Exposure of construction workers to hazardous emissions in highway rehabilitation projects measured with low-cost sensors

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Highlights

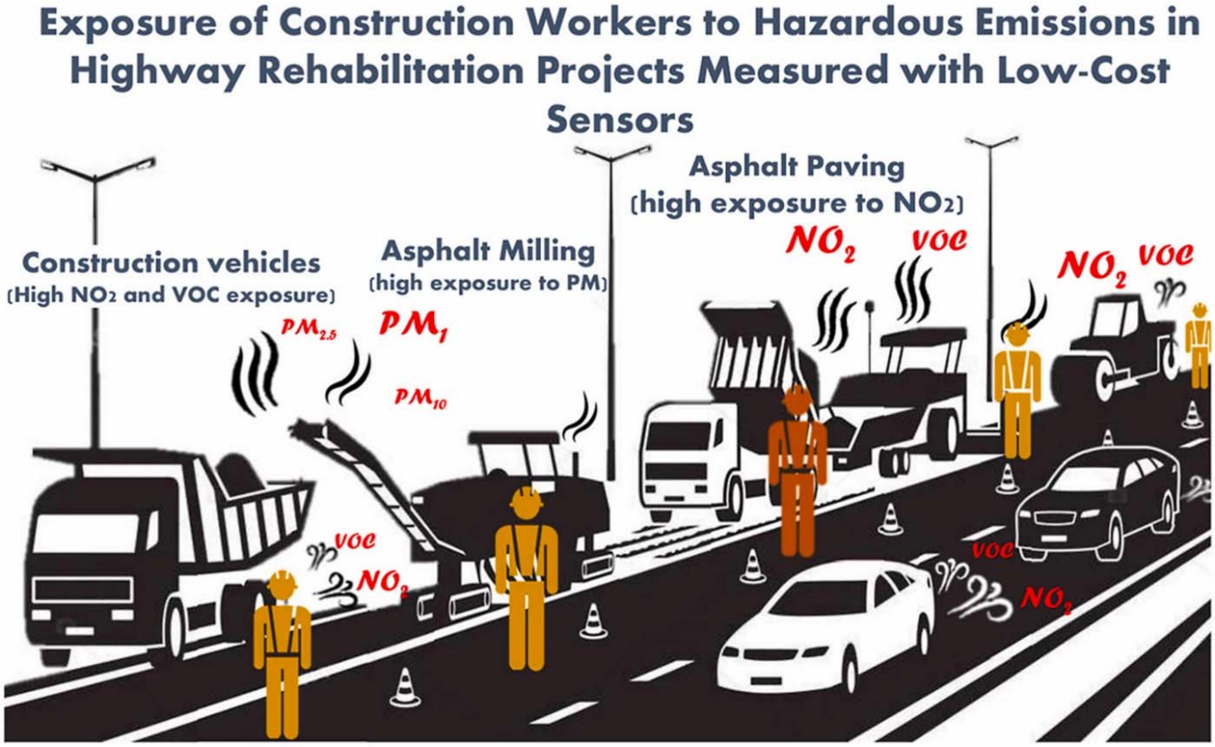
- Using an advanced AQD demonstrates road construction produces hazardous emissions.
- Proximity to source of emissions is the leading factor affecting exposure.
- Asphalt paving workers are at highest risk of hazardous emission exposure.
- Fine dust from hardened asphalt milling may significantly affect worker health.
- Male construction workers are more susceptible to hazardous emission inhalation.

Abstract

Construction workers on highway rehabilitation projects can be exposed to a combination of traffic- and construction-related emissions. To assess the personal exposure a worker experiences, a portable battery-operated Air Quality Device (AQD) was utilised to measure emissions during normal construction operations of a major road rehabilitation project. Emissions measured were nitrogen dioxide (NO_2), Total Volatile Organic Compounds (TVOCs) and Particulate Matter (PM_{10}, $PM_{2.5}$, and PM_1). The objective of the paper is to document the hazardous emissions that construction workers may be exposed to and allow for a basis of informed decision making to mitigate the risks of a road construction project. Most critically, this article is designed to raise awareness of the potential impact to a worker's wellbeing as well as highlight the need for further research. Through statistical analysis, asphalt paving was identified as the most hazardous activity in terms of exposure relative to other activities. This activity was further assessed using discrete-time Markov chain Monte Carlo simulations with results indicating a high probability that workers may be exposed to greater hazardous emission concentrations than measured. Limiting the distance to the source of emissions, large-scale use of warm-mix asphalt and reducing the idling times of construction vehicles were identified as practical mitigation measures to reduce exposure and aid in achieving zero-harm objectives. Finally, it is found that males are more susceptible to long-term implications of hazardous

emission inhalation and should be more aware if the scenarios they might work in expose them to this.

Graphical abstract



Keywords: Air quality; Highway rehabilitation; Worker exposure; Hazardous emissions; Markov chain Monte Carlo

1. Introduction

Air pollution is a known factor affecting the health and safety of societies globally. As humanity expands and cities densify, pollutant concentrations increase and the impact of air pollution on human health becomes increasingly prominent (Birnbaum et al., 2020). The World Health Organization estimates air pollution causes millions of deaths every year (WHO, 2021) with syndromes including heart disease, strokes, various cancers and chronic respiratory diseases. Common sources of air pollution include construction, transportation, industrial facilities, wildfires, and agriculture (Shrestha et al., 2019; WHO, 2021).

Within the construction sector, pollutants often take the form of dust, construction vehicle emissions and emissions from construction products (such as paints, solvents, cleansers and disinfectants, stored fuels and other petroleum based products, etc.) (Wieser et al., 2021). Highway rehabilitation projects which typically accommodate live traffic on adjacent open lanes have additional sources of pollutants by way of vehicle emissions which linger in the air space and create high-concentration corridors along the adjacent work zones (Farrukh and Khreis, 2021). These additional emissions are expected to increase the exposure on highway projects above what is typically found on conventional construction sites. It is reasonable to assume that construction workers are aware of the pollution they are exposed to but few studies have quantified this exposure (Faber et al., 2015). The British Safety Council has recently commented on the lack of research related to construction worker exposure to hazardous emissions and called for "air pollution to be recognised as an occupational health hazard" (BSC, 2020), emphasising the need to further assess the type of pollution workers are exposed to.

