

*Excerpted from the master's thesis:*

**ESTABLISHING TOTAL AIRFLOW REQUIREMENTS FOR UNDERGROUND METAL/NON-METAL MINES WITH TIER IV DIESEL EQUIPMENT**

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# **ESTABLISHING TOTAL AIRFLOW REQUIREMENTS FOR UNDERGROUND METAL/NON-METAL MINES WITH TIER IV DIESEL EQUIPMENT**

## **ABSTRACT**

Traditionally, airflow requirements for diesel equipment operating in underground environments such as mines and tunnels were determined by multiplying the vehicle power by a ventilation rate that was either mandated by regulations(s) or determined empirically from known quantities. In some cases, utilization factors were further used to adjust (reduce) the total airflow calculations for a diesel equipment fleet. However, in light of the drastic reductions to diesel equipment emissions mandated by the US EPA Tier IV and EURO Stage 4 regulations, there is currently a great deal of uncertainty in the underground mining industry among those responsible for the ventilation of planned new mines or the expansion of current mines. Tier IV engine standards mandate a reduction of DPM and NO<sub>x</sub> of approximately 95%, but can ventilation rates at mines with Tier IV equipment (or equivalent) really be reduced by a factor of twenty? This paper outlines some of the factors that affect the airflow required for the ventilation of modern diesel-powered equipment and examines how they can be applied in determining a reasonable ventilation rate for Tier IV compliant equipment operating in subterranean environments.

## **KEYWORDS**

Diesel, Emissions, Particulates, Gases, Heat, Dust, Emissions control, Tier IV, Mine ventilation

## **INTRODUCTION**

The promulgation of new rules either directly or indirectly affecting the toxic emissions of diesel engines has, and will continue to have profound effects on the ventilation quantities necessary for diluting and removing noxious contaminants in underground environments. In much of the world, the emissions of diesel-powered equipment are governed by the U.S. Environmental Protection Agency's (EPA's) "tiered" emissions standards (similar regulations exist elsewhere in North America, Europe and Australasia under the aegis of various other regulatory bodies). Current EPA regulations call for all "off-highway" or nonroad diesel-powered vehicles (such as those found in the mining industry) to meet "Tier IV" emissions standards by 2014, with interim standards being enforced in a "phased" approach leading up to that time. By the time the rule is fully implemented in 2014, toxic emissions (including CO, NO<sub>x</sub> and Particulate Emissions) of nonroad diesel engines will be reduced by approximately 90%. Naturally, this has led to much confusion and uncertainty surrounding the calculation of airflow requirements for underground mines and other industrial excavations.

The determination of airflow quantity is both a difficult and essential step in the mine design process. There are many factors that influence the selection of mining equipment (e.g. host rock strength, mining method, production rates, location, etc.) and wide variations in emissions characteristics even amongst vehicles of similar size and power. Navigating these uncertainties and arriving at a reasonable estimate of total airflow, while difficult, remains one of the most important aspects of underground mine design.

Perhaps not surprisingly given the number of parameters affecting the total airflow required for a piece of diesel equipment, there is currently little consensus as to how the determination for total airflow is performed, and the process can vary considerably from mine to mine, country to country and even province to province. Whatever the criteria used, this is a process that is critical to the success of the mine (particularly in the case of new mine design) and should be performed while carefully considering how the equipment fleet required will be influenced by all of the relevant design parameters. Only once the

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selection of the necessary equipment is made can the process of determining the total amount of airflow required be completed.

Figure 1 shows a graphical representation of the relationship between the initial design parameters with the selection of equipment fleets and ultimately, ventilation rates. This process correctly incorporates the separate calculation of airflow rates (Q) for each of the four contaminant products with the total ventilation amount (or rate) required equivalent to whichever is greatest.

