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Nitrogen oxides gas levels in NATM tunnel construction during the Directive 2017/164/EU transitional period

Niveles de óxidos de nitrógeno en construcción de túneles con el NATM durante el periodo de transición de la Directiva 2017/164/EU

Héctor García González [(*)], Johnatan González García [(**)], Sergio González-Cachón Fernández [(***)], Sergio Pellicer Mateos [(****)]

ABSTRACT

The Directive 2017/164/EU will drastically reduce the NO and NO_2 TLVs in underground mining and tunneling activities. There are concerns regarding the feasibility of the proposed levels and the Directive established a transitional period, ending on 21 August 2023 for the underground mining and tunnel construction sectors which provides for a reassessment of its applicability to these sectors before the end of this period. The study was carried out in a 2 km double highway tunnel, excavation cross-section 102 m^2, excavation method NATM, the selected tunnel is representative of the tunnel construction system in Spain. This paper aims to analyses NO and NO_2 gas levels during NATM tunnel construction and compare results with the actual levels and the levels proposed in the Directive 2017/164/EU. The report concludes that great efforts need to be made to reach the Directive levels in 2023. Recommendations are given to reach the proposed levels.

Keywords: gases; NATM; NO; NO2.

RESUMEN

La Directiva 2017/164/UE reducirá drásticamente los niveles de NO y NO_2 en minería subterránea y construcción de túneles, existe preocupación con respecto a la viabilidad de los niveles propuestos y se estableció un período de transición que finaliza en agosto de 2023, está prevista una reevaluación de su aplicabilidad antes del final de este período. El estudio se realizó en un túnel de autopista de 2 km, sección de excavación de 102 m^2, método de excavación NATM, el túnel seleccionado es representativo del sistema de construcción de túneles en España. Este documento tiene como objetivo analizar los niveles de gas NO y NO_2 durante la construcción del túnel y comparar los resultados con el nivel propuesto en la Directiva 2017/164/UE y los niveles vigentes. El informe concluye que se deben hacer esfuerzos para alcanzar los niveles de la Directiva en 2023. Se dan recomendaciones para alcanzar el nivel propuesto.

Palabras clave: gases; NATM; NO; NO_2.

(*) MSc Engineer. Researcher. Instituto Nacional de Silicosis, 33011, Oviedo (Spain).
(**) MSc Engineer. Technical Director. Perforaciones Noroeste, 33002, Oviedo (Spain).
(***) PhD Engineer. Researcher. Universidad de Oviedo, 33006, Oviedo (Spain).
(****) MSc Engineer. Rail Operations Lead, Crossrail, London (United Kingdom).
Persona de contacto/*Corresponding author*: hectorg@ins.es (H. García-González)
ORCID: http://orcid.org/0000-0002-7285-2347 (H. García-González); http://orcid.org/0000-0003-1091-6058 (J. González); http://orcid.org/0000-0002-2185-8562 (S. González-Cachón); http://orcid.org/0000-0002-7090-7623 (S. Pellicer).

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1. INTRODUCTION

Historically gas hazards in mining and tunnelling were a big health & safety concern. Around 100 years ago several studies with animals were carried out by the Bureau of Mines (USA) to find an ideal gas detector. The studies demonstrated that canaries recovered quickly after breathing carbon monoxide and could be used again and again as a gas detector. Other animals like rabbits, pigeons, mice, and sparrows were also used, when canaries were not available (1).

DRI (direct reading instruments) are the most common in mining and tunneling. These are portable gas detectors and fixed gas detectors. Portable gas detectors are also known as personal gas detectors and are designed to keep personnel safe from gas hazards by monitoring an operator's breathing zone continuously, whilst stationary and moving about. Fixed gas detectors are normally connected to the tally hut or to a control room to check the gas levels in all the parts of the mine. It could be very useful for example in a fire, the tallyman could give clear instructions to miners for a safe evacuation route avoiding gas exposure. Other systems for gas measurements are aerosol sampling filters, or sorbent tubes and short-term detector tubes (colorimetric tubes). The filters or sorbent tubes require a pump for sampling and then the filter is sent to the laboratory for analysis. The big inconvenience with colorimetric tubes is the cross interferences.

