

# In-cab air filtration in plant vehicles to control exposure to hazardous dust: quarry industry example

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**Tackling occupational lung disease is a priority for HSE. In-cab air filtration systems are installed on plant vehicles used in a wide range of industries where drivers can potentially breathe in hazardous airborne dust, such as farming, waste management and quarrying. Plant vehicles include tractors, diggers, dumper trucks, excavators and mechanical shovels. However, little is known about the effectiveness of in-cab air filtration as a control measure. This report describes research to develop this evidence; the research was carried out with the support of the quarry industry as a representative sector.**

**The research looked at the factors that influence the effectiveness of in-cab air filtration systems throughout their operational lifecycle, including system design, in-service use, and maintenance. The research included developing a new scientific method to evaluate filtration system efficiency whilst a vehicle is being driven. The research found: penetration of hazardous dust into vehicle cabs; some vehicle cab filters of low efficiency; and that staff had variable knowledge about the effectiveness of in-cab air filtration and the level of protection it afforded. The research identified practical steps that industry can take to improve protection of workers. Improved understanding of good practice for in-cab air filtration systems is needed by vehicle designers and manufacturers and within the sectors using the vehicles – including the importance of filter maintenance and ensuring that drivers are made aware of the actions they need to take.**

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# **In-cab air filtration in plant vehicles to control exposure to hazardous dust: quarry industry example**

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## KEY MESSAGES

Vehicles such as tractors, diggers, dumper trucks, excavators and mechanical shovels are widely used in many sectors to handle materials. Airborne dust generated from these activities can be a respiratory hazard. However, there is a lack of information on the extent to which these systems provide protection from airborne dust throughout their operational lifespan and on the factors which influence this. This research was undertaken to address this knowledge gap.

- Vehicle cabs can be fitted with higher efficiency filters to improve their exposure reduction capacity and driver protection. These can be supplied and marketed as an alternative by the vehicle manufacturer or can be obtained from third party suppliers to improve performance standards.
- Dutyholders were unable to provide any detail of the filters provided in the vehicles studied in this research project. They tend not to recognise in-cab filtration as a priority topic and thus do not specify the required filtration capability when purchasing filters from suppliers. Suppliers therefore provide filters to performance standards they deem appropriate from the limited overall specification of protection to be afforded that they receive from the end user.
- Cab doors and windows were frequently opened by drivers to aid communication, thereby rendering the filtration system ineffective and increasing the degree of driver exposure to outside contaminants. On this evidence, workers appear not to understand the purpose of the in-cab filtration system and how it is influenced by their behaviour.
- Dust can be carried into the cab on workers' boots and clothing. This can become airborne, contributing to dust levels inside the cab.
- The extent of training provided did not extend to structured training for drivers and maintenance staff in cleaning cab air filters. This is a critical requirement to ensure the effectiveness of in-cab filtration as a control measure.
- To maintain filter performance and effectiveness, dutyholders should schedule filter maintenance according to the work that is undertaken.
- If cab pressurisation is not maintained then dust may enter the cab through poorly-fitting doors or windows. Cab pressure indicators were not installed as a standard feature inside any of the vehicle cabs studied in this research.
- There is evidence to suggest that there are gaps in knowledge of how best to control exposure of vehicle drivers to airborne dust whilst they are in the cab. There is therefore a need to improve control practices throughout the entire life cycle of the vehicle.

## EXECUTIVE SUMMARY

Vehicles such as tractors, diggers, dumper trucks, excavators and mechanical shovels are widely used in many sectors to handle materials. Airborne dust generated from these activities can be a respiratory hazard for workers. Therefore, it is important that workers are protected from exposure using proportionate and practical control measures. Where reliance is placed on in-cab filtration as an exposure control measure, it is important that employers and workers are aware of the performance and potential confounding factors associated with filtration and of their duties under the Control of Substances Hazardous to Health (COSHH) Regulations 2002 (as amended).

The Health and Safety Executive (HSE) currently provides COSHH guidance<sup>1</sup> describing good practice when using control cabins or vehicle cabs with forced filtration. This includes simple measures/checks to ensure effective worker protection.

However, there is little information available in the published literature to indicate:

- the extent of protection which these systems provide when new;
- the extent of protection which these systems continue to provide in practice during their working life, given that their performance may deteriorate with wear and tear;
- the servicing requirements to maintain the above protection, matched to actual challenge; and
- those work-related elements that may confound the above protection.

This project was undertaken to address these knowledge gaps, with the support of the quarry industry to provide examples of the relevant types of plant vehicles. It investigates the lifecycle of in-cab filtration systems, from design and manufacture through to end use, to identify where there are gaps in good practice.

### AIM

The aim of the project was to bring together existing and newly-acquired (through measurement) data on cab contamination, manufacturers' performance standards and employers' expectations, to inform approaches to influencing vehicle drivers and employers about exposure risks and the appropriate use of in-cab filtration as an exposure control measure.

### MAIN FINDINGS

#### Knowledge of Cab Filtration Systems

- Knowledge of quarry staff about the effectiveness of in-cab filtration and the level of protection it afforded was variable. In-cab filtration was not seen consistently as an exposure control measure.
- Having an in-cab filtration system was not the prime concern of quarry managers or supervisors when purchasing a vehicle. They did not specify the filter to any standard and were unable to provide details of the filtration standard for the filters fitted to the vehicles. Although it is not the duty of the supplier to determine the filter performance requirements, it was usually left to them to do so.

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<sup>1</sup> [www.hse.gov.uk/coshh/essentials/index.htm](http://www.hse.gov.uk/coshh/essentials/index.htm)

- Manufacturers' literature on the performance of in-cab air filters was limited.
- Interviews with vehicle manufacturers highlighted that they did not always know the final use of the vehicle and therefore it was difficult to recommend filter upgrades. They tended to retrofit filter elements with high efficiency particulate air (HEPA) filters conforming to the European standard EN 1822. It is unclear whether this is the best approach.
- Manufacturers' information on filter type and filtration efficiency of cab air filters was often incomplete, making it extremely difficult to interpret and compare data. This ambiguity is partly due to manufacturers not adopting one common standard.
- The cab air filters did not carry information on the filtration performance and only displayed the product number information on the filter.
- Information about filter type and performance provided in manufacturers' brochures was sparse.

### **Types of Filter Used**

- Examination of some of the quarry vehicle cab air filters revealed that they had an open structure indicating that they were of low efficiency.
- During interviews with both vehicle and filter manufacturers, and observations made during site visits, it was acknowledged that pre-filters/cleaners were not always fitted to extend the life of the main filter.
- Information on retrofitting/upgrading of the filter element was available from one vehicle manufacturer with some marketing material providing detailed information. The retrofit filter elements tended to be based on HEPA filters conforming to EN 1822.

### **Cab Filtration Measurements**

- On-site measurements showed that the effectiveness of the in-cab air filters was variable. Penetration of particles in the size range 0.5 – 3 µm into vehicle cabs varied between approximately 7 and 42% depending on the vehicle type and manufacturer. This indicated that some vehicles might either be fitted with low efficiency general air conditioning filters and/or dust had entered the cab through unplanned openings.
- One shovel loader had been modified to include a retrofitted in-cab air supply/filter system with the aim of improving worker protection by increasing the filtration efficiency and cab air pressure. This was found to be not as effective as expected with a particle penetration level higher than that found on some standard cabs.

### **Cab Pressurisation**

- The manufacturers design vehicle cabs to operate at a positive pressure with respect to the outside.
- Adequate cab pressurisation was noted as an important feature in protecting workers from exposure to substances hazardous to health, in addition to maintenance of door and window seals.
- Cab pressure indicators were not installed inside vehicle cabs, with the exception of the retrofitted vehicle. A fall in cab pressure can be caused by clogged filters (especially HEPA filters), open doors or windows, filters not being installed correctly or when cab door and/or window seals require changing.

## **Secondary Exposure and Cab Cleanliness**

- Cab doors and windows were frequently opened by drivers to aid communication, thereby rendering the filtration system ineffective and increasing driver exposure to outside contaminants.
- Dust was often brought into the vehicle cab on workers' boots and clothing.
- Cab seat covers were seen to retain dust.
- Dust on the inside of the cab can become airborne caused by the movement of the cab occupants and vibration of the vehicle.
- Although drivers cleaned their cabs, this was inconsistent and often used ineffective methods such as brushing and polishing. The frequency of cleaning varied from daily to weekly.
- Air distribution vents inside vehicle cabs were sometimes located close to the floor to keep the drivers' feet warm. However, this can produce a secondary exposure source as dust settled on the floor is re-dispersed and made airborne by high velocity air exiting the vents.