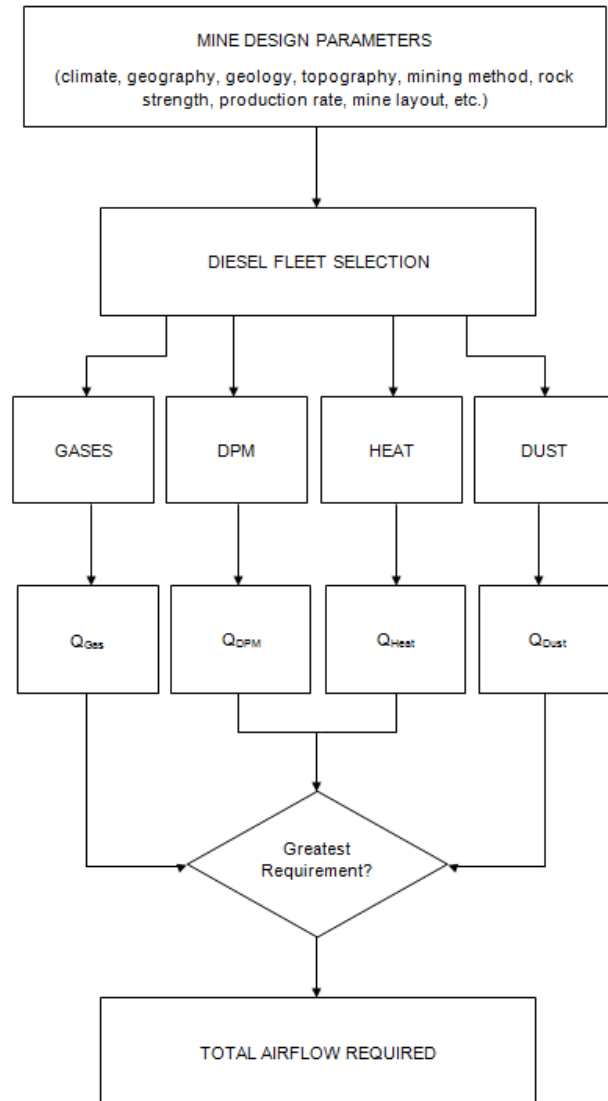


Figure 1 - Relationship between design parameters and ventilation rates

### CONTAMINANT PRODUCTS OF DIESEL EQUIPMENT UNDERGROUND

In addition to the noxious gaseous and particulate components of the exhaust, there are two other contaminants generated by diesel equipment that must be mitigated by the ventilation system. All diesel engines create heat, and in most mining environments, their activities also generate mineral (rock) dust. All of these pollutants represent a danger to the underground workforce and must be mitigated at least partially by the ventilation system. The deleterious health effects of the contaminants associated with diesel

engine use in underground environments are by now well chronicled; this section is intended merely as a review of what the pollutants are, and why their consideration is important in considering total airflow requirements.

### **Gaseous Products of Combustion (POC)**

The gaseous POC from diesel engines include CO, CO<sub>2</sub>, and NO<sub>x</sub>. Although diesel engines also produce water vapour, this is not considered a gaseous contaminant, and its influence on the ambient underground environment will be further addressed in the sub-section addressing “Heat”. The dilution of gaseous POC is achieved by a sufficient quantity of fresh air, with the velocity of airflow also playing a part in removing contaminants from the source where workers are likely to be exposed.

### **Diesel Particulate Matter**

The production of DPM varies considerably among sizes, types, manufacturers and even series of diesel engines. Being sub-micron in size, DPM behaves as an aerosol, and its control is similar to that of any other gaseous contaminant; dilution and removal by the ventilation system. Due to its status as a human carcinogen, the regulation of DPM exposure levels has experienced a state of flux over the last decade, and further changes to statutes are expected in mining regions around the world.

### **Heat**

The heat added to the ambient environment due to the operation of diesel equipment is the result of many factors including the fuel consumption, efficiency and water generation of a particular vehicle and the inlet air temperature and density. In certain environments, heat stress poses a significant health risk to workers, and in some cases, to modern diesel equipment. A sufficient quantity of fresh air acts as a heat sink, removing heat from the equipment and transporting it away from the source(s).

### **Mineral Dust**

Dust is perhaps the most difficult of the contaminant products of diesel equipment to quantify and mitigate. Although diesel engines do not directly produce mineral dust, it is difficult to imagine an underground environment in which the operation of diesel equipment does not directly result in the generation or propagation of mineral dust. The mitigation of dust generated by operating diesel equipment is most commonly accounted for in traditional airflow calculations through the application of minimum airflow velocities where diesel equipment will be operating.

## **EXISTING MODELS FOR AIRFLOW DETERMINATIONS**

The most generally accepted model for determining the total airflow required for a diesel equipment fleet involves utilizing an accepted multiplier (given in the project design criteria) of the equipment power and with percentage reductions made for the utilization and/or availability of individual pieces of equipment. Both the values themselves (0.045 – 1.00 m<sup>3</sup>/s per kW) and the methods for arriving at those values (empirical derivation, statutory compliance, Exhaust Quality Index, ALARA, etc.) demonstrate considerable variability. In addition, whatever criteria are eventually selected must be further balanced within the economic framework of the mine<sup>1</sup>.

What is common among the different methods of determining the proper rate of ventilation is that whatever the method used for arriving at the multiplier, once this number has been identified, it is

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<sup>1</sup> Although direct cost (either capital or operating) should never be used to justify a deficient design or condition with regard to the health and safety of the workforce, the economics of a project must nevertheless be considered during the design process, and responsible compromises may need to be made between operations (production) and ventilation capacity, particularly in the case of existing mines.

generally accepted that it will be sufficient to cover all four contaminant products. Generally, separate calculations for each contaminant are not performed, and when they are, such as in the case of heat load generated by the diesel fleet, this is more often a result of concerns with other phenomena (i.e. strata heat) rather than a particular desire to quantify the ventilation required for the equipment fleet.

In the past, the gaseous and/or particulate emission rates of the diesel-powered equipment were of sufficient quantity that ventilation sufficient to dilute and remove these contaminants could reasonably be expected to provide sufficient airflow for cooling of the air stream and the removal of any dust generated. However, this could potentially lead to great inefficiencies whereby the amount of airflow provided was significantly more than what was required, particularly with more recent, low-emission engines. At the scale of many large mining complexes, these inefficiencies can potentially result in substantial penalties in terms of the capital and operating cost of the ventilation system. More often, the total airflow requirement for underground mines has been undersized (insufficient flow), especially in cases where the impacts of heat and dust were not considered during the design phase and ventilation rates were derived solely from bench tests by regulatory agencies.

### Statutory Compliance

In many parts of the world, ventilation rates are mandated by the relevant regulatory bodies for mining. The origin(s) of the multiplier used, although generally considered to have its roots in a scientific analysis of the various contaminants, is often muddled by time, and the exact justification(s) for the specified numeric multiplier and the influence of other considerations (i.e. economic impact) are not known. This uncertainty is further compounded by the variations found in the required airflow for diesel equipment.