From a construction worker's perspective, the main pollutants of major concern are Particulate Matter (PM_{10}, $PM_{2.5}$, and PM_1), nitrogen dioxide (NO_2) (Dominici et al., 2014; Greater London Authority, 2014; ICE, 2017; BSC, 2020; WHO, 2021) and Total Volatile Organic Compounds (TVOC) (Public Health England, 2019). On a highway rehabilitation project the origin of pollutants can be categorised as illustrated in Table 1. Note this list is not exhaustive.

Table 1. Expected main sources of pollution on a typical highway rehabilitation site.

Construction Activity	**Origin of pollutant**	**Composition**
None - Background	• Passing vehicular traffic including petrol and diesel engines. • Industrial pollution from neighbouring industry may be present.	• PM, NO_2, TVOC from combustion engines. • PM, NO_2, TVOC from industrial pollution.
Paving Operations	• Construction vehicles (diesel and petrol engines). • Asphalt fumes, bitumen additives that may or may not be present.	• PM, NO_2, TVOC from combustion engines. • TVOC, PM from bitumen.
Planing or milling	• Planing or milling machine and construction vehicles (diesel and petrol engines). • Dust emitted from the asphalt (aggregate and bitumen, may contain bitumen additives).	• PM, NO_2, TVOC from combustion engines. • PM from bitumen, tar or aggregate.
Road marking	• Fumes from heated solvent bourne paints.	• TVOC from solvent bourne paints.
Earthworks and lower layer construction (soils and aggregate)	• Construction Vehicles (diesel and petrol engines). • Dust from earthworks, excavation, soil stripping, earthmoving and landscaping operations.	• PM, NO_2, TVOC from combustion engines. • PM from earthwork operations.

PM is made of solid particles and liquid droplets in the air and is reported in a variety of PM_X sizes, measured in microns (i.e. $PM_{2.5}$ refers to tiny particles or droplets in the air that are two and one half microns or less in diameter). NO_2 is a highly reactive gas generated in high temperature combustion engines (petrol and diesel). TVOC is a catch all for organic compounds found as vapour or a gas in the atmosphere. Not all organic compounds are considered hazardous to humans (DEFRA, 2020). Historically, Workplace Exposure Limits (WELs) for TVOCs were set at 300 µg/m3 averaged over 8 h (ECA, 1992) but have since been omitted as TVOCs reveal little regarding the nature of the individual compounds, their concentrations and possible toxicity to humans (Public Health England, 2019). A plethora of research is available on TVOC composition of asphalt fumes and diesel/petrol engines (Kitto et al., 1997; Boczkaj et al., 2014; Chin et al., 2012; Chong et al., 2014; Cui et al., 2020; Khare et al., 2020; Wang et al., 2020; Xiu et al., 2020; Jiang et al., 2021; Li et al., 2021) indicating that a mixture of alkanes, aldehydes and polycyclic aromatic hydrocarbons, among many other compounds, are commonly found. It is noted these compounds differ depending on the type of petroleum mixtures combusted, the type of asphalt manufactured, the additives utilised in the mixtures, and laying temperatures of asphalt, among others. A common shortcoming highlighted in many studies is a lack of standardisation of air quality methodology and reporting (Deygout and Southern, 2012).

The toxicity of pollutants depends on the nature of the pollutant as well as the level of concentration and length of exposure. Inhalation of PM, NO_2 and TVOCs are known to contribute to increased risk of several syndromes, including autism, anxiety, asthma, cancer, chronic obstructive pulmonary disease, central nervous system injuries, hypertension, stroke and more (Thompson, 2018). Fortunately, the physical characteristics of PM allow researchers to compute the health effects of inhaling them as demonstrated by Nyhan et al. (2014) who linked PM inhalation dose to heart rate variability and Yin et al. (2017) correlating high blood pressure to $PM_{2.5}$ inhalation. Chen and Hoek (2020) found that the combined risk ratio for $PM_{2.5}$ and natural-cause mortality was 1.08 per 10 $\mu g/m^3$ with Hu et al. (2022) linking ratios of 1.05 (for total respiratory diseases), 1.25 (for asthma) and 1.07 (for pneumonia) to PM_1 per 10 $\mu g/m^3$. Huangfu and Atkinson (2020) identified positive associations between NO_2 and mortality with a risk ratio of 1.02 per 10 $\mu g/m^3$. Chen et al. (2007) found that high concentrations of NO_2 may even affect the T-cell function responsible for our immune response. TVOCs such as BTEX compounds (benzene, toluene, ethylbenzene, and o,m,p-xylene) commonly found in diesel exhaust emissions stimulate the respiratory system and cause central nerve injuries (Dutta et al., 2009; Durmusoglu et al., 2010). Noteworthy, Chin et al. (2012) found gaseous and particulate emissions generated by diesel engines increase from a maximum of 200 mg/h under normal working conditions to 700 mg/h when idling, highlighting the need to reduce unnecessary idling times of construction vehicles.

The clear risk of work environments with high PM, NO_2 and TVOC concentrations is not only related to a worker's health and safety but also further places a high burden on the health care system and broader economy due to costs associated with days off work and potential job loss (Birnbaum et al., 2020).

The primary objectives of this study are to investigate the exposure of construction workers to hazardous pollution during road rehabilitation projects; identify trends and hotspots across construction sites for various sources of pollution; statistically analyse air quality data, and assess and delineate mitigation measures which may assist crews in reducing their exposure during construction. It is acknowledged that this study collects data from a single scheme but the findings are intended to initiate conversation and discussion to further improve working conditions if that is then deemed necessary.