## **Training**

- Interviews with quarry staff revealed that the knowledge of the effectiveness of in-cab air filtration and the level of protection afforded was variable and it was not consistently seen as an exposure control measure.
- Vehicle manufacturers/suppliers stated that they provided on-site training when new vehicles were purchased. However, it was not clear if leasing companies provided similar training. Limited or no training was provided to drivers regarding the operation of in-cab air filtration systems. Instead, drivers relied heavily on the vehicle handbook to try to understand the filtration system.
- There were widely varying perceptions of drivers, health and safety managers, maintenance mechanics, procurement managers, supervisors and training managers of the benefits of vehicles having positive cab pressure.

## **Maintenance**

- Air filters were maintained by the quarry sites' maintenance staff or external contractors, according to the schedule provided by the manufacturer.
- Vehicle manufacturers recommended that filters should be changed at specified intervals based on 'run hours'.
- Dutyholders did not assess the vehicle service schedule and service hours to assess whether they were adequate or whether they needed to be adjusted.
- Cab door and window seals were observed to be in good condition; an indication that they were well maintained.
- Some drivers and maintenance staff cleaned the cab air filters having learned this from other drivers rather than being properly trained. They often used compressed air to clean the filters, which resulted in a cloud of potentially hazardous dust being generated and possible damage to the filter.
- From the manufacturers' literature, it appeared that some filters could be cleaned but the majority were single-use and cleaning would compromise the filter element.

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# 1. INTRODUCTION

## 1.1 BACKGROUND

Tractors, diggers, dumper trucks, excavators and mechanical shovels are in widespread use in industries such as waste and recycling, quarries, agriculture and construction. They are used to handle materials including mixed waste, stone, grain, animal bedding and feed. Figures 1 - 3 illustrate examples of some of the vehicles that are used within the quarry industry; thereby providing a visual understanding of the vehicles under discussion in this report.



**Figure 1** Example of a dumper truck



**Figure 2** Example of a loading shovel



**Figure 3** Example of an excavator

It is important that workers are protected from exposure to substances hazardous to their health using proportionate and practical control measures. There is evidence that in-cab air filtration systems on materials-handling vehicles and similar equipment provide a degree of protection from any external airborne hazardous agents<sup>1,2</sup>. Therefore, where employers rely on in-cab air filtration as an exposure control measure, it is important as part of their duties under the Control of Substances Hazardous to Health (COSHH) Regulations 2002 (as amended) that they are aware of the performance and potential confounding factors associated with in-cab air filtration. HSE provides guidance documents for some sectors where in-cab air filtration is used. This includes some simple measures/checks to ensure effective worker protection.

Previous HSE research has provided limited information on this topic<sup>3,4</sup>. In one study on compost bioaerosols<sup>3</sup>, workers' potential in-cab exposure was measured as well as the bioaerosol levels outside the vehicle cabs. This allowed for some comparisons to be made and thus the reduction in potential exposure afforded by being inside the cab. However, as this was not the primary focus of the project, it was not rigorously tested. Other work<sup>4</sup> showed that the protection afforded to combine harvester and tractor drivers in cabs could be compromised by poorly-fitted filters and that protection was negated by opening doors and windows, even briefly.

However, there is little information available in the published literature to indicate:

- the extent of protection which these systems provide when new;
- the extent of protection these systems continue to provide in practice during their working life, given that their performance may deteriorate with wear and tear;
- the servicing requirements to maintain the above protection, matched to actual challenge; and
- the human factor elements that may confound the above protection.

This project was undertaken to address these knowledge gaps. It was delivered with the support of the quarry industry to provide examples of the types of plant vehicles where in-cab air filtration is relevant as a control measure.

## **1.2 AIM AND OBJECTIVES**

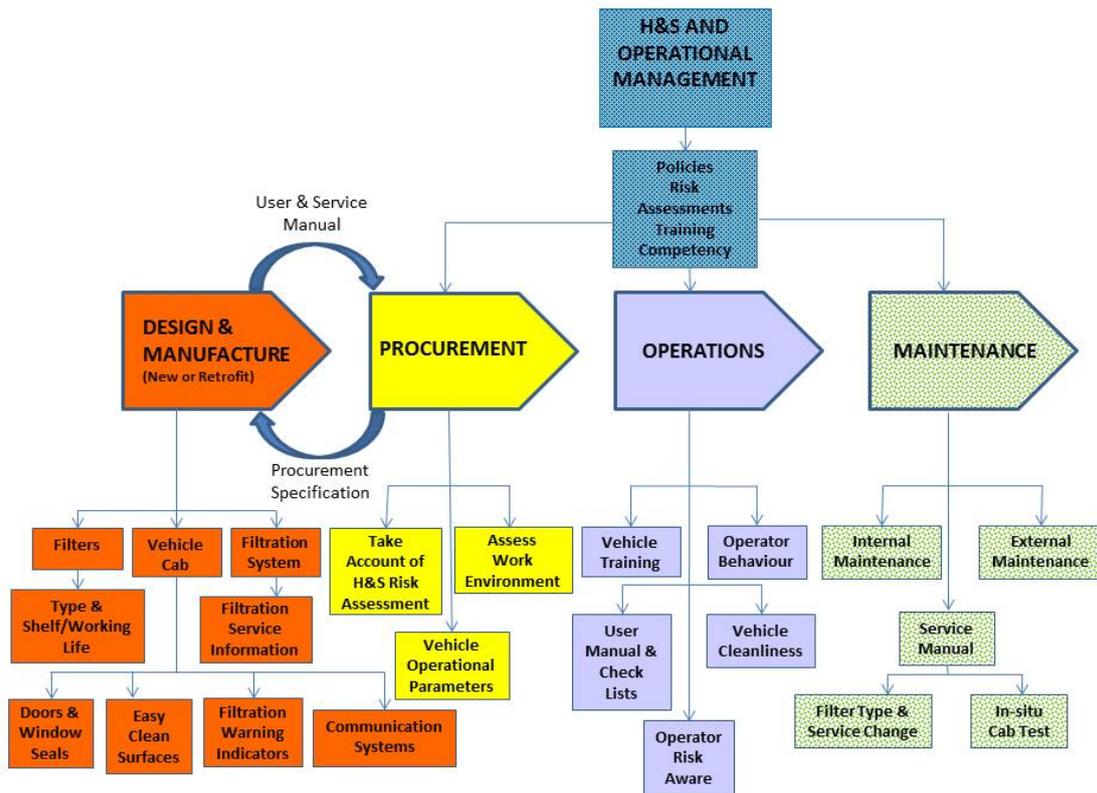
The aim of the project was to bring together existing and newly acquired (through measurement) data on cab contamination, manufacturers' performance standards and dutyholders' expectations, to inform approaches to influence drivers and dutyholders on exposure risks and the appropriate use of in-cab filtration as an exposure control measure. The project sought to establish:

1. The exposure reduction capacity provided by in-cab filtration systems.
2. The performance standards used by manufacturers of vehicles with in-cab filtration systems (or those who produce equipment for retrofitting) and the reasons why those performance standards are used.
3. How suppliers market vehicles with in-cab filtration systems (or equipment for retrofit) and the protection they provide against substances hazardous to health.
4. What protection against substances hazardous to health do employers expect of vehicle in-cab filtration systems (integral or retrofitted) and how they assess the protection afforded.
5. What the drivers understand about the purpose of the in-cab filtration systems and how they work, and their understanding of how their behaviour may influence or contribute to cab contamination.
6. The extent of training to use the in-cab filtration system provided to drivers.
7. Any gaps in good control practice.

## 2. METHOD

### 2.1 OVERVIEW

The approach taken in this study was to consider the lifecycle of vehicle in-cab filtration systems on quarry sites, from design/manufacture through to end user. The four identified stages of the vehicle's in-cab air filtration lifecycle - design and manufacture, procurement, operations and maintenance are shown in Figure 4 together with the associated elements of each stage.



