66600
10. pm2*.mp	22098
11. pm10.mp	12402
12. 7 OR 8 OR 9 OR 10 OR 11	170513
13. 6 AND 12	878

Ovid Global Health

Search Heading	Number of Results
1. Underground.mp	2851
2. Subway.mp	276
3. London Underground.mp	7
4. railroads.mp	417
5. metro.mp	896
6. 1 OR 2 OR 3 Or 4 OR 5	4264
7. air pollution.mp	29332
8. air pollutant*.mp	18345
9. particulate matter.mp	12441
10. pm2*.mp	8987
11. pm10.mp	5440
12. 7 OR 8 OR 9 OR 10 OR 11	33891
13. 6 AND 12	282

CINAHL

Search Heading	Number of Results
1. Subway or metro or underground	2788
2. London Underground	35
3. railroad	1007
4. 1 OR 2 OR 3	3151
5. air pollution	11282
6. air pollutants	5870
7. particulate matter	4938
8. pm2.5	1700
9. pm10	902
10. 5 OR 6 OR 7 OR 8 OR 9	13809
11. 6 AND 12	104

Google Scholar

Search Heading	Number of Results
(subway OR railroad OR metro OR underground OR London underground) AND (air pollution OR air pollutants OR particulate matter OR pm2.5 OR pm10)	773

Figure 2.1: Results for search strategies for each database.

The searches generated 943 results in Ovid MEDLINE, 878 results in Ovid EMBASE, 282 results in Ovid Global Health, 104 results in CINAHL and 773 results in Google Scholler giving a total of 2980 papers yielded by this initial search strategy. The abstracts for each citation identified for each database result were screened for relevance to air quality, subway pollutant sources, subway health studies, transport microenvironment comparisons, that included the subway, and intervention studies.

Following this screening 479 citations were retrieved that fitted the screening criteria: 116 in Ovid MEDLINE, 153 in Ovid EMBASE, 58 in Ovid Global Health, 14 in CINAHL and 138 in Google Scholar. Duplicate removal yielded 233 citations being removed leaving 246 unique references. Further refinement removed 26 citations that were non-English (n=7), abstracts only (n=6), non-subway (n=8) and non-PM (n=5). This resulted in 220 unique citations that were relevant to the PhD title. Only two references were found relating to nitrogen dioxide in the subway with no references to ozone found for the subway environment. This was supplemented by a further 25 citations from a review by Chang et al., (2021) resulting in 245 unique citations. These included studies relating to subway exposure assessment (n=79), health studies (n=59), PM sources (n=58), transport microenvironments (n=25) and intervention studies (n=24). The 245 identified studies form the basis for the literature review.

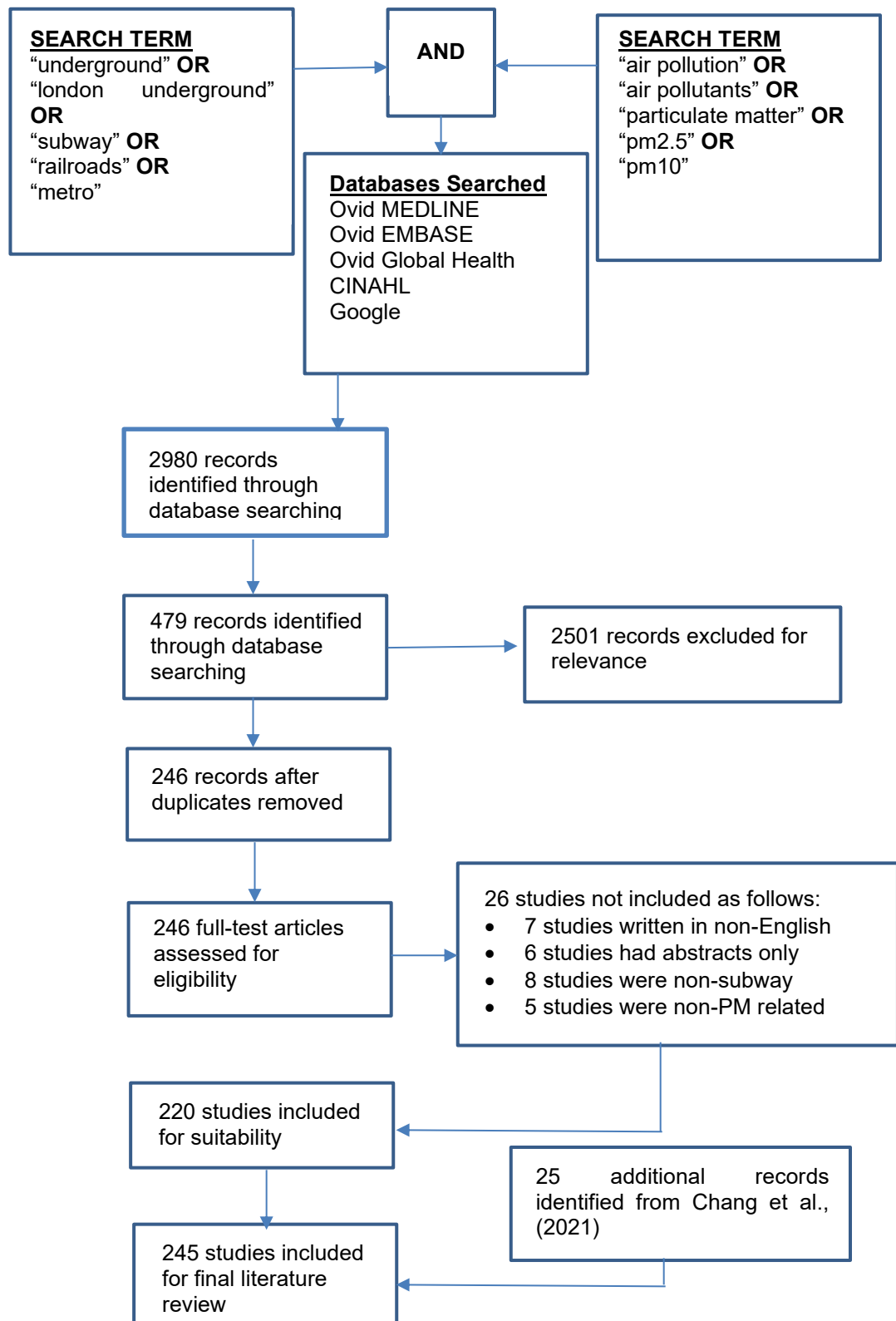


Figure 2.2: Literature search methodology. Papers were selected for inclusion in the review by combining each of the search boxes with the Boolean operator “AND”, across five databases. The papers yielded by this initial search were refined to only those of relevance to the subway and supplemented by relevant papers used in the review of Chang et al., (2021). This yielded the 245 papers forming the core body of literature for this review. Further studies have been included and cited where appropriate.

2.2 The subway microenvironment

Urban transport plans are increasingly incentivising the use of public transport to relieve atmospheric emissions from traffic congestion (Yang et al., 2018). In this context, subway systems offer one of the greenest, most environmentally friendly methods of public transportation in large urban areas (Nieuwenhuijsen, Gomez-Perales and Colvile 2007). They provide a fast, energy efficient, low emission form of commuting whilst relieving surface traffic congestion and have become the leading mode of public transport in most metropolitan areas worldwide (Jung et al., 2010, Moreno et al., 2014).

However, there are increasing concerns regarding the potential health effects of long-term exposure to the elevated concentrations of particulate matter found in the subway (Roy et al., 2022, Wang et al., 2023), leading to a focus on concentrations and the unique physicochemical properties of subway particulate matter (Aarnio et al., 2005, Moreno and de Miguel 2018). Thus, there is an urgent need, given the number of people potentially exposed every day, to understand the consequences to health.

There is increasing toxicological, clinical, and epidemiological evidence linking human exposure to urban air pollution. Health hazards associated with increased mortality and morbidity include respiratory and pulmonary cardiovascular health effects (Amiri et al., 2019). Moreover, elevated levels of $PM_{2.5}$ are strongly correlated with increased chronic obstructive pulmonary disease (COPD) prevalence (Ni, Chuang and Zuo 2015, Doiron et al., 2019, Han et al., 2019) with a lifelong burden on health (Fuller, Friedman and Mudway 2023). Indeed, there is strong evidence that $PM_{2.5}$ exposure affects cardiovascular and respiratory health even at very low concentrations (Dominici et al., 2006) and there are no safe levels of particulate matter (PM), especially fine particulate matter ($PM_{2.5}$) below which no damage to health is observed (Kelly and Fussell 2015). Although it has not yet been determined if subway particulate matter causes increased genotoxicity, inflammatory processes, reactive oxygen species and oxidative stress than urban particulate matter across all size ranges of PM, it is likely, given the known health effects of urban PM, that subway exposure poses a risk to health (COMEAP 2018).

It has long been recognised that subway railway particles originate predominantly from abrasion at the wheel/rail interface, producing differing size distributions, particle morphology, concentrations, and chemical composition relative to ambient particulate matter (Sitzmannn

1999). They are more angular and elongated in shape, chemically dominated by iron and loaded with other transition metals, in comparison to urban air particles (Querol et al., 2012, Moreno et al., 2015). Transition metals, such as Mn, Cr, Cu and Ba, have high oxidative potential, an important determinant for systemic inflammation, giving a clear reason why exposure to subway air may pose a risk to health (Jiménez et al., 2000, Kelly 2003).

The complexity of subway air is compounded by the often poorly ventilated, confined spaces found in subway network systems. There is often little air exchange allowing dust to accumulate in tunnels and platforms (Kang et al., 2008, Chang et al., 2021). This was clearly demonstrated in a newly opened subway platform in Stockholm, where PM concentrations rapidly increased following the platform opening and were strongly linked to train-movements (Cha et al., 2019), thus demonstrating that much of the inhalable PM is produced underground and remains underground (Jung et al., 2010, Sheikh et al., 2022).

2.3 Measuring air quality

Worldwide, studies have found large differences in subway PM concentrations between cities (Johansson and Johansson 2003, Martins et al., 2016, Smith et al., 2020, Luglio et al., 2021). However, directly comparing cities is challenging, due to differing PM size fractions being measured, measurement techniques and instrumentation, measurement locations, measurement periods and whether a conversion factor was used to account for subway environments (Nieuwenhuijsen, Gomez-Perales and Colville 2007). There are also many different subway factors such as train frequency, type of ventilation system, age, tunnel length and depth, rolling stock, wheel material and sources of particulate matter which directly affect measured PM concentrations (Salma, Weidinger and Maenhaut 2007, Carteni, Cascetta and Campana 2015, Pan et al., 2019).

Due to the different physicochemical nature of subway PM in comparison to ambient air (Aarnio et al., 2005, Querol et al., 2012) not all ambient approaches to measuring PM are suitable in the subway (Querol et al., 2012, Cha, Abbasi and Olofsson 2018, Smith et al., 2020), although gravimetric measurements can be used in subway environments (Luglio et al., 2023). Subway PM is substantially denser than ambient PM and factors derived for ambient PM cannot be reliably used to calibrate in the subway (Querol et al., 2012) It is therefore particularly important to derive source-specific correction factors for subway PM measurements as without correction factors

being applied the different instrumentation used by investigators are not directly comparable (Querol et al., 2012, Cha et al., 2019). Very few studies apply specific calibration factors separately for PM_{2.5} and PM₁₀ (Querol et al., 2012).

Optical particle counting (OPC) instruments are widely used in subway studies due to their small size and portability (Chen et al., 2016, Zhang, Xu and Su 2020, Luglio et al., 2023). Optical particle counting based devices have a 200-300 nm lower size cut-off and differences in the size distribution and density of particulate matter in the subway undermines the interpretation of these data without adequate calibration to the measured environments (Querol et al., 2012).

Some researchers use a variety of instrumentation to obtain the full-size range of PM to include ultrafine particles (UFP's) (< 100 nm) (Smith et al., 2020, Kumar et al., 2023). There is a wide variation in approaches adopted in the literature to ensure measurements are comparable to reference instrumentation. These range from not describing any calibration (Pan et al., 2019, Mousavi Fard, Asilian Mahabadi and Khajehnasiri 2021), applying no correction (Zhao et al., 2017, Passi, Nagendra and Maiya 2021), calibrating to ambient air (Onat and Stakeeva 2014, Kumar et al., 2023) and calibration against independent reference instruments in subway environments, often using gravimetric techniques simultaneously with instrument measurements (Moreno et al., 2014, Martins et al., 2016, Luglio et al., 2021).

The majority of subway studies are short-term campaigns (Zhao et al., 2017, Cheng, Ninh and Yeh 2019, Posselt, Neuberger and Kohler 2019), that take place in static locations such as on platforms (Mugica-Alvarez et al., 2012, Cusack et al., 2015, Kumar et al., 2023), which do not accurately reflect exposure across the commuting population. There are very few studies similar to Smith et al., (2020), which reflect exposure across the commuting population and map entire networks that would allow a better comparison between cities. As an example of a city led approach, the Paris subway has been continuously monitoring concentrations of temperature, relative humidity, carbon dioxide, nitrogen oxides, PM_{2.5} and PM₁₀ at five stations since 1997, to improve air quality and reduce PM emissions (RATP 2023). However, the contrasting measurement approaches in subway studies and unique subway factors which directly affect PM measurements in worldwide subway systems makes it difficult to directly compare cities. (Querol et al., 2012).

Despite this, most studies conclude that PM_{2.5} concentrations in subway systems are regularly higher than at street level (Russell et al., 2022, Azad et al., 2023). London is often reported as having the highest PM_{2.5} and PM₁₀ concentrations worldwide (Seaton et al., 2005, Smith et al., 2020). This is due to a combination of the systems age and deep, poorly ventilated tunnels allowing accumulation of particles (Nieuwenhuijsen, Gomez-Perales and Colville 2007). Indeed, gravimetric measurements of PM_{2.5} at Hampstead station, the deepest platform in London, have shown values of 270 – 658 µg m⁻³ (Seaton et al., 2005, Smith et al., 2020) with no improvement in concentrations occurring in the 15 years between these studies, in contrast to the big improvements seen in ambient air quality (Kitwiroon, Beevers and Williams 2019).

Early measurements of size, mass and composition of particulate matter in the London Underground found mean PM₉ concentrations of 795 µg m⁻³ (Priest, Burns and Gorbunov 1998). Moreover, a study of manganese (Mn) exposure of taxi drivers unexpectedly showed that the control group of office workers had higher Mn exposures than taxi drivers due to commuting on the subway (Pfeifer, Harrison and Lynam 1999). Further studies have demonstrated subway users had 3-10 times higher exposures than other transport users in London, when compared over 3-week periods in winter and summer (Sitzmann 1999, Adams et al., 2001).

In many of the world's subway systems airborne PM_{2.5} concentrations have been reported as being elevated far beyond ambient levels; New York 779 µg m⁻³ (Luglio et al., 2021), Stockholm 260 µg m⁻³ (Johansson and Johansson 2003), Seoul 129 µg m⁻³ (Kim et al., 2008), Shanghai 126 µg m⁻³ (Guo et al., 2017), Barcelona 125 µg m⁻³ (Querol et al., 2012), New York 125 µg m⁻³ (Luglio et al., 2023), Seoul 105 µg m⁻³ (Park and Ha 2008), Toronto 100 µg m⁻³ (Van Ryswyk et al., 2017), Prague 93.9 µg m⁻³ (Cusack et al., 2015), Paris 93 µg m⁻³ (Raut 2009) and Los Angeles 57 µg m⁻³ (Kam et al., 2011) among others (Table 2.1). These concentrations are significantly higher than the WHO PM_{2.5} annual guideline of 5 µg m⁻³ and the 24-hour guideline of 15 µg m⁻³, respectively (WHO 2024). Although these are often short-term campaigns that do not necessarily reflect exposure across commuting populations, they demonstrate the urgent need to improve subway air quality,

2.4 Factors affecting concentrations.

There are few studies observing spatial and temporal variations of PM concentrations throughout entire subway networks such as Smith et al., (2020). Studies observing PM concentrations

throughout entire subway networks, have shown heterogeneity where there is no active ventilation, with the highest concentrations on platforms, decreasing in train carriages, with the lowest concentrations at gate-lines and ticket halls (Jung et al., 2010, 4-Rail Services Ltd 2016, Guo et al., 2017). Gaseous pollutants, nitrogen dioxide (NO₂) and ozone (O₃) are generated outside of the subway system, primarily from vehicle exhaust, and enter through tunnel and station entrances as well as ventilation shafts (Cao et al., 2017). There is a paucity of measurements of NO₂ and O₃ in the subway, although Cao et al., (2017) demonstrated NO₂ concentrations decreased as measurements were taken deeper in the subway as the influence of outside air diminished. No measurements of O₃ in subway systems have been found.

Subway air quality depends on a complex interplay of factors involving the wheel/rail interface materials, braking mechanisms, train speed and frequency, passenger densities, ventilation and air conditioning systems, system age, presence or absence of platform screen doors (PSD's), cleaning frequency, tunnel depth, proximity from above-ground air and station design (López González et al., 2014, Martins et al., 2016). The influence of the steel wheel/rail interface significantly increased PM_{2.5} concentrations in Toronto (mean 100 µg m⁻³) compared to the rubber wheel/rail interface used in Montreal (mean 36 µg m⁻³) (Van Ryswyk et al., 2017).

Braking significantly increases the generation and resuspension of particulates on platforms and in train carriages (Cha, Abbasi and Olofsson 2018, Durand 2019) especially at track curvatures or gradients (Jung et al., 2010, Martins et al., 2016, Moreno and de Miguel 2018). Concentrations are enhanced by the turbulence created by the 'piston effect' of trains moving through the tight confines of tunnels (Amato, 2018; Cartenì et al., 2015; Johansson and Johansson, 2003; Ma et al., 2014). The piston effect pushes tunnel air in front of the train and pulls air particles in the vacuum behind, which in the absence of active ventilation (Moreno et al., 2014), pushes polluted air from the tunnel bore into station platforms (Salma, Weidinger and Maenhaut 2007, Saunders et al., 2019).

Table 2.1: Comparison of PM_{2.5} concentrations measured on platforms, inside train carriages and drivers' cab in different subway systems worldwide.

Measurement Location	City	PM _{2.5} (µg m ⁻³)		Reference
		Range (min-max)	Mean	
Platform	New York	392-1499	779	Luglio et al., (2021)
	London		658	Smith et al., (2020)
	London	270-480	-	Seaton et al., (2005)
	Stockholm	105-388	258	Johansson and Johansson (2003)
	Seoul	82-176	129	Kim et al., (2008)
	Shanghai	65-182	126	Guo et al., (2017)
	Barcelona	110-186	125	Querol et al., (2012)
	New York	45-233	125	Luglio et al., (2023)
	Seoul		105	Park and Ha (2008)
	Toronto	50-171	100	Van Ryswyk et al., (2017)
	Prague	-	93.9	Cusack et al., (2015)
	Paris	-	93	Raut (2009)
	Oporto	-	83.7	Martins et al., (2016) Martins et al., (2016)
	Athens	-	68.3	Martins et al., (2016)
	New York	-	62	Chillrud et al., (2004)
	Helsinki	23-103	60	Aarnio et al., (2005)
	Naples	48-90	58	Carteni, Cascetta and Campana (2015)
	Los Angeles	9-130	57	Kam et al., (2011)
Train Carriage	London	39-734	306	Saunders et al., (2019) ^a
	Athens	-	124.8	Martins et al., (2016)
	Seoul		117	Park and Ha (2008)
	London	<4-885	88	Smith et al., (2020)
	London	14-368	68	Saunders et al., (2019) ^b
	Mexico	31-99	57	Gomez-Perales et al., (2004)
	Oporto	-	54.1	Martins et al., (2016)
	Naples	11-59	44	Carteni, Cascetta and Campana (2015)
	Stockholm	7.8-65.9	37.5	Cha, Abbasi and Olofsson (2018)
	Barcelona	17-32	25	Querol et al., (2012)
Drivers Cab	London	130-200	-	Seaton et al., (2005)
	New York		88	Azad et al., (2023)

^a Deep-tunnelled lines.

^b Shallow sub-surface lines.

As a result, platform concentrations are closely correlated with train frequency, displaying a regular diurnal variation linked to vehicle intensity (Zhang, Xu and Su 2020, Kumar et al., 2023). Moreover, after train operating hours, a continuous decrease in concentrations rapidly occurs due to gravitational settling before increasing again when the service resumes, illustrating the coarser

properties of subway particles (Johansson and Johansson 2003, Cha et al., 2019, Kumar et al., 2023). PM concentrations vary in time and space along platforms with maximum levels at the tunnel entrance at train arrival before levels fall when the train stops before increasing at the tunnel exit platform point as trains depart (Moreno et al., 2014, Wang 2016). In fact, concentrations vary throughout stations (Seaton et al., 2005, 4-Rail Services Ltd 2016) with tunnel cleansing only making a minor contribution to the reduction of PM_{2.5} levels (Johansson and Johansson 2003, Gustafsson et al., 2012) or no difference in the Toronto subway (Van Ryswyk et al., 2021)

Train carriage concentrations are affected by the opening and closing of train doors, the presence of carriage air conditioning and windows being open or closed in tunnels (Kim et al., 2012, Martins et al., 2016, Cha et al., 2018). Although PM concentrations inside train carriages are usually lower than on subway platforms, they are often reported to be higher than ambient levels (Rivas, Kumar and Hagen-Zanker 2017, Mohsen, Ahmed and Zhou 2018, Carteni et al., 2020). There are large variations along a line and between lines; trains deep in tunnels away from the influence of outside air have the highest concentrations which decrease as the train goes above ground (Carteni, Cascetta and Campana 2015). In London, Saunders et al., (2019) observed mean PM_{2.5} concentrations ranged from 68 $\mu\text{g m}^{-3}$ in shallow above-ground lines to 306 $\mu\text{g m}^{-3}$ in deep, tunnelled sections compared to an ambient surface mean of 21 $\mu\text{g m}^{-3}$, confirming that PM_{2.5} is generated by subway sources with only a small contribution from the surface. However, a complex relationship exists between PM_{2.5} concentrations, tunnel depth and proximity to above-ground air, for which a better understanding is required (Figuerola-Lara 2019, Saunders et al., 2019).

2.5 Sources of particulate matter

Subway sources and activities generate particles that are physically and chemically different to those in ambient air. The majority of subway PM is created underground and is dominated by iron (Fe) containing particles; substantially different to urban particles (Martins et al., 2016). There is a variable contribution from ambient air drawn into the system through tunnels and stations dependant on the ambient concentration and proximity to outside air (Kim et al., 2008, Martins et al., 2016). Train-specific sources are primarily emitted from the mechanical abrasion processes at the wheel/rail interface, brake blocks, and collector shoes with a contribution from non-train

sources such as cleaning and passengers (Salma, Weidinger and Maenhaut 2007, Moreno et al., 2015, Smith et al., 2020).

These sources are common world-wide and give subway particles their very distinct physicochemical properties (Querol et al., 2012). Iron is consistently the most abundant element contributing between 40 and 80% of PM mass fraction (Seaton et al., 2005, Querol et al., 2012, Martins et al., 2016) with magnetite the dominant form of iron in the London Underground (Sheikh et al., 2022, Kumar et al., 2023). Indeed, Jung et al., (2010) have shown iron containing particles are generated in the tunnels and are in a steady state with little daily change. Particle shape is an important source indicator with subway particles more angular, due to mechanical abrasion and friction, than agglomerates of carbon particles typical of traffic exhaust emissions (Sitzmann 1999). Consequently, particle number concentrations are dominated by the small fraction, although modal particle diameter is greater than in ambient air (Smith et al., 2020) and particle mass is dominated by particles larger than 1µm in diameter (Cha et al., 2018), reflecting the coarser nature of particle composition. This is confirmed by the mean PM_{2.5}/PM₁₀ mass ratio of 0.3 – 0.4 on platforms and in train carriages which is consistent across many systems (Salma, Weidinger and Maenhaut 2007, Querol et al., 2012) and lower than the ambient mean PM_{2.5}/PM₁₀ mass ratio of 0.6 – 0.7 (Munir 2017).

Elemental ratios of metals contained in steel dust can help identify potential sources. In New York City (Chillrud et al., 2004) demonstrated that teenagers using the subway showed increased exposure to manganese (Mn), chromium (Cr) and iron (Fe) and found ratios of the pairs Fe/Mn and Cr/Mn of 107 and 0.34. These are representative of the ratios found in steel, and greater than typical crustal ratios of 55 and 0.11 (Grass et al., 2010). These enhanced ratios have been observed worldwide (Aarnio et al., 2005, Salma, Weidinger and Maenhaut 2007, Smith et al., 2020). Train braking generates high levels of trace elements dependent on the braking system and how hard the brakes are applied (Moreno et al., 2015). The introduction of new rolling stock on one subway line in Toronto led to a 31% decrease in PM_{2.5} concentrations due to reduced use of friction brakes, whereas on a separate line PM_{2.5} concentrations increased by a factor of 1.48 due to the increased use of emergency braking (Van Ryswyk et al., 2021).

In Stockholm, Cha et al., (2018) demonstrated that when trains are in tunnels, or doors are open, significant increases in particulate matter after braking is observed with many metallic elements

being substantially elevated. As a result, the differing metal concentrations observed in subway systems are dependent on the chemical composition of sources; wheels and rails (Fe, Mn, Cr), brakes (Ba, Sb, Cu, Zn, Pb, Ni, Sr), and current supply materials (Cu). Although trace metals represent less than 2% of total PM_{2.5} found in the subway, the determination of metal concentrations, trace metals and iron, is essential for source identification and its toxicological properties (Martins et al., 2016). Both particle size and chemical composition of subway PM differ markedly from outside air and are important parameters when evaluating health effects.

2.6 Health studies

There remains a paucity of experimental studies assessing the deleterious health effects of exposure to subway particulate matter when compared to the knowledge acquired of exposure to ambient PM. There have been no subway epidemiological studies and the few subway in-vivo and in-vitro studies that have assessed health effects have shown inconsistent results. Consequently, little evidence of the short or long-term health impacts of subway PM exposure has been gathered, especially the impact on those with chronic diseases. This is partly due to low disease incidence and small study populations of subway workers leading to statistical underpowering. It is known that the transition metal-rich nature of subway PM could potentially stimulate oxidative stress and reactive oxygen species (ROS) generation, inducing systemic inflammation in biological tissues (Jiménez et al., 2000) but the clinical significance remains unclear.

Three in-vivo studies of human exposure to subway PM have taken place in the Stockholm subway (Klepczynska Nystrom et al., 2010, Lundstrom et al., 2011, Klepczynska-Nystrom et al., 2012). No effect on lung function was found following a 2h exposure on the Stockholm subway of 20 young volunteers, but there was a statistically significant increase of plasma fibrinogen and blood T cell count, indicating a systemic biological response to the subway environment (Klepczynska Nystrom et al., 2010). This study involved mainly young, healthy volunteers or those with mild asthma, over short exposure periods. However, in a follow-up study, 16 mild asthmatics, with similar exposure, showed statistically significant increased activation of T cell markers in bronchoalveolar lavage fluid (BALF) but no increase in blood T cell counts (Klepczynska-Nystrom et al., 2012). Following exposure to Stockholm subway air of healthy and asthmatic individuals, healthy individuals showed increased oxylipin levels, suggesting asthma specific anti-

inflammatory effects (Lundstrom et al., 2011). In contrast, a study in Taipei of heart rate variability (HRV) in young, healthy individuals in different transport modes found decreased HRV with increases in PM_{2.5} (Liu et al., 2015) a marker of autonomic imbalance, similar to previous studies (Kelly and Fussell 2017).

A recent study of nine subway workers in the Paris subway (Canu et al., 2021) quantified PM concentrations and metal concentrations in exhaled breath condensate (EBC), urine and PM. They investigated their associations and assessed the relevance of EBC in biomonitoring. The subway workers were security guards, train drivers and station agents. They were monitored over two-weeks with urine and EBC samples taken pre- and post-shift. For ultrafine particle number concentrations in PM a statistically significant relationship was found with EBC linked with Zn and Cu concentrations in PM₁₀, suggesting EBC could be a relevant matrix when assessing human exposure to UFP's in the subway. The small sample size makes the clinical significance of the study unclear.

There have been six chronic exposure occupational health studies of subway workers, of which, four were in Stockholm (Bigert et al., 2007, Bigert et al., 2008, Gustavsson, Bigert and Pollan 2008, Grass et al., 2010, Bigert et al., 2011, Mehrdad, Aghdaei and Pouryaghoub 2015). Bigert et al., (2007) concluded that subway drivers had no significantly increased risk of myocardial infarction compared to other manual workers and no evidence was found by Gustavsson et al., (2008) of an increase in lung cancer incidence compared to other workers. A study of subway workers in New York City (Grass et al., 2010) found urinary isoprostane concentrations were significantly correlated with cumulative subway PM_{2.5} exposure, suggesting a link to the number of years worked in the subway, although urinary isoprostane levels were not significantly higher than in bus drivers or office workers. These in-vivo studies suffered from a lack of statistical power and inconsistent clinical health outcomes, making it difficult to determine their clinical significance. On the other hand, in-vitro evidence is more compelling in revealing the toxicity of subway PM and the mechanisms involved.

The first study in London to assess the health risks of exposure to subway dust involved in-vitro toxicological testing on type II human alveolar-like A549 epithelial cells (Seaton et al., 2005). Seaton et al., (2005) compared a series of toxicological outcomes of cell exposure to tunnel dust, ambient PM, and titanium oxide (TiO₂). Tunnel dust stimulated more free radical activity, DNA

damage and greater release of lactate dehydrogenase (LDH) and interleukin-8 (IL-8) than the controls. The pro-inflammatory effects of IL-8 release were negated by chelation indicating that soluble transition metals were responsible.

In a similar study in Stockholm, A549 cells were exposed to subway and urban street particles (Karlsson, Nilsson and Moller 2005) with subway particles found to be eight times more genotoxic and four times more likely to cause oxidative stress in lung cells than urban street particles. A further study using A549 cells compared the genotoxicity and ability to induce inflammatory mediators of subway PM, urban street PM, wood pellet combustion and tyre wear (Karlsson et al., 2006). DNA damage from subway PM was significantly higher than other PM types inducing significant changes in TNF- α from human monocyte-derived macrophages, as well as inflammatory cytokines, IL-6 and IL-8. Furthermore, subway particles caused four-fold damage in A549 cell mitochondrial depolarization, compared to controls Fe₃O₄, Fe₂O₄, Fe₂O₃, CuO and Cu-Zn, and was similar to wood and diesel PM, but greater than street PM and tyre/road wear PM (Karlsson 2008). The combination of Fe and Cu was the most efficient in generating ROS, which is significant as this reflects the general composition of subway PM (Loxham and Nieuwenhuijsen 2019).

Inhalable PM₁₀ from two deep platforms at Baker Street on the London Underground was introduced into cultures of A549 cells and human primary airway epithelial cells (Miyashita et al., 2022). Evidence was found of increased risk of pneumococcal infection due to adhesion to airway cells and entry of bacteria in cells, increasing susceptibility to pneumococcal infection. In a mouse model increased mortality and the translocation of pneumococcus into the systemic circulation was observed.

In Paris, the Réseau Express Régional (RER), with the traditional steel-based system (Fe 61%) and the Paris Metro using rubber tyres and wooden brakes (Fe 42%) operate. The elevated iron content of RER PM elicited greater biological effects on murine macrophages with enhanced expression of hemeoxygenase-1 (HO-1), a marker of antioxidant response to oxidative stress, and a time- and dose-dependent increase in TNF- α and MIP-2 production by RAW 264.7 cells (Bachoual 2007). Similarly, a concentration-dependent increase in IL-8 release, ROS generation and HO-1 upregulation from subway PM which crossed the mucous barrier was found (Loxham et al., 2015). There was a greater response to the fine fraction of PM compared to the coarser

fraction, ameliorated by deferoxamine (DFX) and N-acetylcysteine (NAC) in the fine fraction, suggesting an iron-dependent mechanism derived from the wheel/rail interface and braking systems.

As part of the Risk of Airborne Particles - a hybrid Toxicological and Epidemiological study (RAPTES), 31 healthy volunteers were exposed at locations in the Netherlands, including two traffic sites, a subway train station, a farm and an urban background site, each with differing PM sources and concentrations. Subway particles were dominated by a high transition metal content, particularly Fe, Cu and Ni. An in-vitro toxicity study of PM collected at the different sites was conducted by Steenhof et al., (2011). They concluded that the high transition metal content of subway PM was responsible for the large decrease in metabolic activity in macrophages in comparison to the traffic and urban background sites. However, the pro-inflammatory response was highest for PM collected at traffic locations, making it difficult to draw firm conclusions about associations between in vitro toxicity and specific PM components.

It has been proposed that the oxidative potential of PM could be more informative of the biological effects of exposure than PM mass alone (Janssen et al., 2014). The oxidative potential (OP) of PM_{2.5}, collected from several stations in Barcelona, to deplete ascorbic acid (AA) and glutathione (GSH) found antioxidant depletion was not linked to PM_{2.5} concentrations, although it was positively associated with metallic trace elements (Moreno et al., 2017).

In-vitro evidence suggests that the transition metal-rich nature of subway PM is able to elicit greater ROS generation and enhanced oxidative damage than ambient PM. Together with the ability to induce inflammatory responses in cultured human lung tissues, in-vitro studies indicate that the effect occurs despite having a lower particle number count (PNC) than ambient PM. The importance of elevated iron concentrations within the subway is highlighted by iron chelation which significantly reduced in-vitro toxicological effects. Nevertheless, inflammatory responses and ROS generation still took place indicating that genotoxic and oxidative stress potential occurs in the presence of trace metals. This infers these components are working synergistically with iron oxides and it is particle metal enrichment that is responsible for the increased toxicology rather than iron content alone. However, the coarser size fraction and the smaller surface area of subway PM lowers the proportion of the insoluble fraction possibly reducing the reactive toxic potential of subway particles (Loxham and Nieuwenhuijsen 2019). Overall, there are disparities

between the in-vivo and in-vitro evidence, which is likely due to statistical underpowering and poor selection of health outcome measures in-vivo. It is possible that the interplay of complex human tissues and organs modulate the effects of subway PM in-vivo more than cell cultures in-vitro. Despite this, studies suggest that following exposure, elevated levels of iron oxides and trace metals in subway PM cause increased genotoxicity, oxidative stress and systemic inflammation.

2.7 Contribution to personal exposure

Exposure to subway air is repeated daily for most commuters and attempts have been made to quantify the health effects of subway PM_{2.5} exposure based on the co-efficient used for quantifying mortality from ambient PM_{2.5} exposure. There are a number of problems with this; subway PM has different physicochemical properties to ambient PM and health effects are not related to mass concentrations alone (Franklin, Koutrakis and Schwartz 2008, Cassee et al., 2013, COMEAP 2018). Moreover, the higher concentrations found in the subway may not linearly apply to the concentration-response relationship quantifying risk relating ambient exposure and health outcomes (Burnett et al., 2014). Nevertheless, the London Hybrid Exposure Model (LHEM) (Smith et al., 2016) showed that transport microenvironments are important in establishing daily personal exposures with those commuting, particularly by London Underground (mean PM_{2.5} 94 µg m⁻³), having the highest exposures. Studies have estimated an 8-18 µg m⁻³ incremental increase in daily PM_{2.5} exposure to subway PM_{2.5} for passengers in London (Seaton et al., 2005, Saunders et al., 2019). In Barcelona passenger daily exposure was estimated to increase by 10%, but for specific metals this could be one order of magnitude higher (Querol et al., 2012).

2.8 Remedial measures to reduce PM concentrations

Reducing exposure to subway PM through remedial measures is essential to improving air quality for passengers. The combination of Platform Screen Doors (PSD's) and tunnel, platform and carriage ventilation have been shown to be the most effective at reducing PM concentrations and improving air quality for passengers (Moreno et al., 2017, Carteni and Cascetta 2018, Choi et al., 2019). Indeed, in Barcelona tunnel ventilation maintained clean air on platforms reducing PM mass and particle number concentrations by over 50% in the presence of PSD's, with air conditioning in trains leading to substantially lower PM concentrations than on platforms (Moreno et al., 2017). The cleanest, subway system is the high-quality line constructed for the Winter

Olympics in 2006 with rubber wheels, PSD's and a full tunnel and train ventilation system which reduced PM₁₀ concentrations to 23 µg m⁻³ (Carteni and Cascetta 2018)..

These measures are expensive to install in existing subway systems so an approach based on pollution hotspots that pose the greatest risk to exposure may be of more immediate benefit. Targeted measures are required to lower concentrations and any subsequent health effects, and understanding the concentrations and chemical composition is essential to quantifying the effectiveness of any measures introduced (Martins et al., 2016). Older networks with the worst air quality are the most difficult to change, and to tackle this Moreno and de Miguel, (2018) proposed a targeted approach to encourage incremental improvements in air quality towards the WHO PM_{2.5} Air Quality Guideline annual mean level of 10 µg m⁻³ (as it was at the time of the work). In conjunction with the station population-exposure rankings proposed by Smith et al., (2020) transport authorities could dramatically reduce exposure by adopting targeted remedial measures such as active ventilation systems, full-length PSD's and air conditioning in trains at the most polluted stations. (Querol et al., 2012, Cha et al., 2019). Although it is difficult to improve air quality in subway systems, local city or government initiatives to improve subway air quality such as in Paris (RATP 2023) and South Korea (Korea Legislation Research Institute , Kim et al., 2022), where subway air quality PM_{2.5} and PM₁₀ limits have been introduced, demonstrate how policy interventions can bring about improvements.

2.9 Current Knowledge gaps

This literature review has summarised the current knowledge about worldwide subway PM concentrations, the factors affecting PM concentrations, the sources of PM in the subway, current knowledge of the health effects caused by exposure to subway PM, both in-vivo and in-vitro, as well as an estimate of the contribution to daily personal exposure from subway travel and an outline of possible remedial measures. Nevertheless, several knowledge gaps in the current literature have been identified.

Most subway studies have researched concentrations on station platforms for a relatively short period of time, focusing on short-term variations in PM mass in specific stations. There are few studies investigating long-term variability in stations or long-term commuter exposure in train carriages. There have been very few studies of air quality inside train carriages. These studies are difficult to carry out due to the confined space and lack of power in subway train carriages.

They require a large amount of researcher's time travelling around the subway. The available evidence shows that there is a large variation of PM in train carriages and that the factors affecting PM in train carriages are poorly understood. This is important as subway travellers spend most of their commuting time in train carriages.

The interaction between subway generated PM and ambient concentrations and how this is affected by ventilation, in particular passive ventilation systems such as in the London Underground, is unclear. The degree of ingress of ultrafine particles (UFP's) from the ambient environment and how this relates to UFP's generated within the subway system requires further investigation to further understanding of the sources and influencing factors of railway generated PM.

There is evidence of PM chemical composition in subway systems worldwide, but these have focused on specific stations or locations with a limited number of samples. No study has investigated how PM chemical composition throughout an entire line varies over a long period of time and how the chemical composition of those metals most likely to affect the health of subway users varies over time.

Current research into the health effects of PM_{2.5} exposure is based on ambient air, whereas the subway environment is very different, with high concentrations of ROS-generating transition metals. Very few studies have investigated the OP of subway PM to deplete ascorbic acid and/or glutathione. The studies that have taken place have used PM collected from station platforms (Moreno et al., 2017) rather than collected in a train carriage over a typical commuting journey. In-vitro studies have shown that London's subway PM_{2.5} can generate free radicals (Seaton et al., 2005) although no oxidative potential studies have used PM_{2.5} from the London Underground.

There remain important knowledge gaps in the subway literature some of which this thesis will seek to address by undertaking an extensive monitoring campaign in train carriages in the London Underground as part of a MRC study.

Chapter 3 Materials and methods

3.1 Introduction

The MRC study required high-quality reference grade data of study participants personal exposures to all size fractions of PM, oxides of nitrogen (NO₂ and NO_x) and ozone on London Underground and London Overground journeys. To achieve this, I designed a Mobile Reference System (MoRS) that I took onto all train journeys accompanying participants at all times, using MoRS to measure participants personal exposures. MoRS incorporated instrumentation that made use of the of the miniaturisation and reduced power requirements of higher quality measurement instruments to accurately measure participant personal exposures during their train journeys. The instrumentation used in this study and the reasons for the choice of the instrumentation will be outlined in this chapter. Accurately measuring personal exposures was key to understanding any effects on health from linking the acute biological/physiological responses of the participants to subway exposures in comparison to overground exposures. These two environments presented contrasting measurement locations. It was expected that PM_{2.5} would be higher in the subway and NO₂ and O₃ would be higher in the overground making measurements of all three pollutants essential to be able to disentangle their potential effects on health. During all train journeys personal exposure measurements were carried-out whilst the participants were seated in a train carriage.

Train carriages present a challenging measurement location with a lack of power, limited space, constantly changing environmental conditions and differing sources (Querol et al., 2012, Cames and Helmers 2013). Pollutant concentrations change rapidly as the train moves between the underground and above-ground environments with these changing concentrations needing to be captured by the instruments without the influence of relative humidity, temperature, vibrations and changing light sources. There was a need for portable, compact instrumentation that provided a consistency and traceability of response during the journeys. Exposure sampling needed to be carried out at the breathing height of the participants when they were seated. The instruments were required to be battery powered and robust enough to undertake multiple measurements over an 18-month period. The measurements needed to be traceable and to accurately measure the full range of pollutant concentrations during the journeys. The equipment needed to be safe, to other passengers and from damage, when moved around the carriages or railway

environments. As part of the MRC study protocol the equipment was also required to collect PM_{2.5} filter samples for oxidative potential and elemental analysis. I designed MoRS to collect the required PM_{2.5} filter samples and in the Imperial college laboratory I carried out the oxidative potential analysis and extracted the PM_{2.5} from the filters to send to King's College, London, for ICP-MS elemental analysis.

To meet these challenges in reporting high-quality data over the study period the instruments required a robust quality assurance and quality control programme (QA/QC) of testing (Koistinen et al., 1999, DEFRA 2016). I developed a QA/QC programme for instrument testing which is outlined in this chapter. This ensured that the reported data was consistent and comparable across the two measurement locations and was suitable for the statistical analysis required to link the health responses of the participants to subway exposures. This made the choice of sampling equipment critical in achieving a high-quality, exposure assessment in the differing railway environments of the subway and overground.

This chapter outlines how I overcome these measurement challenges by taking advantage of the miniaturisation and reduced power requirements of higher quality measurement instruments. It will further outline how the housing of the instrumentation in a highly portable, manoeuvrable measurement system which I conceptualised and designed, ensured reliable personal exposure measurements were achieved.

3.2 Addressing measurement challenges

There were a number of considerations in how to address the challenges of measuring in train carriages of the two environments of the below-ground subway and the above-ground overground. Traditionally, fixed air quality monitoring stations using reference grade instrumentation have been used to provide ambient air pollution measurements for epidemiological health studies. However, they cannot provide data at the high spatial and temporal resolutions required to reflect the subway environment that participants were exposed to during this study (Castell et al., 2017, Kitagawa et al., 2022). Although the majority of people's daily exposure is to indoor air pollutants (Klepeis et al., 2001, Barkjohn et al., 2020, Zhang and Srinivasan 2020), they are often subjected to their highest exposures in indoor microtransport environments (de Nazelle et al., 2013, Cepeda et al., 2017). Fixed monitoring stations fail to capture these indoor exposures leading to exposure misclassification and bias in personal

exposure estimates (Smith et al., 2016, Brokamp, Brandt and Ryan 2019). For these reasons using a fixed air quality monitoring station approach to measuring in the subway and overground was rejected.

Small sensors were used in the Oxford Street study by Sinharay et al., (2018). They used recent advances in instrument miniaturisation which makes small sensing technologies portable, easy-to-use and low-cost, enabling real-time, high resolution air pollutant monitoring (Castell et al., 2017, Kang et al., 2021). Small air pollution sensors have the potential for detailed personal exposure assessment on an individual scale (Chatzidiakou et al., 2019) and can capture spatial variability to account for the significant disparity between air pollutant concentrations in these microenvironments (Evangelopoulos et al., 2021).

However, when moving small sensors between different environments they are often highly sensitive to changing environmental metrological conditions, making accurate measurements difficult (Cross et al., 2017). Pollutant cross-sensitivities, sensor drift, sensor age and chemical interference often require complex algorithms to adjust for these factors compromising data quality and often leading to a lack reproducibility (Kumar et al., 2010, Aleixandre and Gerboles 2012, Karagulian et al., 2019).

There are also questions regarding quality control and without long-term validation using laboratory and field calibrations (Jiao et al., 2016, Barkjohn et al., 2020, Liu et al., 2020) this could lead to exposure misclassification and misleading data (Chatzidiakou et al., 2020). This makes their use in scientific studies such as panel studies questionable (Cross et al., 2017, Feinberg et al., 2018, Wang et al., 2021). Given the high contrast within and between the subway and overground train carriage environments, with constant changes in temperature and relative humidity and particle chemical and physical composition (Moreno et al., 2017, Martins et al., 2021), and differences in pollutant concentrations, it was decided not to adopt a small sensor approach to this measurement campaign.

There remained a need for a measurement methodology that would provide stable measurements in the two differing transport microenvironments. The instruments used in this study needed to allow intercomparability between these microenvironments without being affected by pollutant cross-sensitivities, sensor drift, sensor age and chemical interference, and respond to differences in particle chemical and physical composition. Reference-grade data that aligned well with fixed

measurement stations was required to enable high-quality personal exposure data to be obtained. The miniaturisation and reduced power requirements of higher quality measurement approaches, similar to those used in fixed measurement stations was the preferred measurement solution.

To address this gap between static reference monitoring stations and easy-to-use small sensing technologies, without compromising data quality, a highly portable air pollution Mobile Reference Station (MoRS) was developed to deliver reliable, reproducible data for the MRC study. In the configuration used for this study, MoRS provided simultaneous measurements of a broad particle size distribution (10nm to 35µm), gaseous pollutant concentrations (oxides of nitrogen and ozone O₃), environmental parameters (noise, relative humidity (RH) and temperature) as well as collecting filter samples for laboratory analysis. In addition, its highly flexible framework allowed MoRS to be rapidly adapted throughout the study in response to distinct challenges, including Covid-19 travel mandates, during its deployment in mainline, subway and overground railway environments. The next section describes the development of the MoRS instrumentation.

3.3 Mobile Reference Station (MoRS)

MoRS was developed to offer a small, flexible, wheeled platform for obtaining high quality measurements of air pollutants over relatively short timescales (minutes to hours) independent of power supply. This was achieved using recent advances in commercially available monitoring equipment which has resulted in smaller, lower power technology. The monitoring equipment was chosen in conjunction with my supervisor, to meet the challenges of being moved between different environments and measuring in train carriages without data quality being compromised and to ensure data comparability between the subway and overground.

Before MoRS could be constructed careful consideration was given to the design and instrument housing for the selected instrumentation for measurements of particulate matter, black carbon, oxides of nitrogen, ozone, carbon dioxide and noise. A major consideration was to select instruments making use of the smaller design and lower power technology. They also were required to report accurate measurements consistently in the varied environmental conditions that were encountered, particularly changes in temperature and relative humidity (Wei et al., 2018, Samad et al., 2020).

3.3.1 Instrument housing

To facilitate repeated measurements on the railways I built a wheeled platform to provide a robust, maneuverable housing for the instrumentation, that could be moved between different environments, and over different surfaces to and from deployments by a single researcher. It also needed to be adaptable, have easy access for instrument repairs, setup and maintenance and with weight kept to a minimum.

The platform was made of 40mm x 40mm aluminum profile to provide a rigid, lightweight structure, divided into four bespoke compartments. To allow MoRS to be wheeled longer distances over rough surface, it was fitted with 10cm diameter wheels with spring attachments to reduce vibrations.

3.3.2 MoRS Measurement Instrumentation

It was important that MoRS could be adapted for different measurement campaigns and the design could be flexible enough to allow for different instruments and configurations in the set-up. MoRS was built by me initially for an “Analysis of Air Quality On Board Trains” study (Rail Safety and Standards Board Ltd 2021). This involved taking almost 100 mainline train journeys (13 Jan 2020 to 02 Dec 2021) measuring all size fractions of PM, BC, NO₂, NO_x and CO₂. This study allowed MoRS to be tested and adapted for measuring in train carriages and for the measurement instrumentation to be modified as required for the study. For the MRC study BC and CO₂ were not measured whereas ozone and noise were measured, along with PM, NO₂ and NO_x and filter samples collected for oxidative potential and elemental analysis. This required me to be able to adapt MoRS for the different studies.

3.3.2.1 Particulate matter measurements

A large array of instrumentation has previously been used by researchers when measuring PM concentrations in subway train carriages. Many have used optical particle counter (OPC) based PM mass measurement devices (Martins et al., 2016, Zheng et al., 2017, Luglio et al., 2023) as these are small and easily carried by researchers in train carriages. Optical particle counting based devices have a 200 - 300 nm lower size cut-off. In this study the full particle size distribution range was required from a minimum of 10 nm to fully capture above and below ground subway sources. This allowed the evolution of the spatiotemporal changes to particle size distribution to be recorded throughout the journey. Previous research has identified particle size ranges in the

subway which are emitted from different source components and shown there is a large contribution of ultrafine particles in the subway (Midander et al., 2012, Cha et al., 2018).

To compensate for the 200 - 300 nm lower size cut-off of optical particle counting devices a dual instrument approach combining an ultrafine particle counter was considered as this approach had been previously used (Cha, Abbasi and Olofsson 2018, Smith et al., 2020). This was rejected as it was decided, in conjunction with my supervisor, that the best measurement method was based on the direct measurement of particle size distribution, across the broad size range of 10 nm to 10 μm . This allowed for the calibration of PM mass size fractions in the different environments to account for variability in sources. The only instrument identified that fulfilled the requirements listed above was a Grimm Mini-Wras Portable Wide Range Aerosol Spectrometer (Model 1371, Grimm Aerosol Technik GmbH, DE) which measured particle size distribution between 10 nm and 35 μm . The Mini-Wras had been successfully used in previous studies in train carriages in the subway (Cha et al., 2019) so was deemed to be the best available instrument for comparable measurements between the overground and subway environments.

3.3.2.2 Grimm Mini-Wras Portable Wide Range Aerosol Spectrometer

The Mini-Wras is a self-contained portable, low power instrument that detects airborne particles based on particle diameter. The Mini-Wras detects a wide range of particle diameters ranging from 10 nm to 35 μm allowing an approach based on the direct measurement of particle size distribution providing a time series for both mass and particle size distribution for each exposure. The Mini-Wras can measure mass concentration from 0.1 $\mu\text{g m}^{-3}$ to 100 mg m^{-3} with a flow rate of 1.2 l min^{-1} . Data storage is on a USB flash memory. It has an internal battery supply with a runtime of eight hours and a weight of 7.6 kg (16.8 lb).

The Mini-Wras is able to detect particles from 10 nm to 35 μm by combining two measurement technologies. A continuous optical detection of particles using scattered light intensity to measure particles with diameters 250 nm–35 μm uses an optical particle counting (OPC) technique. All particles are first passed through the optical particle sensor before being sampled by a Nano-Sizer. Particles between 10 – 200 nm are measured by a Faraday cup electrometer Nano-Sizer using electrical classification detection. The nano-sizer consists of three elements: a unipolar positive electrical diffusion charger, +3,000v to +4,000v, an electrical aerosol separator electrode

(deposition of particles), -320v to -0.85v, and a faraday cup electrometer. On entering the Mini-Wras particles are positively charged in the unipolar corona charger by diffusion.

The charged particles enter the deposition electrode where the particles are distributed over the entire cross-section between the inner and outer electrode. A negative voltage is applied to the inner electrode, which is reduced in 10 discrete steps from -320V down to -0.85V. The resulting variable electric field deflects the positively charged particles towards the inner electrode and the particle fraction that is able to be transmitted enters a Faraday cup electrometer for detection. The actual measurement result is a current that is dependent on the voltage applied to the deposition electrode which is converted by an inversion algorithm to a particle size distribution.

The particle size reported by the Mini Wras nano sizer is based on the calibration curves of DMA classified, monodispersed particles and corresponds to an electrical mobility equivalent diameter. The OPC part of the Mini Wras reports polystyrene latex (PSL) optical equivalent diameters. The Mini-Wras reports particle size data as electrical mobility equivalent diameter for particle sizes from 10 – 200 nm and optical equivalent diameters for particles sizes 250 nm – 35 μ m. Sampling over each size bin in the nano-sizer is carried out over 6 seconds giving a total size resolution of 60 seconds. The nano-sizer reports 10 size bins, with optical detection reporting 31 size bins allowing the full particle size range to be separated into 41 size bins.

The default factory settings for the Mini-Wras are derived from two calibration methods. For the Nano-Sizer (10 – 200 nm) a polydisperse aerosol with particle diameters of 5 to 300 nm is generated from a 0.1% NaCl solution using an aerosol generator. The optical sensor is calibrated with mono-dispersive latex certified by the NIST (National Institute of Standards and Technology). These calibration methods have different properties to ambient and railway aerosols which can lead to incorrect measurements of particle size distributions and mass concentrations without appropriate scaling factors being used (Torrey et al., 2015).

Midway through the MRC study measurements the Mini-Wras received a new software update which included a new data inversion algorithm which uses calibration curves to obtain the best fit for the data (Ahlawat et al., 2022). All data from the Mini-Wras was processed with the new data inversion algorithm.

The Mini-Wras can detect across the wide range of particle emissions from subway sources (wheel/rail interface, brakes, sparking and passengers) (Salma, Weidinger and Maenhaut 2007, Pan et al., 2019), especially the reporting of ultrafine particles (<100 nm). This is important when assessing personal exposure to particulate matter in the subway for the MRC study as it is known that ultrafine particles have the potential to cause adverse health outcomes (Loxham et al., 2013, Schraufnagel 2020).

To reduce the maintenance frequency for the Mini-Wras dryer, an additional dryer (Perma Pure, Fluid Controls Ltd) was installed in the sample inlet stream with dry air supplied by an additional pump (SKC Leland Legacy) and silica gel column although this was later discarded as testing demonstrated that the relative humidity remained below 35% using only the internal silica gel column.

The Mini-Wras recorded external temperature and relative humidity with a temperature and relative humidity sensor (model 1158-EE) and recorded internal relative humidity and temperature.

3.3.2.3 Microaethalometer

During a Rail, Safety and Standards Board (RSSB) (RSSB 2023) study investigating air quality on mainline trains., MoRS measured black carbon (BC) from diesel emissions, as a tracer of train engine activity, using a MA300 Microaethalometer (microAeth, USA). The MA300 measures the rate of decrease of light at 880nm through a sample filter loaded with a continuous collection of BC particles. To overcome filter loading the optical attenuation due to the absorbance of particles on the filter is measured relative to a portion of the filter with no accumulated particles. The optical attenuation is then converted to a mass BC concentration. The MA300 is a self-contained instrument with an internal battery, data storage, pump and an inbuilt GPS. The MA300 was not used in the MRC study as the iron oxide in subway particles is known to interfere with the Microaethalometer measurements of black carbon.

3.3.2.4 Filter Samples

Initially, a single PM_{2.5} filter sample was collected for independent mass calibration via a URG PM_{2.5} cyclone (URG-2000-30EH) at 5 l min⁻¹ using proprietary pumps (Legacy, SKC) with inbuilt battery and flow control. Later this was increased to two identical filter samples with an increased flow rate to provide adequate mass for laboratory analysis. These were collected through an URG

PM_{2.5} cyclone (URG-2000-30EH) via an isokinetic splitter (Model 1102, Bechtel, USA) with flow controlled via two independent pumps each drawing 8.35 l min⁻¹. Initially, these were Legacy pumps but later upgraded to more powerful vacuum pumps (Air Cadet, Cole Palmer, UK), independently controlled by two mass flow controllers (Model MCP-20SLPM, Alicat, USA) and powered with exchangeable 12v 22Ah Lithium polymer batteries (Tracer, UK).

3.3.3 Gaseous Measurements

Gaseous measurements for the MRC study were required due to potential confounders in the health study resulting from the contrasting measurement environments in the subway and the overground. The subway has much higher concentrations of PM_{2.5} compared to the overground but lower concentrations of NO₂ and O₃ were expected.

3.3.3.1 Airyx ICAD NO₂/NO_x Analyser

An Airyx ICAD (Iterative CAavity enhanced DOAS, Airyx GmbH, DE) NO₂ /NO_x analyser was used to measure NO₂ at a 10s resolution via direct optical absorbance between wavelengths of 430 to 465 nm. This allowed the absorption spectrum of NO₂ to be identified and separated from overlapping absorptions such as water vapour. The ICAD method had no significant zero drift and appeared resistant to temperature and relative humidity variations, vibrations and changing light sources. This made the Airyx ICAD suitable for measuring in a railway environment and had previously been used in mobile vehicle measurements (Horbanski et al., 2019, Farren et al., 2023). The instrument had a low weight (<10kg) and was powered with a 12v 22Ah Lithium polymer battery (Tracer, UK).

3.3.3.2 2B Technologies Ozone Monitor

Ozone was measured using a 2B Technologies Ozone Monitor (Model 205 Dual Beam Monitor, 2B Technologies, USA) based on the well-established method of ultraviolet light (UV) absorption at a wavelength of 254 nm, which is a US Environmental Protection Agency Federal Equivalent Method. A photodiode measured the intensity of light in air that passed through an ozone scrubber (I_0) and sampled air (I) that had not passed through the scrubber allowing ozone concentration to be calculated. Changes in relative humidity can influence ozone measurements but the 2B Technologies ozone monitor eliminates water vapour interference by maintaining a humidity equilibrium during the I_0 and I measurement cycles (Wilson and Birks 2006). The Ozone monitor has a limit of detection of 3.0 parts-per-billion by volume (ppbv) to an upper limit of 250 parts-per-

million (ppmv) at a flow rate of 1 l min⁻¹. This instrument had low weight (5.5 lb, 2.5 kg) and low power consumption (~7.2 watt) and was powered with a 12v 22Ah Lithium polymer battery (Tracer, UK).

3.3.3.3 Li-Cor LI-820 CO₂ gas analyser

Carbon dioxide was measured during the RSSB study using a Li-Cor LI-820 CO₂ gas analyser which used a single path, dual wavelength, infrared detection system. It had a measurement range of 0 - 20,000 ppm and was powered with a 12v 22Ah Lithium polymer battery. Carbon dioxide was not measured during the MRC study.

3.3.4 Noise

Noise is an environmental stressor linked with increased blood pressure and reduced heart-rate variability (HRV) as well as being a possible confounder to PM_{2.5} exposure (Huang et al., 2013, Yang et al., 2018, Manohare et al., 2022). Noise levels on the subway often exceed 100db (Xu, Jiang and Huang 2019, Singh et al., 2020). To account for any potential confounding on cardiovascular outcomes, noise was measured at 1s resolution on all subway and overground journeys using a RS-PRO DT-8852 Datalogging Sound Level Meter (RS-PRO, UK). To help reduce noise levels and any related stress, noise cancelling headphones were worn by the participants during each train journey. Noise was only measured during the MRC study.

3.3.5 MoRS development

This first set-up of MoRS (Figure 3.1 V1), measured PM₁₀, PM_{2.5}, NO₂, NO_x, CO₂ and BC on mainline trains between 13 January 2020 and 02 December 2021 (Rail Safety and Standards Board Ltd 2021) over almost 100 journeys. This provided an opportunity to evaluate the performance of the system in a railway environment prior to deployment in the subway. During this study, the system was updated to include a battery powered PC and screen, controlled by a wireless keyboard. These were added allowing connections to the instrument interfaces, displaying real-time measurements. For the MRC study, the 2B Technologies Ozone instrument and the sound meter were added to MoRS and the Microaethalometer and Li-Cor CO₂ analyser were removed. The filter sampling system was changed at this point to collect PM_{2.5} for OP analysis and chemical composition. 25mm PTFE coated glass fibre filters (Pall Corporation, USA, 513-0034) were used to collect PM_{2.5} mass for oxidative potential and 25mm Whatman PTFE membrane filters (Pall Corporation, USA, 514-3122) to collect PM_{2.5} mass for ICP/MS analysis.

3.3.5.1 Adaption of MoRS for Mask Wearing

During the Covid-19 pandemic, the UK entered the first national lockdown from 23 March 2020 to 10 May 2020. On 15 June 2020 wearing a mask or a face covering became compulsory when travelling on public transport, this restriction was ended on 24 February 2022. The first trial measurements using MoRS on the London Overground took place on 27 May 2021. At this time, it was compulsory for users of public transport to wear a mask, unless exempt, including on the London Underground and London Overground. Previous research had shown that participants wearing a mask were likely to experience reduced $PM_{2.5}$ exposure which could lead to a subsequent reduced health effect (Ji, Li and Wang 2021, Kodros et al., 2021, Velasco et al., 2022). At that stage, the longevity of the mask mandate was unknown and neither was the preference of individual COPD patients (who were medically exempt).

A method for obtaining PM measurements that mimicked the mask wearing status of the participants on future journeys therefore needed to be developed. A mannequin head was fitted onto MoRS which was capable of having a mask fitted over the $PM_{2.5}$ cyclone and Mini-Wras inlet. A wire mesh was placed between the mask and the inlets to ensure they remained separate and resembled a typical surgical mask fitting (Figure 3.1 V2). The mannequin head would always be fitted with the same type of surgical mask as the participants to replicate the personal $PM_{2.5}$ exposure of the participants as closely as possible. The gaseous inlets for NO_2 , NO_x and O_3 were not included in this adaption as there is no evidence that gaseous inhalation is affected by mask wearing. Fully laden, MoRS weighed 35kg and the final design and instrument selection is shown in detail in Figure 3.2 with a schematic of MoRS shown in Figure 3.3.



Figure 3.1: MoRS V1 (left) and MoRS V2 (centre) and the mannequin head (right) showing the filter holder set-up

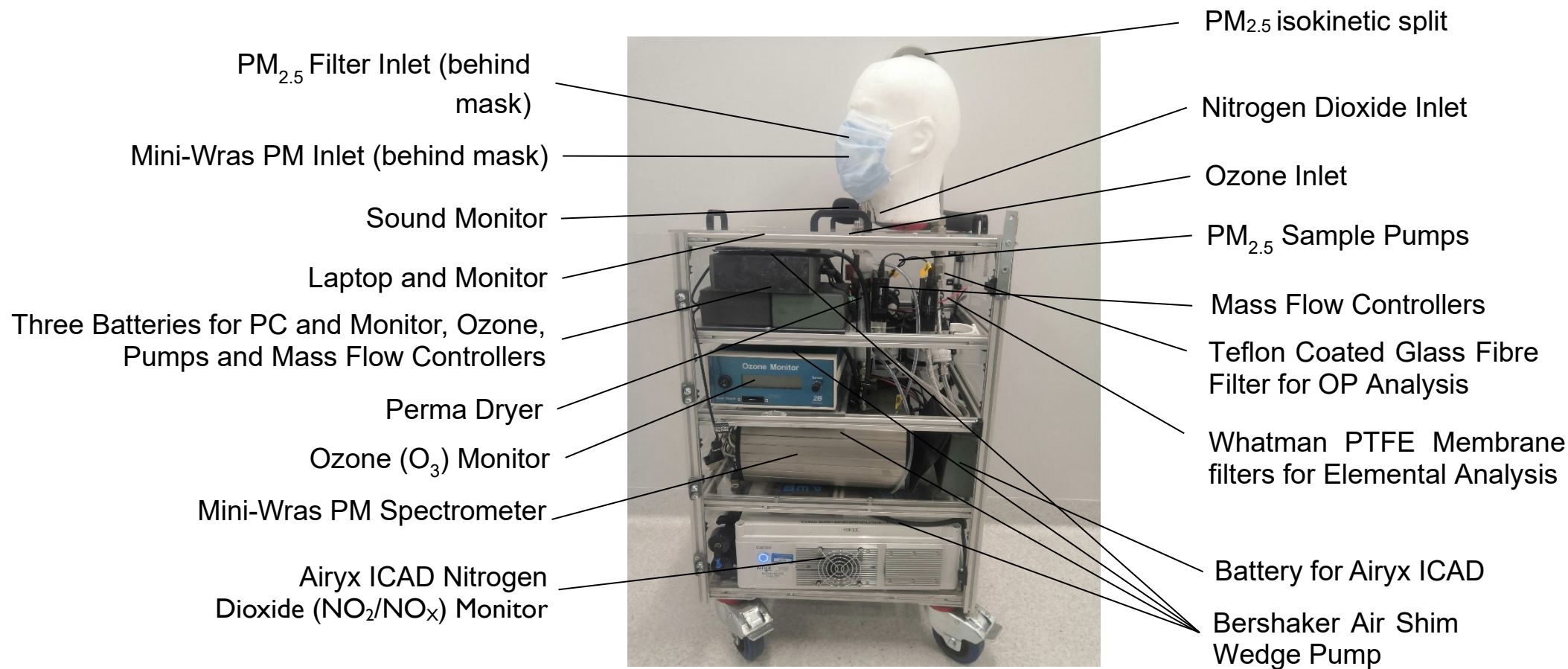


Figure 3.2 The final design and configuration of the Mobile Reference Station (MoRS) for use in the subway exposure assessment to measure personal exposures of the participants in the MRC study.

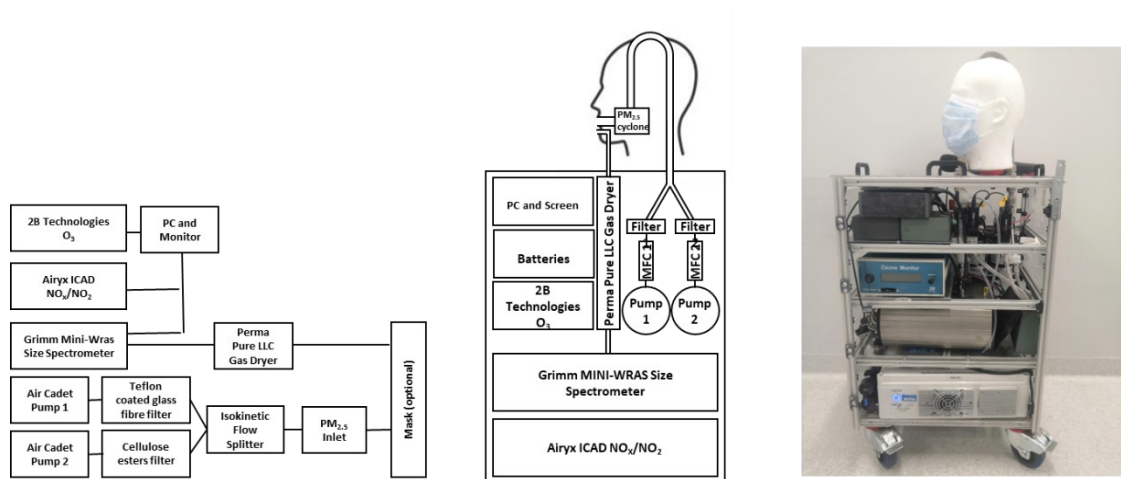


Figure 3.3: Mobile Reference Station (MoRS) (schematic (left), sampling configuration (centre) and picture (right)).

3.4 Data Collection

All the instruments contained within MoRS were able to sample simultaneously with each instrument configured to ensure that the time resolutions were compatible. The full range of instrument measurements are shown in Table 3.1.

I switched on all instruments contained in MoRS in the Imperial College laboratory 30 minutes before deployment. This allowed the instruments to reach their operating temperatures and to perform self-zero tests and internal calibrations. Each instrument was time synched with the onboard PC to ensure that each instrument was time aligned with each other and the onboard PC. If the participants were wearing a mask for the journey, I fitted MoRS with a mask, otherwise the mask would not be fitted. I placed pre-weighed filters into their respective filter holders and I checked the flow through the filters. I changed the filters before each individual train journey, for laboratory and gravimetric analysis. All instruments and batteries were secured with air wedges to stop any instrument or battery movement during the deployment. All time stamps were in GMT throughout the study.

All instruments stored measurement data internally. During the service of the Mini-Wras in October 2022, the software was updated with a new data inversion algorithm included in software version 10 (Ahlawat et al., 2022). All data collected before the software update was recalculated using the data inversion algorithm to ensure data compatibility throughout the study. The Airyx ICAD stored data internally and was connected to the MoRS PC to display on the screen via the internal Wi-Fi module. The 2B Ozone Monitor was connected to the MoRS PC via a RS-232

interface for viewing and storing. This allowed all instrument measurements to be viewed and collected in real-time during the deployment of MoRS. On completion of the train journey, I returned MoRS to the Imperial College laboratory and I archived all data by downloading immediately to the Imperial server.

Table 3.1: Instruments and configuration settings and typical runtimes between charges of equipment used in the Mobile Reference Station (MoRS) for the MRC study.

Model	Make	Measurement	Time Resolution (sec)	Run Time (hours)
ICAD	Airyx	NO _x , NO ₂ (ppb)	10	7.8
205 Dual Beam	2B Technologies	O ₃ (ppb)	10	16.6
Mini-Wras 1371 Spectrometer	Grimm Aerosol Technik GmbH	PM Mass (PM ₁ , PM _{2.5} , PM ₁₀) (µg m ⁻³) Aerosol Size Distribution (10nm - 35µm)	60	8.3
DT-8852 Datalogging Sound Level Meter	RS-Pro	Sound (db)	1	18.0
MCP-20SLPM	Alicat	Mass Flow Controllers (l min ⁻¹)	60	15.2

3.5 Measuring participant personal exposure

3.5.1 Study Route

When selecting the study journey routes there were three main criteria that needed to be fulfilled.

These were:

- Journey start station(s) needed to be within a 20-minute taxi journey of the Sir Michael Uren Hub, Imperial College White City campus (51.515768, -0.224009).
- Journey start station(s) were required to have step-free access to the station platform from street level to ensure level access for the equipment and minimise exertion for the participants.

- Return journey station(s) needed to be terminus station(s) to avoid changing platforms and trains.

Stations which met these criteria are shown in Table 3.2 and were ranked by predicted exposure to subway PM_{2.5} with reference to the PM_{2.5} exposures reported by Smith et al., (2020) and their suitability according to the study criteria.

Table 3.2: Stations with step-free access within a 20-minute taxi journey of Imperial College White City campus showing PM_{2.5} concentrations from Smith et al., (2020) for the LU lines.

Rank	Station	Step-Free Access	Overground Line	LU Line	Mean PM _{2.5} concentrations for LU line
4	Kensal Rise	Yes	Yes	No	
3	Kilburn	Yes	No	Jubilee Line	103
6	Shepherd's Bush	Yes	Yes	No	
1	Willesden Junction	Yes	No	Bakerloo Line	118
2	Willesden Junction	Yes	Yes	No	
5	Wood Lane	Yes	No	Hammersmith & City Line	25

Willesden Junction station (51.6185, -0.5594) was chosen as the most suitable starting station as it had step-free access to the platform level with the Bakerloo and Overground lines both stopping at the station. Southbound Bakerloo line trains terminated at Elephant & Castle station (51.494424, -0.100752), while northbound Overground trains terminated at Watford Junction station (51.6637, 0.3964). Journey times on both routes were approximately 80 minutes with the Bakerloo line journey 27.3 km and the overground journey 37.8 km. All train journeys commenced between 10:00 and 11:00 and took place on Monday and Wednesday. Lift access and the layout of Willesden Junction station is shown in Figure 3.4. There was a regular, frequent service on both lines, with Bakerloo Line trains scheduled every 5 minutes and Overground trains every 15 minutes. Willesden Junction is an above-ground station in an urban background location.

3.5.2 Experimental design

The MRC study addressed the second recommendation of the COMEAP (2018) Dust on the London Underground Report calling for “Well-conducted human exposure studies in volunteers, similar to the studies investigating the health effects of Oxford Street air pollution” Similarly to the Oxford Street study (Sinharay et al., 2018), the MRC study used a randomised crossover design,

which recruited study participants for a London Underground journey and a separate London Overground journey, separated by 3-6 weeks. A cohort of aged matched (50-90), GOLD Stage 2 COPD participants (n=36) and healthy lung function volunteers (n=47) were recruited throughout the study period (26 January 2022 to 17 July 2023). A full breakdown of participant characteristics is given in Table A 1. To ensure consistency across journeys I always deployed and used MoRS accompanying the participants to measure the required participant personal exposure data for each journey for the MRC study.

3.5.3 Subway and Overground Trial Journeys

Permission to travel on the Overground was granted by Arriva on 01 May 2021, however TfL did not grant permission until 1st December 2021. This delay allowed trial journeys to be undertaken to refine the exposure protocol to reduce the walking time for participants and the transportation of MoRS during the exposure journeys. As a result, the rear carriage of the Overground train was used on the outbound journey. When the train terminated, the participants and Mors remained in-situ and returned in the front carriage of the train. The same protocol was followed on the subway journeys, the participants and MoRS boarded the rear of the train on the outbound journey and remained in-situ at Elephant & Castle returning in the front carriage of the train.



Figure 3.4 The station layout at Willesden Junction train station showing (A) the entrance to the station and access bridge across the railway tracks to the lift. (B) the lift from the station concourse to the platform, (C) the walk from the lift to the overground (X) and subway (Y) trains and (D) the subway track in the Elephant & Castle direction.

3.6 Resilience planning

Resilience planning was used to identify potential hazards and threats, and then establish adaptation, mitigation, and recovery plans, thereby reducing likely impacts and ensuring that the study continued in the event of planned or unexpected disruptions. Potential factors included: Imperial College staff availability, participant availability, train and station infrastructure, and instrument breakdown (Table A 2).

3.6.1 Alternative starting stations and lines

Train and station infrastructure was expected to be a major cause of disruption. To mitigate against these railway disruptions a key consideration in the resilience plan was to identify alternative stations and lines that could be used on the subway and overground networks if trains were not available at Willesden Junction station. When seeking alternative stations and comparable subway journeys, there was limited choice within a 30-minute taxi journey from the Imperial White City Campus. Kilburn station on the Jubilee Line was the most suitable station to meet the selection criteria for the alternative subway journey. Smith et al., (2020) measured PM_{2.5} concentrations on the Bakerloo and Jubilee lines and reported mean PM_{2.5} concentrations of 118 and 91 $\mu\text{g m}^{-3}$, respectively, on these lines, which included the non-tunnel outside sections of the journey. Kensal Rise was chosen as the Overground alternative journey.

During the study period access to Willesden Junction was not possible on 15 of the study days. This was due to a combination of train strikes, Overground engineering works, train defects and the lift being out of service. As Overground and subway services share the track at Willesden Junction station, Overground engineering works prevented subway services running to Willesden Junction station. In total seven alternative subway journeys took place on the Jubilee Line and eight alternative journeys took place on the Kensal Rise Overground Line. The resilience plan proved essential in maximising the number of participant journeys by anticipating or being able to react to problems that occurred on the study day.

