Ventilation requirements for diesel equipment in underground mines – Are we using the correct values?

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Ventilation is the primary means of diluting atmospheric contaminants in underground mines. The majority of equipment in underground hard rock mines are diesel powered vehicles, which produce toxic gases such as Carbon Monoxide (CO) and Oxides of Nitrogen (NOx), as well as carcinogenic Diesel Particulate Matter (DPM). The airflow quantity for an underground mine is usually based on the engine power of diesel vehicles used in the mine, multiplied by unit airflow requirement, such as 0.05 to 0.06 cubic metre per second per kilowatt engine power (m³/s per kW) used in Australia or 0.047 to 0.092 m³/s per kW used in Canada. These unit airflow requirements are stated in local mining Occupational Health & Safety (OH&S) regulations.

However, the origin of these unit requirements is not clear, i.e. whether they are derived from scientific studies or are empirically based. Due to this, it is impossible to ensure that the values stated in the regulations are sufficient to dilute contaminants emitted by diesel equipment. This paper traces the history of these requirements based on literature review and online interviews with fellow underground ventilation practitioners and academics to find the origin of these requirements. A review of the relevance of these requirements in today’s situation is also outlined in this paper.

1. INTRODUCTION

Ventilation is the most critical safety aspect in an underground mine. An underground mine consists of a network of tunnels. Due to the confined nature of a tunnel air does not flow freely into an underground mine. The primary objective of a mine ventilation system is to provide sufficient airflow to dilute atmospheric contaminants that are produced by mining activities. The majority of equipment in underground hard rock mines are diesel powered vehicles, which emit toxic gases such as Carbon Monoxide (CO) and Oxides of Nitrogen (NOx). In addition to this, they also emit Diesel Particulate Matter (DPM), which has been officially declared as carcinogenic [1]. As a result of this, the airflow quantity for an underground hard rock mine is usually determined based on the engine power of diesel vehicles used in the mine, by multiplying the engine power with unit airflow requirement, such as 0.05 to 0.06 cubic metre per second per kilowatt engine power (m³/s per kW) as used in Australia or 0.045 to 0.092 m³/s per kW used in Canada. These unit airflow requirements are stated in local mining Occupational Health & Safety (OH&S) regulations.

However, the origin of these unit requirements is not clear. All regulations do not state the reason behind these values. By not knowing the origin of these values, it is impossible to ensure whether the supplied airflow is adequate to dilute contaminants that are emitted by diesel equipment used in an underground mine. This paper traces the history of these requirements based on literature searches and online interviews with underground ventilation practitioners and academics to find the origin of these requirements. A review of the relevance of these requirements in today’s situation is also outlined in this paper.

2. REVIEW ON CURRENT REGULATORY VENTILATION REQUIREMENTS FOR MINE DIESEL VEHICLES

Table 1 shows regulatory ventilation requirements for underground mine diesel vehicles in several countries that have large mining industries.

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2. REVIEW ON CURRENT REGULATORY VENTILATION REQUIREMENTS FOR MINE DIESEL VEHICLES

Table 1 shows regulatory ventilation requirements for underground mine diesel vehicles in several countries that have large mining industries.
Table 1. Regulatory ventilation requirements for underground mine diesel vehicles in major mining countries

<table>
<thead>
<tr>
<th>Location</th>
<th>Ventilation requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Varies by state and territory, from 0.05 to 0.06 m³/s per kW, most commonly 0.06 m³/s per kW</td>
</tr>
<tr>
<td>Canada</td>
<td>Varies by province and territory, from 0.047 to 0.092 m³/s per kW, most commonly 0.06 m³/s per kW</td>
</tr>
<tr>
<td>South Africa</td>
<td>0.06 m³/s per kW based on the best practice</td>
</tr>
</tbody>
</table>

It can be seen from Table 1 that the requirement varies by country. It has to be noted that these values are only to dilute toxic gases. This is because all of these regulations were issued before 2012 and DPM was just officially declared as a hazardous substance in that year [1]. In response to this declaration, the government of the State of Western Australia in Australia issued a new guideline on the management of diesel emission in Western Australian mining operations in 2013. The guideline states that ventilation air quantities six to eight times greater than those currently found in most mines (0.05 to 0.06 m³/s per kW) are required to adequately dilute both toxic gases and DPM below the accepted Threshold Limit Value - Time Weighted Average (TLV-TWA) exposure limit [3]. However, as the origin of these values is not clear, it cannot be ensured that multiplying these values six to eight times will adequately dilute both toxic gases and DPM to below TLV-TWA.