Since the use of animals as gas detectors in mining and tunnel construction, there have been major developments in terms of advancements in personal gas detectors technology. However, there are still some challenges to come, one of the main problems with personal real-time gas monitors are the cross-interferences among the gases, in particular NO2 presence has a strong influence in other gas sensors. (2-4).

The nitrogen oxides (NOx) family, namely nitric oxide or nitrogen monoxide (NO), nitrogen dioxide (NO2), nitrous oxide (N2O), and their derivatives have a wide range of health and environmental impacts. The primary route of exposure to nitrogen oxides is by inhalation, but exposure by any route can cause systemic effects (5). Nitric oxide (NO) spreads to all parts of the respiratory system because of its low solubility in water. Nitrogen oxides diffuse through the Alveolar-cells and the adjacent capillary vessels of the lungs and are damaging to the lung tissue and their function in lungs causing breathing and respiratory problems, and premature deaths (5-7). They are also known to induce structural alterations in DNA that are potentially genotoxic (8).

NO2 is a significant air pollutant in and of itself, but it also interacts with other pollutants in the atmosphere to create ozone (O3) and acid rain that are very damaging to forests and the ecosystem in general (9). Nitrogen dioxide (NO2) can cause irritation to the eyes, nose, throat; causing cough, mucoid frothy sputum, decreased pulmonary function, chronic bronchitis, dyspnea (breathing difficulty); chest pain; pulmonary edema, cyanosis, tachypnea, tachycardia (10). Exposure above 150 ppm for 30 min to an hour results in fatal pulmonary edema or asphyxia and can result in rapid death (11). Below 1.0 ppm, short-term exposures (2 hour or less) do not appear to cause adverse effects in healthy subjects, at least as indicated by traditional measurement of pulmonary function (11). Diesel engine exhaust has been identified as a major contributor to NOx gases (12) and diesel fumes are classified as carcinogenic to humans (Group 1), based on sufficient evidence that exposure is associated with an increased risk of lung cancer (13).

In Spain, the Royal Decree 863/1985 of 2 April 1985 (14) adopting the General Regulation of Mining Basic Safety [RGNBSM] sets out the minimum general safety regulations for the operation of mines, quarries, sea salt mines, groundwater resources, geothermal resources, natural or artificial underground deposits, probes and surface and underground digging whenever any of these works requires the use of mining techniques or explosives, and geological resource processing plants in general, where mining techniques are applied. The air quality in tunnels is regulated by the technical instructions ITC 04.7.06 'Monitoring poisonous gases in the atmosphere during underground activities', of the General Regulation of Mining Basic Safety adopted by Royal Decree 863/1985 of 2 April 1985 (14).

Table 1 shows the Spanish ITC 04.7.06 TLV-TWA TLV-STEL and the proposed values in the Directive 2017/164/EU in transitional period until August 2023.

Table 1. TLVs in tunnelling construction.

	ITC 04.7.06 (ppm)		**Directive 2017/164/EU (ppm)**	
Gas	**TLV-TWA**	**TLV-STEL**	**TLV-TWA**	**TLV-STEL**
CO	25	100	20	100
CO2	5.000	12.500	5000	-
SO2	0,5	1	0,5	1
SH2	5	10	5	10
NO	25	30	2	-
NO2	3	5	0,5	1

Threshold limit value – time-weighted average (TLV-TWA): average exposure on the basis of a 8h/day, 40h/week work schedule. Threshold limit value – short-term exposure limit (TLV-STEL): A 15-minute TWA exposure that should not be exceeded at any time during a workday, even if the 8-hour TWA is within the TLV-TWA.

The Directive 2017/164/EU proposes a reduction in the NO TLV from 25 ppm to 2 ppm and the NO2 levels from 3 ppm to 0,5 ppm to increase the health protection in mines (15).

The gas monitoring in tunnels and mines is mandatory in Europe but there are not many recently published studies about gas monitoring in tunneling during construction. Most of the companies consider this information confidential, a 2009 study from Health and Safety Executive (HSE) recommend the use of real-time monitors with 0,1 ppm resolution.(16)

Real-time gas monitors are used by the construction industry as they provide a means of checking that controls are effective. This is ensured by an alarm and measures thus triggered so that no shift average values exceed the limit values or that the short-term values are complied with (17).