Table 1 gives a selection of statutory ventilation requirements for prominent mining countries.

Table 1 - Selected ventilation regulations for diesel mining equipment (Gangal, 2012)

Location	Statutory Ventilation Rate(s)
Australia	0.06 m <sup>3</sup> /s per kW minimum
Canada	Varies by province from 0.045 – 0.092 m <sup>3</sup> /s per kW minimum – most commonly 0.06 m <sup>3</sup> /s per kW
Chile	2.83 m <sup>3</sup> /min per effective brake horsepower minimum (0.063 m <sup>3</sup> /s per kW equivalent)
China	0.067 m <sup>3</sup> /s per kW
South Africa	0.063 m <sup>3</sup> /s per kW minimum (based on “best practice”)
USA	Based on MSHA certificate – ventilation required to dilute contaminants to specified levels at the tailpipe

Upon examining Table 1, one might ask the question, is the performance of diesel equipment significantly different in Australia than it is in the United States? What about the differences in emissions produced from a diesel engine in Chile’s Copiapó region (elevation 1,000 masl) compared to the performance of the same engine in an Andean mine (elevation 5,000+ masl)? Do the toxic emissions, gaseous or particulate affect miners in B.C. (25 ppm CO PEL) differently than those in the Yukon (50 ppm CO PEL)?

Clearly there are significant, fundamental problems with this method of determining total airflow based on fixed rates of ventilation, yet this is by far the most commonly used method for performing these calculations today and is even written directly into the mining regulations in many important mining regions of the world. Furthermore, the fact that heat and/or dust is not specifically acknowledged as a diesel contaminant as part of the regulations (covered by the word “minimum” in the regulations) can lead to underestimating the amount of airflow required even in cases where newer/cleaner equipment is utilized.

### Direct Engine Testing (EQI, etc.)

In Canada and the United States the regulatory bodies responsible for defining and enforcing mining legislation have developed extensive laboratory testing protocols to measure diesel engine emissions and determine the amount of ventilation required to dilute potentially harmful gaseous and particulate POC at the tailpipe based on each individual engine’s performance.

NRCAN, the regulatory body responsible for setting standards for diesel engines approved for use in Canadian underground mines calculates the Exhaust Quality Index (EQI) for approved diesel engines according to the following formula:

$$EQI = \frac{CO}{50} + \frac{NO}{25} + \frac{DPM}{2} + 1.5 \left[ \frac{SO_2}{3} + \frac{DPM}{2} \right] + 1.2 \left[ \frac{NO_2}{3} + \frac{DPM}{2} \right] \quad (1)$$

where: DPM (mg/m<sup>3</sup>) and gas concentrations (ppm) are measured in raw exhaust gases (NRCAN, 2011).

The engine is run through a fully repeatable 18-mode operational test. Sufficient airflow is provided in order to reduce EQI to a value of “3” for the purpose of establishing the engine’s approved ventilation rate, with the final ventilation rate equivalent to the greatest amount of ventilation required at any point during the test.

In the United States, MSHA certifies a “nameplate” ventilation rate for specific pieces of equipment based on an 8-mode operating test. The amount of air required to dilute gaseous components of the engine exhaust (CO to 50 ppm, CO<sub>2</sub> to 5000 ppm, NO to 25 ppm and NO<sub>2</sub> to 5 ppm) at each mode is calculated, with the approved ventilation rate equal to the highest of the 8-mode test value. MSHA also calculates a “Particulate Index” (PI) for each approved engine, based on a weighted average of the 8-mode tests. The PI for an approved engine is equivalent to the amount of air required to dilute the particulate emissions of an engine to 1 mg/m<sup>3</sup> (note that this value is significantly higher than the 0.16 mg/m<sup>3</sup> MSHA SWA PEL for DPM). It should also be noted that the MSHA PI ventilation rate is for informational purposes only and NOT enforceable by the agency’s inspectorate (Dieselnet, 2012).

The method utilized by NRCAN and MSHA for determining diesel engine airflow requirements applies specific and repeatable criteria to establish ventilation rates for the gaseous and particulate emissions of diesel engines and is generally a more accurate means of determining the total airflow requirements for an individual engine (fleet airflow requirements may be calculated by a simple summation of the total airflow requirements for each piece of equipment in the fleet). Although this accuracy is often helpful in comparing similar pieces of equipment, this method is still deficient in accounting for the heat and dust generated by diesel equipment. As the values generated from the engine testing are generally less than those generated from the direct multiplier, their application in making fleet airflow determinations can lead to estimates of total required airflows that are even less than those made using the regulatory multiplier in practice (keeping in mind that it is not common practice to account for the heat generated from diesel equipment except in cases where environmental heat and/or virgin rock temperature are known concerns).

## Empirical Derivation (Experience)

The empirical method of determining the ventilation rate for underground diesel equipment is perhaps the most accurate, yet hardest to implement method of determining diesel fleet airflows. This is largely because of the number of data points required to establish meaningful values capable of predicting the contaminant production from the combination of complex mining parameters that affect the required flow rates.

In light of the practical requirements for establishing sufficient numbers that are empirically derived, then implemented, vetted and altered as necessary in a somewhat iterative process, it is generally only well-established ventilation consulting firms and the largest of mining corporations that have the ability to determine reasonable ventilation rates based solely on empirical data.

