Environmental Research Group

Crossrail Driver Diesel Exposure Study

King's College London Environmental Research Group

Prepared for Crossrail & ATC

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Executive Summary

This study was carried out by King's College London on Crossrail's behalf to characterise the exposure of mobile machinery operatives and allied personnel within the sub-surface and surface level rail construction environment. 10 operatives were recruited to the study between February and September 2017. These operatives were selected as they represented a wide range of occupations spending significant proportions of their working day underground in proximity to diesel vehicles or machinery. Following recruitment each participant was provided with a portable diesel pollution monitor (Aethlabs AE51 Microaethalometer) and GPS data logger (I-GOTU GT-600) and given appropriate training on their use. They were instructed to carry the monitor with them for 48 hours, including while at work, home and travelling. The monitors continuously logged location and pollution concentrations. Resulting time series data were tagged according to activity categories and analysed for patterns in exposure linked to working procedures.

Three groups of workers were monitored; (i) Mobile Elevated Working Platform (MEWP) supervisor and operators, (ii) driver and shunters on a Class 66 Locomotive, and (iii) the crew of a 'Madvac' suction excavator. The primary purpose of the third deployment was to assess the performance of the tunnel ventilation system, which was disabled for maintenance during the first day of monitoring. Crews in each group followed a similar working pattern of briefing and preparation above ground, followed by the majority of the shift below ground.

The analysis found that, on average, most workers were exposed to higher levels of black carbon when commuting to and from site, than while on shift. This was particularly evident where workers used underground sections of the London Underground or private vehicles. The lowest levels of exposure where while indoors (at home or site office) and while commuting on above ground rail. While the tunnel ventilation system was operational, workers were exposed to lower levels of diesel exhaust while below ground than while working above ground at the railhead adjacent to the tunnel entrances. When tunnel ventilation was switched off, exposure levels increase by a factor of 3 to 5, demonstrating the efficacy of the system.

Short spikes in diesel exhaust exposure occurred amongst all workers, due to standing or working near vehicle or generator exhaust. This occurrence was more frequent in operators than foremen/supervisors and the impact was greater above ground than below, due to the active ventilation causing more rapid dispersion than natural wind. The locomotive driver had the lowest mean exposure levels due to the protective effect of his cab and position away from vehicle and machinery exhausts.

This study did not identify any breaches of occupational exposure limits and worker personal exposure levels were shown to be at least comparative to or lower than those experienced by above ground professional drivers. However, the absence of any clear 'safe threshold' for black carbon exposure means that employer should be encouraged to minimise exposure levels of their workers to diesel exhaust. As series of recommendations are made based on study results to ensure continuing best practise in future projects incorporating construction activities in a tunnel environment.

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1. Background

This report describes a study carried out by King's on Crossrail's behalf to characterise the exposure of mobile machinery operatives and allied personnel within the sub-surface and surface level rail construction environment. It is associated with a wider study funded by the Institute of Occupational Safety and Health designed to parameterise these occupational exposures of professional drivers under real-world conditions (DEMiSt: Driver Diesel Exposure Mitigation Study).

The aim of the project was to monitor how much diesel exhaust operatives inhale during a typical working day within the tunnelling and railhead environment. This aim was achieved through a series of objectives:

- Characterise driver/operative exposure to inhaled diesel emissions at sub-surface and surface level under a range of operating conditions.
- Parameterise driver/operative exposure allowing identification of dominant variables dictating increased and decreased risk of harm from diesel emissions.
- Identify potential intervention methods for health improvement, focusing on strategies that can be applied to existing machinery or working practices.
- Contrast operative exposure to diesel exhaust levels with those typical of non-occupational settings to put results into general context.

The outcome of each objective is described in this report, followed by a series of evidence-based recommendations for future large-scale sub-surface construction projects.