The aim of this research is to consider the feasibility of Threshold limit value (TLV) proposed in the Directive 2017/164/EU, and to give information about the gas levels in an NATM tunnel during construction. These reported effects make it necessary to reach the levels proposed in the European directive or even reduce it if possible.

2. EXPERIMENTAL PROCEDURE

The New Austrian tunneling method (NATM) is a contemporary tunnel design and construction approach that uses advanced monitoring to optimize various wall reinforcing procedures based on the kind of rock encountered during digging. Because the sequential excavation approach can be modified to various ground conditions utilizing shotcrete, flexible support with steel arches, rock bolts, and separating the tunnel section into sections as necessary (top heading, bench, invert). NATM technology has contributed to modernizing the current tunneling business (18). In short the NATM technique was selected for the tunnel due to its adaptability, flexibility, short mobilization time requirements and cost effective construction method. Some of the most iconic NATM tunnels constructed, at least in part with NATM are, the Hakkoda tunnel (26.45 km), the Iwate-Ichinohe Tunnel (25.81 km) both located in Japan, the Koralm Tunnel (KAT) (32.9 km) in Austria, and in Spain Somport (5.7 km), Viella (5.1 Km), Padornelo (5.9 Km), Paracuellos (4.7 km), Guadarrama 2 (3.3 km).

A tunnel project was selected as a representation of the techniques, plant and construction system used in Spain and several other European countries. The project is one of the Government's programmes of major road building schemes. The new road will be approximately 10 km long and includes a 2 km of twin bored tunnels. The excavation cross-section is 102 m^2 for each tunnel, excavation method by using explosives (Drill & Blast) or basic mechanical excavation.

Geology. The tunnel rocks excavated were mainly limestone and slate; there were several faults and problems with water inflows.

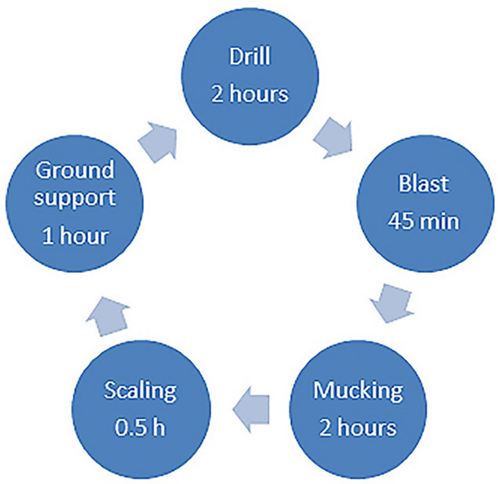

Figure 1. Simplified cycle in tunnel construction.

The underground tunneling construction includes a sequence of steps shown in Fig 1: drill & blast in hard rock or excavation in soft ground, mucking, rock support, and various ancillary works including extension of electricity and ventilation. Basically the construction system requires six workers per tunnel: one drill-rig operator, one shotcrete robot operator, one worker to operate the loader, and 3 articulated dumper drivers. A mechanic and an electrician are available in the yard. Other persons in the tunnels are the engineer, surveyor and pit boss.

The duration of a drill & blast cycle varies depending mainly on geology, but is typically 2 hours for drilling or mechanic excavation with 360º excavator; 45 min for charging, blasting, and smoke clearance; 2–3 hours for mucking out (hauling), about 0.5 hour for removing loose rocks (scaling); followed by the 1 hour of ground support shotcrete plus rock bolts (19, 20).

The tunnel ventilation consists of longitudinal forced ventilation with two Ventilators (one for each tunnel) Cogemacoustic T2 160, 132 Kw, and 2 m diameter flexible duct, the ventilation bagging was extended when required to keep fresh air in the tunnel face.

The main sources of toxic gases in this type of project are the explosives and the diesel fumes (21-25). The explosives used were dynamite, hydrogels and detonating cord the use of anfo was discarded due to the high content in oxides of nitrogen (NOx) gases. The diesel plant used were two Loading shovels CAT 966K and VOLVO L150F, four 360 degree excavators VOLVO EC240B , EC300 ENL, Komatsu PC 2104 and Wacker Nuseon 75z3, four articulated haulers VOLVO A25, and two telehandlers Manitou MRT 1640 and 1233S. The main emissions of concern from plant diesel vehicles are carbon monoxide (CO), nitric oxide (NO) and nitrogen dioxide (NO2), and particle matter with aerodynamic diameter less than 10 μm (PM10) (26, 27) , explosive materials produce a cloud of reaction products, the most toxic of which is nitrogen dioxide (NO2) (28).