**Figure 4** In-cab filtration systems' lifecycle stages

The project used a mixed-method design to investigate the use of in-cab air filtration as a control measure, incorporating facets of: occupational hygiene, filter design and performance, cab protection test method, and work-related behaviour. It included desk-based research to facilitate the individual literature reviews; semi-structured interviews; on-site observation; and testing of the vehicles' filtration systems. A mixed-method design is well suited to the interdisciplinary research<sup>5</sup> aspect of this project. This is because it ensures a more holistic approach to the issues under investigation and provides therefore a stronger approach to the data collection and analytic phases of a research study<sup>5,6</sup>.

Three quarries agreed to participate in the research, to provide a sample. Information on the aim and objectives of the study was provided in the form of a 'briefing note' that was discussed face-to-face with the site managers, following agreement to take part in the research project.

The three participating quarries were:

#### Quarry A:

This quarry provides limestone for the construction industry. Limestone is extracted from the working face using explosives. The stone is then loaded into dumper trucks using loading shovels and transported to the processing area where it is tipped into a crusher or onto a stockpile.

#### Quarry B:

This quarry produces limestone for the construction industry. Limestone is extracted by blasting rock which is then loaded by excavators into dumper trucks and transported to crusher feed points where it is crushed and screened by fixed plant. Various imported aggregates are also stored on site. Material is then either stockpiled or conveyed by dumper and shovel loader from the crushing plant to a road-stone coating plant.

#### Quarry C:

This quarry extracts clay from the working face using an excavator. This is loaded into dumper trucks and is then transported to either storage or processing areas. A loading shovel is used to load clay into the milling plant and shredder units to break the clay into a finer product for storage.

## **2.2 OCCUPATIONAL HYGIENE**

### **2.2.1 General**

The occupational hygiene study comprised a literature review, followed by visits to the three quarries to determine the effectiveness of in-cab filtration systems by measurement of the respirable dust concentrations inside and outside vehicle cabs. Information on other factors that could affect exposures was also gathered from discussion with vehicle drivers and via a questionnaire to capture contextual information.

### **2.2.2 Literature review**

The literature review in respect of occupational hygiene focused on:

- A search of the literature to identify existing information on the exposures inside cabs fitted with air filtration units.
- A request to industry to supply its own exposure data.
- An assessment of the data acquired to identify (where possible) the processes and vehicles that generate airborne dust.

### **2.2.3 Data Collection**

The samples for respirable dust were taken in accordance with HSE guidance method for the determination of hazardous substances (MDHS) 14/4 “General methods for sampling and gravimetric analysis of respirable and inhalable dust”<sup>7</sup> using grade A glass fibre filters (GFA) mounted in respirable cyclone samplers and aspirated at 2.2 l.min<sup>-1</sup>.

Where possible, one sampler was positioned on the front exterior of a selection of vehicles including dumper trucks, loading shovels and excavators. One sampler was also placed behind or to the side of the driver's seat on the inside of the vehicle, close to an air vent.

During sampling, drivers were requested not to clean the cabs/windows or open the cab windows.

## **2.3 FILTER DESIGN AND PERFORMANCE**

### **2.3.1 Literature Review**

The filter design and performance strand was driven by, and built on, a previous short project which examined filter cabs on shovel loaders used for bioaerosol protection in waste and recycling<sup>3</sup>. The data searches were to:

- Identify existing performance standards/test methods to supplement those identified previously for waste and recycling equipment.
- Identify manufacturers' claims for in-cab air filtration equipment performance, where accessible in promotional material.
- Identify the factors most likely to be influential in improving filter performance that can be adopted in good practice guidance.

### **2.3.2 Data Collection**

Information was collected from a wide range of sources, including:

***Internet searches*** - The aim of the Internet searches was to identify companies working in, or related to, quarry vehicle in-cab air filtration. In addition, it offered the opportunity to review the literature available from several vehicle manufacturers and filter suppliers.

***Review of key filter performance standards*** - There are a wide range of standards relating to air filtration; some are general standards whilst others are specific to an industry. Several key standards on in-cab air filter performance were identified.

***Visit to 'Hillhead 2014'*** – Hillhead is the world's biggest international quarry and recycling show and showcases plant, equipment and services for the quarrying, construction and recycling industries. It was visited in order to gain information where possible about the types of air filtration systems used inside vehicle cabs. It was also an opportunity to talk to filter manufacturers/suppliers.

***Semi-structured interviews with a range of suppliers to the quarry industry*** - The main aim of this phase of the project was to recruit and interview several participants who worked in the quarry industry and had an interest in vehicle in-cab air filtration.

Nine interviews were carried out focusing on vehicle in-cab air filtration and were held with a range of companies that manufacture and supply services and equipment to the quarry industry. These included:

- Vehicle filter suppliers (including cab air filters).
- Particle and gas filter manufacturers.

- In-cab air filter retrofitting companies.
- Cab designers/manufacturers.
- Commercial vehicle manufacturers.

## **2.4 CAB PROTECTION TEST**

### **2.4.1 General**

The aim was to design a simple in-situ method to assess the degree of worker protection afforded by the cabs of quarry vehicles against airborne particles. The test method needed to encompass the requirements of the dutyholder ensuring that:

- It was simple to implement.
- It did not interfere with the driver's normal work activities.
- It was relatively inexpensive.

The work involved a search of the literature to see if there were any existing European or International Standards or methods described in peer-reviewed papers that might be applicable.

This information was used to devise a suitable method for testing the protection afforded by vehicle cabs whilst the vehicles were being driven. The method was used at quarry sites A & B on a total of seven vehicles including shovel loaders and dumpers trucks that are commonly in operation. This was regarded as sufficient to give an adequate assessment of the method.

### **2.4.2 Literature Review**

The literature review of methods used to measure cab protection focused on:

- Relevant European and International Standards.
- Peer-reviewed scientific papers which described practical applications of the standards to measure in-cab air filtration systems.
- Peer-reviewed scientific papers which described work on cab protection measurements which were not directly based on any particular standard.

### **2.4.3 Data Collection**

As a result of the literature review (see Section 3.1.3), a test protocol was produced based on that described in ASAE S525 (1998)<sup>8</sup>. The main advantage of this method was that it did not require an externally-generated source of particles and rather relied on particles generated by movement of the vehicle over rough terrain to provide the challenge aerosol.

#### **Test Protocol**

- Real-time dust monitors and particle counters were positioned inside and outside of the vehicle cab.
- The cab pressurisation was measured either before the vehicle set off or after it returned.

- A video camera was located either on the front dashboard or outside the cab to record the movements of the vehicle. This allowed the cause of any unusual peaks to be identified from the logged data.
- The vehicle driver was asked to adjust the filtration/air conditioning system to its normal setting during the tests and the windows were kept closed.

Real-time measurements from the vehicle air vents were carried out to determine the efficiency of the in-cab air filtration system. Real-time measurements of the ambient air inside the cab were carried out to determine the overall protection afforded by the cab; this also included any dust generated from within the cab or dust that leaked into the cab.

All the instruments and the video camera were synchronised before the tests so that they were set to the same time and date. This was important so that the data from the different instruments could be compared and the cause of any unusual peaks in dust concentration identified using the video footage.

Two quarries (A & B) were visited to assess the test method and measure the performance of in-cab air filtration systems fitted to a range of loading shovels and dumper trucks including vehicles from different manufacturers. Sufficient data was gathered during these two visits and a visit to the third quarry was not deemed necessary.

## **2.5 WORK-RELATED ATTITUDES, BEHAVIOURS AND OTHER FACTORS THAT IMPACT ON EXPOSURE**

### **2.5.3 Literature Review**

An initial literature review was undertaken on the ‘attitudes and behaviours’ among drivers, supervisors, trainers, managers and suppliers which influence the operation and maintenance of their vehicles. This covered the ‘quarry industry’, ‘construction industry’ and the ‘demolition’ aspect of the construction industry. The search was limited to the past fifteen years.

Two questions were asked to assist with the search:

- How did in-cab air filtration effectively installed and used, compare with cabs without a filtration system or those with filtration systems but which were not used effectively, in controlling workers’ exposure to dust?
- What information was available about how drivers used and maintained in-cab filtration systems to achieve an effective standard of control of exposure to dust?