3.6.2 Instrument Breakdown

To minimise instrument breakdown, regular servicing was required. The Mini-Wras was returned to the manufacturer in Germany from 13 September 2022 to 17 October 2022 for an annual service. During this time a TSI AM520 SidePak (TSI Inc, Shoreview, MN, USA) was used in place

of the Mini-Wras. The SidePak uses a photometer to measure $PM_{2.5}$ at a 1 sec resolution, and had been previously used in subway studies (Braniš 2006, Zheng et al., 2017). The SidePak was used to sample $PM_{2.5}$ on five journeys including three subway Bakerloo Line journeys and two Overground journeys. Specific subway $PM_{2.5}$ scaling factors were derived for the Sidepak by collocating alongside the Mini-Wras during a subway journey on 17 October 2022, immediately following the return of the Mini-Wras from servicing. Background scaling factors were derived by collating the Sidepak with the Mini-Wras during an overground journey on 24 October 2022. The disadvantage of using a SidePak is that only $PM_{2.5}$ is measured without the full particle size range of the Mini-Wras. The Airyx ICAD and the 2B Ozone monitor were serviced during a break in the participant study journeys and no exposure journeys were missed.

3.7 Quality Assurance and Quality Control

A detailed quality assurance and quality control (QA/QC) procedure and verification process was developed to ensure consistency, comparability, completeness, transparency, and accuracy of the measured data throughout the measurement campaign. The QA/QC process consisted of a planned programme of testing involving standardised technical activities performed in the laboratory and field. The laboratory programme for QA/QC testing is shown in Table 3.3. Regular baseline checks were performed with a Purafil Chemisorbant / activated charcoal scrubber and NO_2 and NO standard gases (NPL 2023) and the NO_2/NO_x ICAD data was scaled accordingly.

It was anticipated that due to low $PM_{2.5}$ background concentrations during the overground journeys a high flow rate, through 25mm diameter filters would be required to enable sufficient mass to be collected on to the filters. A $PM_{2.5}$ cyclone at 16.7 l/min with an isokinetic split via two pumps controlled by two mass flow controllers set to 8.35 l/min each was used to maximise flow through the filters. The filters were pre-weighed and post-weighed after conditioning for 48 hours at 19-21°C and 45-50% relative humidity in accordance with the European reference standard (EN12341) (Green and Fuller 2006, European Commission 2012). Despite the high flow rate, the small mass collected during the overground journeys (0-35 μg) was below the limit of detection. To ensure consistency of approach between the overground and underground measurement approach, the technique adopted by Smith et al., (2020) was used here, whereby contemporaneous concentrations of ambient and subway air were collected and different density corrections were applied to the ambient and subway fractions. Mini-Wras measurements of mean

PM_{2.5} using the Smith et al., (2020) approach and PM_{2.5} mass concentrations measured on the filters were compared and showed a reasonable agreement (Slope = 1.36, R = 0.85) (Figure A 1 A) for subway journeys. However, for the overground journeys there was little agreement between calculated mass after applying scaling factors and PM_{2.5} mass concentrations measured on the filters (Slope = 0.24, R = 0.52) (Figure A 1 B); likely due to the very low concentrations measured. Therefore, to ensure comparability between the subway and overground measurements, the Smith et al., (2020) method was used to calculate PM_{2.5} for all subway and overground journeys.

Table 3.3: The QA/QC programme to ensure instruments were maintained for high-quality data collection.

QA/QC Schedule	Airyx ICAD	Mini-Wras	2B Ozone Monitor	Filters	Noise Monitor
Weekly	Check instrument and connections	Check instrument and connections	Check instrument and connections	Check instrument and connections Clean filter holders before every journey	Check time and date
Bi-Weekly	Zero air check	Zero air check, Flow check	Zero air check	Flow check	Check battery
Monthly	Change filters, Gas Calibrations	Dehumidify desiccant	Change filters		
Quarterly		Clean the spectrometer and pre-impactor Clean PM _{2.5} inlets			
Annually	Service	Service	Service		

3.7.1 Mini-Wras NaCl Aerosol Laboratory Testing

Laboratory measurements were conducted to characterise the Mini-Wras Nano-Sizer (electric sensor) against a reference Scanning Mobility Particle Sizer Spectrometer (SMPS) (3080 DMA, 3775 CPC, TSI Incorporated, USA) using a polydisperse aerosol (5 - 300 nm) generated from 0.1% NaCl solution using an aerosol generator (ATM 226, Topas GmbH, Ge). The aerosol was dried using a silica gel aerosol drier before passing via an isokinetic splitter (Model 1102, Bechtel, USA) to the Mini-Wras and the SMPS (Figure 3.5)

3.7.2 Field intercomparison campaigns

This section presents the methodology for the validation of MoRS instrumentation against reference instrumentation in different locations representative of the locations where MoRS was deployed and the development of scaling factors. To ensure the MoRS instrumentation reported accurate data the instruments were calibrated by being co-located alongside certified reference instrumentation in the field. Co-location of MoRS alongside reference instrumentation allowed the performance of instruments to be assessed against reference instrumentation (NO_2 , NO_x and O_3) and location / source specific scaling factors to be developed using gravimetric filter measurements in the subway where reference instrumentation was not available ($\text{PM}_{2.5}$) to maximise transferability to other locations (Querol et al., 2012, Clements et al., 2017). This allowed specific scaling factors to be derived for use when measuring subway $\text{PM}_{2.5}$ (for the Mini-Wras and Sidepak) using the methodology developed by Smith et al., (2020) whereby urban background and subway scaling factors were proportionally applied to reflect the mix of subway air.

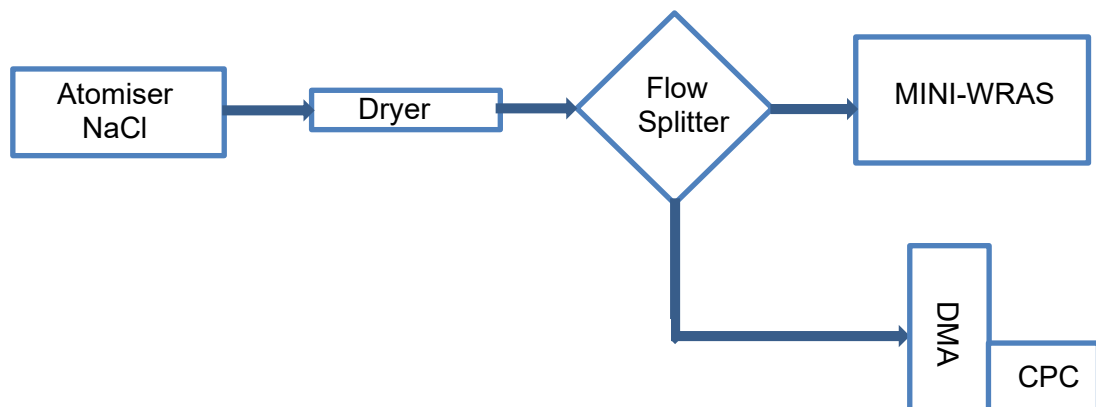


Figure 3.5: Schematic representation of the Nano-Sizer calibration for the Mini-Wras.

As particulate matter in subway and overground environments has different properties, this required derivation of specific calibration factors (Torrey et al., 2015). Scaling factors for MoRS instrumentation against reference instrumentation were derived using Deming Regression which is a commonly used technique when obtaining correction values for atmospheric measurements of air pollution. Deming regression takes into account measurement error in both the dependent and independent variables which is the advantage of using this method over ordinary least squares regression (Wu and Yu 2018). All Deming regression calculations used the R package 'mcr' (Potapov et al., 2023).

Field intercomparison campaigns were carried out at an urban background site, a kerbside site and a subway station platform. These field campaigns were undertaken in four locations: Honor Oak Park (51.449674, -0.037418), North Kensington (51.521050, -0.213492) and Marylebone Road (51.522530, -0.154611) to represent ambient measurements and Hampstead subway station (51.5569, 0.1783) to represent the subway environment (Figure 3.6). Honor Oak Park, North Kensington and Marylebone Road are part of the Automatic Urban and Rural Network (AURN) which constitutes the UK's largest automatic monitoring network (DEFRA 2023, DEFRA 2023, DEFRA 2023).

3.7.3 Field intercomparison background sites

Honor Oak Park and North Kensington are background monitoring stations, away from any immediate traffic influence characterising areas representing urban background environments. MoRS was located on the roof at Honor Oak Park with the inlets placed close to those of the reference instrumentation and sampled continuously for four days from 17 to 20 January 2022 (Figure 3.7). For $PM_{2.5}$ the Mini-Wras was co-located alongside a FIDAS 200E and for NO_2 and NO_x the Airyx ICAD was co-located alongside a N500 (TAPI, USA). This allowed intercomparisons to be made and $PM_{2.5}$ scaling factors to be derived. At the North Kensington site, the 2B Ozone Monitor was co-located alongside a T400 (TAPI, USA) from 01 to 04 April 2022 sampling continuously throughout that period.

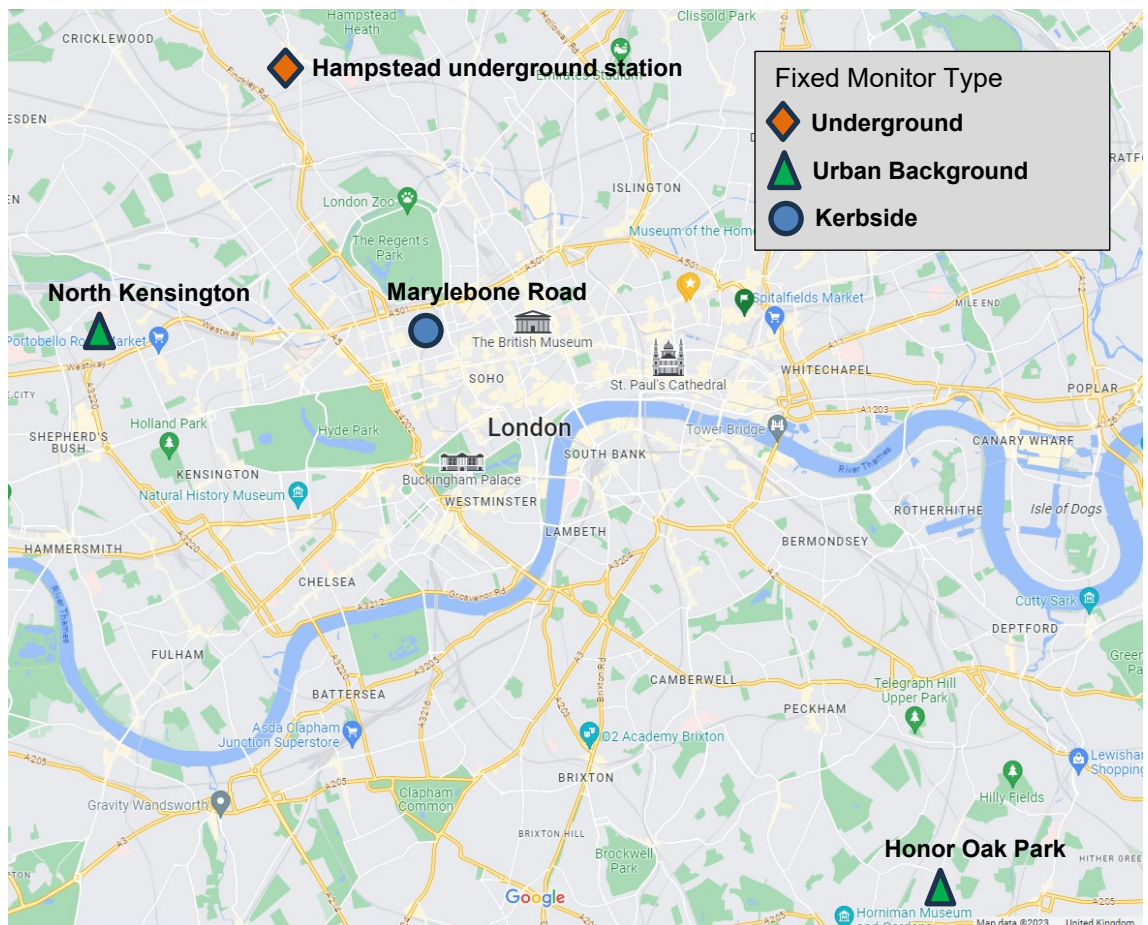


Figure 3.6 Location of fixed background and kerbside monitoring sites and Hampstead underground station used in this study for intercomparisons and co-locations of the Mobile Reference Station (MoRS) instruments against reference instruments.

3.7.4 Marylebone Road Field intercomparison kerbside site

The Marylebone Road kerbside site is on the kerbside of a six-lane highway in Central London and is representative of locations that are exposed to elevated levels of vehicle emissions. The Mini-Wras was co-located on the roof of Marylebone Road alongside a BAM 1022 (Met One Instruments Inc., US) from 16 to 21 November 2022 allowing a $PM_{2.5}$ intercomparison and derivation of scaling factors for these environments (Figure 3.8).



Figure 3.7: The Mobile Reference Station (MoRS) located at the Honor Oak Park, urban background site, for instrument intercomparisons and co-locations with reference instruments at the site.

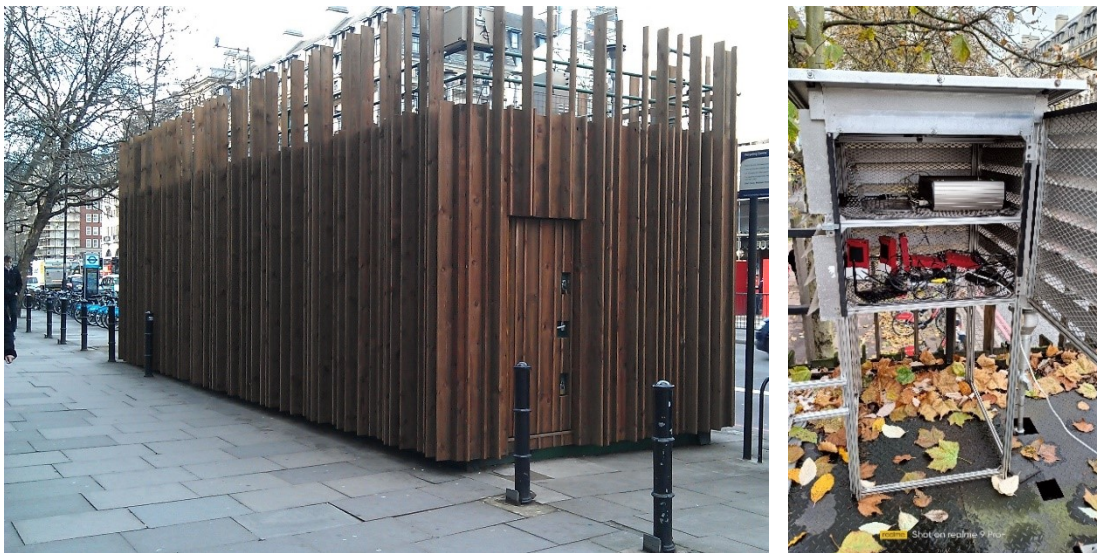


Figure 3.8: The Marylebone Road kerbside site, where the Mini-Wras intercomparison and co-location with the reference instruments took place. The Mini-Wras was placed in a Stevenson Box for protection.

3.7.5 Hampstead Station measurement facility

In conjunction with my supervisor, I installed an air quality measurement facility containing a Partisol 2025 (Thermo Scientific Partisol 2025, Waltham, Ma, USA) on the northbound Hampstead station platform. This facility is in the deepest part of the network, 58.5m below ground-level, giving a representation of air with a strong subway source (Figure 3.9). The Mini-

Wras was calibrated for $\text{PM}_{2.5}$ alongside the Partisol 2025 from 14 to 15 January 2021. Pre-weighed filters were exchanged every two hours and post-weighed to obtain 13 $\text{PM}_{2.5}$ two-hour mass concentrations. All gravimetric weighing took place in a purpose-built temperature and humidity-controlled weigh room in Imperial College, London, according to standard protocols (EN12341) (European Commission 2012).



Figure 3.9: The Mobile Reference Station (MoRS) in the air quality facility on the northbound Hampstead subway platform being co-located alongside a Partisol 2025.

3.8 Results and Discussion

In this section the intercomparison results and scaling factors from co-locations at the urban background and kerbside sites and Hampstead Station are discussed. The Mini-Wras is built for indoor measurements and deriving separate scaling factors for each environment enables a more accurate assessment of $\text{PM}_{2.5}$ concentrations in subway and overground environments.

3.8.1 Laboratory intercomparison using a polydisperse NaCl aerosol

Laboratory intercomparison measurements were conducted in the Imperial College laboratory to evaluate the performance of the Mini-Wras Nano-Sizer against a SMPS configuration described in Tremper et al., (2022) to assess whether peak modal concentrations stay within the 20% uncertainty bounds recommended by the manufacturer (Ahlawat et al., 2022) (Figure 3.10). The Mini-Wras and SMPS modal particle number size diameters (PNSD) agreed well peaking at 52nm in the ultrafine particle size range. The Mini-Wras under reported the modal particle number count by 18% but was still within the $\pm 20\%$ and remains within the $\pm 20\%$ uncertainty between 40 - 100

nm. The Mini-Wras reports a significantly higher particle number count (PNC) than the SMPS at PNSD's below 40nm which is outside of the $\pm 20\%$ uncertainty range of the SMPS. The Mini-Wras PNSD is within the $\pm 20\%$ uncertainty range in the 40nm to 100nm particle size range and above 100nm the Mini-Wras overestimates PNC by 60%.

The Mini-Wras Nano-Sizer had a lower size resolution (10 size bins) compared to the SMPS (73 size bins). These results compared well with a similar NaCl test performed by Ahlawat et al., (2022). The accurate measurement of PNSD remains challenging for a portable device, nevertheless, the Mini-Wras showed a good agreement ($\pm 20\%$) with the SMPS around the modal PNSD. However, aerosol PNSD's below 40nm and above 100nm were overestimated which may be due to the Mini-Wras nan-sizer consisting of a unipolar diffusion charger. This is employed in small instruments to measure particles having a diameter of 10 to 200nm, in comparison to the reference SMPS which has a radioactive aerosol bipolar diffusion charger. The use of a non-radioactive unipolar charger in the Mini-Wras could lead to additional uncertainties as it is known that pre-charged aerosol particles could have an impact on the unipolar charging efficiency of the sampled aerosol (Qi et al., 2009, Kaminski et al., 2013). This could lead to an overestimation of PNSD's below 40nm and above 100nm, although this limitation is offset by the lack of a radioactive source in the Mini-Wras allowing the Mini-Wras to be portable. In the laboratory NaCl test the Mini-Wras overestimated PNSD's in the size ranges likely to have been impacted by the use of an unipolar diffusion charger in the size ranges below 40nm and above 100nm described by Qi et al., (2009) and Kaminski et al., (2013).

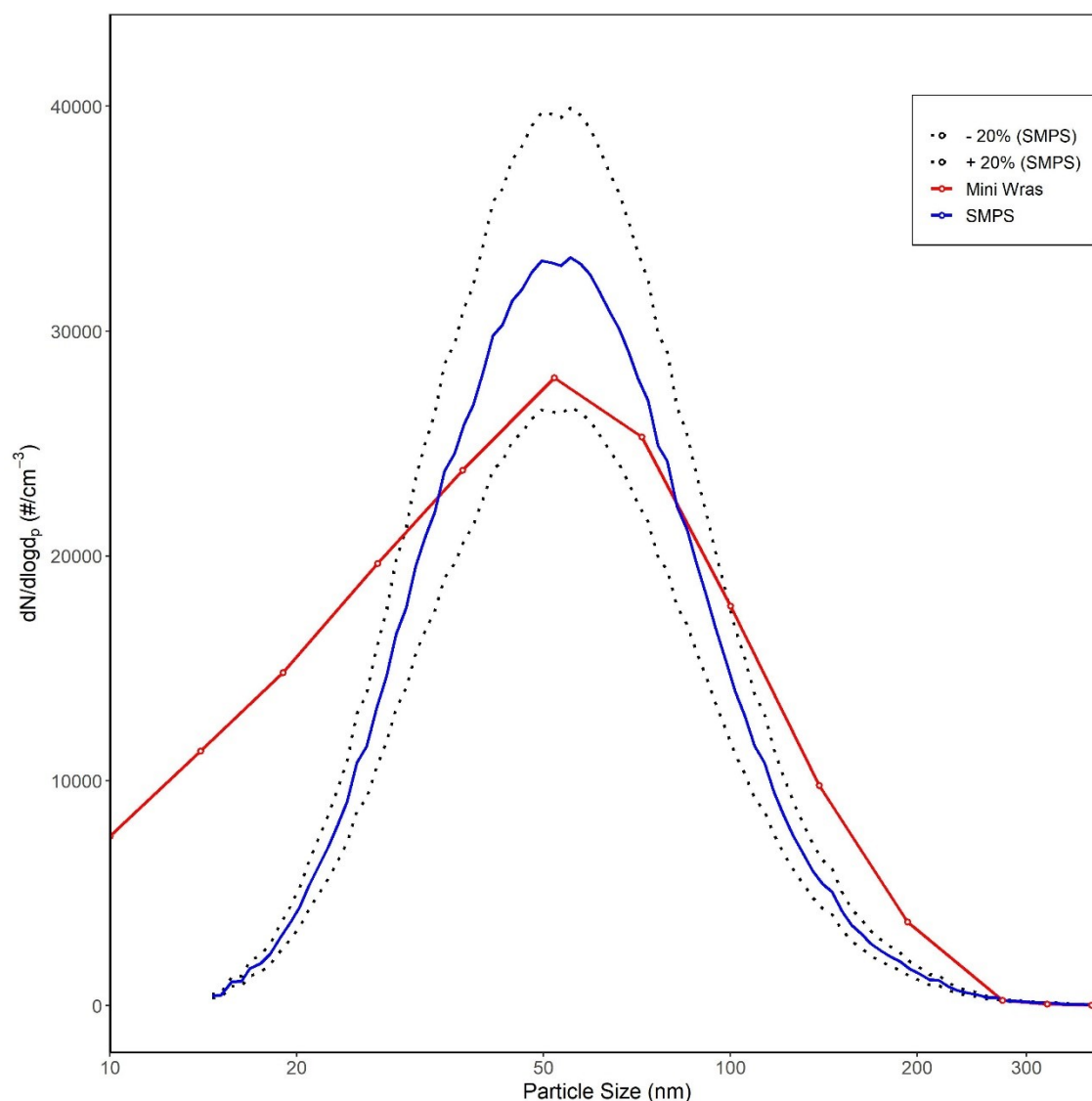


Figure 3.10: Performance of the GRIMM Mini WRAS spectrometer 1371 and SMPS using a polydisperse aerosol generated from a 0.1% NaCl solution using an aerosol generator in the laboratory. The solid line shows the SMPS with the black dotted lines showing the $\pm 20\%$ range. The Mini-Wras is shown as a solid red line with mid points diameters shown as white dots.

3.8.2 Urban background and kerbside site field campaigns

3.8.2.1 Honor Oak Park $PM_{2.5}$ field comparison

During the inter-comparison at Honor Oak Park the Mini-Wras sampled continuously alongside a SMPS (3080, TSI Inc, USA) from 17 to 20 January 2022 (Figure 3.11). During this period the Mini-Wras overestimated PNSD below 100nm beyond the $\pm 20\%$ uncertainty range, with an overestimation between 27nm and 37nm of 27-37%. The SMPS modal PNSD was 64 nm compared to the Mini-Wras modal PNSD of 52 nm. This was an overestimation of 37% of the SMPS modal PNSD by the Mini-Wras, although the Mini-Wras was within the $\pm 20\%$ uncertainty range for all size bins from 100 nm. However, these results are in line with the ambient aerosol

results obtained by Ahlawat et al., (2022) demonstrating why accurate measurement of particle size distribution remains challenging for a portable device. The reasons for the discrepancy between the Mini-Wras and the SMPS could be due to the differences in the size resolutions of the Mini-Wras and SMPS, the use of a non-radioactive unipolar charger by the Mini-Wras or the shorter sampling inlets of the Mini-Wras.

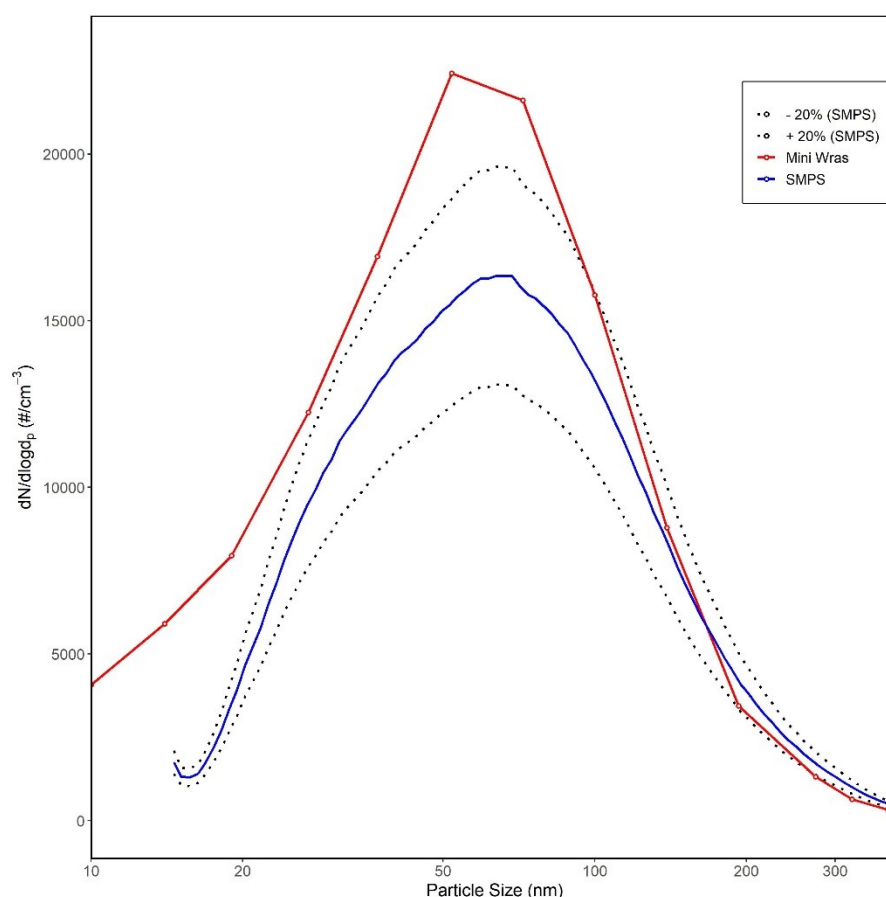


Figure 3.11 : Inter-comparability of the GRIMM Mini Wras spectrometer 1371 and SMPS sampling ambient air at the Honor Oak Park urban background site. The blue solid line shows the SMPS with the black dotted lines showing the SMPS $\pm 20\%$ range. The Mini-Wras is shown as a solid red line with particle size midpoint diameters shown as white dots.

To further understand why the Mini-Wras was overestimating PNSD's below 100nm, temporal variations of the Mini-Wras and SMPS of particle number distribution and particle sizes were calculated and displayed graphically (Figure 3.12). On Monday 17 January the Mini-Wras agreed well with the SMPS peaking with a PNC of 43,067 particles cm^{-3} compared with 42,169 particles cm^{-3} for the SMPS within 2% of the SMPS. The modal peaks of the Mini-Wras and SMPS were 52 nm and 66 nm, respectively. The Mini-Wras was within the $\pm 20\%$ uncertainty range for all size fractions. The temporal variation showed a high pollution episode late in the evening of the 17th January which was picked up by the Mini-Wras and the SMPS.

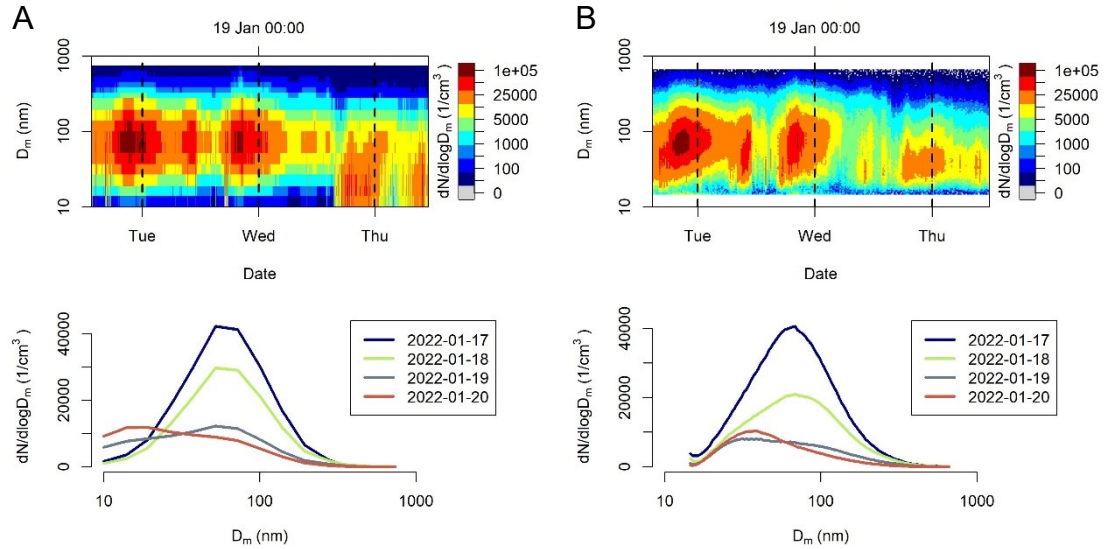


Figure 3.12: Temporal variation of particle number distribution and particle number counts of (A) the Mini-Wras and (B) the SMPS measured at Honor Oak Park from 17 January 2022 to 20 January 2022.

On the 18 January the Mini-Wras overestimated PNC in the sub 100nm fractions by 42%. The overestimation by the Mini-Wras was from higher PNC's recorded by the Mini-Wras in the afternoon and the high episode in the evening, which were both absent from the SMPS. During the following two days both instruments recorded PNC concentrations below 12,000 particles cm^{-3} and displayed more variation in PNSD's. The modal PNSD for the Mini-Wras remained at 52 nm on 19 January compared to a much smaller PNSD mode of 31 nm for the SMPS. However, on 20 January the modal PNSD of the Mini-Wras shifted to 19 nm whereas the SMPS was 36 nm. Although, the Mini-Wras stayed within ± 20 for PNSD's from 42 nm there was more variation in the ultrafine fraction in the Mini-Wras.

The Honor Oak Park intercomparison took place on days when aerosol concentrations varied from over 40,000 to 10,000 particles cm^{-3} . The Mini-Wras agreed with the SMPS at the highest concentrations and measured similar PNC's at low concentrations, although the modal PNSD varied compared to the SMPS. There were occasions, particularly on the 18 and 19 January when the Mini-Wras measured high PNC concentration episodes not recorded by the SMPS, leading to an overestimation of PNCs by the Mini-Wras in comparison to the SMPS. This could potentially have been due to particle losses in the SMPS, as the Mini-Wras was on the roof of Honor Oak Park with a shorter sampling length and no diffusion dryer which may have reduced diffusion losses compared to the SMPS.

3.8.2.2 Deriving PM_{2.5} urban background scaling factors

The Mini-Wras was co-located with a FIDAS 200E at Honor Oak Park from 17 to 20 January 2022 to derive an urban background scaling factor using Deming regression for PM_{2.5}. The Mini-Wras was averaged to 15-minute time resolution to directly compare with the FIDAS 200E. When calculating the Deming Regression, the Mini-Wras was always set to the x-axis and the reference instrument to the y-axis, therefore corrected values were calculated as: corrected data = (raw data * slope) + intercept. The results of the Honor Oak Park Mini-Wras raw co-location scatter plot, the Deming Regression and the corrected scatter plot are shown in Figure 3.13.

The Mini-Wras had a R² value of 0.99 in comparison with the FIDAS 200E at Honor Oak Park with a slope was 0.88, an uncertainty of ± 0.02 , and an intercept of $-2.24 \mu\text{g m}^{-3}$. This gave a scaling factor of $0.88 * \text{Mini-Wras measurement} - 2.24 \mu\text{g m}^{-3}$ which was used to correct the Mini-Wras in background locations. No assessment was made of the impact of relative humidity over the four-day intercomparison period as the Mini-Wras has an internal silica gel column that maintained relative humidity below 35% throughout the measurement period.

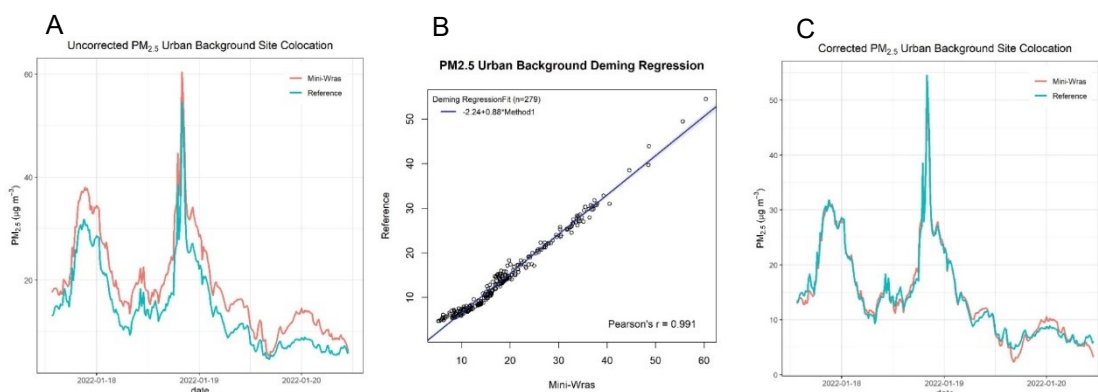


Figure 3.13: Deming regression for the Mini-Wras at the Honor Oak Park urban background site alongside a FIDAS 200E reference instrument showing (A) the raw PM_{2.5} uncorrected values, (B) the PM_{2.5} Deming Regression and (C) the corrected PM_{2.5} values.

3.8.2.3 Honor Oak Park NO₂/NO_x intercomparison

In addition to regular checks against pollutant-free air and gas standards an additional field intercomparison experiment was undertaken at Honor Oak Park with the Airyx ICAD. This was to ensure accurate responses of the instrument in an urban background location. The Airyx ICAD was co-located alongside a N500 reference instrument at Honor Oak Park (Figure 3.14). The Airyx ICAD was averaged to a 15-minute time resolution to directly compare with the N500. The Airyx had an R² value of 1 for NO₂, with a slope of 0.96, uncertainty 0.0 and intercept of 0.25. For

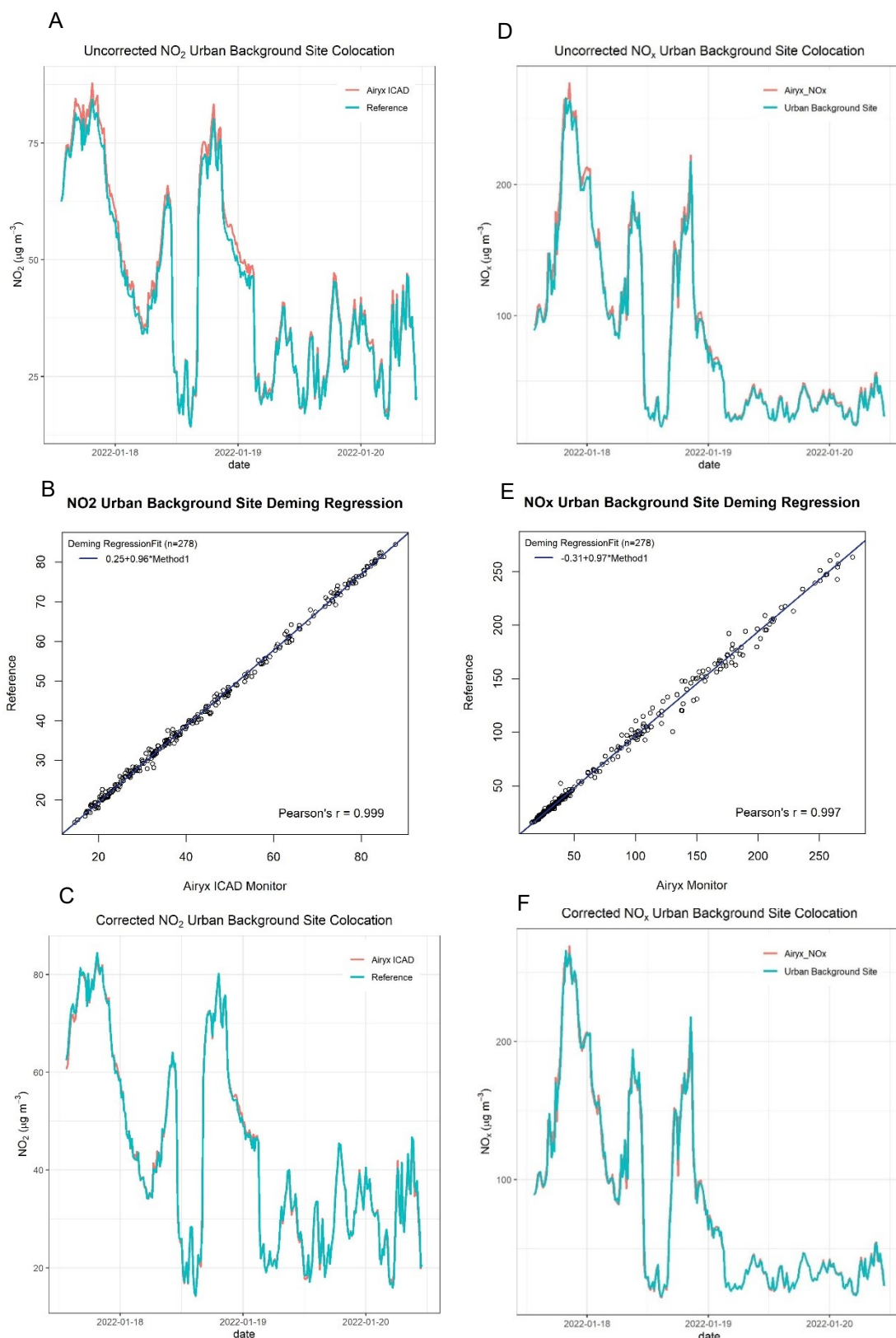


Figure 3.14: Deming regression for the Airyx ICAD at the Honor Oak Park urban background site alongside a N500 reference instrument showing (A) the raw NO₂ uncorrected values, (B) the NO₂ Deming Regression and (C) the corrected NO₂ values. (D), (E) and (F) show the equivalent NO_x values.

3.8.3 North Kensington Field Campaign

3.8.3.1 North Kensington O₃ intercomparison

An intercomparison of the 2B Ozone Monitor with a T400 ozone reference instrument took place at the urban background site at North Kensington from 01 to 04 April 2022. The 2B Ozone Monitor was averaged to 15-minute time resolutions to directly compare with the T400 time resolution to allow a direct intercomparison. The 2B Ozone monitor had a R^2 value of 0.99 compared to the T400, a slope of 0.93 and an intercept of $0.70 \mu\text{g m}^{-3}$ over the 5-day measurement period. (Figure 3.15). No adjustment was made as the 2B Technologies ozone monitor demonstrated R^2 values close to 1 in comparison to the T400 during the measurement period.

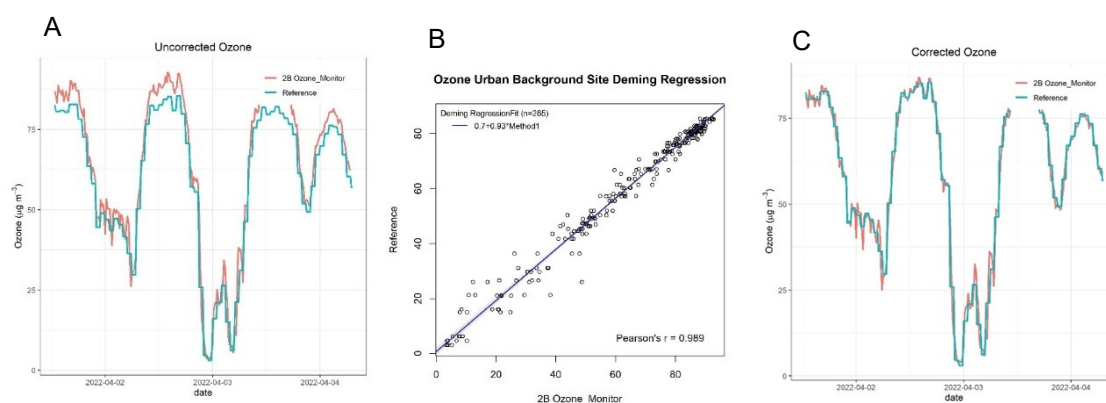


Figure 3.15: Deming regression for the 2B Ozone Monitor at the North Kensington urban background site alongside a T400 reference instrument showing (A) the raw O₃ uncorrected values, (B) the O₃ Deming Regression and (C) the corrected O₃ values.

3.8.4 Marylebone Road Kerbside PM_{2.5} Field Campaign

3.8.4.1 Marylebone Road Kerbside PM_{2.5} intercomparison

The inter-comparison of particle size distributions from a busy 6-lane highway in Central London measured by the Mini-Wras was compared to a SMPS (3080, TSI Inc, USA) at the Marylebone Road kerbside site. The Mini-Wras was placed on the roof of the Marylebone site and co-located with the SMPS for five days from 16 to 21 November 2022 with the Mini-Wras and SMPS inlets both placed within two metres of the kerbside. Ambient air was drawn separately into both instruments to assess the performance of the Mini-Wras when measuring at a kerbside location. (Figure 3.16).

The Mini-Wras was within the $\pm 20\%$ uncertainty range for all size bins below 52 nm with a modal PNSD within 16% of the SMPS at 19 nm. Between PNSD's of 52 and 139 nm the Mini-Wras

overestimated particle numbers by up to 55%. The Mini-Wras failed to detect the increase in PNC at 193 nm underestimating by 21%. For PSND's above 193 nm the Mini-Wras was within the $\pm 20\%$ uncertainty range of the SMPS. The Marylebone Road kerbside site challenges the Mini-Wras with a smaller aerosol size modal PNSD and higher PNC's than the Honor Oak Park background site.

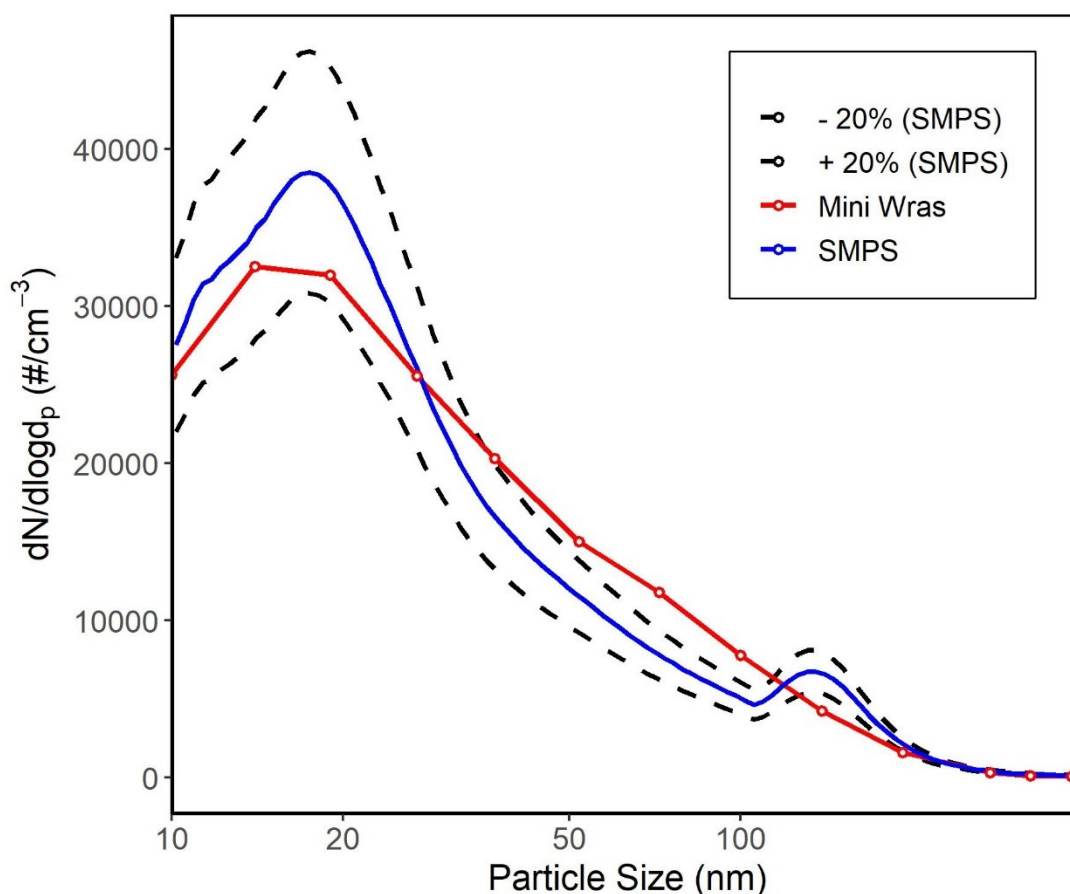


Figure 3.16: Inter-comparability of the GRIMM Mini Wras spectrometer 1371 and SMPS sampling ambient air at the Marylebone Road kerbside site. The blue solid line shows the SMPS with the black dotted lines showing the SMPS $\pm 20\%$ range. The Mini-Wras is shown as a solid red line with particle size mid-point diameters shown as white dots.

3.8.4.2 Deriving $PM_{2.5}$ kerbside scaling factors

The Mini-Wras was co-located with a BAM 1022 (Met One, USA) at Marylebone Road from 16 to 21 November 2022 to derive a Mini-Wras scaling factor in an environment representative of traffic related air pollution. The Mini-Wras was averaged to two-hour time resolution to directly compare with the BAM 1020 and a Deming regression was calculated. The results of the raw scatter plot, the Deming Regression and the corrected scatter plot for the Marylebone Road kerbside site are shown in Figure 3.17. The Mini-Wras co-location gave a R^2 of 0.99 with a slope of 0.97 and an

intercept of $-0.77 \mu\text{g m}^{-3}$. This gave a scaling factor of $0.97 * \text{Mini-Wras measurement} - 0.77 \mu\text{g m}^{-3}$ which was used to correct the Mini-Wras in traffic related or diesel environments.

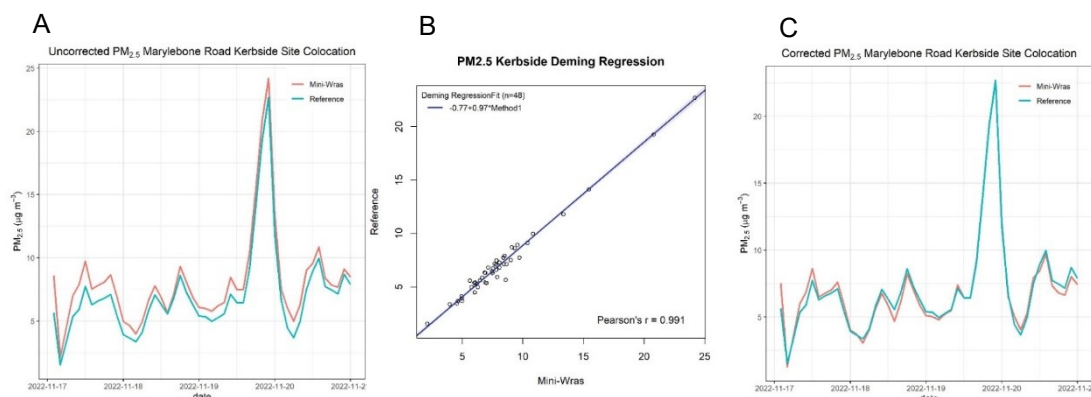


Figure 3.17: Deming regression for the Mini-Wras at the Marylebone Road kerbside site alongside a BAM 1020 reference instrument showing (A) the raw PM_{2.5} uncorrected values, (B) the PM_{2.5} Deming Regression and (C) the corrected PM_{2.5} values.

3.8.5 Hampstead subway Station PM_{2.5} Field Campaign

3.8.5.1 Hampstead subway Station PM_{2.5} intercomparison

The intercomparison when measuring subway particles at Hampstead station was assessed against a Dekati Electrical Low Pressure Impactor (ELPI⁺, Dekati, FI). The ELPI⁺ is a real-time spectrometer measuring a size range from 6 nm - 10 μm over 14 size bins. The intercomparison took place over two days from 26 to 27 January 2023 (Figure 3.18).

The Mini-Wras modal peak was at 14 nm, close to the first peak of 16 nm of the Dekati. For PNSD's between 10 and 27 nm the Mini-Wras was within the $\pm 20\%$ uncertainty range of the Dekati, however the modal peak of the Dekati occurred at 41 nm, which did not occur in the Mini-Wras which was outside of the $\pm 20\%$ uncertainty range of the Dekati modal peak at 41 nm. For PNSD's between 72 and 139 nm the Mini-Wras showed good agreement with the Dekati ($\pm 20\%$) although larger fractions greater than 139 nm were overestimated by the Mini-Wras. The Mini-Wras reported a signal at 449 nm not detected by the Dekati which requires further investigation.

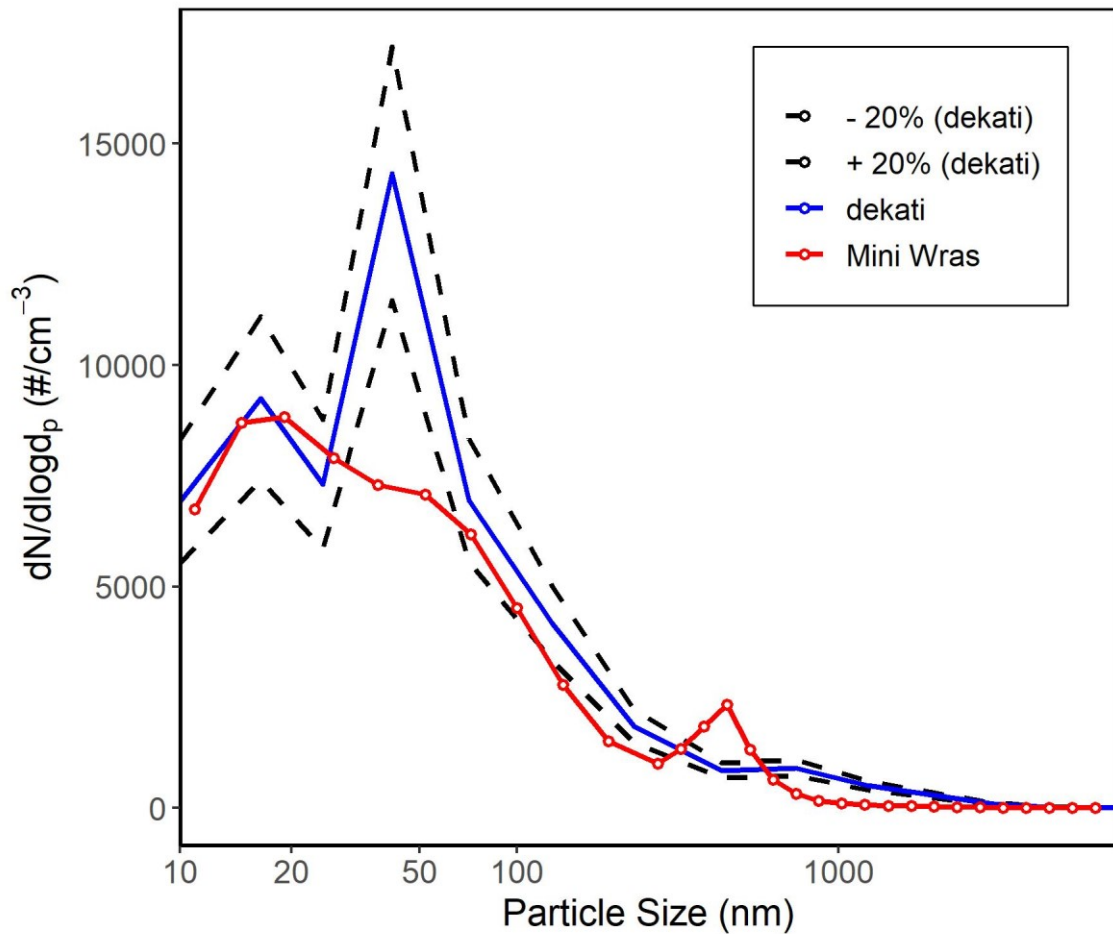


Figure 3.18: Inter-comparability of the GRIMM Mini Wras spectrometer 1371 and a Dekati Electrical Low Pressure Impactor (ELPI+) simultaneously sampling $PM_{2.5}$ on the northbound platform at Hampstead subway station. The solid blue line shows the Dekati with the black dotted lines showing the Dekati $\pm 20\%$ range. The Mini-Wras is shown as a solid red line with particle size mid-point diameters shown as white dots.

3.8.5.2 Deriving $PM_{2.5}$ subway scaling factors

The Mini-Wras and SidePak required a source-specific calibration in the subway environment, to derive $PM_{2.5}$ scaling factors due to variations in the physicochemical properties of outdoor and subway PM, such as refractive index, shape, and density (Querol et al., 2012). The Mini-Wras is designed for indoor environments and, consequently uses a particle density of 1.7 g cm^{-3} to represent typical indoor air particle density (Buonanno et al., 2009). However, this is not representative of particle density in the subway (Querol et al., 2012, Smith et al., 2020) which has been estimated at 5 g cm^{-3} (Cha, Abbasi and Olofsson 2018). Applying a density factor of 1.7 g cm^{-3} would report misleadingly low $PM_{2.5}$ concentrations. Consequently, a $PM_{2.5}$ scaling factor was required to account for the higher particle density of subway air. To obtain scaling factors for measurements of $PM_{2.5}$ in the subway system the Mini-Wras was co-located alongside a Partisol

2025 at Hampstead station from 14 January 2021 to 15 January 2021. Gravimetric PM_{2.5} samples were collected by the Partisol 2025 onto pre-weighed filters which were exchanged every two hours to obtain 13 PM_{2.5} two-hour filter measurements over the measurement period. By using time-averaged two-hour means for the Mini-Wras corresponding to the two-hour time periods of the gravimetric samples obtained from the Partisol 2025, the Mini-Wras measurements were correlated with the Partisol measurements by applying the Deming regression technique (Figure 3.19). This gave a specific subway PM_{2.5} scaling factor.

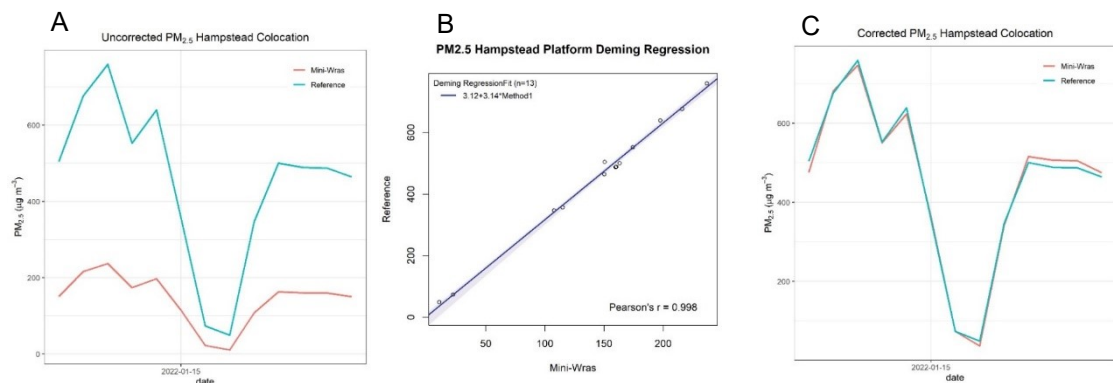


Figure 3.19: Deming regression for the Mini-Wras at the Hampstead Station Measurement site alongside a Partisol 2025 reference instrument showing (A) the raw PM_{2.5} uncorrected values, (B) the PM_{2.5} Deming Regression and (C) the corrected PM_{2.5} values.

From the Partisol gravimetric measurements a regression slope was calculated of 3.14 (± 0.09) with an intercept of 3.12 $\mu\text{g m}^{-3}$ ($R^2 = 0.99$) to give a specific PM_{2.5} subway scaling factor for the Mini-Wras. A slope of 3.14 closely corresponded to the subway particle density of 5 g cm^{-3} estimated by Cha, Abbasi and Olofsson (2018).. However, particles in subway air comprise a mixture of below-ground and above-ground aerosol sources. To reflect these differing sources urban background and subway scaling factors were proportionally applied to derive a proportionate subway scaling factor for the Mini-Wras for use in the tunnelled sections of the subway (Smith et al., 2020). The formula proposed by Smith et al., (2020) (Eq. 1) was used in all tunnelled sections for the scaling of subway PM_{2.5}. For all sections of the subway above-ground, and for overground journeys, the background PM_{2.5} scaling factor of 0.88 was used (Figure A 2) to proportion subway and background PM_{2.5}.

$$[Iu_{\text{true}}]_i = ([Iu]_i - [sb]_i * k_s) * k_u + [sb]_i \quad (\text{Eq. 1})$$

Where lu_{true} is the calibrated concentration at time i , lu is the measured subway concentration, sb is the paired measured concentration from a surface background monitoring site, k_u is the derived subway calibration factor (3.14), and k_s is the surface background calibration factor (0.88).

The SidePak is a laser photometer that requires specific scaling factors to be derived for the subway and overground environments. To obtain correction factors for the SidePak, the SidePak was colocated alongside the Mini-Wras on a Bakerloo subway journey on 17 October 2022. This gave a Deming regression slope of $2.48 (\pm 0.23)$ ($R^2 = 0.87$) (Figure 3.20). For the overground a colocation with the Mini-Wras on an Overground journey on 24 October 2022 a Deming regression slope of $0.72 (\pm 0.25)$ ($R^2 = 0.83$) was calculated (Figure 3.21). Equation 1 was used for the SidePak in all tunnelled sections for the scaling of subway $PM_{2.5}$. For all sections of the subway above-ground, and for overground journeys, the background $PM_{2.5}$ scaling factor of 0.72 was used for the SidePak (Figure A 3).

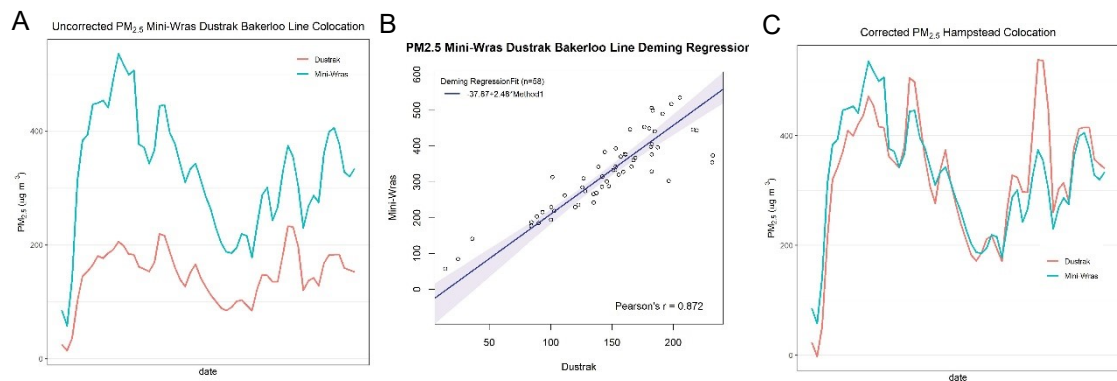


Figure 3.20: Deming regression for the SidePak alongside the Mini-Wras on a Bakerloo line subway journey on 17 October 2022 showing (A) the raw $PM_{2.5}$ uncorrected values, (B) the $PM_{2.5}$ Deming Regression and (C) the corrected $PM_{2.5}$ values.

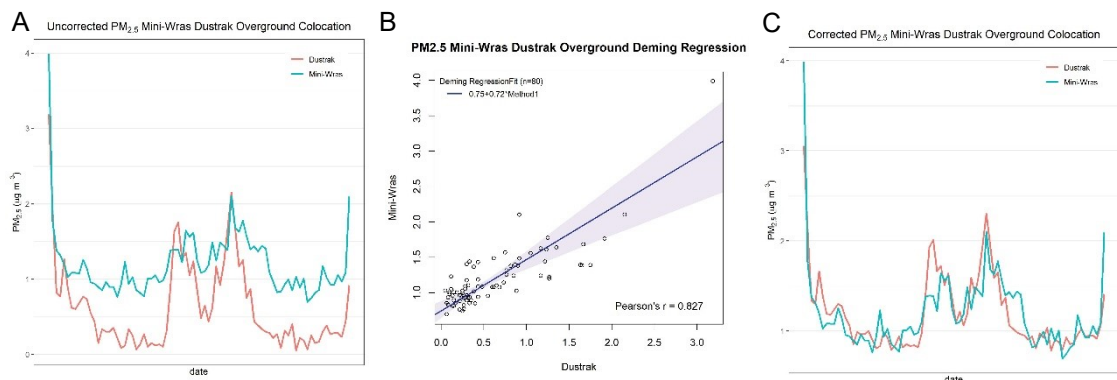


Figure 3.21: Deming regression for the SidePak alongside the Mini-Wras on an Overground journey on 24 October 2022 showing (A) the raw $PM_{2.5}$ uncorrected values, (B) the $PM_{2.5}$ Deming Regression and (C) the corrected $PM_{2.5}$ values.

3.8.6 Summary of derived scaling factors

The Deming Regression technique was used to derive scaling factors for all MoRS instrumentation at those geographical location's representative of the locations where MoRS was employed during the study. The inter-comparability of MoRS measurements to reference instrumentation and the derived scaling factors are shown in Table 3.4.

At background sites, all instruments displayed excellent performance in comparison with reference instruments with R^2 values of 1.00, 1.00, 0.99 and 0.99, for NO_2 , NO_x , $\text{PM}_{2.5}$ and O_3 , respectively. At the Urban Background sites all colocations took place over four days with 15-minute time averages. This gave a total number of points (N) for the Deming regressions of 279 for $\text{PM}_{2.5}$, 278 for NO_2 and NO_x and 265 for O_3 allowing a contrasting range of concentrations to be assessed for each pollutant. This gave a good representation of the scaling factors to be used for the Mini-Wras, and the agreement of the Airyx ICAD and 2B Technologies ozone instruments with reference instruments in urban background environments. The colocation of the Mini-Wras at the kerbside site took place over four days with the Mini-Wras was time-averaged to 2-hours giving a total of N=48 points, allowing contrasting variations in $\text{PM}_{2.5}$ to be assessed over the four days. At the Hampstead station monitoring site the Mini-Wras was collocated with the Partisol for two days and time averaged to 2-hourly intervals. This gave a total of N=15 points (the number of filters in the Partisol), giving a representation of high and low concentrations of subway $\text{PM}_{2.5}$ at Hampstead during train and non-train periods. At the subway site and urban kerbside site the Mini-Wras displayed R^2 values of 1.00 and 0.98. The slopes and intercepts of NO_2 and O_3 at the background sites were very close to 1 and 0 respectively, showing that there was no need to adjust the data for different environments. Similarly, the slopes and intercepts for $\text{PM}_{2.5}$ at both the urban background and kerbside side were close to 1 and 0 respectively, showing that no substantial advantage would have been gained from adjusting to account for different ambient environments. However, the slope and intercept measured in Hampstead station demonstrates the significant adjustment required when measuring $\text{PM}_{2.5}$ concentrations in the subway due to the greater density of subway particles.

3.9 Conclusion

Participant personal exposures to PM, NO_2 and O_3 in train carriages were required to be accurately measured for the MRC study. Accurately measuring participant personal exposures

during their train journeys was key to understanding any effects on health from linking the health responses of the participants to subway exposures. Selecting the correct instrumentation and the method of transporting the sampling equipment was crucial in achieving a high-quality, accurate and reliable exposure assessment in the differing railway environments.

The large contrasts between the two pollutant environments of the subway and overground and the time spent in these microenvironments can significantly contribute to overall daily exposure, especially in the subway. It has been shown how relying on fixed outdoor measurement stations increases the likelihood of exposure misclassification making them unsuitable for this study (Smith et al., 2016). Many researchers have previously used small OPC, sensor-based measurement techniques in subway studies. However, the differing environmental conditions, particularly of temperature and relative humidity and changes in particle chemical and physical composition increase the uncertainties of these instruments. The method adopted made use of the developments in the miniaturisation and reduced power requirements of higher quality measurement approaches, similar to those used in fixed measurement stations. This enabled the development of the Mobile Reference Station (MoRS) used in this study bridging the gap between static reference monitoring stations and the easy-to-use and portability of low-cost sensing technologies.

The MRC study measurement locations were in subway and overground train carriages which required a highly flexible, self-contained, fully battery operated and manoeuvrable measurement system. This led to the development of MoRS to provide the high data capture rate that was required for the MRC study in both measurement locations. MoRS reported PM, NO₂ and O₃ measurements. The intercomparisons showed MoRS had good agreement ($\pm 20\%$) with the SMPS at the fixed ambient measurement locations of Honor Oak Park, North Kensington and Marylebone Road and for the subway at Hampstead station alongside the Dekati ELPI*. Scaling factors were derived for the Mini-Wras for use in the subway and above-ground demonstrating the need for source-specific scaling factors in the subway environment. This measurement approach achieved the aim of providing the high-quality data required for the MRC study.

Table 3.4: Field co-location comparisons between the MoRS and reference instrumentation at Hampstead subway station, an urban kerbside site and urban background sites (mean, median, range and intercept are displayed as $\mu\text{g m}^{-3}$).

Location	Site Name	Instrument	Measurement	Mean	Median	Range	Slope	Intercept	R^2	N
				($\mu\text{g m}^{-3}$)	($\mu\text{g m}^{-3}$)	($\mu\text{g m}^{-3}$)	(uncertainty)	($\mu\text{g m}^{-3}$)		
Subway	Hampstead Station	Mini-Wras	PM _{2.5}	453.7	489.8	26.5 – 904.3	3.14 (± 0.09)	3.12	1.00	13
		1371 Spectrometer								
Kerbside	Marylebone	Mini-Wras	PM _{2.5}	7.1	6.2	0.0 – 31.2	0.97 (± 0.02)	0.77	0.98	48
		1371 Spectrometer								
Urban Background	Honor Oak Park	Mini-Wras	PM _{2.5}	14.5	12.8	1.8 – 68.2	0.88 (± 0.02)	-2.24	0.99	279
		1371 Spectrometer								
Urban Background	Honor Oak Park	Airyx ICAD NO ₂ analyser	NO ₂	43.0	38.5	11.5 – 93.2	0.96 (± 0.00)	0.25	1.00	278
Urban Background	Honor Oak Park	Airyx ICAD NO _x analyser	NO _x	81.6	45.9	11.6 – 305.0	0.97 (± 0.01)	-0.31	1.00	278
Urban Background	North Kensington	2B Technologies O ₃ analyser	O ₃	60.1	68.6	2.6 – 107.4	0.93 (± 0.02)	0.70	0.99	265

Chapter 4 Characterising exposure in the London Underground

4.1 Introduction

The London Underground is an extensive network of electrified railway lines that run below ground in central London and predominantly above-ground in London's suburbs. It is the world's oldest subway system opening on the 10 January 1863, on what is now the Metropolitan Line. The London Underground network now comprises 11 lines (the Elizabeth line is not part of the London Underground network) with 402km of track and 272 stations. The network handles up to five million passenger journeys a day and 1.35 billion per year. The below ground tunnelled sections make up 45% of the network with 55% above-ground. The tunnelled sections of the subway include the deep-tunnelled lines the Bakerloo, Central, Jubilee, Northern, Piccadilly, Victoria and the Waterloo & City Lines. The Circle, District, Hammersmith & City and Metropolitan Lines were built as cut and cover shallow sub-surface lines and are effectively at ground level. On deep tunnel lines the trains are narrower than on sub-surface lines due to the smaller tunnels. (TfL 2019, TfL 2023, TfL 2023).

The Medical Research Council health study [grant number MR/S035613/1] took place on the London Underground Bakerloo line (with alternative journeys on the Jubilee line) and on the Willesden Junction station to Watford Junction station London Overground line (with alternative journeys on the Kensal Rise station to Stratford station line). The study measured exposure in train carriages on individual train journeys, with each participant undertaking one subway and one separate overground journey. Measurements of exposure to PM_{2.5}, NO₂ and O₃ were made in train carriages on each journey. This provided a long-term exposure assessment of concentrations in subway and overground trains.

Passengers spend the majority of their time in the subway travelling in train carriages, rather than waiting on platforms. A long-term exposure assessment with repeated journeys on a specific subway line over many seasons has not previously been undertaken in London or worldwide. It will help to further understand passenger exposure, and any related health effects, as well as identifying possible sources and processes influencing concentrations.

Previous studies have measured PM_{2.5} concentrations in the London Underground. An early study found PM_{2.5} concentrations of 265 µg m⁻³ in the London Underground (Pfeifer, Harrison and

Lynam 1999). In a further study by Sitzmann (1999) PM_5 concentrations of $801 \mu g m^{-3}$ were measured. Seaton et al., (2005) measured $PM_{2.5}$ concentrations and particle number counts (PNC's) on three subway platforms and in driver's cabs over three days and Smith et al., (2020) spatially mapped $PM_{2.5}$ and PNC concentrations in train carriages on all lines on the London Underground network. The study by Smith et al., (2020) investigated the characteristics of the London Underground that could affect $PM_{2.5}$ personal exposure by measuring $PM_{2.5}$ carriage concentrations over several return train journeys. These studies provided an insight into $PM_{2.5}$ concentrations in the London Underground, the spatial variability within and between lines and factors that may have affected concentrations. However, none of these studies looked at NO_2 and O_3 concentrations in the subway nor undertook a long-term spatial and temporal exposure assessment of specific lines. This work therefore provides further evidence investigating factors and processes affecting $PM_{2.5}$, NO_2 and O_3 concentrations in the subway.

This chapter presents a comprehensive characterisation of the spatial and temporal variation of how pollutant concentrations vary along a return Bakerloo Line journey from Willesden Junction station to Elephant & Castle station, or for the alternative journey, a Jubilee Line return journey from Kilburn station to Canning Town station (Figure 4.1). The return overground journeys that form part of the MRC study run from Willesden Junction station to Watford Junction station, and as the alternative journey, from Kensal Rise station to Stratford station (Figure 4.2).



Figure 4.1: Map of the London Underground showing the return subway Bakerloo line from Willesden Junction station to Elephant & Castle station (brown circles) and the alternative return subway Jubilee line journey from Kilburn station to Canning Town station (silver circles).



Figure 4.2: Map of the London Overground showing the return Overground line journey from Willesden Junction station to Watford Junction station (red circles) and the alternative return Overground line journey from Kensal Rise station to Stratford station (blue circles).

4.2 Methods

4.2.1 Train journeys

When determining the train journey routes for the MRC study there were several criteria that needed to be fulfilled. The starting stations were required to have lift access from ground to platform level to avoid stairs and minimise the walking distance for the COPD participants. Ideally, the station was required to have a subway and overground route serving the station and a return train journey of at least 60 minutes (Smith et al., 2020). To fulfil these criteria journeys primarily took place on the Bakerloo Line (n=44) and the Overground line starting from Willesden Junction station (n=48). Provision was made for alternative journeys in cases where the lift was not operational at Willesden Junction station and trains were not available due to engineering works or train strikes. These alternative journeys took place on the Jubilee Line (n=7) and the Kensal Rise branch of the Overground (n=8), which both had lift access to the platforms.

4.2.1.1 Subway journeys

The Bakerloo Line opened in 1906 and runs underneath some of the busiest roads in Central London. Bakerloo Line trains were built in 1972 (Neil 2015) and are the oldest trains currently in service in the London Underground (indeed on any UK rail network). These trains are the only trains on the subway network to have friction and emergency braking, as opposed to regenerative or rheostatic braking, that is controlled by the driver. This type of braking is known to significantly increase braking emissions in comparison to regenerative or rheostatic braking (Van Ryswyk et al., 2017). The section of the Bakerloo Line used in this study starts above ground at Willesden Junction station and continues to Queens Park station above ground (there are three above ground stations) before entering the tunnel between Queens Park and Kilburn Park stations. The tunnelled section of the track runs from Kilburn Park station to Elephant & Castle station and consists of 15 subway stations at varying platform depths of between 7 to 25m (Table 4.1). All below ground Bakerloo line stations consist of a single narrow tunnel with one track and one platform in each direction.

Table 4.1: Tunnel depths (m) below ground-level and the number of interchanges at each station on the Bakerloo line.

Station	Tunnel Depth (m)		
	Outbound	Return	Interchanges
Kilburn Park	7	7	0
Maida Vale	14	14	0
Warwick Avenue	14	14	0
Paddington	16	16	1
Edgware Road	25	25	0
Marylebone	23	23	0
Baker Street	22	19	2
Regent's Park	24	22	0
Oxford Circus	22	22	2
Piccadilly Circus	25	25	1
Charing Cross	24	24	1
Embankment	20	20	2
Waterloo	16	19	2
Lambeth North	16	16	0
Elephant & Castle	23	23	1

A study into station design in the Barcelona subway by Moreno et al., (2014) found that platforms with a design of one track and one platform, similar to the Bakerloo line, had the highest PM concentrations. Wider stations with multiple platforms had lower PM concentrations than single track platforms. The authors also found that passenger entrances to the platform were most effective at reducing platform PM concentrations when they were positioned at the train entry point.

There is limited ventilation within the Bakerloo Line tunnels with air exchanged between the subway and the ambient environment principally through ventilation shafts and station entrances driven by the piston effect of moving trains. The trains are not air conditioned and have windows at either end of the carriage that can be opened. Power is supplied via a DC current third rail system. Trains run from 05:00 until midnight every day except Sunday which runs from 07:00 until midnight. All days have a train frequency of 3-4 minutes with higher frequencies during rush hours.

The Jubilee Line opened in 1977, with the Docklands extension opening in 1999, and is the newest line on the London Underground network. The trains were built in 1996 and have automatic train operation and regenerative braking (Neil 2015). The section of the Jubilee Line used in this study runs above ground from Kilburn station to Finchley Road station before entering the tunnel before Swiss Cottage Station. The train remains in the tunnel until leaving North Greenwich station approaching Canning Town station, which is the final station used in this study before returning to Kilburn station. The tunnelled sections are deeper than the Bakerloo Line consisting of 13 subway stations at varying depths between 14 and 31 m (Table 4.2). As with the Bakerloo Line all below ground stations consist of a single narrow tunnel with one track and one platform, except North Greenwich, which has four platforms and tracks.

Table 4.2: Tunnel depths (m) below ground-level and the number of interchanges at each station on the Jubilee line.