In this study we present an investigation that lasted five months to document the exposure of construction workers to pollution during a major road rehabilitation scheme. Trends and hotspots are identified and air quality data are statistically analysed. The work in this article brings the following contributions: (i) presents a successful real-world deployment of low-cost portable air quality sensors in highway rehabilitation projects; (ii) presents new advanced statistical modelling techniques for air quality data analyses (i.e. Markov chain Monte Carlo simulations), and (iii) provides valuable findings and insights into the air pollutants construction workers are exposed to and ways to mitigate it. Most critically, this article is designed to raise awareness of the potential impact to worker's wellbeing as well as highlight the need for further research. The remaining article is organised as follows. Section 2 presents a critical review of existing air quality assessment literature. Section 3 presents an overview of the methodology, materials and analysis techniques applied in this study. Section 4 presents and discusses the experimental results of our campaign. Section 5 details practical mitigation measures which may easily be implemented during every-day construction activities and Section 6 concludes the article with final remarks.

2. Critical review of existing literature

The recent global discourse surrounding sustainability has contributed to a wealth of research focused on analysing and quantifying various emissions across all sectors with the transportation and construction industries being no exception (Rasdorf et al., 2015; Blaauw et al., 2022; Blaauw and Maina, 2021). This research has however focused largely on environmental emissions (greenhouse gasses) (Santero et al., 2011; Gulotta et al., 2019) rather than relevant socially-oriented pollutants (Bressi et al., 2018) such as PM, NO_2, and TVOCs (WHO, 2021).

Where social emissions have been studied within the construction sector, the focus has largely been on the impacts of nearby construction on indoor air quality (Kirk et al., 2018; Konstantinou et al., 2022; Sá et al., 2022) rather than the more evident need to investigate the hazardous emissions to which workers of those construction sites are exposed.

Construction activities are known to be dynamic sources of pollution producing both environmental and social related emissions (Blaauw et al., 2021). Faber et al. (2015) researched the mean concentration increases of various particulate and gaseous pollutants from typical highway construction activities and found that highway construction often exceeds the World Health Organization's 24-h Air Quality Guidance (AQG) levels. It is noted the 24-h AQG levels may not necessarily be relevant to these types of studies and local WELs may provide more applicable thresholds for comparison. When researching the respirable crystalline silica exposure during asphalt pavement milling, Hammond et al. (2016) found personal exposure of workers did not exceed local WELs.

In the past, road construction air quality studies were often limited by the AQDs utilised which were generally too big to be carried around safely on the person and methodologies reverted to collecting breathing zone air samples providing only a snapshot of air quality at sparse times of data collection (McClean et al., 2004; Chong et al., 2014). These approaches did however have the benefit of characterisation of air sample compositions (Boczkaj et al., 2014; Xiu et al., 2020; Li et al., 2021) but were highly limited in their statistical significance due to limited sample sizes, leading to the general omittance of measuring real-time exposure. Portable low-cost AQDs may assist in overcoming this limitation.

Recently, remarkable strides within the sensor technology field have made a wide selection of low-cost AQDs easily obtainable on the consumer market and have stimulated the scientific community to apply them as tools in human exposure assessments. Their extensive employment in both indoor and outdoor air quality studies with high confidence levels (Tryner et al., 2021; Connolly et al., 2022; Kang et al., 2022; Kortoçi et al., 2022) has also encouraged both debate about their limitations and potentials as well as benefitted in a methodological standardisation of sorts for air quality studies.

Key strengths compared to standard/reference instruments are a) low cost (up to three orders of magnitude lower than their high-end counterparts), b) user-friendly interfaces to allow the general public to easily interact with and interpret data, c) low maintenance requirements, d) small size, portability and ease of handling, and e) high spatial and temporal resolution allowing for real-time data collection (Morawska et al., 2018; Bulot et al., 2020; Chojer et al., 2020; Xiu et al., 2020; Kortoçi et al., 2022).

From a methodological point of view, a clear four step trend is identified across studies, namely:

1. Development of a study protocol (environmental setting, how data will be captured, selection of key pollutants to be measured, etc.).
2. Selection of a low-cost AQD (AQD ability to measure key pollutants, portability, weight, weatherability, battery life, ease of use, etc.);
3. AQD quality assurance (most commonly through correlation to nearby high-end air quality monitoring station as reference instrument), and
4. Data analysis (variety of statistical methods applied with boxplots and regression the most common methods found in literature, determination of background exposure as a contributor to pollution levels).

It is further found that the most commonly measured pollutants among low-cost AQD studies are PM and NO_2 (Kang et al., 2022). The critical omissions from this methodology are the general lack of application of advanced statistical modelling techniques (such as machine learning and Markov chain Monte Carlo simulations) to provide new insights and reduce error, establish predictive relationships among pollutants, and the direct calculation of health impacts from exposure.

Other than previous research examining the impacts of highway construction on local air quality (Font et al., 2014; Faber et al., 2015; Sun et al., 2021) and identifying asphalt paving as the construction activity producing the most pollution (McClean et al., 2004; Chong et al., 2014), little has been done in measuring the exposure of construction workers to pollutants during real projects with no studies having yet measured PM_1 across a highway construction site. PM_1 is often omitted due to the inability of most AQDs to measure it. Additionally, there is a lack of information related to the impacts the proximity to the asphalt paver has on worker exposure and how to mitigate these impacts. This paper contributes toward filling these gaps through unifying emission composition inventories with real-time exposure risk on site.

3. Methods and materials

3.1. Study protocol

The study area consisted of a typical major highway rehabilitation project. Due to sensitivity of results, location specifics have been retained. To obtain the temporal and spatial variations of personal pollution exposure on-site, the normal site activities were categorised into five main groups: 1) site office, 2) site vehicle, 3) general site inspections, 4) asphalt planing, and 5) asphalt laying. A total of 85 h of data was collected for all site categories, normalised to an average of 8 h per activity for correlation to WELs. A sixth group was included in this study (i.e. reference), representing the background air quality of a local city for comparison. The reference results were collected for both quality assurance (comparison to reference monitoring station) and for correlation against site collected data. Data collection occurred both during day and night shifts during colder winter months.