### **2.5.4 Data Collection**

It was important to obtain the views of all involved in the procurement, use and maintenance of in-cab filtration systems to gain a full understanding of the reasons for selecting and using vehicles with in-cab air filtration systems. Therefore, a wide range of quarry staff were interviewed on site to get a range of perceptions on the effectiveness of in-cab air filtration systems and to consider different roles and knowledge.

The researchers developed semi-structured topic guides for the interviews. These were developed after the review of the literature, to determine those factors and issues that were most pertinent for workers in this industry. At each site the following workers were interviewed: three drivers, two supervisors, one health and safety manager, one maintenance mechanic, one procurement manager, and one training manager. The questions for each role focused on: what

was required of the workers during their working day; their perceptions about in-cab air filtration systems; and their knowledge, where relevant, about in-cab air filtration systems. In addition, demographic information, such as the length of time that the participants had worked in the quarry industry, was collected.

The interviews lasted around 24 minutes each. The data were transcribed verbatim to capture all of the information presented and were subjected to a thematic analysis, whilst considering the lifecycle structure as stipulated in this research, as shown in Figure 4 in Section 2.1.

### **2.5.5 Strengths and Limitations of the Behavioural Research**

A mixed-method research approach provides an in-depth assessment of a particular issue or area, and allows researchers to identify those very specific attitudes, behaviours, perceptions and knowledge of a target population. The data generated allow a fuller understanding of the attitudes, behaviours, perceptions and knowledge of the workforce, in this case, of the quarry industry. However, as with any approach the data collected provided a 'snapshot' of the industry, and used small sample sizes in a specific industry sub-sector. The data should be considered in this context, rather than as information to generalise to a larger population, such as to all workers and all the various work practices that occur within quarries. More importantly, the findings could be used to determine other avenues to explore within this specific industry, or with other sectors which use in-cab air filtration systems and may have similar issues or practices to address.

## 3. RESULTS

### 3.1 LITERATURE REVIEW

#### 3.1.1 Occupational Hygiene

The literature search was performed to identify studies of the performance of quarry cab ventilation systems in reducing driver exposure.

There was no information found on the effectiveness of in-cab filtration systems in Great Britain for quarry-based vehicles. There were a limited number of studies found from other countries. These are summarised below.

Respirable dust sampling was reported in the United States of America (USA) for equipment used during the excavation of a large disposal pit<sup>9</sup>. The authors showed that exposures ranged from 0.01 to 3.17 mg.m<sup>-3</sup>. Their findings suggest that any enclosed cab will reduce exposure, but the greatest exposure reduction is for pressurised cab filtration systems.

A study of Respirable Crystalline Silica (RCS) exposures in the USA construction industry found that using an in-cab air filtration system reduced exposure by a factor of six<sup>1</sup>. Similarly, a Norwegian study indicated that tunnel workers operating equipment in enclosed cabs had a three-fold lower RCS exposure than those working in open cabs<sup>10</sup>.

A USA study on retro-fitting of cabs on plant used for surface mining, found an approximate reduction in dust levels of 90%<sup>11</sup>. They noted that effective systems should be properly designed, installed and maintained, and that the filtration system should pressurise the driver's cab. They found that other factors affecting the performance of in-cab air filtration systems were the cab's integrity and cleanliness. The latter prevents secondary exposure arising from re-suspended contamination from the floor and other surfaces. In the study, a floor-mounted cab heater was suspected of re-suspending dust on the floor; while opening the cab door contributed to contamination entering the cab. They also noted that the effectiveness of an electrostatic filter fitted to the filtration system decreased with time.

#### 3.1.2 Filter Design and Performance

There are a wide range of standards that relate to air filtration. Only the ones retrieved in literature searches, raised or mentioned as part of communications with the study participants, were included. These are listed below, along with a short summary, but should not be regarded as an in-depth study of the air filter standards.

*BS EN 1822:2009<sup>12</sup> - High efficiency air filters (EPA, HEPA and ULPA).*

This is a general standard on high efficiency filters and therefore is not specific to an industry sector. The standard details a procedure for the determination of filtration efficiency based on a particle-counting method with a very fine aerosol challenge of approximately 0.3 µm. HEPA filters are divided into two categories; H13 and H14, with filtration efficiencies of greater than 99.95% and 99.995% respectively.

*BS EN 779:2012<sup>13</sup> - Particulate air filters for general ventilation - Determination of the filtration performance - General filters usually used in building HVAC<sup>b</sup> systems.*

This provides a system of comparing the filtration performance of air filters used in air conditioning systems. This is achieved by challenging the filters with a fine and coarse artificial

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<sup>b</sup> HVAC – Heating, Ventilation and Air Conditioning

(synthetic) aerosol, which then allows the filter performance to be graded according to particulate removal capability. Filter efficiencies are lower than for HEPA filters.

*ISO 14269 (Part 4):1997<sup>14</sup> - Tractors and self-propelled machines for agriculture and forestry - Operator enclosure environment.*

This specifies a standard test method for determining performance levels of operator (driver) enclosure panel-type air filters. It is applicable to tractors and self-propelled machines for agriculture and forestry when equipped with an operator enclosure with a ventilation system. The standard does not give a pass/fail criterion. The standard implies that the test dust has been selected with the application and challenge dust in mind. Two grades of dust are used; coarse and fine. The fine test dust is similar to the fine test dust used in BS EN 779<sup>13</sup>.

Part 5 of this standard specifies a test procedure for uniform measurement of the pressurisation inside an operator enclosure. As with Part 4, it does not stipulate a pass/fail criterion.

*BS EN 15695:2009 (Part 2)<sup>15</sup> - Agricultural tractors and self-propelled sprayers - Protection of the operator (driver) against hazardous substances.*

The primary aim of this standard is to limit the exposure of the operator to hazardous substances when applying crop protection products and liquid fertilisers. Part 2<sup>15</sup> of the standard specifies the filter media efficiency test and states that it should be tested in accordance with ISO 14269:4 with the “Fine” dust aerosol. There is a requirement that the filter performance shall be greater than 99% efficient.

It also requires the filter to be tested with a liquid ‘aerosol’ challenge in accordance with EN 1822-2 and EN 1822-5 (HEPA filter test). There is a requirement that the filter performance shall have a maximum aerosol penetration of 0.05%, which suggests H13 classification.

*ISO 10263:2009<sup>16</sup> - Earth-moving machinery - Operator enclosure environment.*

This details the test methods and criteria for the evaluation of the operator enclosure environment in earth-moving machinery. Part 2 details the panel air filter test method, which is the same test method as described in ISO 14269-4. Whilst the test dust specified is ISO 12103-1, (A2 fine - Arizona Road Dust) and (A4 coarse - Arizona Road Dust) they are very similar, if not the same as those specified in ISO 14269. The standard does not specify a pass/fail criterion.

### **3.1.3 Cab Protection Test**

#### **Standards**

Two standards were identified which describe methods to measure driver protection against airborne contaminants afforded by cabs fitted to tractors. These were:

- BS EN 15695-1:2009<sup>17</sup> - Agricultural tractors and self-propelled sprayers. Protection of the operator (driver) against hazardous substances. Part 1: Cab classification, requirements and test procedures. This standard categorises cabs according to the level of protection they afford against different contaminants.
- American Society of Agricultural Engineers Standard ASAE S525 (1998)<sup>8</sup>.

Both methods challenge the tractor under test with an aerosol and measure the effectiveness of the cab protection using optical particle counters (OPCs) placed inside and outside the cab that

measure particles in the 1 - 5  $\mu\text{m}$  size range. The main difference between the two standards is that BS EN 15695-1:2009<sup>17</sup> challenges the cab in a room with a generated test aerosol whereas ASAE S525<sup>8</sup> challenges the cab with particles that are generated naturally as the tractor is driven over a rough terrain. Both standards specify a minimum cab pressure and cab air flow. Either standard could be adapted to measure the penetration of smaller particles such as airborne dust and RCS that can be produced during quarrying operations.

It is recognised that ASAE S525 is written specifically for testing vehicle cabs against pesticide mists and needs to be modified to account for the smaller particles that will likely be generated on quarry sites. However, most hand-held particle counters can measure down to as low as 0.3  $\mu\text{m}$  and so they could be used to investigate the penetration of smaller particles.