Station	Tunnel Depth (m)		
	Outbound	Return	Interchanges
Swiss Cottage	17	17	0
St Johns Wood	18	18	0
Baker Street	23	20	2
Bond Street	31	31	2
Green Park	31	31	2
Westminster	23	31	1
Waterloo	30	30	2
Southwark	14	14	0
London Bridge	27	27	1
Bermondsey	14	14	0
Canada Water	18	18	0
Canary Wharf	19	19	1
North Greenwich	15	15	0

Tunnel ventilation in the Jubilee Line is also driven by train movements via ventilation shafts and platform entrances. Trains carriages have windows at either end of the carriage. Power is supplied via a DC current third rail system. Trains run from 05:00 until midnight every day except Friday night to Sunday morning when an all-night service operates. Train frequencies are 2-3 minutes

for all regular services. The stations common to the Bakerloo and Jubilee lines are Baker Street and Waterloo stations, although the trains are in different tunnels and at different depths.

4.2.1.2 Overground journeys

London Overground trains were brought into service in 2019. The Willesden Junction station to Watford Junction station route and the alternative journey from Kensal Rise station to Stratford station use the same rolling stock. The trains are air conditioned, with carriages having open gangways allowing passengers to walk through the length of the train and the trains run overground for the entirety of the journeys. Between Queen's Park station and Willesden Junction station the Bakerloo and Overground trains share the track which results in a reduced Bakerloo Line service from Elephant & Castle station to Willesden Junction station. This meant that on return journeys from Elephant & Castle station the train terminated at Queens Park station requiring a change of trains to continue to Willesden Junction station. A change of trains was also required at Canning Town station for the return journey on the Jubilee Line.

4.2.2 Exposure measurements

I carried out all exposure measurements using MoRS to measure the personal exposures of participants in train carriages by placing MoRS between the participants (if there were two participants) or next to a single participant (Figure 4.3). I monitored MoRS's on-board PC to ensure the instruments were functioning. For each exposure train journey, I loaded and accompanied MoRS into an electric taxi at Imperial College, White City Campus. Before loading MoRS into the taxi I started and checked all the instruments were working and sampling before leaving the White City laboratory. The taxi drove to Hammersmith Hospital where the participants and the Clinical Research Fellow entered the taxi alongside MoRS and I before driving to Willesden Junction station (or the alternative if it was used) where I unloaded MoRS and the participants disembarked the taxi. At all times during the taxi journey recirculation was on and the windows were closed to minimise exposure to traffic pollution. The same routine was followed on the return taxi journey after the exposure train journey.



Figure 4.3: The positioning of MoRS between the participants measuring at the breathing height of the participants on a subway journey (left) and an Overground journey (right).

On arrival at the station the allocated train journey was taken. At Willesden Junction station the participants and MoRS boarded the Bakerloo Line train at the rear carriage or the Overground train at the front carriage and I placed MoRS in position between the participants (Figure 4.3). At Kilburn station the Jubilee Line train was boarded at the front carriage and at Kensal Rise station the Overground train was boarded at the front carriage. Although it is known that the carriage position on diesel trains affects exposure concentrations (Ham et al., 2017, Jeong, Traub and Evans 2017) it was unknown if carriage position affected concentrations in subway trains. Subway and overground trains are electrically powered and the hypothesis before undertaking the journeys was that carriage position would not affect PM_{2.5} concentrations as there were no location specific sources, although train movement resuspends legacy PM on the subway journey. When deciding the carriage position, it was important to be as close to the platform lift as possible, to avoid participants walking along platforms. Seat position was maintained at termini stations to avoid participants having to change carriage position by walking along the platform. There were no windows in the Overground carriages (due to the air-conditioned carriages). In the underground carriage it was not possible to control the position of the window as in the Bakerloo and Jubilee line trains the windows were at the far end of the carriage with passengers between the participants and the window. The only window in the carriage was at the far end of the carriage as we sat immediately behind the driver compartment. No record was kept of the window position as this often changed during the journey.

In total there were 107 participant exposure train journeys. These comprised 44 Bakerloo Line journeys, 7 Jubilee Line journeys, 48 Willesden Junction station to Watford Junction station Overground journeys and 8 Kensal Rise station to Stratford station Overground journeys. The

journeys and reasons for the alternative journeys are shown in Table B 1. On exposure journeys from 26 September 2022 to 12 October 2022 the Mini-Wras was serviced and a SidePak was used for PM_{2.5} sampling.

Only one participant could undertake an exposure train journey from 26 January 2022 to 25 April 2022. This was due to there being no research nurse to assist the Clinical Research Fellow in taking physiological health measurements in Hammersmith Hospital. A research nurse was recruited to allow two participants to take exposure journeys from 27 April 2022. From 27 April 2022 to 19 July 2023 two participants were taken on the exposure train journeys whenever possible. When the participant exposure journeys began on 26 January 2022 it was compulsory for the participants to wear a mask until the mandate finished on 24 February 2022. However, some participants still choose to wear a mask after 24 February 2022 with 28 journeys undertaken with participants wearing a mask. On all journeys MoRS replicated the mask wearing status of the participants. MoRS accompanied the participants on every exposure journey being placed between the two seated participants and sampling at the breathing height of the sitting participants.

4.2.3 Spatial mapping

All exposure train journeys took place between 10.00 and 13.00 on Mondays and Wednesdays. MoRS measured PM, NO₂, O₃, noise, %RH and temperature at all times from the moment the participants left Hammersmith Hospital. As no GPS location tracking was available underground on the Bakerloo and Jubilee lines a detailed data recording sheet was produced for each line to maintain consistency of recording. I recorded the arrival and departure time at each station and linked to the measured concentrations throughout the journey. All exposure data was averaged to a one-minute time resolution.

4.2.4 Repeated exposure journeys

Although spatially mapping a single journey measurement is useful for displaying pollutant concentrations and interactions throughout the journey, it does not reveal spatial and temporal variation over longer time scales. A strength of this study was the long-term monitoring of the Bakerloo line over 44 separate journeys over 18 months (there were also seven subway journeys on the Jubilee line). Long-term, repeated measurements have the advantages of assessing

detailed patterns in pollutants, reducing the dominance of short-term variability, reducing errors and eliminating outliers which help to formulate comprehensive conclusions (Chang et al., 2021).

Although the return distance travelled on each line was known and was consistent over every journey, the time taken for a return journey varied throughout the study. For example, the return journey time on the Bakerloo line varied between 68 minutes (29 June 2022) and 87 minutes (24 May 2023) with a mean journey time of 77 minutes. On all lines there was a variation in the return journey time over the track distance (Table 4.3). The differences in the return journey times were affected by factors such as train speed, passenger numbers, waiting times at platforms, delays due to signalling, slower trains running in front, speed restrictions, hold ups on the track and differing waits when changing trains at Queen's Park station and at station termini. Due to Bakerloo line trains sharing the track with Overground trains after Queen's Park station the subway train from Elephant & Castle terminated at Queen's Park and the next train was boarded.

Table 4.3: Return distances and return travel time for each line used in the MRC study.

Line	Return Distance (km)	Return Time (mins)	
		Min-Max	Mean
Bakerloo	27.26	68 - 87	77
Jubilee	42.28	67 – 81	72
Willesden Junction Overground	37.82	75 – 96	81
Kensal Rise Overground	21.32	85 – 93	89

Repeated measurements along the same sections of track over time inevitably result in small spatial variations in the train position at a given time. Although the distances between stations are known the tunnel distance between stations are unknown. When a train is moving through a tunnel the exact location of the train is unspecified and cannot be allocated a time point to correspond to instrument measurements. These factors present difficulties in spatially resolving repeated measurements over an exposure journey as the trains spatial position at any given time is never identical over different exposure journeys.

To compensate for the different speeds and journey times of each journey, journey distance was used instead of time as the independent variable. As distance travelled is independent of speed the journey was divided into equal chunks of distance (Apte et al., 2017, Wagner et al., 2021). The distance between each station and the number of measurement points (or minutes) between

each station is known for each journey. By assuming the train always moves at the same constant speed between each station the distance travelled by the train for each minute between the stations can be calculated. The distance between Willesden Junction Station and Kensal Green station is 1.5 km. If the train takes three minutes to travel between the stations this gives three equal chunks of 0.5 km for each minute of train travel allowing the position of the train to be estimated aligning spatial resolution between stations.

The time spent at each station varied so each station was given a platform length distance of 200 m. If the train spent longer than one-minute at the station, the 200 m platform distance was divided into equal chunks dependent on the time the train spent at the station. If the train spent over one-minute at a station the 200 m platform distance was deducted from the distance from the previous stop. If the train stopped at Kensal Green station for one-minute and the train took three-minutes to travel from Willesden Junction station the chunks between the stations were 0.433 km (1.3 km divided by three-minutes) and the station length was 200 m, giving a total distance between Willesden Junction and Kensal Green stations of 1.5 km over four-minutes. This was applied to all measured data points over each exposure journey to give a total distance travelled equal to the return journey length of the line. Whilst each journey would be unique in the number of chunks and chunk lengths, journeys were compatible in total distance travelled for all subway and overground journeys. The chunking method was spatially mapped using `geom_smooth` in the `ggplot2` package in 'r' (Wickham 2023).

4.2.5 Train carriage measurement position

The seating position of a person on diesel trains is known to influence personal PM_{2.5} exposure (Abramesko and Tartakovsky 2017, Ham et al., 2017, Jeong, Traub and Evans 2017), although there have been no studies on the subway. The MRC study protocol required participants to sit in the rear carriage of the Bakerloo line train on the outbound journey (which became the front carriage on the return journey) to reduce the distance walked by participants. To test whether the carriage position would affect PM_{2.5} concentrations three researchers travelled on three return Bakerloo line journeys from Willesden Junction station to Elephant & Castle station. Each researcher carried a TSI AM520 SidePak in a backpack with the sampling inlets at breathing height when sitting. All instruments were zeroed before the commencement of the trial and corrected with scaling factors generated through colocations with reference instruments at the Hampstead test station. Each researcher carried out one return journey measurement in the front

carriage (A), middle carriage (C) and rear carriage (B) using the same Sidepak in each of the carriages. Researchers boarded at Willesden Junction station and stayed in position at Elephant & Castle station before disembarking the train at Willesden Junction station on return (Figure 4.4).



Figure 4.4: Diagram showing the three measurement positions of the researchers for the three Bakerloo line return journeys from Willesden Junction station to Elephant & Castle station in the front (A), rear (B) and middle (C) carriages.

On each return to Willesden Junction station researchers changed carriage position taking measurements with the same SidePak that was issued on the first journey. This ensured that each SidePak took return journey measurements in each of the front, middle and rear carriages.

4.2.6 Calibration factors

Scaling factors for $PM_{2.5}$ of 3.14 and 0.88 were derived for correction of the measured subway and ambient concentrations measured using the Mini-Wras. Due to subway air comprising a mix of subway and ambient particulate sources, measured $PM_{2.5}$ subway concentrations were corrected using the recommendations of Smith et al., (2020) that subway and ambient scaling factors should be proportionally applied to subway air. Urban background $PM_{2.5}$ scaling factors were used to correct Overground train measurements and subway measurements outside of the tunnelled sections in ambient air. $PM_{2.5}$ mass was collected onto the MoRS on-board filters for additional $PM_{2.5}$ mass concentration measurements.

4.3 Results

4.3.1 Subway and overground exposure assessment

4.3.1.1 Subway journeys

When undertaking personal exposure measurements during the train journeys, MoRS measured all PM size fractions, NO₂, NO_x, and O₃ simultaneously. This allowed an exposure assessment of carriage concentrations throughout the journey to be spatially mapped for all four pollutants. An example return Bakerloo line exposure journey on 09 November 2022 characterised PM_{2.5}, NO₂ and O₃ and is shown as a time-series in Figure 4.5. Although this only provides a 'snapshot' of one journey it is useful in giving an insight into the spatial variation of pollutant concentrations along the journey.

For the first eight minutes of the journey the train was above-ground reflecting urban background PM_{2.5} concentrations of 2 µg m⁻³. Carriage PM_{2.5} concentrations built-up rapidly after the train entered the tunnel reaching 581 µg m⁻³ just before Warwick Avenue station within 3 minutes of entering the tunnel, before falling slightly as the train moved along the track before peak concentrations of 594 µg m⁻³ were reached at Marylebone station. From Marylebone station PM_{2.5} concentrations gradually fell until the terminus at Elephant & Castle station. Here the train stopped for five minutes during which time PM_{2.5} concentrations fell from 337 to 113 µg m⁻³ before increasing again when the train started to move. PM_{2.5} increased as the train moved towards Oxford Street station (431 µg m⁻³) before falling until reaching peak concentrations on the return journey of 469 µg m⁻³ at Warwick Avenue station. High PM_{2.5} concentrations were maintained until the train left the tunnel when concentrations fell from 413 to 94 µg m⁻³ immediately after emerging from the tunnel, before quickly returning to background levels. Mean PM_{2.5} concentrations were 382 and 281 µg m⁻³ for the tunnelled sections and the complete return journey, respectively, although it was noticeable that PM_{2.5} varied throughout the tunnelled section of the journey. The concentrations found in the Bakerloo Line on this journey were amongst the highest measured worldwide (Carteni 2016, Xu and Hao 2017).

09 Nov 2022: Willesden Junction to Elephant & Castle
Bakerloo Line Exposure Journey

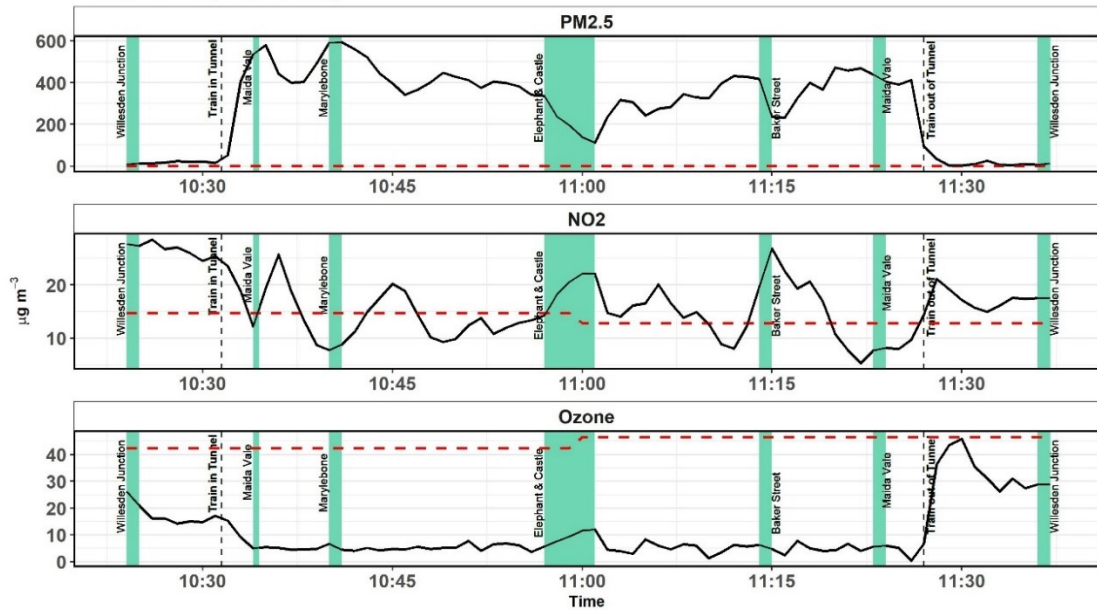


Figure 4.5: Concentrations of PM_{2.5}, NO₂ and O₃ measured along the return journey between Willesden Junction station and Elephant & Castle station on 09 November 2022 on a Bakerloo line subway train. Shaded green areas indicated the times when the train remained in a station. The dotted black lines indicate when the train entered and exited the subway tunnel. Red dotted lines indicate background concentrations. PM_{2.5} has been scaled using the formula proposed by Smith et al., (2020).

Nitrogen dioxide is not generated in the subway system and enters through ventilation shafts and platform entrances from ambient air (Cao et al., 2017). It is evident that NO₂ has a negative correlation with PM_{2.5} with a Pearson correlation between PM_{2.5} and NO₂ for the tunnelled sections showing a moderate negative correlation of -0.55 and demonstrates that ambient air relatively more polluted with NO₂ but less polluted with PM_{2.5} is mixing with air in the subway. The negative correlation with NO₂ is especially noticeable where PM_{2.5} peaked at Maida Vale and Marylebone stations on the outbound journey and where PM_{2.5} falls at Baker Street station, with the inverse true for NO₂. At Elephant & Castle station, where the train was stationary, the combination of an influx of ambient air and PM_{2.5} settling processes significantly reduced PM_{2.5} concentrations. This interaction between PM_{2.5} and NO₂ in the subway has not been reported in the literature. Before entering the tunnel and after leaving the tunnel measured NO₂ concentrations were higher than mean ambient background concentrations. After entry into the tunnel NO₂ concentrations fluctuated between 5 - 27 µg m⁻³ throughout the journey with a mean of 15 µg m⁻³. Mean ambient background NO₂ concentrations were 14 – 16 µg m⁻³ (mean 15 µg m⁻³), while the train was in the tunnel. The highest NO₂ concentration was at Baker Street station on the return journey, with the lowest concentration at Warwick Avenue station on the return journey. The variation in NO₂

concentrations in the tunnelled sections could be dependent on the trains proximity to ventilation shafts and platform passenger entrances through which ambient air was entering the tunnels.

Due to the lack of sunlight in the tunnelled sections of the subway, ozone remained low throughout. During the journey mean O_3 concentrations were $6 \mu\text{g m}^{-3}$ compared to mean ambient background concentrations of $45 \mu\text{g m}^{-3}$. In the subway the highest concentrations of O_3 were at Elephant & Castle station, when the train was stationary ($12 \mu\text{g m}^{-3}$), most likely due to ambient air entering the platform through passenger entrances.

A Jubilee line journey on 19 December 2022 had mean $PM_{2.5}$ concentrations of $150 \mu\text{g m}^{-3}$ in the tunnelled sections of the journey (Figure 4.6). Although this was lower than the Bakerloo line journey, it is still high compared to worldwide subway concentrations. Before entering the tunnel $PM_{2.5}$ concentrations were similar to background concentrations of $1 \mu\text{g m}^{-3}$ before rapidly rising to $199 \mu\text{g m}^{-3}$ at Baker Street station. The highest $PM_{2.5}$ concentrations of $223 \mu\text{g m}^{-3}$ occurred at Southwark station before gradually falling until the train exited the tunnel where they fell to $3 \mu\text{g m}^{-3}$. On the return journey, $PM_{2.5}$ concentrations increased gradually to $211 \mu\text{g m}^{-3}$ between Baker Street and Bond Street stations before falling to background concentrations as the train left the tunnel. This journey showed a similar interaction between $PM_{2.5}$ and NO_2 that was found on the Bakerloo line, with a correlation of -0.57 between $PM_{2.5}$ and NO_2 in the tunnelled sections of the journey. NO_2 concentrations were highest outside of the tunnelled sections (mean $14 \mu\text{g m}^{-3}$). Similarly, to the Bakerloo line, NO_2 concentrations in the tunnelled sections varied throughout the journey, although at lower concentrations ($7 - 15 \mu\text{g m}^{-3}$, mean $10 \mu\text{g m}^{-3}$). Generally, NO_2 concentrations in the Jubilee line were below ambient background levels of $13 - 14 \mu\text{g m}^{-3}$.

19 Dec 2022: Kilburn to Canning Town
Jubilee Line Exposure Journey

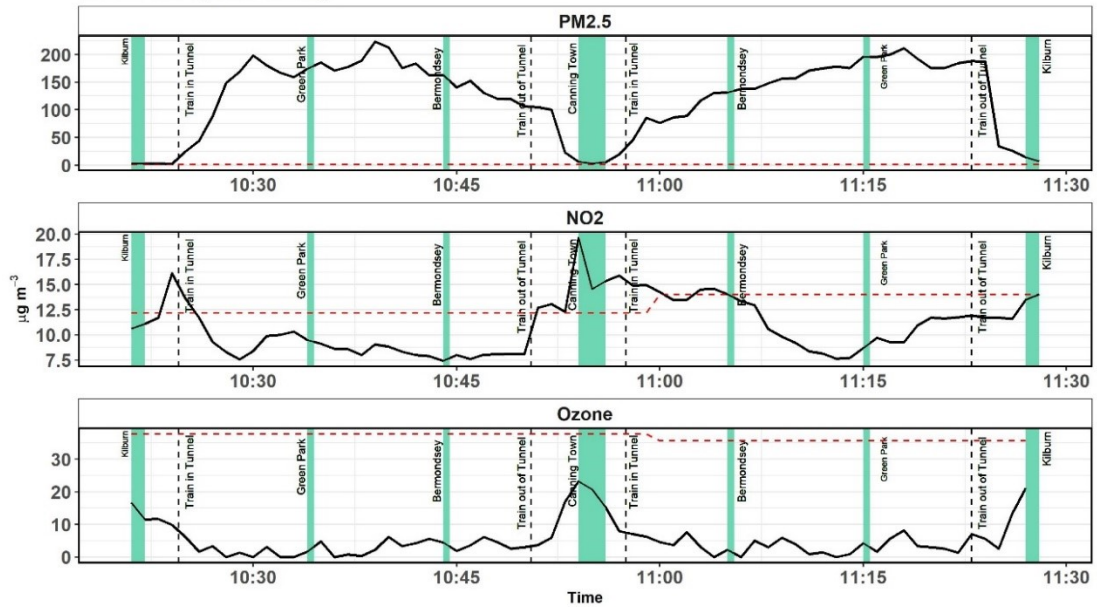


Figure 4.6: Concentrations of PM_{2.5}, NO₂ and O₃ measured along the return journey between Kilburn station and Canning Town station on 19 December 2022 on a Jubilee line subway train. Shaded green areas indicated the times when the train remained in a station. The dotted black lines indicate when the train entered and exited the subway tunnel. Red dotted lines indicate background concentrations. PM_{2.5} has been scaled using the formula proposed by Smith et al., (2020).

The highest O₃ concentrations were found outside of the tunnels when the train was above-ground. At Canning Town station O₃ concentrations approached background concentrations of 38 µg m⁻³, rising from 4 to 23 µg m⁻³ after the train exited the tunnel. When the train re-entered the tunnel O₃ concentrations fell to 8 µg m⁻³. Mean O₃ concentrations in the tunnelled sections were 3 µg m⁻³ with maximum concentrations of 8 µg m⁻³ occurring in the tunnelled section between Bond Street and Baker Street stations. Low ozone concentrations were found in the Bakerloo and Jubilee lines suggesting this is a common phenomenon in the subway.

4.3.1.2 Overground Journeys

Overground journeys took place on two routes, Willesden Junction station to Watford Junction station and Kensal Rise station to Stratford station. An example journey of each overground journey is shown in Figure 4.7. In contrast to the subway journeys, the overground journeys had very low PM_{2.5} concentrations. On the Willesden Junction route PM_{2.5} remained below background concentrations for much of the journey, except at the start of the journey and at the Watford Junction station terminus, with a mean PM_{2.5} concentration of 3 µg m⁻³. Mean PM_{2.5} background concentrations were 3 µg m⁻³ during the journey. On the outbound journey mean NO₂ concentrations of 30 µg m⁻³ were above background concentrations of 10 µg m⁻³ before

approaching background concentrations on the return journey, with mean NO_2 concentrations of $17 \mu\text{g m}^{-3}$ on this section. During this journey mean ozone concentrations of $19 \mu\text{g m}^{-3}$ remained below mean background concentrations of $74 \mu\text{g m}^{-3}$.

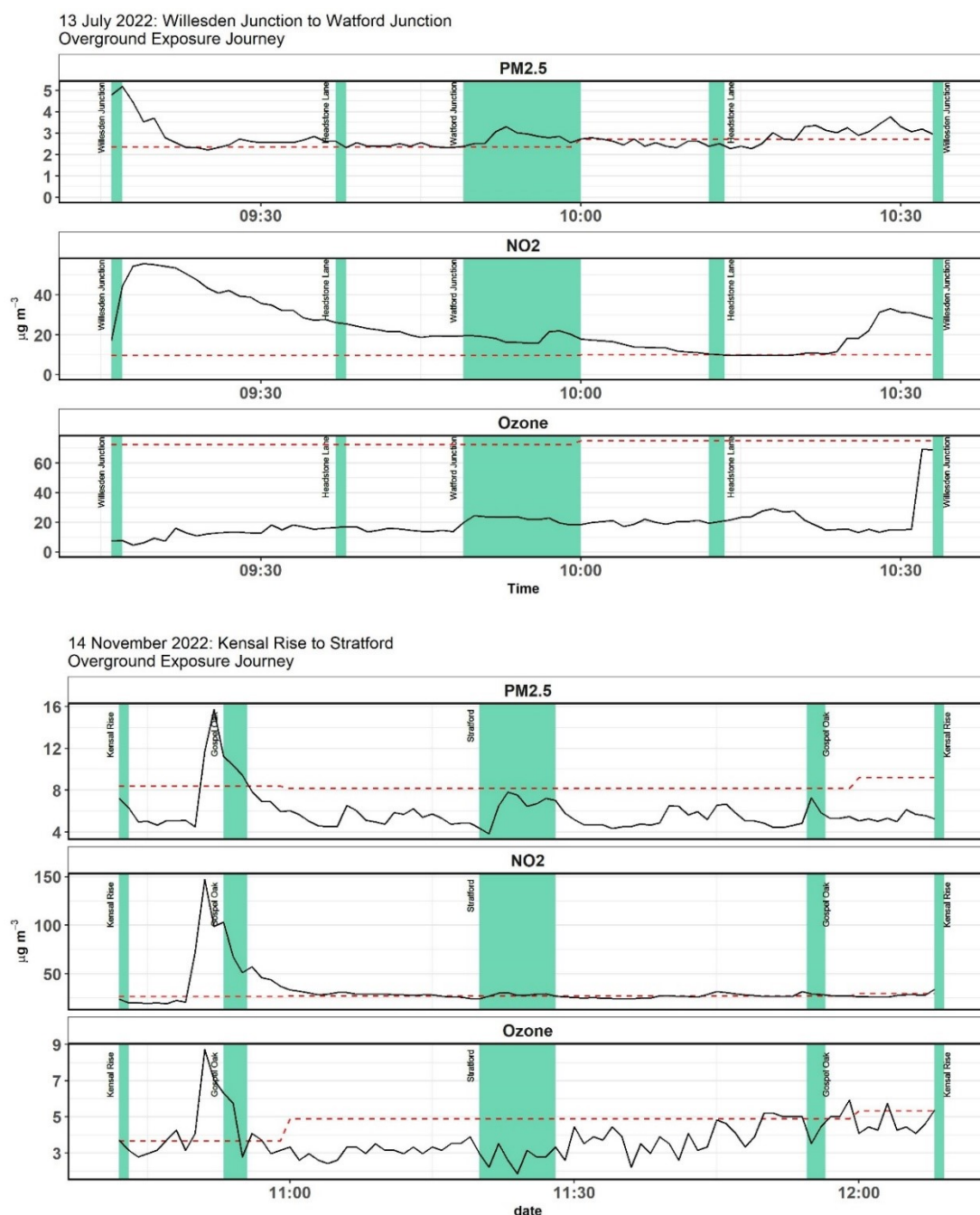


Figure 4.7: Concentrations of $\text{PM}_{2.5}$, NO_2 and O_3 measured along the return journey between Willesden Junction station and Watford Junction station on 13 July 2022 on a Willesden Junction overground train and between Kensal Rise station and Stratford station on 14 November 2022 on a Kensal Rise overground train. Shaded green areas indicated the times when the train remained in a station. Red dotted lines indicate background concentrations. $\text{PM}_{2.5}$ has been adjusted using the formula proposed by Smith et al., (2020).

On the Kensal Rise journey $\text{PM}_{2.5}$ concentrations (mean $6 \mu\text{g m}^{-3}$) were generally lower than background concentrations (mean $8 \mu\text{g m}^{-3}$) except near Gospel Oak where there was likely to

be a strong pollutant source, as all pollutant concentrations increased. NO_2 concentrations during the train journey (mean $32 \mu\text{g m}^{-3}$) were close to background concentrations of $30 \mu\text{g m}^{-3}$, except at Gospel Oak, whilst ozone (mean $4 \mu\text{g m}^{-3}$) was mainly below mean background concentrations ($5 \mu\text{g m}^{-3}$), except at Gospel Oak.

$\text{PM}_{2.5}$ was over 100 and 30 times lower in the Overground than in the Bakerloo and Jubilee lines, although NO_2 and O_3 were higher in the overground, by factors of 2 and 3, respectively, highlighting the importance of measuring all three pollutants for the MRC study.

4.3.1.3 Repeated journeys on the Bakerloo line

Repeated exposure journeys on the Bakerloo line using the chunking method displayed high spatial and temporal resolution (Figure 4.8). Although there were 44 journeys on the Bakerloo line, for consistency, only the 35 journeys where the participants (and MoRS) were not wearing a mask have been analysed. Similar to the single journey, mean $\text{PM}_{2.5}$ concentrations increased rapidly on entering the tunnel reaching a peak between Marylebone and Baker Street stations before falling until the train reached Elephant & Castle station. At the Elephant & Castle station terminus $\text{PM}_{2.5}$ fell rapidly as soon as the train stopped. When the train journey recommenced, concentrations rose but less slowly than on the outbound journey, peaking at Oxford Circus and Warwick Avenue stations before falling rapidly to ambient background concentrations when the train left the tunnel.

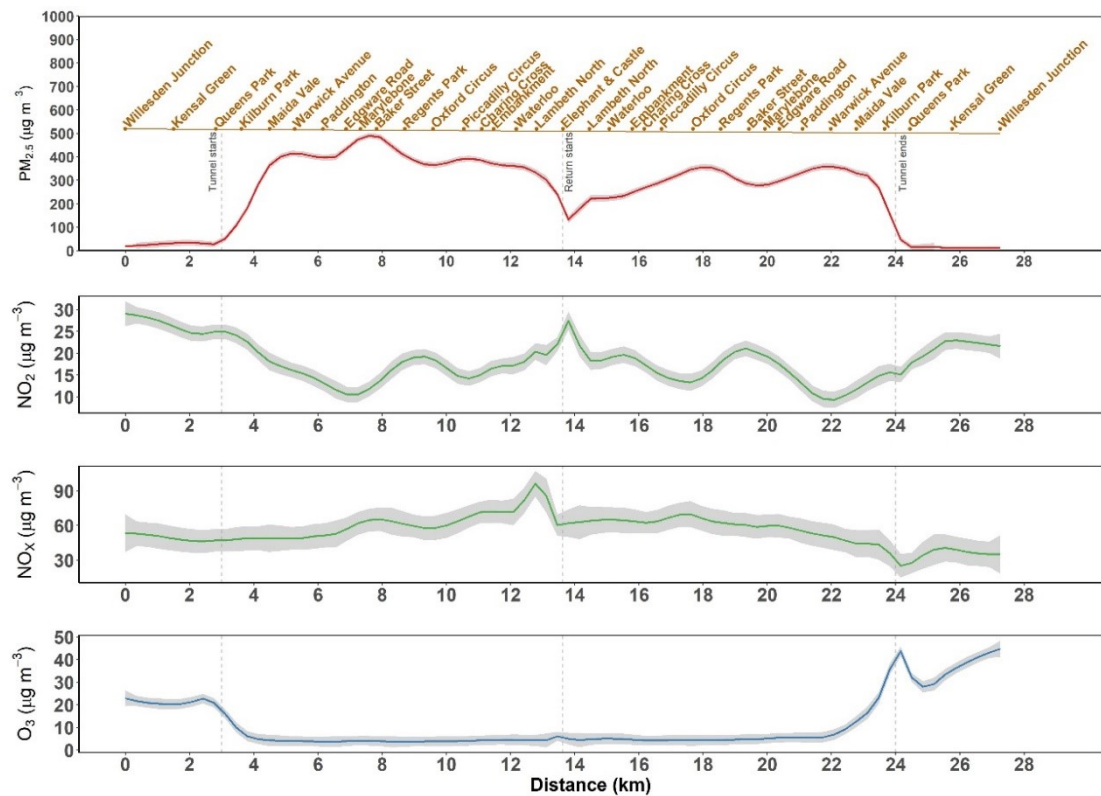


Figure 4.8: Repeated journeys on the Bakerloo line displaying 35 complete return journeys from Willesden Junction station to Elephant & Castle station for $\text{PM}_{2.5}$, NO_2 , NO_x and O_3 . The shaded area represents the 95% confidence intervals. $\text{PM}_{2.5}$ has been scaled using the formula proposed by Smith et al., (2020).

The same inverse relationship between $\text{PM}_{2.5}$ and NO_2 that was observed on the single journey of 19 November 2022 can be seen in the repeated journeys. The Pearson correlation of -0.47 for the repeated journeys has a lower correlation than the single journey correlation of -0.55 suggesting there was a variability in the concentrations of $\text{PM}_{2.5}$ and NO_2 during the Bakerloo line journey, not necessarily linked solely to tunnel depth or distance from tunnel mouths. The variability in $\text{PM}_{2.5}$ could have been caused by braking in different locations and the length of braking time. The extent of emergency braking would also have an influence on $\text{PM}_{2.5}$ concentrations. Other factors could include track gradient and track curvature, especially if the brakes were applied, and the influence of other lines. For NO_2 , the variation could have been caused by the trains speed as it passed ventilation shafts, ambient wind concentrations, wind direction, the ambient concentration and the influence of other lines. For $\text{PM}_{2.5}$ and NO_2 , the length of time the train was stopped at Elephant & Castle station could be a factor. The deepest sections of the Bakerloo line were between Edgware Road and Embankment stations, although this section did not consistently have higher $\text{PM}_{2.5}$ concentrations than shallower sections of the journey such as at Warwick Avenue station.

Repeated journeys on the Bakerloo line showed that NO_x concentrations rose slowly after entering the tunnel, peaking at Lambeth North before falling at Elephant & Castle and continuing to fall on the return journey. The peak at Lambeth North could be influenced by ambient air entering the tunnel from the depot sidings, although this is less noticeable for NO₂. During both legs of the journey, NO_x shows greater variability than the other three pollutants (shown by the wider confidence intervals). Although the correlation between NO₂ and PM_{2.5} during the Bakerloo line journey was -0.47, there was no correlation between NO_x and PM_{2.5}. There was a correlation of 0.45 between NO₂ and NO_x. These results could have resulted from the greater variation in NO_x throughout the journey, compared to PM_{2.5} and NO₂.

4.3.1.4 Repeated journeys on the Jubilee line

The Jubilee line was used as the alternative subway line for when the Bakerloo line was not available (Figure 4.9). As in the Bakerloo line only the two journeys where the participants were not wearing a mask have been analysed. Repeated exposure journeys using the chunking method (n=2) showed mean PM_{2.5} concentrations rapidly increasing after the train entered the tunnel at Swiss Cottage station. Concentrations continued to increase until reaching a peak concentration at London Bridge station before gradually falling as the train moved towards the tunnel exit after North Greenwich station. On exit of the tunnel, concentrations fell rapidly until a change of trains to return took place at Canning Town station. On re-entering the tunnel at North Greenwich station PM_{2.5} concentrations slowly increased until Waterloo station, after which they fell before peaking again at Baker Street station. As on the Bakerloo line PM_{2.5} concentrations fell very quickly to ambient levels as soon as the train left the tunnel.

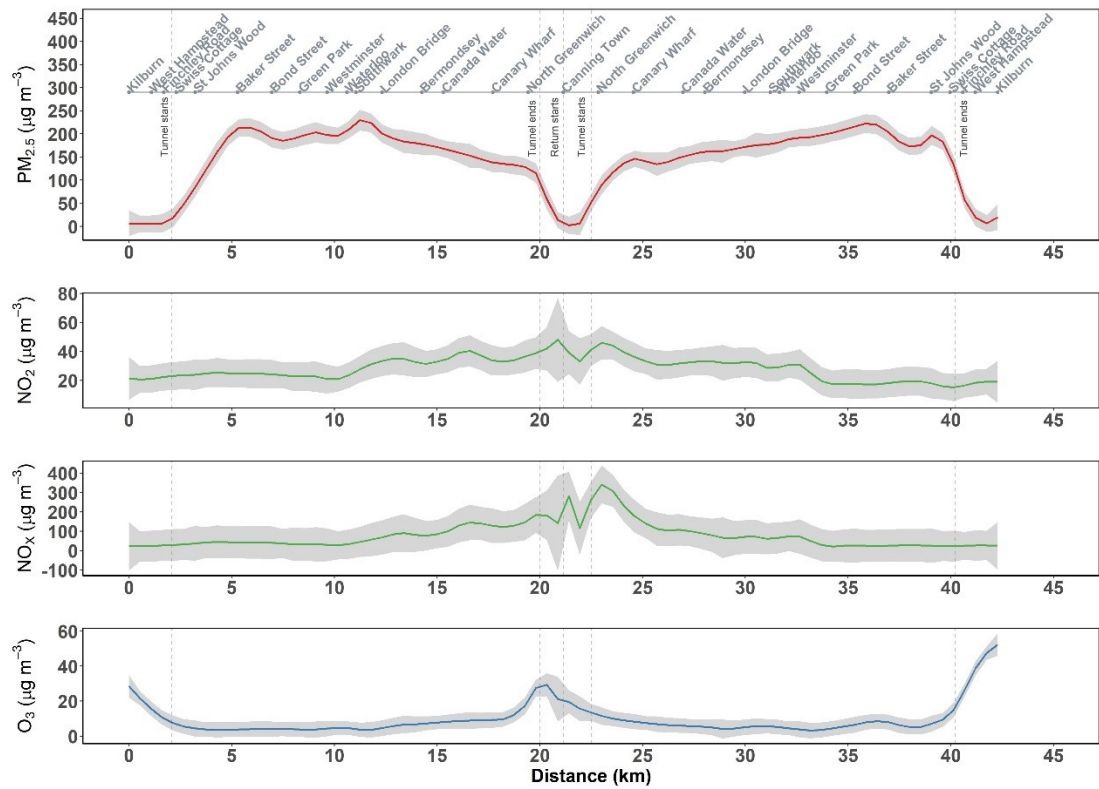


Figure 4.9: Repeated journeys on the Jubilee line displaying two complete return journeys from Kilburn station to Canning Town station for PM_{2.5}, NO₂, NO_x and O₃. The shaded area represents the 95% confidence intervals. PM_{2.5} has been scaled using the formula proposed by Smith et al., (2020)

The deepest sections of the Jubilee line run from Baker Street to London Bridge stations. These were the sections with the highest concentrations of both legs of the journey, although like the Bakerloo line, the relationship between station depth and PM_{2.5} concentrations seems complex. On the return journey, St Johns Wood station, with a station depth of 18m, had higher PM_{2.5} concentrations than Green Park station which has a depth of 31m. There was a negative correlation over the two journeys in the tunnelled sections of -0.44 between PM_{2.5} and NO₂, compared to the correlation of -0.57 on the single journey on 19 December 2022. There was a 0.33 positive correlation between NO_x and PM_{2.5}, although there was a large variation in the two non-masked journeys, making conclusions difficult to draw.

4.3.2 Face mask effect

It is known that wearing a face mask reduces exposure to PM_{2.5} although the exposure reduction will depend on many factors including the type of mask, breathing rate and the fit of the mask around the face (Ji, Li and Wang 2021, Kodros et al., 2021, Velasco et al., 2022). MoRS was adapted to be able to measure PM_{2.5} exposure through a mask on those exposure journeys on which the participants wore a mask. Differentiating the journeys where participants wore a mask

from those where the participants did not wear a mask shows that on the Bakerloo line mask wearing reduced exposure throughout the tunnelled sections of the journey (Figure 4.10)

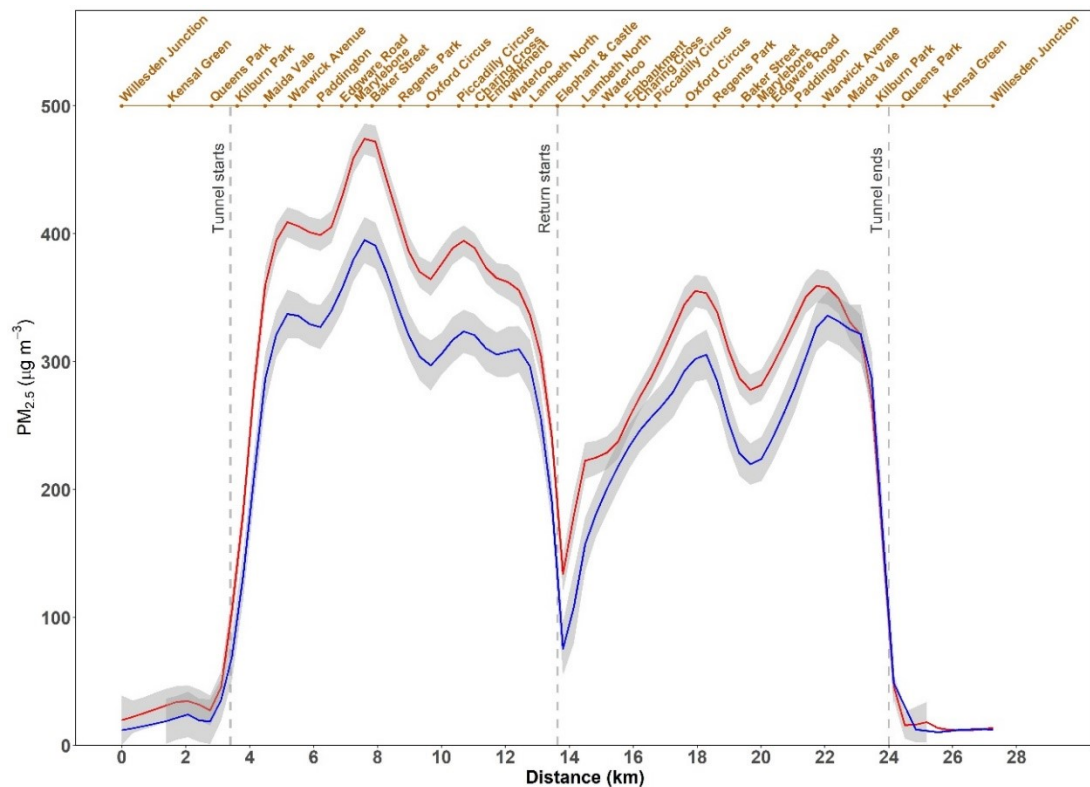


Figure 4.10 Repeat journeys on the return Bakerloo line journey from Willesden Junction station to Elephant & Castle station wearing a mask (blue line) and without wearing a mask (red line). The shaded areas represent the 95% confidence intervals. $PM_{2.5}$ has been adjusted using the formula proposed by Smith et al., (2020).

There was a significant difference in $PM_{2.5}$ concentrations with and without a mask ($p < 0.001$) with mean concentrations of 198 and 242 $\mu g m^{-3}$, respectively, for the complete return journeys, with a 21% difference in cumulative $PM_{2.5}$ exposure (Figure 4.11). The percentage difference remained remarkably consistent throughout the journey (20 - 25%) from Maida Vale station once the variability at the tunnel entrance was removed from the subway air.

These results confirm the hypothesis that face masks significantly reduced $PM_{2.5}$ exposure vindicating the decision to adapt MoRS to measure through a mask to quantify the effects on exposure. Post Covid-19 pandemic, commuters do not generally wear face masks whilst travelling on the subway so the further exposure assessment will focus on the 35 Bakerloo line journeys that were undertaken without a face mask.

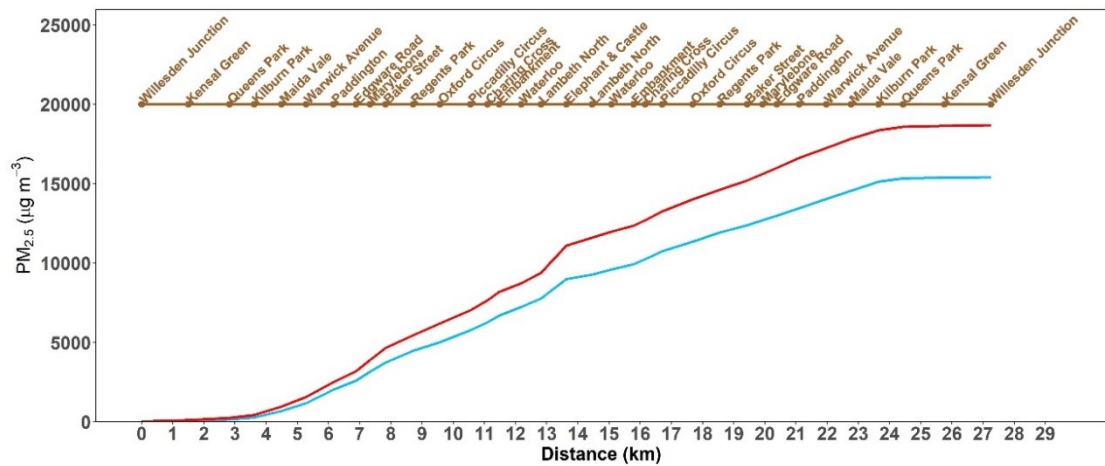


Figure 4.11: Cumulative $PM_{2.5}$ exposure over the complete Bakerloo line return journey wearing a mask (blue line) and without wearing a mask (red line). The shaded area represents the 95% confidence intervals. $PM_{2.5}$ has been adjusted using the formula proposed by Smith et al., (2020).

There were only two journeys on the Jubilee line undertaken without a mask. This makes drawing any conclusions from the Jubilee line data difficult. Where applicable, the non-masked Jubilee line data will be commented upon where it can provide insights into findings from the Bakerloo line but will not be shown in detail. Masks were found to have no effect on overground journeys. This was likely to be due to the daily variation in $PM_{2.5}$ concentrations being greater than the mask effect as mean concentrations of all journeys were $4 \mu g m^{-3}$, and without a mask were also $4 \mu g m^{-3}$.

4.3.3 Outbound and return subway journeys

Spatial mapping of the Bakerloo line suggests that on the outbound journey to Elephant & Castle station $PM_{2.5}$ concentrations were higher than the return journey. The two sections of the journey are displayed in Figure 4.12, with the outbound journey from Willesden Junction station to Elephant & Castle station and the return journey starting at Elephant & Castle station and finishing at Willesden Junction station.

The Bakerloo line trains travelled in separate tunnels on the outbound and return journeys with the separate tunnels only running alongside each other briefly on the northside of Paddington, Piccadilly Circus, Lambeth North and Elephant & Castle stations. Passenger entrances link the tunnels at Kilburn Park, Maida Vale, Warwick Avenue, Paddington, Regents Park, Charing Cross, Lambeth North and Elephant & Castle stations. The other stations do not link the two tunnels as the passenger entrances are not between the tunnels. The passenger entrance on the Southbound Bakerloo line at Baker Street station interchanges with the Northbound Jubilee line.

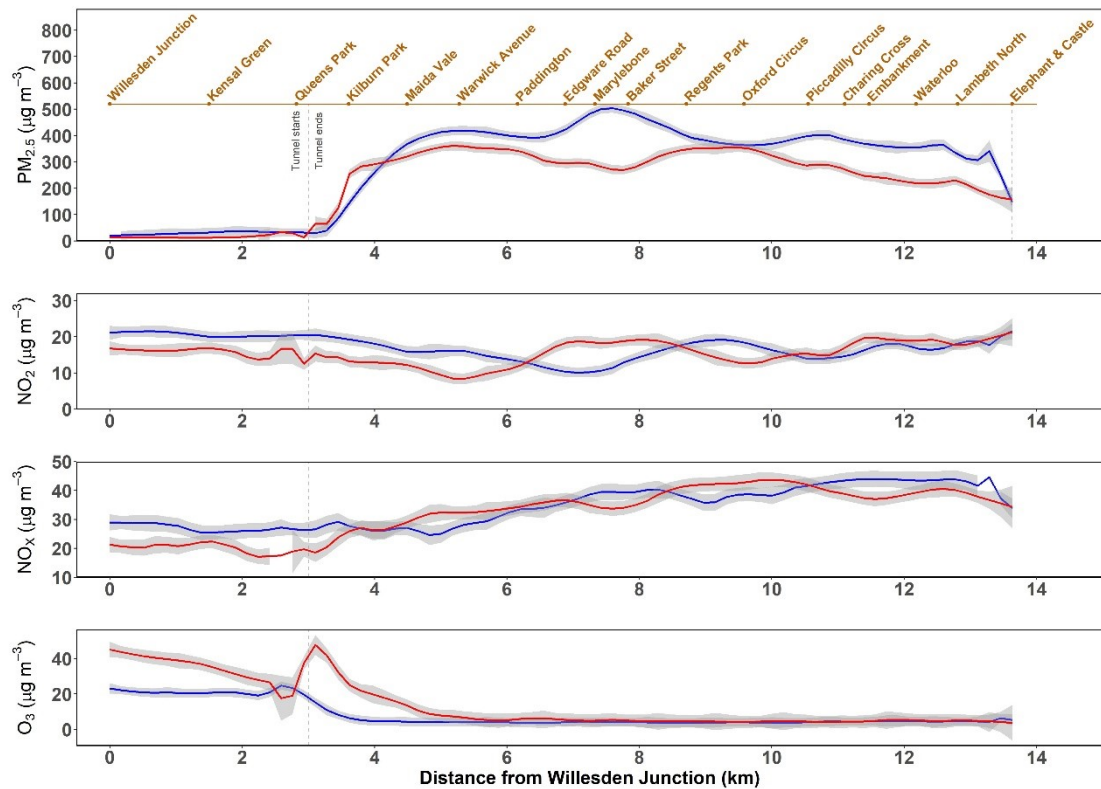


Figure 4.12: Concentrations of PM_{2.5}, NO₂, NO_x and O₃ on the outbound journey from Willesden Junction station to Elephant & Castle station (blue line) and the return journey from Elephant & Castle station to Willesden Junction station (red line). The shaded area represents the 95% confidence intervals. PM_{2.5} has been adjusted using the formula proposed by Smith et al., (2020).

At Baker Street, Regents Park and Waterloo the Bakerloo line stations are at different depths. The outbound journey showed consistently higher PM_{2.5} concentrations throughout the journey compared to the return journey, except at the return tunnel entrance/exit. On the return journey these were higher from Maida Vale station to the tunnel exit likely due to legacy dust already being present in the carriage from the return journey.

The return journey started at Elephant & Castle station where PM_{2.5} concentrations were at their lowest from the waiting time at the station. At Elephant & Castle station there is a continuation of the tunnels that were built for a possible line extension, but now these tunnels are used to house trains overnight when out of service. There are no tunnel openings for ambient air to enter the station in these tunnels. After departing Elephant & Castle station concentrations slowly built until Lambeth North station. Interestingly, PM_{2.5} accumulated in the train carriage less rapidly than when it first entered the tunnel after Queens Park station.

Immediately on departing Lambeth North there is a siding that out of service trains can take to the London Road depot. There is a 750m long single tunnel from the Bakerloo mainline track to

the depot, which is above ground. The effect of the depot tunnel exit/entrance can be seen in the journeys with outbound PM_{2.5} concentrations decreasing around Lambeth North and increasing on the return journey. It is unclear why there is a difference on the journeys as the lines run parallel at the depot entrance sidings.

Concentrations built up in the carriage, until peaking at Oxford Circus station at similar levels to the Outbound journey. This was the inverse of the outbound journey where concentrations steadily decreased from Oxford Circus station to Elephant & Castle station. From Oxford Circus station return journey concentrations decreased until Baker Street/Marylebone stations before they increased again before Warwick Avenue station. There are no station design reasons why PM_{2.5} concentrations should be diametrically opposed along the section from Oxford Circus to Paddington stations, indeed the return Southbound platforms at Baker Street and Regents Park stations are deeper than the outbound platforms.

During the return journey at Baker Street station there was a close convergence of PM_{2.5} concentrations on the Bakerloo and Jubilee lines possibly suggesting that the two lines may have been interacting. This section of the journey was the inverse of the outbound journey, which peaked around Marylebone station. Mean PM_{2.5} concentrations for the outbound and return journeys for each station are shown in Table 4.4. The highest mean PM_{2.5} concentration was at Marylebone station (493 $\mu\text{g m}^{-3}$) on the outbound journey, with the stations either side of Marylebone station, Edgware Road and Baker Street stations, having the next highest concentrations. Only Warwick Avenue station on the return journey had higher mean PM_{2.5} concentrations (360 $\mu\text{g m}^{-3}$) than the outbound subway stations, except Elephant & Castle station, demonstrating the higher PM_{2.5} concentrations on the outbound journey.

Mean (sd) PM_{2.5} concentrations, over the 35 Bakerloo line journeys, for the complete tunnelled sections of the subway journeys were 321 (110.4) $\mu\text{g m}^{-3}$ (median = 328 $\mu\text{g m}^{-3}$), making it comparable with the median PM_{2.5} concentrations recorded on the fully tunnelled Victoria line (361 $\mu\text{g m}^{-3}$) by Smith et al., (2020). For the outbound journey mean PM_{2.5} concentrations were 346 (122) $\mu\text{g m}^{-3}$ (median = 363 $\mu\text{g m}^{-3}$).

Elephant & Castle station showed the greatest variation in PM_{2.5} concentrations ranging from 416 to 33 $\mu\text{g m}^{-3}$ whilst the train was stationary due to the influence of ventilation and settling processes. On the return journey mean PM_{2.5} concentrations dropped to 293 (86) $\mu\text{g m}^{-3}$ (median

= 295 $\mu\text{g m}^{-3}$) a significant mean difference of 53 $\mu\text{g m}^{-3}$ ($p < 0.01$) between the two legs of the journey, demonstrating the difference between the outbound and return journeys.

Table 4.4: Mean $\text{PM}_{2.5}$ ($\mu\text{g m}^{-3}$) concentrations in the Bakerloo line on the outward journey (Willesden Junction station to Elephant & Castle station) and the return journey (Elephant & Castle station to Willesden Junction station). $\text{PM}_{2.5}$ has been adjusted using the formula proposed by Smith et al., (2020).

Subway/Above-ground	Station	Outward $\text{PM}_{2.5}$ ($\mu\text{g m}^{-3}$)	Return $\text{PM}_{2.5}$ ($\mu\text{g m}^{-3}$)
Above-ground	Willesden Junction	20	13
Above-ground	Kensal Green	30	12
Above-ground	Queens Park	30	26
Subway	Kilburn Park	145	200
Subway	Maida Vale	368	316
Subway	Warwick Avenue	416	360
Subway	Paddington	396	343
Subway	Edgware Road	421	291
Subway	Marylebone	493	288
Subway	Baker Street	481	264
Subway	Regents Park	401	353
Subway	Oxford Circus	359	335
Subway	Piccadilly Circus	404	286
Subway	Charing Cross	387	273
Subway	Embankment	370	244
Subway	Waterloo	356	245
Subway	Lambeth North	349	227
Subway	Elephant & Castle	293	155

Outbound and return journeys showed differences in NO_2 concentrations in the two separate tunnels throughout the journeys (Figure 4.12). On the outbound journey NO_2 decreased from the tunnel entrance to Marylebone station, while $\text{PM}_{2.5}$ concentrations were increasing. However, after Marylebone station NO_2 concentrations rapidly increased as $\text{PM}_{2.5}$ concentrations decreased. This pattern continued until the terminus at Elephant & Castle station, where NO_2 reached peak tunnel concentrations. The return journey displayed the same inverse relationship between NO_2 and $\text{PM}_{2.5}$, with decreasing NO_2 concentrations until Oxford Circus station as $\text{PM}_{2.5}$ increased. Ambient air, reflected by NO_2 concentrations along the journey (Cao et al., 2017), appeared to have an influence on $\text{PM}_{2.5}$ concentrations. Overall, there was a -0.47 correlation between $\text{PM}_{2.5}$ and NO_2 in the tunnelled sections of the journey, with a slightly higher correlation of -0.55 on the outbound journey compared to a -0.46 correlation on the return journey. There was no correlation between $\text{PM}_{2.5}$ and NO_x for the overall journey, nor for either leg of the journey.

The only sources of NO₂ and NO_x in the subway is through ventilation shafts and passenger entrances on to platforms, where air exchange is driven by train movements. It is known that PM_{2.5} concentrations are reduced by tunnel, platform and train carriage ventilation rates and these results confirm that ventilation is a major factor in reducing PM_{2.5} in the subway (Park, Woo and Park 2014, Carteni 2016, Moreno et al., 2017).

There are a number of reasons that could explain these differences between the two legs of the journey. The trains ran through two separate tunnels during the journeys. Each tunnel is likely to have its own ventilation system, track curvature, slopes and depths of tunnels, all of which are known to affect PM_{2.5} concentrations (Onat and Stakeeva 2014, Park, Woo and Park 2014, Martins et al., 2016, Moreno et al., 2017). Smith et al., (2020) measured PM_{2.5} concentrations on the Bakerloo line taking between 2 and 5 alternative journeys over a three-month period. It is unknown whether the waiting time at Elephant & Castle station was included but mean concentrations over the tunnelled sections of the journey, excluding Elephant & Castle station were 243 µg m⁻³, compared to 338 µg m⁻³ in this study. Three of the top four stations in this study featured in the most polluted stations in Smith et al., (2020), the exception being Regents Park station which had higher concentrations in this study (376 to 243 µg m⁻³). The differences are likely due to the larger number of repeated journeys, differing instrumentation and any seasonal effects.

On entrance to the tunnel, after Queens Park station, O₃ falls from 16 to 7 µg m⁻³ at Kilburn Park station and continues to fall to 4 µg m⁻³ at Warwick Avenue station. From Warwick Avenue station mean O₃ concentrations were 3 µg m⁻³ on the outbound journey and 4 µg m⁻³ on the return journey. On the return journey from Warwick Avenue to Queens Park stations, after the train left the tunnel, O₃ concentrations rose from 6 µg m⁻³ at Warwick Avenue to 39 µg m⁻³ at Queens Park stations, with the highest concentrations of 43 µg m⁻³ occurring in the tunnel just before the train exited the tunnel. Mean O₃ above-ground concentrations were higher on the return journey, which could be influencing O₃ concentrations from Warwick Avenue station in the tunnelled sections on the return journey. The increase in O₃ concentrations from Warwick Avenue could be due to a pressure wave created by the previous train as it exits the tunnel creating a large vortex drawing ambient air back into the tunnel away from the tunnel exit towards Warwick Avenue (Farammehr 2014). There is a complex interaction between the previous train, the train, tunnel and tunnel pressures which is being reflected in the O₃ measurements taken inside the train carriage.

4.3.3.1 The effect of train carriage measurement position

To understand whether PM_{2.5} concentrations were affected by carriage position, Welch's two sample t-test, was carried out in 'r. Each carriage position tested, front, middle and rear from Willesden Junction station, which were reversed on the return journey, were compared to each other using the t-test. The null hypothesis was that carriage position would not affect PM_{2.5} concentrations in a tested carriage relative to the other tested carriages. Travelling in the front carriage was compared separately to the middle and rear and the middle was compared to the rear. Mean PM_{2.5} concentrations were calculated for each carriage position and the results of each t-test are shown in Table 4.5.

There were no significant differences between carriage position PM_{2.5} concentrations attributable to the carriage in which measurements were taken. This confirmed the hypothesis that there were no differences in PM_{2.5} exposure measurements due to the carriage position in which measurements were taken.

Table 4.5: Concentration of PM_{2.5} in the three measurement positions during the return Bakerloo line journey from Willesden Junction station to Elephant & Castle station with the comparative p-value for each position. PM_{2.5} has been adjusted using the formula proposed by Smith et al., (2020).

Train Position	PM _{2.5} mean (sd) ($\mu\text{g m}^{-3}$)	Pval
Front	319 (248)	
Middle	294 (229)	
Rear	293 (236)	
Front / Middle		0.26
Front / Rear		0.26
Rear / Middle		0.98

4.3.3.2 Concentrations and tunnel depth

Tunnel depth and proximity to tunnel mouths have been found to affect PM_{2.5} concentrations in subways (Onat and Stakeeva 2014, Park et al., 2018, Figueroa-Lara 2019). Differences in the relationships between depth and PM_{2.5} have been found worldwide in subway systems. In London, Smith et al., (2020) found that in the deep-tunnelled Central line, there was a relationship between depth and PM_{2.5} concentrations with the depth of adjacent stations important to PM_{2.5} concentrations. However, Saunders et al., (2019) found no relationship between tunnel depth and PM_{2.5} concentrations attributable to distance from the tunnel entrance. Worldwide, researchers

have found strong correlations between tunnel depth and PM_{2.5} concentrations. (Ma et al., 2014, Onat and Stakeeva 2014, Figueroa-Lara 2019). In Mexico City, Figueroa-Lara (2019) found greater depth led to higher PM_{2.5} concentrations, with correlations of 96% and 98% in the cold and warm seasons, respectively. In Istanbul, Onat and Stakeeva (2014) found a correlation (R^2) of 0.88 ($p < 0.01$) between PM_{2.5} platform concentrations and station depth, with a similar relationship found by Ma et al., (2014). However, in New York, Luglio et al., (2023) found that proximity to the river-tunnel was the major factor affecting PM_{2.5} concentrations, with tunnel depth only having a small effect.

In the Bakerloo line, tunnel depths varied between 7 and 25m below ground level. with the deepest tunnels generally having the highest PM_{2.5} concentrations (Figure 4.13). Elephant & Castle station appears to be an outlier due to the waiting time at the station, although Warwick Avenue station on both sections of the journey recorded high concentrations despite being relatively shallow at 14m deep. There is a moderate Pearson correlation of 0.37 between depth and PM_{2.5}, over the complete return tunnelled journey, excluding Elephant & Castle station.

However, on the outbound journey there is a much higher correlation of 0.71 as PM_{2.5} concentrations in the carriage built up during the journey in the deepest sections of the tunnel without any tunnel mouth influence. On the return journey concentrations started at a lower level than when the train arrived at Elephant & Castle station, influencing concentrations throughout the return journey. This may have had a greater impact on concentrations during the return journey than tunnel depth alone. Due to PM_{2.5} build-up in the train carriage on the return journey, stations approaching the tunnel exit had relatively higher PM_{2.5} concentrations than their depth would suggest, with little correlation between PM_{2.5} and tunnel depth. It is apparent there is a complex relationship between tunnel depth and PM_{2.5} with the evidence from the outbound journey suggesting that deeper sections may have increased PM_{2.5} concentrations. Depth of tunnel could affect ventilation rates (Figueroa-Lara 2019) with the deeper tunnels being less ventilated.

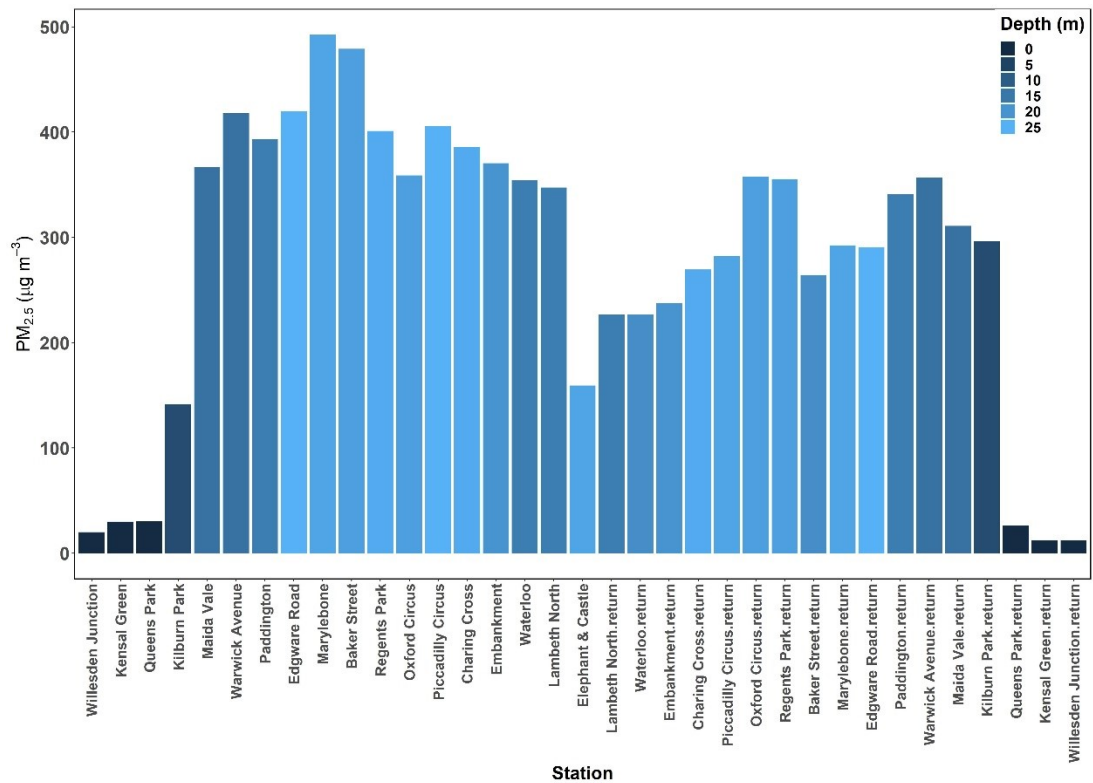


Figure 4.13: Bar chart showing PM_{2.5} concentrations compared to station depth for each station on the return Bakerloo line journey from Willesden Junction station to Elephant & Castle station. PM_{2.5} has been adjusted using the formula proposed by Smith et al., (2020).

In this study NO₂ and NO_x were measured in the train carriage simultaneously with PM_{2.5}, allowing the relationship between tunnel depth and NO₂ and NO_x concentrations to be assessed. In the naturally ventilated system of the London Underground the effect of tunnel depth on NO₂ and NO_x concentrations could show the effectiveness of ambient air being drawn into the subway system, with NO₂ and/or NO_x concentrations acting as a marker of ambient air. NO_x is often used as a marker of anthropogenic sources of vehicle emissions (Krecl et al., 2021) as it removes interactions with ozone and sunlight, whereas measurements of NO₂ are often used for health and compliance. However, there is no sunlight in the tunnelled sections of the subway and ozone measurements have shown very low concentration in the Bakerloo line in the tunnelled sections, suggesting there are no sources of ozone within the Bakerloo line. Therefore, NO₂ concentrations derived from ambient air through ventilation shafts and platform entrances were unlikely to be affected within the tunnelled environment. The effect of tunnel depth on NO₂ and NO_x concentrations in tunnels has not been investigated previously, although Cao et al., (2017) did measure mean NO₂ concentrations on a journey in train carriages but did not report the tunnel concentrations. It is evident that a relationship exists between tunnel depth and NO₂ and NO_x

concentrations with lower concentrations in the deeper sections of the tunnel, probably linked to a lack of ventilation (Figure 4.14 and Figure 4.15).

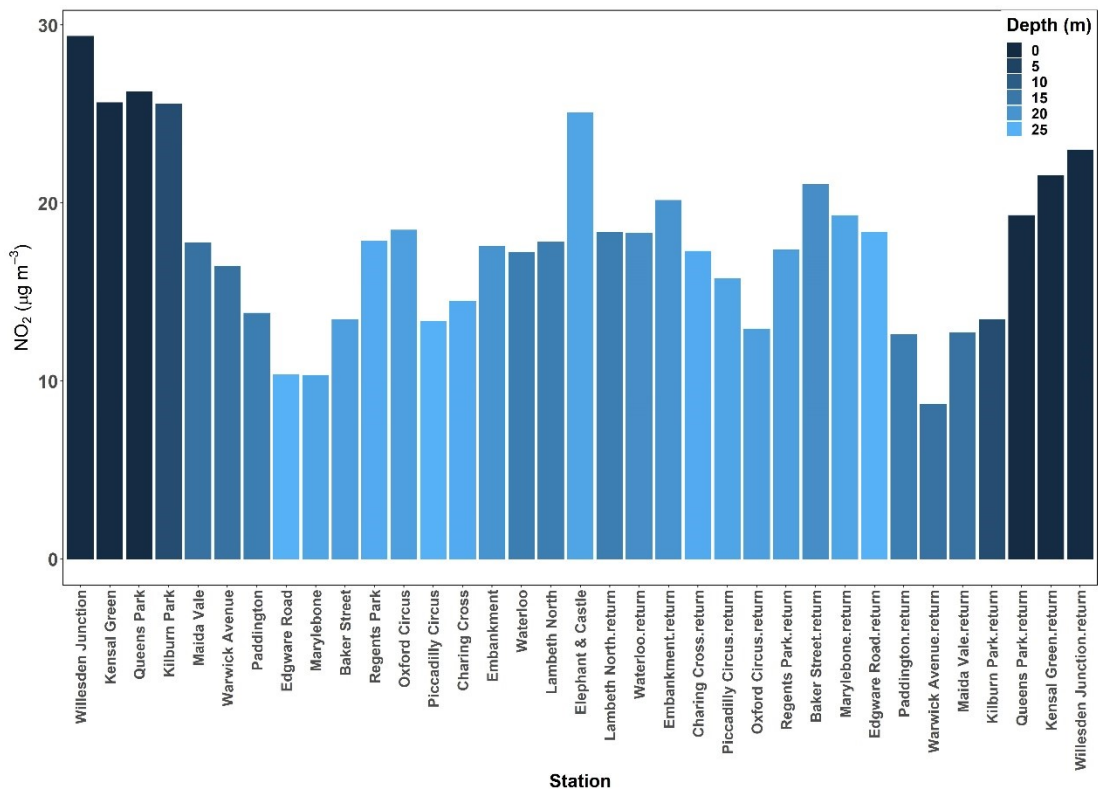


Figure 4.14: Bar chart showing NO₂ concentrations compared to station depth for each station on the return Bakerloo line journey from Willesden Junction station to Elephant & Castle station.

Over the complete journey through the tunnelled section there was little correlation between tunnel depth and NO₂ concentrations. However, on the outbound journey there was a high Pearson correlation of -0.69 with the deepest sections of the tunnel having the lowest NO₂ concentrations. Also, there was a high correlation between PM_{2.5} and NO₂ (-0.64), over this section of the journey suggesting that in this section subway air was not being influenced by the tunnel mouth or other interchanging lines, but by ventilation. There was no correlation between PM_{2.5} or NO₂ and the number of station interchanges, in fact, the only station with a direct link to an interchange was Baker Street station on the outbound journey. The return journey stations closest to the tunnel mouth had low NO₂ concentrations which could be a factor in the high PM_{2.5} levels in these relatively shallower sections of the Bakerloo line. Overall, there was a positive correlation between tunnel depth and PM_{2.5} concentrations and a negative correlation between NO₂ concentrations and tunnel depth. There was a negative correlation between PM_{2.5} and NO₂ in the tunnelled section of the journey (-0.47) demonstrating the complexity of the relationship

between tunnel depth, ambient air, NO₂ and PM_{2.5} concentrations, although there were small differences in the two directions (-0.64 for the outbound journey and -0.50 for the return journey).

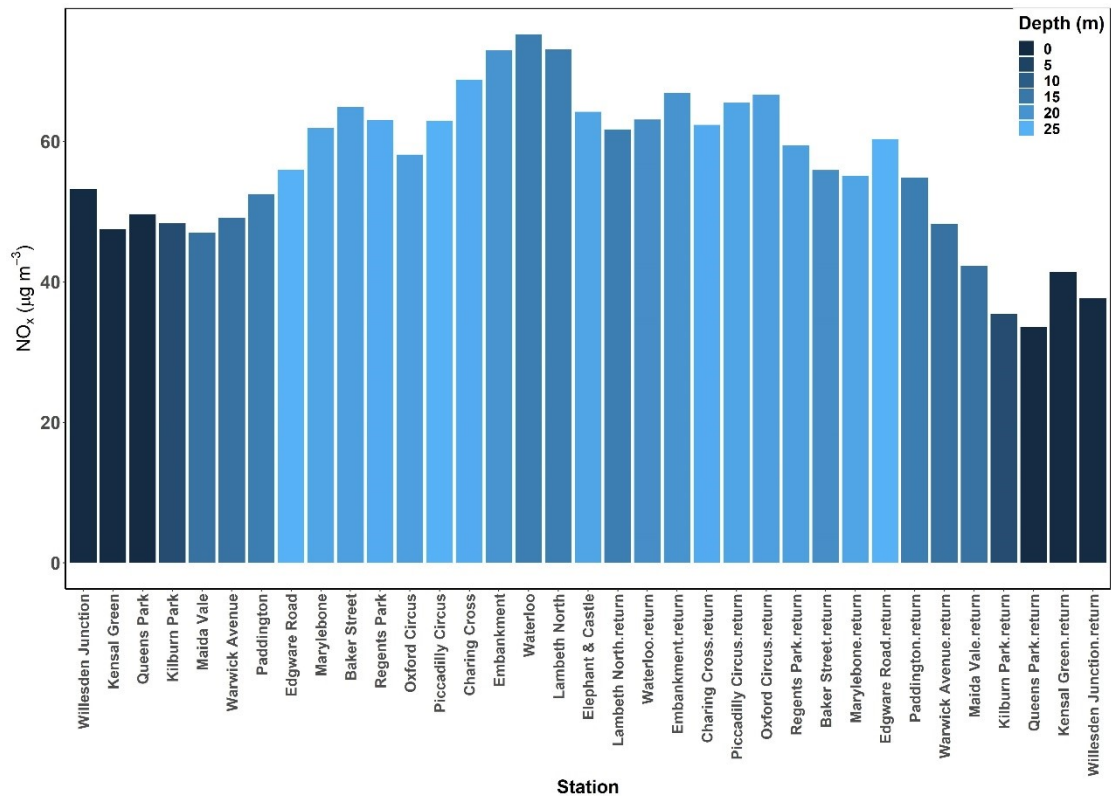


Figure 4.15: Bar chart showing NO_x concentrations compared to station depth for each station on the return Bakerloo line journey from Willesden Junction station to Elephant & Castle station.

For the complete journey in the tunnelled sections, there was a higher correlation between tunnel depth and NO_x (0.59) than for NO₂. On the outbound journey, NO_x had a moderate 0.41 correlation with tunnel depth, but there was a higher correlation of 0.85 between NO_x and tunnel depth on the return journey, which could be linked to the lower PM_{2.5} concentrations observed on the return journey. In contrast to NO₂ concentrations, NO_x concentrations continued to decrease towards the tunnel exit and did not reflect the changes in PM_{2.5} approaching the tunnel exit.

These results confirm previous research suggesting that a complex relationship exists between depth and pollutant concentrations, with tunnel depth influencing both PM_{2.5}, NO₂ and NO_x concentrations. This partially supports the findings of Cao et al., (2017) who demonstrated NO₂ concentrations decreased as measurements were taken deeper in a subway station and in train carriages as the influence of outside air diminished, although NO₂ tunnel concentrations were not reported by Cao et al., (2017).

4.3.4 Particle number counts

Particle number count (PNC) has been widely measured in subway systems worldwide although the measured particle distribution range varies greatly from 10 nm – 10 µm between studies. Differing instruments and measurement locations (concourse, platform and train carriages) were used (Cusack et al., 2015, Kim et al., 2017, Zheng et al., 2017). Understanding how PNC varies inside train carriages during train journeys can help to trace sources of ambient PM particles in tunnels and stations and train-induced particle emissions from mechanical wear and resuspension (Reche et al., 2017, Cha, Abbasi and Olofsson 2018, Cha et al., 2018). On train journeys open windows allow infiltration of particles from the tunnels into the carriage (Martins et al., 2016). The age of the carriages will also allow penetration of particles from the tunnels through gaps in the doors into the carriage (Cha et al., 2018). It has been suggested that where there is a lack of train ventilation particle concentrations can be higher inside train carriages than on platforms (Kim et al., 2008, Park and Ha 2008). As passengers spend the majority of their commuting time in train carriages it is important to understand sources and factors affecting PNC's in carriages (Figure 4.16Figure 4.16).