As ventilation rates based on empirical evidence (compliance or non-compliance with local regulations and often verified) account for all contaminants produced by diesel engines (and yet must still provide a reasonable factor of safety), those values based on vehicle power tend to be higher than those specified by the various regulatory bodies. For determining required airflow based on a diesel vehicle's power, Mine Ventilation Services, Incorporated<sup>2</sup> engineers recommend using a value of 0.080 m<sup>3</sup>/s per kW. The Canadian ventilation consulting firm AirFinders, Incorporated uses a value of approximately 0.063 m<sup>3</sup>/s per kW<sup>3</sup>. After implementation of the MSHA Final Rule for DPM Exposure in 2008, the Senior Ventilation Engineer at Climax Molybdenum's Henderson Mine began using a value of 0.095 m<sup>3</sup>/s per kW for determining all future ventilation requirements based on the operating diesel equipment fleet (Loring, 2010).

Figure 2 shows a comparison of ventilation rates for varying mine types based on a survey of mines conducted in 2001. A significant distinction is clearly visible based on the different mining methods, although it should be noticed that this information was voluntarily provided, and is in no way indicative of industry "best practice" or even regulatory compliance.

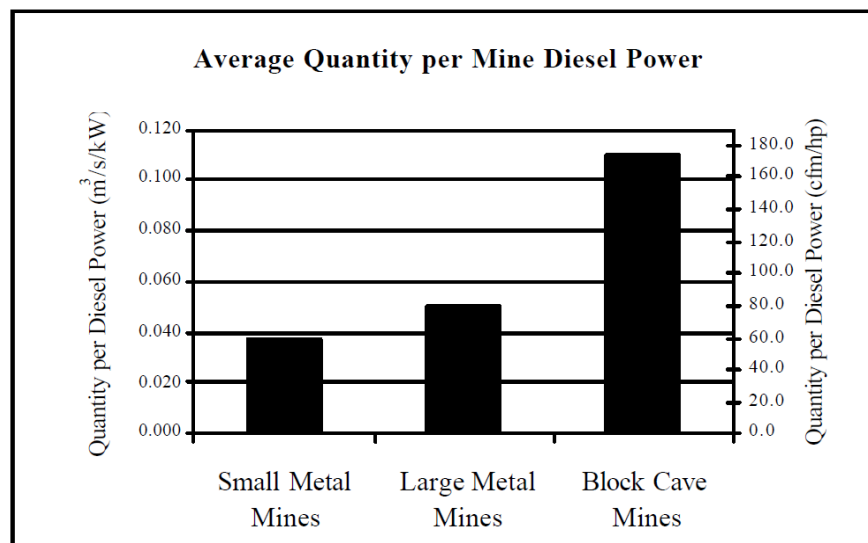


Figure 2 - Ventilation rates utilized for various mines (Wallace, 2001)

<sup>2</sup> The author is employed as a Principal Engineer with MVS, Inc. The ventilation rate referenced was developed empirically as a result of almost 30 years of data collected regarding mine ventilation systems around the world.

<sup>3</sup> This number is used when determining the airflow required for specific equipment utilized in specific areas/situations.

Although less common, total airflow determinations for underground mines are also sometimes made based on production (tonnage) rates. These types of airflow calculations are even more general than the application of ventilation rates based on the diesel vehicle fleet power, and are not adjusted to account for differences in fixed facilities such as underground shops, sumps, lunchrooms, etc.

Figure 3 gives an example of ventilation rates based on total mine production (mass of airflow utilized per mass of ore produced).

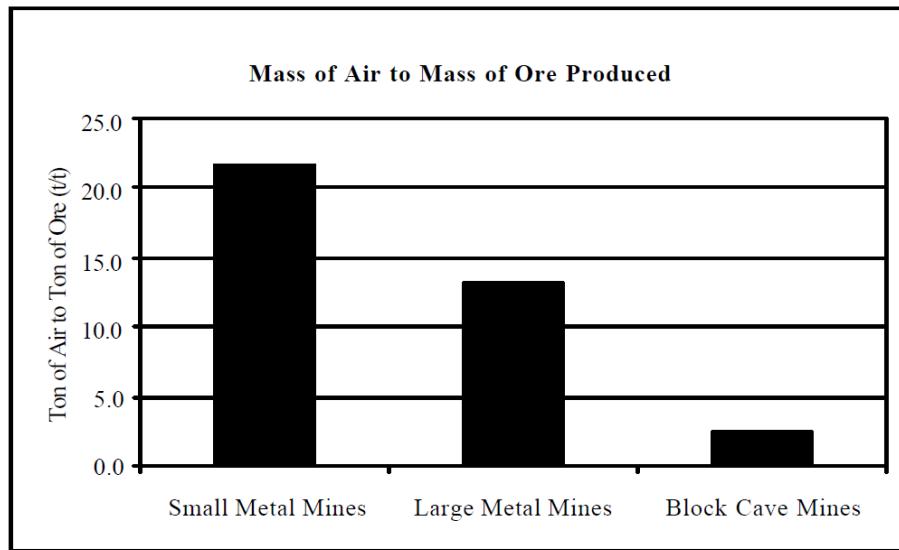


Figure 3 - Ventilation rates based on production rates for various mines (Wallace, 2001)

As might be expected, the amount of air required as a proportionality of mass flow to mass ore shows a distinct inverse trend. While this may be a useful metric for a comparison between mines of similar sizes and operating methodologies, this method of making total airflow determinations for planned mines or mining complexes is NOT recommended due to the great variations in equipment fleets, distribution, local conditions and fixed facilities impacting both mine and ventilation system design.