### **Practical applications of the Standards to measure cab protection**

Several studies report the use of aerosol instrumentation and test methods based on ASAE S525<sup>8</sup> to evaluate cab air filter efficiency and protection afforded by spray cabs to tractor drivers<sup>18,19,20</sup>. Specifically, they used the test method to:

- Look at ways to reduce penetration of pesticides into the cab.
- Test vehicle cabs for leaks.
- Evaluate in-cab air filtration systems following routine maintenance to make sure that they function adequately and have integrity.
- Look at the effectiveness of a retrofitted cab filter system.

Another study used a modified version of the test method used in ASAE S525<sup>8</sup> by placing the tractors inside a temporary enclosure<sup>20</sup>. Ambient aerosol and/or aerosol generated by burning incense sticks were used to challenge the stationary cab's air filtration system. One OPC was used to measure the aerosol concentration outside and inside the cab using separate sampling lines. They compared their measurements with measurements using the method described in ASAE S525<sup>8</sup> and got similar trends, suggesting that static tests could replace dynamic tests.

The efficiency of a vehicle cab for agricultural tractors was determined<sup>2,21</sup>, based on the method used in BS EN 15695<sup>17</sup>. Also described is a method for correcting the efficiency measurement on cabs equipped with high efficiency filters to allow for internal sources of dust generated within the cab. In addition, the OPC method was validated by sampling an aerosol of fluorescein using two cascade impactors placed inside and outside the cab.

### **Measurement of cab protection using methods not directly based on any standard**

Other studies have been carried out to measure the protection afforded against airborne dust by vehicle cabs and to investigate the effects of improvements in cab design on driver protection. Although these do not refer to any particular standard, the methodology is closely related to that described in ASAE S525<sup>8</sup>. Measurements were made in situ with OPCs, dust monitors and gravimetric samplers located on the outside and inside of vehicle cabs.

Measurements of respirable dust levels inside and outside enclosed cabs were undertaken in a series of studies using gravimetric cyclone samplers, and direct-reading dust monitors (DataRam, Thermo Scientific) and OPCs<sup>11,22,23,24</sup>. Specifically they used the methods to:

- Investigate ways of lowering respirable dust levels in an enclosed cab on a surface drill at a silica sand operation.

- Investigate the performance of a modified filtration and pressurisation system designed to give optimal airflow patterns within a cab fitted to a surface drill and to determine the improvement in cab air quality.

In a study conducted in 2008<sup>25</sup>, controlled laboratory experiments were carried out on an enclosed cab test stand at the National Institute for Occupational Safety and Health, USA (NIOSH). Cab protection was determined by comparing particle count concentration inside and outside the cab test stand using OPCs with naturally occurring ambient air particles.

A method for testing inward leakage into tractor cabs by using a challenge aerosol of monodisperse wax particles has been described<sup>4</sup>. Tests were carried out at an arable farm and a tractor manufacturer's premises. Penetration of particles into the cab was determined using an aerodynamic particle sizer (APS, TSI Inc) and Hand-Held Aerosol Monitor (HAM, ppm Ltd).

As a result of the literature search it was decided that the most appropriate and practical method of carrying out on-site measurements of the protection afforded by vehicle cabs fitted to quarry vehicles should be based on ASAE S525 (1998)<sup>8</sup>. The main advantage of this method was that it did not require an externally generated source of particles and relied on particles generated by movement of the vehicle over rough terrain to provide the challenge aerosol. In addition, it did not require the vehicle to be placed inside a test enclosure.

### **3.1.4 Work-Related Attitudes, Behaviours and Other Factors that Impact on Exposure**

The literature contained limited information on the behaviours and perceptions of vehicle drivers (such as opening windows) and how this could contribute to the contamination of the vehicle cab. The research that was available outlined those factors that drivers should consider to maintain cab integrity. Due to the limited research in this area, some of the research reviewed covered dust exposure and those in-cab air filtration systems that span various industries such as mining, construction, waste, recycling and agriculture. Overall, the literature showed that a multi-faceted control strategy would more likely ensure that high levels of protection could be maintained within the cab<sup>26</sup>. The main issues identified from the literature review are detailed as follows within the appropriate categories:

#### **Causes of Worker Dust Exposure**

- Heating units mounted or directed along the floor can disturb and re-suspend settled dust within the cab<sup>8,11,22,27,28</sup>.
- Construction site drivers bringing dirt into the cab<sup>8,22,28</sup>.
- Ineffective protection due to the use of inadequate equipment<sup>29</sup>.
- A lack of control strategies<sup>29</sup>.

#### **Cab Pressurisation**

- One study noted that three criteria need to be met to ensure that cabs are operating at their optimum: 1) pressurisation, 2) minimum penetration with respect to the main pollutants, i.e., closed doors, and 3) filtered airflow<sup>2</sup>.
- A pressurised and high efficiency particulate air (HEPA) filtration system combined with a clean cab leads to higher protection<sup>26</sup>.
- Positive pressurisation used to maintain in-cab air filtration's integrity has been noted in several studies<sup>8,22, 23,27</sup>.

## Clean Cabs

- A clean cab is one factor to consider when exploring controls for vehicle cabs<sup>11,26,27, 28</sup>
- Wiping down the interior of the cab regularly, and if possible daily, can reduce driver exposure<sup>11,27,28</sup>.
- The use of vacuum cleaners to clean the cab interior will reduce the likelihood of driver exposure compared with the use of dry brushing methods<sup>28,29,30</sup>

## Clothing - cleaning and disposal

- Cleanliness of drivers' clothing and boots could impact adversely on the cab's contamination<sup>4,8,11,26,27, 28,</sup>
- If possible, workers should use disposable or washable work clothes when on site and they should shower and change into clean clothing before leaving the site<sup>28</sup>.
- Alternatively, workers should use a vacuum with a high-efficiency filter to remove dust from clothes before entering the cab<sup>28</sup>.

## Windows and Doors

- Opening of windows or doors has been raised as a (potential) factor in lowering protection levels in cab<sup>4,11,28,32,33, 34,</sup>
- Leaving doors open, even for extremely brief periods, can result in a considerable increase in the respirable dust concentration in the cab<sup>23</sup>.
- Poorly designed vehicle doors that inhibit entry and exit may inadvertently contribute to drivers leaving doors open to gain easier vehicle entry<sup>34</sup>.

## Training

- Lack of focus on training for cab drivers undermines the potential effectiveness of in-cab air filtration; organisations should provide training to drivers of enclosed cabs which covers the use of control measures as well as work procedures<sup>28</sup>.

### 3.2 OCCUPATIONAL HYGIENE: IN-CAB CONTROL LONG TERM RESPIRABLE DUST MEASUREMENTS

#### 3.2.1 Pre-measurement questionnaire

A questionnaire was sent to each participating quarry seeking contextual information about when they performed their exposure monitoring. The responses to the questionnaire showed that the use of in-cab air filtration was noted when performing exposure measurements. However, the related contextual information was limited; for instance:

- none carried out assessment of the in-cab air filtration
- other factors such as condition of the cab seals were not commented on.

#### 3.2.2 Site measurements

Three quarries were visited as part of this work. Two (sites A and B) were extracting limestone and the other was extracting clay (site C).

Measurements of respirable dust were collected using an air sampler positioned outside the vehicle and another inside the vehicle. Observations were made on factors that could affect the measured air concentrations inside the cab.

In total, air samples were collected from 14 vehicles. Weather conditions were dry on all but one of the visits, when it rained. The latter was revisited in dry conditions to perform additional measurements.

Inside the cabs, the respirable dust concentrations varied between  $<0.003$  and  $<0.136 \text{ mg.m}^{-3}$ , and on the outside of the cab between  $<0.003$  and  $0.94 \text{ mg.m}^{-3}$ . Generally, the measured respirable dust concentrations inside the cab were lower than outside except for two samples from the clay quarry. This may have been due to the presence inside the cab of dried clay which was re-suspended.

### **3.2.3 Information gathering**

Some drivers indicated that they opened the windows for operational reasons such as communication with other staff.

Cab cleaning varied from daily to weekly, though most were visibly dusty and this dust could be re-suspended. Cleaning regimes varied, but commonly they were cleaned using a hand brush.

When information was sought about the filters fitted to the vehicles it was provided by one site only and consisted of part numbers, and not the filter's efficiency. The cab seals were in good condition on all the vehicles.