2.1. Gas detectors

The gas detectors used in this study are the IBRID MX6 and the DRÄGER X-AM 5000. Fig. 2. MX6 iBrid multi gas portable gas detector and PID (Photoionization Detector) for flammable and toxic gases. Up to 6 gases can be monitored, with audio and visual alarms, and data logging. Full colour display. The Dräger X-am® 5000 belongs to a generation of gas detectors, developed especially for personal monitoring applications. This 1 to 5 gas detector reliably measures combustible gases and vapors as well as oxygen and harmful concentrations of toxic gases.

Figure 2. Real-time gas monitor devise IBRID MX6 and the DRÄGER X-AM 5000.

The main problem with real-time gas monitoring is cross sensitivities, also referred to as interfering gases. Cross interferences are gases that can cause the electrode inside the sensor to react even if the target gas is not present. As can be observed in table 2 the SO_2 measurement in an environment with NO_2 produces strong interference. (1 ppm of NO_2 can cause in the SO_2 sensor a false reading of -1,65 ppm). Note that there are selective filters to avoid or minimise some cross interferences.

Table 2. Cross interference chart in the DRÄGER X-AM 5000 sensors and IBRID MX6 sensors Source: Dräger and Industrial Scientific.

	DRÄGER X-AM 5000		IBRID MX6		
	NO	NO2	CO	SO2	H2S
Interference CO	0	0	1	1%	1%
Interference NO	1	0	25%	1%	1%
Interference NO2	0	1	-5%	-165%	-25%
Interference SO2	0	<-12%	<4%	1	5%
Interference H2S	20%	<-3%	5,0%	1%	1

On the other hand, real-time gas monitors are essential, and of vital importance, in tunnelling and mining works with regard to health & safety. The alarms in the gas monitors ensure that the warnings are not ignored and the user has to acknowledge the danger. It can save lives. The data logging allows professionals to track peak exposures during job functions at the end of a work shift or after a monitoring incident has occurred. In tunnelling, where the exposure to gases has great fluctuations in the exposure during the shift, real-time gas monitors are key to checking the gas levels and protecting workers with triggered alarms. They also allow a correct task evaluation and the application of engineering controls. It is the most suitable way to ensure compliance with the short term value requirements, because results must be available promptly to facilitate an appropriate reaction to the occurrence.

The evolution in gas monitors is continuous, new sensors with very low cross-sensitivities are under review at the moment and they will be on the market in the next few years. Great advances have been achieved in terms of sensitivity, selectivity, the limit of detection, miniaturization and portability for NO2, SO2 and H2S gas sensors using a novel combination of nanomaterials exhibiting various morphologies.(29). The NO sensor used has a range between 0 to 200 ppm, a resolution of 0.1 ppm and ±3% sensitive of the measured value; the NO2 sensor has a range between 0 to 50 ppm, a resolution of 0.02 ppm and ±3%sensitive of the measured value.

2.2. Methods

After walk-through surveys of the site were conducted and information on jobs and tasks was collected, workers were divided into groups performing similar tasks under similar working conditions. (Loading shovel, 360 degree excavator, articulated hauler, jumbo, telehandler, pit boss, surveyor, lead miner, miner). Occupational groups included in this study are described in detail in Table 3.

The measurements were conducted according to Technical instruction 04.7.06 'Monitoring poisonous gases in the atmosphere during underground activities' (14) .These measurements were carried out from an industrial hygiene perspective, with obligatory measurement of worker exposure with samplers at suitable locations (in practice, which enable recording of concentrations in the breathing zone). The measurements were conducted during the shift, in the most unfavourable situation. Control measurements conducted during the periodic measurements in the most unfavourable situation(s) in the working day shall also be taken into account.

Table 3. Main operations in tunnel construction.