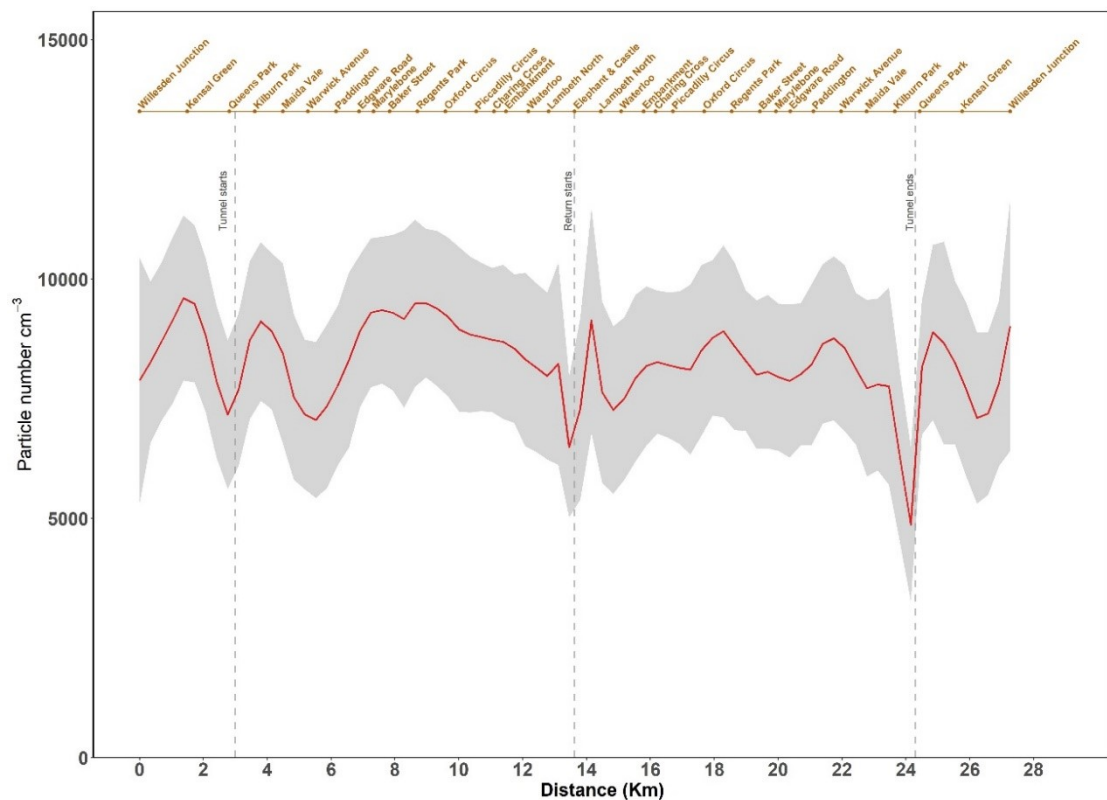


Figure 4.16: Particle number counts (PNC's) for the return Bakerloo line journey from Willesden Junction station to Elephant & Castle station. The shaded area represents the 95% confidence intervals.

Interestingly, PNC's fell on entering the tunnel and exiting the tunnel, which may have been caused by the pressure wave created by the previous train (Farammehr 2014). PNC's showed a great deal of spatial variability during the underground sections of the subway journey. Particle number counts increased rapidly upon entering the tunnel at Kilburn Park station, before falling and increasing rapidly on the approach to the section between Marylebone to Regents Park stations. They continued to steadily fall until reaching Elephant & Castle station. The train movement on leaving Elephant & Castle station resuspended particles leading to an increase at Lambeth North station. The effect on PNC of the depot siding can be seen at Lambeth North station in both directions and was most likely linked to an influx of ambient air drawn into the tunnel by the piston effect of moving trains in both directions. Particle number counts continued to vary on the return journey peaking at Regents Park and Warwick Avenue stations. The high PNC's seen at Kilburn Park station on the outbound journey were not seen on the return journey. There was no correlation between PNC's and $PM_{2.5}$ over the journey, but this would be expected as the majority of PNC's are in the ultrafine range which constitute only a small fraction of the mass (Hinds 1999).

There are high confidence intervals shown in Figure 4.16 indicating the large amount of variability over the separate journeys. There is little similarity between stations on the two legs of the journey. For the tunnelled sections of the journey mean/median PNC's were 8,036 / 8,123 particles cm^{-3} compared to the above-ground mean / median of 7,345 / 5,789 particles cm^{-3} . The above-ground section had a higher standard deviation than the tunnelled sections with a larger overall range indicating greater variability over the journeys. There was a significant difference ($P < 0.03$) in PNC's between the tunnelled and above-ground sections of the journey.

This confirmed the findings of Smith et al., (2020) that PNC's in the subway were higher than in a surface background environment. However, particle number counts in the tunnelled sections of the Bakerloo line were lower than reported by Smith et al., (2020) (mean/median 15,070 / 15,790 particles cm^{-3}) although Smith et al., (2020) measured PNC's from Waterloo to Bond Street stations on the Jubilee line. Background concentrations measured in this study were similar to the measurements taken by Smith et al., (2020) in Hyde Park. Seaton et al., (2005) also reported higher PNC's although these were measured on station platforms and drivers cabs, not carriages. Worldwide there have been limited studies investigating PNC's in train carriages without in-train ventilation. In Finland, Aarnio et al., (2005) reported a PNC of 31,000 particles cm^{-3} in subway

trains, Cheng, Liu and Lin (2009) measured 11,000 particles cm^{-3} in the Taipei subway and Zheng et al., (2017) 1,506 – 11,570 particles cm^{-3} in Hong Kong. Although PNC's in these subway systems are generally higher than was found in the Bakerloo line, these systems have far lower $\text{PM}_{2.5}$ concentrations, with $\text{PM}_{2.5}$ concentrations more aligned to ambient air concentrations making comparisons difficult.

At Elephant & Castle station where the train stopped for a mean time of 5 minutes, with a minimum stop of 2 minutes and a maximum of 16 minutes, PNC's fell from a mean of 7,427 particles cm^{-3} on arrival to 6,431 particles cm^{-3} at departure. This confirms the hypothesis that settling processes were important in the reduced $\text{PM}_{2.5}$ concentrations found in train carriages at Elephant & Castle station.

In the London Underground, using magnetism and high-resolution electron microscopy, Sheikh et al., (2022) estimated that PNC's were dominated by particles in the 5 - 500 nm size range comprising 96.6% of subway particles. During the Bakerloo line journeys 99% of particles were between 10 - 530 nm, with ultrafine particles comprising 82% of total PNC's. The dominance of nano-sized particles compared to coarser particles agrees with previous subway research (Furuya et al., 2001, Birenzvige et al., 2003).

4.3.5 Effect of ventilation on particle size, $\text{PM}_{2.5}$ and NO_2 concentrations

Urban $\text{PM}_{2.5}$ is comprised of a mixture of natural sources (including secondary organic and inorganic aerosols) and anthropogenic sources (such as vehicle emissions) (Hinds 1999, Health Effects Institute 2010), whereas subway $\text{PM}_{2.5}$ is mainly generated by mechanical and frictional process due to train movements (Minguillon et al., 2018, Font et al., 2019). Air exchange in the subway produces a complex mixture of particles from ambient air, train operation emissions, resuspension dust, and passenger-induced particles (Chen and Zhao 2011, Calvo et al., 2013). Understanding particle size distribution in the subway is complex due to these differing sources having different particle size distributions. Particles can be described in terms of modes with each mode having distinctive sources, size ranges, formation mechanisms, chemical composition and deposition pathways (Hinds 1999). Four modes are generally used; the nucleation mode, the Aitken mode, the accumulation mode and the coarse mode (Araujo and Nel 2009) (Figure 4.17).

The nucleation mode (10 – 30 nm) consists of particles directly emitted into the atmosphere primarily from combustion emissions and are representative of traffic related air pollutants. These

particles coagulate rapidly and have relatively short lifetimes (Hinds 1999, Kulmala and Kerminen 2008). The nucleation mode could be representative of ambient air drawn in through ventilation shafts and platform entrances in the subway. Only very fine brake dust, spark discharges or high temperature release of metals from wear from the wheel/rail interface would constitute nucleation mode sources in the subway (Sundh et al., 2009, Midander et al., 2012, Cha et al., 2018).

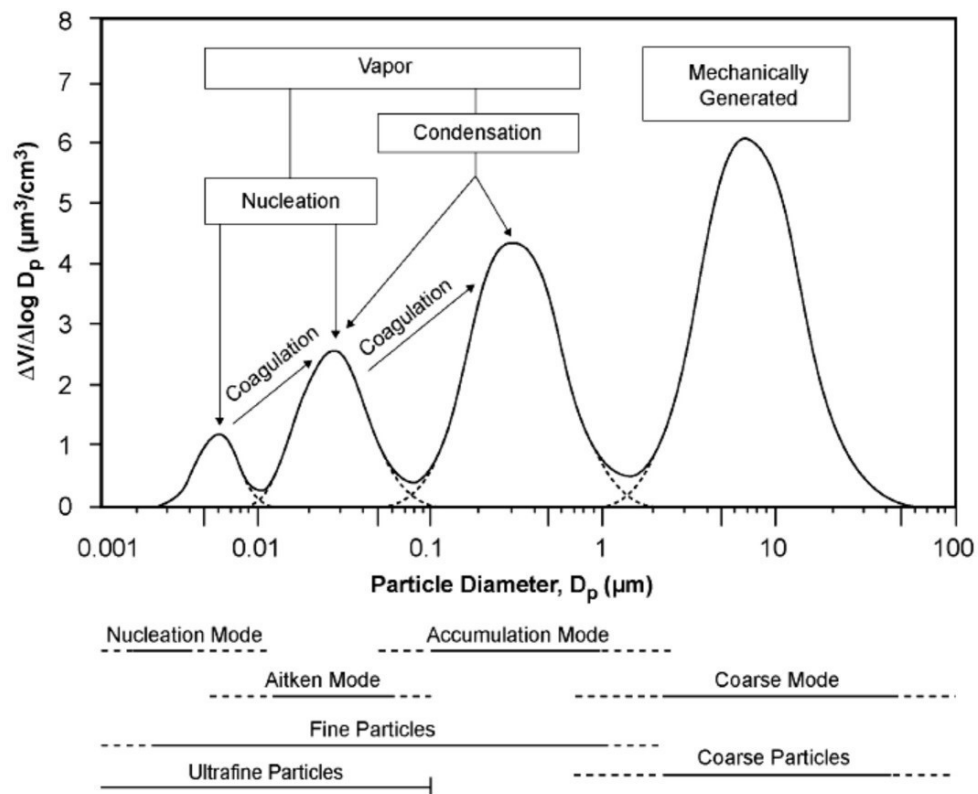


Figure 4.17: Idealised particle size distribution displaying the four modes: nucleation, Aitken, accumulation and coarse modes. Also shown are the major formation and growth mechanisms of the four modes of ambient particles. V = volume, D_p = particle diameter.

The Aitken mode (30-100 nm) results from the agglomeration and condensational growth of nucleation mode particles with short lifetimes before growing into the accumulation mode. The nucleation and Aitken modes comprise ultrafine particles (< 100 nm) that account for the preponderance of PM in the atmosphere on a number basis. However because of their small size, they only account for a small fraction of the total mass of airborne particles (Place, Ziemba and Griffin 2010). Particles in the Aitken mode could be generated in the subway from the wheel/rail interface (Midander et al., 2012).

In the accumulation mode (100nm - 1µm) particles accumulate due to the lack of removal mechanisms and consequently have longer residency times. The nucleation, Aitken and accumulation modes constitute “fine” particles and have significant overlap. The accumulation mode can account for a sizeable part of particle mass (Hinds 1999). In the subway Cha et al., (2018) found particles with a size mode of 170 nm were predominant during train operating periods, while principal component analysis showed particles generated by railway related mechanical wear had a size range of 100 – 500 nm (Cha et al., 2018). These particles would contribute to the accumulation mode.

The coarse mode (> 1µm) represents particles generated by mechanical processes and due to their large size, they settle rapidly. They have little overlap with the fine modes with different sources, chemical compositions and lifetimes (Hinds 1999). In the subway, particles in the accumulation and coarse modes are retained as legacy dust in tunnels and are continuously resuspended by the piston effect of moving trains (Jung et al., 2010, Cha et al., 2018) only settling when there are no train movements (Raut, Chazette and Fortain 2009, Cheng and Yan 2011, Kumar et al., 2023).

Analysing the four particle size modes in subway air could allow sources to be identified from particle sizes and further understanding of the factors affecting PM_{2.5} concentrations over the train journey. The four modes represent distinct size ranges associated with ambient air and subway sources. The Mini-Wras records all particle sizes from 10 nm - 35µm, allowing particle modes to be differentiated during the journeys. There are four (10 nm – 27nm), four (37 nm – 100 nm), 10 (139 nm – 867.18 nm) and 22 (1021.47 nm – 38162.42 nm) size bins in the nucleation, Aitken, accumulation and coarse modes measured by the Mini-Wras.

Repeated journeys allow daily fluctuations in particle size modes to be averaged to reduce the effects of outliers. Journey effects such as train speed, acceleration, stopping times and train braking can be reduced as repeated journeys compensate for any differences over time (Figure 4.18).

There are distinct differences between the modes with the nucleation mode displaying very different properties to the other three modes. The nucleation mode is representative of ambient air drawn into the tunnels and station platforms by the piston effect of the moving train during the journey with a small contribution from train braking (Cha et al., 2018), sparking and high

temperature release of nanoparticles from the wheel/rail interface (Zimmer and Maynard 2002, Sundh et al., 2009, Midander et al., 2012). The contribution of newly formed ambient air will be reduced as particles quickly coagulate and amalgamate into the Aitken and accumulation modes.

The Aitken, accumulation and coarse modes are more representative of subway air from legacy dust and newly formed particles from railway related mechanical wear (Smith et al., 2020). Over 35 Bakerloo line journeys the Aitken mode makes the greatest contribution to particle numbers (58%) with the nucleation mode contributing 23%. Ultrafine particles constituted 82% demonstrating how ultrafine particles dominate particle concentration in the subway on a number basis. The accumulation mode contributes 17% and the coarse mode < 1%. Comparing the Aitken, accumulation and coarse modes to $PM_{2.5}$ and NO_2 concentrations over the repeated journeys on the Bakerloo line shows how the correlation between each mode increases with particle size (Figure 4.18).

The Pearson correlation of all measurements in the tunnelled sections of the Bakerloo line between the Aitken mode and $PM_{2.5}$ concentrations was 0.37 with correlation increasing to 0.44 and 0.81 for the accumulation and coarse modes, respectively. There was no correlation between $PM_{2.5}$ and the nucleation mode. Despite Aitken mode particles constituting a small fraction of $PM_{2.5}$ mass the correlation with $PM_{2.5}$ and the spatial distribution of particle number concentration with $PM_{2.5}$ implies that the Aitken mode has a high proportion of railway emissions. The correlation between the accumulation and coarse modes with $PM_{2.5}$ indicates that the majority of subway $PM_{2.5}$ mass is derived from the mechanical wear of train related components and the wheel/rail interface in legacy dust or from newly formed material (Fridell et al., 2011, Moreno et al., 2015, Cha et al., 2018).

Mean/median particle diameter in the subway tunnelled sections was 51/57 nm with mean/median particle diameter 44/54 nm above-ground. These are smaller particle diameters than reported by Smith et al., (2020) for the subway, taken on the Jubilee line from Waterloo to Bond Street stations, and the above-ground surface background concentrations measured at Hyde Park which could be due to measurement differences in the equipment used. Bakerloo line trains do not have regenerative or rheostatic braking, unlike all other lines, which could lead to higher emissions of brake dust particles less than 100nm contributing to the smaller particle diameters found in this study.

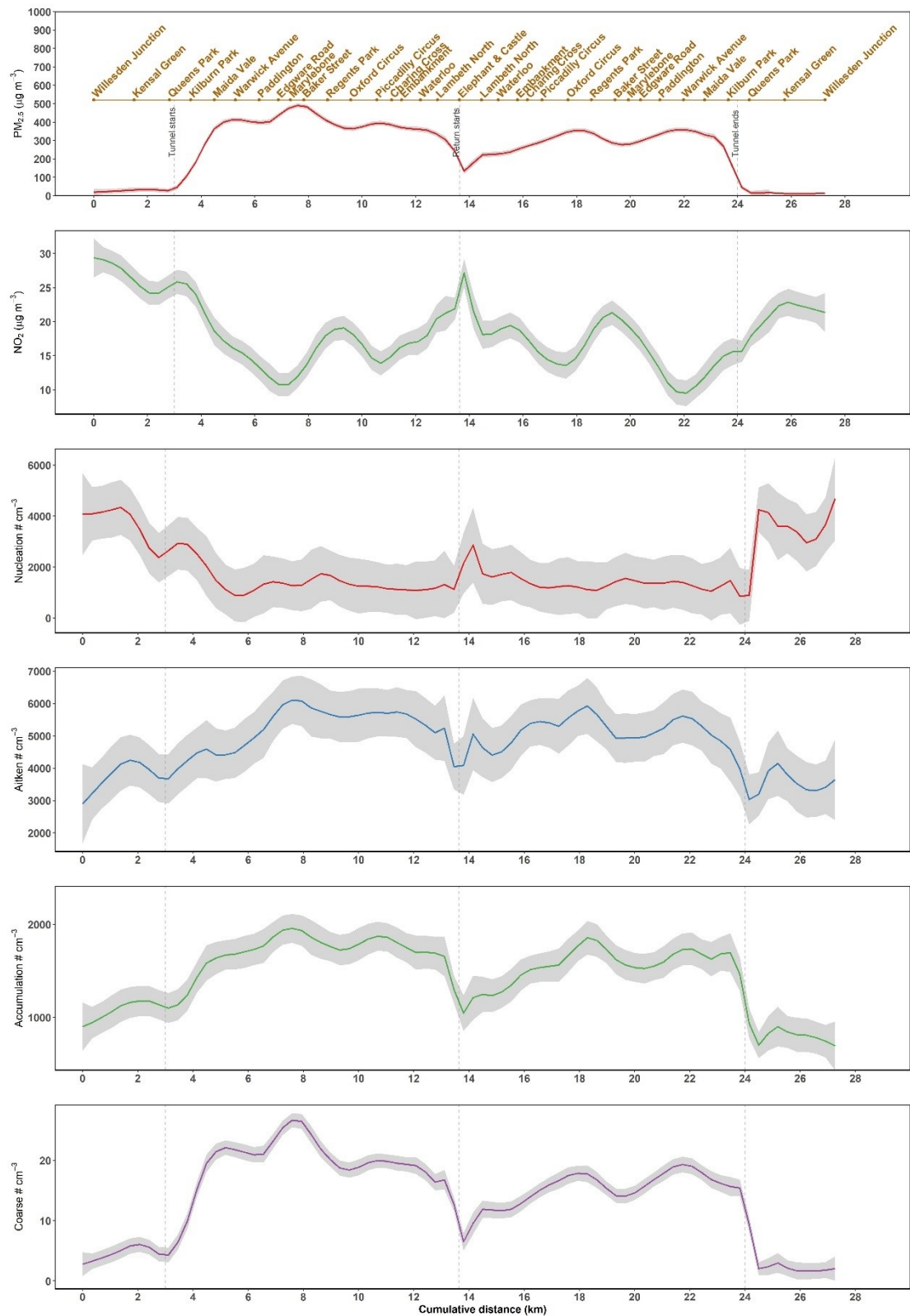


Figure 4.18: $PM_{2.5}$ and NO_2 concentrations compared to the nucleation, Aitken, accumulation and coarse mode particle concentrations for the return Bakerloo line journey from Willesden Junction station to Elephant & Castle station. The shaded area represents the 95% confidence intervals. $PM_{2.5}$ has been adjusted using the formula proposed by Smith et al., (2020).

During the wait at Elephant & Castle station particles in the nucleation mode increased by 40% confirming an influx of ambient air into the train carriage, as train-induced particles would not be

emitted nor resuspended whilst the train was stationary. The 53% fall in coarse particles and reduced PM_{2.5} concentrations confirm that subway PM mass is dominated by coarse particles (Reche et al., 2017).

Mean (sd) PM_{2.5}/ PM₁₀ ratios in the train carriage were 0.58 (0.05) in the subway and 0.56 (0.12) above-ground. The ratios show little difference between the subway environment and the above-ground sections of the Bakerloo line. The mean (sd) PM_{2.5}/ PM₁₀ ratio in the train carriage on the Overground journeys was 0.74 (0.27), significantly higher than the subway. The subway results are similar to the ratio of 0.66 found by Kumar et al., (2023) on a London Underground platform. There are no previous ratio measurements inside train carriages in London.

The nucleation mode can be a marker for ambient air drawn into the subway by moving trains and could be represented by ambient concentrations of NO₂ (Cao et al., 2017) and/or NO_x. Comparing the nucleation mode with NO₂ concentrations (Figure 4.18) suggests there are similarities, particularly at Elephant & Castle and in the tunnel between Regents Park and Oxford Circus stations. Overall, the correlation is weak (-0.07) although this could be due to the low number of size bins (4) measured by the Mini-Wras, the position of the tunnel vents on the street and wind direction, the contribution of nucleation mode particles generated from train movements, as well as coagulation and amalgamation processes reducing concentrations. Comparing the nucleation mode with NO_x concentrations throughout the journey (Figure B 1) shows little similarity with a weak correlation (0.09). Concentrations of NO₂ and NO_x are likely to be related to vehicle exhaust and the ambient concentrations of NO₂ at subway ventilation points. This will affect particle counts in the nucleation mode in the subway, providing the majority of nucleation mode particles in the subway (Mendes et al., 2018). However, Bakerloo line trains have friction and emergency braking controlled by the driver which could be contributing fine brake dust particles in the nucleation mode, providing a mixture of ambient and subway generated particles in the nucleation mode (Cha et al., 2018, Van Ryswyk et al., 2021). The low correlations suggest there could be a proportion of particles from railway related emissions in the nucleation mode.

4.3.6 Seasonality and PM_{2.5} concentrations

Although seasonal effects on PM_{2.5} concentrations in the subway have not been measured in London, they have been widely measured worldwide (Braniš 2006, Martins et al., 2015, Zhang, Xu and Su 2020, Mousavi Fard, Asilian Mahabadi and Khajehnasiri 2021). Studies investigating

seasonal effects on subway $PM_{2.5}$ concentrations have related seasonal effects to outdoor ambient $PM_{2.5}$ concentrations in cities with distinct seasonal differences. In the studies of Braniš (2006) and Zhang, Xu and Su (2020) they found that subway $PM_{2.5}$ concentrations were significantly associated with higher outdoor $PM_{2.5}$ concentrations in the winter seasons compared to the summer. Seasonal subway forced ventilation, with higher ventilation in the summer, led to lower $PM_{2.5}$ concentrations than in the winter when the ventilation was reduced (Martins et al., 2015, Mousavi Fard, Asilian Mahabadi and Khajehnasiri 2021) with particle number concentrations on platforms reduced by up to 50% (Moreno et al., 2017). No studies have been found that investigate seasonal effects on subway $PM_{2.5}$ concentrations in subways similar to the London Underground with natural ventilation. The seasonal effects on $PM_{2.5}$ concentrations on the Bakerloo line are shown in Figure 4.19. The seasonal effects on $PM_{2.5}$ concentrations on the Overground are shown in Figure B 2.

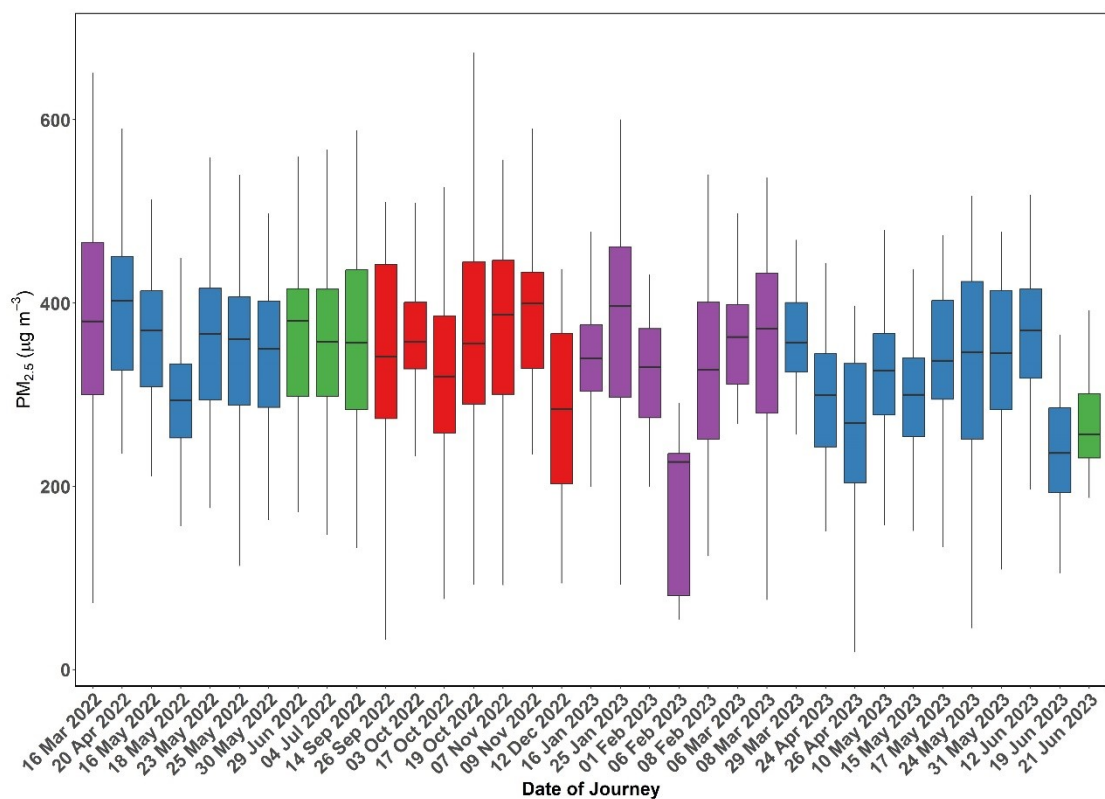


Figure 4.19: Long-term variation of $PM_{2.5}$ concentrations for each return journey from Willesden Junction station to Elephant & Castle station in the tunnelled sections of the Bakerloo line (Winter = purple, Spring = blue, Summer = green and Autumn = red). The lower and upper hinges correspond to the 25th and 75th percentiles, the horizontal line to the median and the whiskers to $1.55 \times$ the IQR (approx. 95% percentile). $PM_{2.5}$ has been adjusted using the formula proposed by Smith et al., (2020).

There were two subway journeys (06 Feb and 19 Jun 2023) with low median $PM_{2.5}$ concentrations due to long waiting times at Elephant & Castle. There were a differing number of journeys across

each season with 15, 4, 7 and 8 in Spring, Summer, Autumn and Winter. Mean $PM_{2.5}$ concentrations were significantly higher on the subway during the Autumn/Winter period ($340 \mu g m^{-3}$) compared to the Spring/Summer period ($315 \mu g m^{-3}$) ($p < 0.01$) (**Error! Reference source not found.**). On the Overground there was no significant difference ($P > 0.05$) between mean $PM_{2.5}$ concentrations during the Autumn/Winter period ($3.4 \mu g m^{-3}$) and the Spring/Summer period ($3.7 \mu g m^{-3}$) (Figure 4.20). Although the Bakerloo line has a significant difference between the seasons, the difference is small and may not be significant with more journeys. The stopping time at Elephant & Castle could be a factor in the difference in seasonality. Although this seems to confirm seasonal differences in $PM_{2.5}$ concentrations found in other worldwide subway systems, in these subway systems $PM_{2.5}$ concentrations were linked to ventilation strength or high ambient concentrations, which was not the case with the Bakerloo line.

Measurement days in this study were predominately Monday and Wednesday with no significant differences that were attributable to the day of the week travelled.

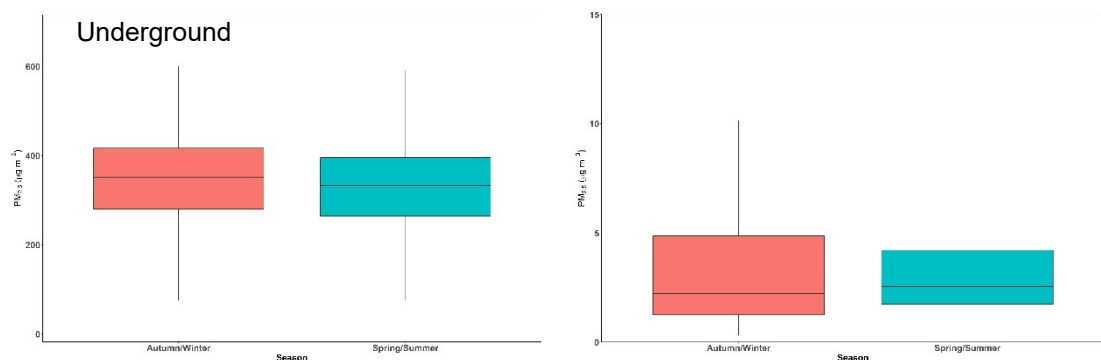


Figure 4.20: $PM_{2.5}$ concentrations in the tunnelled sections of the Bakerloo line showing seasonal variation between Autumn/Winter (red) and Spring/Summer (blue) (left). $PM_{2.5}$ concentrations in the Overground showing seasonal variation between Autumn/Winter (red) and Spring/Summer (blue) (right). The lower and upper hinges correspond to the 25th and 75th percentiles, the horizontal line to the median, and the whiskers to $1.5 \times$ the IQR (approx. 95% percentile). $PM_{2.5}$ has been adjusted using the formula proposed by Smith et al., (2020).

4.3.7 Hampstead station platform measurements

Hampstead subway platform is the deepest platform on the London Underground giving a good representation of air with a strong subway source and has been previously used to measure $PM_{2.5}$ platform concentrations (Seaton et al., 2005, Smith et al., 2020). Measurements taken at Hampstead station can be informative in helping to draw conclusions about the sources and influencing factors affecting $PM_{2.5}$ concentrations in the London Underground. Measurements taken previously at Hampstead station during instrument testing on 08 June 2021 have shown

mean NO₂ concentrations were below 5 µg m⁻³, with similar concentrations of ozone present, indicating a lack of direct ambient air onto the platform. Seaton et al., (2005) and Smith et al., (2020) have previously reported mean platform PM_{2.5} concentrations of 480 and 658 µg m⁻³ at Hampstead station platform.

PM measurements were taken with the Mini-Wras at Hampstead station platform from 14 January to 17 January 2022, including over a weekend (15 and 16 January 2022) (Figure 4.21). Over the four-day measurement period PM_{2.5} and PM₁₀ were closely correlated to the number of trains passing through the platform each hour, findings supported in London and worldwide (Johansson and Johansson 2003, Raut, Chazette and Fortain 2009, Smith et al., 2020). PM concentrations remained high during train operating hours before rapidly falling when trains stopped running. PM_{2.5} and PM₁₀ were highly correlated ($R^2 = 0.99$) throughout the measurement period. Mean PM_{2.5} concentrations during the measurement period were 529 µg m⁻³, which is less than mean PM_{2.5} concentrations recorded by Smith et al., (2020), but this could be due to Smith et al., (2020) having more weekday measurements.

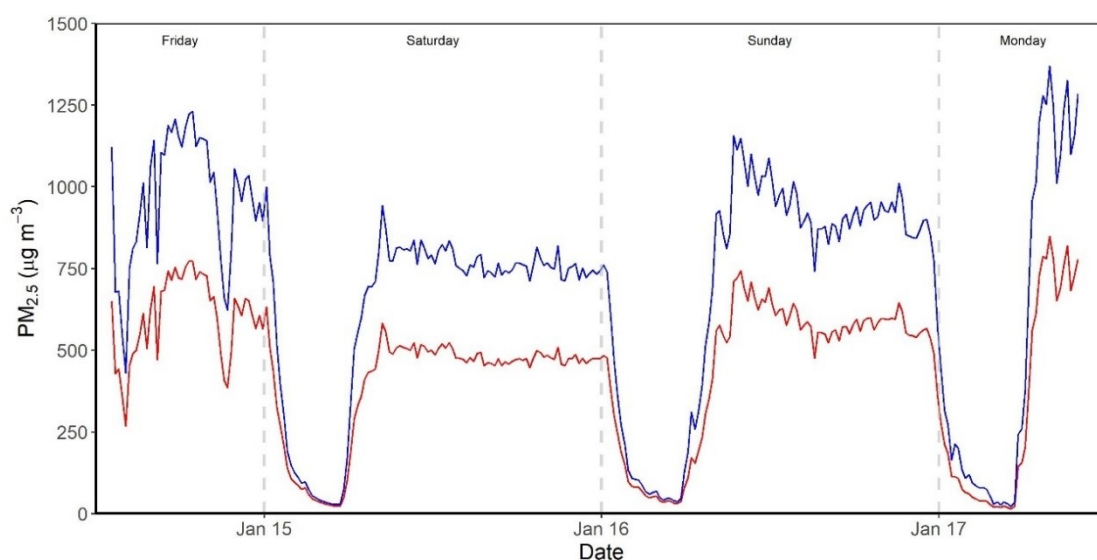


Figure 4.21: Time-series of PM_{2.5} concentrations (red line) and PM₁₀ concentrations (blue line) measured at Hampstead northbound platform. PM_{2.5} has been adjusted using the formula proposed by Smith et al., (2020).

For each of the four days, Friday to Monday, mean PM_{2.5} concentrations were 589, 457, 546 and 617 µg m⁻³, and for the two weekdays mean concentrations were 597 µg m⁻³. During the non-operating hours between 03:00 and 06:00 mean PM_{2.5} concentrations were 37 µg m⁻³, with both PM_{2.5} and PM₁₀ falling significantly. PM_{2.5} concentrations were lower on Saturday compared to

Sunday due to a reduced service due to signalling faults and engineering works. These results demonstrate how the piston effect of moving trains keeps PM material resuspended in the subway environment during train operating hours. Interestingly, the train carriages on the Bakerloo line recorded similar mean PM_{2.5} concentrations to Hampstead at Marylebone and Warwick Avenue stations.

Particle number counts on Hampstead station platform were closely correlated to train movements with a mean PNC of 26,278 particles cm⁻³ during train operating hours before falling to 10,732 particles cm⁻³ during non-operating hours. The PM_{2.5} / PM₁₀ ratio increased from 0.63 to 0.76 (max 0.87) during operating and non-operating hours. This suggests that resettling of PM, particularly PM₁₀, was occurring during the non-operating periods.

Nitrogen dioxide concentrations were low at Hampstead station, although they were still closely linked to train movements, becoming almost zero during non-operating periods. This suggests that there is little infiltration of ambient air into the station when trains are not running. The nucleation mode particles accounted for 14% of total particle counts at Hampstead station during operating hours. This is less than measured in the tunnelled section in train carriages on the Bakerloo line (24%), suggesting that the difference could be due to the lack of particles coming from ambient air, with a large proportion of the nucleation mode at Hampstead station possibly being accounted for by railway related emissions. This is supported by the increase in the Aitken mode at Hampstead station (70%) compared to the Bakerloo line (58%), which could also be caused by increased coagulation and agglomeration of particles moving from the nucleation to Aitken modes. The accumulation and coarse modes were similar at Hampstead station and the Bakerloo line showing how these modes are more related to railway related mechanical emissions. At Hampstead station particles less than 530 nm in size accounted for 99% of all particles.

During non-operating periods the percentage of nucleation mode particles increased to 17%, with decreases in the accumulation and coarse modes, confirming the settling of larger particles during non-operating hours. A contour plot displaying number concentrations for each particle size shows how particle size diameters from 27 to 139 nm dominate particle number concentrations (Figure 4.22).

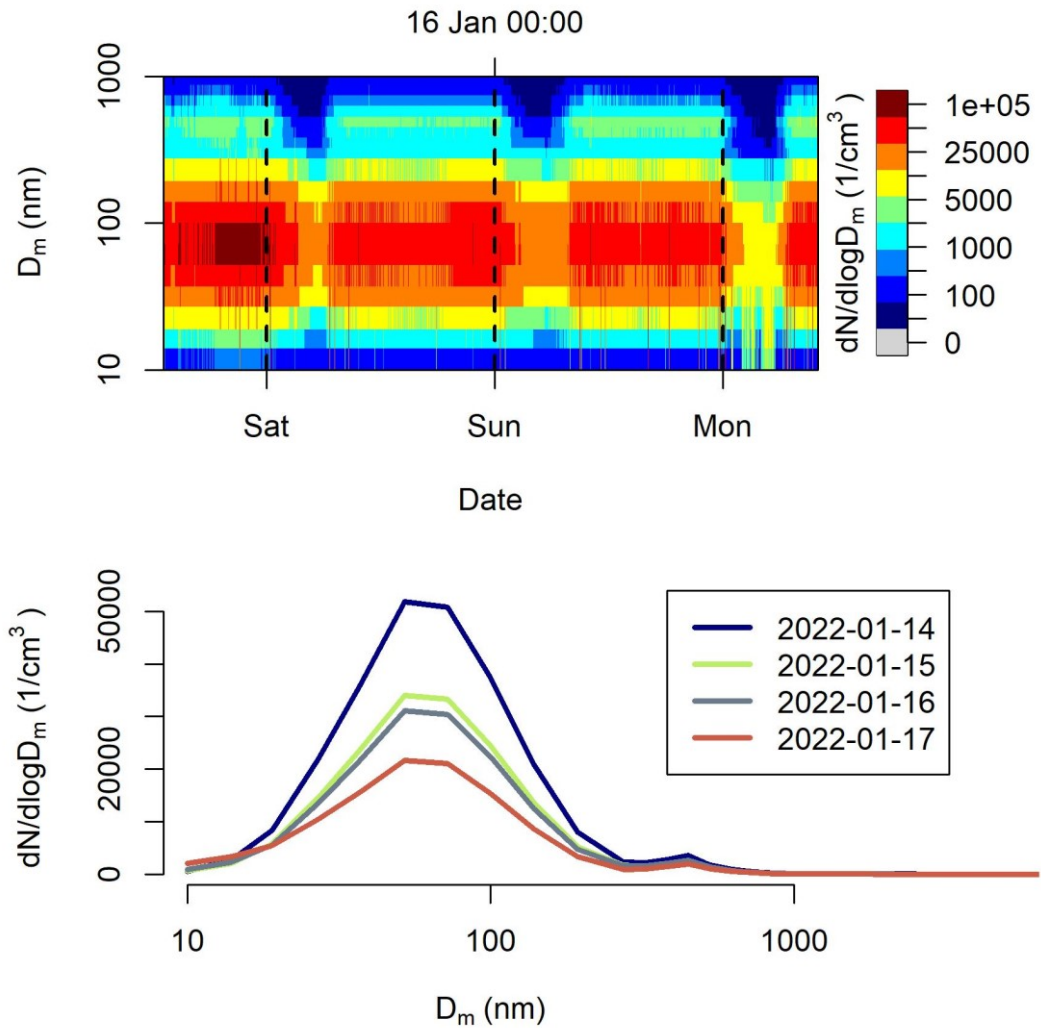


Figure 4.22: A contour plot displaying number concentrations for each particle size at Hampstead station platform over four measurement days from 14 January to 17 January 2022.

The high particle number counts recorded late on Friday evening are not accounted for in mass measurements, which showed a fall in concentrations. The modal particle diameter size range was consistent at 52 nm throughout the measurement period. The low concentrations of particles in the 10 - 19 nm size range, supports the observation that fresh ambient air is not being drawn into Hampstead station platform. The contour plot confirms how Aitken mode particles decrease during non-operating periods, with the greatest fall in the early hours of Monday morning, possibly due to the earlier finishing time of the last train on Sunday. The settling of the coarser material can also be seen in the contour plot during non-operating periods.

4.3.8 Size distributions in different locations

A Dekati Electrical Low Pressure Impactor (ELPI+, Dekati, FI) was used to separately measure subway air at Hampstead station platform and ambient air at the Marylebone Road and Honor Oak sites. This was also used to compare particle size concentrations, particle mass concentrations and PNC's at each location (Figure 4.23).

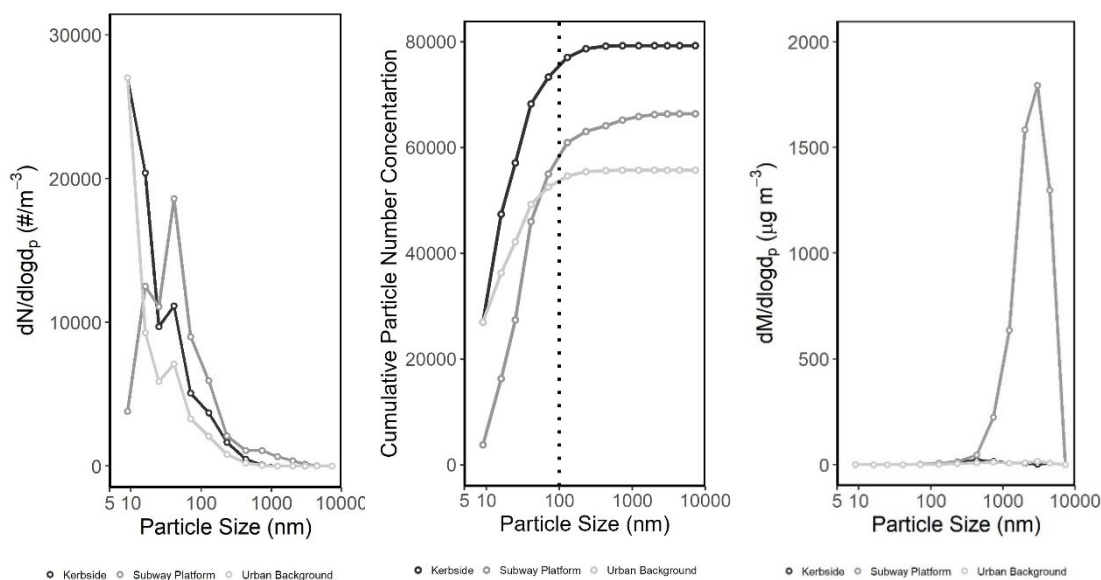


Figure 4.23: A comparison of particle size concentrations, cumulative particle number concentrations and particle mass concentrations at Hampstead station platform, Marylebone Road kerbside site and Honor Oak Park urban background site.

The results show that kerbside and urban background particles have a smaller modal particle diameter than subway particles, with a greater number of particles in the above-ground ambient air being in the nucleation mode compared to subway particles. For PNC's the Dekati measurements confirm the subway findings that PNC's are greater in the Bakerloo line subway than in an above-ground urban background environment. Ultrafine PNC's are higher in the subway than the urban background, although significantly lower for total particle number counts in the ultrafine range compared to the kerbside site. However, particle size mass in the subway is dominated by the 735 nm – 7 μm size range, demonstrating how the coarser fraction constitutes the majority of PM mass in the subway. These results support the Bakerloo line findings that subway PM of railway related mechanical and brake wear induced particles resuspended by the movement of trains constitute the majority of PM mass in the subway. Together with the

Hampstead platform Mini-Wras measurements this supports previous evidence (Jung et al., 2010) that subway generated particles are in a steady state with little daily change.

4.4 Conclusion

An exposure assessment of all fractions of PM, NO₂ and O₃ on the London Underground was derived from MRC study participant measurements in train carriages on the Bakerloo and Jubilee lines. In this chapter a methodology was developed to align the spatial and temporal variation on each individual journey by chunking the journeys into discrete distances for each unique time point on the journey. This allowed a statistical analysis to be conducted on the subway measurements. In total, 35 Bakerloo line journeys were assessed with this dataset being one of the most comprehensive to date. The chunking method proved robust at allowing detailed identification of possible sources and processes influencing concentrations.

Mean PM_{2.5} concentrations were 321 µg m⁻³ in the tunnelled sections of the Bakerloo line journeys making these measurements amongst the highest recorded worldwide. The low confidence intervals over the 35 Bakerloo line journeys suggests there was little spatial variation across the journeys. This could potentially be useful when evaluating other lines on the London Underground as it may be possible to obtain an assessment of PM_{2.5} concentrations with fewer journeys, although this would be dependent on contributing factors and sources remaining stable during the measurement period. It was found there was a significant difference in PM_{2.5} and NO₂ concentrations dependant on the direction of travel in the outbound and return journeys on the Bakerloo line. Amongst the factors influencing concentrations it is evident that a complex relationship exists between tunnel depth, PM_{2.5} and NO₂ concentrations. A high correlation between tunnel depth, PM_{2.5} and NO₂ concentrations was found with the deepest tunnels having the highest PM_{2.5} concentrations and the lowest NO₂ concentrations. This is the first time that the relationship between PM_{2.5} and NO₂ has been investigated in the tunnels of any subway system.

Different PM size distributions and particle number counts have been investigated in the subway but not the differing PM modes. The nucleation mode can be a marker for ambient air drawn into the subway through ventilation shafts and station entrances by passing trains and can be represented by NO₂ concentrations. However, the data from the Bakerloo line journeys and Hamstead station indicates that a proportion of the nucleation mode is likely to consist of railway related emissions from the release of very fine brake dust, spark discharges and high temperature

release of metals from the wheel/rail interface. Railway related emissions were also found in the Aitken and accumulation modes confirming previous research that railway related emissions occur principally at a size mode of 170 nm and railway related mechanical wear between a size range of 100 - 500 nm with 82% of ultrafine particles and 99% of particles below 530 nm in the subway. It was clearly shown at Hampstead and Elephant & Castle stations that PM settling processes were important in the subway and train movements maintained high $PM_{2.5}$ concentrations by continually resuspending particles. This chapter has given a unique understanding of the factors and contributing sources that are responsible for the high $PM_{2.5}$ concentrations that have been found on the Bakerloo line.

Chapter 5 Laboratory analysis of metals and oxidative potential

5.1 Background

The MRC study required PM_{2.5} captured from the Bakerloo line on the London Underground and on the London Overground journeys to be examined for its oxidative potential (OP) to determine how the oxidative capacity of the captured PM_{2.5} relates to inflammatory responses and the degree of oxidative injury in the circulation and in the lungs in both healthy and COPD participants. Although there have not been any previous OP studies on the London Underground, studies have assessed the OP of subway PM_{2.5} in other worldwide subway systems (Steenhof et al., 2011, Janssen et al., 2014). These studies suggest that airway oxidative stress can occur following exposures to PM_{2.5} derived from subway systems, with resultant systemic inflammation. As a large component of PM_{2.5} derived from subways consists of transition metals including iron oxides, it stands to reason that these species could be responsible for the biological findings. It would be of value to understand the OP of London Underground PM_{2.5} and how this could impact on health.

In the absence of any evidence on the relative OP per unit mass exposure of London Underground PM_{2.5}, I undertook the necessary laboratory analysis of PM_{2.5} that I had collected onto filters during the study train journeys. This allowed me to quantify the OP of PM_{2.5} collected on the London Underground and London Overground. In addition, I used the aqua regia method for filter digestion of the collected PM_{2.5} from each filter to send for ICP-MS analysis to quantify the elemental composition of the PM_{2.5} that I had collected onto filters during the study train journeys.

5.2 Introduction

The previous chapters have set out a methodology for collecting high-quality personal exposure data for use in the MRC study on London Underground and London Overground trains, where a large contrast in mean PM_{2.5} concentrations was demonstrated. There is a complex interaction of factors affecting air quality in the subway, including direction of travel, ventilation, legacy PM material and freshly emitted PM emissions from train related activity, seasonal effects, confined tunnel spaces and tunnel depth. These contribute to mean PM_{2.5} concentrations of 321 $\mu\text{g m}^{-3}$ found in the tunnelled sections of the Bakerloo line (198 $\mu\text{g m}^{-3}$ for the complete journey) which are amongst the highest recorded worldwide. This compares to mean PM_{2.5} concentrations of 4

$\mu\text{g m}^{-3}$ measured on the London Overground. Although subway PM has higher $\text{PM}_{2.5}$ concentrations than ambient PM, subway PM has substantially different physicochemical properties (Sitzmann 1999, Aarnio et al., 2005, Querol et al., 2012) making the consequences for health from exposure to subway PM still uncertain due to a lack of evidence (Loxham and Nieuwenhuijsen 2019).

Although epidemiological studies have linked inhalation of ambient PM with adverse health effects and mortality (Brunekreef and Holgate 2002), the health effects have been associated with PM mass concentration alone. Whilst mass concentrations are used for PM health guidelines (World Health Organisation 2021) the toxicity of PM is dependent on its sources, constituents and biological activity or a combination of properties including its chemical composition (Borm et al., 2007, Ayres et al., 2008). Due to the complex composition of ambient PM and potential synergies between components, a component-based approach is difficult to achieve, which has led to approaches based on deriving biological activity per unit mass being used (Borm et al., 2007). The observed biological activity can give insights into the mechanisms of PM-induced toxicity. A growing body of evidence has widely suggested that oxidative stress is an important underlying mechanism in triggering adverse health effects due to the capacity of inhaled particles to induce oxidative stress at the air–lung interface (Borm et al., 2007, Janssen et al., 2014).

The capacity of ambient PM to elicit injury represents a function both of their inherent pro-oxidant and pro-inflammatory properties, but also the robustness of an individual's antioxidant defences. Oxidative stress is an important mechanism leading to inflammation which plays a key role in airways disease and coronary heart disease, both of which have been linked to PM exposure (Donaldson et al., 2003). PM-mediated oxidative stress occurs when the generation of reactive oxygen species (ROS), or free radicals, exceeds the available antioxidant defences (Kelly 2003). This may occur through inhalation of exogenous oxidants on particles or the endogenous generation of reactive oxygen species (ROS) in the lungs by particle components (Sarnat, Chang and Weber 2016).

It is well-established that transition metals have a high oxidative potential and contribute to the generation of ROS through redox reactions resulting in oxidative stress (Verma et al., 2010), potentially inducing systemic inflammation in biological tissues (Jiménez et al., 2000).

Since subway PM is dominated by redox-active transition metals such as Mn, Cr, Fe and Cu, exposure to subway PM could potentially stimulate oxidative stress and ROS generation inducing pro-inflammatory effects (Steenhof et al., 2011). However, the evidence is contradictory when it comes to elucidating the toxicological effects of subway PM. Whilst studies such as Karlsson, Nilsson and Moller (2005) found that subway PM was eight times more genotoxic and was four times more likely to cause oxidative stress in lung cells than urban street PM, others such as Spagnolo et al., (2015) found no evidence of increased levels of cytotoxicity or oxidative stress. However, in-vitro studies by Seaton et al., (2005) found that transition metals from the London Underground were responsible for the generation of free-radicals causing pro-inflammatory effects.

It has been suggested that oxidative potential (OP), defined as the capacity to produce reactive oxygen species with simultaneous antioxidant depletion, is a possible determinant of the health impact of PM (Cesari et al., 2019, in 't Veld et al., 2023) that may help to identify some of the possible drivers of the associated health effects (Daellenbach et al., 2020). As an additional metric for PM toxicity, OP may be associated with biological responses to PM exposures, making it more informative than particulate mass alone (Yadav and Phuleria 2020). The focus on the quantification of OP has arisen from the hypothesis that the capacity of particles to elicit oxidative stress at the air–lung interface, as well as systemically, is linked to the pathophysiological responses observed in populations exposed to elevated concentrations of ambient PM (Kelly et al., 2011).

There have been limited studies investigating the OP of subway PM. As part of the RAPTES project in the Netherlands, Steenhof et al., (2011) found that the subway site had very high OP, possibly due to the high metal content. In a further RAPTES project study, Janssen et al., (2014) found the highest OP was at a subway station. A study of six stations in the Barcelona subway system showed low OP but considerable variation between stations, with the metallic trace metals Cu and Sb likely to be affecting OP more than the iron component alone. There have been limited studies investigating the OP of subway PM.

This chapter quantifies the oxidative potential (OP) of PM_{2.5} collected on the London Underground and London Overground. It will also address the components driving any observed activity by quantifying the concentrations of metals, as key drivers of OP, in subway PM_{2.5} collected at the

same time. Although OP has been recognised as a metric for oxidative stress and ROS generation there has been no consensus for the best measurement of OP and which assay is the most appropriate (Ayres et al., 2008, Janssen et al., 2014, Moreno et al., 2017). Studies have made use of various assays, including the ability of PM to induce hydroxyl radicals ($\bullet\text{OH}$) (Shi et al., 2006), deplete antioxidants (Mudway et al., 2004) and electron transfer measured by the consumption of dithiothreitol (DTT) (Biswas et al., 2009).

This study used the method developed of particle-induced depletion of antioxidants adding synthetic ascorbate acid (AA) (vitamin C) (Imperial College SOP37d, Kelly 2015) and reduced glutathione (GSH) (Imperial College SOP4, Kelly 2015) to the filter samples, in place of a synthetic respiratory tract lining fluid (RTLFL), to measure the oxidative potential of particles as a metric of the damaging health effects of PM (Zielinski et al., 1999, Mudway et al., 2004, Borm et al., 2007). The respiratory tract lining fluid contains high concentrations of the antioxidants, ascorbate acid (Skoza, Snyder and Kikkawa 1983), reduced glutathione and uric acid (UA) (van der Vliet et al., 1999), and represents the first physical interface encountered by inhaled particles (Ayres et al., 2008). Two of these antioxidants, AA and GSH, were used to quantify the particle-induced antioxidant depletion by subway and overground $\text{PM}_{2.5}$. Previous studies in the subway using UA have not observed any oxidation of UA using this method, so it was not used in this study (Moreno et al., 2017).

A parallel metal analysis using inductively coupled plasma mass spectroscopy (ICP-MS) determined the chemical composition of subway and overground $\text{PM}_{2.5}$ to help understand which metals were most active in antioxidant depletion. This could help to clarify which PM chemical components are possible toxicological drivers of any associated health effects found from exposure to subway $\text{PM}_{2.5}$.

5.3 Methodology

5.3.1 $\text{PM}_{2.5}$ filter collection

The MRC study required a chemical and OP analysis of $\text{PM}_{2.5}$ collected on subway and overground train journeys. Using MoRS I collected two identical $\text{PM}_{2.5}$ filter samples, one for chemical analysis and one for OP analysis. I placed the sampled filters in the Imperial College weigh room where the filters were pre-equilibrated before weighing for at least 48 h in a conditioned room (20 °C and 50% relative humidity) in accordance with the European reference

standard (EN12341) (Green and Fuller 2006, European Commission 2012). As discussed in Chapter 3, the small mass collected during the overground journeys (0-35 μg) is below the limit of detection. To ensure consistency of approach between the overground and underground measurement approach, the technique adopted by (Smith et al., 2020) was used here, whereby contemporaneous concentrations of ambient and subway air were collected and different density corrections were applied to the ambient and subway fractions.

I fitted a fresh filter for OP analysis and a separate fresh filter for chemical analysis into their respective filter holders before each train journey. Field blanks and lab blanks were used to provide background concentrations. In total 108 separate filter samples for OP and chemical analysis were taken over the train journeys, comprising 56 overground journeys and 52 subway journeys. The mass on the subway filters ranged from 98 – 318 $\mu\text{g m}^{-3}$ and on the overground from <1 – 27 $\mu\text{g m}^{-3}$ (Table C 1).

5.3.2 Filter preparation for toxicological analysis

Following particle sampling using filters during the train journeys, I prepared the first 24 filters for OP analysis for extraction of $\text{PM}_{2.5}$ from the 25mm PTFE coated glass fibre filters (Imperial College SOP 37, Kelly 2015). The filters were placed in 50ml Falcon tubes and covered with 5ml of HPLC-grade methanol. The Falcon tubes were placed in an ultrasonic bath and filled to three-quarters full with DI water. The Falcon tubes were sonicated with no heat applied for 10 minutes. Following sonication, the filters were placed in 5ml of fresh HPLC-grade methanol and sonicated for 10 minutes with no heat. Following the second sonication, the filters were removed from the Falcon tubes and the Falcon tubes were dried by placing them in a nitrogen evaporator with the probes placed just above the methanol surface. When the methanol had fully evaporated from the Falcon tubes, the tubes were capped for extraction of the PM material deposited in the tubes. Following the removal of the filters from the Falcon tubes, the filters were dried for 24 hours in a fume cupboard before being conditioned for 48 hours in a weigh room prior to weighing to determine the extracted $\text{PM}_{2.5}$ mass (Green and Fuller 2006). When the filters were weighed it was found the filters had lost filter material during the extraction process and weighed less than the original blank filter. The $\text{PM}_{2.5}$ mass extracted from the filter was unknown causing a new method for filter preparation for OP analysis to be developed.

I prepared the remaining 82 filters for OP analysis using an alternative method. The alternative method involved cutting each filter into four quarters using a ceramic knife. All equipment used during this process was metal-free to avoid contaminating the filters. Each filter was placed onto a template and held in place with plastic tweezers, previously cleaned in methanol, before cutting the filter. Using a section of filter containing the collected PM_{2.5} was the methodology used by Moreno et al., (2017), when punches of a filter were used. It was not possible to use punches of filters in this study as the PM_{2.5} formed concentric circles on the filters when it was collected which would have resulted in unequal masses on each filter punch. Using a quarter of the filter gave equal masses on each quarter filter. One quarter was used for AA analysis and one quarter was used for GSH analysis. After cutting, each quarter filter was placed in a 1.5ml attached screw cap microcentrifuge tube and placed in a -20°C freezer before use.

5.3.3 Filter processing for ascorbic acid

It was not possible to use the synthetic respiratory tract lining fluid (RTLFL) method (Zielinski et al., 1999, Mudway et al., 2004, Borm et al., 2007) for the AA and GSH assays as these assay employs the use of a high performance liquid chromatography (HPLC) instrument. During the period of the OP analysis the HPLC in the Imperial laboratory was unavailable, so the method of particle-induced depletion of antioxidants adding synthetic ascorbate acid (AA) and reduced glutathione (GSH) was used. For ascorbic acid analysis of the filters a 200 µM ascorbic acid (AA) stock solution was prepared from 2.5 ml aliquots of 2 mM AA in 22.5ml of HPLC-grade water treated previously with Chelex-100 resin (Sigma, UK). HPLC-grade water treated with Chelex was used for preparation of all stocks and dilutions to ensure any metal traces were kept to a minimum. In batches of 24 filters, 900 µl aliquots of 200 µM AA was added to each quarter filter and a prepared quarter filter blank. To control for background oxidation and cross-contamination on filter blanks, 100 µl aliquots of in-house controls consisting of a particle free, negative M120 control (Cabot Corporation, USA), a positive NIST 1648a control (urban particulate from NIST, USA) and 100 µM copper chloride (CuCl) solution were separately added to 1.5 ml Eppendorf tubes containing 900 µl of 200 µM AA. These controls deliver a known oxidation for control purposes. The positive NIST control is used to obtain an incubation period that results in a 50% depletion of the antioxidant (two hours for AA and four hours for GSH) and the controls are used to normalise batch-to-batch variation. For particle-free controls, C0, which acted as a particle-free blank control and C2, which acted as a procedural blank, 900 µl of 200 µM AA was added to two separate 1.5

ml Eppendorf tubes. All samples and controls were vortexed before being incubated for 2 hours at 37°C with constant shaking (Vortex Genie-2, shaking mode no 3). The C0 sample was not incubated and was placed in a fridge.

After two hours all samples and controls were removed from the incubator and placed in a centrifuge at 13,000rpm for one hour at 4°C. The centrifuge was set to 4°C to minimise any oxidation at this point. The C2 sample was placed directly into the fridge without centrifuging. Whilst the samples and controls were being centrifuged, a set of six calibration standards were prepared (Table C 2). Following centrifuging, 150 µl aliquots of each standard, controls, including C0 and C2, and sample supernatants were pipetted in duplicate into a 96 well-plate following a template (Table C 3). To determine AA depletion the 96 well-plate was placed in a spectrophotometric plate reader (Spectramax190, Molecular Devices, UK) at 37°C measuring the absorption at a wavelength of 265nm with SoftMax Pro v4.8 software. Two readings were taken of the well-plate and the mean of the two results was taken. A calibration curve derived from the standards was used to correct the results for the 200 µM AA stock used in the assays. AA depletion was ascertained over four batches in filter date order.

5.3.4 Filter processing for glutathione

For the determination of reduced glutathione (GSH), 450 µl aliquots of Chelex treated HPLC-grade water was added to each quarter filter in prepared 1.5 ml Eppendorf tubes. A quarter filter blank was placed into a 1.5ml Eppendorf tube and a 450 µl aliquot of Chelex treated HPLC-grade water was added. For the particle-free controls, C0 and C4, separate 450 µl aliquots of Chelex treated HPLC-grade water was added to 1.5 ml Eppendorf tubes and 450 µl aliquots of NIST and M120 controls were added to 1.5 ml Eppendorf tubes. All samples and controls were placed in an incubator for 10 minutes at 37°C with no shaking. Following incubation, 50 µl aliquots of 2 mM GSH was added to all samples, blanks and controls. All samples, blanks and controls were vortexed before being placed in an incubator for 4 hours at 37°C with constant shaking at mode 3, except the C0 sample which was placed in a fridge.

After one hour the C0 control was removed from the fridge and a 16.7 µL aliquot was added to 983.3 µL of cold 100 mM Sodium phosphate buffer pH7.5 containing 1 mM EDTA (PO₄ buffer) and placed into a -20°C freezer. 1 mM DTNB (5,5'-dithio-bis-(2-nitrobenzoic acid)) (9.905 mg DTNB/10 ml PO₄ buffer) was prepared and stored at 4°C. After four hours incubation, the C4

control was placed into a fridge, and the remaining samples and controls were centrifuged at 13,000 rpm for one hour at 4°C. The centrifuge was set to 4°C to minimise any oxidation at this point. Following centrifuging, 16.7 µl aliquots of all samples, blanks and controls, including C4, were added to 983.3 µl of cold PO₄ buffer in 1.5 ml Eppendorf tubes. All tubes were immediately frozen at -20°C until day of analysis to minimise any additional oxidation occurring.

When required, the samples and controls were thawed for the determination of total (GSX) and oxidised (GSSG) glutathione concentrations. Reduced glutathione (GSH) concentration was obtained by subtraction of 2x the GSSG value from the GSX value. 1 mM NADPH (Nicotinamide adenine dinucleotide phosphate) (8.8 mg NADPH/10 ml PO₄ buffer) was freshly made for each assay. A set of standards were prepared with 3.3 mM GSSG and PO₄ buffer (Table C 4). 260 µl aliquots of each standard, sample, blank and control were added to two sets of individual 1.5 ml Eppendorf tubes. For measurement of GSSG, 10 µl of 2-vinyl-pyridine (2-VP) was added to one set of tubes. These were vortexed for 5 seconds and incubated at room temperature for one hour.

While the GSSG aliquots containing 2-VP were incubating, total glutathione (GSX) was determined. To a 96 well-plate 50 µl aliquots of the standards, samples, blanks and controls were pipetted following a template (Table C 5). The well-plate was placed in a spectrophotometric plate reader at 30°C while a substrate consisting of 5.85 ml PO₄ buffer, 2.8 ml 1 mM DTNB and 3.75 ml 1 mM NADPH was prepared. The substrate was mixed throughout before adding 18.7 units of glutathione reductase (G3664) enzyme and mixed. The 96 well-plate was removed from the plate reader and an eight-channel pipette was used to aliquot 100 µl of substrate into each standard, sample, blank and control in the 96 well-plate. To determine GSX, the 96 well-plate was placed into the plate reader and read at wavelength 412nm. A calibration curve derived from the standards was used to correct the results for GSX for the assays.

To determine oxidised glutathione (GSSG), aliquots containing 2-VP were pipetted into a 96-well plate and the same procedure was followed for the GSSG standards, controls, blanks and samples as previously outlined for the GSX determination. A calibration curve derived from the standards was used to correct the results for GSSG for the assays. The reduced glutathione (GSH) was then obtained by subtraction of the 2 * GSSG value from the GSX value. GSH for all filters was determined over eight batches in filter date order.

5.3.5 Filter preparation for acid digestion for ICP-MS elemental analysis

The chemical analysis of metals from PM_{2.5} mass collected onto 25 mm Whatman PTFE membrane filters during the train journeys required acid digestion before analysis by ICP-MS. An aqua regia method was used for filter digestion, based on Harrison, Jones and Lawrence (2003). This used a standard protocol comprising a 1:3 dilution of ICP-MS-grade Ultrapur 60% nitric acid : ICP-MS-grade Ultrapur 30% hydrochloric acid for the aqua regia preparation (Uddin et al., 2016). All aqua regia was made fresh on the day of use.

Prior to filter digestion 120 50 ml ICP-MS grade certified metal-free Elkay centrifuge tubes (Elkay, UK) and 135 15ml ICP-MS grade certified metal-free Elkay centrifuge tubes were acid washed with a 5% nitric acid solution (8ml Ultrapur 60% acid diluted to 100ml with HPLC water), rinsed with HPLC-grade water and dried in a fume hood for 12 hours. Due to a shortage of 50 ml metal-free Elkay centrifuge tubes, 16 50 ml non-certified metal free Elkay centrifuge tubes were acid washed using the same protocol. To reduce contamination the non-metal certified tubes were solely used with filters that had sampled subway air due to the higher PM_{2.5} mass collected onto the filters.

Filters were randomly batched and individually transferred into 50 ml tubes using plastic tweezers that were washed in 5% nitric acid solution between each filter. Each tube was individually labelled with a Tuf-tag written in biro, placed on the top of the tube. 3 ml of aqua regia (0.75 ml 60% nitric acid : 2.25 ml hydrochloric acid) was added to each tube containing the filters and the tubes were capped tightly and carefully vortexed. Filters were placed face-down in tubes, with the exposed side facing the aqua regia for maximum extraction. The tubes were placed in a water bath (3/4 filled with de-ionised water) at 80°C, which was in a fume cupboard, for 90 minutes.

After 90 minutes, the tubes were removed from the water bath and left to cool for one hour. When sufficiently cool the tubes were centrifuged for 10 minutes at 3,000 rpm at 15°C. Immediately after centrifuging, a 9.625 ml aliquot of Chelex treated HPLC-grade water and a 10 µl aliquot of a 10 ppm diluted yttrium internal standard was added to an acid-washed 15ml Elkay tube and a 0.375 ml aliquot of the supernatant aqua regia solution from a filter sample was added to the 15 ml tube. This was repeated for each sample. One blank yttrium only was prepared. A 0.375ml aliquot of freshly prepared aqua regia was added to an acid-washed 15ml Elkay tube containing 9.625ml Chelex treated HPLC-grade water and 10 µl of a 10 ppm diluted yttrium internal standard. Each

tube had a final acid concentration of 3.75% aqua regia solution which was carefully vortexed and labelled before being sent to King's College, London, for ICP-MS analysis. In total 123 15 ml tubes were sent to King's College for ICP-MS analysis including 116 filter samples, six blank filters and one yttrium only blank.

5.3.6 Quantifying AA and GSH depletion

The capacity of subway and overground PM_{2.5} to deplete antioxidants was quantified using AA depletion (OP^{AA}) and glutathione depletion (OP^{GSH}) for each filter sample. To obtain a metric for an accessible representation of oxidation percentage depletion per μg of PM_{2.5} (OP μg^{-1}), OP^{AA} and OP^{GSH} were divided by the PM_{2.5} mass (Ayres et al., 2008) on each quarter filter represented by OP^{AA} μg^{-1} and OP^{GSH} μg^{-1} . This allowed a value to be derived to represent the depletion capacity per unit mass of each PM_{2.5} filter in the two railway environments. To understand the oxidative activity per volume (m^3) of subway or ambient air for each filter, OP^{AA} μg^{-1} and OP^{GSH} μg^{-1} were multiplied by the volume of air (m^3) passed through each filter measured during the filter collection to derive OP^{AA} m^{-3} and OP^{GSH} m^{-3} . To ensure that each OP value of a specific assay and sample were comparable particle mass-normalised (OP μg^{-1} , per μg of PM_{2.5}) and volume-normalised (OP m^{-3} , per volume of air) metrics were used in the analysis where the OP value of the specific assay and sample is normalised by the total PM_{2.5} mass on the filter or by the volume of air passed through collected filter.

These values for OP μg^{-1} or OP m^{-3} can be useful when describing chemical composition influences and exposure or epidemiological outcomes of PM_{2.5} OP depletion. It is likely that OP μg^{-1} is a more revealing metric when considering how chemical composition influences PM_{2.5} OP whereas OP m^{-3} is more useful when exploring exposure or epidemiological outcomes (Bates et al., 2019, Campbell et al., 2021).

5.3.7 Metals analysed by ICP-MS

Following the acid digestion of each filter sample and blanks, the samples and blanks were sent to King's College, London for ICP-MS analysis. The metals species analysed for each filter sample sent for ICP-MS analysis are shown Table 5.1. The list was selected based on those transition metals known to be present in the subway (Querol et al., 2012, Gao et al., 2020, Smith et al., 2020) and other metals derived from railway related emissions known to affect health. As well as transition metals, other metals and metalloids such as lead and arsenic, can exert toxic

effects via mechanisms other than direct generation of ROS warranting their inclusion (Loxham et al., 2013). Laboratory blank filters were analysed following the same methodology as the sample filters and concentrations were subtracted from those found for the samples to calculate the subway and overground metal concentrations. A dilution factor derived from the acid digestion process was used to determine the final metal concentrations for each filter.

5.4 Results

5.4.1 Underground and overground antioxidant consumed

After the exclusion of the first 24 filters and following filter processing for OP^{AA} and OP^{GSH} , $PM_{2.5}$ from 40 subway and 42 overground filters were analysed for their capacity to deplete OP^{AA} and OP^{GSH} during the incubation period (2 hours for OP^{AA} and 4 hours for OP^{GSH}). The subway filters comprised 34 Bakerloo line and six Jubilee line filters, and the Overground 34 Willesden and eight Kensal Rise filters. The raw data from the OP^{AA} depletion had a starting OP^{AA} concentration of $200 \mu\text{mol L}^{-1}$, represented by C0. The OP^{AA} depletion for the controls C2 and the in-house negative (M120) and in-house positive control (NIST) were as expected following incubation. The field and lab blanks had a similar OP^{AA} depletion to the negative controls C2 and M120, suggesting the blanks had little or no reactivity with OP^{AA} . The Bakerloo line displayed greater OP^{AA} depletion than the Jubilee line, with both showing a higher depletion of OP^{AA} than the overground lines (Figure 5.1).

Overall, there was less oxidation of OP^{GSH} compared to OP^{AA} oxidation for the Bakerloo line filters. For the Jubilee and overground filters, it appeared there was greater oxidation of OP^{GSH} than OP^{AA} . However, there was clearly a high reactivity of the blank filter material with OP^{GSH} in the assays, depleting OP^{GSH} by a mean of $48.5 \mu\text{mol L}^{-1}$ below the starting OP^{GSH} concentration of $200 \mu\text{mol L}^{-1}$.

For OP^{AA} and OP^{GSH} all controls displayed expected results demonstrating the accuracy of the assay results.

Table 5.1: Metals analysed by ICP-MS analysis from filter samples collected on subway and overground trains during the MRC study.

Element	Reason for inclusion	Reference
Aluminium (Al)	Found in wheel/brake abrasion	Smith et al., (2020)
Antimony (Sb)	Found in wheel/brake abrasion	Smith et al., (2020) Moreno et al., (2017)
Arsenic (As)	Found in wheel/brake abrasion	Smith et al., (2020)
Barium (Ba)	Found in wheel/brake abrasion	Smith et al., (2020)
Boron (B)	Found in subway anti-friction materials	Smith et al., (2020)
Cadmium (Cd)	Transition metal found in wheel/brake abrasion	Smith et al., (2020), Ji et al., (2021)
Calcium (Ca)	High subway concentration	Smith et al., (2020)
Cerium (Ce)	Transition metal found in the subway	Smith et al., (2020)
Chromium (Cr)	Transition metal component of steel used in wheel, rail and electrification	Ji et al., (2021) Chillrud et al., (2004)
Cobalt (Co)	Transition metal found in the wheel/brake abrasion	Smith et al., (2020), Ji et al., (2021)
Copper (Cu)	Transition metal component of steel used in wheel, rail and electrification	Smith et al., (2020) Ji et al., (2021) Moreno et al., (2017)
Iron (Fe)	Transition metal component of steel used in wheel, rail and electrification	Smith et al., (2020) Ji et al., (2021)
Lead (Pb)	Found to be enriched in the subway	Font et al., (2019)
Lithium (Li)	Found in subway anti-friction materials	Smith et al., (2020)
Magnesium (Mg)	Component of steel used in wheel, rail and electrification	Chillrud et al., (2004)
Manganese (Mn)	Transition metal component of steel used in wheel, rail and electrification	Smith et al., (2020) Ji et al., (2021)
Molybdenum (Mo)	Transition metal found in anti-friction materials	Smith et al., (2020)
Nickel (Ni)	Transition metal found in the subway	Smith et al., (2020)
Niobium (Nb)	Transition metal found in the subway	Smith et al., (2020)
Potassium (K)	High subway concentrations	Smith et al., (2020)
Selenium (Se)	Found in subway anti-friction materials	Smith et al., (2020)
Sodium (Na)	Found in high concentrations in the subway	Smith et al., (2020)
Strontium (Sr)	Found in wheel/brake abrasion	Martins et al., (2016) Ji et al., (2021)
Titanium (Ti)	Transition metal found in the subway	Smith et al., (2020)
Vanadium (V)	Transition metal found in the subway	Smith et al., (2020) Ji et al., (2021)
Zinc (Zn)	Transition metal component of steel used in wheel, rail and electrification	Ji et al., (2021)

To normalise each filter to the starting concentration of $200 \mu\text{mol L}^{-1}$, total glutathione (GSX) and oxidised glutathione (GSSG) for each filter were initially scaled relative to particle-free controls C0 and C4. After C0 and C4 normalisation and following incubation GSX should be equal for all filters ($200 \mu\text{mol L}^{-1}$) and was normalised to the mean filter GSX ($181.1 \mu\text{mol L}^{-1}$) with GSH being adjusted accordingly. All subway and overground filters were corrected for mean background OP^{GSH} % oxidation registered across all of the field and lab blanks ($48.5 \mu\text{mol L}^{-1}$). OP^{AA} depletion was C0 and C2 normalised and corrected for background % oxidation registered across all of the field and lab blanks ($4.8 \mu\text{mol L}^{-1}$).