### **ALARA**

The ALARA principle or industry “best practice” are also sometimes used to determine the amount of ventilation required for underground diesel equipment. Sometimes (although rarely) this concept is mentioned specifically in mining legislation, as is the case in South Africa (Gangal, 2012). While certainly admirable in theory, in application the concept of “best practice” is not well defined, and subjective by nature. As such, concepts such as ALARA, “best practice” and any other similar programs should only be used to augment whatever engineering method has been chosen to determine total airflow requirements for mines. While this may in some cases result in increases to the total quantity of airflow required for a particular mine or section of a mine based on specific contaminants, this approach should be commended and implemented where practicable.

### **PROPOSED NEW MODEL FOR CALCULATED DIESEL EQUIPMENT AIRFLOW**

In light of the drastic reductions in the amount of gaseous POC and DPM achieved in Tier IV and equivalent certified engines, the process for determining the total airflow required for these engines has become significantly more complex, with a need to evaluate each contaminant type and the airflow



required to control their potentially harmful effects individually; a necessity in order to fully mitigate all of the hazards associated with diesel equipment.

Although dust is often a design consideration during ventilation system planning exercises, particularly in cases where silica is present, it is rarely directly associated with the equipment fleet. And despite the fact that much attention has been shown to reducing the amount of gaseous and particulate emissions emitted by modern diesel engines, almost no thought has been given to reducing the amount of heat generated by this equipment (this is a factor of fuel consumed, so ultimately, reductions may not even be possible at similar power levels). This is further compounded by the trend for ever-increasing power in underground equipment and results in heat being one of the most difficult contaminants to control in the underground mining environment (Brake, 2008).

It is this disconnect between what is currently considered and what *should be* considered when determining total airflow requirements for an underground mine based on its predicted equipment fleet that necessitates the adoption of a new paradigm by industry practitioners and which forms the impetus for this research. In the future, any determination of total airflow based on the equipment fleet must consider the toxic exhaust gases, DPM, waste heat and dust in order to be complete.

### **Gaseous POC and DPM**

Prior to the separate consideration of heat and dust, it was necessary to apply a ventilation rate that would account for these considerations even when reductions had been made to the gaseous and particulate contaminant emissions of approved diesel engines over the last decade. This is likely the principal reason why there has not been a prior recalculation of ventilation rates (when applied globally as part of a total airflow determination for a mine diesel fleet) even though nameplate ventilation rates for approved engines have been dropping substantially over the past several years.

As the methodology for determining ventilation rates for “approved” engines by NRCan and MSHA has been previously discussed, it will not be repeated here. Instead, we will look at a recent summary of ventilation rates based on engine type (non-Tier to Tiers I – IV) compiled by Robert Haney (MSHA, Ret.).

A summary of Dr. Haney’s findings is presented in Table 2. Note that PI for MSHA approved engines is based on the dilution of DPM to the arbitrary value of 1.0 mg/m<sup>3</sup> and that approximately five times more airflow is required to meet the U.S. statutory requirements for DPM exposure in metal/non-metal mines (non-coal).

One of the most striking findings of this study is the great discrepancy between historically used ventilation rates (the most common of which being 0.063 m<sup>3</sup>/s per kW) and those that would actually be required to meet modern standards for DPM in the non-Tier rated engines of the past. Also of note is the great reduction in measured ventilation rates required for Tier IVi engines (although only two were available for study).

Approved ventilation rates should be available in the future for all Tier IV engines, and nameplate values from NRCan and MSHA can be used for existing equipment fleets and older engines *provided that the airflow required based on the contaminants of heat and dust are also calculated*. For more general calculations, and in cases where the exact equipment may not be known (i.e. conceptual or prefeasibility designs), a value of 0.028 m<sup>3</sup>/s per kW may be used for determining the airflow required for diluting gaseous contaminants and 0.011 m<sup>3</sup>/s per kW for DPM (these numbers include a 10% factor of safety above the average values measured for Tier IV engines). Once the adoption of Tier IV engines becomes more widespread, these numbers can be verified empirically and altered to better reflect the actual conditions experienced underground if necessary.

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Table 2 - Historic Ventilation Rates for Approved MSHA Engines (Haney, 2012)

EPA Tier	Number of Engines Tested	Gaseous Vent Rate m <sup>3</sup> /s/kW (cfm/hp)	PI m <sup>3</sup> /s/kW (cfm/hp)	PI X 5 m <sup>3</sup> /s/kW (cfm/hp)
Non EPA Compliant < 73 kW (99 hp)	21	0.05 ± 0.057 (79 ± 90)	0.119 ± 0.088 (188 ± 139)	0.595 ± 0.438 (942 ± 693)
Non EPA Compliant > 73 kW (99 hp)	41	0.038 ± 0.008 (60 ± 12)	0.059 ± 0.024 (94 ± 38)	0.297 ± 0.119 (324 ± 120)
Tier I/II < 73 kW (99 hp)	73	0.03 ± 0.0095 (60 ± 15)*	0.041 ± 0.015 (65 ± 24)	0.206 ± 0.076 (324 ± 120)
Tier I/II > 73 kW (99 hp)	141	0.035 ± 0.008 (55 ± 12)*	0.012 ± 0.01 (31 ± 15)	0.098 ± 0.047 (156 ± 74)
Tier III < 73 kW (99 hp)	27	0.032 ± 0.004 (50 ± 7)**	0.028 ± 0.015 (44 ± 23)	0.139 ± 0.071 (219 ± 113)
Tier III > 73 kW (99 hp)	47	0.025 ± 0.003 (39 ± 5)**	0.025 ± 0.009 (39 ± 14)	0.123 ± 0.046 (194 ± 72)
Tier IV	2	0.025 ± 0.003 (39 ± 5)**	0.002 (3.2)***	0.010 (16)***