2. Methods

2.1 Recruitment and study setting

Following meetings with Crossrail and ATC (Crossrail's rail fit-out and commissioning subcontractor), it was agreed that ATC's Environmental Advisor would act as Gatekeeper for the study. The Gatekeeper facilitated site visits with King's staff, recruited and interacted with study participants and provided technical material on mobile machinery, operating conditions and ventilation systems.

10 operatives were recruited to the study between February and September 2017. These operatives were selected as they represented a wide range of occupations spending significant proportions of their working day underground in proximity to diesel vehicles or machinery. Operatives were selected in groups, allowing comparison of exposure levels between roles; driver, operative and foreman/supervisor. Each group followed the same general shift pattern; arrival on site, shift briefing in or near site office, aboveground preparation work, below ground work, return to surface, departure from site and travel home. Two groups worked on day shifts (approximately 07:00 to 18:00 including briefing) and one group night shift (approximately 19:00 to 07:00).

2.1.1. Group 1: Mobile Elevated Working Platform Operator and Foreman

The first deployment assessed the exposure of Mobile Elevated Working Platform (MEWP) operators. A MEWP is a rail-mounted gantry used to provide access to the tunnel roof and associated ancillaries. MEWPs operated in the Crossrail tunnel environment were powered by 129 kW diesel engines fitted with a Tier 4 Diesel Particulate Filter (DPF) located toward the rear of the machinery.

The MEWP was typically positioned on the platform while working, with the foreman supervising from below (as illustrated in Figure 1). Operators typically walked behind the machinery while tracking.

Figure 1: Mobile Elevated Working Platform of the type operated in the Crossrail tunnel environment.

2.1.2. Group 2: Class 66 Locomotive Shunters (2), Driver and Supervisor

The second deployment assessed the exposure of the crew of a Class 66 Locomotive (Figure 2). The Class 66 was powered by a two stroke 2238 kW diesel engine. The Locomotive was assigned dispensation from Non-

Road Mobile Machinery requirements for emissions control as no applicable DPF was manufactured for this engine size and type.

The crew comprised of two shunters, a driver and a supervisor. The shunters typically operated on and around the wagons, with one typically located at the rear of the train. The driver remained in his cabin while underground, including while stationary. The supervisor typically stood back from the train, overseeing activity on and around the machinery.

Figure 2: Class 66 Locomotive operated in the Crossrail tunnel environment.

Figure 3: Madvac suction excavator of the type operated by Group 3.

2.1.3. Group 3: Madvac Operatives (3) and Foreman

The third deployment assessed the exposure of the crew of a 'Madvac' suction excavator (Figure 3). The Madvac was powered by a diesel engine fitted with a Tier 4 DPF. The crew comprised three operatives and one foreman.

The primary purpose of the Group 3 deployment was to assess the performance of the tunnel ventilation system. This was disabled for maintenance during the first day of monitoring, then fully operational on the second day. Working practices on the two days were very similar, allowing a direct comparison of diesel exhaust exposure with and without tunnel ventilation.

2.1.4. Railhead and tunnel environment

Crews in each group followed a similar working pattern. Following arrival on site, a shift briefing was held in or around the site office (above ground) lasting around 30 minutes. Crews would then prepare equipment and materials before heading underground. This lasted between 30 minutes and several hours. GPS signal was lost when the crew moved underground, allowing an accurate assessment of movements above and time spent below ground.

The majority of diesel exhaust exposure above ground was primarily caused by public vehicle emissions (while commuting) and construction-related vehicles and stationary diesel generators (while at the railhead). Additional sources of black carbon detected by the monitors included cigarette smoke and cooking (while at home). Smoking was not permitted below ground but was permitted at the railhead. Aside from the maintenance period coinciding with Group 3's experiment, the below ground ventilation systems ran continuously throughout. Air flow was set centrally each day, based on the quantity of plant and the cumulative emissions of plant in each section of the tunnel. This calculation factored in gradient, distance to vent shafts and low points in the tunnels.