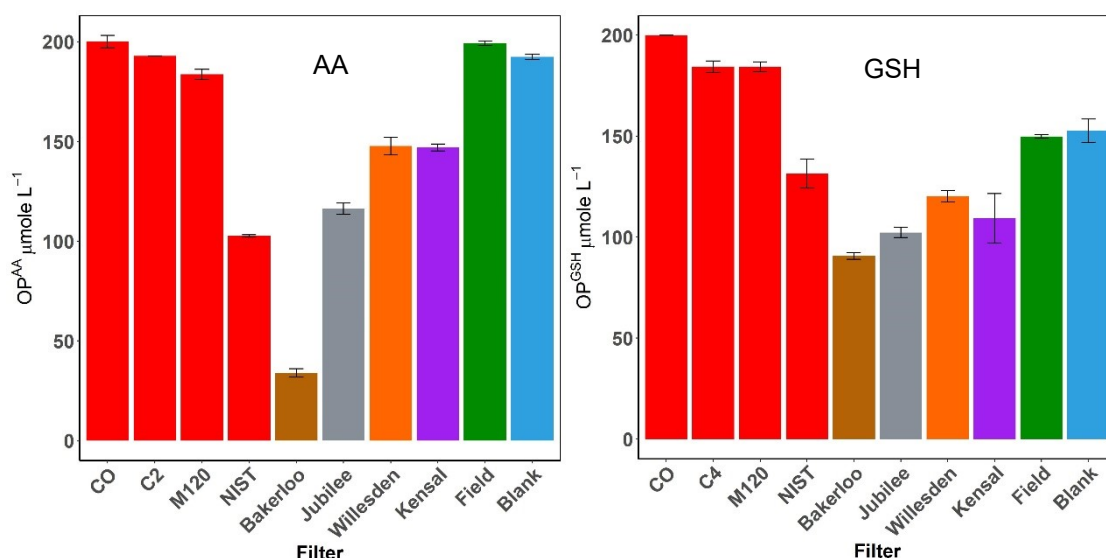


Figure 5.1: Induced OP^{AA} and OP^{GSH} depletion of antioxidant treatment on $\text{PM}_{2.5}$. For OP^{AA} depletion antioxidant remaining after 2 hours incubation for all filters. C0 before the incubation period, C2 particle free control, M120 negative control, NIST1648a positive control, Bakerloo, Jubilee, Willesden and Kensal Rise lines, field blanks and lab blank. For OP^{GSH} depletion antioxidant remaining after 4 hours incubation for all filters. C0 before the incubation period, C4 particle free control, M120 negative control, NIST1648a positive control, Bakerloo, Jubilee, Willesden and Kensal Rise lines, field blanks and lab blank.

Bakerloo line OP^{AA} consumption was depleted in excess of the Jubilee line (71% difference) with the subway journeys showing greater depletion than the overground. The Bakerloo line depletion was greater than the positive NIST control (difference 67%). For OP^{GSH} , after correction for the blanks, the Bakerloo line displayed the highest depletion, followed by the Jubilee line and overground lines. After correction, the Bakerloo line had a similar depletion to the positive NIST control.

5.4.2 Determination of antioxidant depletion rates

5.4.2.1 OP^{AA} and OP^{GSH} depletion rates per unit mass

There was considerable variation when OP^{AA} was mass normalised per unit mass ($OP^{AA} \mu g^{-1}$) during each subway journey on the Bakerloo and the Jubilee lines (Figure 5.2). There was a greater range of OP^{AA} depletion per unit mass on the Jubilee line ($0.28 - 2.21 \mu g^{-1}$) compared to the Bakerloo line ($0.60 - 2.16 \mu g^{-1}$), with a mean Bakerloo line $OP^{AA} \mu g^{-1}$ of $1.36 \mu g^{-1}$ which was greater than the mean Jubilee line $OP^{AA} \mu g^{-1}$ of $1.20 \mu g^{-1}$, although there was no significant difference. Four of the six Jubilee line journeys took place with a mask which could account for the greater variation of $OP^{AA} \mu g^{-1}$ on the Jubilee line (on the Bakerloo line 2 of the 34 journeys used a mask).

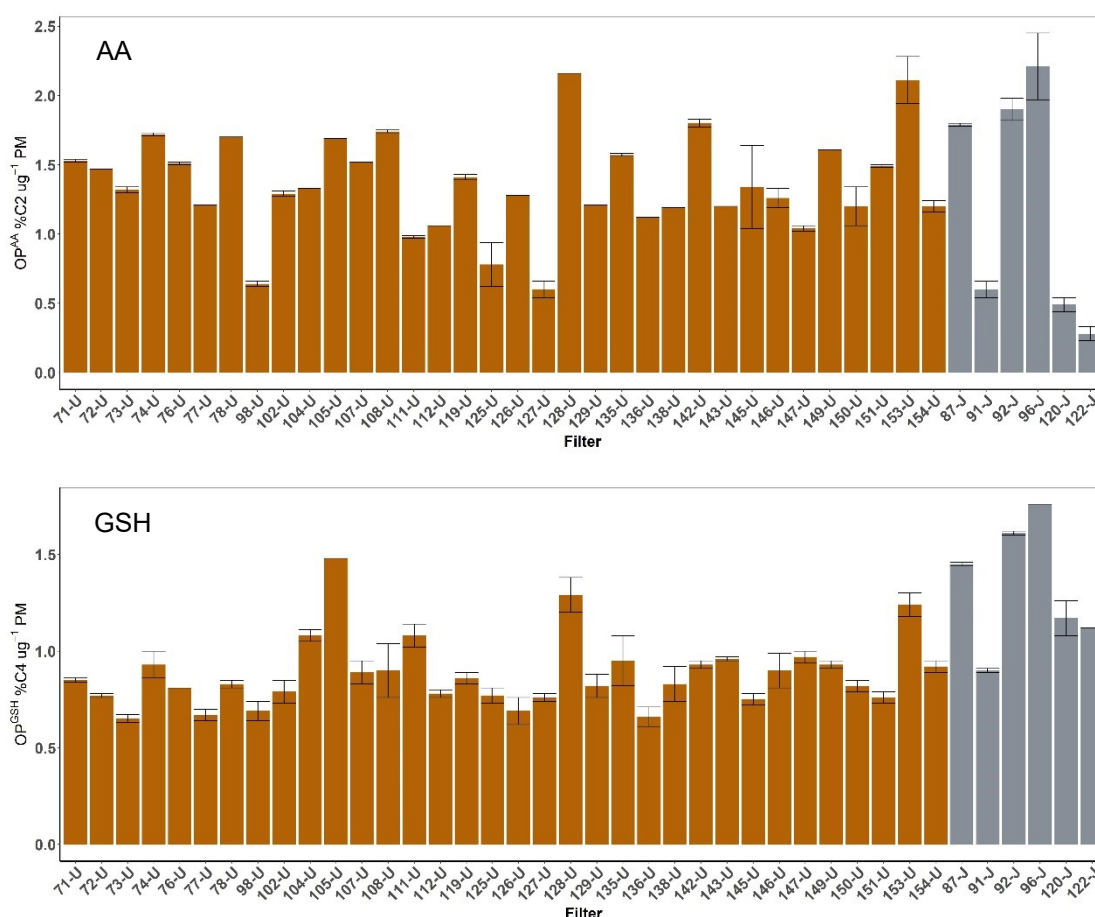


Figure 5.2: OP^{AA} antioxidant % C2 depletion per unit mass of $PM_{2.5}$ for the Bakerloo line (brown) and Jubilee line (silver) and OP^{GSH} antioxidant % C4 depletion per unit mass of $PM_{2.5}$ for the Bakerloo line (brown) and Jubilee line (silver).

There was less variation on each journey when considering OP^{GSH} per unit mass on the subway journeys with a Bakerloo line $OP^{GSH} \mu g^{-1}$ range of $0.65 - 1.48 \mu g^{-1}$ and a Jubilee line $OP^{GSH} \mu g^{-1}$

range of 0.9 – 1.76 μg^{-1} with both having a similar range (Figure 5.2). Mean Bakerloo line OP^{GSH} μg^{-1} was 0.88 μg^{-1} with a significantly higher mean Jubilee line OP^{GSH} μg^{-1} of 1.30 μg^{-1} ($p < 0.05$).

The mean result for OP^{AA} μg^{-1} of 1.36 μg^{-1} for the Bakerloo line was lower than those found at platforms in the Barcelona subway with a mean OP^{AA} μg^{-1} of 1.63 μg^{-1} (Moreno et al., 2017) and similar to the mean OP^{AA} μg^{-1} of 1.36 μg^{-1} and 1.35 OP^{AA} μg^{-1} found at London background and London roadside sites, respectively (Kelly et al., 2011). The Barcelona results showed a greater variation of OP^{AA} μg^{-1} (0.9 – 2.4 μg^{-1}) than the Bakerloo line, reflecting the wider range of locations sampled in Barcelona. For OP^{GSH} depletion, the Bakerloo line had the same mean OP^{GSH} μg^{-1} of 0.88 μg^{-1} as the Barcelona study, and it was higher than at London background and roadside sites, mean 0.53 and 0.77 μg^{-1} , respectively. The Jubilee line showed the highest mean OP^{GSH} μg^{-1} . Both the Kelly et al., (2011) and Moreno et al., (2017) studies used a similar RTLF model to this study making the results comparable.

5.4.2.2 AA and GSH depletion rates per unit volume

Mean OP^{AA} per unit volume of air (Figure 5.3) was significantly higher on the Bakerloo line (79.0 m^{-3}) than on the Jubilee line (38.8 m^{-3}) ($p < 0.05$), although both subway lines showed considerable variation. Bakerloo line OP^{AA} m^{-3} ranged from 37.4 – 114.0 m^{-3} with the Jubilee line ranging from 9.27 – 78.8 m^{-3} . For OP^{GSH} depletion per unit volume of air, the Bakerloo line had a mean OP^{GSH} m^{-3} of 51.1 m^{-3} with a range of 31.4 – 73.0 m^{-3} . Mean Bakerloo line OP^{GSH} m^{-3} was greater than the Jubilee line, 43.6 m^{-3} , although not significantly different, with a Jubilee line range of 31.4 – 62.6 m^{-3} .

Mean Bakerloo line OP^{AA} m^{-3} of 79.0 m^{-3} was lower than found in Barcelona (87.7 m^{-3}) but higher than the OP^{AA} m^{-3} of 26.3 and 33.9 m^{-3} found at London background and roadside sites. For mean OP^{GSH} m^{-3} the Bakerloo line (51.1 m^{-3}) was higher than in Barcelona (49.7 m^{-3}) and London background and roadside of 10.3 and 19.2 m^{-3} , respectively. These results suggest that there was little difference in OP deletion between the Bakerloo line and the Barcelona subway, but the Bakerloo line shows greater OP^{AA} and OP^{GSH} depletion than London background and roadside sites. Jubilee line OP^{AA} and OP^{GSH} depletion per unit volume of air was lower than the Bakerloo line and the Barcelona subway, but greater than London background and roadside sites.

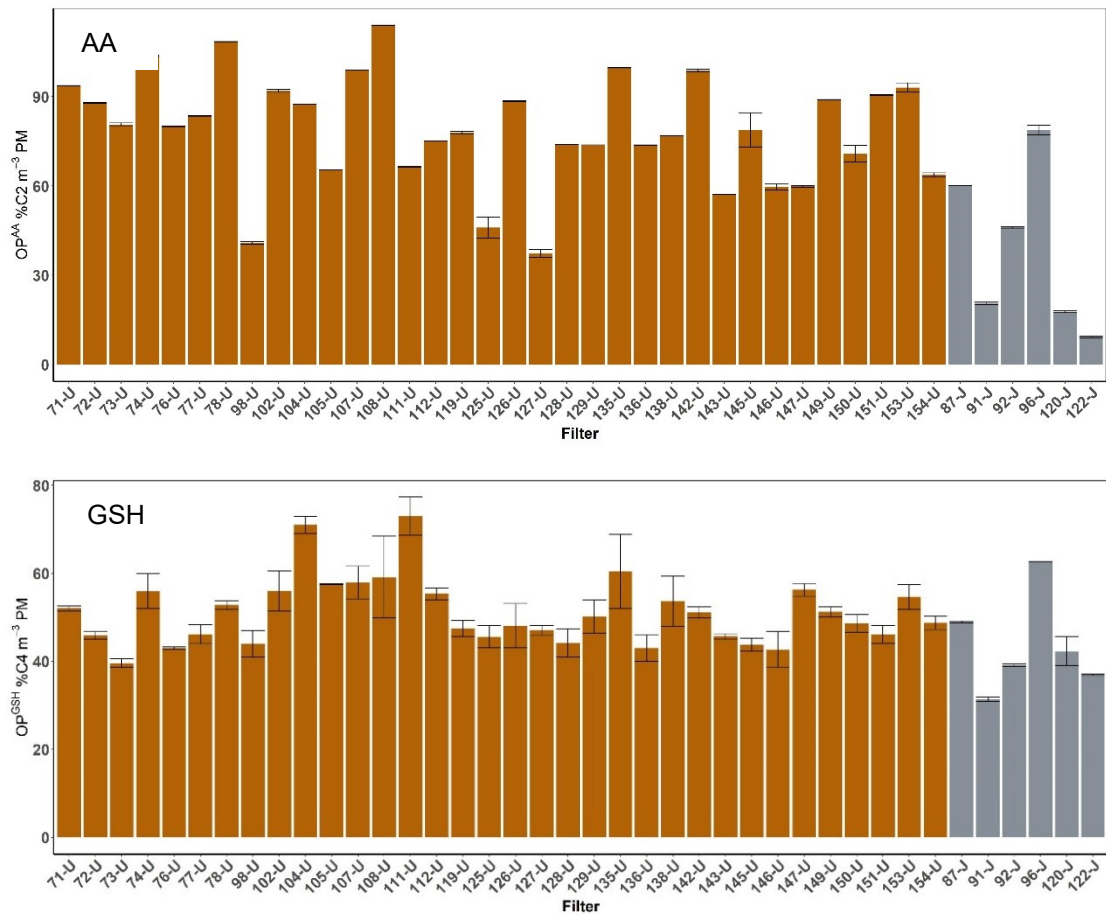


Figure 5.3: OP^{AA} antioxidant % C2 depletion per unit volume of PM_{2.5} for the Bakerloo line (brown) and Jubilee line (silver) and OP^{GSH} antioxidant % C4 depletion per unit volume of PM_{2.5} for the Bakerloo line (brown) and Jubilee line (silver).

For the Overground, Willesden and Kensal Rise lines, OP depletions for OP^{AA} and OP^{GSH} μg^{-1} and m^{-3} (Figure C 1 and Figure C 2) showed large variations. Mean Overground OP^{AA} μg^{-1} was 47.6 μg^{-1} for the Willesden line (range 0 – 182.7 μg^{-1}) and 30.3 μg^{-1} for the Kensal Rise line (range 0 – 75.1 μg^{-1}). Mean Overground OP^{GSH} μg^{-1} was 14.0 μg^{-1} for the Willesden line (range 0 – 48.7 μg^{-1}) and 8.9 μg^{-1} for the Kensal Rise line (range 0 – 22.2 μg^{-1}). For OP^{AA} per unit volume of air, mean OP^{AA} m^{-3} was 22.6 m^{-3} (range 0 – 55.5 m^{-3}) on the Willesden line and 20.4 m^{-3} (range 0 – 50.0 m^{-3}) on the Kensal Rise line. Mean OP^{GSH} m^{-3} on the Willesden line was 8.1 m^{-3} (range 0 – 21.4 m^{-3}) and 13.0 m^{-3} (range 0 – 25.7 m^{-3}) on the Kensal Rise line. The results show a wide range of values for all OP Overground results, especially when compared to the subway OP results. This is likely due to the very low concentrations of PM_{2.5} collected onto filters in both overground environments. Due to the filters being quartered, the PM_{2.5} concentrations on the filters used for the OP assays ranged from < 1 – 3 $\mu\text{g m}^{-3}$ on the Willesden line and < 1 – 7 $\mu\text{g m}^{-3}$ on the Kensal Rise line.

³ on the Kensal Rise line. These compared to Bakerloo line PM_{2.5} (per quarter) of 35 – 80 µg m⁻³ and Jubilee line PM_{2.5} (per quarter) of 24 – 39 µg m⁻³. Due to the low PM_{2.5} mass on the overground filters there was little depletion of AA and GSH in the assays so these will not be considered further as they were below the LOD.

5.4.3 PM_{2.5} metal composition

Many studies have measured the chemical composition of subway PM_{2.5} worldwide (Murrini et al., 2009, Querol et al., 2012, Perrino et al., 2015) and in the London Underground (Seaton et al., 2005, Smith et al., 2020, Kumar et al., 2023) with iron (Fe) having the largest contribution to PM_{2.5} mass. Unlike other studies which analysed total carbon, elemental carbon, inorganic and organic compounds, in this study only the 26 selected metals were analysed for the subway and overground. The metal content for the Bakerloo and Jubilee lines showed that Fe was the dominant metal and that all transition metals associated with the subway environment had high concentrations. As, Cd, Ce, Cs and Nb, were below the detection limit and were therefore excluded from further analysis (Table C 6). In the London Underground Fe particles, in the form of magnetite (Kumar et al., 2023), along with Al, Ba, Co, Cr, Cu, Mg, Mn, Sb, Sr and Zn were sourced in the subway from interactions from wheels, tracks and brake pads (Moreno et al., 2015). Friction reducing lubrication materials found in the subway include Mo, Se and B with Se with B and Li acting as additives to oils and greases (Smith et al., 2020).

Smith et al., (2020) measured mean Fe concentrations of 184 µg m⁻³ at Hampstead station. Mean Fe concentrations were 142 µg m⁻³ on the Bakerloo line. However, PM_{2.5} concentrations were higher at Hampstead station compared to the Bakerloo line which could account for the difference in mean Fe concentrations. In this study, Fe comprised 86% of the metal content measured on the Bakerloo line filters (81% on the Jubilee line) (Table C 6). The results per ng m⁻³ ug⁻¹ PM for each metal are shown for both lines in Figure 5.4. This shows that Fe ng m⁻³ ug⁻¹ PM was 23% higher in the Bakerloo line than the Jubilee line. This could be due to mechanical braking employed on Bakerloo line trains compared to rheostatic on the Jubilee line. Mechanical braking, especially emergency braking, is known to significantly increase PM_{2.5} and most likely Fe emissions (Van Ryswyk et al., 2021). The Bakerloo line is built underneath the road system in Central London with many sharp track curvatures and track gradients which could cause additional track and wheel related Fe emissions (Martins et al., 2016). Metals per µg showed varying levels of difference between the Bakerloo and Jubilee line with Cu, Fe, Mn and Ti

significantly higher on the Bakerloo line with B and Mo significantly higher on the Jubilee line. The other metals showed little difference across the two lines.

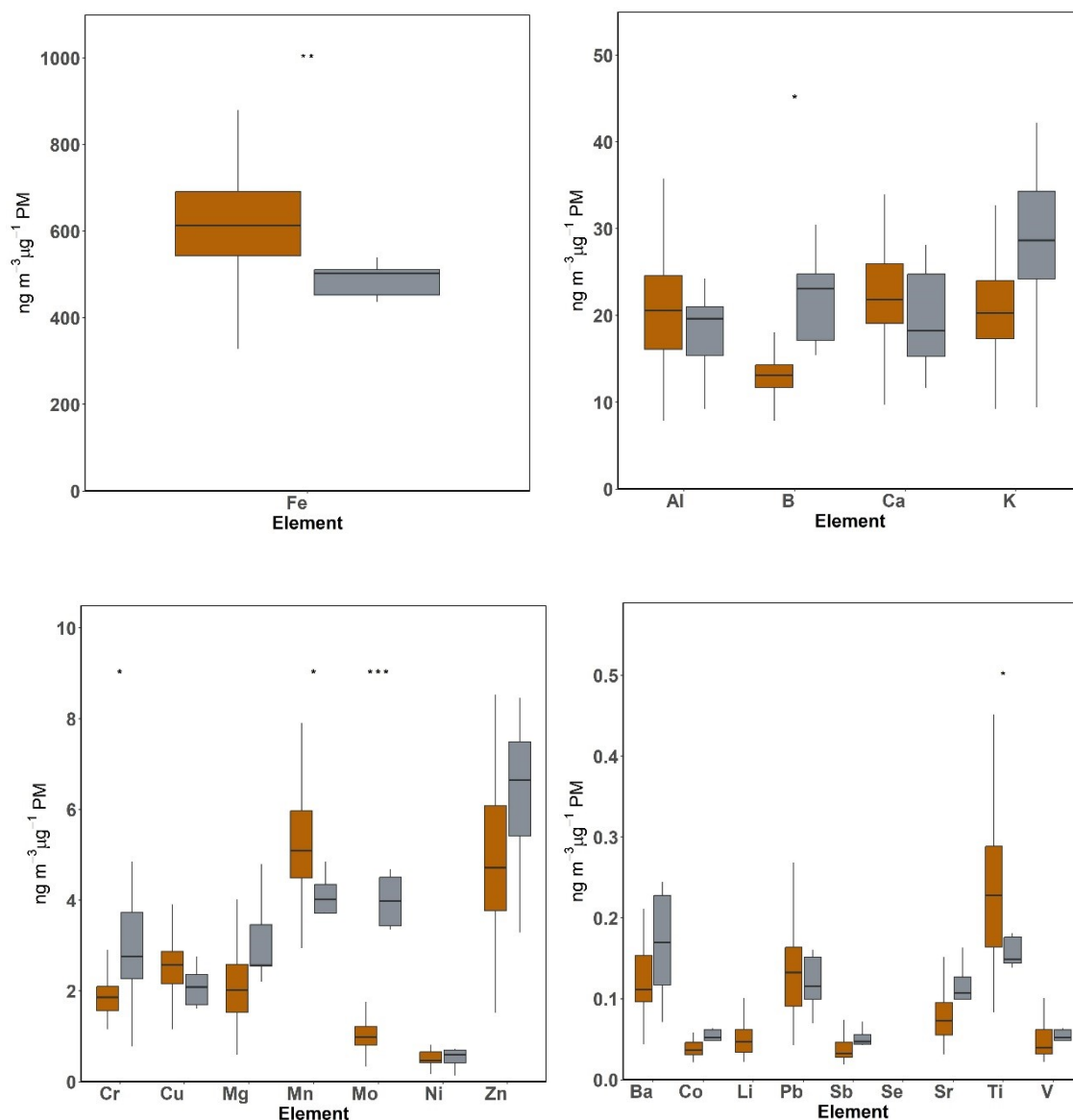


Figure 5.4: Metal concentrations per unit mass of PM_{2.5} (ng m⁻³ μg⁻¹ PM) in the Bakerloo line (brown) and Jubilee line (silver). Note the differing y-axis as metal concentrations decrease. Statistically significant differences are according to the Mann Whitney test, * p<0.05, ** p<0.01 and *** p<0.001.

5.5 Effects of subway PM_{2.5} chemical composition on OP

The associations between PM_{2.5} chemical composition and OP per unit PM_{2.5} mass and per unit volume in the subway for the Bakerloo and Jubilee lines are shown using the corPlot function in the openair 'r' package (Carslaw 2012) (Figure 5.5 and Figure 5.6). To allow a direct comparison between chemical composition and OP, metal concentrations were normalised to per unit mass

to correspond to $OP^{AA} \mu g^{-1}$ and $OP^{GSH} \mu g^{-1}$ and to unit volume to correspond to $OP^{AA} m^{-3}$ and $OP^{GSH} m^{-3}$. Correlations and p-values are shown in Table C 7.

All 34 Bakerloo line samples and all six Jubilee line samples were used in the correlations. P-values for the correlations of each metal with OP^{AA} and OP^{GSH} per unit mass and per unit volume on both lines were calculated with p-values < 0.05 considered significant and p-values < 0.01 considered highly significant (Table C 7). There was a highly significant positive correlation between $OP^{AA} \mu g^{-1}$ and $OP^{GSH} \mu g^{-1}$ on both lines and between $OP^{AA} m^{-3}$ and $OP^{GSH} m^{-3}$ on the Jubilee line although there was a lack of a significant association between $OP^{AA} m^{-3}$ and $OP^{GSH} m^{-3}$ on the Bakerloo line, which could have been due to the much higher concentrations of $PM_{2.5}$ on the Bakerloo line.

A range of transition metals associated with railway-related emissions, Co, Cr, Cu, Fe, Mn, Mo, Ti and V were highly significantly positively correlated with $OP^{AA} \mu g^{-1}$ and $OP^{GSH} \mu g^{-1}$ on the Bakerloo line. Ni was only highly significantly positively correlated with $OP^{AA} \mu g^{-1}$ on the Bakerloo line. Non-transition metals associated with railway-related emissions, Al, B, Ba, were highly significantly positively correlated with $OP^{AA} \mu g^{-1}$ and $OP^{GSH} \mu g^{-1}$, (Li was only highly significantly correlated with $OP^{AA} \mu g^{-1}$). The metals K and Pb were highly significantly correlated with $OP^{AA} \mu g^{-1}$ and $OP^{GSH} \mu g^{-1}$. When considering OP^{AA} and OP^{GSH} per unit volume, only Se was significantly correlated with $OP^{GSH} m^{-3}$, whereas the transition metals Fe, Ni, Ti and Zn (not significant per unit mass) and the non-transition metal Al, were significantly positively correlated with $OP^{AA} m^{-3}$ and $OP^{GSH} m^{-3}$. There were no significant positive correlations between metals and any OP metric on the Jubilee line. This could have been due to the low number of samples ($n=6$) and that four of these journeys involved wearing a mask, which may have preferentially removed some of the larger particles.

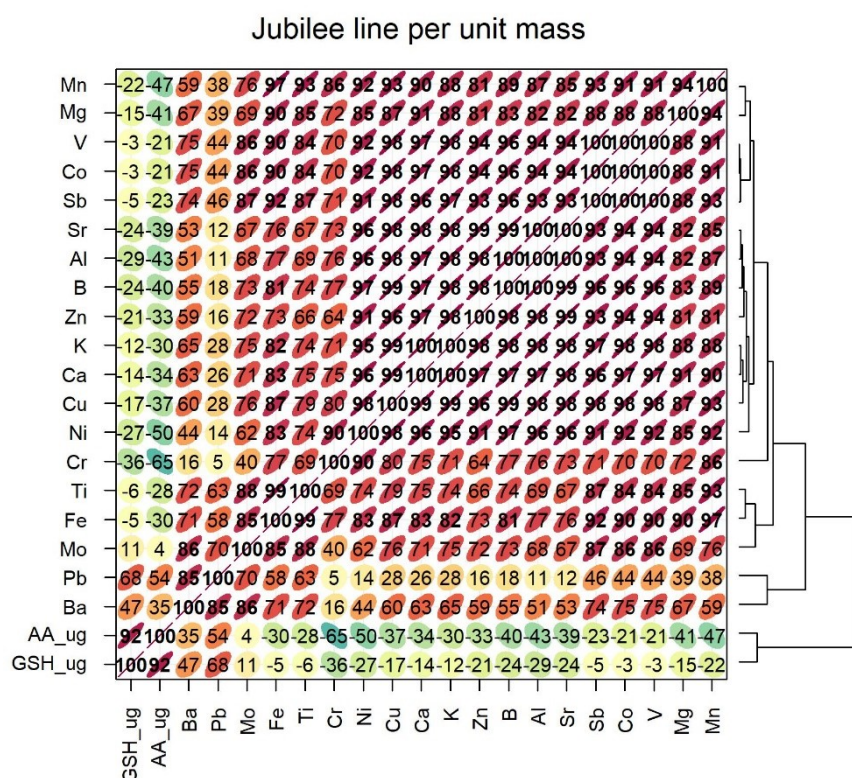
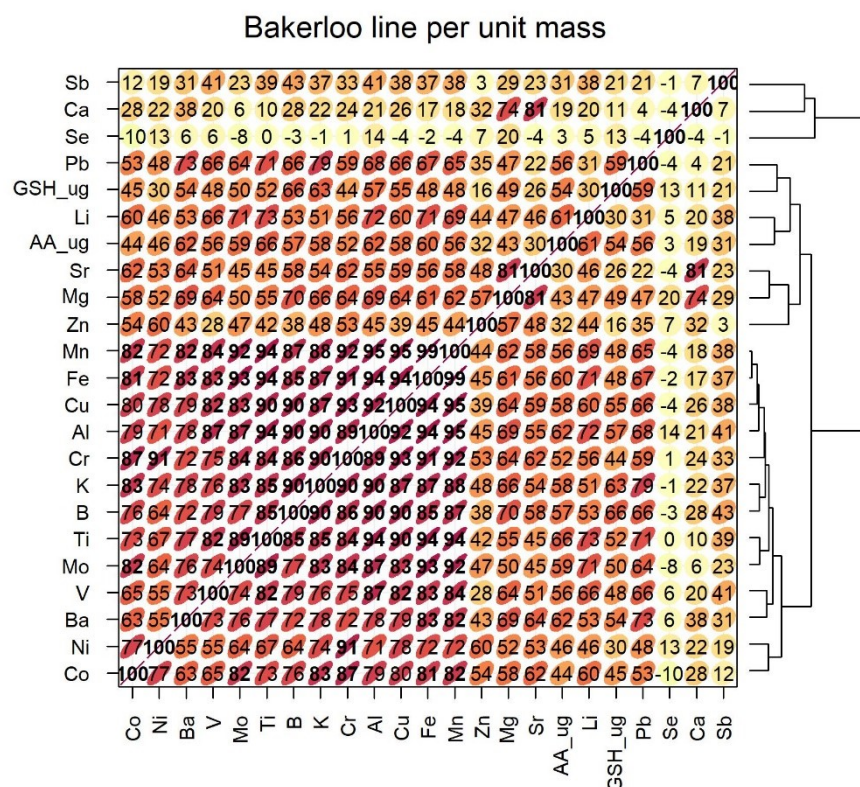


Figure 5.5: Correlation plots of OP^{AA} and OP^{GSH} per unit of mass ($OP\text{ ug}^{-1}$) and metal concentrations per unit of mass ($\text{ng m}^{-3}\text{ ug}^{-1}$) on the Bakerloo and Jubilee lines.

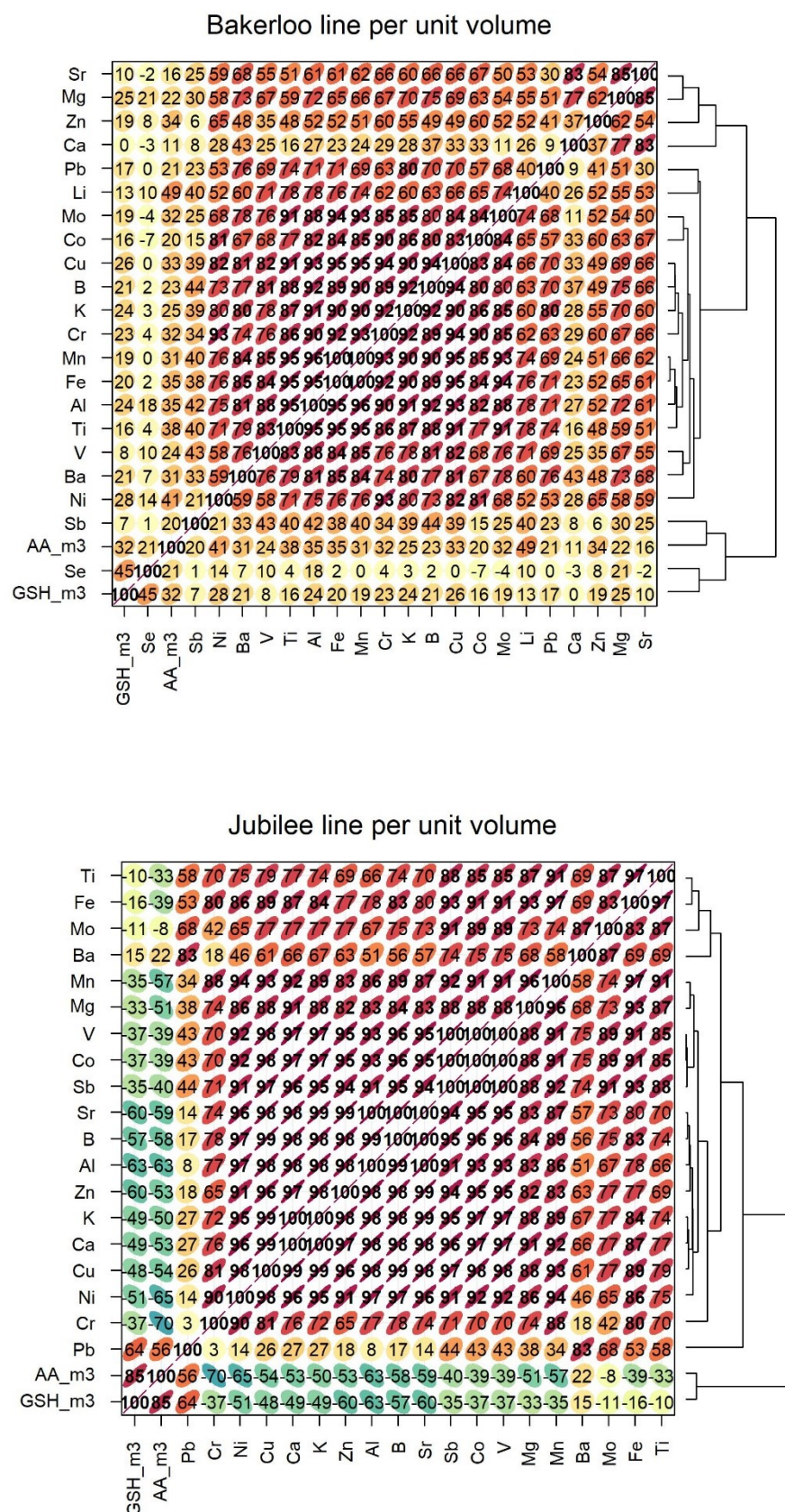


Figure 5.6: Correlation plots of OP^{AA} and OP^{GSH} per unit of volume ($OP\ m^{-3}$) and metal concentrations per unit volume ($ng\ m^{-3}\ m^{-3}$) on the Bakerloo and Jubilee lines.

There was a high degree of agreement in the highly significantly correlated metals associated with OP^{AA} and OP^{GSH} depletion per unit mass, particularly with railway related transition metals. This is important as OP per unit mass is more informative when considering the role of chemical composition on OP than per unit volume of air (Bates et al., 2019, Puthussery et al., 2020, Campbell et al., 2021). In comparison to the results found in the Barcelona subway for OP^{AA} μg^{-1} , only Pb was found to be highly significantly correlated on the Bakerloo line and the Barcelona subway. In terms of OP^{GSH} m^{-3} , only Ba and Cu were found to be highly correlated in both subway systems.

This could have been due to the Barcelona study using the full metal concentrations, rather than normalising the metal content per unit mass of $PM_{2.5}$ and per volume of air. The Barcelona study was also conducted on six different platforms with differing platform designs, $PM_{2.5}$ concentrations and metal concentrations leading to a large variation in metal and OP results for the different stations. When the results from each platform were combined this may not have given a clear representation of OP^{AA} and OP^{GSH} in the Barcelona subway.

The metals significantly correlated with OP^{AA} and OP^{GSH} per unit mass show good agreement with ambient results influenced by traffic related air pollution, particularly with the transition metals (Bates et al., 2019, Campbell et al., 2021) and in particular for Ba, Cu and Mo at roadside sites in London (Kelly et al., 2011). These results confirm that transition metals are particularly important in their contribution to OP^{AA} and OP^{GSH} per unit mass on the Bakerloo line, being major components of train related emissions. Indeed, evidence suggests that there are higher concentrations of Fe and other transition metals in the subway compared to ambient $PM_{2.5}$ (Kam et al., 2011, Loxham et al., 2013) and the transition metals could be influencing toxic effects from redox-cycling reactions producing ROS (Loxham et al., 2013, Campbell et al., 2021). In the Los Angeles subway Kam et al., (2011) found transition metals were enriched and suggested they may have been contributing to the generation of ROS resulting in oxidative stress.

An in-vitro toxicity study conducted by Steenhof et al., (2011) in the Netherlands found subway particles contained a high transition metal content, particularly Fe, Cu and Ni, which they concluded led to a large decrease in metabolic activity in macrophages in comparison to traffic and urban background sites. There are many factors that could influence the correlation between metal composition and OP including water solubility, chemical form, oxidation state and redox

potential. The capacity for ROS generation could be influenced by water solubility, particularly the magnetite form of Fe which has been shown to have low water solubility in the subway (Mugica-Alvarez et al., 2012). The high number of transition metals found to be highly correlated to OP depletion per unit mass on the Bakerloo line suggests that these metals may be working synergistically with iron oxides and it is particle metal enrichment that is responsible for the increased antioxidant depletion rather than iron content alone (Loxham and Nieuwenhuijsen 2019). The high correlations of Fe with Cu, Mo, and Ba, all known to be drivers of OP depletion (Kelly et al., 2011) on the Bakerloo line support this suggestion.

The results showed that Bakerloo line subway PM_{2.5} depleted OP^{AA} greater than the positive NIST control, unlike Jubilee line PM_{2.5}. Neither Bakerloo nor Jubilee line PM_{2.5} was able to deplete OP^{GSH} greater than the positive NIST control, suggesting that the capacity of particles in the Bakerloo line was greater in the depletion of OP^{AA} over OP^{GSH}. This was despite there being a high correlation associating OP^{AA} and OP^{GSH} per unit of mass. Despite the increased capacity of OP^{AA} activity on the Bakerloo line, there was considerable variation over the different journeys when considering OP^{AA} µg⁻¹. There was less variation of subway depletion of OP^{GSH} than OP^{AA}, on a per mass and volume basis, maybe caused by some metals which have the capacity to deplete OP^{AA} varying more throughout the different journeys. There were distinct differences between OP^{AA} and OP^{GSH} per unit of mass and per unit volume of air most likely due to the increased particle concentrations found in the Bakerloo line. The results suggest that Bakerloo and Jubilee line PM_{2.5} have a similar capacity to London roadside PM_{2.5} to elicit oxidative stress at the air–lung interface, potentially inducing systemic and pro- inflammatory responses in biological tissues

5.6 Conclusion

This study used PM_{2.5} filter samples collected on the Bakerloo and Jubilee lines to undertake an OP analysis of the antioxidants AA and GSH. The results showed that the depletion of OP^{AA} by Bakerloo line PM_{2.5} was greater than the Jubilee line (although not significant) and the positive NIST control. OP^{GSH} depletion was higher in the Bakerloo line compared to the Jubilee line but deleted OP^{GSH} similarly to the positive NIST control. When OP^{AA} and OP^{GSH} were investigated per unit mass or volume of air, the Bakerloo line showed greater depletion of OP^{AA} µg⁻¹ than the Jubilee line but less depletion of OP^{GSH} µg⁻¹, although both lines showed a great deal of variation.

For $OP^{AA} \text{ m}^{-3}$ and $OP^{GSH} \text{ m}^{-3}$ the Bakerloo line showed greater antioxidant depletion capacity. The oxidative potential depletion of OP^{AA} and OP^{GSH} on the Bakerloo line was found to be similar to the Barcelona subway but greater than London roadside and background sites.

Filters were analysed for chemical composition by ICP-MS analysis for metals produced by train related activities in the subway. There were high levels of transition metals that were highly correlated to each other suggesting related emission sources in the subway. Correlations between OP^{AA} and OP^{GSH} and the metal content for each sample on a normalised per unit mass basis showed highly significant positive correlations between the transition metals Co, Cr, Cu, Fe, Mn, Mo, Ti, Ni and V and OP^{AA} and $OP^{GSH} \mu\text{g}^{-1}$ as well as with Al, B, Ba and Li. Although there was less correlation between OP^{AA} and OP^{GSH} per volume of air, transition metals Fe, Ni, Ti and Zn as well as Al were found to be highly significantly positively correlated with $OP^{AA} \text{ m}^{-3}$. These metals are mainly associated with wheel/rail and brake wear in the subway, which are likely to be particularly high in the Bakerloo line due to the degree of driver control over braking and the long track curvatures found in the Bakerloo line. This could explain why there were no significant positive correlations found in the Jubilee line (as well as the low number of samples) between metal composition and OP^{AA} and OP^{GSH} .

Although Fe was the largest $PM_{2.5}$ component in both subway lines it is possible that due to the low water solubility of magnetite Fe, it is a synergy of Fe working with other transition metals that is responsible for the elevated depletion of OP^{AA} in the Bakerloo line. The high correlation between these metals could elevate the overall depletion capacity to be greater than the individual components alone.

On an equal mass basis the subway lines showed elevated OP^{AA} and OP^{GSH} when compared to roadside and background sites in London (Kelly et al., 2011). This suggests that subway $PM_{2.5}$, particularly the Bakerloo line, has the capacity to drive the oxidation of antioxidants and induce oxidative stress at the air-lung interface, in a similar way to roadside $PM_{2.5}$. This capacity is induced by train related emissions of transition metals suggesting there is a need to further investigate the relationship between the effect of PM emissions and sources on OP to better understand the link between subway $PM_{2.5}$ and health.

Chapter 6 Multi-omic signatures of traffic related air pollution

6.1 Background

Following discussions with my supervisor, it was proposed that I would undertake a cross-omic analysis of metabolites and transcripts derived from blood serum samples taken from the participants during the train journey trial days from the MRC study. However, it was not possible to undertake the proposed multi-omic analysis due to delays brought about by the Covid-19 epidemic delaying the MRC study. Therefore, it was decided to prepare for a later multi-omic analysis of blood serum samples from the MRC study by using metabolomic (van Veldhoven et al., 2019) and transcriptomic (Espín-Pérez et al., 2018) data derived from the Oxford Street study (Sinharay et al., 2018) as a template on which to develop a methodology to investigate molecular signatures arising from exposure to subway air. The datasets previously prepared by van Veldhoven et al., (2019) and Espín-Pérez et al., (2018) were used to undertake a re-analysis of the metabolomic and transcriptomic data from the Oxford Street data, including a new multi-omic analysis of the data. This would provide the framework and techniques that I would require for a later multi-omic analysis of the blood serum samples collected from the MRC study.

The Oxford Street study took place in two contrasting locations; Oxford Street in Central London, a street dominated by diesel vehicles, and Hyde Park, a large park near Oxford Street. Participant volunteers walked for 2-hours in both locations, with each walk separated by 3-6 weeks. Hyde Park acted as a control to Oxford Street to understand the health effects of breathing traffic related air pollutants (TRAP).

During the Oxford Street study, each participant had multiple blood samples taken as input for transcriptomics analysis and untargeted metabolomic analysis. The samples were taken at three timepoints: baseline, (2 hours before the walk), and 2 and 24 hours after the walk. Similarly, in the MRC study participants had blood samples taken at the same time points: baseline (2 hours before the train journey) and 2 and 24 hours after the train journey. The Oxford Street data has previously been used for metabolomic (van Veldhoven et al., 2019) and transcriptomic analysis (Espín-Pérez et al., 2018) and it is proposed to integrate metabolomic and transcriptomic datasets to investigate multi-omic signatures of exposure to TRAP. The methodology that is proposed for the Oxford Street study could be extended to study multi-omics signatures of subway air

exposures, once these data become available. Such an approach could help to better understand the molecular pathways involved and their connection to potential health effects.

This chapter sets out the new methodology that was developed for a multi-omic approach to the Oxford Street study combining transcriptomics and metabolomics on the same participants over multiple time points to investigate the health effects of TRAP exposure. The results are discussed and it is set out how the methodology developed in this chapter could be used in a further study investigating multi-omic signatures arising from biological responses to exposures in the subway environment.

6.2 Introduction

Traffic-related air pollution (TRAP) is one of the major sources of air pollution exposure in urban areas and cities and has been associated with a wide range of adverse human health effects (Strak et al., 2021, Health Effects Institute 2022) including increased mortality and morbidity (Rosenlund et al., 2009, Atkinson et al., 2010, Amiri et al., 2019). TRAP comprises a mixture of vehicle exhaust pollutants, including particulate matter, PM₁₀ and PM_{2.5} and ultrafine particles, oxides of nitrogen (NO₂ and NO_x), non-exhaust emissions (brake and tyre wear) and Black Carbon (BC) (Samoli et al., 2016, Boogaard et al., 2022, Fussell et al., 2022). PM_{2.5} has been classified as a severe health hazard (Bilal, Nichol and Spak 2017) with no established threshold below which it would be harmless (Chen and Zhao 2011). Exposure to PM_{2.5} has been increasingly linked to respiratory and cardiovascular diseases (Alexeeff et al., 2021), possibly via the activation of systemic inflammation (Chao et al., 2018, Zhang et al., 2022) and the triggering of oxidative stress and inflammatory markers (Zhong et al., 2016, Barnes 2022, Ljubičić et al., 2022). Understanding distinct endpoints and biomarkers associated with short and long-term exposure to TRAP related pollutants could reveal the mechanistic processes involved in increased inflammation and oxidative stress (Liang et al., 2018, Liao et al., 2022).

Understanding the mechanistic basis of air pollution toxicity is dependent on accurately characterizing both exposure and biological responses (Liang et al., 2023). However, the underlying biological mechanisms have not been fully elucidated and principally due to the absence of robust and dedicated biomarkers (Krauskopf et al., 2019, Zhang et al., 2022), classical epidemiological methods cannot accurately ascertain the short-term impacts of exposures to TRAP (Liang et al., 2023).

The advent of omics-based high-throughput technologies allows dedicated biomarkers associated with TRAP exposure to be identified at a cellular level and identified through molecular changes and biological pathways (Alfano et al., 2018, Espín-Pérez et al., 2018). Metabolomics and transcriptomics provide powerful analytical methods allowing pathomolecular mechanisms to be mapped to molecular and biochemical pathways involved. This allows the triggering of a systemic response to be observed in the peripheral blood (Vlaanderen et al., 2017, Zhang et al., 2022). Metabolomics systematically investigates metabolites, such as amino acids, fatty acids and lipids, and their impact on oxidative stress and inflammation pathways in human health and disease (Bundy, Davey and Viant 2009, Liang et al., 2020). Untargeted metabolomics offers a valuable approach to the identification and quantification of TRAP exposure on the composition of the blood metabolome (van Veldhoven et al., 2019, Olena et al., 2022, Petrick and Shomron 2022). Transcriptomics allows the identification of genes that are differentially expressed in response to exposure and can be used as exposure biomarkers (Vrijens et al., 2017, Porcu et al., 2021).

The Oxford Street study used a randomised, cross-over study design whereby vulnerable (participants with COPD and ischemic heart disease) and healthy participants walked in the distinct environments of Oxford Street and Hyde Park. The cross-over design improved statistical power allowing the accurate modelling of between subject variability. This is the first study to combine metabolomics and transcriptomics from the same participants, over multiple timepoints, to identify multi-omic modifications associated with TRAP exposure.

6.3 Methods

6.3.1 Oxford Street study design

Vulnerable participants with either at least GOLD Stage 2 COPD (Chronic Obstructive Pulmonary Disease) (GOLD 2023) (n=40) or IHD (ischemic heart disease) (n=39), who had no previous evidence of airflow obstruction, were recruited from the outpatient respiratory and cardiology clinics at the Royal Brompton & Harefield NHS Foundation Trust (Sinharay et al. 2018). Separately healthy volunteers (n=40) with no evidence of airflow obstruction were recruited through advertising placed within the public areas of the Royal Brompton Hospital. All participants were required to walk for two hours either along Oxford Street in Central London which was dominated by diesel traffic or in nearby Hyde Park, which was much less polluted. The study used

a randomised, crossover design whereby each participant acted as their own control over the two locations of the walk.

The location for the first walk was randomised and the second walk took place 3-6 weeks later. Participants arrived at the Brompton Hospital in a hybrid car before undergoing a series of physiological health measurements including blood sample collections. They were then driven to their assigned walking location where they walked on predefined routes for two hours from 11am to 1pm, walking on average 5km. Following the walk participants were driven back to the Brompton hospital in a hybrid car, where their age, sex, date of birth, body mass index (BMI) and blood pressure were recorded along with data for distance walked, diet, medication and caffeine intake. A second blood sample was collected at the hospital 2 hours after the walk and a third sample 24 hours after walking. Whole blood and serum samples were taken from participants and stored at -80°C until further omics analysis. A subset of the study population (n=60) was selected for subsequent omics analysis. Informed written consent was obtained from all participants and the study was approved by the London City Road and Hampstead Ethics Committee (Sinharay et al. 2018).

6.3.2 Participant exposure measurements

Participants carried a backpack during each walk containing the measurement apparatus. PM_{2.5} and PM₁₀ were measured using a light scattering sensor (AM510 SidePak Personal Aerosol Monitors, TSI Ltd, MI, USA) measuring particles in the size range 200 nm – 2.5 µm and a unipolar diffusion charger (Philips Aerosense NanoTracer; measuring a size range of 10 – 300 nm) which was used as a proxy for ultrafine particle concentrations (PNCT). BC was measured with a microAeth AE51 (Aethlabs, CA, USA; flow rate 100 mL per min) using an optical absorption measurement method. In Oxford Street NO₂ measurements were taken from a stationary kerbside monitoring site (51.51392, -0.15279) repeatedly passed during the Oxford Street walks. Due to the unavailability of monitoring sites in Hyde Park, NO₂ measurements for the Hyde Park walks were taken from the nearest background monitoring site located in North Kensington (51.52104, -0.21349). Temperature, relative humidity and noise (Bruel and Kjaer Type 2236 Sound level meter, Naerum, Denmark) were electronically logged during the walk. Participant exposures prior to the walking exposures were modelled for average air pollution estimates one year before the experiment.

Only those participants with complete exposure data for both walks were included in the final dataset resulting in 50 participants having full exposure data for all measured pollutants.

6.3.3 Omics data acquisition and pre-processing

A total of 6 blood samples were collected for each participant. These were used to measure untargeted metabolomics and gene expression. A subset of 60 participants were selected for omics profiling.

6.3.3.1 Metabolomics data

The methods for the acquisition of untargeted metabolomics data have previously been described by van Veldhoven et al., (2019). Participant blood serum samples were prepared by mixing 20 µl of serum with 100 µl of acetonitrile in polypropylene microcentrifuge tubes which were centrifuged before collecting 50µl of the supernatant. The analysis was performed with an Agilent ultra-high performance liquid chromatography coupled with a quadrupole time of flight spectrometer (UHPLC-QTOF). Separation was obtained with a reversed phase column, ionisation with an electrospray ionisation selected in positive ion mode. Unique features characterised by monoisotopic mass and retention time were extracted from total ion chromatograms with the Agilent Mass Hunter and Profinder Pro software.

For each of the subset of 60 participants in the study the raw metabolomic dataset comprised 10,073 metabolites. The pre-processing of the data was done by extracting the features from the raw data with the molecular feature extraction function of the Agilent Profinder software. In this new study we included data filtering in order to remove features with poor analytical detection. Features with a very short retention times (below 1min) and very large mass (>1500 Da) were also removed. In the present analyses we revisited the pre-processing of the metabolomics data by including several additional filtering steps. This involved excluding metabolomic features with over 40% of missing values resulting in 4,033 features being excluded, giving a final dataset of 6,040 metabolomic features measured in the 50 participants with full exposure data representing 300 metabolomic profiles. The data was $\log_{10}$ transformed and missing data was added through a left-centred missing data imputation method with the impute CMD r package (Lazer, Burger and Wieczorek 2022).

A four-step process was used to categorise metabolomic features:

- Similarity in retention time and correlation in intensity across the samples was used to categorise LC-MS features identifying ions originating from the same compound.
- m/z values of all the features were compared against the Human Metabolome Database (HMDB) (The Metabolomics Innovation Centre 2023) and Metlin (Metlin 2023) using $[M+H]^+$, $[M-H_2O+H]^+$, and $[M+Na]^+$ as adducts and mass tolerance of ± 8 ppm.
- Representative samples were reanalysed using pure standards, when available, and in addition, the retention times and MS/MS spectra were compared. The MS/MS spectra were matched against those available in mzCloud (m/z CLOUD 2023) or Metlin if no standards were available.
- The Chemical Analysis Working Group of the Metabolomics Standards Initiative (Sumner et al., 2007) was used to verify the level of identification.

6.3.4 Transcriptomics data

6.3.4.1 RNA Isolation and microarray analysis

The preparation of RNA analysis of the Oxford Street study participants blood serums has previously been described by Espín-Pérez et al., (2018) where total RNA was isolated using the RiboPure -Blood kit (Ambion) following manufacturer's instructions. The isolated RNA was hybridized on SurePrint G3 Human Gene Expression v2 or 3 8x60K Microarray Kit using 200ng of material. The Agilent Feature Extraction Software was used to extract raw data on pixel intensities. Probes were matched to gene names based on their ID, using a database (accession ID GPL21185) on the NCBI platform allowing Whole Human Genome microarrays for mRNA to be derived. The whole-genome gene expression dataset was cleaned for incorrectly labelled transcripts and $\log_2$ normalised. This resulted in 30,923 transcripts being assayed in 42 participants who had complete exposure data giving 252 profiles. These 252 profiles were all included in the 300 metabolomic profiles.

6.3.5 Technical confounding correction

During data acquisition of untargeted metabolomics data and transcriptomic data, technical confounding may introduce residual noise or "batch effects" due to samples being handled over multiple batches over different time periods (Leek et al., 2010, Luo et al., 2010). The residual technical noise introduced by the analysis can lead to confounding of the data and was corrected as proposed by McHale et al., (2011) and Chadeau-Hyam et al., (2014). This involved applying

a linear mixed model for each omic measurement (each metabolomic feature or transcript was set as the outcome) (Pinheiro et al., 2023). Technical confounders (batch ID for metabolomics data; dates of RNA isolation, of hybridisation, and of labelling for transcripts) were set as random intercepts. The corresponding random effect estimate was subtracted from the measured level of each (metabolomic or transcriptomic) biomarker. The resulting 'denoised' data were used in the subsequent analysis.

6.3.6 Statistical analysis

6.3.6.1 Univariate analysis

Due to the repeated measurement design of the study a total of six observations (6 sets of omic profiles) were available for each participant. To accommodate this, a flexible multivariate normal (MVN) model was fitted to identify metabolic (van Veldhoven et al., 2019) and transcriptomic (Espín-Pérez et al., 2018) changes associated with exposure to TRAPs, using the `glis` function from the `nlme` package (Pinheiro et al., 2023). The variance-covariance of the residuals was defined with an unstructured correlation structure, with a constant covariance specified for each time (baseline, +2h and +24h) and site (Oxford Street or Hyde Park) combination.

A principal Component Analysis (PCA) performed on the metabolomic data for all 300 samples revealed five outlying samples, each coming from a different individual (Figure 6.1). The outliers were removed from the 300 samples and the remaining 295 samples were used for the subsequent regression analysis. To ensure the removal of the five outliers did not alter the findings, sensitivity analysis was performed on the MVN model by comparing the results when the 5 outliers were included and excluded. Both MVN models showed comparable results with the 5 outliers not showing a pattern in time points or locations.

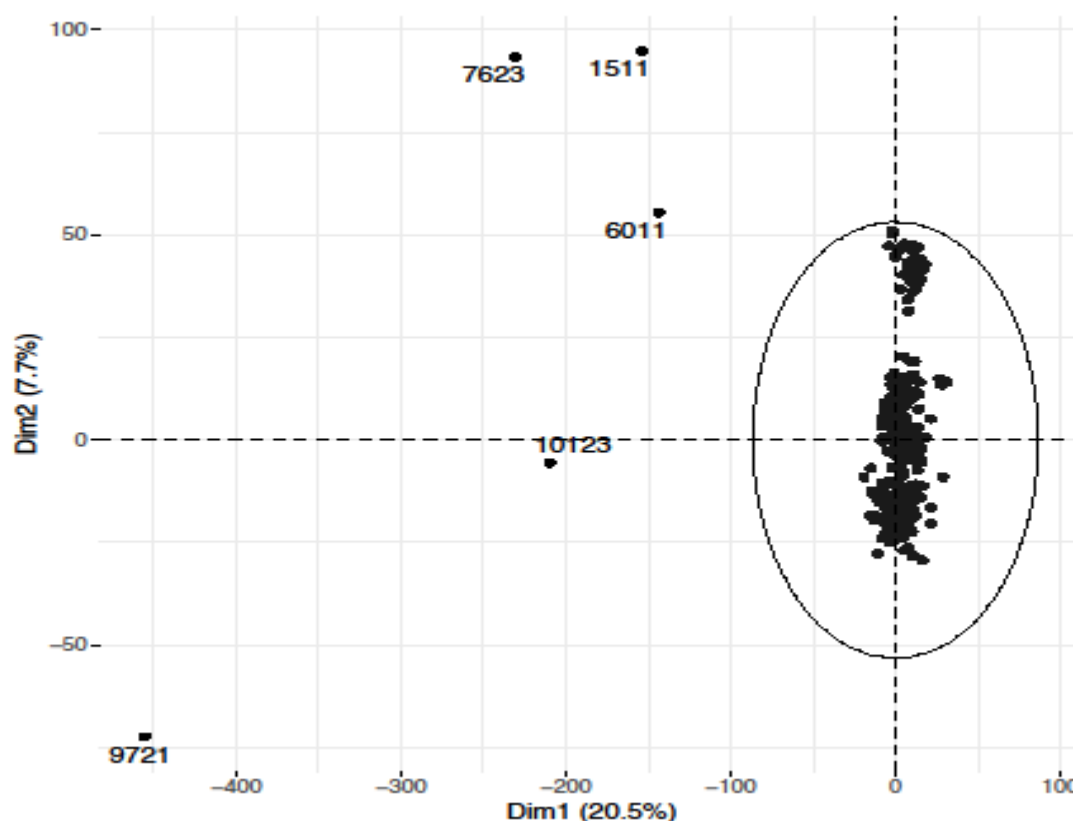


Figure 6.1: Score plots of the first (x-axis) and second (y-axis) principal components from principal component analysis (PCA) applied to the 300 metabolic profiles collected for the 50 participants. The 5 outlying observations are 1511, 6011, 7623, 9721 and 10123

Models for each of the TRAP exposures (PM_{10} , $PM_{2.5}$, NO_2 , BC and PNCT) were adjusted for sex, age, BMI and health group (COPD, IHD or healthy). Although caffeine intake and annual pollutant exposure were considered confounders in van Veldhoven et al., (2019) they were not included in this MVN model as they were not related to exposures. Correction for multiple testing was achieved using the Bonferroni approach, correcting for the effective number of tests (ENT) performed in the metabolomic and transcriptomic data ensuring a family wise error rate below 0.05. As previously proposed (Castagné and Chadeau-Hyam 2019) the ENT was proxied by the number of principal components needed to explain >99% of the variance of the full-resolution data: $n=299$ and $n=202$, for the metabolomic and transcriptomic data, respectively. As a more stringent alternative we also report the association for Bonferroni correction correcting for $n=6,040$ and $n=30,923$ tests for metabolomic and transcriptomic data, respectively.

6.3.7 Pathway analysis

Functional analysis of metabolomic features associated with each TRAP, was performed using the Mummichog algorithm (Li et al., 2013), using the MetaboAnalyst “functional analysis” (Pang

et al., 2021, MetaboAnalyst 2023). The output of the p-values and t-scores of each MVN model for each TRAP were used as the input for the Mummichog algorithm to perform an over-representation analysis with a mass tolerance of 8.0 ppm in positive mode, resulting in p-values for six pathways for each TRAP exposure using a Fisher's Exact Test. The default database on MetaboAnalyst was used, combining the KEGG, BiGG, and Edinburgh Models. The significant thresholds recommended by MetaboAnalyst, of 0.05 for PM_{2.5} and PM₁₀, 0.01 for PCNT and BC, and 0.005 for NO₂ were used in the analysis.

6.3.8 Conditional independence network

A conditional independence network approach was adopted to visualise the complex (partial) correlation structure across TRAP-associated metabolic features. To identify conditionally independent correlations between selected -omic features graphical LASSO (gLASSO) models were applied and calibrated using a stability based approach as implemented in the sharp r package (Bodinier et al., 2023). Briefly, the gLASSO was fitted to (n=500) independent 80% subsamples of the study population. For each subsample, several values of the penalty λ (controlling the sparsity of the graph) were considered, using a discrete grid. Edge selection proportion was calculated, for each value of the penalty parameter, as the number of times the edge was included across the 500 subsamples. For each combination of λ and threshold in selection proportion (π) over which edges are considered as stably selected, a likelihood-based stability score was calculated, and the most stable model was defined as the one maximising the score (Bodinier et al., 2023).

Due to the high correlation of metabolic features and to aid visualisation of the network, the MVN-selected Bonferroni significant metabolic features associated with TRAP exposure were dimensionality reduced through stability-calibrated consensus clustering over 500 (80%) subsamples of the study population (Bodinier et al., 2023) and the optimal number of clusters was calibrated so that it maximised the stability of the co-membership across sub-samples. Each resulting cluster was represented by its medoid. Metabolomic and multi-omic networks were estimated separately at three time points: 2 hours before (baseline), 2 and +24 hours after each walk.

6.4 Results

6.4.1 Data overview

The characteristics of the study population used in the Oxford Street study, who had full exposure data (n=50) stratified by health groups are reported in Table 6.1. The population comprised 18 healthy participants, 18 with COPD and 14 with IHD. There were overall more male (n=32) than female (n=18) participants, especially in the IHD group. The mean age of participants was 65.5 years and was similar across the three groups as were BMI, diastolic and systolic blood pressures.

Exposure to all TRAPs was all significantly higher in Oxford Street compared to Hyde Park (Figure 6.2). Although PM₁₀, PM_{2.5} and NO₂ concentrations in Oxford Street and Hyde Park showed some overlapping distributions, BC and PCNT had the most significant differences.

6.4.2 Metabolomic and transcriptomic markers of TRAP exposures

The MVN multivariate model, after adjustment for age, sex, BMI and health group, and using Bonferroni correction for ENT=299 tests identified 230 unique metabolic features associated with at least one TRAP exposure. Of these, 168 were associated with NO₂, 43 with BC, 18 with PCNT, 14 with PM₁₀ and 8 with PM_{2.5} (Figure 6.3). As a more conservative multiple testing correction and to improve interpretability a Bonferroni correction for the 6,040 metabolites tests was applied. This resulted in a unique set of 78 Bonferroni significant metabolic features associated with at least one TRAP exposure (Figure 6.3 and Figure 6.4 (A)).

Table 6.1: Characteristics of the study population with full exposure data in the Oxford Street II study (COPD: Chronic Obstructive Pulmonary Disease, IHD: Ischemic Heart Disease. P-values were calculated using a paired t-test.

	COPD (n = 18)	HEALTHY (n = 18)	IHD (n = 14)	Overall	p-value
Sex					
FEMALE	8 (44.4%)	9 (50.0%)	1 (7.1%)	18 (36.0%)	0.028
MALE	10 (55.6%)	9 (50.0%)	13 (92.9%)	32 (64.0%)	
Age					
Mean (SD)	67.7 (5.71)	64.1 (6.77)	64.5 (6.45)	65.5 (6.41)	0.661
BMI					
Mean (SD)	25.6 (3.88)	21.4 (3.41)	27.6 (4.28)	24.6 (4.58)	0.446
DBP (mmHg)					
Mean (SD)	152 (17.0)	136 (18.3)	126 (14.2)	137 (19.0)	0.26
SBP (mmHg)					
Mean (SD)	90.0 (7.62)	74.7 (9.08)	76.0 (9.02)	79.0 (10.6)	0.468

The dominant pollutant exposure was NO₂ accounting for 67 unique metabolite associations with PCNT, BC and PM₁₀ exposure accounting for 3, 3 and 1 exclusive associations, respectively. There were no significant hits exclusively linked to exposure to PM_{2.5}. A further two metabolomic features showed overlap between PM₁₀ and PM_{2.5}, with overlap between NO₂ and BC, and BC and PNCT each identified with one metabolite (Figure 6.4 A).

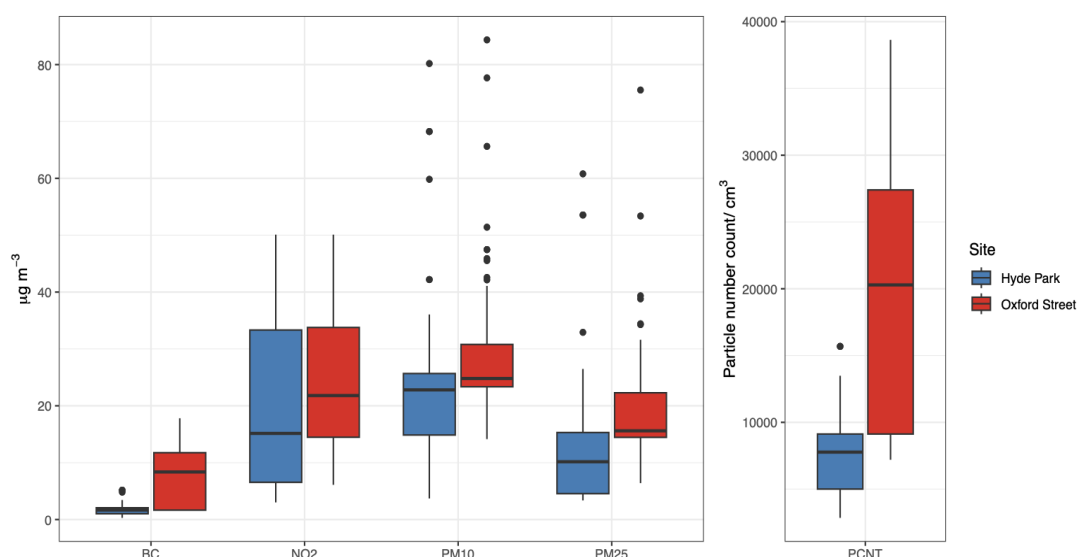


Figure 6.2: Boxplot summary of Traffic Related Air Pollutants (TRAP's) concentrations for BC, NO₂, PM₁₀, PM_{2.5} and particle number count (PNCT) for the participant exposure walks in Oxford Street (red) and Hyde Park (blue). The lower and upper hinges correspond to the 25th and 75th percentiles, the horizontal line to the median, and the whiskers to $1.5 \times$ the IQR (approx. 95% percentile).

This was consistent with previous analysis (van Veldhoven et al., 2019) where 29 metabolic features were significantly linked to TRAP exposure with 26 related to NO₂ exposure, including an overlap of 18 NO₂ associated features. Likewise, a small number of associations with PM₁₀ and BC were found with no unique associations with PM_{2.5}, with, unlike this study, no PNCT associations. In both studies associations to PM_{2.5} were only found in conjunction with PM₁₀. Minimal overlap of significant metabolic features was observed across TRAP exposures. Consensus clustering on these 78 features identified 63 clusters (Figure D 1), 52 of which included a single feature, 8 included 2 features, 2 included 3 features and 1, four features (Figure D 2). All TRAP-associated features, except one feature from cluster 56, had comparable retention times to other features from the same cluster, potentially indicating their structural proximity (Figure D 2).

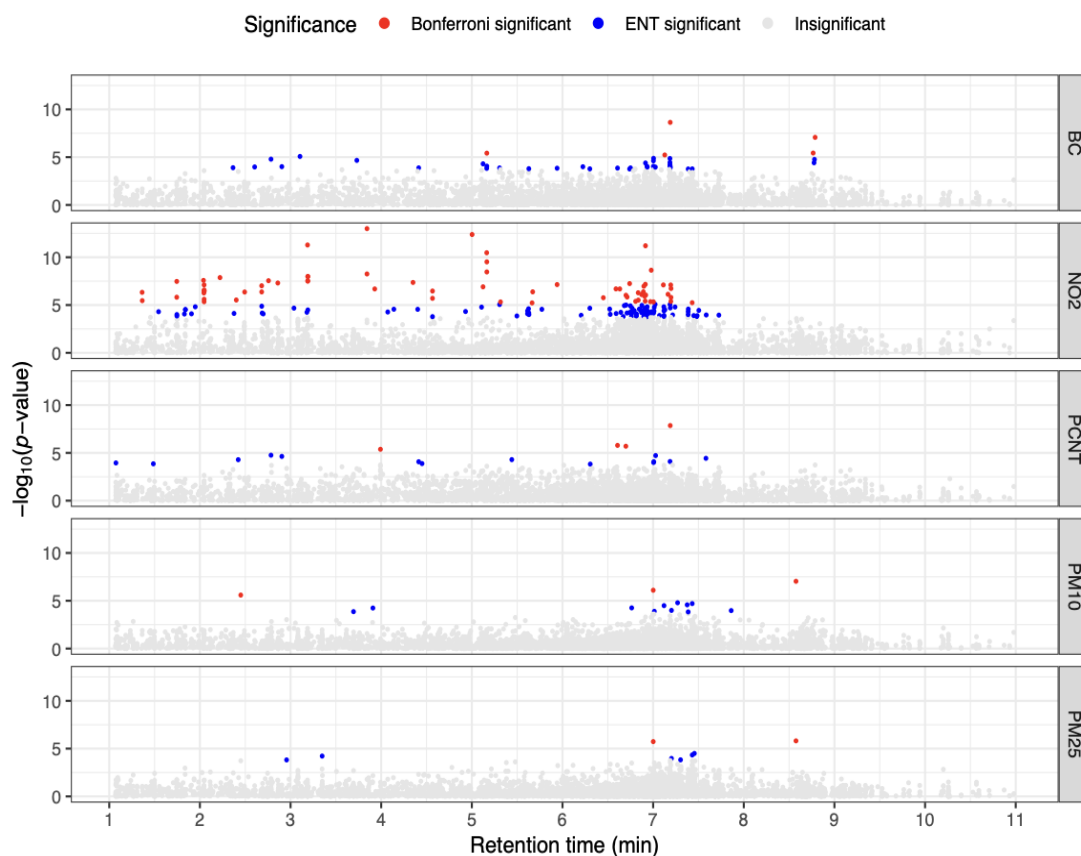


Figure 6.3: Manhattan Plots illustrating the association between metabolic features and each individual TRAP from the MVN univariate analysis. Distinctive plots are shown here for associations with BC, NO₂, PCNT, PM₁₀ and PM_{2.5} from top to bottom. Metabolic features are plotted by their retention time (min) and $-\log_{10}$ p-values from the MVN model. Features in red are significantly associated with TRAP exposure after Bonferroni correction, features in blue after Bonferroni correction ($n=78$) and using the ENT ($n=299$).

The analysis of mRNA data identified 53 unique mRNA differentially expressed transcripts in relation to at least one TRAP exposure (Figure 6.4 B). Of these, 29 were associated exclusively with exposure to NO₂. A total of 12, 6, 3 and 1 were uniquely associated with exposure to PM₁₀, PM_{2.5}, PCNT and BC respectively. Only one mRNA was found to be associated with exposure to BC. Two mRNAs were associated with exposure to both PM₁₀ and PM_{2.5} (Figure 6.4 B). Of these 53 TRAP-related mRNAs, 38 were mapped to a known gene (Table D 1).

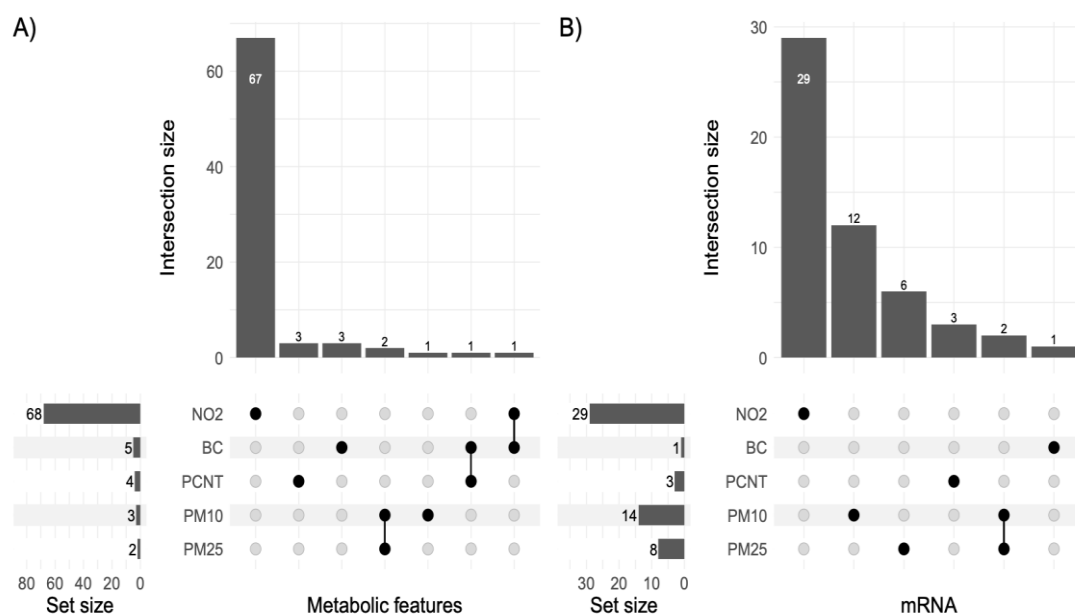


Figure 6.4: Upset plots indicating the number of unique metabolic features and mRNA significantly associated with at least one TRAP exposure in Oxford Street. Panel A. Illustrates the 78 metabolic features associated with at least one TRAP or combination of TRAPs from the MVN model and after Bonferroni correction. Panel B. Summarises the 53 significant mRNA associated to each individual TRAP from the MVN model and after Bonferroni correction using the ENT (n=202).

The differences in the results obtained in the present study and previous analyses (Espín-Pérez et al., 2018, van Veldhoven et al., 2019) can be explained by the refined modifications undertaken in the data cleansing processes undertaken, which is a key step in obtaining sound and solid results (Chadeau-Hyam et al., 2013, Tugizimana et al., 2016). Data cleaning in this study removed confounding due to residual noise from 'batch and array effects'. Furthermore, score plots from a principal component analysis (PCA) of 300 metabolic profiles of the 50 subjects revealed five outlying observations that were removed from the analysis (Figure 6.1), which were not removed by van Veldhoven et al., (2019). The differing approaches to data cleansing and exposure data have led to a greater number of metabolites features associated with TRAP exposure in this study and a lower number of mRNAs. However, in both approaches, NO₂ was found to be the dominant pollutant with minimal overlap between metabolomic markers of TRAP exposure, possibly suggesting exposure-specific metabolic pathways.

6.4.3 Pathway enrichment and annotations

The Mummichog algorithm was used to investigate how exposure to TRAP may affect various metabolic pathways using the full dataset of p-values and t-scores (n=6,040) generated from the MVN models for different TRAP exposures as inputs. Seven enriched metabolic pathways were

identified with an enrichment p-value < 0.05. Each of these pathways had at least four putative matches (Figure 6.5).