\*Based on NO

\*\*Based on CO<sub>2</sub>

\*\*\*Based on a PI of 0.01 gm/hp-hr

## Heat

The determination of the total airflow required for cooling Tier IV diesel equipment is not significantly different than the determination of cooling airflow required for other diesel equipment; however, it has become an even more critical step in the ventilation planning process owing to the drastic reductions in airflow required for the dilution of exhaust gases and DPM which now render the heat generated by equipment significantly more impactful to the design calculations. As was previously mentioned in the introduction to this section, heat has traditionally been an unregarded product of diesel equipment use underground, commonly leading to situations where the ventilation system is undersized for the equipment fleet and resulting in increased risk to the workforce and/or diminished production capacity.

Owing to the overall efficiency of internal combustion engines, diesel-powered equipment can be expected to produce roughly three times as much heat (kW) as mechanical work (kW). Of this heat production, approximately one-third is produced as direct radiative losses from the machine, one-third is produced as heat from the exhaust gases and one-third as shaft output power (less work done against gravity) that is later converted to heat due to frictional power losses (McPherson, 1993). The heat produced by diesel equipment is also different from that produced by other sources also in that a significant portion of the heat generated is produced as latent heat. Through water vapour in the exhaust gases,

emissions controls<sup>4</sup> and evaporation associated with the cooling system of the equipment and from tunnel walls, anywhere from 3 – 10 litres of water are produced by the equipment for each litre of fuel consumed.

This relationship of heat produced relative to work performed is illustrated in Figure 4.

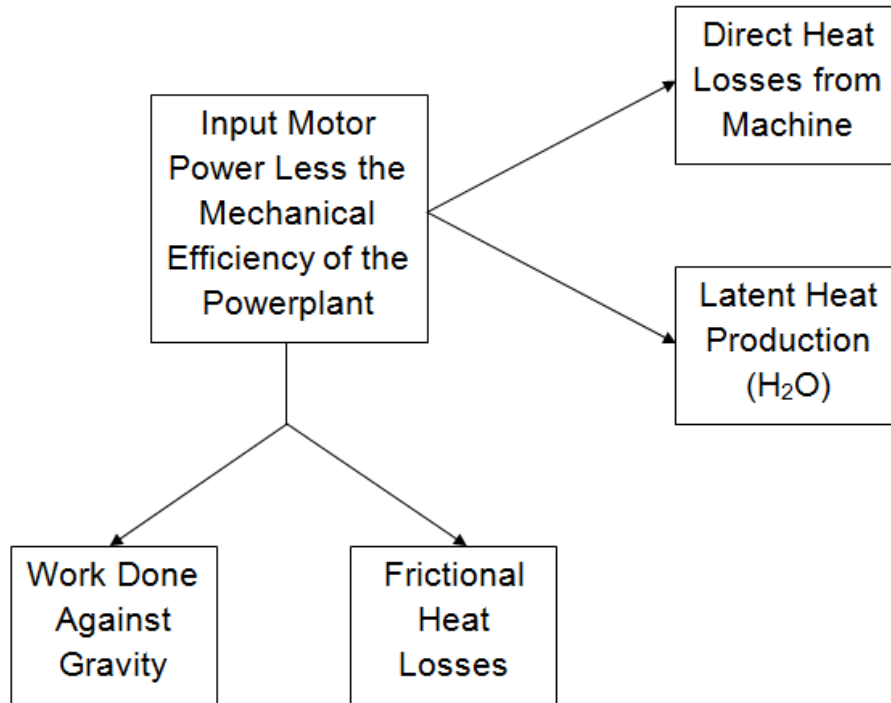


Figure 4 - Heat production of diesel engines by type/mode

From Figure 4 it is obvious that the heat produced by diesel equipment relative to the work performed is significant and must be accounted for. Unlike many contaminants mitigated by the ventilation system, it is not necessary to determine the maximum heat production of the equipment, and in planning exercises the average rate of heat production is generally calculated and used in determining the proper ventilation rate(s) required. Calculating the heat production from a diesel-powered machine can be practically accomplished through the following process.