Task	Description & Risks
Drill and blast & Rock bolt perforation and installation. 16 samples more than 480 readings.	The excavation method is drilling and blasting with a jumbo (drill rig). There is a helper at the face to assist with drill bit changes. A third worker prepares the explosives outside the tunnel. After completing the perforation, the charge of explosives starts with a telehandler, the rock is blasted. The main risks are total dust, respirable dust, silica dust and gases remaining in the tunnel from previous cycle.
Mucking. 13 samples more than 390 readings.	The blasted rock is loaded and transported out of the tunnel by a team formed with a loader driver and three articulated dumper drivers. The main risks are: - Diesel exhaust (drilling, loading, and transport equipment) - Nitrogen dioxide and carbon monoxide Sulfur dioxide (SO2) and Hydrogen sulfide (diesel powered equipment, blasting). - Oil mist and oil vapor (diesel-powered equipment) - Total dust and silica dust (drilling, loading, and transport operations).
Shotcreting operators. 5 samples more than 150 readings.	Shotcrete is applied on the tunnel walls for rock support. The operator with a remote control directs a nozzle, which sprays wet concrete onto the excavated surface. The concrete is mixed offsite and brought into the tunnel with a diesel lorry. The main risks are: - Total dust, respirable dust, and a-quartz (shotcreting) - Nitrogen dioxide and carbon monoxide (diesel powered equipment) and diesel exhaust.
Excavation/ scaling. 5 samples more than 150 readings.	After loading a 360º excavator with an hydraulic hammer remove all the soft material in the tunnel face, if the rocks is soft the tunnel advance can continue with the excavator. The main risks are: - Total dust, respirable dust, and a-quartz - Nitrogen dioxide and carbon monoxide (diesel powered equipment) and diesel exhaust.
Ancillary works. Maintenance 6 samples more than 180 readings.	Ancillary works as cable extension, ventilation duct extension, etc. The main risks are; - A mix of previous tasks risks. The ancillary works can be done on demand during the shift.

Concentrations of CO, CO_2, NO, NO_2, SO_2, H_2S were measured with direct-reading electrochemical sensors with a data logging facility built into the instrument (IBRID MX6 and the DRÄGER X-AM 5000.). An averaging period of one reading every 60 seconds was selected, a minimum of 30 readings were taken in each worker position during the similar exposure levels task, and the average of the 30 samples was calculated to give the gas exposure. The detection limit of nitrogen monoxide (NO), nitrogen dioxide (NO2), Sulfur dioxide (SO2) and Hydrogen sulphide (H2S) were 0.1 ppm and 2 ppm for the carbon monoxide.

Measuring procedures for the performance of workplace measurements are suitable if they satisfy the performance requirements of European standard EN 482 Workplace exposure - General requirements for the performance of procedures for the measurement of chemical agents (30). According to this standard for short term measurements in the range of half to double the exposure limit value the relative expanded uncertainty for analytical procedures to determine hazardous substances at the workplace should be ≤ 50%; and ≤ 30% for long term exposures.

The gas direct reading instruments have accuracy < 4% of the measured value, after the reading, a correction must be done in case of cross interferences table 2. (The cross-interference correction accuracy is 30%). The final measurement must be checked to ensure it fulfills the UNE-EN-482.

The sampling campaign was carried out in 5 different days to ensure representatively, 45 samples were considered for the study (each one is the average of 30 readings during the similar exposure levels task) for evaluating the tunnel cycle.

Averaging by measurement over the total exposure time during a shift is a particularly suitable way of establishing the shift average value. For the purpose of the study it was considered the worst case possible scenario.

3. RESULTS AND DISCUSSION

The 45 NO and NO_2 measurements are represented in Fig 3. The error bars represent the standard deviation. All the measurements are lower than the actual legal requirements, but it is observed that a few values exceed the 2 ppm for NO and 0,5 ppm NO_2 proposed in the Directive 2017/164/EU, and there are several values between 0,5 x TLV and TLV.

3.1. The results were divided into the different sequences in NATM construction

Drill and blast crew, rock bolt perforation and installation.

During this task, all the 16 measurements for the gases (NO, and NO_2) are below 0,5 x TLV. (Current TLV)

If we compare the measurements with the Directive 2017/164/EU (ppm), NO2 gas fulfills the limits but two NO measurements exceed the TLV and 2 measurements will be in the range of half to TLV. In other words, during this task, the miners will be over the limit of 2 ppm NO 12% of the time and 19% of the time near the limit.

