Air Pollution Exposure and Health Impacts of Commuting by Bus, Underground, and Bicycling in Central London —A Pilot study

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Background — transport and health

Commuters' air pollution exposure / mode choice / active and public transport

- Transport activity as one major contributor to urban air pollution, including black carbon (BC), ultrafine particles (UFP), carbon monoxide (CO), fine particle mass (PM2.5) and carbon dioxide (CO2) (Brunekreef et al., 2009; Krzyżanowski et al., 2005).

- Commute travel modes can explain more of commuters' exposure variability than meteorology (i.e. wind speed and temperature) and traffic count (de Nazelle et al., 2012; Kaur & Nieuwenhuijsen, 2009)

- Public and active transport are effective at both reducing GHG emissions and improving health and thus promoted in policy worldwide, yet potentially problematic

.

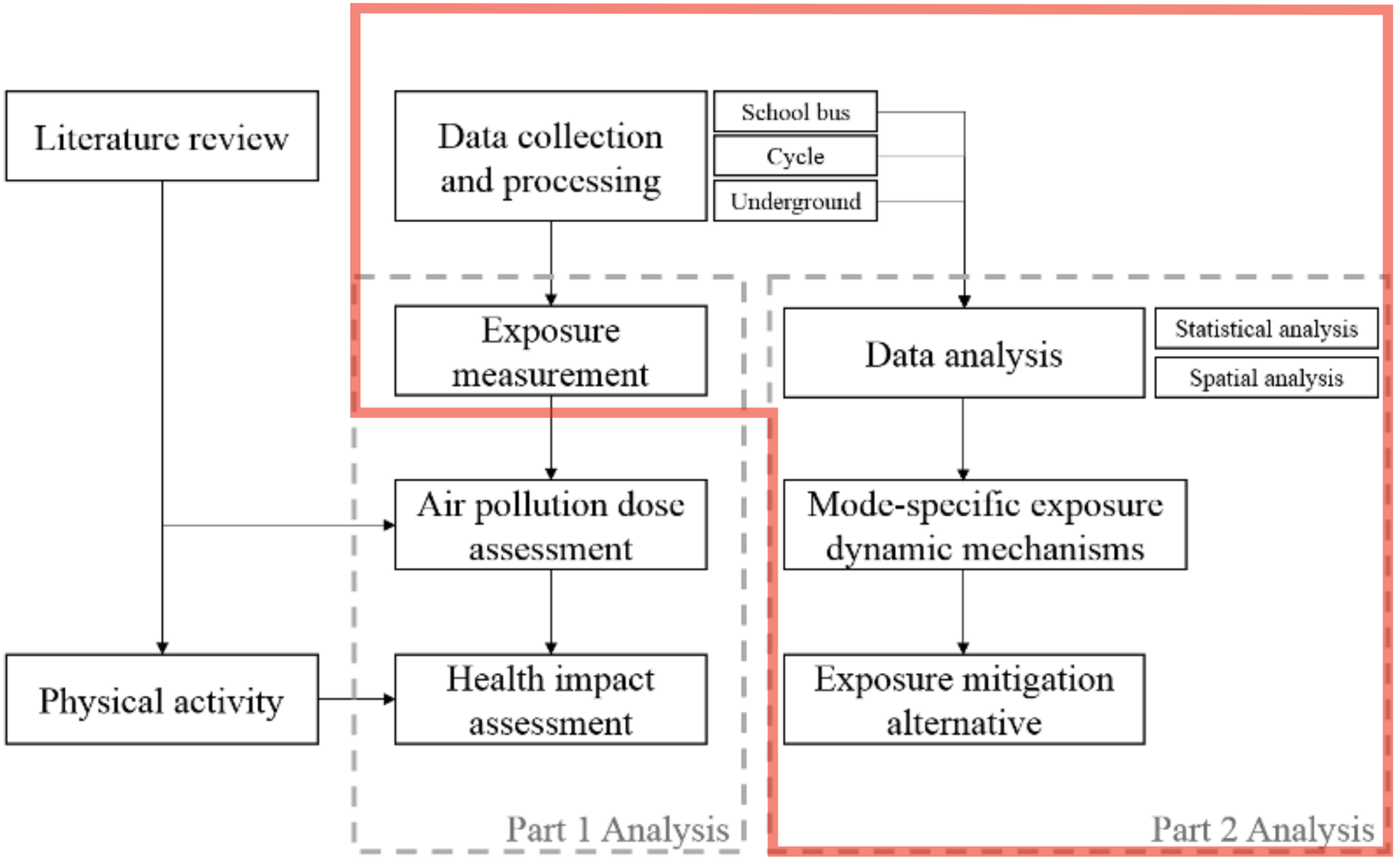
Background — exposure science

Exposure sensing / personal activity space / Lung Deposited Surface Area

- Wearable/portable sensors as paradigmatic practice for exposure measurement
- Complemented with action videography, event recordings, and GPS tracking
- Studied dominantly employed PM2.5, black carbon, etc as exposure metrics, but less used lung deposited surface area (LDSA) that are found more health-relevant