### **3.3 DIRECT-READING INSTRUMENTS: MEASUREMENT OF IN-CAB FILTRATION EFFICIENCY AND REAL - TIME VARIATIONS IN AIRBORNE DUST LEVELS**

The method of using OPCs or direct-reading dust monitors, to measure cab protection has potential drawbacks since it relies on the outside concentration of particles being high enough to create a measurable concentration above background inside the cab. If the background level of airborne dust inside the cab is high, this will result in an overestimation of penetration and hence an underestimation of protection. Also, if the airborne dust concentration is too high then the use of certain types of real-time instrument can result in measurement errors.

The results of the current on-site measurements comparing traditional hand-held OPCs with much cheaper OPCs which have recently become available, showed that when they are used to measure comparable particle sizes, there is good agreement in cab penetration measured by the two types of OPC. This suggests that the cheaper OPCs could be used as a viable method to carry out inexpensive on-site measurements of cab penetration.

Dust concentrations measured inside the vehicle cabs using the direct-reading dust monitors ranged from  $0.006 - 0.1 \text{ mg.m}^{-3}$ . These should not be taken as absolute values since the dust monitors are calibrated in the factory using a different dust type and so their response will likely be different. However, the results indicate that airborne concentrations were generally low.

## 4. DISCUSSION

### 4.1 LIFECYCLE STAGE 1 - VEHICLE CAB DESIGN AND MANUFACTURE

#### 4.1.1 Filtration

- It was generally found that there was limited information available from manufacturers on the performance of in-cab air filtration systems. The in-cab air filtration system was described very briefly, if at all, in the vehicle brochure in the 'Cab environment' section. This would suggest that it is not a main priority for the manufacturer and not regarded as a major selling point. Interviews with quarry staff highlighted that minimal information on the filtration system was available to the vehicle users.
- Interviewees noted that their knowledge on the structure and integral nature of the in-cab air filter was based on perceptions rather than evidence. One health and safety manager quoted *"The depth of my knowledge of the actual filtration systems is minimal."*
- One filter manufacturer complained that vehicle manufacturers did not fit the correct filters in tractors (he was referring to crop-spraying activities). He described the factory-fitted filters as *"... like an orange paper filter which is similar to an air filter that you'd put in the inlet for a car... So, it's an engine air filter which is not in our filter grading system."*
- The role of the filter was described by manufacturers as both for comfort and for dust control. One stated that they make no claim that the filters have any effect against hazardous substances.
- In-cab air filters are marked only with the manufacturers' part number and carry no information on their filtration efficiency.
- Visual inspection of some of the filter elements revealed that they had an open structure, indicating that they were of low efficiency.
- Some vehicle manufacturers described the use of alternative filters that provided higher filtration efficiency, increased dust capacity and were easier to clean. However, they also stated that they should not be used against hazardous dusts. The ventilation system would need to be able to operate with the added resistance provided by high efficiency filters.
- Manufacturers' brochures sometimes mentioned the use of pre-filters/cleaners to extend the life of the higher efficiency filter. However, pre-filters/cleaners did not appear to be fitted to vehicles. These can extend the life of the main filter and hence reduce operational costs (filter cost and human resource), since the main filter will not require replacing as frequently. Main filters that are of low efficiency do not significantly benefit from the additional use of pre-filters. Filters fitted to the cab's recirculation system generally do not need pre-filters as the cab air should already have passed through the main filter.
- Retrofitted filter elements are sold by some vehicle and filter manufacturers. Often the performance of the filter or its impact on the air flow rate and cab pressure is not checked.

- A retrofitted in-cab air filtration system had been installed on a shovel loader used on one quarry site. The measured filtration efficiency using real-time instruments was lower than would be expected for such a system. The reason was not clear, but one explanation might be that the system had been incorrectly installed. Re-suspension of dust within the cab was not considered a possible reason since the vehicle was relatively new and the inside was observed to be clean.
- HEPA filters create a much higher pressure drop than lower efficiency filters, resulting in a lower cab air flow rate. There is therefore a compromise between filter efficiency and pressure drop. There was some divergence in views between filter manufacturers as to the effect of fitting HEPA filters. Two filter manufacturers stated that the pressure drop across a HEPA filter would be much higher than across a standard filter, with one quoted as saying that the pressure drop would be: *“much higher .... many times, the original filter”*. On the other hand, another manufacturer commented that *“there would be slightly more restriction because obviously it might be cleaning the air more, it’s not particularly noticeable within a cab”*. Another commented *“The air pressure on the filter will diminish slightly with a HEPA filter fitted but, obviously, it varies from machine to machine and normally ..... if there’s an up to three speed fan fitted to the cab then they may ... instead of putting it on the first setting you perhaps need to put it on the second setting to maintain the same airflow through the filter”* and went on to say *“There’s not a major issue with HEPA paper filters”, “.....But normally there wouldn’t be a great difference in airflow and fitting a HEPA filter compared with a standard grade filter”*.
- None of the vehicles tested, with one exception, had a low-pressure cab alarm. A visual cab pressure indicator was installed inside the cab of the shovel loader with the retrofitted filtration system fitted and was the only one observed during this study. A change in cab pressurisation would indicate to the driver that: a) the filters needed changing; b) that a door or window was not closed properly; c) that the filters were not installed or seated correctly; or, d) that the cab door and/or window seals required changing. Regardless of filter efficiency, a significant drop in cab pressurisation could result in the infiltration of outside contaminants through adventitious openings. The pressure device could be connected to an audible or visual warning indicator that alerts the driver to a potential problem. This could then be investigated by the driver or the vehicle maintenance mechanic. It could also help to train the vehicle driver to keep windows and doors closed. The literature search also revealed that adequate cab pressurisation was an essential requirement in maintaining efficient in-cab air filter systems.

#### **4.1.2 Secondary exposure**

- It was observed during the occupational hygiene study that some cab seat covers retained dust more than others. For instance, seats made from fabric material were more likely to retain dust than seats made from plastic. This could potentially lead to a secondary source of exposure if the dust were disturbed and rendered airborne, such as when the driver sits on the seat.
- During the occupational hygiene survey, it was also observed that the air distribution vents inside vehicle cabs were sometimes located close to the floor to keep the driver’s feet warm. This meant that there was the potential to produce a secondary exposure source, from dust settled on the floor being re-dispersed and made airborne by high-velocity air from the vents. Vehicle cab ventilation systems with larger vents

provide air to the cab at a lower velocity and cause less disturbance. Also, the use of replaceable/disposable mats reduces the amount of dust that builds up.

- Some vehicles have opening front windscreens. Manufacturers could not explain why this feature was required, other than it was common practice. They did not want to sell vehicles with sealed windows if their competitors continued to sell vehicles with opening windows. Opening cab windows leads to increased driver exposure to airborne material, as most of the air enters the cab via this route, bypassing the filtration system; it also results in a loss of cab pressurisation. One vehicle manufacturer, when asked at interview why the windows opened at all he said, “*traditionally how the industry you know, sort of requested it*”. Another vehicle manufacturer said he was ‘amazed’ that many excavators and shovel loaders had front opening windows and commented: “*..... looking back that’s madness because all you had was a metre and a half square of dirty air coming in*”.
- Maintaining a positive pressure within the vehicle cab is important to prevent ingress of dust via leakage routes, such as poorly fitting doors and windows. However, there were different perceptions among interviewees on the benefits of vehicles having positive cab pressurisation. Some stated that it was beneficial, as it worked to reduce the dust within the cab. Others felt that positive pressure was not needed in the cab, as it was not a high-risk environment, such as would be found at waste sites: “*...we don’t have any machines where we’ve got positive cab pressure, as you would with waste sites, but our main concern is dust, of course...*” (Procurement manager).