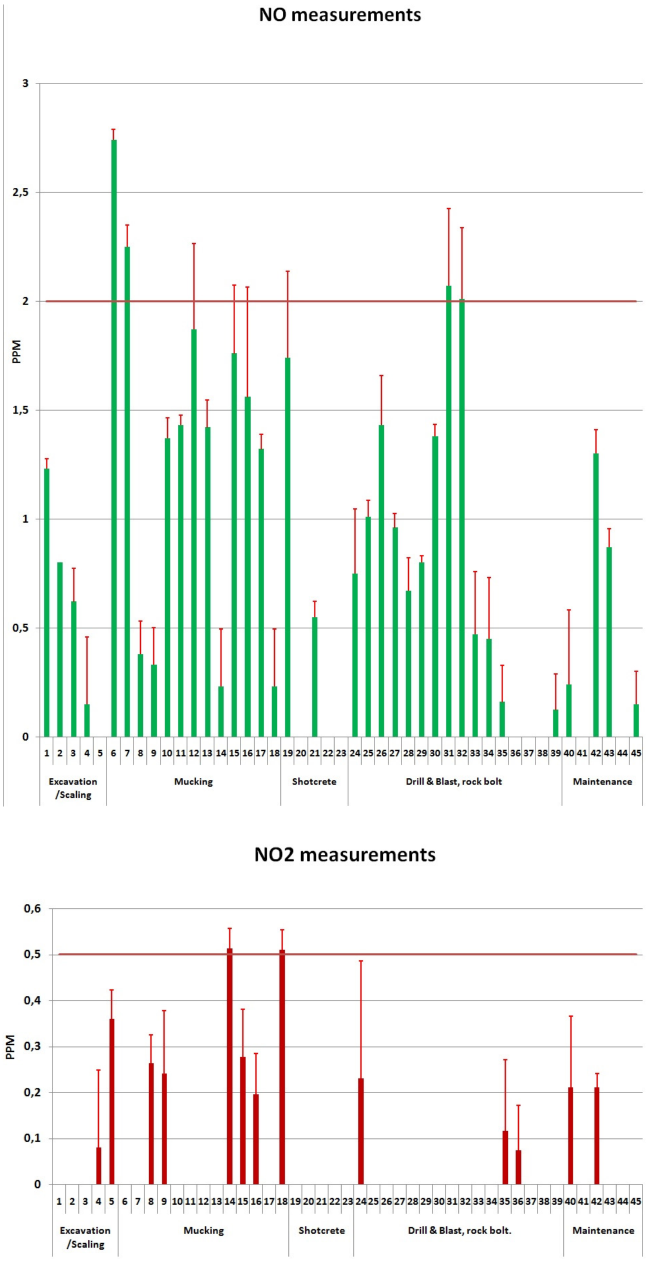

Figure 3. NO and NO2 measurements and standard desviation.

3.2. Mucking

During this task, all the 13 measurements for the gases NO, and NO_2 are below 0,5 x TLV. It is noted that CO and CO_2 had 5 measurements between a 0.5 x TLV to TLV.

If we compare the measurements with the Directive 2017/164/EU (ppm), two measurements will be exceeding the TLVs and 7 measurements will be in the range of half to double the exposure limit. In other words, during this task, the miners will be over the limit of 2ppm NO 15% of the time and around 54% of the time near the limit.

3.3. Shotcrete

During this task, all the 5 measurements for NO, and NO_2 are below 0,5 x TLV.

If we compare the measurements with the Directive 2017/164/EU (ppm), only one NO measurements will be in the range of half to TLV. During this task, the miners will be near the limit for around 20% of the time.

3.4. Excavation/scaling

During this task, all the 5 measurements for NO, and NO_2 are below 0,5 x TLV.

If we compare the measurements with the Directive 2017/164/EU (ppm), only one NO measurements will be in the range of half to TLV. During this task, the miners will be near the limit for around 20% of the time.

3.5. Ancillary works. Maintenance

During this task, all the 6 measurements for NO, and NO_2 were below 0,5 x TLV.

If we compare the measurements with the Directive 2017/164/EU (ppm), only one NO measurements will be in the range of half to TLV. During this task, the miners will be near the limit around 16% of the time.

Fig 4 in red, it is shown the periods of time that exceed the TLV Directive 2017/164/EU, the worst tasks are mucking and drill & blast.