3.2. Instrumentation

The AQD was attached to the data collection participant's chest to collect air quality samples from a representative breathing zone of the worker. The participants were quality inspectors and the job role required them to be physically involved in each construction activity. Due to the light weight of the AQD, a prerequisite for the study, the AQD posed no additional risk to the worker during normal construction activities. Air quality data logging intervals were set to 1 s and 1 min, respectively. The AQD was calibrated for 15 min before each session of measurement as recommended (Khreis et al., 2022). The AQD utilised a laser particle counter and photovoltaic cell to measure fine particles (i.e. PM) and a separate metal oxide membrane for NO_2 detection heated to 350 °C. Air intake was controlled by a fan spinning at 15,000 RPM for consistency at a nominal air-flow rate of 9.2 L per minute (L/min). The AQDs are known to be affected by relative humidity and all results obtained for this study were limited to clement weather with relative humidity below 50%. Relative humidity was measured using the on-site weather monitoring station. To support inhalation dose analyses, the participants in this study wore smart watches to measure breath frequency and heart rate during normal construction activities.

3.3. Quality assurance

A quality assurance test was conducted to determine the correlation between the AQD and a local high-end government-operated air quality monitoring station positioned in a local city. For the assessment, air quality measurements of a local city were collected for 48 h and compared to the local monitoring station data on the same period and location. Results showed a variance of 4% for NO_2 and 11% for $PM_{2.5}$, illustrated in Fig. 1. The local air quality station did not provide measurements for PM_{10}, PM_1 or TVOC and no correlations were conducted for these pollutants. The similarity in measurements indicates that the NO_2 and PM measurements via our low-cost AQD are reliable.

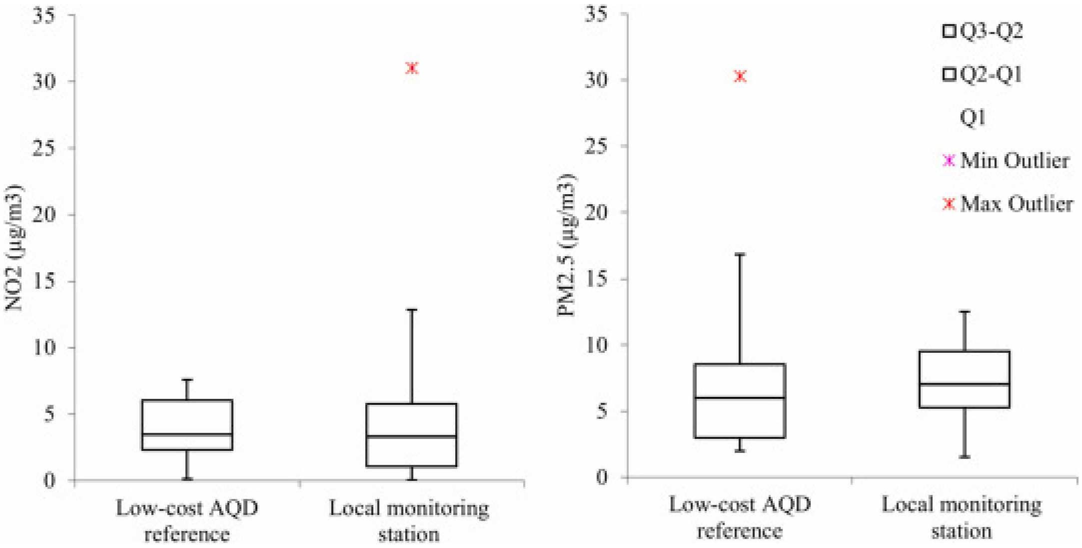


Fig. 1. Outdoor NO_2 (left) and $PM_{2.5}$ (right) shown as boxplots with corresponding median for both low-cost AQD and the local monitoring station.

3.4. Data analyses

The first step of data analysis involved exporting the various data sets from the AQD and inspecting the real-time data of each sampling session as part of data pre-processing. All data captured during periods of relative humidity exceeding 50% were deleted together with missing data. Timeseries and boxplot graphs were then used to check and clear any obvious outliers (problematic and representing measurement errors). Note, true outliers representing natural variations in the population were retained. To investigate the effects of different construction activities (i.e. on site, in the site vehicle, and in the site office) the mean exposure concentrations for each emission were calculated for the 8 h analysis period and compared to the reference results for trend identification. A variance analysis was performed to identify differences in emission concentrations between the typical site activities. Regression and machine learning techniques were employed to determine the relationship among emissions. The mean exposure concentrations (C_{avg}) of each site activity were calculated by averaging the sampled data in the time sequence during the analysis period. This data allowed for additional investigations of health considerations such as the inhalation dose of a typical construction worker for each site activity.

3.5. Development of discrete-time Markov chain Monte Carlo model

Markov chain Monte Carlo (MCMC) simulations are a statistical method used in probability analyses to obtain information about distributions, used especially for posteriori distributions in Bayesian inference (van Ravenzwaaij et al., 2018; Blaauw et al., 2022). A great strength of MCMCs is that they can draw data from a distribution where, for example, the only thing known about the distribution is its density. This is particularly useful in concepts that are difficult to quantify such as dynamic air quality assessments (Dominici et al., 2002; Oettl et al., 2003; Chen and Wu, 2020; Alyousifi et al., 2021; Liu et al., 2022).

An MCMC model was developed for application in this study. The MCMC model has been calibrated to 'ideal' air quality data and is inherently biased towards good air quality inputs. The model utilises a hybrid bottom-up/top-down strategy to incorporate the temporal and spatial dependence of the risk of exposure, both within and outside of high exposure zones (discussed in later sections) for the duration of exposure to the source of emissions. This allows the model to circumvent the common short-coming related to air quality predictions that rely on fixed-point monitoring.

The model was developed to be a comparative model, requiring a minimum of two data sets (i.e. low- and high-exposure zones). As the model is inherently biased towards 'ideal' air quality, its ability to conform to data sets will reflect the nature of the data (i.e. good or bad air quality), most notably in the ability of simulations to converge. Convergence occurs when the generated Markov chain distribution converges to the posteriori distribution being modelled and is assessed based on the ability of the distribution to reach stationarity. Convergence is also used to determine the accuracy of the probability predictions. A shrink factor is used to monitor whether the simulations have converged to equilibrium. If equilibrium is achieved, the shrink factor will be one. MCMC algorithms were obtained from Kruschke (2015).