Study design

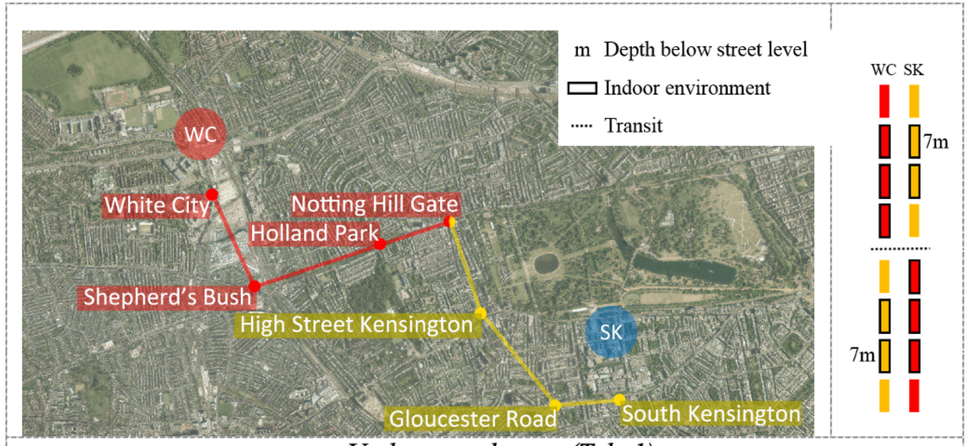
Framework



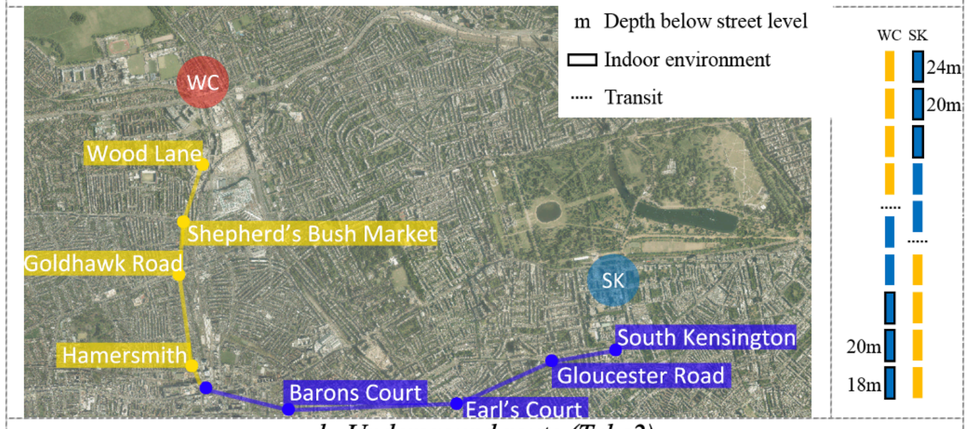
Study design

Sites, routes, and modes

London Underground (two lines with fixed route)

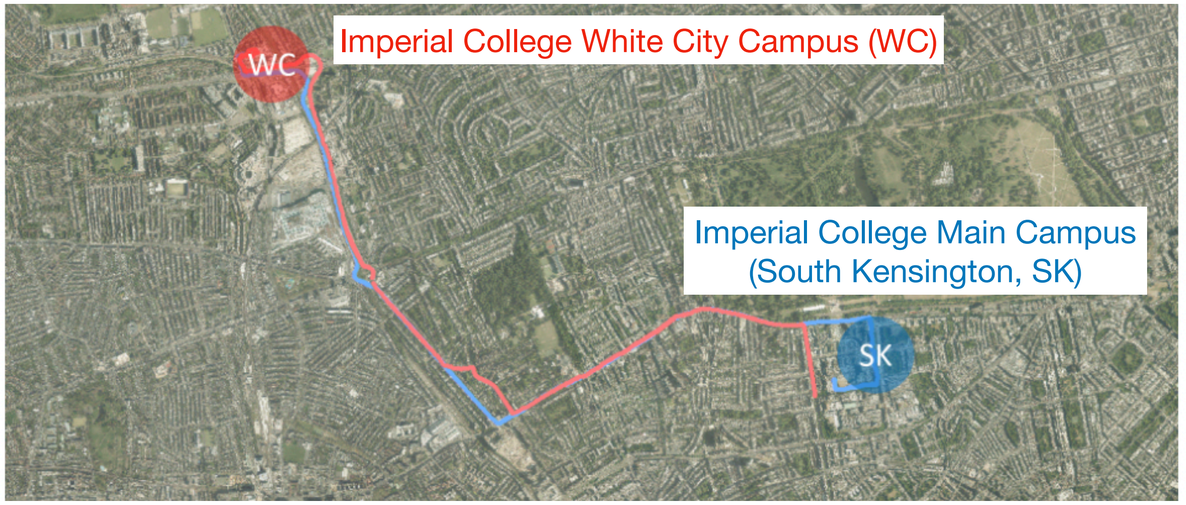


a. Underground route (Tube1)