2.2 Exposure monitoring

Following recruitment each participant was provided with a portable diesel pollution monitor (Aethlabs AE51 Microaethalometer) and coupled GPS data logger (I-GOTU GT-600) and given appropriate training on their use. They were instructed to carry the monitor with them for 48 hours, including while at work, home and travelling. The monitors continuously pumped air through a short sample tube clipped close to the participant's face. At the end of their monitoring period, the participants completed a short questionnaire relating to their working hours, vehicle details and proximity to other exhaust emissions. Smoking habits and commuting mode were also recorded.

Prior to and following the monitoring campaign, all instruments were tested for accuracy and precision and calibrated against reference monitors. Measurements were ratified and scaled according to predefined data management protocols. Questionnaire responses were checked against records held by the Gatekeeper.

2.3 Exposure characterisation

Measurements were aggregated to one minute means and linked to GPS location data, where available (no GPS data were available underground). Location-linked pollutant measurements were then tagged according to an activity matrix shown in Table 1 utilising GPS data, questionnaire responses and visual inspection of time series data. Tagged data were used to create summary statistics of exposure levels for each operative, averaged across their monitoring period. More detailed analysis of measurements during occupational activities was then carried out to identify contrasts and patterns in operator behaviour and work environment that may have influenced exposure levels.

Activity	
Indoors: At home/residence	**Below ground: Ventilation off**
Indoors: Site office	**Other: Smoking**
Travel: Commute	**Other: Unknown**
Outdoors: Railhead	**Other: Instrument fault**
Below ground: Ventilation on	

Table 1: Activity tags used to characterise exposure data

3. Results

3.1 Questionnaire responses

DEM001 (Mewp Operator) and DEM002 (MEWP Foreman) were monitored during their day shift (08:00 to 17:00). Both participants reported travelling between place of residence and site by London Underground. Neither reported smoking habits and there was no evidence from the exposure data of smoking. Both reported that the ventilation system was working during their shift. The foreman reported that the MEWP's engine was switched off when idle.

DEM003 to DEM006 were monitored during their night shift (19:00 – 07:00). DEM003 (Shunter 1) did not report smoking or commuting habits. DEM004 (Shunter 2) reporting smoking during the experiment and commuted by London Underground. DEM005 (Loco Driver) reported smoking and commuted by London Underground, over ground train and walk. DEM006 (Supervisor) reported being a non-smoker and commuted by London Underground, bus and walk.

DEM007 to DEM010 were monitored during their day shift (day 1: 07:30 – 18:00, day 2: 07:00 – 17:30). Madvac operatives DEM007, DEM008 and DEM010 did not report commuting or smoking habits. The Foreman (DEM009) reported being a non-smoker who commuted by van.

3.2 Exposure summary

Table 2 and Table 3 show mean and peak (1-minute maximum) black carbon exposure concentrations in each environmental category following activity tagging. In some cases user error, most commonly forgetting to charge the unit overnight, meant that data from two full shifts were not available, however, nine of the 10 participants captured at least one full shift. The exception was DEM008 (Madvac operative), who's instrument developed a fault resulting in only 10 hours of valid data.

These figures show that cigarette smoking produced the highest exposure levels (>130 μg/m^3), although these were over short periods. Concentrations of black carbon in each participant's residences were lowest on average (0.9 – 3.1 μg/m^3), although the office and briefing means were as low in some cases. Each of these three categories are indoor environments and demonstrate that, in the absence of significant indoor sources, buildings generally have a protective effect from diesel exhaust emissions, even when a source such as a diesel generator is close by. However, peak concentrations in the indoor environments were, in some cases, up to 10 times higher than the mean, revealing the presence of short elevated periods of exposure indicative of strong transient sources, such as cooking, or an exhaust plume entering through an open door.