A different approach is used in the United States, which also has a large mining industry. The Mine Safety and Health Administration (MSHA) certifies ventilation requirement for various diesel engines used in underground mine [4] [5]. The amount of air required to dilute gaseous components of the engine exhaust to be below TLV-TWA adopted by MSHA (CO to 50 ppm, CO₂ to 5000 ppm, NO to 25 ppm, and NO₂ to 5 ppm) at each mode is calculated based on an engine testing program. MSHA also calculates the ventilation requirement to dilute DPM emissions of an engine to 1 mg/m³, which is termed as Particulate Index (PI). The PI is informational only and not enforceable by MSHA inspectorate. The ventilation requirement based on gases is what the mine must provide for the operation of the engine underground [4] [6]. Table 2 shows some examples of MSHA’s certified ventilation requirements for diesel engines used in underground mine. It has to be noted that the original values are shown in Imperial units and they were converted to SI units in this table by the author.

Table 2. Examples of MSHA’s certified ventilation requirements [7]

<table>
<thead>
<tr>
<th>Engine manufacturer</th>
<th>Model</th>
<th>Power kW @ RPM at 305 m elevation</th>
<th>Airflow to dilute gases (m³/s)</th>
<th>Particulate Index (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caterpillar</td>
<td>3054 DIT</td>
<td>81 @ 2400</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>3306 DITA</td>
<td>123 @ 2200</td>
<td>5.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Cummins</td>
<td>QSX15</td>
<td>336 @ 2000</td>
<td>8.3</td>
<td>8.0</td>
</tr>
<tr>
<td>Cummins</td>
<td>QSK19</td>
<td>567 @ 2100</td>
<td>23.6</td>
<td>11.8</td>
</tr>
<tr>
<td>Volvo</td>
<td>TAD1340VE</td>
<td>259 @ 2100</td>
<td>7.3</td>
<td>5.0</td>
</tr>
<tr>
<td>Volvo</td>
<td>TAD1344VE</td>
<td>357 @ 2100</td>
<td>9.9</td>
<td>5.9</td>
</tr>
</tbody>
</table>

As the engine power is also shown in the certification, the ventilation requirement in m³/s per kW for each engine can therefore be calculated. The results are shown in Table 3.

Table 3. Examples of ventilation requirements for MSHA certified diesel engines

<table>
<thead>
<tr>
<th>Engine manufacturer</th>
<th>Model</th>
<th>Ventilation requirement to dilute gases (m³/s per kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caterpillar</td>
<td>3054 DIT</td>
<td>0.052</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>3306 DITA</td>
<td>0.041</td>
</tr>
<tr>
<td>Cummins</td>
<td>QSX15</td>
<td>0.025</td>
</tr>
<tr>
<td>Cummins</td>
<td>QSK19</td>
<td>0.042</td>
</tr>
<tr>
<td>Volvo</td>
<td>TAD1340VE</td>
<td>0.028</td>
</tr>
<tr>
<td>Volvo</td>
<td>TAD1344VE</td>
<td>0.028</td>
</tr>
</tbody>
</table>
Most of the ventilation requirements shown in Table 3 are less than the values shown in Table 1. It has to be noted that the TLV-TWA for highly toxic gases, CO and NO₂, adopted by MSHA is about double that of TLV-TWA adopted by countries listed in Table 1. Table 4 shows TLV-TWA for CO and NO₂ in these countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>TLV-TWA for CO (ppm)</th>
<th>TLV-TWA for NO₂ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>Canada</td>
<td>Varies by province and territory, 20 to 50</td>
<td>Varies by province and territory, 2 to 5</td>
</tr>
<tr>
<td>South Africa</td>
<td>30</td>
<td>3</td>
</tr>
</tbody>
</table>

When values in Table 3 are doubled, the results are similar to the values in Table 1. Upon examining this, one might ask the question “Are values in Table 1 based on a testing program similar to the one carried out by MSHA?” Literature searches and discussion with underground ventilation practitioners and academics did not find evidence that such a testing program has been carried out in these countries. Another question is “Did the United States use the same approach as Australia, Canada and South Africa in the past? If yes, when did it change the approach to the one based on an engine testing program?” The only way to answer these questions is to trace the history of these requirements in past OH&S regulations.

3. HISTORY OF REGULATORY VENTILATION REQUIREMENTS

The history of ventilation requirements in past OH&S regulations was traced by literature searches and online interviews done via the Underground Ventilation Committee (UVC) discussion group, which is administered by the Society for Mining, Metallurgy, and Exploration (SME). The 215 members of this discussion group are practitioners and academics in the area of underground ventilation from around the world. This group can be found in [10].