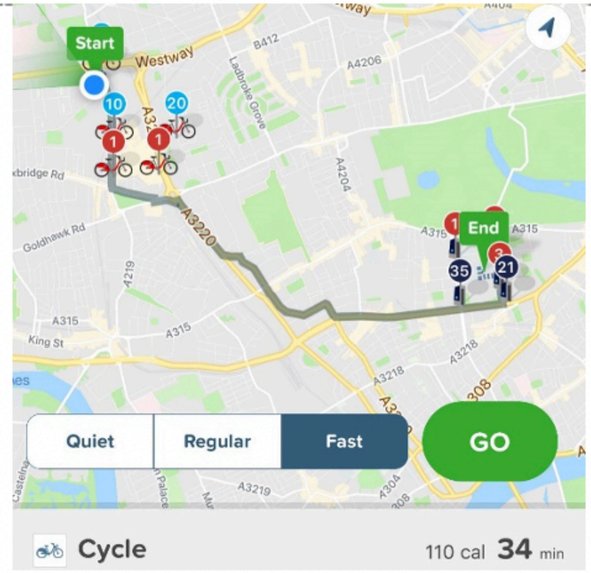


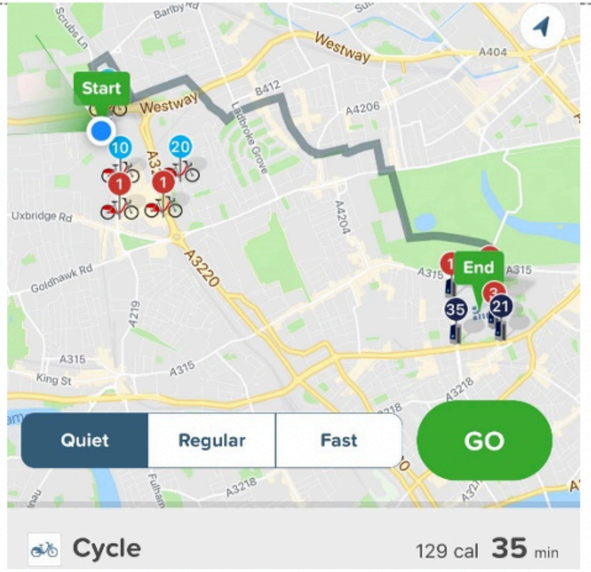
b. Underground route (Tube2)

School Bus (fixed route)



Cycling (app-recommended routes, including fastest and quietest)





Study design

Experiment design

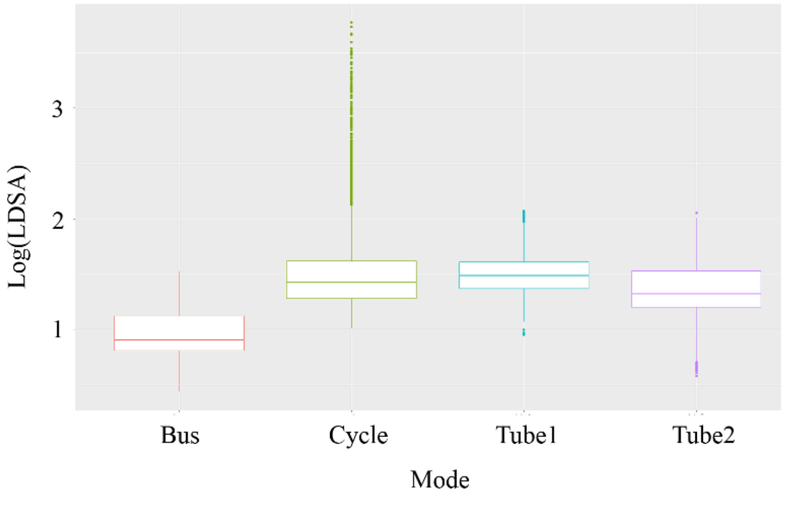
Table 2. Instrument used in commutes by each mode

Mode	LDSA sensor	Mobile phone		Action Camera
		GPS	Event recording	
School bus	V	V		
cycle	V	V		V
Tube	V		V	

- Three peak hours: morning, noon, and afternoon peak hours.
  - WC School bus: 8.10 am, 12.10 pm, and 5.55 pm
  - SK School bus: 9.15 am, 13.15 am, and 5.15 pm
  - Other modes: 8.00 am - 10.00 am, 11.30 am - 1.30 pm, and 4.30 pm - 6.30 pm
- 30 experiments conducted
  - **24** trips during three peak hours (i.e. morning, noon, and afternoon), departing from two origins (i.e. WC or SK), using four travel modes, i.e., school bus, cycle, Tube 1 (Central and Circle), and Tube 2 (Circle and Piccadilly)
  - **6** cycling trips on alternative routes
- Instrumentation
  - Lung Deposited Surface Area (Naneos partector)
  - Action videography (Tomtom Bandit action camera)
  - GPS tracking and event recording (mobile phone)

Results

Exposure comparison by mode



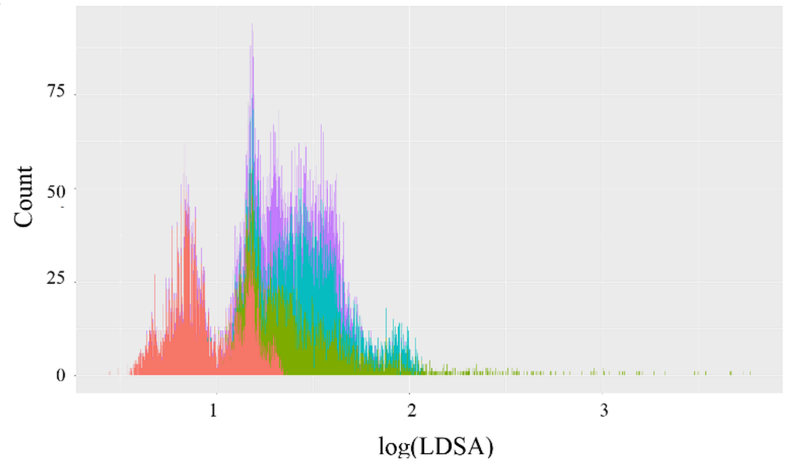


Figure 4. IQR box plot and histogram for exposure comparisons

Table 3. Summary statistics of AP exposures by travel mode, route, and time of day