3.6. Inhalation dose

According to the Exposure Factors Handbook of the US Environmental Protection Agency, exposure assessment is a comprehensive evaluation of the characteristics of specific pollutant exposure (e.g., exposure concentrations, duration, and frequency) and the characteristics of specific exposure objects (e.g., age and sex) (EPA, 2011). This exposure, or inhalation dose (*D*), may be quantified using Equation (1) (Cepeda et al., 2017):

$$D = C_{avg} \times IR_{(\Delta t)} \times \Delta t \tag{1}$$

where *D* is the mean inhalation dose for each site activity (μg); C_{avg} is the mean exposure concentration for each site activity (μg/m^3), and $IR_{(\Delta t)}$ is the inhalation rate per site activity for its average duration in minutes (Δt) measured in cubic metres per minute (m^3/min). To calculate the mean exposure concentration (C_{avg}), Equation (2) is utilised:

$$C_{avg} = \frac{\int_{t1}^{t2} C(t) \times dt}{t_2 - t_1} \qquad \text{(Eq. 2)}$$

where t_2 and t_1 are the start and finish times of each activity (min) and $C(t)$ is the measured concentration at the moment *t* (μg/m^3). The inhalation rate ($IR_{(\Delta t)}$) is the most difficult parameter to estimate (Dons et al., 2017) in worker exposure epidemiological studies. The inhalation rate in this study is calculated using Equation (3):

$$IR_{(\Delta t)} = e^{-8.57} \times {HR_{(\Delta t)}}^{1.72} \times {f_{b(\Delta t)}}^{0.611} \times age^{0.298} \times sex^{-0.206} \times {FVC_{(\Delta t)}}^{0.614} \qquad \text{(Eq. 3)}$$

Where $HR_{(\Delta t)}$) is the heart rate as the mean beat at the start and finish times of each activity (bpm); $f_{b(\Delta t)}$ is the breath frequency as the breaths per minute during each activity; $FVC_{(\Delta t)}$ is the forced vital capacity (litres); *age* is the age of the construction worker (20–60 years used for this study), and *sex* of the construction worker (value of 1 for males and 2 for females).

4. Results and discussion

4.1. Mean exposure concentrations

Mean exposure concentrations (C_{avg}) of all site activities were calculated using Equation (2), presented in Fig. 2. Results show that the site activities may generally be ranked (in order of risk) as follows: asphalt laying (paving) > asphalt planing (milling) > general inspections > site vehicle > site office.

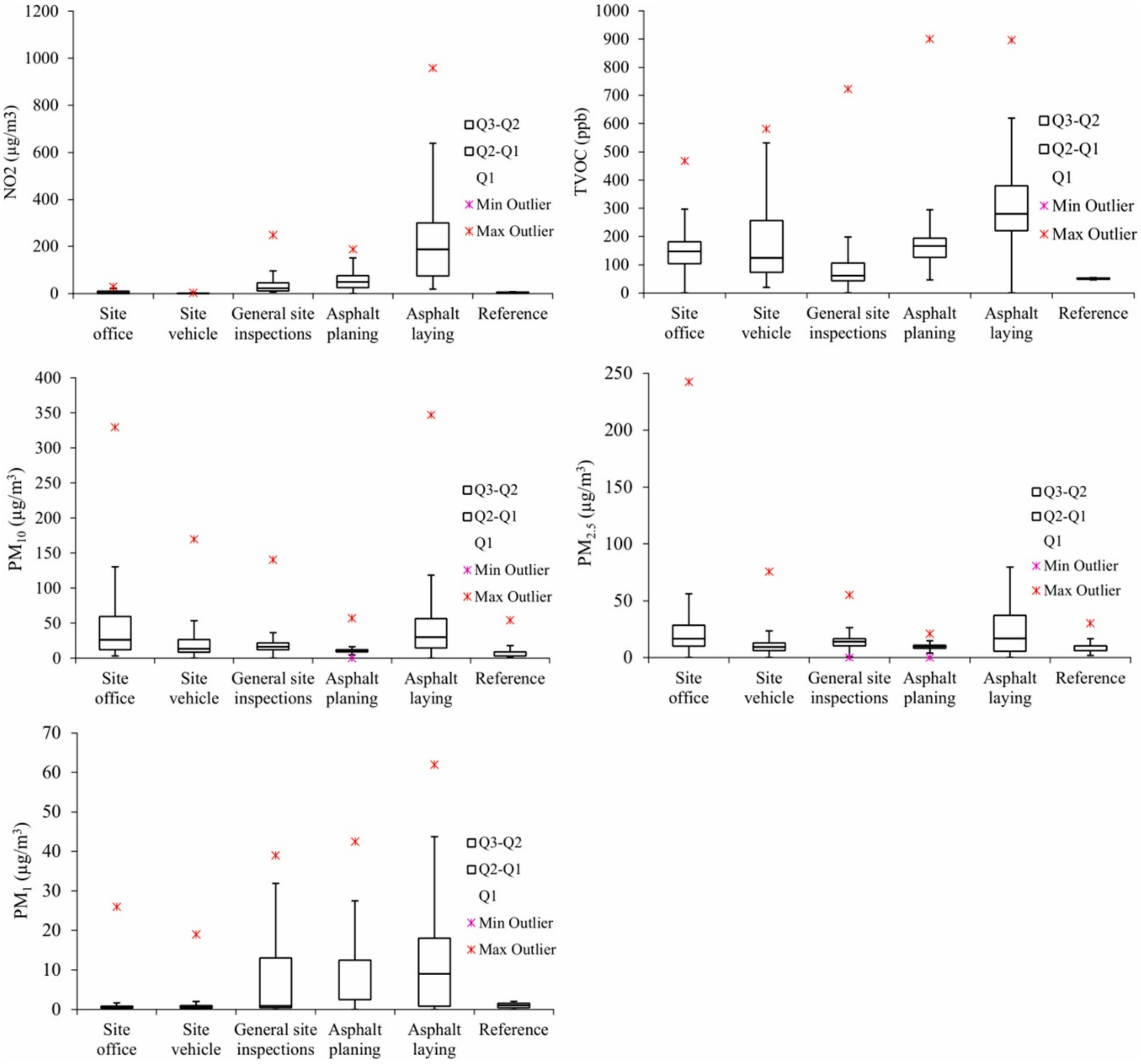


Fig. 2. Mean spatial emission concentrations – NO_2 (top left), TVOC (top right), PM_{10} (middle left), $PM_{2.5}$ (middle right), PM_1 (bottom left).