Based on these searches and interviews, some traces of the past regulations were found. They are summarized as follows.

3.1. The United States

In 1942, The United States Bureau of Mines (USBM) conducted several tests on diesel locomotives used to excavate the Delaware aqueduct [11]. These tests measured the amount of air that was required to dilute exhaust gases to be below the then safe concentration limit (CO to 100 ppm, CO₂ to 10000 ppm, and Oxides of Nitrogen to 36.5 ppm). The tests found that airflow quantity of 65 to 75 cubic feet per minute (cfm) per brake horsepower (0.041 to 0.048 m³/s per kW) must be supplied. Six years later, it was recommended that 75 cfm of airflow per brake horsepower should be used when using diesel engines in underground [12]. No explanation was provided for this value but since the authors of this paper were working at USBM, it can be concluded that this value was based on the 1942 testing at the Delaware aqueduct tunnel.

A value of 100 cfm per brake horsepower (0.063 m³/s per kW) had been used [4], which was based on USBM engine tests. The author of this paper did not mention the timeframe of the usage of this value. There is an indication in his paper that this value was used around 1972 when TLV-TWA of CO was reduced from 100 to 50 ppm. It appears that in response to this change, USBM conducted some engine tests and found the value of 100 cfm per brake horsepower.

No information was found regarding when the ventilation requirement in the United States changed to the one based on MSHA’s engine testing program. The only information found is that this approach was already adopted in 1978 [13].

3.2. Australia

Unlike in the United States where mining OH&S regulations are administered by central (federal) government, in Australia they are administered by local (state and territory) governments. As a result, the ventilation requirement varies by State. The value is commonly 0.06 m³/s per kW, although Western Australia stipulates that when the raw
exhaust gases contain less than 1500 ppm of CO and 1000 ppm of Oxides of Nitrogen, the value of 0.05 m³/s per kW can be used [14]. It has to be noted that the value of 0.06 m³/s per kW is similar to 100 cfm per brake horsepower used in the United States in the early 1970s.

In the 1980s, the value of 0.04 m³/s per kW was adopted across all states. This value is similar to the one derived by USBM’s Delaware aqueduct tests. Since 1990s, the values of 0.05 and 0.06 m³/s per kW have been adopted across all states until today, except in Queensland. It removed the ventilation requirement from its mining OH&S regulation in 2001 and since then has been stipulating that underground mines in that state must provide adequate ventilation [15]. In practice, some mines in Queensland tend to follow the value adopted in Western Australia, e.g. [16].

3.3. Canada

Like Australia, mining OH&S regulations are administered by local (provincial and territory) governments, which results in a variation of ventilation requirements across all provinces. The exceptions are Crown Corporations and uranium mines that fall under Federal jurisdiction [2]. All provinces and territories except Ontario and Yukon adopt the value based on Canadian Standards Association (CSA) standards, which were published in 1988 for gassy underground coal mines and in 1990 for non-gassy underground mines [2]. These standards are based on Exhaust Quality Index (EQI), which is calculated using the following equation (gases in ppm and DPM in mg/m³, measured in the engine exhaust after any treatment device):

$$EQI = \frac{CO}{50} + \frac{NO}{25} + \frac{DPM}{2} + 1.5\left(\frac{SO_2}{3} + \frac{DPM}{2}\right) + 1.2\left(\frac{NO_2}{3} + \frac{DPM}{2}\right)$$

The ventilation requirement is calculated based on the airflow quantity required to achieve EQI value of 3. The value varies between provinces and territories with 0.06 m³/s per kW as the common value. There is no information found whether these jurisdictions adopted CSA standards immediately after their release. It appears that all except Saskatchewan and Northwest & Nunavut did that. These two jurisdictions adopted them between 2002 and 2012 [2] [17].

As mentioned before, Ontario and Yukon are yet to adopt these standards. Ontario adopted 0.06 m³/s per kW in 1990 and has been doing so until today [18]. Yukon has also adopted 0.06 m³/s per kW [2]. It is interesting to note that they adopt the same common value as the other jurisdictions that adopt CSA standards, and this value is same as that adopted in Australia.

It was found that the ventilation requirements of 0.06 to 0.09 m³/s per kW were already recommended to be used in the province of Quebec in 1975 [19], long before CSA standards were published. In the late 1960’s values between 50 to 100 cfm per brake horsepower (0.032 to 0.063 m³/s per kW) were used [20]. It is interesting to note that these values are similar with the finding in USBM’s Delaware aqueduct test that is mentioned in Section 3.1.