First, the Total Heat is determined based on the fuel consumption rate:

$$Q_T = \frac{f_c \times C_{diesel}}{3600} \quad (2)$$

where:  $Q_T$  = total heat (kW)  
 $f_c$  = fuel consumption (litres/hr)  
 $C_{diesel}$  = heat content of diesel (kJ/litre)

Next, the Latent Heat is calculated:

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<sup>4</sup> Many Tier IV and equivalent engine packages have added SCR controls which involve the direct injection of a water-based urea solution directly to the exhaust system of the engine consumed at a rate of 3 – 5% of total fuel use.

$$Q_l = \frac{V_{H2O} \times l_{H2O}}{3600} \quad (3)$$

where:  $Q_l$  = latent heat (kW)  
 $V_{H2O}$  = volume of water production (litres/hr)  
 $l$  = latent heat of vaporisation of water (kJ/kg)

The Sensible Heat generated is simply the difference between the Total Heat and the Latent Heat:

$$Q_s = Q_T - Q_l \quad (4)$$

where:  $Q_s$  = sensible heat (kW)  
 $Q_T$  = total heat (kW)  
 $Q_l$  = latent heat (kW)

The associated temperature rise in the ambient air across the machine is a function of the flow rate of air:

$$\Delta T = \frac{Q_s}{m_{air} \times C_p} \quad (5)$$

where:  $\Delta T$  = temperature change (K)  
 $Q_s$  = sensible heat (kW)  
 $\dot{m}_{air}$  = mass flow rate of air (kg/s)  
 $C_p$  = specific heat of dry air (kJ/kgK)

Often this equation is changed slightly to solve for the ventilation rate necessary to limit the temperature increase across the machine to a certain maximum value, or to ensure that conditions do not reach the design criteria for stop-work temperature. Note that the mass flow rate of air should be converted to a volume flow rate using the air density in order that a proper comparison to the other ventilation rates can be made:

$$VR = \frac{v_{air}}{P_{machine}} \quad (6)$$

where:  $VR$  = ventilation rate (m<sup>3</sup>/s per kW)  
 $v_{air}$  = ventilation rate (m<sup>3</sup>/s)  
 $P_{machine}$  = machine power (kW)

Now it is possible to both calculate the heat added to the mine environment and establish criteria for evaluation and comparison based on the other contaminant products of the diesel equipment fleet.

### Mineral Dust

Although the dust created by Tier IV diesel-powered equipment does not vary significantly from that generated by older equipment, the examination of how much airflow is required to remove the hazard has become more important based on the reduction(s) of the airflow required based on other contaminant products (i.e. gases, DPM). As long as mechanical equipment is utilized to break, load and transport material in underground mines, dust will be generated at the sites where the mineral is disturbed, and it will be equally important to eliminate, minimize or remove this hazard from the ambient underground environment as long as there are people present in these areas.

Although many forms of dust control in underground environments exist, including the extremely effective use of water sprays and dust filtration units, ventilation remains the most commonly used means of diluting and removing mineral dust from the underground environment. Respirable (sub-micron) dust settles from the airstream at an almost negligible rate, and should be controlled via dilution in a manner similar to other gaseous contaminants. In the case of larger particles it is primarily the airflow velocity that dictates the distance and time the dust particles will be entrained in the air stream<sup>5</sup> (McPherson, 1993). If the airflow velocity is too great, then additional dust particles can be picked up by the ventilating air.

Figure 5 illustrates the relationship between dust concentration and air stream velocity.

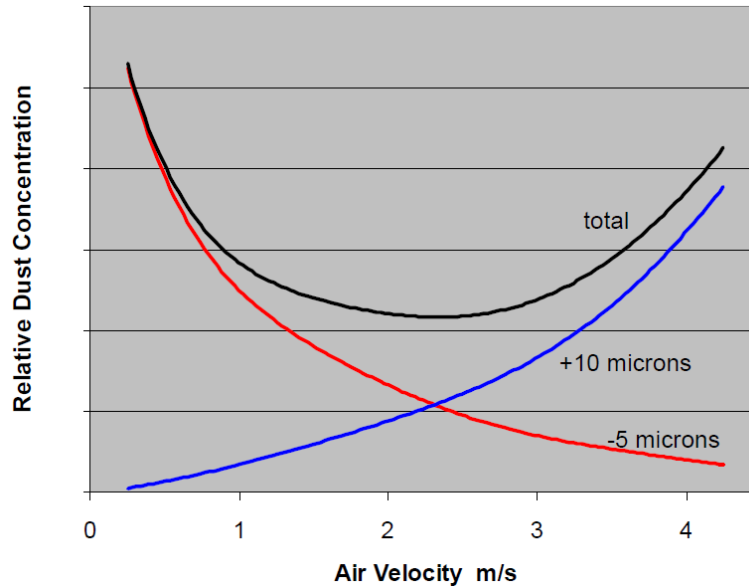


Figure 5 - Dust concentrations at various air velocities (McPherson, 1993)

From Figure 5 it can be seen that airborne dust concentrations are minimized at an airflow velocity of approximately 2.2 m/s. However; the curve becomes relatively flat above approximately 1 m/s, which should be considered the minimum airflow velocity in areas where diesel equipment is in operation.

A further benefit of an airflow velocity of at least 1 m/s in development and production locations such as loading points and muck bays is that it also contributes to a significant airflow penetration distance into areas that are not part of the primary ventilation circuit. In studies conducted by C. A. Rawlins and H.R. Phillips for a blind heading (LHD Load Point) a “figure of eight” pattern of flow for dust dispersion was measured against various airflow velocities in the connecting drift. In this case, penetration distance into the blind headings of 3 m by 3 m and 4 m by 4 m cross-section was maximized between 1.3 and 1.4 m/s; with a significant benefit achieved at 1 m/s. This information is provided graphically in Figure 6.

Selecting appropriate airflow velocities for design criteria can also prevent the stratification of exhaust gases and respirable dust within mine entries where diesel equipment is operating. Homotropical ventilation should also be considered along haulage routes to further minimize the generation and propagation of harmful mineral dust underground.