Mean black carbon concentration (μg/m^3)	At home	Travel to/ from work	Office	Briefing	Railhead	Below ground (fan on)	Below ground (fan off)	Smoking
MEWP Operator	2.2	4.1	3.0	5.6	8.4	9.0		
MEWP Foreman	0.9	5.2		2.9	2.5	5.9		
Loco Shunter A	1.7	2.5	3.4	2.9	19.5	2.4		
Loco Shunter B	1.2	4.9	1.5	2.7	6.2	4.5		152.3
Loco Driver	3.1	5.7	3.2	2.4	3.8	1.9		138.6
Loco Supervisor	1.6	20.6	2.4	4.2	3.5	2.4		
Madvac Operator A	1.4	7.6	5.0	8.0	7.6	7.2	27.5	133.0
Madvac Operator B	1.7	13.6	3.7	1.7	2.9	3.5	17.7	
Madvac Foreman	1.7	14.1	1.0	3.7	6.9	3.9	12.0	

Table 2: Mean black carbon exposure concentrations in each environment category.

Maximum black carbon concentration (µg/m³)	At home	Travel to/ from work	Office	Briefing	Railhead	Below ground	Below ground (fan off)	Smoking
MEWP Operator	30.6	19.1	11.6	49.0	77.2	192.6		
MEWP Foreman	1.6	36.4		22.3	13.4	28.3		
Loco Shunter A	6.2	30.9	5.4	9.4	181.0	44.8		
Loco Shunter B	15.8	55.8	12.2	15.9	145.6	46.5		523.5
Loco Driver	15.6	22.1	8.8	8.5	73.4	29.5		500.4
Loco Supervisor	8.4	110.8	11.2	18.3	61.3	34.6		
Madvac Operator A	17.8	48.1	20.8	31.2	230.7	20.3	506.0	587.5
Madvac Operator B	12.1	63.9	20.8	9.0	86.1	14.1	207.2	
Madvac Foreman	19.7	62.0	2.4	6.9	326.0	9.1	131.8	

Table 3: Peak (1-minute maximum) black carbon exposure concentrations in each environment category.

Mean and peak exposures while travelling to work were variable between participants, dependent on mode of transport taken. The highest mean and peak exposures while travelling was the Loco Supervisor, who travelled by bus and London Underground, followed by the Madvac Foreman, who travelled by Van. Loco Shunter A had the lowest commute exposure, but no travel information was available for this participant. The MEWP operators and Loco Shunter A all reported traveling by London Underground, however, the GPS data shows that this was mostly on the over ground sections and exposure levels were relatively low.

These travel patterns match previous studies[1,2], where underground sections of the London Underground have found to contain particularly high levels of particulate pollution (predominantly black iron, rather than black carbon) caused by rail and brake abrasion within the tunnel environment. It is interesting to note that these levels are far higher than those experienced in the Crossrail construction tunnel environment, likely due to better ventilation and, most significantly, lower frequency of train movements. Published studies also report higher commuter exposure in cars, vans and buses than walking, cycling and above ground rail.

Operators worked in two distinct outdoor environments – above ground at the railhead and below ground in the tunnel. Seven of the nine participants that completed the full experiment were exposed to higher mean levels of diesel exhaust at the railhead than below ground. Above and below ground shift means are shown in Table 4, with shift mean exposures from transport workers gathered during previous studies with the same methodology. Across the cohort, Crossrail workers were exposed to similar levels of diesel exhaust than two of the three comparative professional drivers. Driver exposure has been shown to be very variable, dependent on vehicle and levels of congestion, resulting in a wide range of mean exposures. This issue is being further investigated as part of the wider DEMiSt study funded by the Institute of Occupational Safety and Health.

The occupational exposure limit for black carbon is 3,000-3,500 µg/m3 averaged over an eight hour shift, many times higher than levels that Crossrail workers were exposed to. There is no applicable ambient (i.e., non-occupational) standard for black carbon. However, as black carbon is a component of fine particulate matter ($PM_{2.5}$), the closest applicable ambient standard is the WHO ambient air quality guideline for $PM_{2.5}$. This is set at 25 µg/m averaged 24 hours.