Molecular Pathways	Number of metabolites in pathway	Number of overlapping features	NO ₂	PCNT	BC	PM _{2.5}	PM ₁₀
De novo fatty acid biosynthesis	106	32	0.54	0.42	0.01	0.01	0.05
Tryptophan metabolism	94	63	0.02	0.58	0.45	0.99	0.39
Prostaglandin formation from arachidonate	78	60	1	0.65	0.66	0.02	0.05
Chondroitin sulfate degradation	37	4	0	1	1	1	0.28
Heparan sulfate degradation	34	6	0.03	1	1	1	0.19
Biopterin metabolism	22	9	0.16	0.17	0.01	0.68	0.19
Caffeine metabolism	11	10	0.02	1	1	0.74	0.95

p-value
■ < 0.05
■ < 0.1
■ >= 0.1

Figure 6.5: Functional analysis indicating the pathways associated with each TRAP exposure. Colours indicate the strength of the association (orange for p-value <0.5 and blue for p-value <0.1). Each pathway reported the number of features identified by the mummichog in the dataset for each pathway and the number of features included in the pathway as part of the mummichog database.

Among these identified pathways, one was linked to PM_{2.5} and PM₁₀ exposure (prostaglandin formation) and another associated to PM_{2.5}, PM₁₀ and BC (de novo fatty acid synthesis). NO₂ exposure was exclusively associated to four pathways (tryptophan metabolism, chondroitin sulphate degradation, heparan sulfate degradation and caffeine metabolism) and BC was exclusively associated with biopterin metabolism. There were no exclusive associations to PM_{2.5} and PM₁₀, with PNCT having no associations. The enriched pathways were further validated by performing detailed annotations on the selected features associated with TRAP exposure.

Out of 78 TRAP associated features, 33 metabolomic features were annotated (Level 1 Schymanski scale) (Table D 2). ((Schymanski et al., 2014) , representing 14 unique metabolites. All annotated features were associated with NO₂ exposure. Among these 14 compounds, four compounds (caffeine, phenylalanine and 2 acyl-carnitines) were found in van Veldhoven et al., (2019). Higher levels of Cortisol, Cortisone, Indoleacetic acid (IAA) and Indole-3-propionic acid (IPA) and lower levels of isoleucine were revealed in this new analysis to be associated with TRAP exposure. Although stress is known to elevate cortisol levels (Bertollo et al., 2020), stress levels were not measured and could not be used as a confounder in this study. These annotations confirmed three pathways identified by the Mummichog algorithm, Biopterin metabolism

(Phenylalanine), caffeine metabolism (Caffeine and Paraxanthine) and Tryptophan metabolism (IAA and IPA). The pathway analysis points to metabolomic alterations, particularly to oxidative stress perturbations, previously associated with TRAP exposures (Liang et al., 2023).

Tryptophan is an essential amino acid crucial to bodily processes, such as gastrointestinal functions, immunity, metabolism and the nervous system, and is essential for protein synthesis. It can be broken down through three primary pathways: kynurenine, serotonin and the indole pathway. Tryptophan is a precursor of kynurenine and is involved in oxidative stress and inflammatory pathways and the regulation of immunity, neuronal function and intestinal homeostasis (Davis and Liu 2015, Tsuji et al., 2023). In accordance with these findings, a recent review on the effects of air pollution on the metabolome has classified tryptophan as one of the most frequent pathways associated with air pollution exposure in the literature (Liang et al., 2023). The indole pathway, involving the gut microbiome, can degrade tryptophan into downstream metabolites like IAA and IPA through enzymatic reactions. The study results indicate that short-term exposure to NO₂ in TRAP significantly influences the indole pathway by increasing the levels of IAA and IPA.

To investigate this further, the metabolomic data was analysed for tryptophan and kynurenine, which is also central to tryptophan metabolism. Both compounds were found in the data from their mass and retention times. An imbalance in the kynurenine/tryptophan ratio has been associated to various diseases, including lung cancer risk (Chuang et al., 2014). Tryptophan was found to be positively associated with NO₂ exposure ($p=0.0000305$, $\beta = 0.0312$), while kynurenine was negatively associated ($p=0.00417$, $\beta=-0.0024$), indicating an imbalance linked to NO₂ exposure. Recent evidence suggests that air pollutants may influence the human biome (gut, lung and skin) (Mousavi et al., 2022).

Although the specific mechanisms are not well understood, changes in the gut microbiome due to TRAP exposure have been observed in normal weight, overweight and obese adolescents (Alderete et al., 2018, Fouladi et al., 2020) and asthmatic children (Zheng et al., 2020). This analysis also revealed Cortisone and Cortisol levels increasing after exposure to NO₂. In two recent studies (Sun et al., 2022, Wang et al., 2022), elevated levels of glucocorticoids were observed in PM exposed populations in rural China. Further evidence suggests a potential link between TRAP exposure and the activation of the hypothalamic-pituitary-adrenal axis (HPA),

which releases glucocorticoids and induces gut microbiome dysbiosis (Cerdá et al., 2016, Pan et al., 2021, Sun et al., 2022), aligning with findings from this study.

6.4.4 Metabolomic network analysis

To understand how TRAP associated metabolic features are correlated with each other, conditional independence network models were applied to the 63 metabolic clusters significantly associated with at least one TRAP at each time point (Figure 6.6) and were calibrated via stability (Figure D 3). The organisation of the nodes was kept identical between the 6 networks to allow comparison of the appearing and disappearing edges. Metabolic features were coloured by their association to a TRAP (Figure 6.6 A) or according to their involvement in Mummichog pathways (Figure 6.6 B). The network constructed using data measured two hours before each walk (baseline) may be interpreted as an individual's metabolomic status for the TRAP related features immediately before exposure. Comparing the network topology before and after the walks provides insights into acute and lagged exposure related effects in metabolomic profiles following exposure. The baseline network reveals that metabolomic clusters associated with different TRAPs are not necessarily interconnected (Figure 6.6 A) and some pathways may be shared among TRAP related metabolomic features (Figure 6.6 B).

The network topology constructed two hours after exposure resembles the baseline network, indicating modest or local changes in the correlation structure across metabolic features. However, several notable changes, particularly in modules containing Lyso PE, were observed suggesting potential pathway modifications and alterations associated with TRAP exposure. In the network inferred 24 hours after exposure, some restructuring is seen with some correlation patterns reverting back to their pre-experiment state. Certain correlations, such as those involving the Lyso PE module, remain altered even 24 hours after exposure, which may be suggestive of potential pathway modifications and alterations associated with TRAP exposures on the metabolome. Thus, as it was not possible to annotate all significant features it was not possible to go further in the biological interpretation of the pathways. Additionally, some new edges appeared in the network 24 hours after exposures, such as edges involving cluster 38, potentially an indication of the lagging effects of TRAP exposures.

A multi-omic conditional independence network was constructed combining the 63 metabolomic clusters with the 38 annotated mRNA (out of 53 TRAP related mRNAs) (Figure 6.7). Similar to

the metabolomic network, the multi-omic network was constructed for each of the three timepoints (-2 hours, baseline, +2 hours and + 24 hours) and calibrated via stability (Figure D 4).

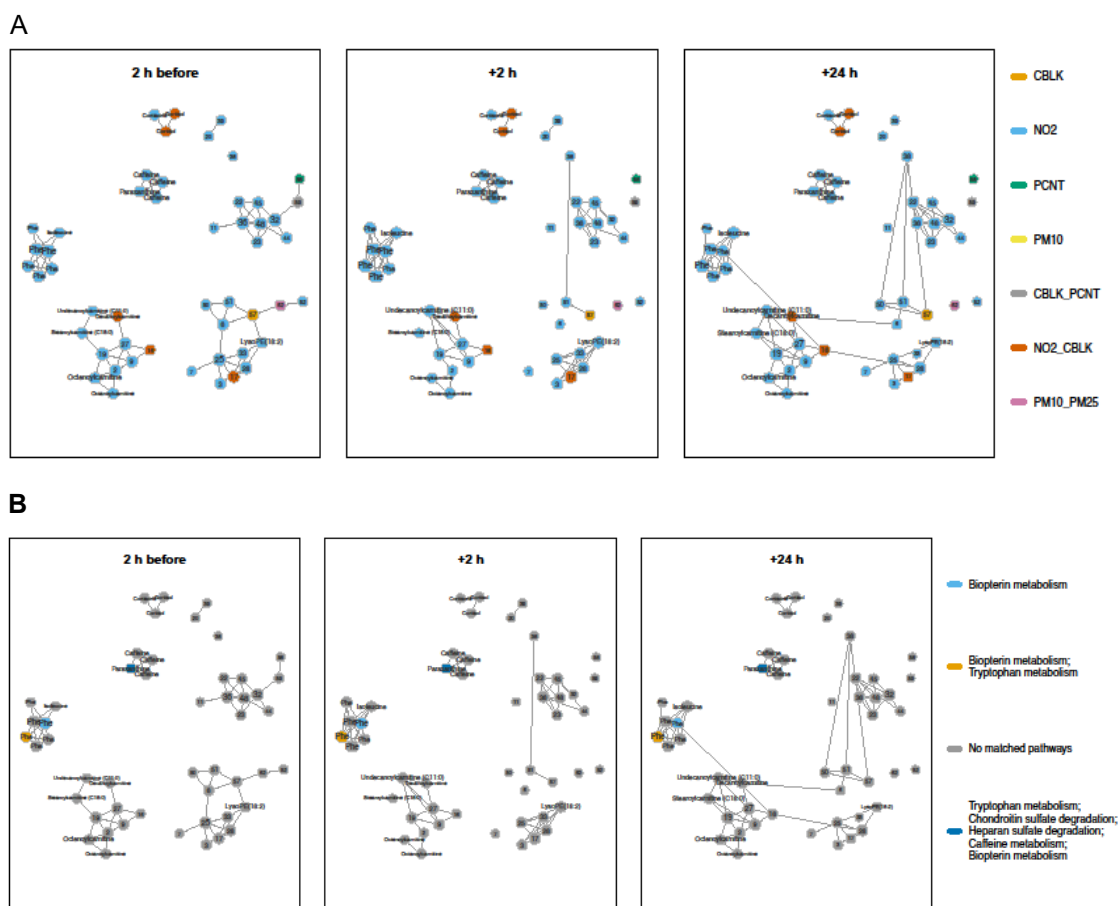


Figure 6.6: Conditional independence network on clusters of metabolic features significantly associated with TRAP exposure, at 2 hours before visits and -2 hours (baseline) 2 and +24 hours after visits. Each node represents a feature or cluster of features and each edge represents a correlation between two features conditional on all other features. Panel A shows nodes coloured by association to each TRAP exposure. Panel B shows nodes coloured by association to one or multiple pathways enriched with the mummichog tool.

The baseline network identified four cross-omic edges between metabolomic clusters and specific mRNAs. The four cross-omic edges identified were between cluster 8 and SDR42E1, cluster 20 and TMEM38A, cluster 19 and RNU11 and between Octanoylcarnitine (cluster 38) and SR3PXD2A. The network topology was substantially modified two hours after exposure with these cross-omic edges disappearing from the network and new cross-omic links being estimated between clusters 17 and 57 and GOS2, between cluster 6 and GOS2 and TMEM38A and between Octanoylcarnitine and DMRTC1. Twenty-four hours after exposure two additional cross-omic edges were observed IPA and cluster 6 and 57 with GOS2 edge Undecanoylcarnitine with MPRIP. There were eight cross-omic edges that reverted to pre-exposure (baseline) status after being perturbed by TRAP during the exposure walk. These were clusters 3 and 33, 3 and LysoPE,

9 and Undecanoylcarnitine, Phenylalantine and Phenylalantine, 17 and LysoPE, 25 and LysoPE, 36 and 44 and 44 and 45. These changes indicate possible short-term acute effects of TRAP exposure. Although no specific functions were associated with these mRNAs, the involvement of GOS2 has been found in multiple metabolism regulation pathways, including lipid metabolism (Heckmann et al., 2013). The network potentially suggests a perturbation in lipid metabolism, in association with IPA and carnitines, linked to gut permeability and microbiome activity.

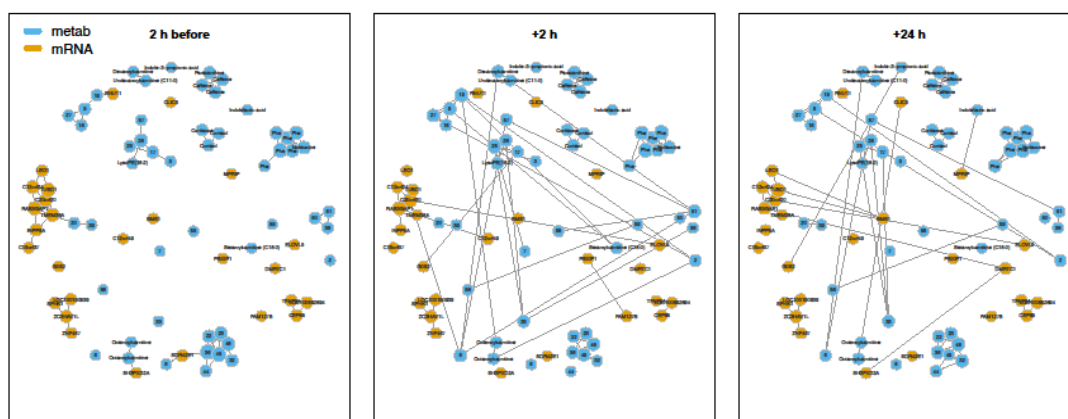


Figure 6.7: Conditional independence network of 63 clusters of metabolic features and 38 mRNA features significantly associated with TRAP exposure, at baseline -2 hours (baseline) before exposure walk, 2 hours and +24 hours after the exposure walk. Each node represents a feature or cluster of features and each edge represents a correlation between two features conditional on all other features.

The conditional networks revealed that the same metabolites were involved in multiple pathways, highlighting the complexity and intricacy of mechanisms associated with TRAP exposures. Two-hours after exposure different topologies in the network were seen in the leukotriene and linoleate pathways. These pathways were not restored to their initial states 24 hours after exposure potentially indicating acute and longer-term effects of TRAP exposure. Interestingly, exposure to particulate matter did not share common pathways with other TRAP exposures, potentially suggesting distinct effects for PM exposure. Overall, most of the pathways associated with TRAP exposure in this study were related to increased oxidative stress and inflammation, in accordance with existing literature on the effects of exposure to TRAP pollutants.

6.5 Conclusion

The Oxford Street study had a complex study design (similar to the MRC study) and it provided an opportunity to develop a new methodology to analyse high throughput metabolomic and transcriptomic data in three different health groups over multiple time points. Using metabolomic

and transcriptomic data derived from previous studies by van Veldhoven et al., (2019) and Espín-Pérez et al., (2018) a new methodology was developed to re-analyse this data.

This work has investigated multi-omic signatures from exposure to TRAP in participants taking part in a crossover study in two distinct locations in London. The study encompassed vulnerable participants with COPD and IHD and those with healthy lung function and many metabolomic and mRNA alterations associated with TRAP exposure have been uncovered. This novel research combines metabolomic data and transcriptomics data collected from the same individuals at multiple timepoints, shedding new, unique insights onto potential multi-omic changes associated to TRAP exposure. The hypothesis of a connection between NO₂ exposure and the balance of tryptophan and kynurenine is strongly supported by this investigation. This underlines the influence of air pollutants on the human biome, providing compelling evidence of a potential impact on the gut microbiome dysbiosis due to short-term NO₂ exposure.

The methodology developed in the Oxford Street study to investigate multi-omic signatures from TRAP exposure could be applied to the MRC subway study to give an insight into how metabolomic features and mRNAs may be associated to exposure to subway air. The Oxford Street study and the MRC study have many similarities. Both studies used a vulnerable population. Oxford Street used COPD and IHD participants and the MRC study used COPD participants with both studies using a healthy control group. There are two differing study locations in each study with the subway and overground train journeys being used to replicate Oxford Street and Hyde Park. Although PM_{2.5}, PM₁₀, NO₂ and PNCT were measured in both studies, O₃ was additionally measured in the MRC study with no measurements of BC, which was measured in the Oxford Street study. Exposure measurements on the railways were taken with higher quality instrumentation that was placed between the stationary participants. This was not possible in Oxford Street as each participant was accompanied by a researcher who carried a backpack containing the instrumentation whilst the participants were walking. In the Oxford Street study, NO₂ was measured by a fixed monitoring site on Oxford Street that was passed repeatedly as the participants walked along Oxford Street, although this would not have provided accurate personal exposure measurements of NO₂ at all points of the walk away from the monitor. Additionally, in Hyde Park, measurements of NO₂ were taken from measurements at the North Kensington background site as a proxy for NO₂ exposure in Hyde Park. It is likely that exposure

measurements taken during the MRC study better reflected the personal exposures of the participants during the exposure trials.

The same time points, in the MRC and Oxford Street studies, were used for all physiological and health outcome measurements, including blood serum measurements which were taken at baseline, 2-hours and 24-hours post-exposure in both studies. Due to the repeated measurement design a total of six observations (6 sets of omic profiles) were available in both studies for each participant. The flexible multivariate normal (MVN) model which was fitted to identify metabolic and transcriptomic changes associated with pollutant exposures (using the `gls` function from the `nlme` package), in the Oxford Street study could be used in the MRC study. There would be no changes required in the confounders of the study (age, sex, BMI and health group), with minor changes to exposures (O_3 replacing BC). The repeated study design incorporated into the statistical model was replicated in each study design.

Using the models developed for the Oxford Street study use in the MRC study would allow the combining of metabolomic clusters and annotated mRNAs to identify biological pathways linked to inflammation and oxidative stress following exposure to subway air. The methods described in the Oxford Street study could be applied to the MRC study to further understanding of the health effects of subway exposure on the molecular and biochemical pathways involved.

Chapter 7 Discussion and conclusion

7.1 Summary

The aim of this thesis was to provide high-quality reference grade data for a MRC funded study investigating “Exposure to particulate matter on the London Underground in healthy subjects and participants with Chronic Obstructive Pulmonary Disease (COPD)”. Providing this data required an extensive long-term measurement campaign on the London Underground and London Overground from 26 January 2022 to 19 July 2023. This involved 108 train journeys, 53 subway journeys and 55 overground journeys. This is the first study to present such a large and extensive dataset of air quality in a subway system anywhere in the world including measuring all fractions of PM, NO₂ and O₃ simultaneously. The sampling campaigns yielded an exposure assessment of the subway environment over repeated journeys providing valuable information of PM_{2.5} concentrations, PM size fractions and particle number counts, NO₂ and O₃ concentrations, as well as the chemical composition and toxicity of subway PM_{2.5}.

This chapter revisits the aims and objectives of the thesis and seeks to build on the main literature gaps identified in the literature review in Chapter 2. The strengths and weaknesses of this study will be discussed and the final section provides evidenced-based proposals on mitigation and reducing commuter personal exposures in the London Underground and future directions for research.

The MRC study cohort comprised participants with at least GOLD stage 2 COPD (n=36) and healthy lung function participants (n=47) who were required to have personal exposures measurements of all fractions of PM, NO₂ and O₃ taken at all times on the train journeys. By measuring the gaseous pollutants, the effects of these pollutants on health can be disentangled from PM_{2.5} to understand which pollutants are most responsible for any health effects arising from subway exposure. This was vital in understanding any effects on health from linking the health responses of the participants to subway exposures.

Chapter 3 set out how this was achieved and how the challenges in measuring pollutant concentrations over many months in the diverse environments of subway and overground train carriages were overcome. Data was required that was consistent and comparable across the two measurement locations with instruments required to be battery powered due to the lack of power

in the carriages. The correct instrumentation and developing a method of transporting the sampling equipment in train carriages led to the deployment of a Mobile Reference Station (MoRS) that was built, developed and adapted for this study. MoRS made use of the miniaturisation and reduced power requirements of higher quality measurement approaches similar to those used in fixed measurement stations bridging the gap between static reference monitoring stations and easy to use and portable low-cost sensing technologies.

To achieve a high data capture rate a robust QA/QC programme was required that maintained consistency, comparability, completeness, transparency, and accuracy of the measured data throughout the measurement campaign. This included a comprehensive set of laboratory and field experiments that were undertaken to ensure accurate responses of the instruments in environments representing the differing exposures that were encountered in the two distinct measurement environments. In addition to field intercomparison campaigns, scaling factors for each instrument were derived from co-locations alongside reference instrumentation.

The intercomparisons showed MoRS had good agreement ($\pm 20\%$) with the SMPS at the fixed ambient measurement locations of Honor Oak Park, North Kensington and Marylebone Road and for the subway at Hampstead station using a Dekati ELPI*.

During the intercomparison field campaigns, source-specific scaling factors were derived for the Mini-Wras at each site for use in the subway and overground. As it is known that the particle density of subway $PM_{2.5}$ is greater than ambient air a source specific scaling factor was required for subway $PM_{2.5}$. Using Deming regression, a regression slope of 3.14 was calculated following a co-location of the Mini-Wras alongside a Partisol 2020 on the platform of Hampstead subway station. To reflect that subway particles consist of a mixture of subway air and ambient air, subway and urban background scaling factors were proportionally applied to the tunnelled sections of the subway as proposed by Smith et al., (2020). The field intercomparison campaigns and source specific scaling factors derived for Mini-Wras measurements in the subway gave confidence that the aim of the thesis in providing high-quality reference grade data in subway and overground train carriages had been achieved.

A long-term exposure assessment of the Bakerloo line was outlined in Chapter 4. The exposure assessment of PM, NO_2 and O_3 from 26 January 2022 to 19 July 2023 including 35 Bakerloo line return journeys from Willesden Junction station to Elephant & Castle station were assessed

making this dataset one of the most comprehensive to date. This allowed the factors and processes affecting PM_{2.5}, NO₂ and O₃ concentrations in the subway to be investigated. A methodology was developed to align the spatial and temporal variation on each individual subway journey by chunking the journeys into discrete distances for each time point on the journey providing an insight into factors affecting spatial and temporal variability of pollutants in the subway. This allowed a statistical analysis to be conducted on the subway measurements to identify interactions between PM_{2.5} and NO₂ throughout the tunnelled sections of the subway journeys.

In the tunnelled sections of the Bakerloo line mean PM_{2.5} concentrations of 321 µg m⁻³ (with maximum concentration of 493 µg m⁻³ recorded at Marylebone station) were amongst the highest recorded worldwide in a subway line. Significant differences were found dependant on the direction of travel, despite tunnel depth being similar in both directions. This implies that ventilation is likely to be different in the two distinct tunnels in which the train was travelling. A better understanding of the ventilation in the return tunnel, if applied to the outbound tunnel, could help to reduce PM_{2.5} concentrations on the outbound journey. A correlation of -0.47 was found between PM_{2.5} and NO₂ suggesting that ventilation was lowering PM_{2.5} concentrations where there was an influx of ambient air into the tunnels. It has been shown that the deepest tunnels have significantly higher PM_{2.5} and lower NO₂ concentrations with a high correlation between tunnel depth, PM_{2.5} and NO₂. Further measurements of NO₂ and NO_x could help to further understanding and improve ventilation in subway tunnels to lower PM_{2.5} concentrations.

For the first time the use of PM_{2.5} size distributions and particle number counts were used to identify possible sources and processes influencing concentrations in the subway. This provided evidence that PM_{2.5} settling processes play a key role, along with ventilation and tunnel depth, in driving PM_{2.5} concentrations through train movements. It was shown that the nucleation mode could be a marker for ambient air in the subway. However, the correlation between the nucleation mode and NO₂/NO_x (as a proxy for ambient air) was weak and together with data from Hampstead station this suggests that train related emissions from the release of very fine brake dust, spark discharges and high temperature release of metals from the wheel/rail interface could be contributing to the nucleation mode in the subway. This confirms previous findings that the nucleation mode in the subway is a mixture of ambient and subway generated particles. Railway related emissions were also found in the Aitken and accumulation modes confirming previous

research that suggested railway related emissions occur principally at a size mode of 170nm and railway related mechanical wear between a size range of 100 – 500 nm. It was found that 82% of subway particles were ultrafine particles and 99% of particles were below 530 nm, confirming the importance of measuring in these fine particle ranges. Coarse particles, together with larger particles in the accumulation mode, were confirmed to constitute the majority of PM_{2.5} mass. This chapter gave an improved understanding of the factors and contributing sources that are responsible for the high PM_{2.5} concentrations found on the Bakerloo line.

Chapter 5 sets out the methodology and results outlining the chemical composition and oxidative potential analysis of PM_{2.5} on the Bakerloo and Jubilee lines. PM_{2.5} filter samples were collected during each train journey during the MRC study onto two separate filters for chemical and oxidative potential analysis. The filters were quartered and incubated in separate assays of ascorbic acid (AA) and reduced glutathione (GSH) to determine the capacity of subway PM_{2.5} to deplete these antioxidants as a reflection of the ability of subway PM_{2.5} to elicit oxidative stress at the air-lung interface. Bakerloo line PM_{2.5} was able to deplete OP^{AA} to a greater capacity than the NIST positive control and in a similar capacity to the NIST positive control for OP^{GSH} depletion.

When normalised on a per unit mass basis, OP^{AA} µg⁻¹ and OP^{GSH} µg⁻¹ for the Bakerloo line showed a similar depletion to the Barcelona study (Moreno et al., 2017) but greater than found at background and roadside sites in London (Kelly et al., 2011). Similar results were found for OP^{AA} and OP^{GSH} per unit volume of air (m⁻³) for the Bakerloo line in comparison to Barcelona and London. The Jubilee line capacity to deplete the two antioxidants was generally lower than the Bakerloo line except for mass normalised depletion of OP^{GSH} which showed increased depletion, although for all assays it was lower than the positive NIST control. Despite this, the Jubilee line displayed a greater capacity to deplete OP^{AA} and OP^{GSH} than London background and roadside sites.

It is known that subway PM_{2.5} is dominated by Fe and other transition metals derived from train related emissions in the subway. Correlation plots between OP^{AA} and OP^{GSH} per unit mass and metal concentration on the same basis showed highly significant positive correlations between Al, B, Ba, Co, Cr, Cu, Fe, K, Mn, Mo, Ni, Pb, Ti and V. There was less correlation between OP^{AA} and OP^{GSH} and metals per unit volume with Al, Fe, Ni, Ti and Zn being significant for OP^{AA} m⁻³ and only Se being significant for OP^{GSH} m⁻³. A high number of transition metals were found to be

correlated to antioxidant depletion per unit mass on the Bakerloo line and it could be there is a synergy of metallic reactions causing the depletion of OP^{AA} and OP^{GSH} , rather than just Fe alone. There were no significant correlations in the Jubilee line. The results found on the Bakerloo line were different to those found in Barcelona. This could have been due to the higher $PM_{2.5}$ concentrations in the Bakerloo line and the Barcelona study not normalising metal concentrations for $PM_{2.5}$ mass and the volume of air and taking measurements at six different platforms with differing $PM_{2.5}$ concentrations.

The results show that Bakerloo line $PM_{2.5}$ was able to deplete OP^{AA} greater than the positive NIST control and deplete OP^{GSH} at a similar rate to the NIST control. There was a strong positive correlation between OP^{AA} and OP^{GSH} and transition metals, per unit mass in the Bakerloo line. Both the Bakerloo and Jubilee lines had the capacity to deplete OP^{AA} and OP^{GSH} in excess of London background and roadside sites when normalised for mass and volume. These results imply that subway $PM_{2.5}$, particularly the Bakerloo line, has the capacity to drive the oxidation of antioxidants and induce oxidative stress at the air-lung interface, in a similar way to roadside $PM_{2.5}$ and the toxicity of subway $PM_{2.5}$ needs further exploration. This suggests there is a need to further investigate the relationship between the effect of subway PM emissions and sources on the oxidative potential of subway $PM_{2.5}$ to better understand the link between subway $PM_{2.5}$ and health.

The MRC study was based on the protocols from the Oxford Street study (Sinharay et al., 2018). During the Oxford Street study vulnerable participants with COPD or IHD and healthy participants walked for two hours in either a street heavily polluted from diesel emissions or in a large park. Blood samples were taken from the participants at three time points which were 2 hours before exposure (the walk) (baseline) 2 hours and +24 hours after exposure. The MRC study replicated this by using heavily polluted subway trains and less polluted overground trains. In the MRC study the train journey replaced the walks, with blood taken from the participants at the same time points. An exposure assessment of the subway and overground journeys has made available a full dataset of PM, NO_2 and O_3 exposure concentrations which could be used in a multi-omic study combining metabolomics and transcriptomics from each participant, to identify multi-omic modifications associated with exposure to subway air.

The Oxford Street multi-omic study provided a methodology for a multi-omic analysis of metabolomic and transcriptomic data derived from the MRC study participants blood samples. The statistical analysis outlined could be used for repeated measurements in a multivariate normal model (MVN) to identify omic changes associated with exposure to subway air pollutants. The MRC study provides a richer exposure dataset than the Oxford Street study with personal exposure measurements of additional pollutants. The pathway analysis developed using the Mummichog algorithm provides a mechanism to identify metabolomic pathways associated with subway exposure with the potential of annotations to identify any metabolomic and transcriptomic features identified in the analysis.

The conditional independence network developed for the Oxford Street study for metabolomic, transcriptomic and multi-omic networks at the three measured time-points gave insight into how metabolomic features and mRNAs were associated with traffic related air pollution (TRAP) exposure. This combined metabolomic clusters and annotated mRNAs allowing biological pathways linked to inflammation and oxidative stress to be identified. This methodology could be expanded to the MRC study providing a unique insight into the health effects of subway exposure on the molecular and biochemical pathways involved.

7.2 Strengths and limitations

7.2.1 Strengths

A major strength of this study were the repeated journeys that took place on the Bakerloo line providing one of the most comprehensive datasets of subway exposure to date. As part of the only panel study of this magnitude to take place in a subway environment, simultaneous measurements of all fractions of PM, NO₂ and O₃ were taken over 44 Bakerloo line journeys (and seven Jubilee line journeys). The measurements took place in train carriages, where passengers spend the majority of their time when travelling in the subway. This gave a new insight into these pollutant concentrations and the factors and influencing sources affecting concentrations. The low variability of PM_{2.5} during the subway train journeys (shown by the small confidence intervals over the repeated journeys), suggests that PM_{2.5} in the tunnelled subway environment may be stable over time. This implies that repeated personal exposure measurements may not be required in subway health studies for each journey although physiological and health outcome measurements would be required for each journey. Further analysis of the implications of the low

PM_{2.5} variability on the repeated journeys would be required to understand the implications for future health studies.

The instrumentation used in this study allowed high quality, reference grade data to be collected for all three pollutants. No previous study has collected these three pollutants simultaneously to understand, in particular, the interaction between all PM fractions and NO₂. MoRS proved highly effective at measuring these pollutant concentrations. The adaptability of MoRS allowed the mask wearing status of participants to be mimicked to allow the study to continue through the Covid-19 mask wearing mandates. This adaptability also allowed the evolution of MoRS to continue a high data capture rate and to deliver on the aims of this thesis in providing participant personal exposure measurements for the MRC study. By measuring all size fractions of PM, a full understanding of changes in particle number counts and particle size distribution throughout the Bakerloo line could be determined helping to reveal sources and factors affecting PM_{2.5} concentrations.

The comprehensive QA/QC programme ensured the MoRS instrumentation was thoroughly evaluated through a planned programme of testing involving standardised technical activities performed in the laboratory and field. The laboratory and field intercomparisons of the Mini-Wras with reference instrumentation showed the strengths and weaknesses of the Mini-Wras in accurately reporting PM size fractions and particle number counts. The Airyx ICAD was maintained through regular baseline checks with a Purafil Chemisorbant / activated charcoal scrubber and NO₂ and NO standard gases. The derivation of source-specific scaling factors to apply to measured PM_{2.5} is often overlooked in subway studies but is vital in obtaining trustworthy data due to the greater density of subway PM_{2.5} in comparison to ambient air.

Although filter samples are often collected in the subway, the collection is often performed on station platforms with high volume samplers, rather than in train carriages. Collecting PM_{2.5} mass onto filters in train carriages gave a more accurate assessment of commuters personal exposure to the metal constituents and toxicity of PM_{2.5}. An analysis of the association between the oxidative potential of subway PM_{2.5} and the chemical composition of PM_{2.5} was able to show the strong positive correlations between antioxidant depletion and subway derived metals per unit mass, especially transition metals. This potentially suggests that subway PM_{2.5} could have a

similar capacity to drive the oxidation of antioxidants and induce oxidative stress at the air-lung interface as roadside PM_{2.5} and merits further investigation.

The use of the methodology developed for the cross-omic study of the Oxford Street data provides an original insight into investigating the molecular and biochemical pathways involved in any health effects from travelling on the London Underground. The similarities between the design of the Oxford Street study and the MRC study allow the models developed for the Oxford Street study to be used in the MRC study and it is recommended that a pilot study using blood serum from the MRC study be used for a metabolomic, transcriptomic and multi-omic study of subway air. In the MRC study participants wore noise cancelling headphones to reduce stress from noise in the subway. Other measures related to stress such as the number of passengers in the carriage, light and green spaces were not recorded.

7.2.2 Limitations

Due to a combination of Covid-19 restrictions and delays in obtaining permission to travel from Transport for London, the start of the MRC study was delayed until 26 January 2022. On the commencement of the study there were further delays as only one participant could undertake an exposure train journey from 26 January 2022 to 25 April 2022 due to there being no research nurse in place. Although 83 participants took part in the study (36 with COPD and 47 healthy participants) over 108 train journeys, the studies statistical power was based on 120 participants (60 with COPD and 60 healthy participants). Having the full number of participants would have allowed more train journeys and a larger exposure dataset increasing statistical power.

Although MoRS was adapted to mimic the mask wearing status of the participants, mask wearing, outside of the mandatory period, is not representative of commuter exposure. Due to the travel mandates on mask wearing, 10 of the 44 Bakerloo line journeys and 5 out of seven Jubilee line journeys took place whilst wearing a mask. Mask wearing was shown to reduce PM_{2.5} concentrations meaning that the journeys undertaken by the participants wearing a mask were not included in the analysis. This particularly affected the Jubilee line journeys as it was not possible to undertake an analysis based on two non-masked journeys.

7.3 Subway air quality implications

This extensive study provided a comprehensive assessment of PM in the Bakerloo line and insights for research on other London Underground deep-tunnelled lines. Furthermore, the results

and methodologies adopted may be useful in helping to understand and improve air quality in subway systems in London and worldwide to reduce PM exposure whenever technically possible.

Mean PM_{2.5} concentrations in the tunnelled sections of the Bakerloo line were 321 µg m⁻³, which would represent a daily incremental increase of 12 µg m⁻³ over their usual exposure for a passenger travelling for one-hour on the Bakerloo line. This represents an annual incremental increase of 7.9 µg m⁻³ in PM_{2.5} exposure. These estimates are in line with previous studies (Seaton et al., 2005, Saunders et al., 2019) although it is important to recognise that the health effects of subway travel are unknown and it is not possible to confer WHO air quality standards to the subway. However, it has been shown there is a 6% increase in relative risk for each 10 µg m⁻³ increase in long-term PM_{2.5} (Pope et al., 2004), which could suggest a typical commuter would have a 7% increase in risk for cardiovascular mortality. Although there is an absence of data indicating the relative risk of subway travel, the results indicate that the Precautionary Principal (Publications Office of the European Union 2017) calling for mitigation effects should operate to protect workers and commuters.

The results from the oxidative potential analysis of OP^{AA} and OP^{GSH} suggests that subway PM_{2.5}, especially from the Bakerloo line, had the capacity to deplete OP^{AA} greater than the positive NIST control and for OP^{GSH} by the same amount as the positive NIST control following incubation. Subway PM_{2.5}, on the Bakerloo and Jubilee lines, showed elevated OP^{AA} and OP^{GSH} depletion compared to London background and roadside sites per unit mass and unit volume of air, suggesting a need to further investigate the ability of subway PM_{2.5} to induce oxidative stress at the air-lung interface.

On the Bakerloo line the return journey was found to have significantly lower PM_{2.5} concentrations than the outbound journey. The reasons for the differences in PM_{2.5} and NO₂ concentrations on the outbound and return Bakerloo line journeys should be further investigated to understand the differences in ventilation to potentially reduce outbound PM_{2.5} concentrations. The outcomes could be applied to other deep-tunnelled lines.. Improved ventilation lowers PM_{2.5} concentrations in the subway and upgrading the ventilation system, possibly through increased extraction fans in the ventilation shafts along the tunnels, could improve air quality.

The trains on the Bakerloo line are the oldest on any network in the UK and upgrading this rolling stock to include train carriage ventilation systems with forced air supply would lower PM_{2.5}

concentrations. New rolling stock could lower braking emissions by having a rheostatic or regenerative braking system.

The results expressed in this thesis are especially important to understand the exposure of passengers to subway PM and any inherent health effects. This study provides a basis to begin to effectively control specific train related emission sources and to improve air quality management in the London Underground. This work can provide a tool to move towards a reduction of PM_{2.5} concentrations in the subway and encourage the application of practical and focused air quality mitigation strategies in the London Underground and worldwide subway systems.

7.4 Future research and recommendations

This research has helped to strengthen the understanding and characterisation of particulate matter particle number counts, particle size distributions, concentrations, chemical composition and toxicity as well as providing an extensive understanding of personal exposure of passengers travelling on the Bakerloo line. Recommendations can be made to Transport for London for the London Underground and for worldwide subway systems based on this research and current established research. This can help future work and to answer outstanding questions in improving subway air quality. The age of the London Underground presents challenges to immediate modifications but there are short-term solutions that could be adopted to inform future improvement work.

- There should be an increase in the sampling of PM, and possibly NO₂, in the London Underground to ascertain the causes of the fluctuations in PM_{2.5} found in this study. PM_{2.5} concentrations varied throughout the Bakerloo line and although there was a relationship with tunnel depth the reasons for these fluctuations were more than tunnel depth alone. Spatial variation of PM in the London Underground could be further understood by following the examples of Paris and Seoul in having continuous monitoring of key pollutants. This could be throughout the deep tunnelled lines, including on platforms, in train carriages and in tunnels to provide an evidence-based approach to understanding sources and factors affecting concentrations. The establishment of a real-time, system-wide monitoring network can raise awareness of the effects of air quality interventions on subway air quality.

- The use of air purifiers on platforms has been extensive in Seoul and although more research into their effects on air quality on platforms and train carriages is required air purifiers could offer a solution to reducing PM concentrations if adopted. Research should be carried out into their effectiveness in the subway.
- Spatial variability of PM_{2.5} on platforms could be investigated to further understanding of the factors affecting concentrations along the platform. An insight into how ventilation on platforms affects PM_{2.5} concentrations could help in mitigation on platforms and more widely throughout subway lines and the network.
- Improved tunnel ventilation could be investigated with additional fans and increased flow. Together with a monitoring system to investigate its effectiveness, experimental ventilation systems could be trialled.
- The upgrading of rolling stock has been shown to lead to significant improvements in air quality (Van Ryswyk et al., 2021). This could be prioritised on the lines with the oldest trains and the worst air quality. New rolling stock should be fitted with air conditioning within a closed system that does not allow open windows as air conditioning within train carriages has a clear beneficial effect on air quality (Moreno et al., 2017)..
- An assessment of air quality on the newly opened Elizabeth Line could demonstrate the effectiveness of platform screen doors and ventilation systems as a benchmark for future lines that are built.
- As interim measures to improve air quality on the London Underground and worldwide the recommendations of Moreno and de Miguel (2018) and Smith et al., (2020) could be adopted. Smith et al., (2020) proposed a passenger population-weighted exposure ranked by passenger numbers and PM_{2.5} concentrations at each station as a means of prioritising remedial measures to affect as many passengers as possible. This could be used in conjunction with the proposal by Moreno and de Miguel (2018) of a targeted colour-coded framework, similar to the WHO interim air pollution targets, with which to mark progress on subway air quality levels.
- To further studies in worldwide subway systems there needs to be a standardisation of measurement techniques. Whilst there will be differences in instrumentation used, measurement locations and duration, many studies have failed to adequately calibrate their instruments for the subway environment. This study has shown how the derivation

of source-specific scaling factors for the subway system being investigated is vital for reliable, trustworthy data and to allow comparisons between different subway networks and systems.

References

- 4-Rail Services Ltd. "Respirable airborne dust monitoring at various London Underground stations and train lines." Retrieved 16 May, 2020, from <http://content.tfl.gov.uk/dust-monitoring-london-underground-network.pdf>. 2016.
- Aarnio, P., T. Yli-Tuomi, A. Kousa, T. Makela, A. Hirsikko, K. Hameri, M. Raisanen, R. Hillamo, T. Koskentalo and M. Jantunen. The concentrations and composition of and exposure to fine particles (PM_{2.5}) in the Helsinki subway system, *Atmospheric Environment*, 39, 5059-5066, doi: 10.1016/j.atmosenv.2005.05.012, 2005.
- Abadie, M. O., G. Le Nir, J. Nicole, C. Honore, P. Blondeau and K. Anne *Indoor air quality in metro systems: a survey*. Indoor Air 2014. 2014.
- Abbasi, S., A. Jansson, U. Sellgren and U. Olofsson. Particle emissions from rail traffic: A literature review, *Critical Reviews in Environmental Science and Technology*, 43(23), 2511-2544, doi: doi.org/10.1080/10643389.2012.685348, 2013.
- Abramesko, V. and L. Tartakovsky. Ultrafine particle air pollution inside diesel-propelled passenger trains, *Environmental Pollution*, 226, 288-296, doi: doi.org/10.1016/j.envpol.2017.03.072, 2017.
- Adams, H. S., M. J. Nieuwenhuijsen, R. N. Colville, M. A. S. McMullen and P. Khandelwal. Fine particle (PM_{2.5}) personal exposure levels in transport microenvironments, London, UK, *Science of the Total Environment*, 279, 29-44, doi: Doi 10.1016/S0048-9697(01)00723-9, 2001.
- Ahlatwat, A., K. Weinhold, J. Marval, P. Tronville, A. Leskinen, M. Komppula, H. Gerwig, L. Gerling, S. Weber, R. B. Jørgensen, T. N. Jensen, M. Merizak, U. Vogt, C. Ribalta, M. Viana, A. Schmitz, M. Chiesa, G. Gerosa, L. Keck, M. Pesch, G. Steiner, T. Krinke, T. Tritscher, W. Birmili and A. Wiedensohler. Performance analysis of the NanoScan SMPS and the Mini WRAS Ultrafine Aerosol Particle Size Spectrometers, *Atmos. Meas. Tech. Discuss.*, 2022, 1-26, doi: 10.5194/amt-2022-155, 2022.
- Alderete, T. L., R. B. Jones, Z. Chen, J. S. Kim, R. Habre, F. Lurmann, F. D. Gilliland and M. I. Goran. Exposure to traffic-related air pollution and the composition of the gut microbiota in overweight and obese adolescents, *Environ Res*, 161, 472-478, doi: 10.1016/j.envres.2017.11.046, 2018.
- Aleixandre, M. and M. Gerboles. Review of Small Commercial Sensors for Indicative Monitoring of Ambient Gas, *Chemical Engineering Transactions*, 30, 169-174, doi: 10.3303/CET1230029, 2012.
- Alexeeff, S. E., K. Deosaransingh, N. S. Liao, S. K. Van Den Eeden, J. Schwartz and S. Sidney. Particulate Matter and Cardiovascular Risk in Adults with Chronic Obstructive Pulmonary Disease, *Am J Respir Crit Care Med*, 204, 159-167, doi: 10.1164/rccm.202007-2901OC, 2021.
- Alfano, R., Z. Herceg, T. S. Nawrot, M. Chadeau-Hyam, A. Ghantous and M. Plusquin. The Impact of Air Pollution on Our Epigenome: How Far Is the Evidence? (A Systematic Review), *Current Environmental Health Reports*, 5, 544-578, doi: 10.1007/s40572-018-0218-8, 2018.
- Amato, F. *Non-Exhaust Emissions*. USA, Academic Press. (2018).
- Amiri, A., B. Mahalingam, A. Derbes, J. Haney, S. Alexander and W. H. Orman. The Impact of Chronic Ambient Exposure to PM_{2.5} and Ozone on Asthma Prevalence and COPD Mortality Rates in the Southeastern United States, *Annu Rev Nurs Res*, 38, 15-34, doi: 10.1891/0739-6686.38.15, 2019.
- Apte, J. S., K. P. Messier, S. Gani, M. Brauer, T. W. Kirchstetter, M. M. Lunden, J. D. Marshall, C. J. Portier, R. C. H. Vermeulen and S. P. Hamburg. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data, *Environmental Science & Technology*, 51, 6999-7008, doi: 10.1021/acs.est.7b00891, 2017.
- Araujo, J. A. and A. E. Nel. Particulate matter and atherosclerosis: role of particle size, composition and oxidative stress, *Particle and Fibre Toxicology*, 6, 24, doi: 10.1186/1743-8977-6-24, 2009.
- Atkinson, R. W., G. W. Fuller, H. R. Anderson, R. M. Harrison and B. Armstrong. Urban ambient particle metrics and health: a time-series analysis, *Epidemiology*, 21, 501-511, doi: 10.1097/EDE.0b013e3181debc88, 2010.
- Ayres, J. G., P. Borm, F. R. Cassee, V. Castranova, K. Donaldson, A. Ghio, R. M. Harrison, R. Hider, F. Kelly, I. M. Kooter, F. Marano, R. L. Maynard, I. Mudway, A. Nel, C. Sioutas, S. Smith, A. Baeza-Squiban, A. Cho, S. Duggan and J. Froines. Evaluating the Toxicity of Airborne Particulate Matter and Nanoparticles by Measuring Oxidative Stress

- Potential—A Workshop Report and Consensus Statement, *Inhalation Toxicology*, 20, 75-99, doi: 10.1080/08958370701665517, 2008.
- Azad, S., D. G. Luglio, T. Gordon, G. Thurston and M. Ghandehari. Particulate matter concentration and composition in the New York City subway system, *Atmospheric Pollution Research*, 14, 101767, doi: doi.org/10.1016/j.apr.2023.101767, 2023.
- Babu, P., M. Khare and R. Goyal. Chemical Characterization of Airborne Particles Collected in an Underground Metro Station Platform in Delhi City, *Athens Journal of Sciences-*, 3, 45-54, doi: doi.org/10.30958/ajs.3-1-4, 2015.
- Bachoual, R.: Biological Effects of Particles from the Paris Subway System, 2007.
- Barkjohn, K. K., M. H. Bergin, C. Norris, J. J. Schauer, Y. Zhang, M. Black, M. Hu and J. Zhang. Using Low-cost sensors to Quantify the Effects of Air Filtration on Indoor and Personal Exposure Relevant PM_{2.5} Concentrations in Beijing, China, *Aerosol and Air Quality Research*, 20, 297-313, doi: 10.4209/aaqr.2018.11.0394, 2020.
- Barnes, J. H., T. J. Chatterton and J. W. S. Longhurst. Emissions vs exposure: Increasing injustice from road traffic-related air pollution in the United Kingdom, *Transportation Research Part D: Transport and Environment*, 73, 56-66, doi: doi.org/10.1016/j.trd.2019.05.012, 2019.
- Barnes, P. J.: Oxidative Stress in Chronic Obstructive Pulmonary Disease, *Antioxidants (Basel)*, 11, doi: 10.3390/antiox11050965, 2022.
- Bates, J. T., T. Fang, V. Verma, L. Zeng, R. J. Weber, P. E. Tolbert, J. Y. Abrams, S. E. Sarnat, M. Klein, J. A. Mulholland and A. G. Russell. Review of Acellular Assays of Ambient Particulate Matter Oxidative Potential: Methods and Relationships with Composition, Sources, and Health Effects, *Environmental Science & Technology*, 53, 4003-4019, doi: 10.1021/acs.est.8b03430, 2019.
- Beaudoin, J., Y. H. Farzin and C. Y. C. Lin Lawell. Public transit investment and sustainable transportation: A review of studies of transit's impact on traffic congestion and air quality, *Research in Transportation Economics*, 52, 15-22, doi: doi.org/10.1016/j.retrec.2015.10.004, 2015.
- Bergvall, C. and R. Westerholm. Identification and Determination of Highly Carcinogenic Dibenzopyrene Isomers in Air Particulate Samples from a Street Canyon, a Rooftop, and a Subway Station in Stockholm, *Environmental Science & Technology*, 41, 731-737, doi: 10.1021/es062232p, 2007.
- Bertollo, A. G., R. E. Grolli, M. E. Plissari, V. A. Gasparin, J. Quevedo, G. Z. Réus, M. D. Bagatini and Z. M. Ignácio. Stress and serum cortisol levels in major depressive disorder: a cross-sectional study, *AIMS Neurosci*, 7, 459-469, doi: 10.3934/Neuroscience.2020028, 2020.
- Bigert, C., M. Alderling, M. Svartengren, N. Plato, U. de Faire and P. Gustavsson. Blood markers of inflammation and coagulation and exposure to airborne particles in employees in the Stockholm underground, *Occup Environ Med*, 65, 655-658, doi: 10.1136/oem.2007.038273, 2008.
- Bigert, C., M. Alderling, M. Svartengren, N. Plato and P. Gustavsson. No short-term respiratory effects among particle-exposed employees in the Stockholm subway, *Scandinavian Journal of Work Environment & Health*, 37, 129-135, doi: 10.5271/sjweh.3074, 2011.
- Bigert, C., K. Klerdal, N. Hammar and P. Gustavsson. Myocardial infarction in Swedish subway drivers, *Scandinavian Journal of Work Environment & Health*, 33, 267-271, doi: DOI 10.5271/sjweh.1142, 2007.
- Bilal, M., J. E. Nichol and S. N. Spak. A New Approach for Estimation of Fine Particulate Concentrations Using Satellite Aerosol Optical Depth and Binning of Meteorological Variables, *Aerosol and Air Quality Research*, 17, 356-367, doi: 10.4209/aaqr.2016.03.0097, 2017.
- Birenzve, A., J. Eversole, M. Seaver, S. Francesconi, E. Valdes and H. Kulaga. Aerosol characteristics in a subway environment, *Aerosol Science and Technology*, 37, 210-220, doi: 10.1080/02786820390112614, 2003.
- Biswas, S., V. Verma, J. J. Schauer, F. R. Cassee, A. K. Cho and C. Sioutas. Oxidative Potential of Semi-Volatile and Non Volatile Particulate Matter (PM) from Heavy-Duty Vehicles Retrofitted with Emission Control Technologies, *Environmental Science & Technology*, 43, 3905-3912, doi: 10.1021/es9000592, 2009.
- Bodinier, B., D. Vuckovic, S. Rodrigues, S. Filippi, J. Chiquet and M. Chadeau-Hyam. Automated calibration of consensus weighted distance-based clustering approaches using sharp, *Bioinformatics*, 39, doi: 10.1093/bioinformatics/btad635, 2023.
- Bolourchi, A., F. Atabi, F. Moattar and M. Ehyaei. Experimental and numerical analyses of particulate matter concentrations in underground subway station, *International Journal of Environmental Science and Technology*, 15, 2569-2580, 2018.

- Boogaard, H., A. P. Patton, R. W. Atkinson, J. R. Brook, H. H. Chang, D. L. Crouse, J. C. Fussell, G. Hoek, B. Hoffmann, R. Kappeler, M. Kutlar Joss, M. Ondras, S. K. Sagiv, E. Samoli, R. Shaikh, A. Smargiassi, A. A. Szpiro, E. D. S. Van Vliet, D. Vienneau, J. Weuve, F. W. Lurmann and F. Forastiere. Long-term exposure to traffic-related air pollution and selected health outcomes: A systematic review and meta-analysis, *Environment International*, 164, 107262, doi: doi.org/10.1016/j.envint.2022.107262, 2022.
- Borm, P. J., F. Kelly, N. Künzli, R. P. Schins and K. Donaldson. Oxidant generation by particulate matter: from biologically effective dose to a promising, novel metric, *Occup Environ Med*, 64, 73-74, doi: 10.1136/oem.2006.029090, 2007.
- Branis, M.: Personal exposure to PM₁₀ in the Prague underground *Journal of Aerosol Science*, 35(SUPPL. 2), S1271-S1272, doi: dx.doi.org/10.1016/s0021-... 2004.
- Braniš, M.: The contribution of ambient sources to particulate pollution in spaces and trains of the Prague underground transport system, *Atmospheric Environment*, 40, 348-356, doi: doi.org/10.1016/j.atmosenv.2005.09.060, 2006.
- Brokamp, C., E. Brandt and P. Ryan. Assessing Exposure to Outdoor Air Pollution for Epidemiological Studies: Model-based and Personal Sampling Strategies, *Journal of Allergy and Clinical Immunology*, 143, doi: 10.1016/j.jaci.2019.04.019, 2019.
- Brook, R. D., S. Rajagopalan, C. A. Pope, J. R. Brook, A. Bhatnagar, A. V. Diez-Roux, F. Holguin, Y. Hong, R. V. Luepker, M. A. Mittleman, A. Peters, D. Siscovick, S. C. Smith, L. Whitset and J. D. Kaufman. Particulate Matter Air Pollution and Cardiovascular Disease, *Circulation*, 121, 2331-2378, doi: doi:10.1161/CIR.0b013e3181dbee1, 2010.
- Brunekreef, B. and S. T. Holgate. Air pollution and health, *The Lancet*, 360, 1233-1242, doi: doi.org/10.1016/S0140-6736(02)11274-8, 2002.
- Bundy, J. G., M. P. Davey and M. R. Viant. Environmental metabolomics: a critical review and future perspectives, *Metabolomics*, 5, 3-21, doi: 10.1007/s11306-008-0152-0, 2009.
- Buonanno, G., M. Dell'Isola, L. Stabile and A. Viola. Uncertainty Budget of the SMPS-APS System in the Measurement of PM₁, PM_{2.5}, and PM₁₀, *Aerosol Science and Technology*, 43, 1130-1141, doi: 10.1080/02786820903204078, 2009.
- Burnett, R., H. Chen, M. Szyszkowicz, N. Fann, B. Hubbell, C. A. Pope, 3rd, J. S. Apte, M. Brauer, A. Cohen, S. Weichenthal, J. Coggins, Q. Di, B. Brunekreef, J. Frostad, S. S. Lim, H. Kan, K. D. Walker, G. D. Thurston, R. B. Hayes, C. C. Lim, M. C. Turner, M. Jerrett, D. Krewski, S. M. Gapstur, W. R. Diver, B. Ostro, D. Goldberg, D. L. Crouse, R. V. Martin, P. Peters, L. Pinault, M. Tjepkema, A. van Donkelaar, P. J. Villeneuve, A. B. Miller, P. Yin, M. Zhou, L. Wang, N. A. H. Janssen, M. Marra, R. W. Atkinson, H. Tsang, T. Quoc Thach, J. B. Cannon, R. T. Allen, J. E. Hart, F. Laden, G. Cesaroni, F. Forastiere, G. Weinmayr, A. Jaensch, G. Nagel, H. Concin and J. V. Spadaro. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter, *Proc Natl Acad Sci U S A*, 115, 9592-9597, doi: 10.1073/pnas.1803222115, 2018.
- Burnett, R. T., C. A. Pope, 3rd, M. Ezzati, C. Olives, S. S. Lim, S. Mehta, H. H. Shin, G. Singh, B. Hubbell, M. Brauer, H. R. Anderson, K. R. Smith, J. R. Balmes, N. G. Bruce, H. Kan, F. Laden, A. Pruss-Ustun, M. C. Turner, S. M. Gapstur, W. R. Diver and A. Cohen. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure, *Environ Health Perspect*, 122, 397-403, doi: 10.1289/ehp.1307049, 2014.
- Calvo, A. I., C. Alves, A. Castro, V. Pont, A. M. Vicente and R. Fraile. Research on aerosol sources and chemical composition: Past, current and emerging issues, *Atmospheric Research*, 120-121, 1-28, doi: doi.org/10.1016/j.atmosres.2012.09.021, 2013.
- Cames, M. and E. Helmers. Critical evaluation of the European diesel car boom - global comparison, environmental effects and various national strategies, *Environmental Sciences Europe*, 25, 15, doi: 10.1186/2190-4715-25-15, 2013.
- Campbell, S. J., K. Wolfer, B. Uttinger, J. Westwood, Z. H. Zhang, N. Bukowiecki, S. S. Steimer, T. V. Vu, J. Xu, N. Straw, S. Thomson, A. Elzein, Y. Sun, D. Liu, L. Li, P. Fu, A. C. Lewis, R. M. Harrison, W. J. Bloss, M. Loh, M. R. Miller, Z. Shi and M. Kalberer. Atmospheric conditions and composition that influence PM_{2.5} oxidative potential in Beijing, China, *Atmos. Chem. Phys.*, 21, 5549-5573, doi: 10.5194/acp-21-5549-2021, 2021.
- Canu, I. G., C. Cr    , M. Hemmendinger, T. B. Rayana, S. Besan    n, V. Jouannique, A. Debatisse, P. Wild, J. Sauvain and G. Su    rez. Particle and metal exposure in Parisian subway: Relationship between exposure biomarkers in air, exhaled breath condensate, and urine, *International Journal of Hygiene and Environmental Health*, 237, 113837, doi: doi.org/10.1016/j.ijheh.2021.113837, 2021.

- Cao, S. J., X. R. Kong, L. Li, W. Zhang, Z. P. Ye and Y. Deng. An investigation of the PM_{2.5} and NO₂ concentrations and their human health impacts in the metro subway system of Suzhou, China, *Environ Sci Process Impacts*, 19, 666-675, doi: 10.1039/c6em00655h, 2017.
- Cao, S. J., X. R. Kong, L. Y. Li, W. R. Zhang, Z. P. Ye and Y. L. Deng. An investigation of the PM_{2.5} and NO₂ concentrations and their human health impacts in the metro subway system of Suzhou, China, *Environmental Science-Processes & Impacts*, 19, 666-675, doi: 10.1039/c6em00655h, 2017.
- Carroll, P., B. Caulfield and A. Ahern. Measuring the potential emission reductions from a shift towards public transport, *Transportation Research Part D: Transport and Environment*, 73, 338-351, doi: doi.org/10.1016/j.trd.2019.07.010, 2019.
- Carslaw, D. C. "The openair manual — open-source tools for analysing air pollution data. ." Retrieved 12 June, 2023, from <http://www.openair-project.org>. 2012.
- Carteni, A.: Particulate Matter Concentrations in Urban Metro Systems: Case Studies and a Literature Review, 2016 IEEE 16th International Conference on Environment and Electrical Engineering (Eeeic), 2016.
- Carteni, A. and F. Cascetta. Particulate matter concentrations in a high-quality rubber-tyred metro system: the case study of Turin in Italy, *International Journal of Environmental Science and Technology*, 15, 1921-1930, doi: 10.1007/s13762-017-1566-x, 2018.
- Carteni, A., F. Cascetta and S. Campana. Underground and ground-level particulate matter concentrations in an Italian metro system, *Atmospheric Environment*, 101, 328-337, doi: 10.1016/j.atmosenv.2014.11.030, 2015.
- Carteni, A., F. Cascetta, I. Henke and C. Moliterno. The role of particle resuspension within PM concentrations in underground subway systems, *International Journal of Environmental Science and Technology*, 17, 4075-4094, 2020.
- Cassee, F. R., M. E. Héroux, M. E. Gerlofs-Nijland and F. J. Kelly. Particulate matter beyond mass: recent health evidence on the role of fractions, chemical constituents and sources of emission, *Inhal Toxicol*, 25, 802-812, doi: 10.3109/08958378.2013.850127, 2013.
- Castagné, R. and M. Chadeau-Hyam (2019). Chapter 8 - Univariate Statistical Modeling, Multiple Testing Correction, and Visualization in Metabolome-Wide Association Studies. *The Handbook of Metabolic Phenotyping*. J. C. Lindon, J. K. Nicholson and E. Holmes, Elsevier: 237-260.
- Castell, N., F. R. Dauge, P. Schneider, M. Vogt, U. Lerner, B. Fishbain, D. Broday and A. Bartonova. Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates?, *Environment international*, 99, 293-302, doi: 10.1016/j.envint.2016.12.007, 2017.
- Cepeda, M., J. Schoufour, R. Freak-Poli, C. M. Koolhaas, K. Dhana, W. M. Bramer and O. H. Franco. Levels of ambient air pollution according to mode of transport: a systematic review, *Lancet Public Health*, 2, e23-e34, doi: 10.1016/s2468-2667(16)30021-4, 2017.
- Cerdá, B., M. Pérez, J. D. Pérez-Santiago, J. F. Tornero-Aguilera, R. González-Soltero and M. Larrosa. Gut Microbiota Modification: Another Piece in the Puzzle of the Benefits of Physical Exercise in Health?, *Front Physiol*, 7, 51, doi: 10.3389/fphys.2016.00051, 2016.
- Cesari, D., E. Merico, F. M. Grasso, S. Decesari, F. Belosi, F. Manarini, P. De Nuntiis, M. Rinaldi, F. Volpi, A. Gambaro, E. Morabito and D. Contini. Source Apportionment of PM_{2.5} and of its Oxidative Potential in an Industrial Suburban Site in South Italy, *Atmosphere*, 10, 758, 2019.
- Cha, Y. Y., S. Abbasi and U. Olofsson. Indoor and outdoor measurement of airborne particulates on a commuter train running partly in tunnels, *Proceedings of the Institution of Mechanical Engineers Part F-Journal of Rail and Rapid Transit*, 232, 3-13, doi: 10.1177/0954409716642492, 2018.
- Cha, Y. Y., U. Olofsson, M. Gustafsson and C. Johansson. On particulate emissions from moving trains in a tunnel environment, *Transportation Research Part D-Transport and Environment*, 59, 35-45, doi: 10.1016/j.trd.2017.12.016, 2018.
- Cha, Y. Y., M. H. Tu, M. Elmgren, S. Silvergren and U. Olofsson. Factors affecting the exposure of passengers, service staff and train drivers inside trains to airborne particles, *Environmental Research*, 166, 16-24, doi: 10.1016/j.envres.2018.05.026, 2018.
- Cha, Y. Y., M. H. Tu, M. Elmgren, S. Silvergren and U. Olofsson. Variation in Airborne Particulate Levels at a Newly Opened Underground Railway Station, *Aerosol and Air Quality Research*, 19, 737-748, doi: 10.4209/aaqr.2018.06.0225, 2019.
- Chadeau-Hyam, M., G. Campanella, T. Jombart, L. Bottolo, L. Portengen, P. Vineis, B. Liqueur and R. C. H. Vermeulen. Deciphering the complex: Methodological overview of

- statistical models to derive OMICS-based biomarkers, *Environmental and Molecular Mutagenesis*, 54, 542-557, doi: doi.org/10.1002/em.21797, 2013.
- Chadeau-Hyam, M., R. C. Vermeulen, D. G. HeBELS, R. Castagné, G. Campanella, L. Portengen, R. S. Kelly, I. A. Bergdahl, B. Melin, G. Hallmans, D. Palli, V. Krogh, R. Tumino, C. Sacerdote, S. Panico, T. M. de Kok, M. T. Smith, J. C. Kleinjans, P. Vineis and S. A. Kyrtpoulos. Prediagnostic transcriptomic markers of Chronic lymphocytic leukemia reveal perturbations 10 years before diagnosis, *Ann Oncol*, 25, 1065-1072, doi: 10.1093/annonc/mdu056, 2014.
- Chang, L., W. T. Chong, X. Wang, F. Pei, X. Zhang, T. Wang, C. Wang and S. Pan. Recent progress in research on PM2.5 in subways, *Environmental Science. Processes & Impacts*, 23, 642-663, doi: dx.doi.org/10.1039/d1em00002k, 2021.
- Chao, H.-R., J.-W. Hsu, H.-Y. Ku, S.-L. Wang, H.-B. Huang, S.-H. Liou and T.-C. Tsou. Inflammatory Response and PM2.5 Exposure of Urban Traffic Conductors, *Aerosol and Air Quality Research*, 18, 2633-2642, doi: 10.4209/aaqr.2018.04.0132, 2018.
- Chatzidiakou, L., A. Krause, Y. Han, W. Chen, L. Yan, O. Popoola, M. Kellaway, Y. Wu, J. Liu, M. Hu, B. Barratt, F. Kelly, T. Zhu and R. Jones. Using low-cost sensor technologies and advanced computational methods to improve dose estimations in health panel studies: results of the AIRLESS project (link to full text: <https://rdcu.be/b6dUz>), *Journal of Exposure Science and Environmental Epidemiology*, doi: 10.1038/s41370-020-0259-6, 2020.
- Chatzidiakou, L., A. Krause, O. A. M. Popoola, A. Di Antonio, M. Kellaway, Y. Han, F. A. Squires, T. Wang, H. Zhang, Q. Wang, Y. Fan, S. Chen, M. Hu, J. K. Quint, B. Barratt, F. J. Kelly, T. Zhu and R. L. Jones. Characterising low-cost sensors in highly portable platforms to quantify personal exposure in diverse environments, *Atmos. Meas. Tech.*, 12, 4643-4657, doi: 10.5194/amt-12-4643-2019, 2019.
- Chen, C. and B. Zhao. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor, *Atmospheric Environment*, 45, 275-288, doi: doi.org/10.1016/j.atmosenv.2010.09.048, 2011.
- Chen, Y., F. Sung, M. Chen, I. Mao and C. Lu. Indoor air quality in the metro system in North Taiwan, *International Journal of Environmental Research and Public Health*, 13, doi: 10.3390/ijerph13121200, 2016.
- Cheng, Y.-H., Y.-L. Lin and C.-C. Liu. Levels of PM10 and PM2. 5 in Taipei rapid transit system, *Atmospheric Environment*, 42, 7242-7249, 2008.
- Cheng, Y. H., C. C. Liu and Y. L. Lin. Levels of ultrafine particles in the Taipei Rapid Transit System, *Transportation Research Part D-Transport and Environment*, 14, 479-486, doi: 10.1016/j.trd.2009.06.002, 2009.
- Cheng, Y. H., X. H. Ninh and S. L. Yeh. Dominant Factors Influencing the Concentrations of Particulate Matters inside Train Carriages Traveling in Different Environments in the Taipei Mass Rapid Transit System, *Aerosol and Air Quality Research*, 19, 1579-1592, doi: 10.4209/aaqr.2018.09.0335, 2019.
- Cheng, Y. H. and J. W. Yan. Comparisons of particulate matter, CO, and CO2 levels in underground and ground-level stations in the Taipei mass rapid transit system, *Atmospheric Environment*, 45(28), 4882-4891, 2011.
- Chillrud, S. N., D. Epstein, J. M. Ross, S. N. Sax, D. Pederson, J. D. Spengler and P. L. Kinney. Elevated airborne exposures of teenagers to manganese, chromium, and iron from steel dust and New York City's subway system, *Environmental Science & Technology*, 38, 732-737, 2004.
- Choi, S., J.-H. Park, S.-Y. Bae, S.-Y. Kim, H. Byun, H. Kwak, S. Hwang, J. Park, H. Park and K.-H. Lee. Characteristics of PM10 levels monitored for more than a decade in subway stations in South Korea, *Aerosol and Air Quality Research*, 19, 2763-2756, doi: doi.org/10.4209/aaqr.2019.05.0263 2019.
- Chowdhury, R., D. Shah and A. R. Payal. Healthy Worker Effect Phenomenon: Revisited with Emphasis on Statistical Methods - A Review, *Indian J Occup Environ Med*, 21, 2-8, doi: 10.4103/ijoem.IJOEM_53_16, 2017.
- Chuang, S. C., A. Fanidi, P. M. Ueland, C. Relton, O. Midttun, S. E. Vollset, M. J. Gunter, M. J. Seckl, R. C. Travis, N. Wareham, A. Trichopoulou, P. Lagiou, D. Trichopoulos, P. H. Peeters, H. B. Bueno-de-Mesquita, H. Boeing, A. Wientzek, T. Kuehn, R. Kaaks, R. Tumino, C. Agnoli, D. Palli, A. Naccarati, E. A. Aicua, M. J. Sánchez, J. R. Quirós, M. D. Chirlaque, A. Agudo, M. Johansson, K. Grankvist, M. C. Boutron-Ruault, F. Clavel-Chapelon, G. Fagherazzi, E. Weiderpass, E. Riboli, P. J. Brennan, P. Vineis and M. Johansson. Circulating biomarkers of tryptophan and the kynurenine pathway and lung cancer risk, *Cancer Epidemiol Biomarkers Prev*, 23, 461-468, doi: 10.1158/1055-9965.Epi-13-0770, 2014.