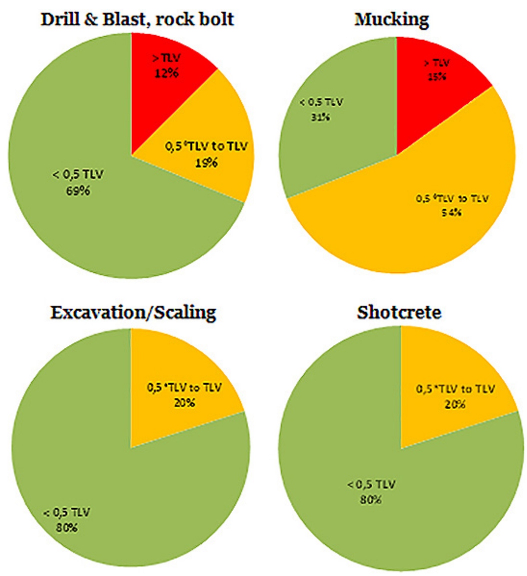

Figure 4. Exposition risk in % time in different tasks in NATM applying Directive 2017/164/EU levels.

To calculate the workers´ exposure, all the measurements during the shift must be averaged over the total exposure time, not only considering the worst task. In a normal cycle (2 hours drilling, 3 mucking, 1-hour shotcrete, 1-hour scaling) the tunnel studied will not exceed the TLV limits proposed in the Directive, but if we consider other scenarios, like for example a break down during mucking, (operation with more exposure Fig.4) the limits could be exceeded. This study allows a correct task evaluation to apply engineering controls to the required task.

A gas levels reduction should be done before August 2023 to ensure continuity on tunnel works and to improve health & safety.

Nowadays for reduction NO and NO2 levels a series of measurements are taken into account (25, 31) even though that the complete elimination is not technically possible in most of the tunnels and mines.

1. Electric machinery. The main plant manufactures are testing new electric models, Volvo, Epiroc etc. There are some plant available roofbolters, scaling equipment, drilling equipment, explosives loaders, loaders, forklifts and personal transportation vehicles.
2. The principal mining contractors in Spain, require subcontractors to use only the new Tier 4, Stage 5 plant, and replace it every 3 years where electric vehicles cannot be used.
3. Some plant manufactures are adding urea AUS32 (AdBlue), it is used to reduce harmful NOx emissions. AdBlue is injected from a dedicated tank into the exhaust pipe, in front of the Selective Catalytic Reduction (SCR). As it is heated in the exhaust, the AdBlue changes into ammonia (NH3) and carbon dioxide (CO2). When the nitrogen oxide (NOx) gases from the exhaust pipe react inside the catalyst with the ammonia, the NOx molecules in the exhaust are converted into harmless nitrogen and water, which is released into the atmosphere as steam. However, it is important to follow the correct storage, handling and disposal advice in order to maximize performance and ensure a safe operation.
4. Efficiency of explosives used, via better designed tunnel cuts and layout of drilling holes.
5. Engineering controls for example: using diesel exhaust gas after-treatment systems like catalytic converters to oxidise organic substances and gases, and catalysed and non-catalysed particulate traps to remove particulate matter.
6. Switching off engines whenever possible, rather than leaving them idling, and adopting a programme of regular engine maintenance.
7. Spraying systems located near the tunnel face are switched on before the start of blasting and remain in operation for around 30 minutes after detonation.
8. Water curtains with sprinklers along the tunnel.
9. Adequate ventilation, a safe, efficient and economical ventilation system is essential for gas reduction. The ventilation systems have to be optimized for adequate distribution and guidance of the fresh air streams for immediate dilution and exhausting of the gaseous and particulate components. There are technical limitations to reducing these components with ventilation airflow.

4. CONCLUSIONS

The study concluded that the NATM tunnels construction in Spain is close to the limits proposed in the Directive 2017/164/EU for NO and NO2 gases. Nevertheless, efforts need to be made to ensure compliance within the limits to avoid delays in the tunnel construction in 2023.

Real-time personal gas samplers are evolving quickly; some models without cross interferences (or low cross interferences) will probably be fully checked by 2023.

Electric plant machinery for tunnels is now a reality but not common in tunnel construction. It is expected that some contractors will turn to electric plant machinery in the following years.

The blast operations and ventilation systems in the tunnels need to be optimized and revised to reduce the gas levels.

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