#### **4.2 LIFECYCLE STAGE 2 - PROCUREMENT**

- It was clear from the site interviews that whilst managers or supervisors stipulated having an in-cab air filtration system, it was not their prime concern when purchasing a vehicle and was not an essential element when devising the specification. Manufacturers often had ‘standard’ filters which were fitted to each vehicle unless a higher efficiency was specified by the purchaser. However, dutyholders did not specify the cab air filter to any particular standard and were unable to provide details of the filtration standard for the filters fitted to the vehicles. For instance, some quarry staff stated that the only essential specification was that the vehicles should have an in-cab air filtration system. Others were not aware that in-cab air filtration systems differed between manufacturers, nor had they assessed the effectiveness of different systems. Interviews with vehicle and filter manufacturers highlighted that they did not always know the final use of the vehicle and therefore it was difficult to recommend filter specifications or upgrades.
- During the occupational hygiene survey, it was found that the filters did not carry information on the filtration performance; and interviews with filter suppliers highlighted that only the product number information was marked on the filter.
- During the on-site interviews and interviews with manufacturers it became apparent that manufacturers designed their vehicles for a worldwide market and so it was less likely that dutyholders would influence the vehicle specification at the procurement stage. Some manufacturers offered filter upgrades but stated that these were rarely requested. Another manufacturer was reluctant to offer anything but its standard filter (which they considered was ‘adequate’), due to the worldwide sales market.
- It was clear from vehicle advertising brochures and from the on-site interviews that, with few exceptions, information was poor on: the types of air filters fitted to vehicle

cabs; the types of filter available; their shelf-life; their maintenance requirements; and their performance. It was usually only briefly described in the 'vehicle cab environment' section of the manufacturer's brochure. This would indicate that it was considered a low priority by the manufacturers, probably because it was not regarded as a major selling point. Specification of filter performance to common standards was not used throughout the industry and so it was difficult for dutyholders to compare filtration performance.

- Some manufacturers offered upgrades to higher efficiency filters but stipulated that these should not be used if challenged with hazardous dusts. However, one manufacturer commented that only approximately 0.1% of vehicles sold were fitted with the higher efficiency filters, and this would typically be for green waste recycling applications and was specifically at the request of the customer.
- Air conditioning (AC) was not always specified i.e. whilst some manufacturers' brochures described AC as optional, other manufacturers stated it was standard. It was observed that cabs were generally fitted with AC, some of which provided automatic heating and cooling to the cab - these usually recirculated some of the air within the cab. This was observed from the manufacturers advertising brochures, during on-site measurements, during interviews with vehicle manufacturers and during on-site behavioural interviews. During work-related behaviour and perception interviews, AC was seen as a requirement to support drivers' comfort levels. Some vehicle drivers revealed that in-cab air conditioning systems reduced the need for them to open a window or door during hot weather, thereby reducing the likelihood of outside contaminants entering the cab. Cabs fitted with automatic cab heating and cooling for temperature control might reduce the likelihood of the driver opening a window during hot weather, thereby preventing outside contaminants from entering the cab by this route.

### **4.3 LIFECYCLE STAGE 3 - OPERATION**

#### **4.3.1 Exposure Control**

- It was found from the on-site interviews that cab doors and windows were frequently opened to aid communication. At all sites, drivers opened cab windows to talk to lorry drivers and to listen for buzzers in loading/unloading areas. For example, the windows of an excavator were opened so that the driver could hear if the vehicle was going into gravel when extracting clay. In addition, doors were opened during lunch and comfort breaks. Some communication systems, such as closed-circuit television (CCTV) with monitors located inside the cab, radios, traffic lights, horns, public address (PA) systems and 2-way radios were provided on-site, but were not always used. There was a perception that it was acceptable to open windows/doors as this assisted with improving the air flow in the cab.
- Video evidence during one quarry visit showed the driver getting out of the vehicle and leaving the door open during this time. Site interviews also revealed that drivers often leave their cabs up to 5 times a day, due to the tasks assigned. This could potentially lead to short-term exposure to high concentrations of airborne dust, depending on location. A few drivers believed that opening doors and windows for a short duration and specific purpose was acceptable. Others believed that the windows needed to be open to maintain the quality of their work, for example, drivers of excavators claimed they were able to judge the depth of dig from the noise generated.

- Long-term air monitoring can mask short-term peak exposures that show poor working practices. From the occupational hygiene measurements and the real-time measurements of cab protection, it was found that the effectiveness of the cab air filters was variable. Penetration of particles in the size range 0.5 – 3 µm into vehicle cabs was quite high and varied between approximately 7 & 42% depending on the vehicle type and manufacturer. This indicated, for example, one or more of the following: (i) they were fitted with low efficiency, general air conditioning filters, (ii) filters were poorly maintained (not cleaned, if appropriate, when loaded with dust or replaced when damaged), (iii) dust entered the cab through adventitious openings mainly created by poorly-fitting windows and doors. Low cab pressure is one indicator that the door and window seals are defective or inadequate and require replacing. The cabs of dumper trucks generally appeared to offer the least protection against outside airborne dust, showing the highest levels of penetration of particles into the cab environment. The cabs of shovel loaders appeared to offer a higher level of protection, showing lower values of particle penetration, indicating that they were fitted with higher efficiency filters and/or were better sealed or pressurised than the cabs of the dumper trucks. Higher efficiency replacement filters were available for some vehicles. In addition, there are retrofitting companies which can install high efficiency positive pressure HEPA filtration systems to vehicle cabs.
- Gravimetric measurements of airborne dust showed low average concentrations of respirable dust inside and outside the cab, for all vehicles included in the study. The real-time dust monitors, however, indicated many short-term peaks in respirable dust concentration inside and outside the cab.
- Measurements of cab pressure carried out during the real-time dust measurements revealed that it was sometimes below the minimum value recommended in BS EN 15695-1:2009-228 (20 Pa) or ASAE S525 (1998)<sup>32</sup> (59 Pa). There was one occasion when the measured cab pressure was zero at the end of the test, indicating that the vehicle ventilation was not switched on. One vehicle with a retrofitted in-cab air filtration system had a display of cab pressure inside the cab that would alert the driver to a low cab air pressure situation or if the ventilation system was turned off.

#### **4.3.2 Cleanliness**

- This is already discussed in section 4.1 (Vehicle cab design and manufacture), but is also an important part of vehicle operation. On-site interviews and general observations made during occupational hygiene measurements revealed that dust on the inside of the cab can become airborne, due to the movement of the cab occupants, vibration of the vehicle or air from the air vents. For example, occupational hygiene measurements made at Quarry C, revealed that in some instances dust concentrations inside the cab were higher than outside. It was observed that the drivers' levels of cab cleanliness could differ and maintenance of vehicles was inconsistent. For example, although drivers regularly cleaned their cabs, this was often done using poor and ineffective practices, such as brushing and polishing; this practice could also cause further spread of contaminant within the cab. Indications were that the frequency of cleaning ranged from daily to weekly, and the amount of cleaning seemed to depend on the age of the vehicle. Often, drivers of newer vehicles were more "proud" of their vehicle and would therefore clean it more regularly. Good cab hygiene minimises secondary exposure from settled dust on the interior of the cab, and published literature<sup>11</sup> advises that cabs should be wiped down frequently with a damp cloth, daily if possible. HSE advice recommends cleaning cabs with a suitable vacuum cleaner rather than dry brushing, in order to reduce worker exposure.

- Measurement of the penetration of particles into the cab, using the real-time instruments, showed some unusual peaks in concentration inside the cab that did not relate to increases in particle concentration outside the cab. This may have been due to re-suspension of settled dust within the cab, or to another aerosol source, such as cigarette smoke. In addition, gravimetric measurements carried out at Quarry C, revealed high airborne dust concentrations inside the cab.
- One of the vehicle manufacturer's representatives remarked that when they changed the filters there was little evidence of dust inside the air conditioning units and that, in their opinion, "90%" of dust entered the vehicle cab via the door, or was brought in on clothing. The representative also commented that driver behaviour was the most important factor in reducing dust in vehicle cabs.

### **4.3.3 Training**

- The on-site interviews revealed that knowledge of the effectiveness of in-cab air filtration systems and the level of protection that they afforded was variable and it was not consistently seen as an exposure control measure. For example, interviewees acknowledged that it was essential to have an in-cab air filtration system, but some admitted thinking that there was little or no difference in the level of protection offered by different systems.
- From the on-site interviews it was apparent that there was limited or no training provided to drivers on the operation of the in-cab air filtration system. Instead, drivers relied heavily on the vehicle handbook to try to understand the filtration system. There were also misconceptions on how in-cab air filtration worked in practice. For example, the perception was that as the filter collects more dust it becomes less efficient (the opposite of what actually happens with mechanical filters). Drivers were also often unsure as to where the filters were located and when they should be cleaned or replaced.
- The four companies involved in cab design/manufacture all made reference to designing the vehicle cab to operate at a positive air pressure. However, the on-site interviews revealed that there were different perceptions of the benefits of vehicles having positive cab pressure. Some interviewees stated that it was beneficial to have vehicles with positive cab pressure, as this feature worked to reduce the dust levels within the cab. Conversely, others felt that positive pressure was not needed in the cab, as it was not a high-risk environment.