		White City			South Kensington			
		Morning	**Noon**	**Afternoon**	**Morning**	**Noon**	**Afternoon**	**Total**
School bus	A.M.	13.1	10.6	7.2	9.3	13.9	6.0	9.7
	Median	14.4	9.9	7.0	9.1	14.3	5.7	8.0
	Range	5.5-33.3	3.0-16.2	4.6-11.0	5.1-15.4	5.8-22.6	2.7-11.8	2.7-33.3
	N	1,499	1,279	1,718	1,251	2,064	2,854	10,665
	STD							4.2
Cycle	A.M.	45.0	42.1	54.3	28.0	39.9	110.6	53.6
	Median	31.7	22.2	35.7	19.4	19.0	33.6	26.6
	Range	12.0-912.3	12.3-1137	16.9-512.0	10.6-365.8	10.2-2842.7	14.9-5915.2	10.2-5915.2
	N	1,524	1,504	1,346	1,705	1,483	1,645	9,207
	STD							189.3
Tube 1	A.M.	25.7	33.8	33.8	35.0	44.7	44.8	36.5
	Median	18.0	30.7	30.8	19.4	37.1	39.6	30.6
	Range	11.7-84.5	20.1-73.1	18.4-104.5	8.9-109.0	20.3-109.8	14.6-117.8	8.9-117.8
	N	1,426	1,452	2,620	1,373	1,425	1,940	10,236
	STD							12.0
Tube 2	A.M.	29.0	12.8	21.2	29.5	26.4	29.6	24.9
	Median	26.6	8.8	17.1	23.5	21.6	29.1	21.0
	Range	15.9-70.2	3.8-48.4	9.6-61.5	16.2-100.1	9.4-113.2	11.5-70.6	3.8-113.2
	N	1,190	1,171	1,849	1,364	1,532	1,534	8,640
	STD							10.5

A.M.: arithimic means
STD: standard deviation
N: sample (commute time in seconds)

Table 4. Exposure level in cycling on alternative path

		White City			South Kensington			
		Morning	**Noon**	**Afternoon**	**Morning**	**Noon**	**Afternoon**	**Total**
Cycle alt.	A.M.	35.6	20.4	27.4	20.3	24.1	28.5	26.1
	Median	28.9	15.0	23.7	13.7	19.5	20.0	20.7
	Min.	8.3	4.6	8.7	8.6	10.2	10.4	4.6
	Max.	382.8	374.3	212.0	202.8	289.7	1069.1	109.1
	N	1,714	1,628	1,786	1,768	1,659	1,735	10,290

Results

Mode-specific exposure determinants (school bus)

- Event analysis
  - Morning (AC-on), noon (AC-off), afternoon (natural ventilation)
  - Exposure decreased when AC were turned on
- Regression analysis: time stamp as independent variables
  - R2 = 0.786 (R=.**887**) and 0.861 (R=.**930**) for noon WC and SK trips
  - R2 = 0.795 (R=**-.892**) and 0.795 (R=**-.904**) for morning WC and SK trips.
- Spatial analysis
  - Intersection, motorways, and junctions linked to higher exposure
  - Agreeing with Rivas et al. (2017) and Li et al. (2015).