- Clements, A. L., W. G. Griswold, A. Rs, J. E. Johnston, M. M. Herting, J. Thorson, A. Collier-Oxandale and M. Hannigan. Low-Cost Air Quality Monitoring Tools: From Research to Practice (A Workshop Summary), Sensors (Basel, Switzerland), 17, 2478, doi: 10.3390/s17112478, 2017.
- Cohen, A. J., M. Brauer, R. Burnett, H. R. Anderson, J. Frostad, K. Estep, K. Balakrishnan, B. Brunekreef, L. Dandona, R. Dandona, V. Feigin, G. Freedman, B. Hubbell, A. Jobling, H. Kan, L. Knibbs, Y. Liu, R. Martin, L. Morawska, C. A. Pope, 3rd, H. Shin, K. Straif, G. Shaddick, M. Thomas, R. van Dingenen, A. van Donkelaar, T. Vos, C. J. L. Murray and M. H. Forouzanfar. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015, Lancet, 389, 1907-1918, doi: 10.1016/s0140-6736(17)30505-6, 2017.
- Colombi, C., S. Angius, V. Gianelle and M. Lazzarini. Particulate matter concentrations, Physical characteristics and elemental composition in the Milan underground transport system, Atmospheric Environment, 70, 166-178, doi: doi.org/10.1016/j.atmosenv.2013.01.035, 2013.
- COMEAP. "COMEAP Statement: Dust on the London Underground " Retrieved 13 October, 2022, from https://webarchive.nationalarchives.gov.uk/ukgwa/20140505113327mp/http://www.comeap.org.uk/images/stories/Documents/Statements/Dust_on_the_London_Underground_Statement_Dec_98.pdf. 1998.
- COMEAP. Exploratory assessment: personal exposure to fine particulate matter while commuting on the London Underground, 2018.
- COMEAP. Literature searches commissioned by Transport for London COMEAP/2018/04 WORKING PAPER 1, 2018.
- COMEAP. Results of London Underground workers exposure to respirable dust: 2005-2017 COMEAP/2018/04 WORKING PAPER 3, 2018.
- COMEAP. "STATEMENT ON THE EVIDENCE FOR HEALTH EFFECTS IN THE TRAVELLING PUBLIC ASSOCIATED WITH EXPOSURE TO PARTICULATE MATTER IN THE LONDON UNDERGROUND." Retrieved 13 October, 2022, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/769884/COMEAP_TfL_Statement.pdf. 2018.
- COMEAP. A viewpoint on the characterisation of airborne particulate matter in the London Underground: COMEAP/2018/04 WORKING PAPER 2, 2018.
- COMEAP. A viewpoint on the comparison of published health-based exposure limits (occupational and population) with PM concentrations in the London Underground: COMEAP/2018/04 WORKING PAPER 6, 2018.
- COMEAP. Viewpoint on the mechanistic evidence for health effects of particulate matter in the London Underground: COMEAP/2018/04 WORKING PAPER 4, 2018.
- Cooper, D. M. and M. Loxham. Particulate matter and the airway epithelium: the special case of the underground?, European Respiratory Review, 28, 30, doi: dx.doi.org/10.1183/16000617.0066-2019, 2019.
- Cross, E. S., L. R. Williams, D. K. Lewis, G. R. Magoon, T. B. Onasch, M. L. Kaminsky, D. R. Worsnop and J. T. Jayne. Use of electrochemical sensors for measurement of air pollution: correcting interference response and validating measurements, Atmos. Meas. Tech., 10, 3575-3588, doi: 10.5194/amt-10-3575-2017, 2017.
- Cusack, M., N. Talbot, J. Ondráček, M. Minguillón, V. Martins, K. Klouda, J. Schwarz and V. Ždímal. Variability of aerosols and chemical composition of PM₁₀, PM_{2.5} and PM₁ on a platform of the Prague underground metro, Atmospheric Environment, 118, 176-183, doi: doi.org/10.1016/j.atmosenv.2015.08.013, 2015.
- Daellenbach, K. R., G. Uzu, J. Jiang, L.-E. Cassagnes, Z. Leni, A. Vlachou, G. Stefanelli, F. Canonaco, S. Weber, A. Segers, J. J. P. Kuenen, M. Schaap, O. Favez, A. Albinet, S. Aksoyoglu, J. Dommen, U. Baltensperger, M. Geiser, I. El Haddad, J.-L. Jaffrezo and A. S. H. Prévôt. Sources of particulate-matter air pollution and its oxidative potential in Europe, Nature, 587, 414-419, doi: 10.1038/s41586-020-2902-8, 2020.
- Davis, I. and A. Liu. What is the tryptophan kynurenine pathway and why is it important to neurotherapeutics?, Expert Rev Neurother, 15, 719-721, doi: 10.1586/14737175.2015.1049999, 2015.
- de Nazelle, A., E. Seto, D. Donaire-Gonzalez, M. Mendez, J. Matamala, M. J. Nieuwenhuijsen and M. Jerrett. Improving estimates of air pollution exposure through ubiquitous sensing

- technologies, *Environmental pollution* (1987), 176, 92-99, doi: 10.1016/j.envpol.2012.12.032, 2013.
- DEFRA. "Quality Assurance and Quality Control (QA/QC) Procedures for UK Air Quality Monitoring under 2008/50/EC and 2004/107/EC." Retrieved 11 January, 2023, from https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1902040953_All_Networks_QAQC_Document_2012_Issue2.pdf. 2016.
- DEFRA. "Automatic Urban and Rural Network (AURN)." Retrieved 15 February, 2023, from <https://uk-air.defra.gov.uk/networks/network-info?view=aurn>. 2023.
- DEFRA. "Site Information for London Honor Oak Park." Retrieved 22 March, 2023, from https://uk-air.defra.gov.uk/networks/site-info?site_id=HP1. 2023.
- DEFRA. "Site Information for London Marylebone Road." Retrieved 22 March, 2023, from https://uk-air.defra.gov.uk/networks/site-info?site_id=MY1. 2023.
- DEFRA. "Site Information for London N. Kensington." Retrieved 22 March, 2023, from https://uk-air.defra.gov.uk/networks/site-info?site_id=KC1. 2023.
- Dockery, D. W., C. A. Pope, X. Xu, J. D. Spengler, J. H. Ware, M. E. Fay, B. G. Ferris and F. E. Speizer. An Association between Air Pollution and Mortality in Six U.S. Cities, *New England Journal of Medicine*, 329, 1753-1759, doi: 10.1056/nejm199312093292401, 1993.
- Doiron, D., K. de Hoogh, N. Probst-Hensch, I. Fortier, Y. Cai, S. De Matteis and A. L. Hansell. Air pollution, lung function and COPD: results from the population-based UK Biobank study, *Eur Respir J*, 54, doi: 10.1183/13993003.02140-2018, 2019.
- Dominici, F., R. D. Peng, M. L. Bell, L. Pham, A. McDermott, S. L. Zeger and J. M. Samet. Fine Particulate Air Pollution and Hospital Admission for Cardiovascular and Respiratory Diseases, *JAMA*, 295, 1127-1134, doi: 10.1001/jama.295.10.1127, 2006.
- Donaldson, K., V. Stone, P. J. Borm, L. A. Jimenez, P. S. Gilmour, R. P. Schins, A. M. Knaapen, I. Rahman, S. P. Faux, D. M. Brown and W. MacNee. Oxidative stress and calcium signaling in the adverse effects of environmental particles (PM10), *Free Radic Biol Med*, 34, 1369-1382, doi: 10.1016/s0891-5849(03)00150-3, 2003.
- Durand, A.: CFD study of dispersion of particles generated by mechanical braking: application to trains in underground stations, 2019.
- Espín-Pérez, A., J. Krauskopf, M. Chadeau-Hyam, K. van Veldhoven, F. Chung, P. Cullinan, J. Piepers, M. van Herwijnen, N. Kubesch, G. Carrasco-Turigas, M. Nieuwenhuijsen, P. Vineis, J. C. S. Kleinjans and T. M. C. M. de Kok. Short-term transcriptome and microRNAs responses to exposure to different air pollutants in two population studies, *Environmental Pollution*, 242, 182-190, doi: doi.org/10.1016/j.envpol.2018.06.051, 2018.
- European Commission. "Standardization mandate to CEN, CENELEC and ETSI in support of the implementation of the ambient air quality." Retrieved 07 September, 2023, from <https://law.resource.org/pub/eu/mandates/m503.pdf>. 2012.
- Evangelopoulos, D., L. Chatzidiakou, H. Walton, K. Katsouyanni, F. J. Kelly, J. K. Quint, R. L. Jones and B. Barratt. Personal exposure to air pollution and respiratory health of COPD patients in London, *European Respiratory Journal*, 2003432, doi: 10.1183/13993003.03432-2020, 2021.
- Faramehr, S. (2014). *Aerodynamic of the Trains in Tunnels*, University of Birmingham.
- Farren, N. J., C. Schmidt, H. Juchem, D. Pöhler, S. E. Wilde, R. L. Wagner, S. Wilson, M. D. Shaw and D. C. Carslaw. Emission ratio determination from road vehicles using a range of remote emission sensing techniques, *Science of The Total Environment*, 875, 162621, doi: doi.org/10.1016/j.scitotenv.2023.162621, 2023.
- Feinberg, S., R. Williams, G. S. W. Hagler, J. Rickard, R. Brown, D. Garver, G. Harshfield, P. Stauffer, E. Mattson, R. Judge and S. Garvey. Long-term evaluation of air sensor technology under ambient conditions in Denver, Colorado, *Atmos Meas Tech*, 11, 4605-4615, doi: 10.5194/amt-11-4605-2018, 2018.
- Figuerola-Lara, J. J.: Effect of platform subway depth on the presence of Airborne PM2.5, metals, and toxic organic species, doi: doi.org/10.1016/j.jhazmat.2019.05.091, 2019.
- Font, O., T. Moreno, X. Querol, V. Martins, D. S. Rodas, E. de Miguel and M. Capdevila. Origin and speciation of major and trace PM elements in the barcelona subway system, *Transportation Research Part D: Transport and Environment*, 72, 17-35, 2019.
- Fouladi, F., M. J. Bailey, W. B. Patterson, M. Sioda, I. C. Blakley, A. A. Fodor, R. B. Jones, Z. Chen, J. S. Kim, F. Lurmann, C. Martino, R. Knight, F. D. Gilliland and T. L. Alderete. Air pollution exposure is associated with the gut microbiome as revealed by shotgun

- metagenomic sequencing, *Environment International*, 138, 105604, doi: doi.org/10.1016/j.envint.2020.105604, 2020.
- Franklin, M., P. Koutrakis and P. Schwartz. The role of particle composition on the association between PM_{2.5} and mortality, *Epidemiology*, 19, 680-689, doi: 10.1097/ede.0b013e3181812bb7, 2008.
- Fridell, E., A. Björk, M. Ferm and A. Ekberg. On-board measurements of particulate matter emissions from a passenger train, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 225, 99-106, 2011.
- Fuller, G. W., S. Friedman and I. Mudway. "Impacts of air pollution across the life course – evidence highlight note." Retrieved 30 April 2023, from <https://www.london.gov.uk/sites/default/files/2023-04/Imperial%20College%20London%20Projects%20-%20Impacts%20of%20air%20pollution%20across%20the%20life%20course%20%E2%80%93%20evidence%20highlight%20note.pdf>. 2023.
- Furuya, K., Y. Kudo, K. Okinaga, M. Yamuki, S. Takahashi, Y. Araki and Y. Hisamatsu. Seasonal variation and their characterization of suspended particulate matter in the air of subway stations, *Journal of Trace and Microprobe Techniques*, 19, 469-485, doi: Doi 10.1081/Tma-100107583, 2001.
- Fussell, J. C., M. Franklin, D. C. Green, M. Gustafsson, R. M. Harrison, W. Hicks, F. J. Kelly, F. Kishta, M. R. Miller, I. S. Mudway, F. Oroumihyeh, L. Selley, M. Wang and Y. Zhu. A Review of Road Traffic-Derived Non-Exhaust Particles: Emissions, Physicochemical Characteristics, Health Risks, and Mitigation Measures, *Environmental Science & Technology*, 56, 6813-6835, doi: 10.1021/acs.est.2c01072, 2022.
- Gao, D., S. Ripley, S. Weichenthal and K. J. Godri Pollitt. Ambient particulate matter oxidative potential: Chemical determinants, associated health effects, and strategies for risk management, *Free Radical Biology and Medicine*, 151, 7-25, doi: doi.org/10.1016/j.freeradbiomed.2020.04.028, 2020.
- Gascon, M., O. Marquet, E. Gràcia-Lavedan, A. Ambròs, T. Götschi, A. d. Nazelle, L. I. Panis, R. Gerike, C. Brand, E. Dons, U. Eriksson, F. Iacorossi, I. Àvila-Palència, T. Cole-Hunter and M. J. Nieuwenhuisen. What explains public transport use? Evidence from seven European cities, *Transport Policy*, 99, 362-374, doi: doi.org/10.1016/j.tranpol.2020.08.009, 2020.
- GOLD. "Global Initiative for Chronic Obstructive Lung Disease,." Retrieved 7 January, 2023, from <https://goldcopd.org/>. 2023.
- Gomez-Perales, J. E., R. N. Colvile, M. J. Nieuwenhuisen, A. Fernandez-Bremauntz, V. J. Gutierrez-Avedoy, V. H. Paramo-Figueroa, S. Blanco-Jimenez, E. Bueno-Lopez, F. Mandujano, R. Bernabe-Cabanillas and E. Ortiz-Segovia. Commuters' exposure to PM_{2.5}, CO, and benzene in public transport in the metropolitan area of Mexico City, *Atmospheric Environment*, 38, 1219-1229, doi: 10.1016/j.atmosenv.2003.11.008, 2004.
- Grass, D. S., J. M. Ross, F. Family, J. Barbour, H. J. Simpson, D. Coulibaly, J. Hernandez, Y. D. Chen, V. Slavkovich, Y. L. Li, J. Graziano, R. M. Santella, P. Brandt-Rauf and S. N. Chillrud. Airborne particulate metals in the New York City subway: A pilot study to assess the potential for health impacts, *Environmental Research*, 110, 1-11, doi: 10.1016/j.envres.2009.10.006, 2010.
- Green, D. and G. W. Fuller. The implications of tapered element oscillating microbalance (TEOM) software configuration on particulate matter measurements in the UK and Europe, *Atmospheric Environment*, 40, 5608-5616, doi: doi.org/10.1016/j.atmosenv.2006.04.052, 2006.
- Greenbaum, D. S. *Air Pollution and Cancer*. France, International Agency for Research on Cancer, (2018).
- Guo, E. B., H. G. Shen, L. He and J. W. Zhang. Investigation of air pollution of Shanghai subway stations in ventilation seasons in terms of PM_{2.5} and PM₁₀, *Toxicology and Industrial Health*, 33, 588-600, doi: 10.1177/0748233717693547, 2017.
- Guo, L., Y. J. Hu, Q. Q. Hu, J. Lin, C. L. Li, J. M. Chen, L. N. Li and H. B. Fu. Characteristics and chemical compositions of particulate matter collected at the selected metro stations of Shanghai, China, *Science of the Total Environment*, 496, 443-452, doi: 10.1016/j.scitotenv.2014.07.055, 2014.
- Gustafsson, M., G. Blomqvist, E. Swietlicki and A. Dahl. Inhalable railroad particles at ground level and subterranean stations – Physical and chemical properties and relation to train traffic., *Transportation Research Part D Transport and Environment*, 17, 277-285, doi: 10.1016/j.trd.2011.12.006, 2012.

- Gustavsson, P., C. Bigert and M. Pollan. Incidence of lung cancer among subway drivers in Stockholm, *American Journal of Industrial Medicine*, 51, 545-547, doi: [dx.doi.org/10.1002/ajim.20584](https://doi.org/10.1002/ajim.20584), 2008.
- Ham, W., A. Vijayan, N. Schulte and J. D. Herner. Commuter exposure to PM_{2.5}, BC, and UFP in six common transport microenvironments in Sacramento, California, *Atmospheric Environment*, 167, 335-345, doi: doi.org/10.1016/j.atmosenv.2017.08.024, 2017.
- Han, F., X. Yang, D. Xu, Q. Wang and D. Xu. Association between outdoor PM_{2.5} and prevalence of COPD: a systematic review and meta-analysis, *Postgrad Med J*, 95, 612-618, doi: [10.1136/postgradmedj-2019-136675](https://doi.org/10.1136/postgradmedj-2019-136675), 2019.
- Harrison, R. M., A. M. Jones and R. G. Lawrence. A pragmatic mass closure model for airborne particulate matter at urban background and roadside sites, *Atmospheric Environment*, 37, 4927-4933, doi: doi.org/10.1016/j.atmosenv.2003.08.025, 2003.
- Health Effects Institute. "Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects." Retrieved 09 January, 2023, from <https://www.healtheffects.org/publication/traffic-related-air-pollution-critical-review-literature-emissions-exposure-and-health>. 2010.
- Health Effects Institute. "Systematic Review and Meta-analysis of Selected Health Effects of Long-Term Exposure to Traffic-Related Air Pollution." Retrieved 08 December, 2022, from <https://www.healtheffects.org/publication/systematic-review-and-meta-analysis-selected-health-effects-long-term-exposure-traffic>. 2022.
- Heckmann, B. L., X. Zhang, X. Xie and J. Liu. The G0/G1 switch gene 2 (G0S2): Regulating metabolism and beyond, *Biochimica et Biophysica Acta (BBA) - Molecular and Cell Biology of Lipids*, 1831, 276-281, doi: doi.org/10.1016/j.bbalip.2012.09.016, 2013.
- Hinds, W. C. *Aerosol Technology: Properties, behavior, and measurement of airbourne particles*. Canada, John Wiley & Sons. (1999).
- Hoek, G., R. M. Krishnan, R. Beelen, A. Peters, B. Ostro, B. Brunekreef and J. D. Kaufman. Long-term air pollution exposure and cardio- respiratory mortality: a review, *Environ Health*, 12, 43, doi: [10.1186/1476-069x-12-43](https://doi.org/10.1186/1476-069x-12-43), 2013.
- Horbanski, M., D. Pöhler, J. Lampel and U. Platt. The ICAD (iterative cavity-enhanced DOAS) method, *Atmos. Meas. Tech.*, 12, 3365-3381, doi: [10.5194/amt-12-3365-2019](https://doi.org/10.5194/amt-12-3365-2019), 2019.
- HSE. "EH40/2005 Workplace exposure limits." Retrieved 05 January 2023, 2023, from <https://www.hse.gov.uk/pubns/priced/eh40.pdf>. 2020.
- Huang, J., F. Deng, S. Wu, H. Lu, Y. Hao and X. Guo. The impacts of short-term exposure to noise and traffic-related air pollution on heart rate variability in young healthy adults, *Journal of Exposure Science & Environmental Epidemiology*, 23, 559-564, doi: [10.1038/jes.2013.21](https://doi.org/10.1038/jes.2013.21), 2013.
- Hwang, S. H., W. M. Park, J. B. Park and T. Nam. Characteristics of PM₁₀ and CO₂ concentrations on 100 underground subway station platforms in 2014 and 2015, *Atmospheric Environment*, 167, 143-149, doi: doi.org/10.1016/j.atmosenv.2017.08.019, 2017.
- in 't Veld, M., M. Pandolfi, F. Amato, N. Pérez, C. Reche, P. Dominutti, J. Jaffrezo, A. Alastuey, X. Querol and G. Uzu. Discovering oxidative potential (OP) drivers of atmospheric PM₁₀, PM_{2.5}, and PM₁ simultaneously in North-Eastern Spain, *Science of The Total Environment*, 857, 159386, doi: doi.org/10.1016/j.scitotenv.2022.159386, 2023.
- International Agency for Research on Cancer. "DIESEL ENGINE EXHAUST CARCINOGENIC." Retrieved 08 December, 2022, from https://www.iarc.who.int/wp-content/uploads/2018/07/pr213_E.pdf. 2012.
- ITA. Examples of Benefits of Underground Urban Public Transportation Systems TUNNELLING AND UNDERGROUND SPACE TECHNOLOGY, 1987.
- Janssen, N. A. H., M. Strak, A. Yang, B. Hellack, F. J. Kelly, T. A. J. Kuhlbusch, R. M. Harrison, B. Brunekreef, F. R. Cassee, M. Steenhof and G. Hoek. Associations between three specific a-cellular measures of the oxidative potential of particulate matter and markers of acute airway and nasal inflammation in healthy volunteers, *Occupational and Environmental Medicine*, 72(1), 49-56, 2015.
- Janssen, N. A. H., A. Yang, M. Strak, M. Steenhof, B. Hellack, M. E. Gerlofs-Nijland, T. Kuhlbusch, F. Kelly, R. Harrison, B. Brunekreef, G. Hoek and F. Cassee. Oxidative potential of particulate matter collected at sites with different source characteristics, *Science of The Total Environment*, 472, 572-581, doi: doi.org/10.1016/j.scitotenv.2013.11.099, 2014.
- Janssen, N. A. H., A. L. Yang, M. Strak, M. Steenhof, B. Hellack, M. E. Gerlofs-Nijland, T. Kuhlbusch, F. Kelly, R. M. Harrison, B. Brunekreef, G. Hoek and F. Cassee. Oxidative potential of particulate matter collected at sites with different source characteristics,

- Science of the Total Environment, 472, 572-581, doi: 10.1016/j.scitotenv.2013.11.099, 2014.
- Jeong, C.-H., A. Traub and G. J. Evans. Exposure to ultrafine particles and black carbon in diesel-powered commuter trains, *Atmospheric Environment*, 155, 46-52, doi: doi.org/10.1016/j.atmosenv.2017.02.015, 2017.
- Ji, W., X. Li and C. Wang. Composition and exposure characteristics of PM_{2.5} on subway platforms and estimates of exposure reduction by protective masks, *Environmental Research*, 197, 111042, doi: dx.doi.org/10.1016/j.envres.2021.111042, 2021.
- Ji, W., C. Liu, Z. Liu, C. Wang and X. Li. Concentration, composition, and exposure contributions of fine particulate matter on subway concourses in China, *Environmental Pollution*, 275, 116627, doi: dx.doi.org/10.1016/j.envpol.2021.116627, 2021.
- Jiao, W., G. Hagler, R. Williams, R. Sharpe, R. Brown, D. Garver, R. Judge, M. Caudill, J. Rickard, M. Davis, L. Weinstock, S. Zimmer-Dauphinee and K. Buckley. Community Air Sensor Network (CAIRSENSE) project: evaluation of low-cost sensor performance in a suburban environment in the southeastern United States, *Atmos. Meas. Tech.*, 9, 5281-5292, doi: 10.5194/amt-9-5281-2016, 2016.
- Jiménez, L. A., J. Thompson, D. A. Brown, I. Rahman, F. Antonicelli, R. Duffin, E. M. Drost, R. T. Hay, K. Donaldson and W. MacNee. Activation of NF-kappaB by PM(10) occurs via an iron-mediated mechanism in the absence of IkappaB degradation, *Toxicol Appl Pharmacol*, 166, 101-110, doi: 10.1006/taap.2000.8957, 2000.
- Johansson, C. and P. A. Johansson. Particulate matter in the underground of Stockholm, *Atmospheric Environment*, 37, 3-9, doi: 10.1016/S1352-2310(02)00833-6, 2003.
- Joshi, S. S., M. R. Miller and D. E. Newby. Air pollution and cardiovascular disease: the Paul Wood Lecture, *British Cardiovascular Society* 2021, *Heart*, 108, 1267-1273, doi: 10.1136/heartjnl-2021-319844, 2022.
- Jung, H. J., B. Kim, J. Ryu, S. Maskey, J. C. Kim, J. Sohn and C. U. Ro. Source identification of particulate matter collected at underground subway stations in Seoul, Korea using quantitative single-particle analysis, *Atmospheric Environment*, 44, 2287-2293, doi: 10.1016/j.atmosenv.2010.04.003, 2010.
- Jung, M. H., H. R. Kim, Y. J. Park, D. S. Park, K. H. Chung and S. M. Oh. Genotoxic effects and oxidative stress induced by organic extracts of particulate matter (PM₁₀) collected from a subway tunnel in Seoul, Korea, *Mutation Research*, 749, 39-47, 2012.
- Kam, W., K. Cheung, N. Daher and C. Sioutas. Particulate matter (PM) concentrations in underground and ground-level rail systems of the Los Angeles Metro, *Atmospheric Environment*, 45, 1506-1516, 2011.
- Kam, W., Z. Ning, M. M. Shafer, J. J. Schauer and C. Sioutas. Chemical characterization and redox potential of coarse and fine particulate matter (PM) in underground and ground-level rail systems of the Los Angeles Metro, *Environmental Science & Technology*, 45, 6769-6776, doi: dx.doi.org/10.1021/es201195e, 2011.
- Kamani, H., M. Hoseini, M. Seyedsalehi, Y. Mahdavi, J. Jaafari and G. Safari. Concentration and characterization of airborne particles in Tehran's subway system, *Environmental Science and Pollution Research*, 21, 7319-7328, doi: 10.1007/s11356-014-2659-4, 2014.
- Kaminski, H., T. A. J. Kuhlbusch, S. Rath, U. Götz, M. Sprenger, D. Wels, J. Polloczek, V. Bachmann, N. Dziurawitz, H.-J. Kiesling, A. Schwegelshohn, C. Monz, D. Dahmann and C. Asbach. Comparability of mobility particle sizers and diffusion chargers, *Journal of Aerosol Science*, 57, 156-178, doi: doi.org/10.1016/j.jaerosci.2012.10.008, 2013.
- Kang, S., H. Hwang, Y. Park, H. Kim and C. U. Ro. Chemical compositions of subway particles in Seoul, Korea determined by a quantitative single particle analysis, *Environmental Science & Technology*, 42, 9051-9057, doi: 10.1021/es802267b, 2008.
- Kang, Y., L. Aye, T. D. Ngo and J. Zhou. Performance evaluation of low-cost air quality sensors: A review, *The Science of the total environment*, 151769-151769, doi: 10.1016/j.scitotenv.2021.151769, 2021.
- Karagulian, F., M. Barbieri, A. Kotsev, L. Spinelle, M. Gerboles, F. Lagler, N. Redon, S. Crunaire and A. Borowiak. Review of the Performance of Low-Cost Sensors for Air Quality Monitoring, *Atmosphere*, 10, 506, 2019.
- Karlsson, H. L.: Mechanisms related to the genotoxicity of particles in the subway and from other sources, *Chem. Res. Toxicol*, doi: 10.1021/tx7003568, 2008.
- Karlsson, H. L., A. Holgersson and L. Moller. Mechanisms related to the genotoxicity of particles in the subway and from other sources, *Chemical Research in Toxicology*, 21, 726-731, doi: <https://dx.doi.org/10.1021/tx7003568>, 2008.
- Karlsson, H. L., A. G. Ljungman, J. Lindbom and L. Moller. Comparison of genotoxic and inflammatory effects of particles generated by wood combustion, a road simulator and

- collected from street and subway, *Toxicology Letters*, 165, 203-211, doi: 10.1016/j.toxlet.2006.04.003, 2006.
- Karlsson, H. L., L. Nilsson and L. Moller. Subway particles are more genotoxic than street particles and induce oxidative stress in cultured human lung cells, *Chemical Research in Toxicology*, 18, 19-23, doi: 10.1021/tx049723c, 2005.
- Kelly, F., A. Armstrong, R. Artkinson, H. R. Anderson, B. Barratt, S. Beevers, D. Cook, D. Green, D. Derwent, I. Mudway and P. Wilkenson (2011). The London Low Emission Zone Baseline Study, Health Effects Institute. **163**.
- Kelly, F. J.: Oxidative stress: its role in air pollution and adverse health effects, *Occup Environ Med*, 60, 612-616, doi: 10.1136/oem.60.8.612, 2003.
- Kelly, F. J. and J. C. Fussell. Air pollution and public health: emerging hazards and improved understanding of risk, *Environ Geochem Health*, 37, 631-649, doi: 10.1007/s10653-015-9720-1, 2015.
- Kelly, F. J. and J. C. Fussell. Role of oxidative stress in cardiovascular disease outcomes following exposure to ambient air pollution, *Free Radic Biol Med*, 110, 345-367, doi: 10.1016/j.freeradbiomed.2017.06.019, 2017.
- Kim, K. H., D. X. Ho, J. S. Jeon and J. C. Kim. A noticeable shift in particulate matter levels after platform screen door installation in a Korean subway station, *Atmospheric Environment*, 49, 219-223, doi: 10.1016/j.atmosenv.2011.11.058, 2012.
- Kim, K. Y., Y. S. Kim, Y. M. Roh, C. M. Lee and C. N. Kim. Spatial distribution of particulate matter (PM₁₀ and PM_{2.5}) in Seoul Metropolitan Subway stations, *Journal of Hazardous Materials*, 154, 440-443, doi: doi.org/10.1016/j.jhazmat.2007.10.042, 2008.
- Kim, M., S. Park, H. Namgung and S. Kwon. Estimation of inhaled airborne particle number concentration by subway users in Seoul, Korea, *Environmental Pollution*, 231, 663-670, doi: <https://dx.doi.org/10.1016/j.envpol.2017.08.077>, 2017.
- Kim, S. G., G. Sung, S. J. Yook, M. Kim and D. Park. Reducing PM₁₀ and PM_{2.5} Concentrations in a Subway Station by Changing the Diffuser Arrangement, *Toxics*, 10, doi: 10.3390/toxics10090537, 2022.
- Kitagawa, Y. K. L., P. Kumar, E. S. Galvão, J. M. Santos, N. C. Reis Jr, E. G. S. Nascimento and D. M. Moreira. Exposure and dose assessment of school children to air pollutants in a tropical coastal-urban area, *The Science of the total environment*, 803, 149747-149747, doi: 10.1016/j.scitotenv.2021.149747, 2022.
- Kitwiroon, N., S. Beevers and M. Williams. "The WHO Air Quality Guideline for PM_{2.5} - CMAQ modelling of future scenarios." *DEFRA* Retrieved 20 June, 2020, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_t_data/file/930113/annex2-pm25-kings-college-report.pdf. 2019, 21 June 2020.
- Klepczynska-Nystrom, A., B. M. Larsson, J. Grunewald, C. Pousette, A. Lundin, A. Eklund and M. Svartengren. Health effects of a subway environment in mild asthmatic volunteers, *Respir Med*, 106, 25-33, doi: 10.1016/j.rmed.2011.09.008, 2012.
- Klepczynska Nystrom, A., M. Svartengren, J. Grunewald, C. Pousette, I. Rodin, A. Lundin, C. M. Skold, A. Eklund and B. M. Larsson. Health effects of a subway environment in healthy volunteers, *Eur Respir J*, 36, 240-248, doi: 10.1183/09031936.00099909, 2010.
- Klepeis, N. E., W. C. Nelson, W. R. Ott, J. P. Robinson, A. M. Tsang, P. Switzer, J. V. Behar, S. C. Hern and W. H. Engelmann. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, *Journal of exposure science & environmental epidemiology*, 11, 231-252, doi: 10.1038/sj.jea.7500165, 2001.
- Kodros, J. K., K. O'Dell, J. M. Samet, C. L'Orange, J. R. Pierce and J. Volckens. Quantifying the Health Benefits of Face Masks and Respirators to Mitigate Exposure to Severe Air Pollution, *Geohealth*, 5, e2021GH000482, doi: 10.1029/2021gh000482, 2021.
- Koistinen, K. J., A. Kousa, V. Tenhola, O. Hanninen, M. J. Jantunen, L. Oglesby, N. Kuenzli and L. Georgoulis. Fine particle (PM₂₅) measurement methodology, quality assurance procedures, and pilot results of the EXPOLIS study, *J Air Waste Manag Assoc*, 49, 1212-1220, doi: 10.1080/10473289.1999.10463916, 1999.
- Korea Legislation Research Institute. "Indoor Air Quality Act." Retrieved 06 January, 2023, from https://elaw.klri.re.kr/eng_service/lawView.do?hseq=41231&lang=ENG.
- Krauskopf, J., K. van Veldhoven, M. Chadeau-Hyam, R. Vermeulen, G. Carrasco-Turigas, M. Nieuwenhuijsen, P. Vineis, T. M. de Kok and J. C. Kleinjans. Short-term exposure to traffic-related air pollution reveals a compound-specific circulating miRNA profile indicating multiple disease risks, *Environment International*, 128, 193-200, doi: doi.org/10.1016/j.envint.2019.04.063, 2019.
- Krecl, P., R. M. Harrison, C. Johansson, A. C. Targino, D. C. Beddows, T. Ellermann, C. Lara and M. Ketzel. Long-term trends in nitrogen oxides concentrations and on-road vehicle

- emission factors in Copenhagen, London and Stockholm, *Environmental Pollution*, 290, 118105, doi: doi.org/10.1016/j.envpol.2021.118105, 2021.
- Kulmala, M. and V.-M. Kerminen. On the formation and growth of atmospheric nanoparticles, *Atmospheric Research*, 90, 132-150, doi: doi.org/10.1016/j.atmosres.2008.01.005, 2008.
- Kumar, P., A. Robins, S. Vardoulakis and R. Britter. A review of the characteristics of nanoparticles in the urban atmosphere and the prospects for developing regulatory controls, *Atmospheric Environment*, 44, 5035-5052, doi: doi.org/10.1016/j.atmosenv.2010.08.016, 2010.
- Kumar, P., J. C. Zavala-Reyes, G. Kalaiarasan, H. Abubakar-Waziri, G. Young, I. Mudway, C. Dilliway, R. Lakhdar, S. Mumby, M. M. Kłosowski, C. C. Pain, I. M. Adcock, J. S. Watson, M. A. Sephton, K. F. Chung and A. E. Porter. Characteristics of fine and ultrafine aerosols in the London underground, *Science of The Total Environment*, 858, 159315, doi: doi.org/10.1016/j.scitotenv.2022.159315, 2023.
- Landrigan, P. J., R. Fuller, N. J. R. Acosta, O. Adeyi, R. Arnold, N. Basu, A. B. Baldé, R. Bertollini, S. Bose-O'Reilly, J. I. Boufford, P. N. Breyse, T. Chiles, C. Mahidol, A. M. Coll-Seck, M. L. Cropper, J. Fobil, V. Fuster, M. Greenstone, A. Haines, D. Hanrahan, D. Hunter, M. Khare, A. Krupnick, B. Lanphear, B. Lohani, K. Martin, K. V. Mathiasen, M. A. McTeer, C. J. L. Murray, J. D. Ndahimananjara, F. Perera, J. Potočník, A. S. Preker, J. Ramesh, J. Rockström, C. Salinas, L. D. Samson, K. Sandilya, P. D. Sly, K. R. Smith, A. Steiner, R. B. Stewart, W. A. Suk, O. C. P. van Schayck, G. N. Yadama, K. Yumkella and M. Zhong. The Lancet Commission on pollution and health, *The Lancet*, 391, 462-512, doi: doi.org/10.1016/S0140-6736(17)32345-0, 2018.
- Lazer, C., T. Burger and S. Wieczorek. "imputeLCMD: A Collection of Methods for Left-Censored Missing Data Imputation." Retrieved 20 Mach 2023, from <https://cran.rstudio.com/web/packages/imputeLCMD/index.html>. 2022.
- Leek, J. T., R. B. Scharpf, H. C. Bravo, D. Simcha, B. Langmead, W. E. Johnson, D. Geman, K. Baggerly and R. A. Irizarry. Tackling the widespread and critical impact of batch effects in high-throughput data, *Nat Rev Genet*, 11, 733-739, doi: 10.1038/nrg2825, 2010.
- Li, S., Y. Liu, A.-O. Purevjav and L. Yang. Does subway expansion improve air quality?, *Journal of Environmental Economics and Management*, 96, 213-235, doi: doi.org/10.1016/j.jeem.2019.05.005, 2019.
- Li, S., Y. Park, S. Duraisingham, F. H. Strobel, N. Khan, Q. A. Soltow, D. P. Jones and B. Pulendran. Predicting network activity from high throughput metabolomics, *PLoS Comput Biol*, 9, e1003123, doi: 10.1371/journal.pcbi.1003123, 2013.
- Liang, D., Z. Li, J. Vlaanderen, Z. Tang, D. P. Jones, R. Vermeulen and J. A. Sarnat. A State-of-the-Science Review on High-Resolution Metabolomics Application in Air Pollution Health Research: Current Progress, Analytical Challenges, and Recommendations for Future Direction, *Environmental Health Perspectives*, 131, 056002, doi: doi:10.1289/EHP11851, 2023.
- Liang, D., Z. Li, J. Vlaanderen, Z. Tang, D. P. Jones, R. Vermeulen and J. A. Sarnat. A State-of-the-Science Review on High-Resolution Metabolomics Application in Air Pollution Health Research: Current Progress, Analytical Challenges, and Recommendations for Future Direction, *Environ Health Perspect*, 131, 56002, doi: 10.1289/ehp11851, 2023.
- Liang, D., J. L. Moutinho, R. Golan, T. Yu, C. N. Ladva, M. Niedzwiecki, D. I. Walker, S. E. Sarnat, H. H. Chang, R. Greenwald, D. P. Jones, A. G. Russell and J. A. Sarnat. Use of high-resolution metabolomics for the identification of metabolic signals associated with traffic-related air pollution, *Environ Int*, 120, 145-154, doi: 10.1016/j.envint.2018.07.044, 2018.
- Liang, L., J. Ye, L. Han, W. Qiu, H. Zhang, Y. Yu, T. Zhu, F. Xu, X. Zhan, P. Bao, W. Ji and X. Gu. Examining the blood amino acid status in pretherapeutic patients with hyperphenylalaninemia, *Journal of Clinical Laboratory Analysis*, 34, e23106, doi: doi.org/10.1002/jcla.23106, 2020.
- Liao, J., R. Gheissari, D. C. Thomas, F. D. Gilliland, F. Lurmann, K. T. Islam and Z. Chen. Transcriptomic and metabolomic associations with exposures to air pollutants among young adults with childhood asthma history, *Environmental Pollution*, 299, 118903, doi: doi.org/10.1016/j.envpol.2022.118903, 2022.
- Liu, W. T., C. M. Ma, I. J. Liu, B. C. Han, H. C. Chuang and K. J. Chuang. Effects of commuting mode on air pollution exposure and cardiovascular health among young adults in Taipei, Taiwan, *International Journal of Hygiene and Environmental Health*, 218, 319-323, doi: 10.1016/j.ijheh.2015.01.003, 2015.

- Liu, X., R. Jayaratne, P. Thai, T. Kuhn, I. Zing, B. Christensen, R. Lamont, M. Dunbabin, S. Zhu, J. Gao, D. Wainwright, D. Neale, R. Kan, J. Kirkwood and L. Morawska. Low-cost sensors as an alternative for long-term air quality monitoring, *Environmental research*, 185, 109438, doi: 10.1016/j.envres.2020.109438, 2020.
- Ljubičić, Đ., V. Balta, D. Dilber, H. Vražić, D. Đikić, D. Odeh, J. Habek, E. L. Vukovac and N. Tudorić. Association of chronic inflammation with cardiovascular risk in chronic obstructive pulmonary disease-A cross-sectional study, *Health Sci Rep*, 5, e586, doi: 10.1002/hsr2.586, 2022.
- López González, M., M. Galdo Vega, J. M. Fernández Oro and E. Blanco Marigorta. Numerical modeling of the piston effect in longitudinal ventilation systems for subway tunnels, *Tunnelling and Underground Space Technology Incorporating Trenchless Technology Research*, 4022-4037, 2014.
- Loxham, M., M. J. Cooper, M. E. Gerlofs-Nijland, F. R. Cassee, D. E. Davies, M. R. Palmer and D. A. Teagle. Physicochemical characterization of airborne particulate matter at a mainline underground railway station, *Environmental Science & Technology*, 47, 3614-3622, doi: dx.doi.org/10.1021/es304481m, 2013.
- Loxham, M., R. J. Morgan-Walsh, M. J. Cooper, C. Blume, E. J. Swindle, P. W. Dennison, P. H. Howarth, F. R. Cassee, D. A. H. Teagle, M. R. Palmer and D. E. Davies. The Effects on Bronchial Epithelial Mucociliary Cultures of Coarse, Fine, and Ultrafine Particulate Matter From an Underground Railway Station, *Toxicological Sciences*, 145, 98-107, doi: 10.1093/toxsci/kfv034, 2015.
- Loxham, M. and M. J. Nieuwenhuijsen. Health effects of particulate matter air pollution in underground railway systems - a critical review of the evidence, *Particle and Fibre Toxicology*, 16, 12, doi: 10.1186/s12989-019-0296-2, 2019.
- Lu, H., Y. Zhu, Y. Qi and J. Yu. Do Urban Subway Openings Reduce PM_{2.5} Concentrations? Evidence from China, *Sustainability*, 10, 4147, 2018.
- Lu, S., D. Liu, W. Zhang, P. Liu, Y. Fei, Y. Gu, M. Wu, S. Yu, S. Yonemochi, X. Wang and Q. Wang. Physico-chemical characterization of PM_{2.5} in the microenvironment of Shanghai subway, *Atmospheric Research*, 153, 543-552, doi: doi.org/10.1016/j.atmosres.2014.10.006, 2015.
- Luglio, D. G., T. Huynh, A. Saporito and T. Gordon. Investigation of a river-tunnel effect on PM_{2.5} concentrations in New York City subway stations, *Transportation Research Part D: Transport and Environment*, 115, 103579, doi: doi.org/10.1016/j.trd.2022.103579, 2023.
- Luglio, D. G., M. Katsigeorgis, J. Hess, R. Kim, J. Adragna, A. Raja, C. Gordon, J. Fine, G. Thurston and T. Gordon. PM 2.5 concentration and composition in subway systems in the Northeastern United States, *Environmental health perspectives*, 129, 027001, doi: doi.org/10.1289/EHP7202, 2021.
- Lundstrom, S. L., B. Levanen, M. Nording, A. Klepczynska-Nystrom, M. Skold, J. Z. Haeggstrom, J. Grunewald, M. Svartengren, B. D. Hammock, B. M. Larsson, A. Eklund, A. M. Wheelock and C. E. Wheelock. Asthmatics Exhibit Altered Oxylin Profiles Compared to Healthy Individuals after Subway Air Exposure, *Plos One*, 6, doi: 10.1371/journal.pone.0023864, 2011.
- Luo, J., M. Schumacher, A. Scherer, D. Sanoudou, D. Megherbi, T. Davison, T. Shi, W. Tong, L. Shi, H. Hong, C. Zhao, F. Elloumi, W. Shi, R. Thomas, S. Lin, G. Tillinghast, G. Liu, Y. Zhou, D. Herman, Y. Li, Y. Deng, H. Fang, P. Bushel, M. Woods and J. Zhang. A comparison of batch effect removal methods for enhancement of prediction performance using MAQC-II microarray gene expression data, *Pharmacogenomics J*, 10, 278-291, doi: 10.1038/tpj.2010.57, 2010.
- m/z CLOUD. "Advanced Mass Spectral Database." Retrieved 16 Septemebr, 2023, from <https://www.mzcloud.org/>. 2023.
- Ma, C.-J., S. Matuyama, K. Sera and S.-D. Kim. Physicochemical properties of indoor particulate matter collected on subway platforms in Japan, *Asian Journal of Atmospheric Environment*, 6, 73-82, doi: dx.doi.org/10.5572/ajae.2012.6.2.073, 2012.
- Ma, C. J.: Exposure to Fine Particle along Different Commuting Routes in Urban Area of Fukuoka, Japan, *Asian Journal of Atmospheric Environment*, 9, 205-213, doi: 10.5572/ajae.2015.9.3.205, 2015.
- Ma, H., H. Shen, Z. Liang, L. Zhang and C. Xia. Passengers' Exposure to PM 2.5, PM 10, and CO 2 in Typical Underground Subway Platforms in Shanghai, *Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning*, 237-245, doi: 10.1007/978-3-642-39584-0_26, 2014.
- Ma, H., H. G. Shen, Z. Liang, L. C. Zhang and C. Xia. Passengers' Exposure to PM_{2.5}, PM₁₀, and CO₂ in Typical Underground Subway Platforms in Shanghai, *Proceedings of the*

- 8th International Symposium on Heating, Ventilation and Air Conditioning, Vol 1: Indoor and Outdoor Environment, 261, 237-245, doi: 10.1007/978-3-642-39584-0_26, 2014.
- Manohare, M., B. Garg, E. Rajasekar and M. Parida. Evaluation of change in heart rate variability due to different soundscapes, *Noise Mapping*, 9, 234-248, doi: doi:10.1515/noise-2022-0158, 2022.
- Martins, V., C. Correia, I. Cunha-Lopes, T. Faria, E. Diapouli, M. I. Manousakas, K. Eleftheriadis and S. M. Almeida. Chemical characterisation of particulate matter in urban transport modes, *Journal of Environmental Sciences (China)*, 100, 51-61, doi: dx.doi.org/10.1016/j.jes.2020.07.008, 2021.
- Martins, V., T. Moreno, L. Mendes, K. Eleftheriadis, E. Diapouli, C. A. Alves, M. Duarte, E. de Miguel, M. Capdevila, X. Querol and M. C. Minguillon. Factors controlling air quality in different European subway systems, *Environmental Research*, 146, 35-46, doi: 10.1016/j.envres.2015.12.007, 2016.
- Martins, V., T. Moreno, M. C. Minguillon, F. Amato, E. de Miguel, M. Capdevila and X. Querol. Exposure to airborne particulate matter in the subway system, *Science of the Total Environment*, 511, 711-722, doi: 10.1016/j.scitotenv.2014.12.013, 2015.
- Martins, V., T. Moreno, M. C. Minguillon, B. L. van Drooge, C. Reche, F. Amato, E. de Miguel, M. Capdevila, S. Centelles and X. Querol. Origin of inorganic and organic components of PM_{2.5} in subway stations of Barcelona, Spain, *Environmental Pollution*, 208, 125-136, doi: 10.1016/j.envpol.2015.07.004, 2016.
- McHale, C. M., L. Zhang, Q. Lan, R. Vermeulen, G. Li, A. E. Hubbard, K. E. Porter, R. Thomas, C. J. Portier, M. Shen, S. M. Rappaport, S. Yin, M. T. Smith and N. Rothman. Global gene expression profiling of a population exposed to a range of benzene levels, *Environ Health Perspect*, 119, 628-634, doi: 10.1289/ehp.1002546, 2011.
- Mehrdad, R., S. Aghdaei and G. Pouryaghoub. Urinary 8-hydroxy-deoxyguanosine as a biomarker of oxidative DNA damage in employees of subway system, *Acta Med Iran*, 53, 287-292, 2015.
- Mendes, L., M. I. Gini, G. Biskos, I. Colbeck and K. Eleftheriadis. Airborne ultrafine particles in a naturally ventilated metro station: Dominant sources and mixing state determined by particle size distribution and volatility measurements, *Environmental Pollution*, 239, 82-94, doi: doi.org/10.1016/j.envpol.2018.03.067, 2018.
- MetaboAnalyst. "MetaboAnalyst 5.0." Retrieved 16 September 2023, from <https://www.metaboanalyst.ca/MetaboAnalyst/home.xhtml>. 2023.
- Metlin. "Setting the Standard." from metlin.scripps.edu. 2023.
- Midander, K., K. Elihn, A. Wallen, L. Belova, A. K. Karlsson and I. O. Wallinder. Characterisation of nano- and micron-sized airborne and collected subway particles, a multi-analytical approach, *Science of the Total Environment*, 427-428, 390-400, doi: dx.doi.org/10.1016/j.scitotenv.2012.04.014, 2012.
- Minguillon, M. C., C. Reche, V. Martins, F. Amato, E. de Miguel, M. Capdevila, S. Centelles, X. Querol and T. Moreno. Aerosol sources in subway environments, *Environmental Research*, 167, 314-328, doi: <https://dx.doi.org/10.1016/j.envres.2018.07.034>, 2018.
- Miyashita, L., R. Shears, G. Foley, S. Semple, A. Kadioglu and J. Grigg. Underground railway particulate matter and susceptibility to pneumococcal infection, *eBioMedicine*, 80, 104063, doi: doi.org/10.1016/j.ebiom.2022.104063, 2022.
- Mohsen, M., M. B. Ahmed and J. L. Zhou. Particulate matter concentrations and heavy metal contamination levels in the railway transport system of Sydney, Australia, *Transportation Research Part D-Transport and Environment*, 62, 112-124, doi: 10.1016/j.trd.2018.02.015, 2018.
- Moreno, T. and E. de Miguel. Improving air quality in subway systems: An overview, *Environmental Pollution*, 239, 829-831, doi: 10.1016/j.envpol.2018.01.077, 2018.
- Moreno, T., F. J. Kelly, C. Dunster, A. Oliete, V. Martins, C. Reche, M. C. Minguillon, F. Amato, M. Capdevila, E. de Miguel and X. Querol. Oxidative potential of subway PM_{2.5}, *Atmospheric Environment*, 148, 230-238, doi: 10.1016/j.atmosenv.2016.10.045, 2017.
- Moreno, T., V. Martins, X. Querol, T. Jones, K. BeruBe, M. C. Minguillon, F. Amato, M. Capdevila, E. de Miguel, S. Centelles and W. Gibbons. A new look at inhalable metalliferous airborne particles on rail subway platforms, *Science of the Total Environment*, 505, 367-375, doi: 10.1016/j.scitotenv.2014.10.013, 2015.
- Moreno, T., N. Perez, C. Reche, V. Martins, E. de Miguel, M. Capdevila, S. Centelles, M. C. Minguillon, F. Amato, A. Alastuey, X. Querol and W. Gibbons. Subway platform air quality: Assessing the influences of tunnel ventilation, train piston effect and station design, *Atmospheric Environment*, 92, 461-468, doi: 10.1016/j.atmosenv.2014.04.043, 2014.

- Moreno, T., X. Querol, V. Martins, M. C. Minguillon, C. Reche, L. H. Ku, H. R. Eun, K. H. Ahn, M. Capdevila and E. de Miguel. Formation and alteration of airborne particles in the subway environment, *Environmental Science. Processes & Impacts*, 19, 59-64, doi: dx.doi.org/10.1039/c6em00576d, 2017.
- Moreno, T., C. Reche, M. C. Minguillon, M. Capdevila, E. de Miguel and X. Querol. The effect of ventilation protocols on airborne particulate matter in subway systems, *Science of the Total Environment*, 584-585, 1317-1323, doi: 10.1016/j.scitotenv.2017.02.003, 2017.
- Mousavi Fard, Z. S., H. Asilian Mahabadi and F. Khajehnasiri. Investigation of Suspended Particle Concentrations (PM10, PM2.5, TSP) in Tehran Subway Line one Stations in the Spring and Autumn, *Pollution*, 7, 669-680, 2021.
- Mousavi, S. E., J. M. Delgado-Saborit, A. Adivi, S. Pauwels and L. Godderis. Air pollution and endocrine disruptors induce human microbiome imbalances: A systematic review of recent evidence and possible biological mechanisms, *Sci Total Environ*, 816, 151654, doi: 10.1016/j.scitotenv.2021.151654, 2022.
- Mudway, I. S., N. Stenfors, S. T. Duggan, H. Roxborough, H. Zielinski, S. L. Marklund, A. Blomberg, A. J. Frew, T. Sandström and F. J. Kelly. An in vitro and in vivo investigation of the effects of diesel exhaust on human airway lining fluid antioxidants, *Archives of Biochemistry and Biophysics*, 423, 200-212, doi: doi.org/10.1016/j.abb.2003.12.018, 2004.
- Mugica-Alvarez, V., J. Figueroa-Lara, M. Romero-Romo, J. Sepulveda-Sanchez and T. Lopez-Moreno. Concentrations and properties of airborne particles in the Mexico City subway system, *Atmospheric Environment*, 2012.
- Munir, S.: Analysing Temporal Trends in the Ratios of PM2.5/PM10 in the UK, *Aerosol and Air Quality Research*, 17, 34-38, 2017.
- Murrini, L. G., V. Solanes, M. Debray, A. J. Kreiner, J. Davidson, M. Davidson, M. Vazquez and M. Ozafran. Concentrations and elemental composition of particulate matter in the Buenos Aires underground system, *Atmospheric Environment*, 43(30), 4577-4583, 2009.
- Murrini, L. G., V. Solanes, M. Debray, A. J. Kreiner, J. Davidson, M. Davidson, M. Vázquez and M. Ozafrán. Concentrations and elemental composition of particulate matter in the Buenos Aires underground system, *Atmospheric Environment*, 43, 4577-4583, doi: doi.org/10.1016/j.atmosenv.2009.06.025, 2009.
- Neil, G. "London Underground Rolling Stock Information Sheet." Retrieved 24 January 2023, from <https://www.whatdotheyknow.com/request/239641/response/590412/attach/3/RS%20Info%20Sheets%204%20Edition.pdf>. 2015.
- Ni, L., C. C. Chuang and L. Zuo. Fine particulate matter in acute exacerbation of COPD, *Front Physiol*, 6, 294, doi: 10.3389/fphys.2015.00294, 2015.
- Nieuwenhuijsen, M. J., J. E. Gomez-Perales and R. N. Colville. Levels of particulate air pollution, its elemental composition, determinants and health effects in metro systems, *Atmospheric Environment*, 41, 7995-8006, doi: 10.1016/j.atmosenv.2007.08.002, 2007.
- NPL. "Air quality monitoring." Retrieved 29 March 2023, from <https://www.npl.co.uk/products-services/gas/air-quality-monitoring>. 2023.
- Olena, G., J. Ayoung, H. Shizhen, Y. Zhebin, B. Jeroen de, G. M. P. Maria, C. E. Ikenna, K. Sara, E. W. Craig, P. Annette, V. Jelle, H. Kees de, S. Augustin, C.-H. Marc, C. H. V. Roel, G. Ulrike, P.-H. Nicole and M. Erik. Air pollution, metabolites and respiratory health across the life-course, *European Respiratory Review*, 31, 220038, doi: 10.1183/16000617.0038-2022, 2022.
- Onat, B. and B. Stakeeva. Assessment of fine particulate matters in the subway system of Istanbul, *Indoor and Built Environment*, 23, 574-583, doi: doi.org/10.1177/1420326X12464507, 2014.
- Pan, B., M. Chen, X. Zhang, S. Liang, X. Qin, L. Qiu, Q. Cao, R. Peng, S. Tao, Z. Li, Y. Zhu, H. Kan, Y. Xu and Z. Ying. Hypothalamic-pituitary-adrenal axis mediates ambient PM(2.5) exposure-induced pulmonary inflammation, *Ecotoxicol Environ Saf*, 208, 111464, doi: 10.1016/j.ecoenv.2020.111464, 2021.
- Pan, S., S. Du, X. Wang, X. Zhang, L. Xia, J. Liu, F. Pei and Y. Wei. Analysis and interpretation of the particulate matter (PM10 and PM2.5) concentrations at the subway stations in Beijing, China, *Sustainable cities and society*, 45, 366-377, 2019.
- Pan, S., L. Fan, J. Liu, J. Xie, Y. Sun, N. Cui, L. Zhang and B. Zheng. A Review of the Piston Effect in Subway Stations, *Advances in Mechanical Engineering*, 5, 950205, doi: 10.1155/2013/950205, 2013.

- Pang, Z., J. Chong, G. Zhou, D. A. de Lima Morais, L. Chang, M. Barrette, C. Gauthier, P.-É. Jacques, S. Li and J. Xia. MetaboAnalyst 5.0: narrowing the gap between raw spectra and functional insights, *Nucleic Acids Research*, 49, W388-W396, doi: 10.1093/nar/gkab382, 2021.
- Park, D. U. and K. C. Ha. Characteristics of PM₁₀, PM_{2.5}, CO₂ and CO monitored in interiors and platforms of subway train in Seoul, Korea, *Environment International*, 34, 629-634, doi: dx.doi.org/10.1016/j.envint.2007.12.007, 2008.
- Park, J., H. Woo and J. Park. Major factors affecting the aerosol particulate concentration in the underground stations, *Indoor and Built Environment*, 23, 629-639, 2014.
- Park, J. H., H. Y. Woo and J. C. Park. Major factors affecting the aerosol particulate concentration in the underground stations, *Indoor and Built Environment*, 23, 629-639, doi: 10.1177/1420326x12466875, 2014.
- Park, S., M. Kim, M. Kim, H.-G. Namgung, K.-T. Kim, K. H. Cho and S.-B. Kwon. Predicting PM₁₀ concentration in Seoul metropolitan subway stations using artificial neural network (ANN), *Journal of hazardous materials*, 341, 75-82, 2018.
- Passi, A., Nagendra, S and Maiya, M Assesment of indoor and outdoor exposure to airbourne particles in subway metro systems and their associated health risks, *WIT Transactions on Ecology and the Environment*, 252, 85-96, doi: 10.2495/AIR210081, 2021.
- Perrino, C., F. Marcovecchio, L. Tofful and S. Canepari. Particulate matter concentration and chemical composition in the metro system of Rome, Italy, *Environmental Science & Pollution Research*, 22, 9204-9214, doi: <https://dx.doi.org/10.1007/s11356-014-4019-9>, 2015.
- Petrick, L. M. and N. Shomron. AI/ML-driven advances in untargeted metabolomics and exposomics for biomedical applications, *Cell Reports Physical Science*, 3, 100978, doi: doi.org/10.1016/j.xcrp.2022.100978, 2022.
- Pfeifer, G. D., R. M. Harrison and D. R. Lynam. Personal exposures to airborne metals in London taxi drivers and office workers in 1995 and 1996, *The Science of the Total Environment*, 235, 253-260, doi: 10.1016/s0048-9697(99)00201-6, 1999.
- Pinheiro, J., D. Bates, S. Debroy, D. Sarkar, S. Heisterkamp, B. Van Willigen and J. Ranke. "nlme: Linear and Nonlinear Mixed Effects Models." Retrieved 05 March, 2023, from <https://cran.r-project.org/web/packages/nlme/nlme.pdf>. 2023.
- Place, P. F., L. D. Ziemba and R. J. Griffin. Observations of nucleation-mode particle events and size distributions at a rural New England site, *Atmospheric Environment*, 44, 88-94, doi: doi.org/10.1016/j.atmosenv.2009.09.030, 2010.
- Pope, C. A., R. T. Burnett, G. D. Thurston, M. J. Thun, E. E. Calle, D. Krewski and J. J. Godleski. Cardiovascular Mortality and Long-Term Exposure to Particulate Air Pollution, *Circulation*, 109, 71-77, doi: doi:10.1161/01.CIR.0000108927.80044.7F, 2004.
- Pope III, C. A., R. T. Burnett, M. J. Thun, E. E. Calle, D. Krewski, K. Ito and G. D. Thurston. Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution, *JAMA*, 287, 1132-1141, doi: 10.1001/jama.287.9.1132, 2002.
- Porcu, E., M. C. Sadler, K. Lepik, C. Auwerx, A. R. Wood, A. Weihs, M. S. B. Sleiman, D. M. Ribeiro, S. Bandinelli, T. Tanaka, M. Nauck, U. Völker, O. Delaneau, A. Metspalu, A. Teumer, T. Frayling, F. A. Santoni, A. Reymond and Z. Kutalik. Differentially expressed genes reflect disease-induced rather than disease-causing changes in the transcriptome, *Nature Communications*, 12, 5647, doi: 10.1038/s41467-021-25805-y, 2021.
- Posselt, K. P., M. Neuberger and D. Kohler. Fine and ultrafine particle exposure during commuting by subway in Vienna, *Wiener Klinische Wochenschrift*, 131, 374-380, doi: <https://dx.doi.org/10.1007/s00508-019-1516-3>, 2019.
- Potapov, S., F. Model, A. Schuetzenmeister, E. Manuilova, F. Dufey and J. Raymaekers. "Package 'mcr'" Retrieved 21 January, 2023, from <https://cran.r-project.org/web/packages/mcr/mcr.pdf>. 2023.
- Priest, N. D., G. Burns and B. Gorbunov. Dust levels on The London Underground: A health hazard to Commuters?, *Urban Pollution Centre*, Middlesex University, 1998.
- Publications Office of the European Union. "The precautionary principle: Decision-making under uncertainty." Retrieved 07 June, 2023, from <https://op.europa.eu/en/publication-detail/-/publication/1c737cfe-beb8-11e7-a7f8-01aa75ed71a1/language-en>. 2017.
- Puthussery, J. V., A. Singh, P. Rai, D. Bhattu, V. Kumar, P. Vats, M. Furger, N. Rastogi, J. G. Slowik, D. Ganguly, A. S. H. Prevot, S. N. Tripathi and V. Verma. Real-Time Measurements of PM_{2.5} Oxidative Potential Using a Dithiothreitol Assay in Delhi, India, *Environmental Science & Technology Letters*, 7, 504-510, doi: 10.1021/acs.estlett.0c00342, 2020.

- Qi, C., C. Asbach, W. G. Shin, H. Fissan and D. Y. H. Pui. The Effect of Particle Pre-Existing Charge on Unipolar Charging and Its Implication on Electrical Aerosol Measurements, *Aerosol Science and Technology*, 43, 232-240, doi: 10.1080/02786820802587912, 2009.
- Querol, X., T. Moreno, A. Karanasiou, C. Reche, A. Alastuey, M. Viana, O. Font, J. Gil, E. de Miguel and M. Capdevila. Variability of levels and composition of PM₁₀ and PM_{2.5} in the Barcelona metro system, *Atmospheric Chemistry and Physics*, 12, 5055-5076, doi: 10.5194/acp-12-5055-2012, 2012.
- R_Core_Team. "R: A language and environment for statistical computing, R.F.f.S. Computing." Retrieved 19 October, 2019, from <https://www.r-project.org/>. 2021.
- Rail Safety and Standards Board Ltd. "Analysis of Air Quality On Board Trains." Retrieved 05 May, 2023, from <https://www.rssb.co.uk/-/media/Project/RSSB/RssbWebsite/Documents/Registered/Research-Projects/2021/12/02/09/21/2021-11-T1188-analysis-of-air-quality-on-trains.pdf>. 2021.
- RATP. "Air quality in stations." Retrieved 20 February 2023, from <https://air-interieur.ratp.fr/>. 2023.
- Raut, J.-C., P. Chazette and A. Fortain. Link between aerosol optical, microphysical and chemical measurements in an underground railway station in Paris, *Atmospheric Environment*, 43, 860-868, doi: doi.org/10.1016/j.atmosenv.2008.10.038, 2009.
- Raut, J. C.: Link between aerosol optical, microphysical and chemical measurements in an underground railway station in Paris, doi: doi.org/10.1016/j.atmosenv.2008.10.038, 2009.
- Reche, C., T. Moreno, V. Martins, M. Minguillon, T. Jones, E. de Miguel, M. Capdevila, S. Centelles and X. Querol. Factors controlling particle number concentration and size at metro stations, *Atmospheric Environment*, 2017.
- Ripanuucci, G., M. Grana, L. Vicentini, A. Magrini and A. Bergamaschi. Dust in the Underground Railway Tunnels of an Italian Town, *Journal of Occupational and Environmental Hygiene*, 3, 16-25, doi: 10.1080/15459620500444004, 2006.
- Rivas, B., P. Kumar and A. Hagen-Zanker. Exposure to air pollutants during commuting in London: Are there inequalities among different socio-economic groups?, *Environment International*, 101, 143-157, doi: 10.1016/j.envint.2017.01.019, 2017.
- Rosenlund, M., F. Forastiere, D. Porta, M. D. Sario, C. Badaloni and C. A. Perucci. Traffic-related air pollution in relation to respiratory symptoms, allergic sensitisation and lung function in schoolchildren, *Thorax*, 64, 573-580, doi: 10.1136/thx.2007.094953, 2009.
- Roy, D., E. S. Lyou, J. Kim, T. K. Lee and J. Park. Commuters health risk associated with particulate matter exposures in subway system – Globally, *Building and Environment*, 216, 109036, doi: doi.org/10.1016/j.buildenv.2022.109036, 2022.
- RSSB. "Rail Safety and Standards Board,." from <https://www.rssb.co.uk/>. 2023.
- Russell, H. S., N. Kappelt, D. Fessa, L. B. Frederickson, E. Bagkis, P. Apostolidis, K. Karatzas, J. A. Schmidt, O. Hertel and M. S. Johnson. Particulate air pollution in the Copenhagen metro part 2: Low-cost sensors and micro-environment classification, *Environment International*, 170, 107645, doi: doi.org/10.1016/j.envint.2022.107645, 2022.
- Salma, I., M. Posfai, K. Kovacs, E. Kuzmann, Z. Homonnay and J. Posta. Properties and sources of individual particles and some chemical species in the aerosol of a metropolitan underground railway station, *Atmospheric Environment*, 43, 3460-3466, doi: 10.1016/j.atmosenv.2009.04.042, 2009.
- Salma, I., T. Weidinger and W. Maenhaut. Time-resolved mass concentration, composition and sources of aerosol particles in a metropolitan underground railway station, *Atmospheric Environment*, 41, 8391-8405, doi: 10.1016/j.atmosenv.2007.06.017, 2007.
- Samad, A., D. R. Obando Nuñez, G. C. Solis Castillo, B. Laquai and U. Vogt. Effect of Relative Humidity and Air Temperature on the Results Obtained from Low-Cost Gas Sensors for Ambient Air Quality Measurements, *Sensors*, 20, 5175, doi: doi:10.3390/s20185175, 2020.
- Samoli, E., R. W. Atkinson, A. Analitis, G. W. Fuller, D. C. Green, I. Mudway, H. R. Anderson and F. J. Kelly. Associations of short-term exposure to traffic-related air pollution with cardiovascular and respiratory hospital admissions in London, UK, *Occupational and Environmental Medicine*, 73, 300-307, doi: 10.1136/oemed-2015-103136, 2016.
- Sarnat, S. E., H. H. Chang and R. J. Weber. Ambient PM_{2.5} and Health: Does PM_{2.5} Oxidative Potential Play a Role?, *American Journal of Respiratory and Critical Care Medicine*, 194, 530-531, doi: 10.1164/rccm.201603-0589ED, 2016.
- Saunders, B. M., James D. Smith, Thomas E.L. Smith, David C. Green and B. Barratt. Spatial variability of fine particulate matter pollution (PM_{2.5}) on the London Underground network, doi: 10.1016/j.uclim.2019.100535, 2019.

- Schraufnagel, D. E.: The health effects of ultrafine particles, *Experimental & Molecular Medicine*, 52, 311-317, doi: 10.1038/s12276-020-0403-3, 2020.
- Schymanski, E. L., J. Jeon, R. Gulde, K. Fenner, M. Ruff, H. P. Singer and J. Hollender. Identifying Small Molecules via High Resolution Mass Spectrometry: Communicating Confidence, *Environmental Science & Technology*, 48, 2097-2098, doi: 10.1021/es5002105, 2014.
- Seaton, A., J. Cherrie, M. Dennekamp, K. Donaldson, J. F. Hurley and C. L. Tran. The London Underground: dust and hazards to health, *Occupational & Environmental Medicine*, 62, 355-362, doi: 10.1136/oem.2004.014332, 2005.
- Shakya, K. M., A. Saad and A. Aharonian. Commuter exposure to particulate matter at underground subway stations in Philadelphia, *Building and Environment*, 186, 107322, doi: 10.1016/j.buildenv.2020.107322, 2020.
- Sheikh, H. A., P. Y. Tung, E. Ringe and R. J. Harrison. Magnetic and microscopic investigation of airborne iron oxide nanoparticles in the London Underground, *Scientific Reports*, 12, 20298, doi: 10.1038/s41598-022-24679-4, 2022.
- Shi, T., R. Duffin, P. J. A. Borm, H. Li, C. Weishaupt and R. P. F. Schins. Hydroxyl-radical-dependent DNA damage by ambient particulate matter from contrasting sampling locations, *Environmental Research*, 101, 18-24, doi: doi.org/10.1016/j.envres.2005.09.005, 2006.
- Singh, T., T. Biggs, E. Crossley, M. Faoury, A. Mahmood, A. Salamat, T. Patterson, N. Jayakody, A. Dando, F. Sipaul, K. Marinakis, H. Sudhoff and P. Brown. Noise Exposure on the London Underground, an Observational Study over a Decade, *Laryngoscope*, 130, 2891-2895, doi: dx.doi.org/10.1002/lary.28547, 2020.
- Sinharay, R., J. Gong, B. Barratt, P. Ohman-Strickland, S. Ernst, F. J. Kelly, J. J. Zhang, P. Collins, P. Cullinan and K. F. Chung. Respiratory and cardiovascular responses to walking down a traffic-polluted road compared with walking in a traffic-free area in participants aged 60 years and older with chronic lung or heart disease and age-matched healthy controls: a randomised, crossover study, *Lancet*, 391, 339-349, doi: 10.1016/S0140-6736(17)32643-0, 2018.
- Sitzmann, B.: Characterisation of airborne particles in London by computer-controlled scanning electron microscopy, doi: doi.org/10.1016/S0048-9697(99)00326-5, 1999.
- Skoza, L., A. Snyder and Y. Kikkawa. Ascorbic acid in bronchoalveolar wash, *Lung*, 161, 99-109, doi: 10.1007/BF02713848, 1983.
- Smith, J., B. Barratt, G. Fuller, F. Kelly, M. Loxham, E. Nicolosi, M. Priestman, A. Tremper and D. Green. PM_{2.5} on the London Underground, *Environment international*, 134, 105188, doi: doi.org/10.1016/j.envint.2019.105188, 2020.
- Smith, J. D., C. Mitsakou, N. Kitwiroon, B. M. Barratt, H. A. Walton, J. G. Taylor, H. R. Anderson, F. J. Kelly and S. D. Beevers. London Hybrid Exposure Model: Improving Human Exposure Estimates to NO₂ and PM_{2.5} in an Urban Setting, *Environ Sci Technol*, 50, 11760-11768, doi: 10.1021/acs.est.6b01817, 2016.
- Spagnolo, A. M., G. Ottria, F. Perdelli and M. L. Cristina. Chemical characterisation of the coarse and fine particulate matter in the environment of an underground railway system: cytotoxic effects and oxidative stress-a preliminary study, *International Journal of Environmental Research and Public Health*, 12, 4031-4046, doi: 10.3390/ijerph120404031, 2015.
- Steenhof, M., I. Gosens, M. Strak, K. J. Godri, G. Hoek, F. R. Cassee, I. S. Mudway, F. J. Kelly, R. M. Harrison, E. Lebrecht, B. Brunekreef, N. A. Janssen and R. H. Pieters. In vitro toxicity of particulate matter (PM) collected at different sites in the Netherlands is associated with PM composition, size fraction and oxidative potential--the RAPTES project, *Particle & Fibre Toxicology [Electronic Resource]*, 8, 26, doi: dx.doi.org/10.1186/1743-8977-8-26, 2011.
- Strak, M., G. Weinmayr, S. Rodopoulou, J. Chen, K. d. Hoogh, Z. J. Andersen, R. Atkinson, M. Bauwelinck, T. Bekkevold, T. Bellander, M.-C. Boutron-Ruault, J. Brandt, G. Cesaroni, H. Concin, D. Fehst, F. Forastiere, J. Gulliver, O. Hertel, B. Hoffmann, U. A. Hvidtfeldt, N. A. H. Janssen, K.-H. Jöckel, J. T. Jørgensen, M. Ketzel, J. O. Klompmaker, A. Lager, K. Leander, S. Liu, P. Ljungman, P. K. E. Magnusson, A. J. Mehta, G. Nagel, B. Oftedal, G. Pershagen, A. Peters, O. Raaschou-Nielsen, M. Renzi, D. Rizzuto, Y. T. v. d. Schouw, S. Schramm, G. Severi, T. Sigsgaard, M. Sørensen, M. Stafoggia, A. Tjønneland, W. M. M. Verschuren, D. Vienneau, K. Wolf, K. Katsouyanni, B. Brunekreef, G. Hoek and E. Samoli. Long term exposure to low level air pollution and mortality in eight European cohorts within the ELAPSE project: pooled analysis, *BMJ*, 374, n1904, doi: 10.1136/bmj.n1904, 2021.

- Sumner, L. W., A. Amberg, D. Barrett, M. H. Beale, R. Beger, C. A. Daykin, T. W. Fan, O. Fiehn, R. Goodacre, J. L. Griffin, T. Hankemeier, N. Hardy, J. Harnly, R. Higashi, J. Kopka, A. N. Lane, J. C. Lindon, P. Marriott, A. W. Nicholls, M. D. Reilly, J. J. Thaden and M. R. Viant. Proposed minimum reporting standards for chemical analysis Chemical Analysis Working Group (CAWG) Metabolomics Standards Initiative (MSI), *Metabolomics*, 3, 211-221, doi: 10.1007/s11306-007-0082-2, 2007.
- Sun, Y., G. Deng, J. Fan, F. Feng, Q. Ge, Y. Song and X. Kang. Associations of air PM_{2.5} level with gut microbiota in Chinese Han preschoolers and effect modification by oxytocin receptor gene polymorphism, *Environ Res*, 214, 114123, doi: 10.1016/j.envres.2022.114123, 2022.
- Sundh, J., U. Olofsson, L. Olander and A. Jansson. Wear rate testing in relation to airborne particles generated in a wheel-rail contact, *Lubrication Science*, 21, 135-150, doi: <https://doi.org/10.1002/ls.80>, 2009.
- TfL. "Tube trivia and facts." Retrieved 11 December, 2022, from <https://madeby.tfl.gov.uk/2019/07/29/tube-trivia-and-facts/>. 2019.
- TfL. "A brief history of the Underground." Retrieved 14 January 2023, from <https://tfl.gov.uk/corporate/about-tfl/culture-and-heritage/londons-transport-a-history/london-underground/a-brief-history-of-the-underground>. 2023.
- TfL. "What we do." Retrieved 21 January 2023, from <https://tfl.gov.uk/corporate/about-tfl/what-we-do#:~:text=Managing%20the%20Tube,trains%2C%20stations%20and%20control%20centres>. 2023.
- The Metabolomics Innovation Centre. "The Human Metabolome Database (HMDB)." Retrieved 23 March, 2023, from <https://hmdb.ca/>. 2023.
- Torrey, C. M., K. A. Moon, D. A. Williams, T. Green, J. E. Cohen, A. Navas-Acien and P. N. Breyse. Waterpipe cafes in Baltimore, Maryland: Carbon monoxide, particulate matter, and nicotine exposure, *J Expo Sci Environ Epidemiol*, 25, 405-410, doi: 10.1038/jes.2014.19, 2015.
- Transport for London. "Everything you need to know about the Elizabeth line." Retrieved 23 July, 2023, from <https://tfl.gov.uk/travel-information/improvements-and-projects/everything-you-need-to-know-about-the-elizabeth-line>. 2023.
- Transport for London. "What we do." Retrieved 05 March, 2023, from <https://tfl.gov.uk/corporate/about-tfl/what-we-do#:~:text=The%20Tube%20handles%20up%20to,trains%20whizzing%20around%20the%20Capital>. 2023.
- Tremper, A. H., C. Jephcote, J. Gulliver, L. Hibbs, D. C. Green, A. Font, M. Priestman, A. L. Hansell and G. W. Fuller. Sources of particle number concentration and noise near London Gatwick Airport, *Environment International*, 161, 107092, doi: doi.org/10.1016/j.envint.2022.107092, 2022.
- Tsuji, A., Y. Ikeda, S. Yoshikawa, K. Taniguchi, H. Sawamura, S. Morikawa, M. Nakashima, T. Asai and S. Matsuda. The Tryptophan and Kynurenine Pathway Involved in the Development of Immune-Related Diseases, *International Journal of Molecular Sciences*, 24, 5742, 2023.
- Tugizimana, F., P. A. Steenkamp, L. A. Piater and I. A. Dubery. A Conversation on Data Mining Strategies in LC-MS Untargeted Metabolomics: Pre-Processing and Pre-Treatment Steps, *Metabolites*, 6, doi: 10.3390/metabo6040040, 2016.
- Uddin, A. B. M. H., R. S. Khalid, M. Alaama, A. M. Abdualkader, A. Kasmuri and S. A. Abbas. Comparative study of three digestion methods for elemental analysis in traditional medicine products using atomic absorption spectrometry, *Journal of Analytical Science and Technology*, 7, 6, doi: 10.1186/s40543-016-0085-6, 2016.
- United Nations. "World Urbanization Prospects 2018." *United Nations*, from <https://population.un.org/wup/publications/Files/WUP2018-Highlights.pdf>. 2019.
- UTIP. "World Metro Figures 2021." Retrieved 03 March, 2023, from <https://cms.uitp.org/wp/wp-content/uploads/2022/05/Statistics-Brief-Metro-Figures-2021-web.pdf>. 2021.
- Vallabani, N. V. S., O. Gruziova, K. Elihn, A. T. Juárez-Facio, S. S. Steimer, J. Kuhn, S. Silvergren, J. Portugal, B. Piña, U. Olofsson, C. Johansson and H. L. Karlsson. Toxicity and health effects of ultrafine particles: Towards an understanding of the relative impacts of different transport modes, *Environmental Research*, 231, 116186, doi: doi.org/10.1016/j.envres.2023.116186, 2023.
- van der Vliet, A., C. A. O'Neill, C. E. Cross, J. M. Koostra, W. G. Volz, B. Halliwell and S. Louie. Determination of low-molecular-mass antioxidant concentrations in human respiratory tract lining fluids, *Am J Physiol*, 276, L289-296, doi: 10.1152/ajplung.1999.276.2.L289, 1999.

- Van Ryswyk, K., A. T. Anastasopoulos, G. Evans, L. Sun, K. Sabaliauskas, R. Kulka, L. Wallace and S. Weichenthal. Metro Commuter Exposures to Particulate Air Pollution and PM_{2.5}-Associated Elements in Three Canadian Cities: The Urban Transportation Exposure Study, *Environ Sci Technol*, 51, 5713-5720, doi: 10.1021/acs.est.6b05775, 2017.
- Van Ryswyk, K., R. Kulka, L. Marro, D. Yang, E. Toma, L. Mehta, L. McNeil-Taboika and G. J. Evans. Impacts of Subway System Modifications on Air Quality in Subway Platforms and Trains, *Environmental Science & Technology*, 30, 30, doi: <https://dx.doi.org/10.1021/acs.est.1c00703>, 2021.
- van Veldhoven, K., A. Kiss, P. Keski-Rahkonen, N. Robinot, A. Scalbert, P. Cullinan, K. F. Chung, P. Collins, R. Sinharay, B. M. Barratt, M. Nieuwenhuijsen, A. A. Rodoreda, G. Carrasco-Turigas, J. Vlaanderen, R. Vermeulen, L. Portengen, S. A. Kyrtopoulos, E. Ponzi, M. Chadeau-Hyam and P. Vineis. Impact of short-term traffic-related air pollution on the metabolome – Results from two metabolome-wide experimental studies, *Environment International*, 123, 124-131, doi: doi.org/10.1016/j.envint.2018.11.034, 2019.
- Velasco, E., H. H. Ha, A. D. Pham and S. Rastan. Effectiveness of wearing face masks against traffic particles on the streets of Ho Chi Minh City, Vietnam, *Environmental Science: Atmospheres*, 2, 1450-1468, doi: 10.1039/D2EA00071G, 2022.
- Verma, V., M. M. Shafer, J. J. Schauer and C. Sioutas. Contribution of transition metals in the reactive oxygen species activity of PM emissions from retrofitted heavy-duty vehicles, *Atmospheric Environment*, 44, 5165-5173, doi: doi.org/10.1016/j.atmosenv.2010.08.052, 2010.
- Vlaanderen, J. J., N. A. Janssen, G. Hoek, P. Keski-Rahkonen, D. K. Barupal, F. R. Cassee, I. Gosens, M. Strak, M. Steenhof, Q. Lan, B. Brunekreef, A. Scalbert and R. C. H. Vermeulen. The impact of ambient air pollution on the human blood metabolome, *Environmental Research*, 156, 341-348, doi: doi.org/10.1016/j.envres.2017.03.042, 2017.
- Vrijens, K., E. Winckelmans, M. Tsamou, W. Baeyens, P. D. Boever, D. Jennen, T. M. d. Kok, E. D. Hond, W. Lefebvre, M. Plusquin, H. Reynders, G. Schoeters, N. V. Larebeke, C. Vanpoucke, J. Kleinjans and T. S. Nawrot. Sex-Specific Associations between Particulate Matter Exposure and Gene Expression in Independent Discovery and Validation Cohorts of Middle-Aged Men and Women, *Environmental Health Perspectives*, 125, 660-669, doi: doi:10.1289/EHP370, 2017.
- Wagner, R. L., N. J. Farren, J. Davison, S. Young, J. R. Hopkins, A. C. Lewis, D. C. Carslaw and M. D. Shaw. Application of a mobile laboratory using a selected-ion flow-tube mass spectrometer (SIFT-MS) for characterisation of volatile organic compounds and atmospheric trace gases, *Atmos. Meas. Tech.*, 14, 6083-6100, doi: 10.5194/amt-14-6083-2021, 2021.
- Wang, J., G. Chen, J. Hou, D. Wei, P. Liu, L. Nie, K. Fan, L. Wang, Q. Xu, Y. Song, M. Wang, W. Huo, T. Jing, W. Li, Y. Guo, C. Wang and Z. Mao. Associations of residential greenness, ambient air pollution, biological sex, and glucocorticoids levels in rural China, *Ecotoxicol Environ Saf*, 242, 113945, doi: 10.1016/j.ecoenv.2022.113945, 2022.
- Wang, J., R. Xue, C. Li, L. Hu, Q. Li, Y. Sun, Y. Chen, W. Yuan, Q. Xia, L. Hu, Y. Wei and M. He. Inhalation of subway fine particles induces murine extrapulmonary organs damage, *Science of The Total Environment*, 878, 163181, doi: doi.org/10.1016/j.scitotenv.2023.163181, 2023.
- Wang, J. J.: Characteristics of particulate matter (PM) concentrations influenced by piston wind and train door opening in the Shanghai subway system, *Transportation Research Part D Transport and Environment* 2016.
- Wang, W.-C. V., S.-C. C. Lung, C.-H. Liu, T.-Y. J. Wen, S.-C. Hu and L.-J. Chen. Evaluation and Application of a Novel Low-Cost Wearable Sensing Device in Assessing Real-Time PM_{2.5} Exposure in Major Asian Transportation Modes, *Atmosphere*, 12, 270, doi: doi:10.3390/atmos12020270, 2021.
- Wang, Y., J. Tao, R. Wang and C. Mi. Can the New Subway Line Openings Mitigate PM₁₀ Concentration? Evidence from Chinese Cities Based on the PSM-DID Method, *International Journal of Environmental Research & Public Health* [Electronic Resource], 17, 27, doi: dx.doi.org/10.3390/ijerph17134638, 2020.
- Wei, P., Z. Ning, S. Ye, L. Sun, F. Yang, K. C. Wong, D. Westerdahl and P. K. K. Louie. Impact Analysis of Temperature and Humidity Conditions on Electrochemical Sensor Response in Ambient Air Quality Monitoring, *Sensors (Basel)*, 18, doi: 10.3390/s18020059, 2018.