## **4.4 LIFECYCLE STAGE 4 - MAINTENANCE**

- On-site interviews and questions asked of quarry workers during the occupational hygiene visits revealed that air filters were maintained by the site's maintenance staff or external contractors, according to the schedule provided by the manufacturer. Most of those asked did not assess if the schedule/service hours were adequate or needed to be adjusted e.g. could the in-cab air filters become blocked before the scheduled maintenance? One of the sites noted that any future contracts with filter manufacturers/suppliers would have the in-cab air filtration system considered as a separate part of the maintenance contract.
- On-site questions about the filter cleaning regime revealed that some drivers and maintenance staff periodically removed and cleaned the filters because they thought it would improve filtration efficiency. Whilst this is not the case, cleaning the filter will increase air flow into the cab and therefore increase cab pressure, which will reduce the

risk of dust infiltrating the cab through any adventitious openings. The cleaning practice of tapping the filter to release dust, could potentially lead to high short-term exposures to hazardous substances that have become airborne.

- The required maintenance schedule is dictated by the specific conditions of the quarry, such as ambient airborne dust concentrations, the length of time that a vehicle is in a dusty location, and the size of airborne particles that are generated. Smaller dust particles will clog (or 'blind') a mechanical filter faster than will larger particles, and will be more difficult to remove if the filter is re-usable.
- During the on-site interviews and the occupational hygiene visits, it was noted that cab door and window seals were generally in good condition; an indication that the vehicles were probably being well-maintained. However, there were reports of 'third parties' running cables across the seals when installing two-way radios - potentially compromising the seals.
- During the 3 site visits, it was noted that there was a mixture of leased and owned vehicles. Commonly, leased vehicles were maintained by the owner using standard maintenance times provided by the manufacturer. This could result in a difference in maintenance schedules between owned and leased (contracted) vehicles.
- During on-site interviews and the occupational hygiene visits, it was noted that some drivers and maintenance staff cleaned the in-cab air filters outside of the routine maintenance schedule. This could have been in an attempt to extend the life of the filter or when replacements were not immediately available. Drivers tended to learn this practice from other drivers, rather than being trained to do so. They often used compressed air or mechanical shock to clean the filters, which resulted in the generation of an airborne cloud of potentially hazardous dust, as well as risking damage to the filter element or filter seal.

## 5. CONCLUSIONS

### **In-cab Air Filtration**

- Quarry staff had variable knowledge about the effectiveness of in-cab air filtration and the level of protection it afforded. It was not viewed consistently as an exposure control measure.
- Managers and supervisors did not specify the in-cab air filter to any particular standard, as it was not recognised as a priority feature. Their lack of knowledge in this area meant that they were unable to provide details of the filtration standard for the filters fitted to the vehicles. As such, the suppliers provided filters as they deemed appropriate within the overall specifications that they received.
- Interviews with vehicle manufacturers highlighted that they did not always know the final use of the vehicle and therefore it was difficult to recommend appropriate filter upgrades.
- Information from filter manufacturers on filter type and filtration efficiency was often incomplete, making it extremely difficult for vehicle purchasers to interpret and compare data. This situation is partly due to manufacturers not adopting one common standard.
- Vehicle cab air filters can be upgraded with higher efficiency filters to improve driver protection. Upgraded filters are usually provided as an alternative by the vehicle manufacturer or can be obtained from third party filter suppliers.
- The cab air filters did not carry information on the filtration performance and only displayed the product number information on the filter.
- Information on filter type and performance, provided by vehicle/cab manufacturers in their brochures, was sparse, most likely because they regarded these features as a low priority.
- Examination of some of the vehicle cab air filters revealed that they had an open structure, indicating that they were of low efficiency.
- From interviews with vehicle and filter manufacturers, and observations on-site, it was apparent that there was acceptance that although pre-filters/cleaners should be fitted to extend the life of the main filter, this did not always happen.
- On-site measurements showed penetration of particles into the vehicle cabs, indicating that they were either fitted with low efficiency general air conditioning filters and/or dust entered the cab via other routes. Penetration was generally significantly higher for cabs of dumper trucks than for cabs of shovel loaders, indicating that the cabs of the shovel loaders were fitted with higher efficiency filters and/or were better sealed or pressurised than the cabs of the dumper trucks.
- At one quarry, the in-cab air supply/filter system of a shovel loader had been modified, to increase the filtration efficiency and cab pressurisation. This was carried out with the aim of improving worker protection. Observation showed however, that resultant penetration level of particles into the vehicle cab was generally higher than observed on vehicle cabs that were unmodified. The reason was not clear, but one explanation might be that the retrofit filter system had been incorrectly installed.

### **Cab Pressurisation**

- If cab pressurisation is not maintained, then particles may enter the cab through poorly-fitting doors or windows. Cab pressure indicators were not installed as a standard feature inside any of the vehicle cabs observed in this study.

- A fall in cab pressure can be caused by: clogged filters (especially high efficiency particulate air filters); open doors or windows; filters not being installed correctly; or when cab seals require changing.

### **Secondary Exposure and Cab Cleanliness**

- Cab doors and windows were frequently opened by drivers to aid communication, thereby rendering the in-cab air filtration system ineffective, and increasing driver exposure to outside contaminants.
- Dust was brought into the vehicle cab by dirt from workers' boots and clothing. Movement of the cab occupants and vibration of the vehicle could cause this dust to become airborne.
- Cab cleanliness was variable, and drivers often used ineffective cleaning practices, such as brushes and polish, that could also lead to an increase in potential exposure by spreading contaminants within the cab. The frequency of cleaning varied from daily to weekly.
- Air distribution vents inside vehicle cabs were sometimes located close to the floor to keep the driver's feet warm. This could result in dust that had settled on the floor being re-dispersed and made airborne by high velocity air from the vents.

### **Maintenance and Training**

- Air filters were maintained by the site's maintenance staff or external contractors, according to the schedule provided by the manufacturer. Most of the quarry staff interviewed did not assess whether the schedule/service hours were adequate or whether they needed to be adjusted.
- Some drivers and maintenance staff cleaned the cab air filters using practices learned informally from other drivers whilst others used what they perceived as effective practices, rather than receiving structured training. Compressed air was commonly used to clean the filters, which could generate an airborne cloud of potentially hazardous dust, leading to the potential for worker exposure; and could cause damage to the filter.
- From the manufacturers' vehicle literature, it appeared that some filters could be cleaned, but the majority were single-use and cleaning would compromise the filter element.
- Cab window and door seals were observed to be in good condition, an indication that they were being well-maintained.

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# In-cab air filtration in plant vehicles to control exposure to hazardous dust: quarry industry example

Tackling occupational lung disease is a priority for HSE. In-cab air filtration systems are installed on plant vehicles used in a wide range of industries where drivers can potentially breathe in hazardous airborne dust, such as farming, waste management and quarrying. Plant vehicles include tractors, diggers, dumper trucks, excavators and mechanical shovels. However, little is known about the effectiveness of in-cab air filtration as a control measure. This report describes research to develop this evidence; the research was carried out with the support of the quarry industry as a representative sector.

The research looked at the factors that influence the effectiveness of in-cab air filtration systems throughout their operational lifecycle, including system design, in-service use, and maintenance. The research included developing a new scientific method to evaluate filtration system efficiency whilst a vehicle is being driven. The research found: penetration of hazardous dust into vehicle cabs; some vehicle cab filters of low efficiency; and that staff had variable knowledge about the effectiveness of in-cab air filtration and the level of protection it afforded. The research identified practical steps that industry can take to improve protection of workers. Improved understanding of good practice for in-cab air filtration systems is needed by vehicle designers and manufacturers and within the sectors using the vehicles – including the importance of filter maintenance and ensuring that drivers are made aware of the actions they need to take.

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