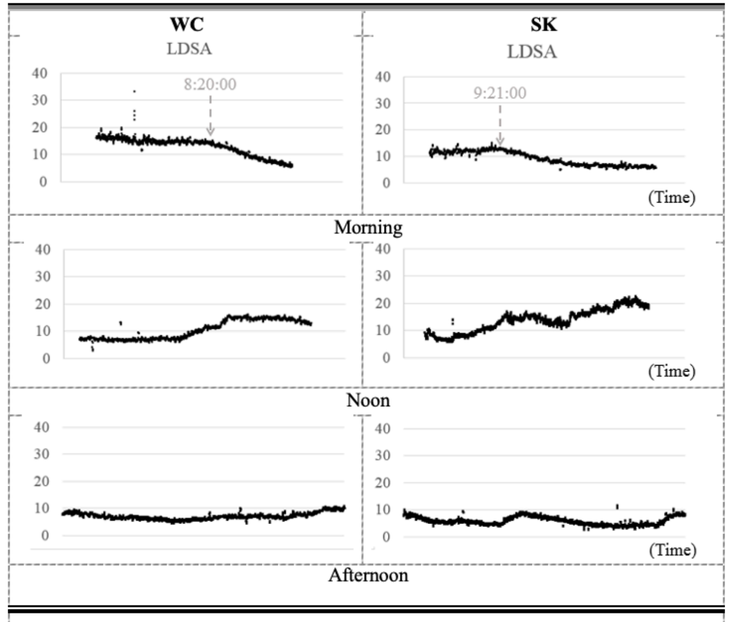


Figure 7. Temporal change of exposure during school bus trips

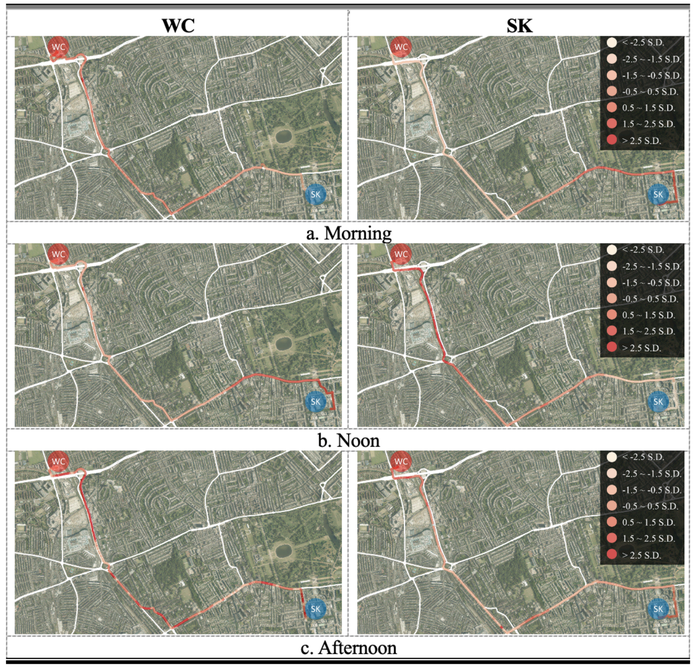


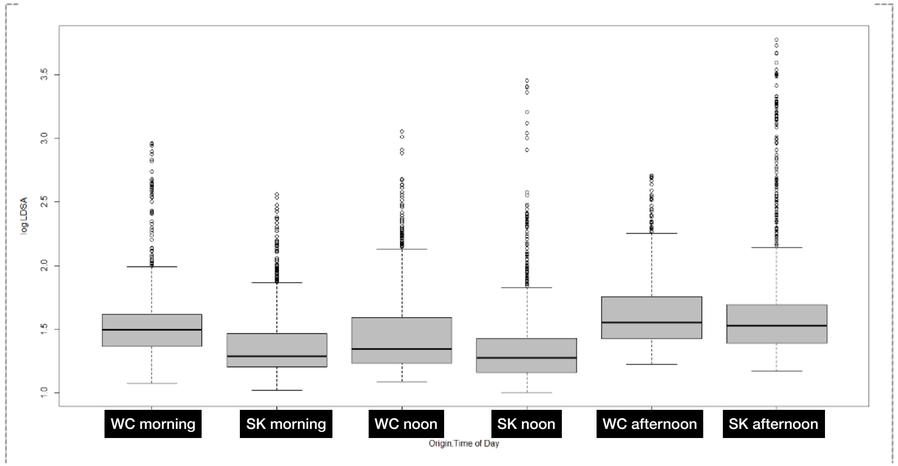
Figure 8. Exposure and speed level mapping for school bus trips

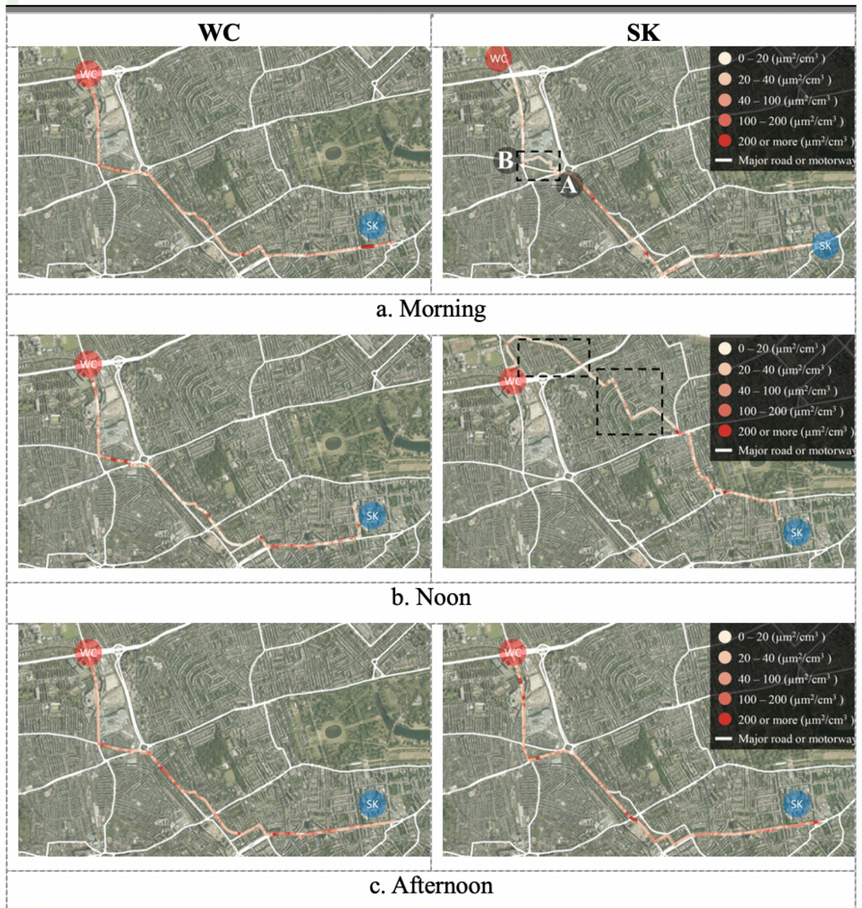
Results

Mode-specific exposure determinants (cycling)

- Descriptive statistics:
  - Morning: WC>SK; Noon: WC=SK (p=.61); Afternoon: WC<SK
  - Potentially because of the different travel patterns among the three peak hours, i.e. more traffic in the morning from Zone 2 (WC) to Zone 1 (SK), and in the afternoon from Zone 1 to Zone 2.

- Spatial analysis
  - High in intersections.
  - Low in
    - backstreet in residential area
    - residential area
    - green park





Results

Mode-specific exposure determinants (cycling)

- Event analysis (for all events with 100+ LDSA)
  - waiting at intersection
  - following or being overtaken by bus or vehicles manufactured before 2012
  - passing by worksite