From the various data it is seen that even though certain site activities have exposure concentrations significantly higher than background reference levels, with the asphalt paving having an NO_2 increase of 4000% in comparison, the mean concentrations of all activities are still below the local WELs (960 $\mu g/m_3$ for NO_2 and 4000 $\mu g/m^3$ for PM).

For asphalt laying, it is believed that the proximity to the source of emissions is the leading contributor to this exposure and is investigated further in subsequent sections. For asphalt planing it is seen that the heavier dust particles (PM_{10} and $PM_{2.5}$) typically do not enter the air as this dust is easily suppressed by water and suction control measures applied on site. An increased concentration of finer dust particles (PM_1) is observed, due to the inability of suppression measures to capture these fine particles (USDHHS, 2009) which in turn enter the wider air zones. It is known that milled asphalt dust contains respirable crystalline silica in concentrations between 5 and 23% (Hammond et al., 2016) with clear health effects. However, the impact of dust containing possible carcinogenic material from hardened bitumen and tar milling is not well documented and currently do not have any WELs. As many roads still contain high levels of historic tar bound material in lower layers, it is concerning that workers may be exposed to this material and this risk should not be ignored.

An additional analysis was conducted to investigate how the average hourly emissions change during a typical construction shift, as shown in Fig. 3. It is noted that emission concentrations are influenced most by the construction activity and that the average hourly emission concentrations are similar to the average 8-h concentrations indicating little variance in risk of exposure regardless of the time spent in the hazardous zone.

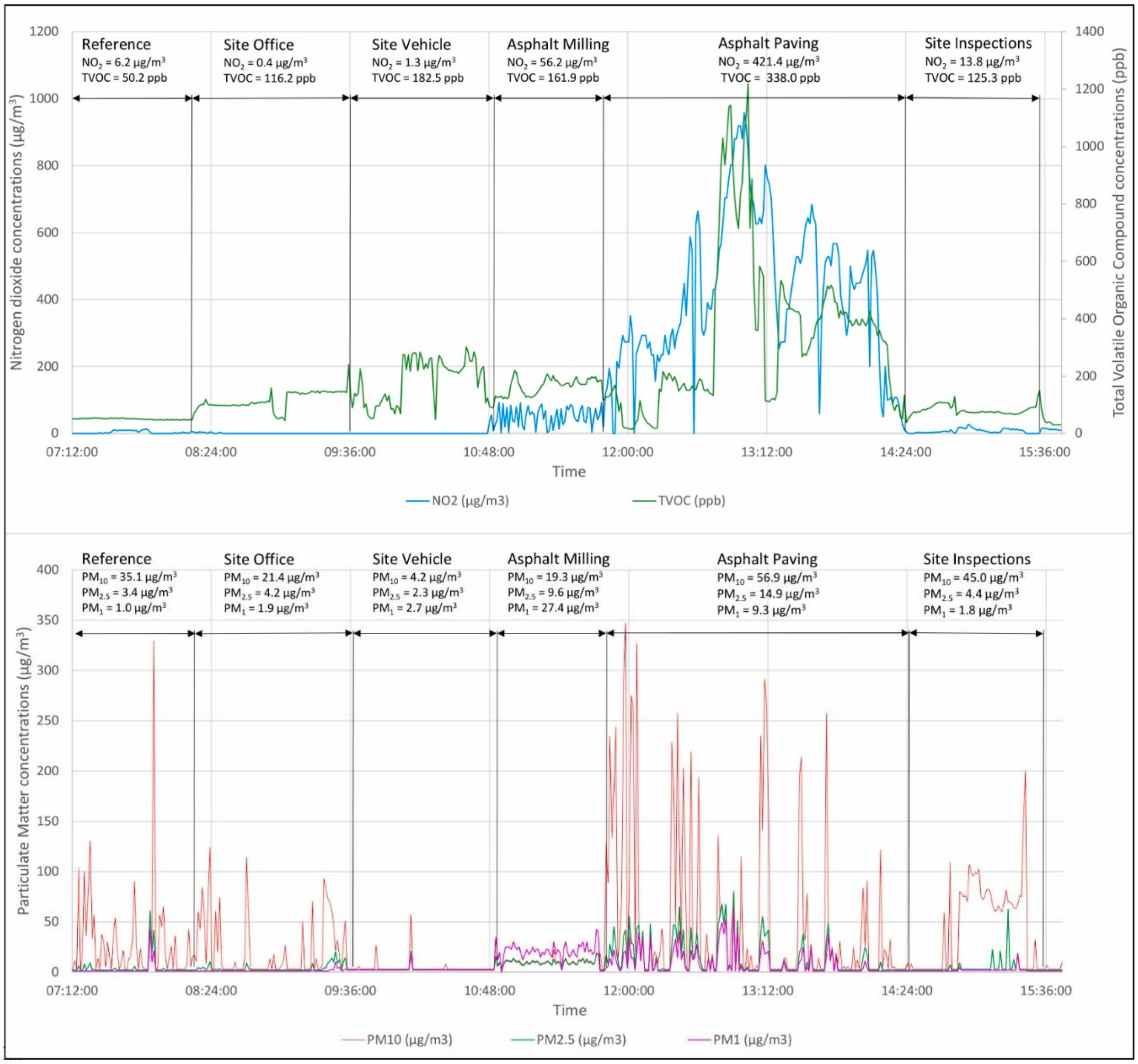


Fig. 3. Typical construction shift with average hourly pollution concentrations.

4.2. Impact of proximity to a source of emissions

To investigate the impact proximity to the source of hazardous emissions has on the exposure of a typical construction worker, only asphalt laying (paving) and asphalt planing (milling) were investigated. A work zone vicinity of 6 m was applied (which correlates well to the exclusion zones of most pavers) to this assessment and data was obtained within and outside of this 6 m zone for both asphalt planing and asphalt laying activities.