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[1] Vilcassim, M. J. R., et al. (2014). "Black Carbon and Particulate Matter (PM2.5) Concentrations in New York City's Subway Stations." Environmental Science & Technology 48(24): 14738-14745.

[2] Seaton, A., et al. (2005). "The London Underground: dust and hazards to health." Occupational and Environmental Medicine 62(6): 355-362.

Worker	Shift mean black carbon exposure (µg/m³)	
	Above ground	Below ground
Crossrail workers		
MEWP Operator	8.4	9.0
MEWP Foreman	2.5	5.9
Loco Shunter A	19.5	2.4
Loco Shunter B	6.2	4.5
Loco Driver	3.8	1.9
Loco Supervisor	3.5	2.4
Madvac Operative A	7.6	7.2
Madvac Operative B	2.9	3.5
Madvac Foreman	6.9	3.9
Crossrail worker mean	6.3	4.2
Workers from previous transport studies		
Taxi Driver 1	4.5	-
Taxi Driver 2	5.2	-
Ambulance Driver	23.7	-
Cycle Courier	2.3	-

Table 4: Above and below ground shift means for the Crossrail workers, plus indicative comparisons from previous studies of transport workers.
Note that comparative worker exposures were not measured over the same period. Below ground exposure measurements during the period of disabled tunnel ventilation has been excluded.

3.3 Factors affecting worker exposure

Analysis of high resolution time series data relating to specific activities revealed further information of the conditions that led to elevated work exposure. While mean exposures were well below occupational limits, by identifying these activities, evidence for exposure mitigation could be established.

Figure 4 shows a detailed extract from the first day of monitoring of the Loco supervisor. This illustrates how spikes in exposure occurred throughout the shift, except while indoors. Exposure levels above ground were higher than those below ground likely due to regular movements of the locomotive around the railhead and proximity to other vehicles and generator. Below ground, when the loco was mostly stationary, exposure levels were similar to those indoors, except for a period of activity around 01:00. All occupational exposures were lower than those recorded during his journey home on the London Underground at 06:30.

Figure 5 illustrates the contrast between two workers, Loco Shunter A and Loco Driver, in and around the Class 66 Locomotive. The shunter's proximity to the engine exhaust and the protective effect of the engine's cab produce a large differential in exposure levels. Peak concentrations recorded by the Loco Driver were caused by either his own, or standing amongst cigarette smokers.

The impact of the ventilation system shutdown on black carbon exposure levels of the Madvac workers can be seen in Figure 6. The left hand panel shows the first day shift, with no ventilation. Concentrations of the Madvac operative exceeded 100 µg/m³ on several occasions. The right hand panel shows the second day shift, with ventilation in normal operation. On the second day, concentrations did not exceed 10 µg/m³. As with the loco workers, the foreman's exposure was typically below that of the operative. A series of short peaks of over 500 µg/m³ indicated smoking by or near the operative while above ground.