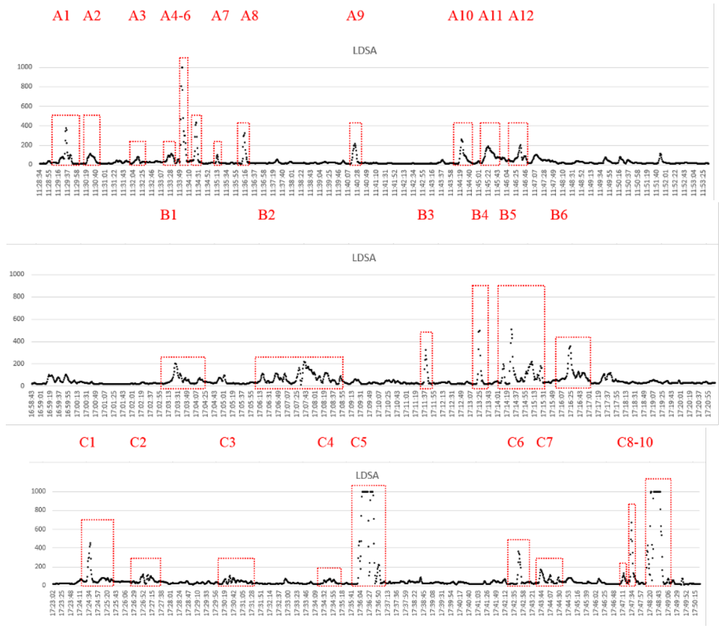


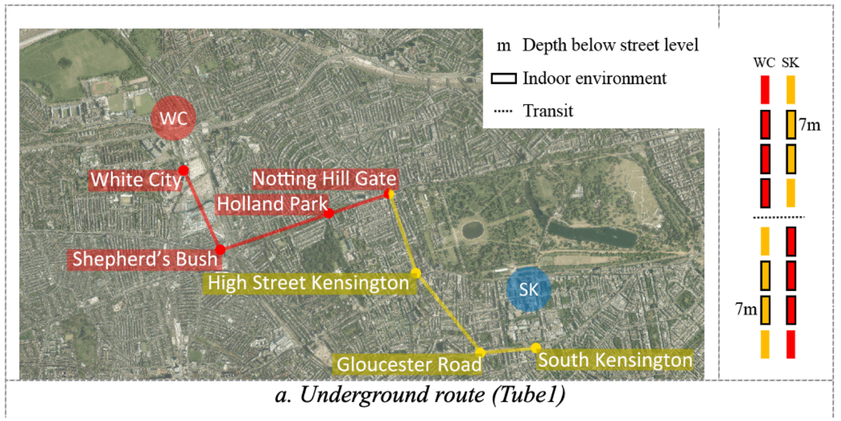
Table 7. Event analysis for cycle trips

Event ID	Event description
A1	Following 11 bus, and then overtaking it
A2	Overtaken by 11 bus and passing by food stalls
A3	Following 11 bus
A4	Following 10 vehicles
A5	Overtaking 11 bus, 05, 04, 06 and 08 vehicles
A6	Following 06 vehicles
A7	Overtaken by 11 ambulance
A8	Passing through 08 vehicles
A9	Overtaking 10 vehicles
A10	Waiting at intersection when 08 vehicles passed by
A11	Overtaken by 03 vehicles and following 11 vehicles
A12	Overtaken by 08 and 11 vehicles
B1	Following 03 vehicles
B2	Waiting at intersection while 03 vehicles passed by, overtaking 09 vehicles, overtaken by 04 vehicles, overtaking 04 and 11 vehicles, and following 11 vehicles, and overtaking 04 and 06 vehicles
B3	Following 08 cars
B4	Overtaking 03 cars
B5	Overtaking 08 cars, following 03 and 08 cars
B6	Following 03 cars[?] and bus
C1	Overtaken by 08 cars[?], an HGV, and then 04 vehicles
C2	Overtaking 07 vehicles, and then overtaking an HGV and a bus
C3	Overtaking 05 vehicles, and then overtaking 04 cars
C4	Passing through worksite
C5	Waiting at intersection behind 06 vehicles, and then overtaking 09 vehicles
C6	Following 10 vehicles and 2 buses
C7	Overtaken by 10 vehicles, and then 06 vehicles
C8	Overtaken by 05 vehicles
C9	Passing through worksite
C10	Overtaking bus, 05 vehicles, and then 06 vehicles

Numbers (03-11) mean manufactured years estimated by number of plate

Results

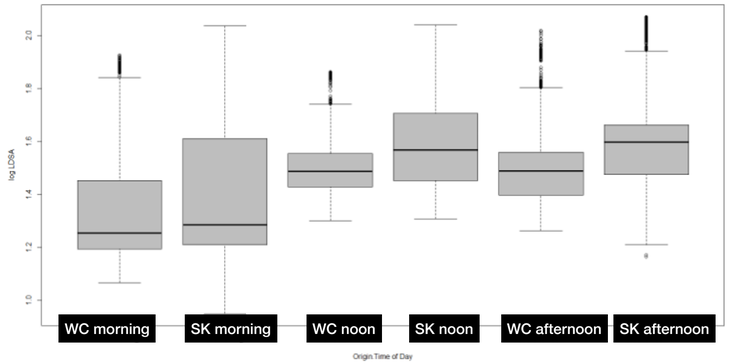
Mode-specific exposure determinants (Tube 1)



a. Underground route (Tube1)

- Descriptive statistics:
  - Exposure levels during each peak hour: SK trip > WC trips
  - Potentially because of transfer at **indoor platform in SK trips (Notting Hill Gate on Central) while outdoor in WC trips (Notting Hill Gate on Circle)**

- Event analysis



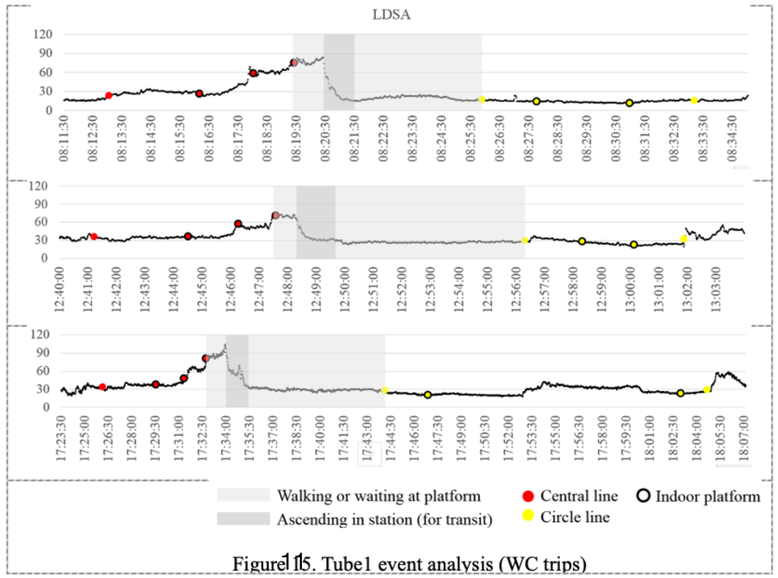


Figure 15. Tube1 event analysis (WC trips)