3.4. South Africa

Unlike Australia and Canada, the ventilation requirement is not stated in the mining OH&S regulations. The value that is recommended, 0.06 m³/s per kW, is based on the best practice [21] [22] [23]. There is no explanation for the meaning of “best practice” found in both references. It has to be noted that this value is the same as that commonly used in Australia and Canada.

In the past, the value of 100 cfm per brake horsepower (0.063 m³/s per kW) was used. This was not stated in the OH&S regulations at that time [24]. There is no explanation found behind the adoption of this value. However, it is interesting to note that this value is the same as the one used in the United States in early 1970s.

4. DISCUSSION

A review of the history of ventilation requirements in the United States, Australia, Canada, and South Africa has found similarity between values used in the present and the past. Online interviews via the UVC discussion group found an indication that the other countries simply “copied and pasted” the values derived in the United States, and
then embedded it in regulations and guidelines that were not updated for a long time. It has to be noted that typical mining OH&S regulations are usually in place for more than 10 years. An example of this is the regulation in the State of Western Australia in Australia which has been in place since 1995.

This practice has caused people in the mining industry to ignore the background of these values. As mentioned before, the TLV-TWA for CO and NO₂ adopted in MSHA’s certification program is about double the ones adopted in Australia, Canada, and South Africa. Therefore, directly adopting values derived in the United States is misleading. These countries should conduct engine tests to derive their own ventilation requirements.

Figure 1 shows the health impact of Carbon Monoxide as a function of concentration and exposure time. The TLV-TWA adopted in Australia and South Africa (30 ppm) is shown as a vertical dashed line. It is clear that this is the concentration limit where there is no perceptible effect at 8 hours of exposure time.

Figure 1. Health effect of Carbon Monoxide as a function of concentration and exposure time [25]

Several studies mentioned in US National Research Council study on rocket emission toxicants [26] state that healthy subjects exposed to NO₂ for 2 hours at a concentration of 5.0 ppm exhibited increased airway resistance and impaired oxygen exchange in the lung.

It is interesting to note that the limit for CO and NO₂ used by MSHA’s certification program is above the latest TLV-TWA recommended by American Conference of Governmental Industrial Hygienist (ACGIH), which is 25 ppm for CO and 3 ppm for NO₂ [27]. These limits are similar with the ones adopted in Australia, Canada, and South Africa. It appears that the limits used by MSHA are based on 1972’s TLV-TWA [4]. Therefore, it can be argued that these limits, or even lower, should be used in the engine testing, rather than those currently used by MSHA.

5. RELEVANCE OF CURRENT VENTILATION REQUIREMENTS IN TODAY’S SITUATION

The requirements described before are based on TLV-TWA, which is based on an 8 hour working period per day. However, many underground mines in the world currently employ 12 hour working periods per day. Therefore, TLV-TWA is no longer valid in this situation.

Safe Work Australia proposed that the safe concentration limit for toxic gases in a 12 hour working period should be half of their TLV-TWA [28]. Therefore, the safe concentration limit for CO and NO₂ in today’s situation should be
15 and 1.5 ppm respectively in Australia and South Africa, 10 to 25 and 1 to 2.5 ppm respectively in Canada, and 12.5 and 1.5 ppm respectively in the United States. Engine tests should be conducted to derive the correct requirements based on these safe concentration limits.

DPM must also be included in these tests as the 1942’s USBM tests and the current MSHA certification program do not include it (PI is included in MSHA program, but it is not enforceable, see Section 2). Heat must also be included as new equipment is larger than their predecessors; therefore they emit more heat than their predecessors did.

The introduction of equipment with Tier IV engines into the mining industry also warrants a review on current requirements. A study carried out by [5] found that although it is claimed that toxic emissions (gases and DPM) of these engines will be reduced by 90%, the airflow requirements are unlikely to decrease by 90%. No engine tests were included in this study as these engines were not available for testing during this study.

6. CONCLUSION

The review of the history of ventilation requirements in the past regulations found that the current values are incorrect due to the differences of TLV-TWA between countries and longer working hour in many of today’s mines compared to that when the values were derived. OH&S regulators in these countries should review these values and derive new ones based on an engine testing program. Adjusted safe concentration limits should be used in this testing program when working hour is not 8 hours per day. DPM and heat must be included in this testing program.

7. ACKNOWLEDGEMENT

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References


[27] American Conference of Governmental Industrial Hygienist (ACGIH), 2013. Table of exposure limits for chemical and biological substances.