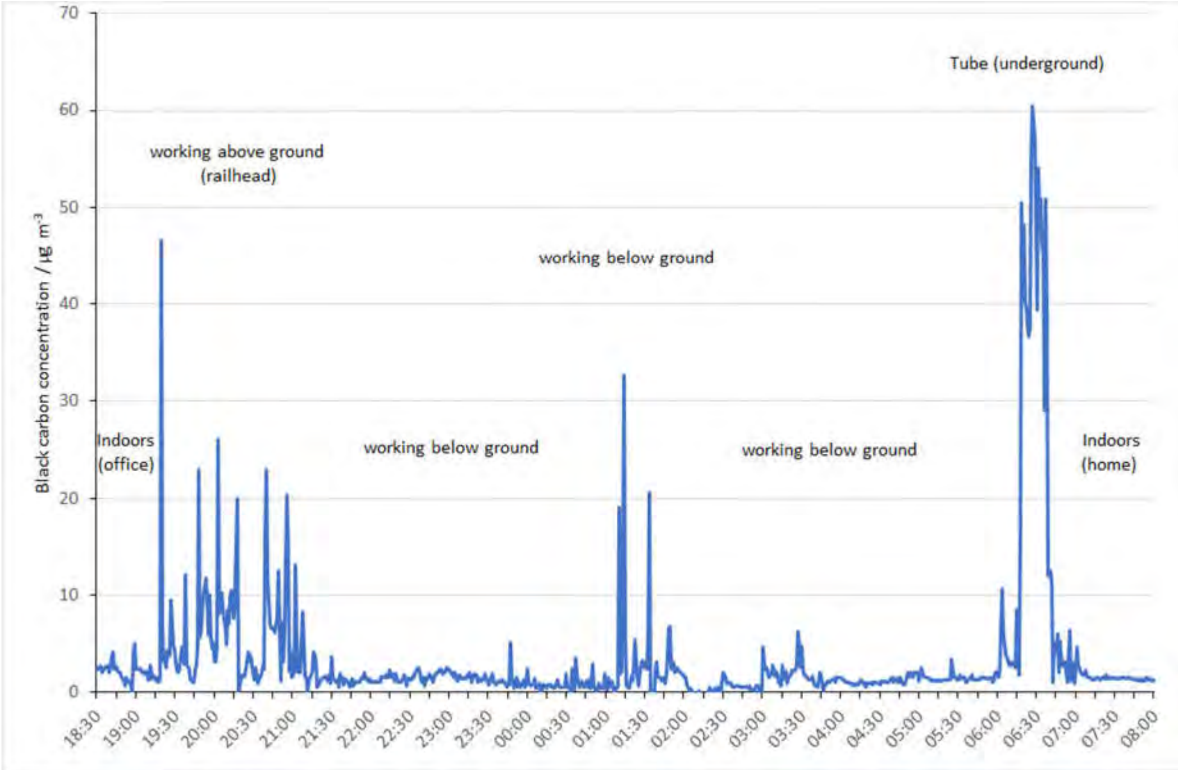

Figure 4: Extract from DEM006 (Loco Supervisor) time series data illustrating variation in exposure levels between different activities across the shift and journey home.