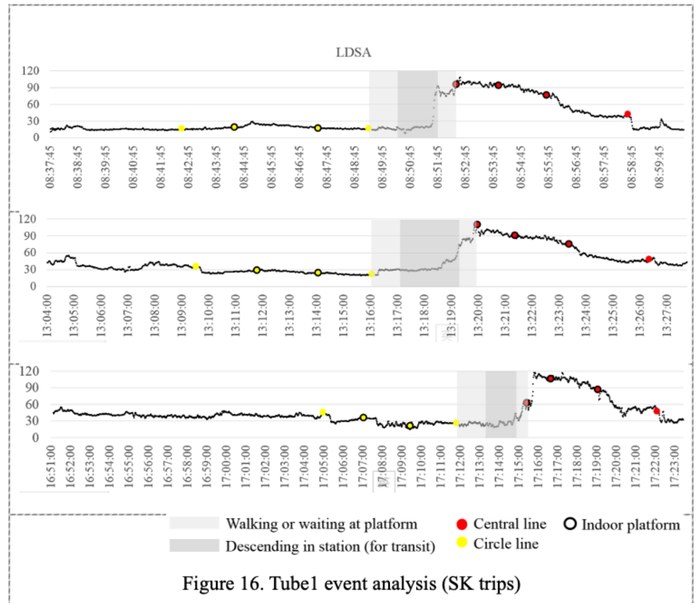
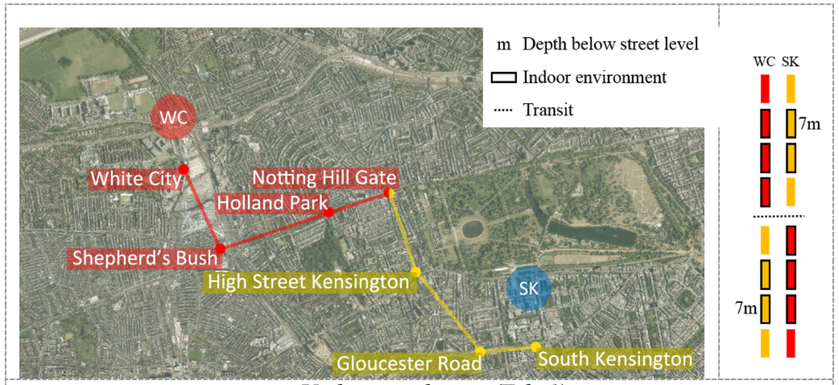


Figure 16. Tube1 event analysis (SK trips)

Results

Mode-specific exposure determinants (Tube 1)



a. Underground route (Tube1)

- Regression analysis
  - In-door (+)
  - In-cabin (-): protective effect

Table 10. Correlation and regression analysis results for Tube1

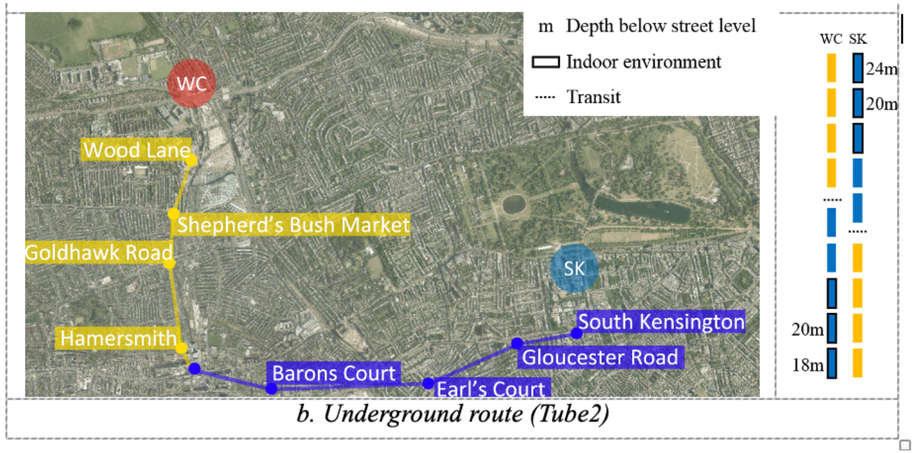
	WC			SK		
	Morning	**Noon**	**Afternoon**	**Morning**	**Noon**	**Afternoon**
Corr.	0.11	0.13	0.08	0.56	0.40	0.66
Bicep	*21.6	*31.5	*34.3	*16.8	*33.4	*36.8
Indoor	*35.2	*13.6	*30.5	*38.7	*24.4	*29.4
In-cabin	*-4.9	*-3.0	*-10.0	0.6 (p=0.68)	-1.3 (p=0.26)	-2.8 (p=0.02)
R^2	0.67	0.33	0.63	0.61	0.28	0.31
N	1,426	1,452	2,620	1,373	1,425	1,940

*significant at the 0.01 level

Results

Mode-specific exposure determinants (Tube 2)

- Event analysis
  - lower in **Circle Line** stations, as they are all outdoor stations in Tube 2 trips
  - the exposures on **Piccadilly Line** increased over time in WC trips but decreased in SK trips
  - events during outside-station transfer at Hammersmith: food stalls and smoking
- Regression analysis
  - Similar with Tube 1 result



b. Underground route (Tube2)