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<sup>5</sup> The time taken for dust particles to settle is also heavily dependent on their shape and mass.

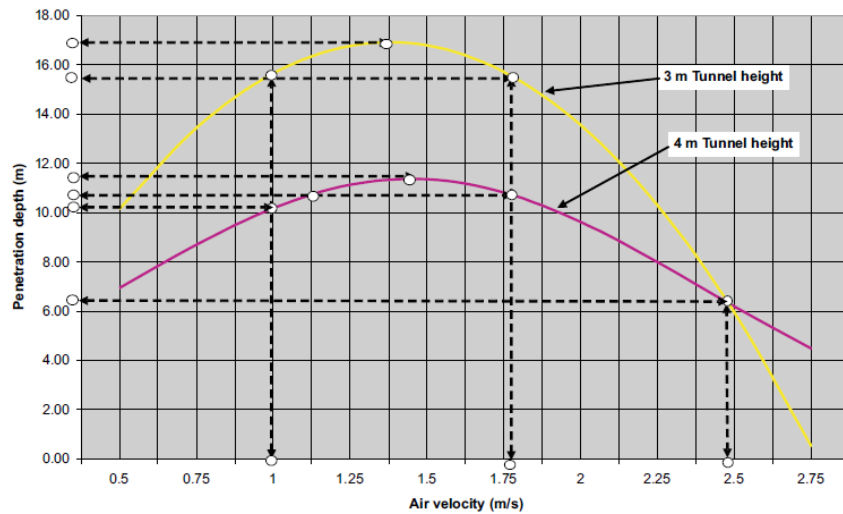


Figure 6 - Air penetration depth vs. airflow velocity (Rawlins and Hardin, 2005)

Ultimately, since dust control in modern underground mining environments usually incorporates combination of active and passive installations including but not limited to the ventilation system, using the minimum velocity requirement alone for dust control may lead to overestimating the ventilation requirement. Also, the minimum requirement associated with one drift based on airflow velocity may not be sufficient when there are multiple vehicles operating in that drift. Therefore, minimum velocity should only be used as the governing criteria in areas where no other dust control measures are in place and only one piece of diesel equipment is expected to be in operation.

### COMPARISON OF METHODS FOR DETERMINING AIRFLOW REQUIREMENT(S)

Now that the predominant methods for determining the airflow required for diesel equipment fleets have been outlined, a brief comparison of the methods (old and new) will be performed utilizing a test case featuring an actual piece of mining equipment. The total airflow required for this LHD will be determined utilizing the existing methods of Direct Engine Testing and Empirical Derivation, as well as individually for the contaminants of Gaseous POC, DPM, Heat and Dust. The results will then be presented for the purpose of evaluation and comparison.

The LHD selected for this comparison is the commercially available Sandvik<sup>6</sup> LH517 powered by a Volvo TAD1361VE 285 kW Tier IVi engine. This LHD has a rated capacity of 17,200 kg in its 7 cubic meter bucket and is approved for use in underground mines by NRCan under CSA M424.2-90 (Non-Gassy Mines). Minimum drift dimensions of approximately 5 m wide by 6.5 m high are required for this loader to achieve full mobility.

The results of the total required airflow determination for the test LHD using the various methods of calculation are shown in Table 3.

This example clearly illustrates not only the differences between the methods of calculation, but in this case, the profound changes in the total airflow determination caused by the addition of heat and dust as design criteria. While it may be possible to justify a reduction in the airflow required for dust control

<sup>6</sup> This machine (and engine) were chosen at random due to the availability of the pertinent engine data. This does not constitute any endorsement of these products and companies, or statement regarding their suitability for or use in underground environments.

Table 3 - Comparison of methods for calculating required LHD airflow

<b>Method of determining Airflow</b>	Total Airflow (m <sup>3</sup> /s)	Ventilation Rate (m <sup>3</sup> /s per kW)	% of Greatest (%)
Direct Engine Testing*	5.9	0.021	18%
Empirical Derivation	18.0	0.063	55%
Proposed Method: Gases	8.0	0.028	25%
Proposed Method: DPM	3.1	0.011	10%
Proposed Method: Heat	21.4	0.075	66%
Proposed Method: Dust	32.5	N/A	100%

\*NRCan, 2011

provided that other design features (e.g. water sprays) are added to the area in question, the mitigation of heat (the next highest airflow requirement) remains a concern and could even be exacerbated by the addition of water to the local environment (raising the humidity and, ultimately, the wet-bulb temperature). Despite the significant reductions made in the gaseous POC and DPM emissions of the Tier IVi engine, the overall airflow required has not significantly changed and may even be *increased* in cases where the critical design parameters of heat and dust were not previously considered.

## CONCLUSIONS

Despite the uncertainty associated with the changes to diesel equipment emissions resulting from the EPA Tier IV and equivalent regulations and their potential impacts on ventilation system for underground mines, it is important to note that mine airflow requirements are unlikely to decrease by 90% as a result of the 90% reduction in emissions associated with Tier IV diesel engines. What is more likely is that other parameters will take precedence, and that in the future, airflow calculations will become slightly more complex and based on a combination of factors that will be unique to each mine. It will take some time for the use of Tier IV diesel-powered engines to change the methods by which we calculate total airflow requirements, and longer still for a consistent new methodology to emerge, if one does at all.

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