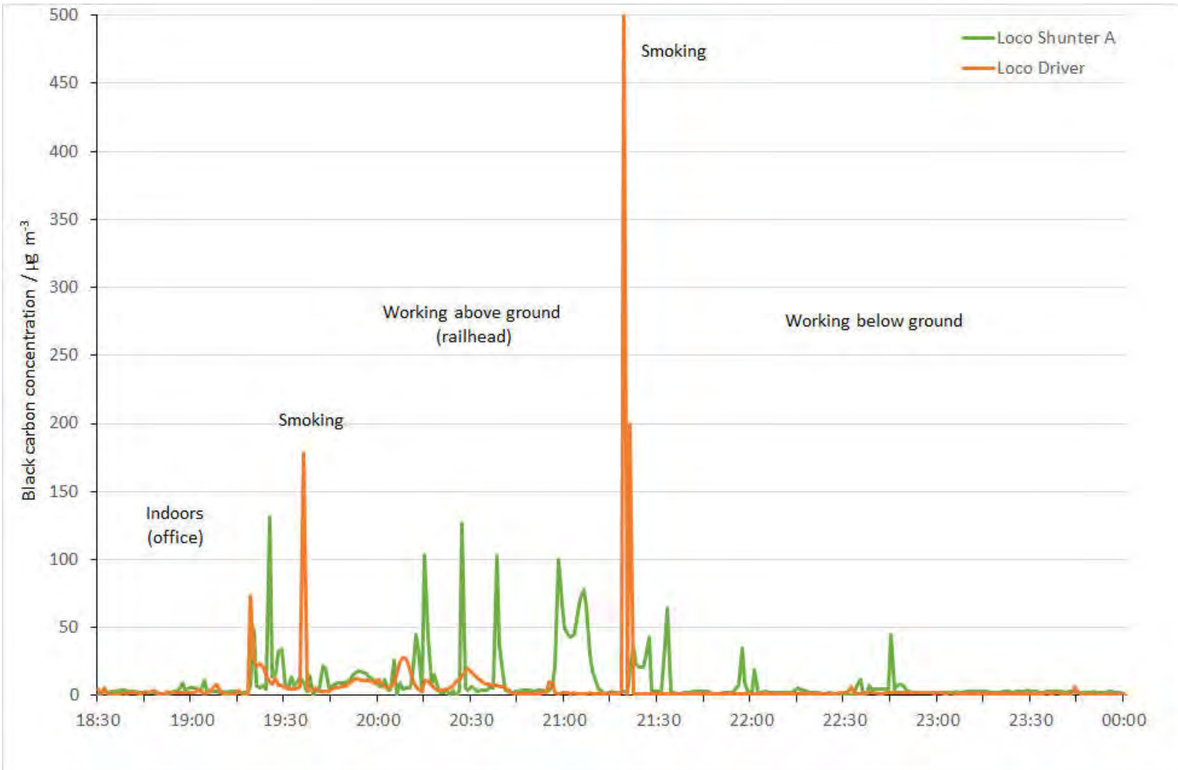

Figure 5: Extract from the Loco Shunter A and Loco Driver time series data, illustrating contrasts in exposure levels between the two job roles in and around the same vehicle.