- WHO. "What are the WHO Air quality guidelines?" Retrieved 03 March, 2024, from <https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines>. 2024.
- Wickham, H. "Package 'ggplot2'." Retrieved 12 April, 2023, from <https://cran.r-project.org/web/packages/ggplot2/ggplot2.pdf>. 2023.
- Wilson, K. L. and J. W. Birks. Mechanism and Elimination of a Water Vapor Interference in the Measurement of Ozone by UV Absorbance, *Environmental Science & Technology*, 40, 6361-6367, doi: 10.1021/es052590c, 2006.
- World Health Organisation. "WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide." Retrieved 04 March, 2023, from <https://apps.who.int/iris/handle/10665/345329>. 2021.
- Wu, C. and J. Z. Yu. Evaluation of linear regression techniques for atmospheric applications: the importance of appropriate weighting, *Atmospheric Measurement Techniques*, 11, 1233-1250, doi: 10.5194/amt-11-1233-2018, 2018.
- Xu, B. and J. Hao. Air quality inside subway metro indoor environment worldwide: A review, *Environment International*, 107, 33-46, doi: dx.doi.org/10.1016/j.envint.2017.06.016, 2017.
- Xu, S. Y., C. Jiang and L. Huang. Public health impacts from subway noise: Case study Hong Kong, *The Journal of the Acoustical Society of America*, 145, 1867-1867, doi: 10.1121/1.5101747, 2019.
- Yadav, S. and H. C. Phuleria (2020). Oxidative Potential of Particulate Matter: A Prospective Measure to Assess PM Toxicity. *Measurement, Analysis and Remediation of Environmental Pollutants*. T. Gupta, S. P. Singh, P. Rajput and A. K. Agarwal. Singapore, Springer Singapore: 333-356.
- Yang, J., S. Chen, P. Qin, F. Lu and A. A. Liu. The effect of subway expansions on vehicle congestion: Evidence from Beijing, *Journal of Environmental Economics and Management*, 88, 114-133, doi: doi.org/10.1016/j.jeem.2017.09.007, 2018.
- Yang, X., X. Jia, W. Dong, S. Wu, M. R. Miller, D. Hu, H. Li, L. Pan, F. Deng and X. Guo. Cardiovascular benefits of reducing personal exposure to traffic-related noise and particulate air pollution: A randomized crossover study in the Beijing subway system, *Indoor Air*, 13, 13, doi: dx.doi.org/10.1111/ina.12485, 2018.
- Yang, Z., Z. He, K. Zhang, L. Zeng and A. de Nazelle. Investigation into Beijing commuters' exposure to ultrafine particles in four transportation modes: bus, car, bicycle and subway, *Atmospheric Environment*, 266, 118734, doi: 10.1016/j.atmosenv.2021.118734, 2021.
- Zhang, A. L., J. R. Balmes, L. Lutzker, J. K. Mann, H. G. Margolis, T. Tyner, N. Holland, E. M. Noth, F. Lurmann, S. K. Hammond and S. M. Holm. Traffic-related air pollution, biomarkers of metabolic dysfunction, oxidative stress, and CC16 in children, *J Expo Sci Environ Epidemiol*, 32, 530-537, doi: 10.1038/s41370-021-00378-6, 2022.
- Zhang, H. and R. Srinivasan. A Systematic Review of Air Quality Sensors, Guidelines, and Measurement Studies for Indoor Air Quality Management, *Sustainability*, 12, 9045, 2020.
- Zhang, X., Y. Xu and J. Su. Temporal and spatial characteristics of particulate matters in metro stations of Shanghai, China, *Building and Environment*, 179, 106956, doi: doi.org/10.1016/j.buildenv.2020.106956, 2020.
- Zhao, L., J. Wang, H. O. Gao, Y. Xie, R. Jiang, Q. Hu and Y. Sun. Evaluation of particulate matter concentration in Shanghai's metro system and strategy for improvement, *Transportation Research Part D: Transport and Environment*, 53, 115-127, doi: doi.org/10.1016/j.trd.2017.04.010, 2017.
- Zheng, H. L., W. J. Deng, Y. Cheng and W. Guo. Characteristics of PM_{2.5}, CO₂ and particle-number concentration in mass transit railway carriages in Hong Kong, *Environmental Geochemistry & Health*, 39, 739-750, doi: dx.doi.org/10.1007/s10653-016-9844-y, 2017.
- Zheng, P., B. Zhang, K. Zhang, X. Lv, Q. Wang and X. Bai. The Impact of Air Pollution on Intestinal Microbiome of Asthmatic Children: A Panel Study, *Biomed Res Int*, 2020, 5753427, doi: 10.1155/2020/5753427, 2020.
- Zhong, J., A. Cayir, L. Trevisi, M. Sanchez-Guerra, X. Lin, C. Peng, M.-A. Bind, D. Prada, H. Laue, K. J. M. Brennan, A. Dereix, D. Sparrow, P. Vokonas, J. Schwartz and A. A. Baccarelli. Traffic-Related Air Pollution, Blood Pressure, and Adaptive Response of Mitochondrial Abundance, Circulation, 133, 378-387, doi: doi:10.1161/CIRCULATIONAHA.115.018802, 2016.

- Zielinski, H., I. S. Mudway, K. A. Bérubé, S. Murphy, R. Richards and F. J. Kelly. Modeling the interactions of particulates with epithelial lining fluid antioxidants, *Am J Physiol*, 277, L719-726, doi: 10.1152/ajplung.1999.277.4.L719, 1999.
- Zimmer, A. T. and A. D. Maynard. Investigation of the aerosols produced by a high-speed, hand-held grinder using various substrates, *Ann Occup Hyg*, 46, 663-672, doi: 10.1093/annhyg/mef089, 2002.

Appendix A: Supplementary for Chapter 3

Table A 1: Baseline characteristics of participants.

Characteristic	Healthy, N = 46 ¹	COPD, N = 30 ¹
Sex		
Female	25 (54%)	16 (53%)
Male	21 (46%)	14 (47%)
Age	66 (58, 69)	72 (69, 76)
BMI	23.9 (22.0, 26.4)	27.8 (24.8, 31.4)
FVC; % Predicted	98 (88, 108)	82 (75, 91)
FVC; L	3.42 (2.91, 4.05)	2.53 (2.26, 3.22)
FEV1; % Predicted	93 (81, 101)	64 (51, 67)
FEV1; L	2.54 (1.95, 2.98)	1.47 (1.08, 1.80)
R5Hz (kPa/l/s)	3.16 (2.19, 3.72)	4.36 (3.63, 4.91)
R5-20 (kPa/l/s)	0.32 (0.05, 0.80)	1.58 (1.10, 2.03)
R20Hz (kPa/l/s)	2.57 (2.25, 3.14)	2.76 (2.42, 3.32)
Augmentation Index (%)	29 (23, 33)	29 (23, 36)
PWV (m/s)	8.20 (7.25, 9.17)	10.05 (9.20, 10.90)
Heart Rate	60 (53, 69)	66 (62, 71)
Peripheral systolic blood pressure (mm/Hg)	132 (124, 142)	142 (134, 152)
¹ n (%); Median (IQR)		

Table A 2: The resilience plan for the MRC study.

Area	Sub Area	Specific	Impact	Remediation/Resilience	Action on Day	Refined Impact
Staff	Unavailable	Clinical Research Fellow (CRF)	No one to take physiological measurements	The Research Nurse is unable to cover as ethics requires a Physician	Study visits and journeys cancelled	No participant exposures
		PhD student	No one to take exposure measurements	Take alternative member of staff, ensure back-up is available		None
Participants	Unavailable for one journey on day	One participant	Reduced participant exposures	Ensure participants are fully aware of the timetable	Take one extra student if possible	Reduced participant exposures
		Two participants	Reduced participant exposures	Ensure participants are fully aware of the timetable	Abort study and cancel	Reduced participant and student exposures
		Student	Reduced student exposures	Ensure students are fully aware of the timetable	Reschedule student for another day or take another student	Reduced student exposures
	Unwell before the start	Participant or student	Reduced participant and student exposures		Remove from study day	Reduced participant and student exposures
	Unwell on journey	Participant or student	Reduced participant and student exposures		Abort study	Reduced participant and student exposures
	Unavailable the day following (+24 hours)	Participant	Reduced participant exposures	Ensure participants are fully aware of the timetable	Exclude the participant from the study	Reduced number of participants
Transport	Taxi	Late	Delayed start / finish	Ensure taxi company is aware of timetable. CRF to log participant collection. Will wait 60 minutes before aborting	Log taxi movements	Delayed start / finish
		Aborts	Delayed start / finish	Ensure taxi company is aware of timetable	Order replacement	Delayed start / finish

	Wrong taxi (not electric)	Potential impact of self-pollution	Ensure taxi company is aware of requirements	Ensure taxi has recirculation and air conditioning on during journey	None
Station	Lift not working before start of journey	Equipment unable to get to platform and participants required to use stairs	Phone station before going to station	Switch to subway/overground alternative route	None
	Lift not working before end of journey	Equipment unable to get off platform and participants required to use stairs		Travel to alternative step free access station and re-route taxi pick-up	Delayed finish
Train	Disruption on journey	Delayed start / finish	Subsistence may be required		Delayed start / finish
	Notified of a major disruption (e.g. strike)	Reduced participant and student exposures	May not be required to randomise journey	Switch to subway or overground alternative unless already done	Different route sampled with possible reduced exposures
	Major disruption on the study day	Reduced participant and student exposures		Switch to subway or overground alternative unless already done	Different route sampled with possible reduced exposures
	Overground train breaks down	Variable exposure/ finish too late		<1 hour continue with journey. >1 hour get cab back to Hospital	Delayed start / finish or reduced patient and student exposures
	Subway problem	Variable exposure / finish too late		<1 hour wait continue with journey. >1 hour get cab back to hospital	Delayed start / finish or reduced patient and student exposures

Measurement	Malfunction before start	Mini-Wras	No PM measurements	Ensure service schedule is in place, spare parts are in the lab for repair	Take SidePak	Reduced measurement quality
		NO ₂ / NO _x	No NO ₂ / NO _x measurements	Ensure service schedule is in place, spare parts are in the lab for repair	Take Aeroqual	Reduced measurement quality
		O ₃	No O ₃ measurements	Ensure service schedule is in place, spare parts are in the lab for repair	Take Aeroqual	Reduced measurement quality
		Noise	No noise measurements	Ensure service schedule is in place, spare parts are in the lab for repair	Take spare	None
		Pumps	No PM mass filter samples	Ensure service schedule is in place, spare parts are in the lab for repair	Replace pump	None
		Mass Flow Controller (MFC)	Lack of flow control		Replace MFC with a rot	
		MoRS Trolley	No measurements	Service MoRS, check bolts integrity. Ensure service schedule is in place and spare parts in the lab for rapid repair.		No participant and student exposures
		Batteries	Reduced measurement availability	Ensure spare battery remains charged	Take spare	None
	Malfunction during journey	All	Reduced measurement availability	Ensure basic tools and repair components are available	Make best effort to repair	Reduced measurement availability
	Data archiving	Data moved to server	Potential data loss	Automated file transfer	Ensure MoRS has Wi-Fi and check data was transferred	None

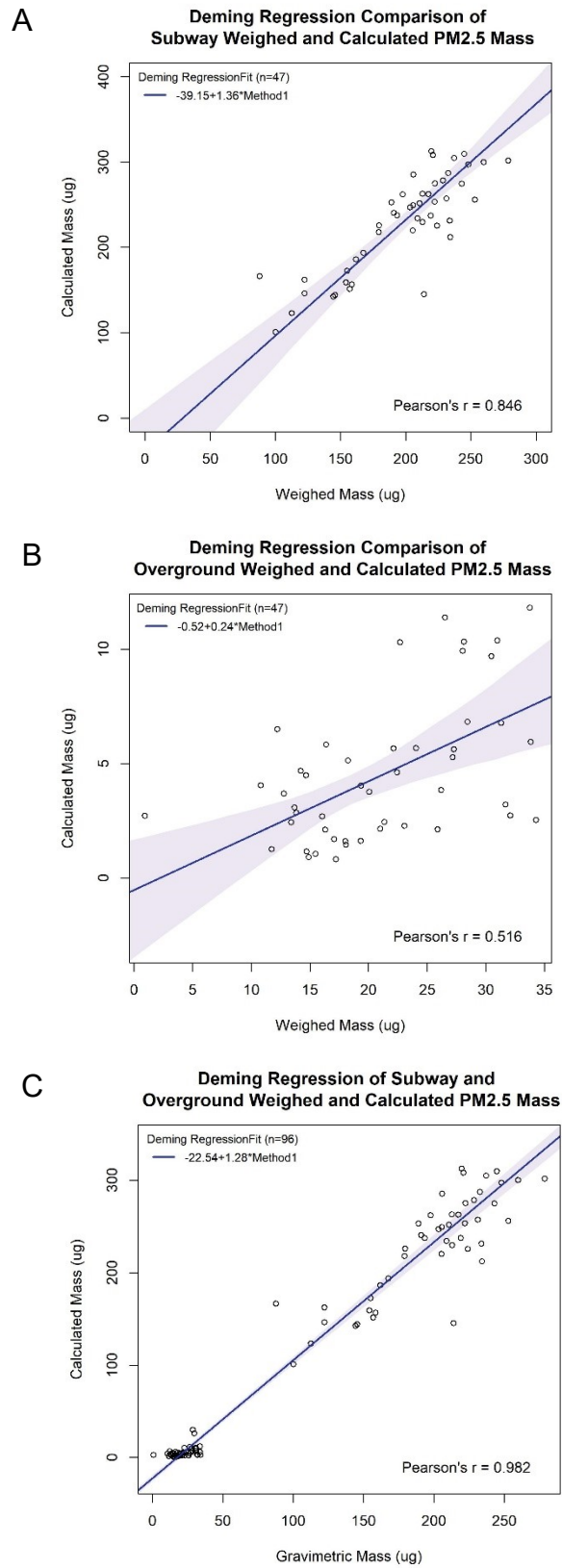


Figure A 1: Deming regression comparison of weighed and calculated PM_{2.5} mass for the subway (A), overground (B) and subway and overground (C).

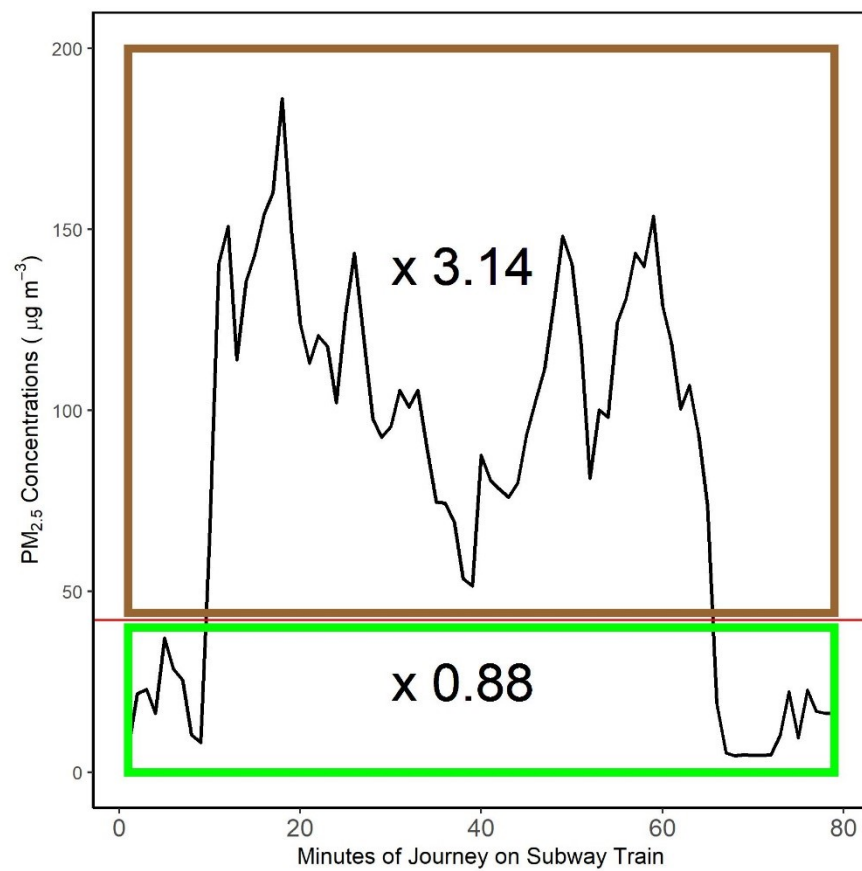


Figure A 2: Scaling factors for the Mini-Wras were proportionally applied to subway PM_{2.5} measurement to reflect that subway air comprise a mixture of above-ground (green box) and below-ground subway aerosol (brown box).

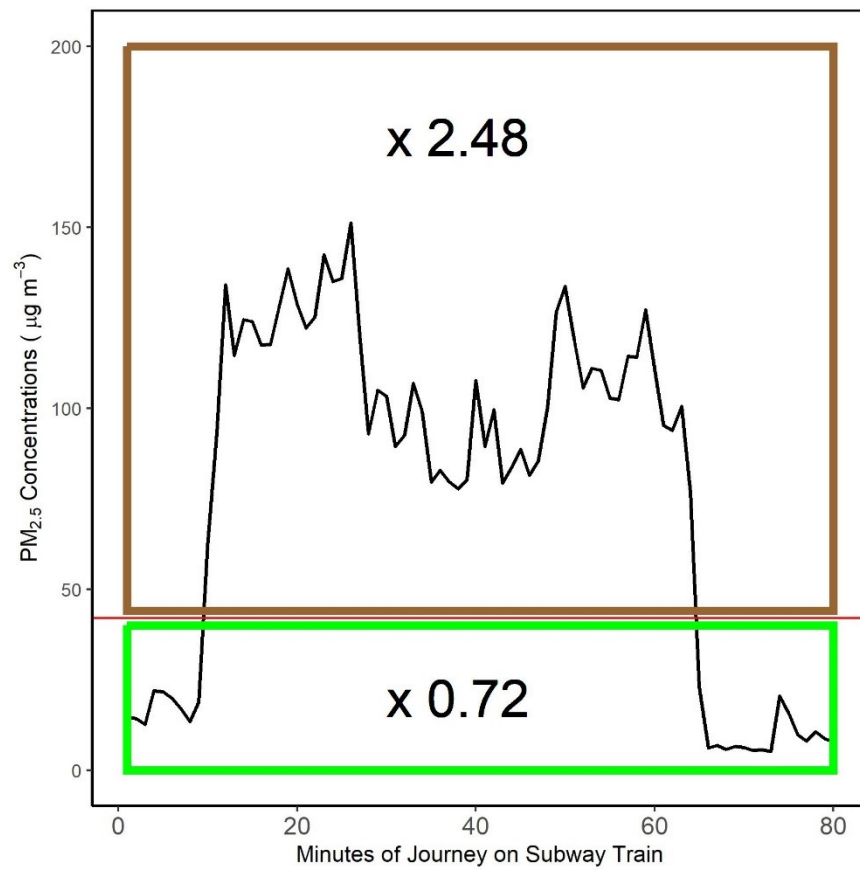


Figure A 3: Scaling factors for the SidePak were proportionally applied to subway PM_{2.5} measurement to reflect that subway air comprise a mixture of above-ground (green box) and below-ground subway aerosol (brown box).

Appendix B: Supplementary for Chapter 4

Table B 1: Date of each participant journey during the MRC health study showing the line of the journey and reasons for alternative journeys.

Journey	Bakerloo Line	Jubilee Line	Willesden Overground	Kensal Rise	Notes
1			26/01/2022		
2			07/02/2022		
3	09/02/2022				
4	14/02/2022				
5	16/02/2022				
6	22/02/2022				
7	28/02/2022				
8			02/03/2022		
9			08/03/2022		
10			14/03/2022		
11	16/03/2022				
12			21/03/2022		
13			23/03/2022		No participants one volunteer student
14			28/03/2022		
15		04/04/2022			No Bakerloo Line trains train damaged by umbrella
16			06/04/2022		
17	20/04/2022				
18			25/04/2022		
19			27/04/2022		
20	04/05/2022				
21			09/05/2022		
22			11/05/2022		
23	16/05/2022				
24	18/05/2022				
25	23/05/2022				
26	25/05/2022				
27	30/05/2022				
28	07/06/2022				
29			09/06/2022		
30	27/06/2022				
31	29/06/2022				
32	04/07/2022				
33			06/07/2022		
34			13/07/2022		
35			18/07/2022		

36			20/07/2022		
37			25/07/2022		
38		27/07/2022			Overground Strike no trains at Willesden Junction
39			01/08/2022		
40			03/08/2022		
41			08/08/2022		
42		10/08/2022			Lift out of order at Willesden Junction
43		22/08/2022			Lift out of order at Willesden Junction
44			24/08/2022		Lift out of order at Willesden Junction
45			31/08/2022		Lift out of order at Willesden Junction
46			05/09/2022		Lift out of order at Willesden Junction
47		07/09/2022			Lift out of order at Willesden Junction
48			12/09/2022		Lift out of order at Willesden Junction
49	14/09/2022				
50	26/09/2022				
51			28/09/2022		SidePak used - Mini-Wras being serviced
52	03/10/2022				SidePak used - Mini-Wras being serviced
53	05/10/2022				SidePak used - Mini-Wras being serviced
54			12/10/2022		SidePak used - Mini-Wras being serviced
55	17/10/2022				
56	19/10/2022				
57			24/10/2022		
58			26/10/2022		
59	07/11/2022				
60	09/11/2022				
61				14/11/2022	Lift out of order at Willesden Junction
62			16/11/2022		
63			21/11/2022		
64			28/11/2022		
65			05/12/2022		
66			07/12/2022		
67	12/12/2022				
68		19/12/2022			No service through Willesden Junction on subway or Overground
69				21/12/2022	No service through Willesden Junction on subway or Overground
70		04/01/2023			Train strike no Bakerloo Line to Willesden Junction
71			09/01/2023		
72			11/01/2023		
73	16/01/2023				
74	25/01/2023				
75	01/02/2023				

76	06/02/2023			
77	08/02/2023			
78			13/02/2023	No service at Willesden Junction due to engineering works
79			15/02/2023	No service at Willesden Junction due to engineering works
80		22/02/2023		
81		27/02/2023		
82		01/03/2023		
83	06/03/2023			
84	08/03/2023			
85		20/03/2023		
86		27/03/2023		
87	29/03/2023			
88		03/04/2023		
89		17/04/2023		
90		19/04/2023		
91	24/04/2023			
92	26/04/2023			
93		03/05/2023		
94	10/05/2023			
95	15/05/2023			
96	17/05/2023			
97		22/05/2023		
98	24/05/2023			
99	31/05/2023			
100	12/06/2023			
101		14/06/2023		
102	19/06/2023			
103	21/06/2023			
104		05/07/2023		
105		10/07/2023		
106		12/07/2023		
107		19/07/2023		

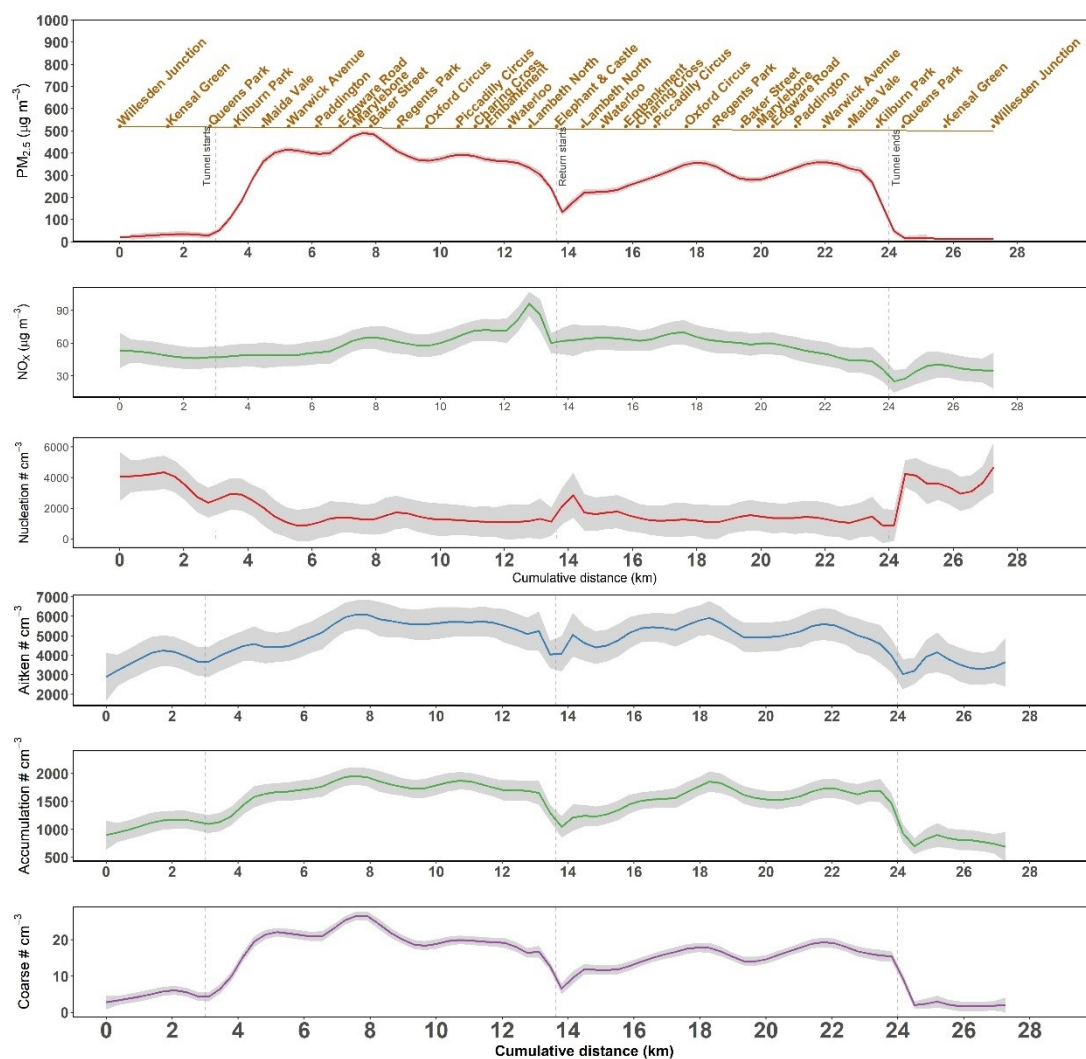


Figure B 1: $PM_{2.5}$ and NO_x concentrations compared to the nucleation, Aitken, accumulation and coarse mode particle concentrations for the return Bakerloo line journey from Willesden Junction station to Elephant & Castle station. The shaded area represents the 95% confidence intervals. $PM_{2.5}$ has been adjusted using the formula proposed by Smith et al., (2020)

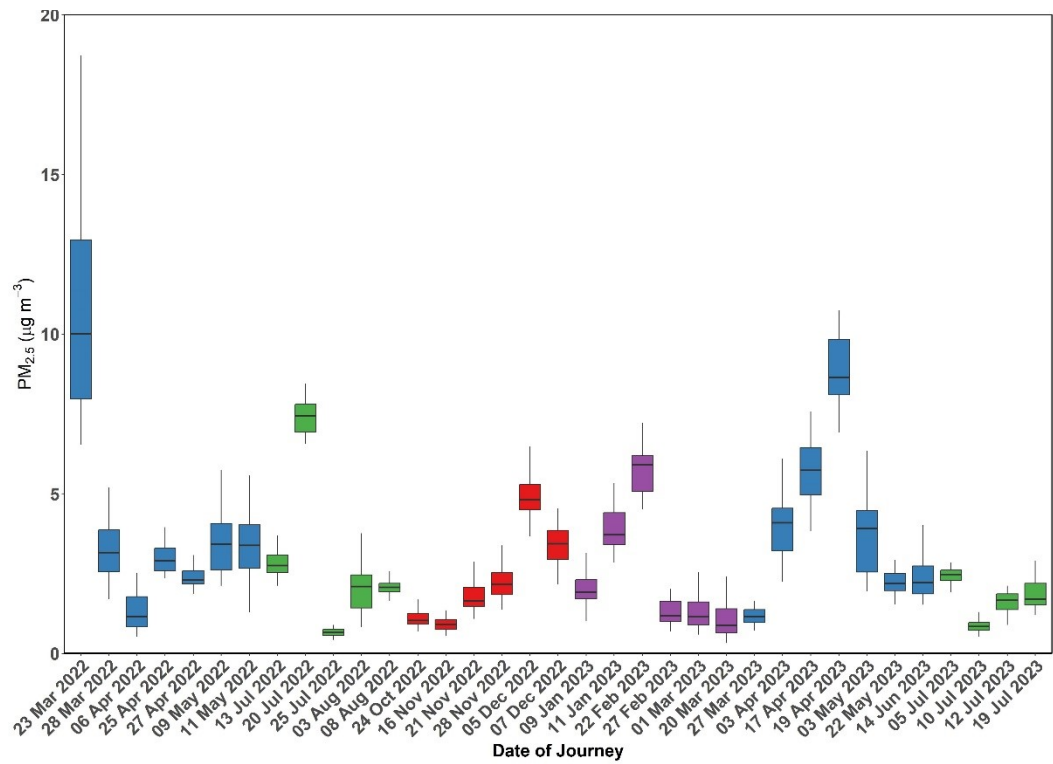


Figure B 2: Long-term variation of PM_{2.5} concentrations for each return journey from Willesden Junction station to Watford Junction station. Winter = purple, Spring = blue, Summer = green and Autumn = red). The lower and upper hinges correspond to the 25th and 75th percentiles, the horizontal line to the median and the whiskers to 1.55 × the IQR (approx. 95% percentile).

Appendix C: Supplementary for Chapter 5

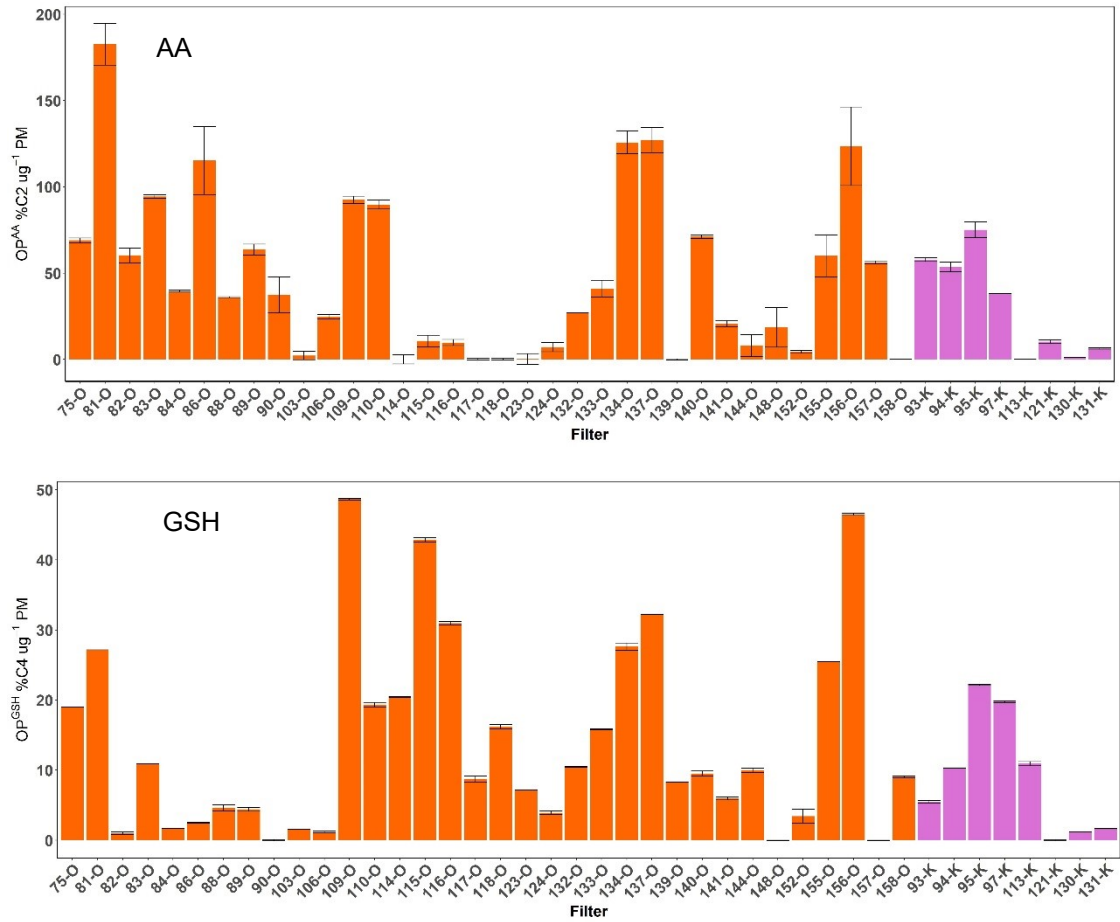


Figure C 1: OP^{AA} antioxidant % C2 depletion per unit mass of PM_{2.5} for the Overground Willesden line (orange) and Overground Kensal Rise line (purple) and OP^{GSH} antioxidant % C4 depletion per unit mass of PM_{2.5} for the Overground Willesden line (orange) and Overground Kensal Rise line (purple).

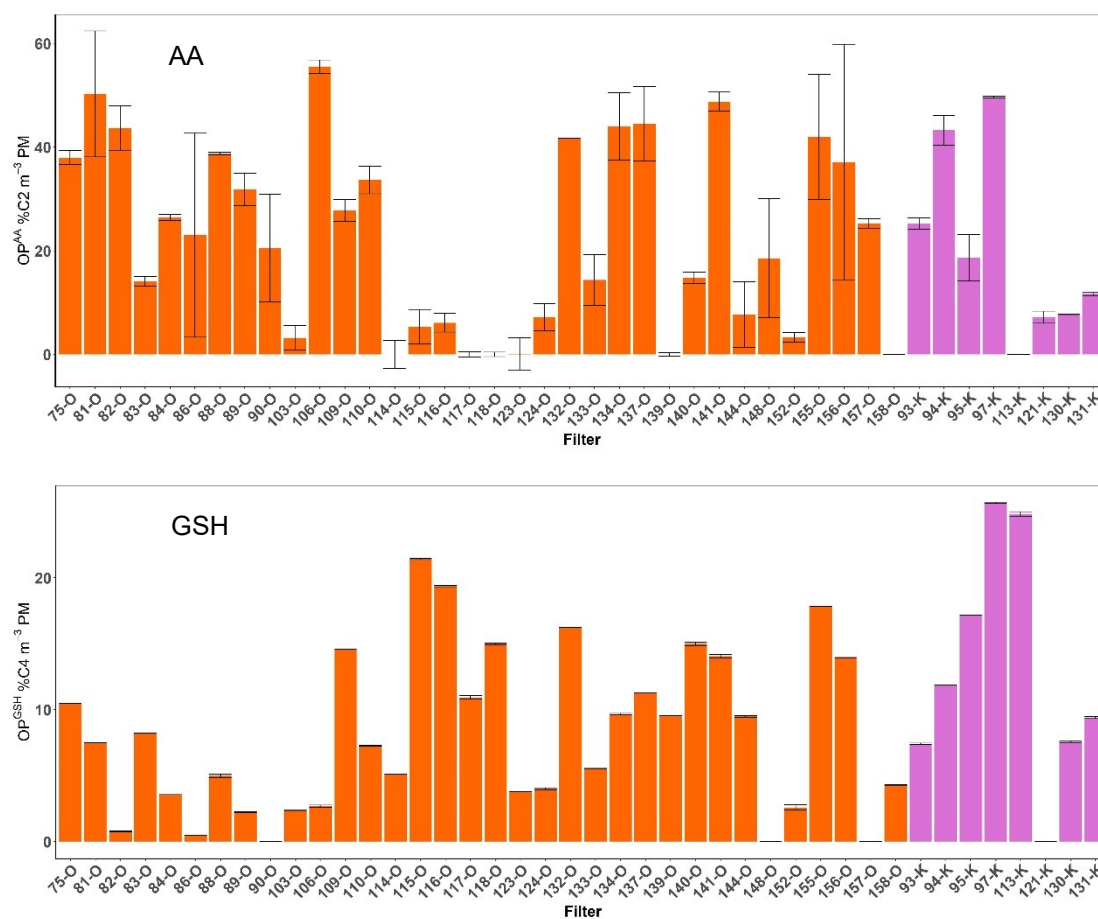


Figure C 2: OP^{AA} antioxidant % C2 depletion per unit volume of PM_{2.5} for the Overground Willesden line (brown) and Overground Kensal Rise line (silver) and OP^{GSH} antioxidant % C4 depletion per unit volume of PM_{2.5} for the Overground Willesden line (brown) and Overground Kensal Rise line (silver).

Table C 1: Filer samples for each journey showing the sample number, journey, date, PM_{2.5} (µg m⁻³) and flow (l).

Sample	Journey	Date	PM2.5	Flow (l)
41	Willesden	26/01/2022	6.0	1006.2
43	Willesden	07/02/2022	2.5	1094.0
44	Bakerloo	09/02/2022	186.4	1020.2
45	Bakerloo	14/02/2022	171.5	952.4
46	Willesden	27/04/2022	2.8	1063.2
47	Bakerloo	16/02/2022	172.1	857.2
48	Bakerloo	22/02/2022	187.7	958.2
49	Bakerloo	28/02/2022	170.5	875.2
50	Willesden	02/03/2022	8.2	982.2
51	Willesden	08/03/2022	10.4	962.4
52	Willesden	25/04/2022	3.7	1152.6
53	Willesden	23/03/2022	3.2	961.4
54	Willesden	14/03/2022	2.6	1134.1
55	Bakerloo	16/03/2022	265.1	962.2
56	Willesden	21/03/2022	12.6	1016.9
58	Willesden	28/03/2022	12.6	1014.5
59	Jubilee	04/04/2022	196.5	914.0
60	Willesden	06/04/2022	1.4	1066.4
61	Bakerloo	20/04/2022	246.3	886.5
66	Bakerloo	04/05/2022	213.0	1126.9
67	Willesden	09/05/2022	3.8	1042.2
68	Willesden	11/05/2022	4.5	1224.7
69	Bakerloo	16/05/2022	308.1	1163.9
70	Bakerloo	18/05/2022	253.2	1127.7
71	Bakerloo	23/05/2022	255.4	1040.7
72	Bakerloo	25/05/2022	278.2	1162.4
73	Bakerloo	30/05/2022	278.4	1135.9
74	Bakerloo	07/06/2022	222.6	924.8
75	Willesden	09/06/2022	2.2	1011.9
76	Bakerloo	27/06/2022	213.8	1009.2
77	Bakerloo	29/06/2022	318.0	1149.1
78	Bakerloo	04/07/2022	235.1	923.6
81	Willesden	06/07/2022	1.1	1032.5
82	Willesden	13/07/2022	3.0	1032.5
83	Willesden	18/07/2022	3.5	1175.8
84	Willesden	20/07/2022	8.7	1046.7
86	Willesden	25/07/2022	0.7	888.2
87	Jubilee	27/07/2022	122.0	905.8
88	Willesden	01/08/2022	3.1	731.3
89	Willesden	03/08/2022	2.3	1132.3
90	Willesden	08/08/2022	2.2	1001.0
91	Jubilee	10/08/2022	155.0	1116.0
92	Jubilee	22/08/2022	97.7	1006.0
93	Kensal	24/08/2022	5.4	999.7
94	Kensal	31/08/2022	5.1	1103.5

95	Kensal	05/09/2022	3.7	1196.6
96	Jubilee	07/09/2022	154.5	1082.4
97	Kensal	12/09/2022	5.3	1020.8
98	Bakerloo	14/09/2022	310.1	1215.1
102	Bakerloo	26/09/2022	312.0	1094.0
103	Willesden	28/09/2022	5.8	986.0
104	Bakerloo	03/10/2022	232.1	882.4
105	Bakerloo	05/10/2022	155.3	1001.6
106	Willesden	12/10/2022	10.9	1211.8
107	Bakerloo	17/10/2022	250.8	964.5
108	Bakerloo	19/10/2022	237.5	905.5
109	Willesden	24/10/2022	1.2	1016.9
110	Willesden	26/10/2022	1.5	1012.4
111	Bakerloo	07/11/2022	271.7	1001.7
112	Bakerloo	09/11/2022	260.6	917.2
113	Kensal	14/11/2022	10.2	1126.2
114	Willesden	16/11/2022	1.0	966.4
115	Willesden	21/11/2022	2.4	1180.6
116	Willesden	28/11/2022	2.8	1110.1
117	Willesden	05/12/2022	5.1	1027.4
118	Willesden	07/12/2022	4.0	1091.1
119	Bakerloo	12/12/2022	195.2	881.2
120	Jubilee	19/12/2022	147.8	1021.3
121	Kensal	21/12/2022	2.5	902.2
122	Jubilee	04/01/2023	129.4	977.2
123	Willesden	09/01/2023	2.1	994.6
124	Willesden	11/01/2023	4.3	1044.4
125	Bakerloo	16/01/2023	244.2	1028.9
126	Bakerloo	25/01/2023	266.2	960.4
127	Bakerloo	01/02/2023	252.0	1016.7
128	Bakerloo	06/02/2023	137.9	1006.9
129	Bakerloo	08/02/2023	232.7	956.2
130	Kensal	09/01/2023	26.5	1048.2
131	Kensal	11/01/2023	24.0	1082.3
132	Willesden	22/02/2023	5.9	957.7
133	Willesden	27/02/2023	1.5	1038.2
134	Willesden	01/03/2023	1.8	1281.3
135	Bakerloo	06/03/2022	220.1	868.5
136	Bakerloo	08/03/2023	255.4	972.8
137	Willesden	27/03/2023	1.6	1169.0
138	Bakerloo	29/03/2023	272.8	982.0
139	Willesden	03/04/2023	5.1	1115.2
140	Willesden	17/04/2023	5.6	891.5
141	Willesden	19/04/2023	10.3	1094.5
142	Bakerloo	24/04/2023	220.0	1001.7
143	Bakerloo	26/04/2023	225.8	1181.7
144	Willesden	03/05/2023	3.1	821.4
145	Bakerloo	10/05/2023	225.8	962.9

146	Bakerloo	15/05/2023	213.4	1126.9
147	Bakerloo	17/05/2023	235.2	1018.5
148	Willesden	22/05/2023	2.6	983.2
149	Bakerloo	24/05/2023	210.0	948.2
150	Bakerloo	31/05/2023	230.0	972.7
151	Bakerloo	12/06/2023	233.4	960.9
152	Willesden	14/06/2023	3.3	1085.2
153	Bakerloo	19/06/2023	167.7	950.0
154	Bakerloo	21/06/2023	197.8	930.0
155	Willesden	05/07/2023	2.7	954.6
156	Willesden	10/07/2023	1.4	1126.2
157	Willesden	12/07/2023	1.6	907.6
158	Willesden	19/07/2023	2.0	1035.2

Table C 2: Preparation for ascorbic acid standards.

Standard	AA μ M	Preparation
Std 1	0	1000 μ l Chelex treated HPLC-grade water
Std 2	50	200 μ l Std 3 + 800 μ l Chelex treated HPLC-grade water
Std 3	100	500 μ l Std 4 + 500 μ l Chelex treated HPLC-grade water
Std 4	150	600 Std 5 + 600 μ l Chelex treated HPLC-grade water
Std 5	200	1000 μ l 200 μ M AA
Std 6	250	200 μ l 2mM AA + 800 μ l Chelex treated HPLC-grade water

Table C 3: Example ascorbic acid template for standards, controls and samples.

Row/ Column	1	2	3	4	5	6	7	8	9	10	11	12
A	Std 1	Std 3	Std 6	M120 B	CO B	72	76	80	84	Blank	91	
B	Std 1	Std 4	Std 6	M120 B	CO B	72	76	80	84	Blank	91	
C	Std 1	Std 4	NIST A	CuCl A	C2 A	73	77	81	85	88	92	
D	Std 2	Std 4	NIST A	CuCl A	C2 A	73	77	81	85	88	92	
E	Std 2	Std 5	NIST B	CuCl B	C2 B	74	78	82	86	89	93	
F	Std 2	Std 5	NIST B	CuCl B	C2 B	74	78	82	86	89	93	
G	Std 3	Std 5	M120 A	CO A	71	75	79	83	87	90	94	
H	Std 3	Std 6	M120 A	CO A	71	75	79	83	87	90	94	

Table C 4: Preparation for glutathione standards.

Std no	1	2	3	4	5	6	7	8	9	10	11	12
μl GSSG	0	91	182	273	364	455	546	636	727	818	909	1000
μl PO ₄ buffer	1000	909	818	727	636	546	455	364	273	182	91	0
GSX pmols/50 μl	0	30	60	90	120	150	180	210	240	270	300	330

Table C 5: Example glutathione template for standards, controls and samples.

Row/ Column	1	2	3	4	5	6	7	8	9	10	11	12
A					M120						Blank	
	Std 1	Std 5	Std 9	CO A	A	71 A	73 A	75 A	77 A	79 A	A	
B					M120						Blank	
	Std 1	Std 5	Std 9	CO A	A	71 A	73 A	75 A	77 A	79 A	A	
C			Std		M120						Blank	
	Std 2	Std 6	10	CO B	B	71 B	73 B	75 B	77 B	79 B	B	
D			Std		M120						Blank	
	Std 2	Std 6	10	CO B	B	71 B	73 B	75 B	77 B	79 B	B	
E			Std		NIST							
	Std 3	Std 7	11	C4 A	A	72 A	74 A	76 A	78 A	80 A	81A	
F			Std11		NIST							
	Std 3	Std 7		C4 A	A	72 A	74 A	76 A	78 A	80 A	81A	
G			Std		NIST							
	Std 4	Std 8	12	C4 B	B	72 B	74 B	76 B	78 B	80 B	81B	
H			Std		NIST							
	Std 4	Std 8	12	C4 B	B	72 B	74 B	76 B	78 B	80 B	81B	

Table C 6: Metal concentrations (ng m⁻³) for the selected metals in the Bakerloo subway and Jubilee subway lines.

	Mean (ng m ⁻³)	Bakerloo line			Mean (ng m ⁻³)	Jubilee Line		
		Sd (ng m ⁻³)	Max (ng m ⁻³)	Min (ng m ⁻³)		Sd (ng m ⁻³)	Max (ng m ⁻³)	Min (ng m ⁻³)
Al	4785	1470	8888	2354	2398	700	2990	1129
B	2946	438	3879	2248	2710	1081	3530	674
Ba	29	10	51	14	22	10	37	9
Ca	5844	4406	32577	2634	2131	1153	3202	-23
Co	9	3	19	7	7	3	8	0
Cr	432	122	816	208	390	209	716	95
Cu	577	121	913	320	254	96	331	67
Fe	142401	35993	228539	59800	60168	21748	79417	21028
K	4640	938	7240	2870	3691	1298	4647	1146
Li	11	4	18	7	0	0	0	0
Mg	486	173	1029	190	343	205	621	0
Mn	1210	326	2018	555	503	182	647	169
Mo	235	74	459	104	497	187	709	178
Ni	123	43	278	55	69	30	103	17
Pb	30	11	59	14	18	10	37	9
Sb	11	13	93	6	6	3	7	0
Se	0	2	9	0	0	0	0	0
Sr	18	7	46	8	12	7	16	0
Ti	53	18	85	23	18	11	28	0
V	11	4	18	7	7	3	8	0
Zn	1269	705	4223	485	784	463	1119	0

Table C 7: Bakerloo and Jubilee line OP^{AA} and OP^{GSH} correlations and p-values for each element.

Line	Element	OP ^{GSH} ug ⁻¹ correlation	P-val OP ^{GSH} ug ⁻¹	OP ^{AA} ug ⁻¹ correlation	P-val OP ^{AA} ug ⁻¹	OP ^{GSH} m ⁻³ correlation	P-val OP ^{GSH} m ⁻³	OP ^{AA} m ⁻³ correlation	P-val OP ^{AA} m ⁻³
Bakerloo	Zn	0.16	0.355	0.32	0.064	0.19	0.283	0.34	0.048
Bakerloo	V	0.48	0.004	0.56	0.001	0.08	0.653	0.24	0.17
Bakerloo	Ti	0.52	0.001	0.66	0	0.16	0.363	0.38	0.027
Bakerloo	Sr	0.26	0.133	0.3	0.084	0.1	0.575	0.16	0.364
Bakerloo	Se	0.13	0.449	0.03	0.862	0.45	0.007	0.21	0.244
Bakerloo	Sb	0.21	0.241	0.31	0.078	0.07	0.68	0.2	0.263
Bakerloo	Pb	0.59	0	0.56	0.001	0.17	0.332	0.21	0.229
Bakerloo	Ni	0.3	0.086	0.46	0.006	0.28	0.107	0.41	0.015
Bakerloo	Mo	0.5	0.003	0.59	0	0.19	0.285	0.32	0.063
Bakerloo	Mn	0.48	0.004	0.56	0.001	0.19	0.285	0.31	0.077
Bakerloo	Mg	0.49	0.004	0.43	0.011	0.25	0.154	0.22	0.219
Bakerloo	Li	0.3	0.084	0.61	0	0.13	0.45	0.49	0.003
Bakerloo	K	0.63	0	0.58	0	0.24	0.18	0.25	0.151
Bakerloo	Fe	0.48	0.004	0.6	0	0.2	0.263	0.35	0.046
Bakerloo	Cu	0.55	0.001	0.58	0	0.26	0.143	0.33	0.059
Bakerloo	Cr	0.44	0.01	0.52	0.002	0.23	0.194	0.32	0.064
Bakerloo	Co	0.45	0.008	0.44	0.009	0.16	0.37	0.2	0.246
Bakerloo	Ca	0.11	0.523	0.19	0.272	0	0.994	0.11	0.539
Bakerloo	Ba	0.54	0.001	0.62	0	0.21	0.232	0.31	0.072
Bakerloo	B	0.66	0	0.57	0	0.21	0.223	0.23	0.2
Bakerloo	Al	0.57	0	0.62	0	0.24	0.164	0.35	0.04
Jubilee	Zn	-0.21	0.683	-0.33	0.526	-0.6	0.203	-0.53	0.278
Jubilee	V	-0.03	0.956	-0.21	0.689	-0.37	0.476	-0.39	0.444
Jubilee	Ti	-0.06	0.904	-0.28	0.598	-0.1	0.843	-0.33	0.523
Jubilee	Sr	-0.24	0.643	-0.39	0.442	-0.6	0.206	-0.59	0.222
Jubilee	Sb	-0.05	0.927	-0.23	0.661	-0.35	0.491	-0.4	0.436
Jubilee	Pb	0.68	0.134	0.54	0.267	0.64	0.173	0.56	0.247
Jubilee	Ni	-0.27	0.61	-0.5	0.315	-0.51	0.296	-0.65	0.165
Jubilee	Mo	0.11	0.843	0.04	0.947	-0.11	0.831	-0.08	0.878
Jubilee	Mn	-0.22	0.673	-0.47	0.343	-0.35	0.502	-0.57	0.233
Jubilee	Mg	-0.15	0.783	-0.41	0.423	-0.33	0.523	-0.51	0.304
Jubilee	K	-0.12	0.822	-0.3	0.564	-0.49	0.321	-0.5	0.318
Jubilee	Fe	-0.05	0.922	-0.3	0.569	-0.16	0.763	-0.39	0.442
Jubilee	Cu	-0.17	0.746	-0.37	0.473	-0.48	0.336	-0.54	0.266
Jubilee	Cr	-0.36	0.487	-0.65	0.166	-0.37	0.465	-0.7	0.122
Jubilee	Co	-0.03	0.956	-0.21	0.689	-0.37	0.476	-0.39	0.444
Jubilee	Ca	-0.14	0.791	-0.34	0.504	-0.49	0.327	-0.53	0.284
Jubilee	Ba	0.47	0.346	0.35	0.498	0.15	0.779	0.22	0.679
Jubilee	B	-0.24	0.64	-0.4	0.435	-0.57	0.237	-0.58	0.225
Jubilee	Al	-0.29	0.581	-0.43	0.39	-0.63	0.184	-0.63	0.184

Appendix D: Supplementary for Chapter 6

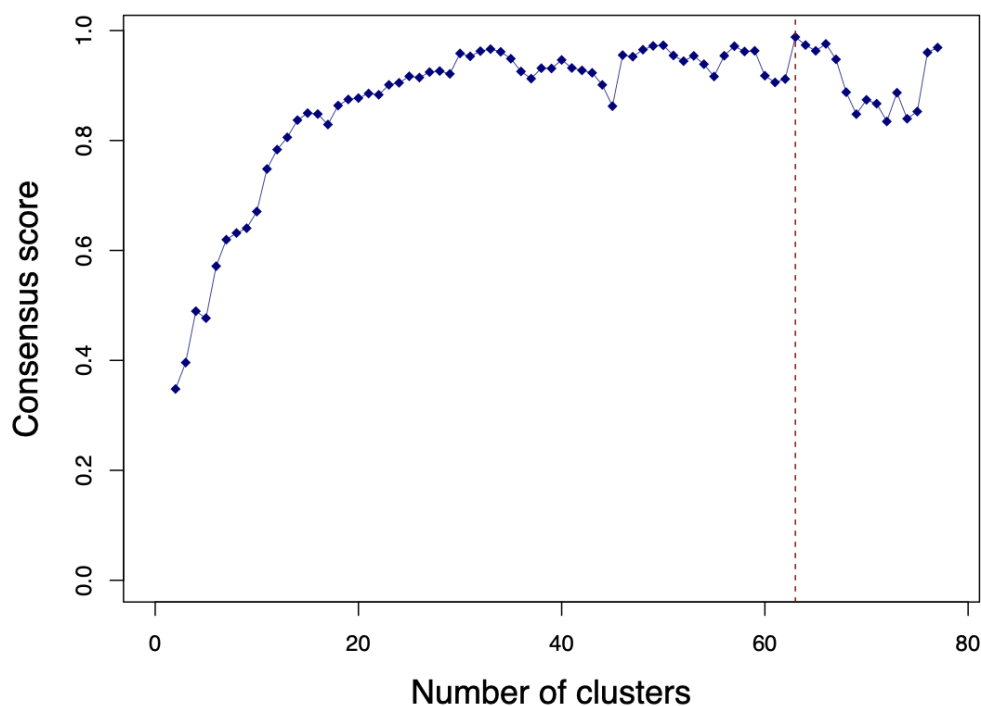


Figure D 1: Calibration plot for consensus clustering of the 78 metabolic features selected with the MVN model as significantly associated to TRAP exposure. The stability score was plotted against the number of clusters ranging from $n = 2$ to $n = 77$. The highest stability score was achieved at 63 clusters (red dotted line).

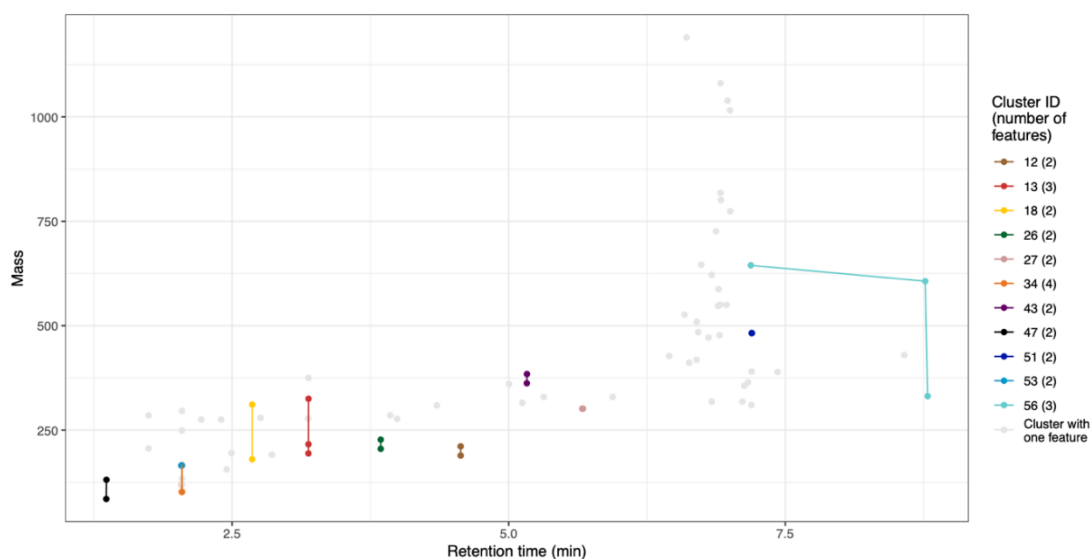


Figure D 2: Scatter plot of molecular mass (Y axis) as a function of retention time (in minutes, X axis) for the 78 metabolic features found associated with at least on TRAP exposure. Features that have been clustered together are coloured by their cluster ID and united by a line, the colours are detailed in the legend. Clusters of single features are plotted in light grey.

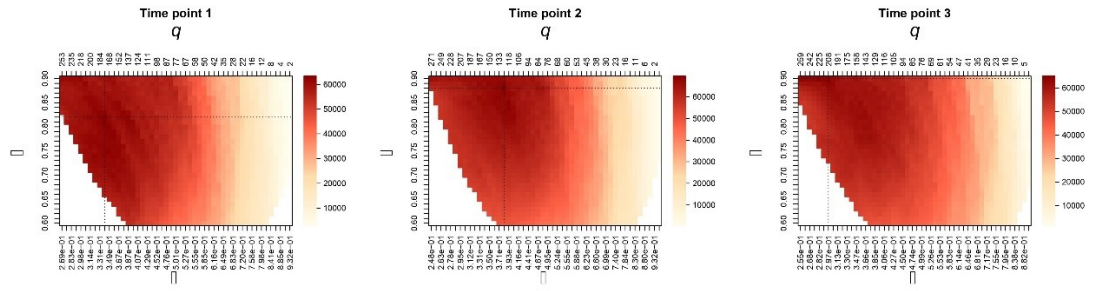


Figure D 3: Calibration plots for metabolomics networks, for the three time points, 2 h before walks (time point 1), 2 h (time point 2) and 24 h (time point 3) after walks. The colour denotes the stability score for each combination of the two hyperparameters: penalisation (λ) and threshold of selection proportion (π).

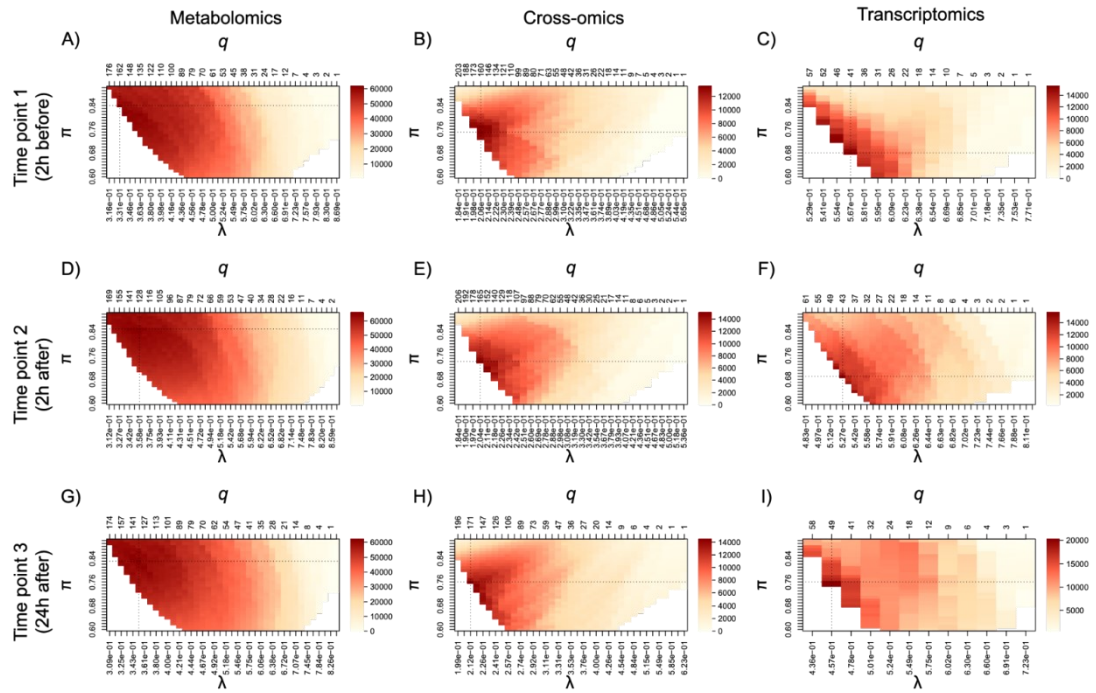


Figure D 4: Calibration plots for multi-omic networks, for the three time points, 2 h before walks (time point 1), 2 h (time point 2) and 24 h (time point 3) after walks. At each time point, a calibration plot is shown for each block: metabolomics only, between metabolomics and transcriptomics, and transcriptomics only. The colour denotes the stability score for each combination of the two hyperparameters: penalisation (λ) and threshold of selection proportion (π).

Table D 1: List of all 38 mRNA that were found as significantly associated to at least one TRAP in our MVN model with their corresponding gene symbol and Beta coefficients.

Accession number	Gene symbol	Regression coefficients				
		PM25	PM10	NO2	BC	PCNT
A_24_P373844	KCTD15	0.00165777	0.0016477	0.01647895	0.01309058	6.16E-06
A_23_P35456	SH3PXD2A	-0.0016961	0.00078837	-0.0056235	0.00154447	-1.54E-07
A_23_P129458	SDR42E1	-0.0028878	-0.0002495	-0.0084621	-0.0054769	-8.73E-07
A_23_P74609	G0S2	0.00447517	-0.0011805	0.02123222	-0.0093609	-1.65E-06
A_33_P3378056	TFAP2A	-0.0018742	-0.0018	0.01657733	0.00763885	6.88E-06
A_21_P0014020	LOC100652894	-0.0009254	-0.0021256	0.01346835	0.00075634	1.40E-06
A_33_P3214432	ZC3HAV1L	-0.0006607	0.00748795	-0.0219629	0.02582521	9.29E-06
A_23_P200874	CEP85	0.00216714	0.00065595	0.01147049	0.0030797	2.35E-06
A_33_P3238052	C12orf24	-0.0024834	-0.0013697	-0.0056377	-0.0054273	-3.84E-06
A_33_P3222069	SPHK1	0.00797911	0.01329894	-0.0172166	0.01971206	1.21E-05
A_24_P110914	LOC100190939	0.00032535	0.00667395	-0.0236742	0.0387678	1.55E-05
A_23_P50942	RAB3GAP1	-0.0024316	-0.0012112	-0.0036613	-0.0022998	-1.15E-06
A_23_P160618	SH2D2A	0.00046065	-0.0004135	0.00667315	-0.0090209	-4.73E-06
A_24_P26897	INPP5A	-0.0040903	-0.0019997	-0.0062311	-0.0054748	-5.29E-06
A_21_P0014093	LOC100507039	-0.0057799	0.00071668	-0.0114499	0.02211534	8.37E-06
A_32_P179998	DMRTC1	-0.0070384	-0.0057513	-0.007327	-0.0165631	-8.10E-06
A_24_P218074	ZNF467	-0.0070019	-0.0053192	-0.0099231	0.0069592	-3.61E-07
A_23_P17307	C20orf20	-0.002697	-0.0026592	-0.0042223	-0.0024362	-2.60E-06
A_23_P416774	CLIC5	0.00515385	0.00436823	0.00145155	0.01327942	7.33E-06
A_33_P3273719	ELOVL5	-0.0028675	-0.0019266	2.42E-05	-0.0115789	-7.55E-06
A_21_P0000664	CD4	-0.0073369	-0.005244	-0.0074411	-0.019483	-1.48E-05
A_21_P0000502	RNU11	-0.006583	-0.0091321	-0.0038552	-0.0155414	-4.85E-06
A_24_P18105	ASPH	-0.0085671	-0.0099755	-0.0003802	-0.0067193	-6.23E-06
A_19_P00803575	MPRIP	0.01227539	0.01242791	-0.0015842	0.01857774	8.11E-06
A_23_P143143	ID2	-0.0054379	-0.005371	0.000733	-0.0038134	-2.45E-06
A_33_P3270109	LEO1	-0.0061374	-0.006666	-0.0015051	-0.0035368	-4.24E-07
A_21_P0000508	SNAR-D	-0.0084485	-0.0091237	-0.0037879	-0.0031301	-2.53E-06
A_24_P226355	RANBP9	-0.0071246	-0.0074181	-0.0012348	-0.0052291	-1.35E-06
A_33_P3410011	PBXIP1	-0.011505	-0.0128731	-0.0048778	-0.0090772	-4.50E-06
A_33_P3296169	CDC47	-0.0070674	-0.0079957	-0.0030621	-0.0153971	-7.41E-06
A_24_P109633	ITPK1	0.00637306	0.00800379	0.00188442	0.00584336	7.97E-07
A_23_P101392	TMEM38A	-0.0067507	-0.0052426	-0.0045572	-0.0081761	-4.94E-06
A_33_P3239134	POM121L4P	-0.0099143	-0.0052324	0.00020308	0.00524576	1.39E-06
A_32_P85330	C15orf37	-0.011681	-0.0093355	-0.0059541	-0.0110182	-6.12E-06
A_23_P26895	TUBD1	-0.0058598	-0.0046933	-0.0020756	-0.0040502	-1.39E-06
A_23_P13797	C12orf49	-0.00692	-0.0046471	-0.0017332	-0.0067706	-3.36E-06
A_23_P109420	BMS1	-0.0066379	-0.006063	-0.0026631	-0.0061718	-4.65E-06
A_24_P101629	FAM127B	-0.0077941	-0.0075366	-0.0021754	-0.0060775	-3.40E-06

Table D 2: List of all 78 metabolic features that were found as significantly associated to at least one TRAP in our MVN model with their corresponding Beta coefficients and Annotations. Bold beta coefficients indicate the significant features. Annotations in bold have been confirmed by mass, RT matching and MS/MS spectra. Annotations not in bold have been confirmed with mass and MS/MS matching.

Retention time (min)	Monoisotopic Mass	Number of associated TRAP	Regression coefficients					Cluster membership	Annotation
			PM2.5	PM10	NO2	BC	PCNT		
2.494	194.9746	1	0.006	-0.001	0.031	0.012	1.00E-05	1	
2.859	191.0982	1	-0.01	0.001	-0.022	0.015	-6.60E-07	2	
6.914	1080.6346	1	-0.01	-0.009	-0.018	0.014	2.20E-06	3	
3.187	278.0331	1	0.003	0.002	0.019	-0.02	-4.90E-06	4	Caffeine
3.19	375.0063	1	-0.001	-0.002	0.016	-0.014	-5.30E-06	5	Caffeine
7.194	310.1447	1	-0.012	-0.007	0.032	-0.023	-9.20E-06	6	
6.918	800.9799	1	-0.001	0	-0.025	0.001	-6.90E-06	7	
6.589	526.3199	1	0.004	0.002	0.018	-0.022	-1.10E-05	8	
2.401	275.1731	1	-0.004	-0.001	-0.011	0.009	6.90E-07	9	
7.164	364.1552	1	0.003	0	0.017	-0.013	-5.70E-06	10	
6.835	621.9284	1	0.001	-0.002	0.011	-0.01	-7.10E-06	11	
4.566	211.0606	1	0.007	0.003	0.012	-0.006	-3.00E-06	12	Indole-3-propionic acid
4.566	189.0787	1	0.004	0.001	0.008	-0.007	-3.20E-06	12	Indole-3-propionic acid
3.19	194.0802	1	0	-0.001	0.016	-0.013	-1.90E-06	13	Caffeine
3.19	216.0619	1	0.002	0	0.016	-0.013	-2.50E-06	13	Caffeine
3.191	325.0236	1	0.002	0	0.018	-0.013	-1.40E-06	13	Caffeine
5.316	329.2565	1	-0.003	-0.002	0.011	-0.022	-8.70E-06	14	Undecanoylcarnitine (C11:0)
2.046	249.0319	1	0	-0.001	-0.005	0.007	3.90E-06	15	Phenylalanine
5.941	329.2392	1	-0.002	0.001	-0.008	0.017	5.40E-06	16	
6.916	817.9539	1	0.006	0.005	-0.013	0.025	6.30E-06	17	
2.681	180.0644	1	0.003	0	0.012	-0.014	-5.30E-06	18	Paraxanthine
2.682	311.0078	1	0.003	0	0.011	-0.005	-5.80E-07	18	Paraxanthine
2.221	275.1732	1	-0.003	-0.002	-0.009	0.005	3.10E-06	19	
1.744	284.9736	1	0.002	0.002	-0.009	0.006	3.80E-07	20	
6.451	427.3655	1	-0.001	0	-0.006	0.005	1.20E-07	21	Stearoylcarnitine (C18:0)
6.632	411.3015	1	0.001	0	0.005	-0.003	6.10E-08	22	
6.741	645.9504	1	0.002	0	0.006	-0.005	-1.40E-06	23	
6.837	318.1474	1	0.002	0	0.007	-0.011	-4.20E-06	24	
6.912	550.3041	1	0.001	0.001	-0.01	0.015	4.00E-06	25	
3.843	227.0561	1	0.002	0.001	0.009	-0.009	-3.50E-06	26	Indolelactic acid
3.843	205.0735	1	0.002	0.001	0.011	-0.013	-2.70E-06	26	Indolelactic acid
5.664	301.2077	1	-0.003	-0.001	-0.008	0.005	1.90E-06	27	
5.671	301.2068	1	-0.003	-0.001	-0.009	0.003	4.10E-07	27	
6.979	1038.6552	1	-0.001	0.001	-0.016	0.03	6.40E-06	28	
5.165	382.1966	2	-0.001	-0.006	0.014	-0.042	-1.80E-05	29	Cortisol
2.046	296.0202	1	0.001	0.002	-0.007	0.005	2.60E-06	30	Phenylalanine
2.047	134.0727	1	0.005	0.004	-0.008	0.012	5.70E-06	31	Phenylalanine
6.873	726.0012	1	0.001	-0.001	0.006	-0.008	-4.20E-06	32	
7.003	773.9645	1	0.001	0	-0.006	0.008	2.60E-06	33	

2.044	119.0738	1	0.003	0.003	-0.006	0.008	3.10E-06	34	Phenylalanine
2.045	102.0469	1	0.002	0.002	-0.006	0.008	3.90E-06	34	Phenylalanine
2.046	166.0825	1	0.001	0.002	-0.006	0.008	3.80E-06	34	Phenylalanine
2.046	102.0467	1	0.002	0.002	-0.005	0.008	3.70E-06	34	Phenylalanine
5.003	360.1938	1	0	-0.001	0.013	-0.012	-4.10E-06	35	Cortisone
6.97	549.9001	1	0.004	0.002	0.004	0	1.50E-06	36	
2.757	279.1467	1	-0.004	0.001	-0.013	0.015	6.80E-06	37	
7.431	389.2648	1	0	0	-0.005	0.003	8.10E-07	38	
1.745	206.0381	1	0	0.003	-0.011	0.018	5.40E-06	39	
3.929	285.1935	1	0	0.002	-0.009	0.015	5.20E-06	40	Octenonylcarnitine
4.351	309.1936	1	0	0.002	-0.008	0.013	6.00E-06	41	Octanoylcarnitine
5.123	315.2412	1	-0.004	-0.004	0.021	-0.033	-1.40E-05	42	Decanoylcarnitine
5.164	362.2091	1	-0.002	-0.006	0.017	-0.028	-5.60E-06	43	Cortisol
5.165	384.1925	1	-0.001	-0.006	0.014	-0.027	-8.60E-06	43	Cortisol
6.7	509.3399	1	0.001	0	0.006	-0.005	-9.40E-07	44	
6.713	484.3444	1	0.001	0	0.004	-0.004	-2.00E-06	45	
6.892	547.3482	1	0.001	0	0.01	-0.013	-5.20E-06	46	
1.362	85.0893	1	0.003	0.004	-0.007	0.009	3.70E-06	47	Isoleucine
1.364	131.0946	1	0.004	0.005	-0.007	0.011	4.90E-06	47	Isoleucine
6.807	471.647	1	0.002	0.001	0.005	-0.009	-3.40E-06	48	
2.047	119.0736	1	-0.001	0	-0.006	0.007	2.80E-06	49	Phenylalanine
7.113	318.1503	1	0.002	0.001	0.007	0	4.70E-07	50	
7.197	482.2165	1	-0.002	-0.001	-0.004	-0.001	-2.10E-07	51	
7.197	482.2173	1	-0.001	0	-0.005	0	-5.80E-08	51	
6.897	587.2991	1	0	0	-0.005	0.007	1.20E-06	52	
2.04	165.0795	1	0.001	0.001	-0.006	0.007	2.90E-06	53	Phenylalanine
2.047	165.0795	1	0.001	0.002	-0.006	0.006	2.70E-06	53	Phenylalanine
6.906	477.2857	1	0	-0.001	-0.009	0.017	1.60E-06	54	LysoPE(18:2)
7.195	390.2372	1	0	0	0.002	-0.001	-1.90E-07	55	
7.189	644.5358	2	-0.005	-0.006	-0.001	-0.039	-1.70E-05	56	
8.765	606.5602	1	-0.005	-0.008	0.004	-0.032	-9.00E-06	56	
8.787	331.2644	1	-0.006	-0.007	0.002	-0.038	-1.30E-05	56	
7.128	356.1455	1	-0.004	-0.005	0.009	-0.029	-9.80E-06	57	
3.992	277.074	1	0.001	0.001	0.001	0.011	9.40E-06	58	
6.607	1190.2365	1	0.002	0.003	0	0.022	1.20E-05	59	
6.699	418.1757	1	0.01	0.01	-0.004	0.028	1.90E-05	60	
7.001	1015.6548	2	-0.024	-0.021	-0.005	-0.006	-4.90E-06	61	
8.576	429.7421	2	-0.027	-0.027	-0.002	0.003	2.60E-06	62	
2.451	156.0763	1	0.017	0.019	0.001	0.016	4.70E-07	63	