For asphalt planing, results showed no observable difference between exposure regardless of how close a worker is to the source of emissions. This is due to the exhaust system of the planer located at a higher level than other construction vehicles. Asphalt planers are also fitted with dust suppression systems such as extraction/filtration and water suppression which capture the majority of heavier dust particles. However, it is found that fine dust (PM_1) typically escapes this containment and can rapidly contaminate the surrounding areas (USDHHS, 2009) as illustrated in supplementary Figure S-1. Fine dust particles are more likely to penetrate deeper into a worker's airways (Zhang et al., 2019) and even though the PM_1 data reflects generally low risk in terms of WELs, certain hazards, such as carcinogenic material, may not have been investigated in detail.

For asphalt laying, results show statistically significant differences dependent on proximity to the source of emissions with the 6 m vicinity verified as relevant, shown in Fig. 4 for NO_2 and TVOC. It is suspected that the combination of exhaust emissions generated by the asphalt paver and fumes emitted from the heated asphalt being laid, linger within this 6 m vicinity before rising due to the high temperatures of asphalt laid (between 160 and 180 °C for this study), creating a super concentrated channel of potentially hazardous emissions as illustrated in supplementary Figure S-2.

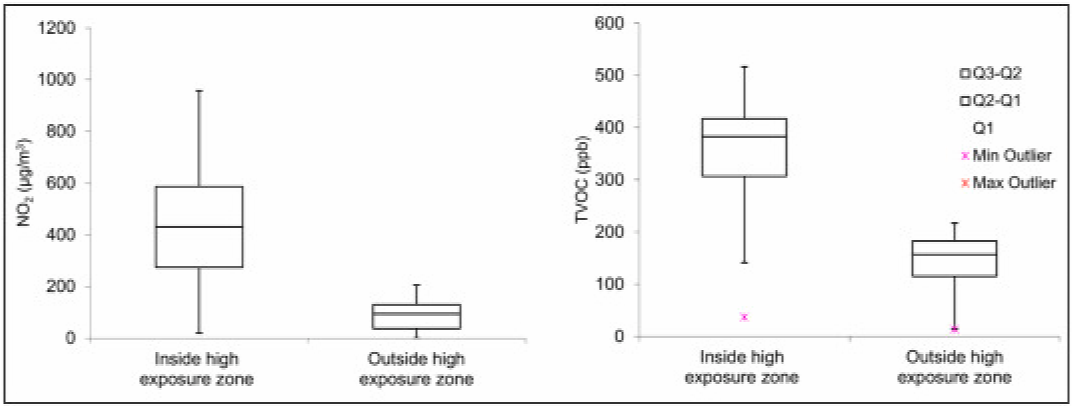


Fig. 4. NO_2 correlations within and outside of high exposure zones during typical asphalt laying (paving) operations.

4.3. Discrete-time Markov chain Monte Carlo simulation

As asphalt paving is a dynamic process with the high exposure zone constantly moving and the fumes generated appear to be influenced by the speed of the paving, temperature of asphalt being laid and surrounding air conditions, it is not possible to measure the entire exposure zone and rather snapshots in time of specific measuring points (similar to many air quality monitoring stations in a small zone) are obtained through data collection. To get a better sense of the concentration of emissions within these exposure zones, a discrete-time Markov chain Monte Carlo simulation was applied to the NO_2 and TVOC data.

The objective of the MCMC simulations is to investigate the dynamic nature of hazardous exposure within the exposure zones which are assessed through both the probability distribution of the simulation results as well as the ability of the model to conform to the data (i.e. convergence). This approach follows conventional methods of predicting air quality of major cities based on fixed point air quality monitoring stations. Simulation results are shown in Fig. 5 for NO_2 exposure. Simulation results for TVOC showed low exposure regardless of exposure zone and these results are provided in supplementary Figure S-3.

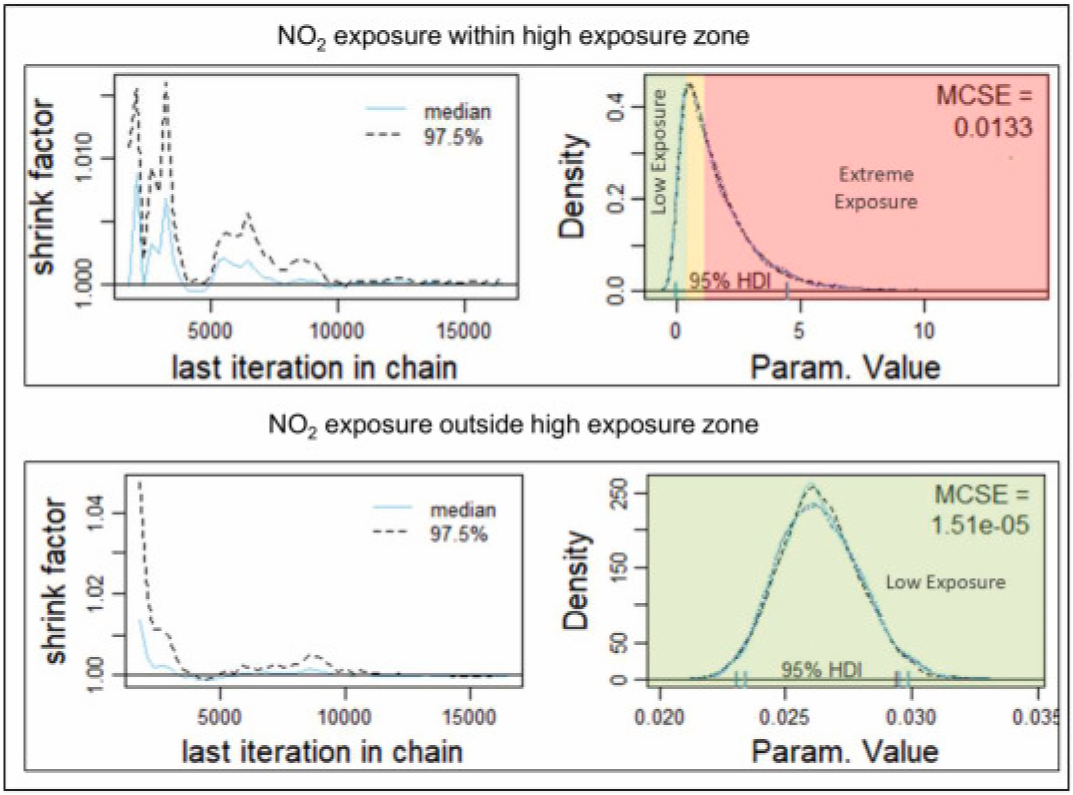


Fig. 5. NO_2 exposure within (top) and outside (bottom) high exposure zones – Convergence (left) and probability of exposure (right). Parameter values in mg/m.^{3}.