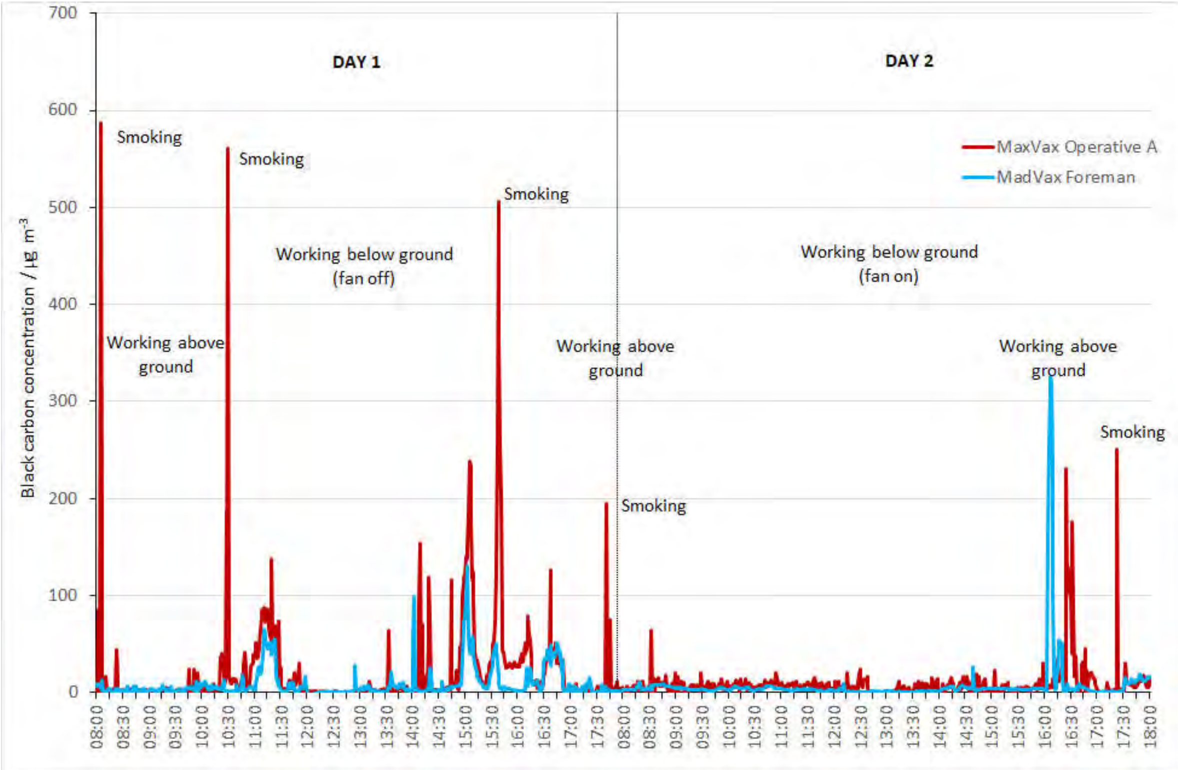

Figure 6: Time series data from Madvac Operative A and Madvac Foreman over two shifts, with contrasts in below ground exposure caused by ventilation system maintenance on Day 1.

4. Discussion

The aim of the study was to characterise the exposure of mobile machinery operatives and allied personnel within the sub-surface and surface level rail construction environment to diesel exhaust emissions. Diesel exhaust is a known carcinogen and has been linked to a range of cardiovascular and respiratory health problems. By characterising the extent and nature of diesel exhaust amongst workers, recommendations could be made as to whether and how exposure could be mitigated beyond precautions already being taken.

This study utilised high resolution portable exposure monitoring equipment to characterise Crossrail worker exposure to black carbon emissions across a range of occupational and non-occupational environments. Black carbon is an indicator of incomplete fuel combustion, the primary source of which in the occupational environment was diesel exhaust. The study did not assess exposure to non-exhaust particles, such as resuspended dust, which would not have been detected by the instruments used.

Ten workers were continuously monitored over a period of up to 48 hours, coupled with GPS trackers and a short questionnaire. Resulting time series data were tagged according to activity categories and analysed for patterns in exposure linked to working procedures.

The analysis found that, on average, most workers were exposed to higher levels of black carbon when travelling to and from site, than while on shift. This was particularly evident where workers used underground sections of the London Underground or private vehicles. The lowest levels of exposure where while indoors (at home or site office) and while commuting on above ground rail.

While the tunnel ventilation system was operational, workers were exposed to lower levels of diesel exhaust while below ground than while working at the rail head. When tunnel ventilation was switched off, exposure levels increase by a factor of 3 to 5, demonstrating the efficacy of the system.

Short spikes in diesel exhaust exposure occurred amongst all workers, due to standing or working near vehicle or generator exhaust. This occurrence was more frequent in operators than foremen/supervisors and the impact was greater above ground than below, due to the active ventilation causing more rapid dispersion than natural wind. The locomotive driver had the lowest mean exposure levels due to the protective effect of his cab and position away from vehicle and machinery exhausts. Black carbon concentrations have been shown to decrease exponentially away from the source, therefore moving even short distances way from an exhaust can make a major difference to exposure.

5. Recommendations

This study did not identify any breaches of occupational exposure limits and worker personal exposure levels were shown to be at least comparative to or lower than those experienced by above ground professional drivers. However, the absence of any clear 'safe threshold' for black carbon exposure means that employer should be encouraged to minimise exposure levels of their workers to diesel exhaust.

The following recommendations are made based on the study results to ensure continuing best practise in future projects incorporating construction activities in a tunnel environment:

- Employees should be made aware of the risks of standing near the exhaust of diesel vehicles both above and below ground.
- Where workers are required to operate close to vehicle exhaust, a crew rotational system should be used to avoid any single worker experiencing significantly higher levels of exposure than others.
- Tunnel ventilation systems are an effective method of reducing exposure and should be kept operational at all times. Below ground working while ventilation system maintenance is underway should be avoided wherever possible.
- The fitting of diesel particulate filters (DPFs) to vehicles and machinery should not be considered a complete solution to worker exposure, but part of a wider mitigation regime.
- Whenever possible, the idling of diesel vehicles should be avoided. However, in certain circumstances, the effectiveness of DPFs can be reduced in cold start conditions, therefore vehicles should be considered on a case by case basis.
- Summary results of this study should be fed back to tunnel workers and study participants to demonstrate exposure levels in relation to occupational and non-occupational settings.

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