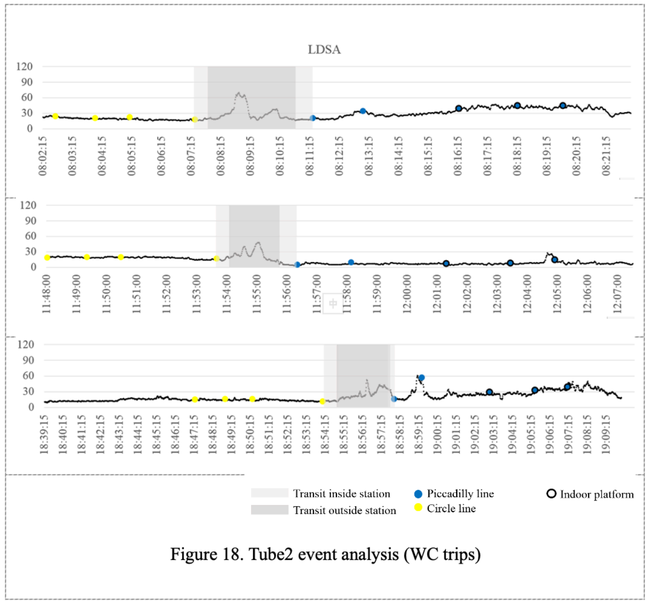


Figure 18. Tube2 event analysis (WC trips)

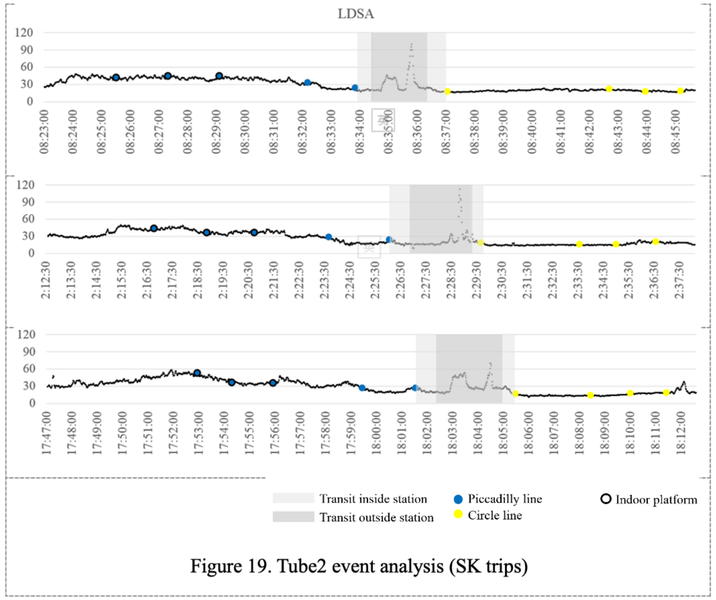


Figure 19. Tube2 event analysis (SK trips)

Table 11. Correlation and regression analysis results for Tube2

	WC			SK		
	Morning	**Noon**	**Afternoon**	**Morning**	**Noon**	**Afternoon**
Corr.	0.04	-0.23	0.17	0.31	0.14	0.42
Bicep	*26.4	*17.5	*19.0	*32.5	*23.0	*34.3
Indoor	*16.0	*-6.8	*14.1	*15.2	*18.7	*12.0
In-cabin	*-2.3	*-3.5	*-0.9	*-8.5	*-5.8	*-11.9
R^2	0.45	0.18	0.38	0.31	0.62	0.24
N	1,190	1,171	1,849	1,364	1,531	1,533

*significant at the 0.01 level

Conclusion

- Exposure comparison (mean LDSA):
  - cycling (53.6) > Tube 1_more indoor stations (36.5) > Tube 2_more outdoor stations (24.9) > school bus (9.7)
  - cycling on fastest routes (53.6) >> cycling on alternative path (23.1)

- Mode-specific determinants
  - Cyclists' exposure is subject to immediate traffic microenvironments (i.e. vehicle type and age, cycle path deployment, and land use).
  - Ventilation significantly influences AP levels during both school bus trips (i.e. AC settings) and underground trips (i.e. station, platform and cabin environment).
  - Outside-station transfer could increase underground commuters' exposure.

- LDSA-based measurement results consistent with existing PM-based findings

- Policy implications:
  - Cycling on alternative paths can half exposure
  - Turning on AC for ventilation in bus
  - Underground design (where people enter [station], wait [platform], and move [cabin] matter)

Limitations

- Different time of day and day week measured due to limited time and amount of sensors
- Manual data collection and extraction
  - Number plate identification
  - Event recording missing other factors
  - Cannot detect distance from cars ahead
- Qualitative/categorical data analysis

Thank you

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Results

Health impact assessment

Table 5. AP exposure, inhaled doses, and health risks

AP	LDSA	Estimated $PM_{2.5}$	Mean travel time (s/trip)	Commute time (h/week)	APD*	APb*	PAF (AP)
Bus	9.7	10.5	1778	4.9	834.8	0.0	1.000
Cycle	53.6	**58.0**	1535	4.3	1437.7	7.3	1.045
Tube1	36.5	39.5	1706	4.7	918.4	1.0	1.006
Tube2	24.9	26.9	1440	4.0	874.6	0.5	1.003
Cycle.alt	26.1	28.2	1715	4.8	1147.4	3.8	1.023

Table 6. Health benefits of PA and net health outcomes

PA		Transformation function		PAF (PA)		PAF (AP)*PAF (PA)	
	MET	0.5	0.375	0.5	0.375	0.5	0.375
Bus	0	-	-	1.000	1.000	1.000	1.000
Cycle	17.05	4.13	2.90	0.842	0.850	0.880	0.888
Tube1	0	-	-	1.000	1.000	1.006	1.006
Tube2	0	-	-	1.000	1.000	1.003	1.003
Cycle.alt	19.06	4.37	3.02	0.834	0.844	0.853	0.863