When assessing the NO_2 results of Fig. 5, a significant difference is observed in predictions. Within the high exposure zone, the model predicts a skewed distribution of high probability a worker may be exposed to emissions substantially above that of the local WELs with poor convergence observed. This risk of exposure appears to drastically decreases as the worker moves outside the high exposure zone with good convergence of the model observed. The inability of the model to conform to the dataset shown within the high exposure zone validates the bad air quality of the data. These results suggest further research is essential to understand the impacts to construction workers who are required to be within these exposure zones.

4.4. Inhalation dose

An additional assessment was conducted in this study related to the inhalation dose of a typical crew member for each site activity. Data were obtained from the main data collection participant, who is a fit and healthy 30-year-old male. The participant had an average heart rate ($HT_{(\Delta t)}$) of 56, breath frequency per minute ($f_{b(\Delta t)}$) of 15, Forced Vital Capacity ($FVC_{(\Delta t)}$) of 5, age of 30 and was male (*sex* = 1). These particulars were applied to Equations (1)–(3) together with the mean emission concentrations previously calculated to determine the inhalation doses for a typical 8-h exposure period per site activity, summarised in Table 2.

Table 2. Inhalation doses for typical 8-h exposure period for 30-year-old male (participant).

Pollutant	Unit	Site Office	Asphalt Paving	Asphalt Milling	Site Vehicle	Site Inspections
NO_2	µg	7.6	811.5	197.2	16.7	48.4
VOC	ppb	506.8	1109.5	700.4	637.4	307.3
PM_{10}	µg	74.4	94.4	24.0	14.7	157.9
$PM_{2.5}$	µg	13.5	27.9	18.5	8.1	26.5
PM_1	µg	6.7	18.0	96.2	9.8	6.3

From Table 2 it is seen that, similar to previous results, asphalt paving and milling remain the highest exposure activities with the greatest risk of inhaling hazardous emissions. Results indicate that, compared to reference background air quality, asphalt pavers may have an increased natural-cause mortality risk of 80% due to NO_2 inhalation (Huangfu and Atkinson, 2020), 8% due to $PM_{2.5}$ inhalation (Chen and Hoek, 2020). Regarding PM_1 inhalation, it is found that asphalt millers may have a 5% increased risk of total respiratory diseases, 25% increased risk of developing asthma and a 7% increased risk of contracting pneumonia (Hu et al., 2022). These results are influenced by the findings of other studies and may be an overestimation of the impact on workers for this study. Further research is required to verify epidemiological consequences of construction workers in similar environments.

To determine the risk factor of different construction workers (dependent on age and sex) a secondary assessment was conducted with relevant results shown in Table 3. For this assessment, typical heart rate, breath frequency per minute, and FVC estimates for both male and female workers of different age groups were obtained from the US Department of Health and Human Services (USDHHS, 2011) for heart rate, Royal College of Physicians (RCP, 2017) for breath frequency, and Quanjer et al. (2012) for FVC.

Table 3. Increased risk of exposure due to age and sex.

Worker Description	Risk Factor
Female (20 years old)	0.67
Male (20 years old)	0.83
Study participant (30 year old male) - Baseline	1.00
Female (60 years old)	1.23
Male (60 years old)	1.63

A noticeable observation from Table 3 is that males are more susceptible to long-term implications of hazardous emission inhalation and further research is required in this area to better understand the underlying reasons.

5. Policy implications

The results in this paper suggest that construction workers are exposed to high concentrations of hazardous emissions on highway rehabilitation sites. Asphalt paving has been identified as a more hazardous construction activity compared to other site activities with the high exposure zone surrounding the paver having a high probability of exceeding WELs in terms of NO_2 emissions. Various controls have been identified in this study to reduce exposure according to the hierarchy of controls, namely:

1. Substitute: replace the hazard through use of a less hazardous paving material in terms of fume generation during construction of the layer (i.e. warm-mix asphalt);
2. Engineering Controls: isolate people from the hazard through strict adherence to exposure zones;
3. Administrative Controls: change the way people work by providing additional training and informing workers of the risks they are exposed to, reduce idling times of construction vehicles on site, and
4. Personal Protective Equipment: consider the use of PPE to mitigate the residual and unavoidable risks to be as low as reasonably practicable (i.e. additional respiratory equipment).

6. Conclusions

In this paper, a dynamic approach to air quality monitoring and prediction of exposure to hazardous emissions of construction workers on a major road rehabilitation project is presented. MCMC techniques were applied to datasets allowing for temporal and spatial modelling of risks across a typical construction site. The results in this paper suggest that construction workers are exposed to high concentrations of hazardous emissions on highway rehabilitation sites and additional research is essential to further understand the impact on workers and if there is a need to protect them.

A key objective of this paper is to use the risk of exposure to hazardous emissions and develop a social-impact assessment of construction gangs on highway rehabilitation sites. Most critically, this article is designed to raise awareness of the potential impact to worker's wellbeing as well as highlight the need for further research. The complex distribution of the concentrations of hazardous emissions and the dynamic nature of construction sites makes data collection and analysis difficult and often result in over-simplification of assessments. This is compounded by a lack of conformity with regards to methodology and reporting the pollutants found on a construction site. Further research is required towards standardisation of methodologies (Deygout and Southern, 2012) and the identification of individual components in PM and TVOC emissions.

This paper contributes to a better understanding of the potential risks associated with personal exposure to hazardous emissions on construction sites. Control and management can aid in limiting these risks. These results add a metric that the industry may apply to govern health and safety matters and make more reliable decisions regarding alternative methods of working and protecting staff.

Author statement

Sheldon Blaauw: Conceptualization, Methodology, Project Administration, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft; James Maina: Supervision, Writing – Review and Editing; Johan O'Connell: Validation, Writing – Review and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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