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Mining Engineering; Sep 2001; 53, 9; ProQuest
pg. 45

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Nonmeeting paper number 00-307. Original manuscript submitted for review February 2000 and accepted for publication February 2001. Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME prior to Dec. 31, 2001.

Abstract

In response to the underground mining industry's growing concern with the exposure of workers to the diesel particulate matter (DPM) component of diesel exhaust, a method was developed to estimate the average workplace concentration of DPM that could be expected from using the new lower DPM-emitting engines now being approved by the US Mine Safety and Health Administration (MSHA) when these new engines are equipped with state-of-the-art exhaust-control technology for filtering and combusting DPM. The resulting estimate uses the MSHA-reported particulate index for these engines, the prevailing rule-of-thumb ventilation rate of 150 cfm/hp and the available diesel-exhaust filter technology that has been shown to be at least 80% effective in reducing tailpipe DPM. In the estimate calculation, every engine used in an underground mine is assumed to be equipped with this control technology. Under the stated reasonable conditions, an average DPM level of 90 μg/m^3 (mass) is predicted as technically feasible.

Introduction

There is growing concern within the underground mining industry about the exposure of workers to the diesel particulate matter (DPM) component of diesel exhaust. In January 2001, MSHA promulgated rules for the control of worker exposure to DPM in coal mines (MSHA, 2001a) and metal and nonmetal mines (MSHA, 2001b). The National Institute for Occupational Safety and Health (NIOSH) has been focused on whether a recommended exposure limit (REL) for DPM should be established based on health-effects research. NIOSH is also considering the technically feasible level of DPM reduction that is achievable using existing control technology.

The MSHA-proposed rule governing DPM exposure in coal mines requires the use of a particulate filter on the exhaust of diesel equipment used in permissible areas. In contrast, the MSHA-proposed rule for DPM exposure in metal and nonmetal mines allows the use of any engineering control technology, so long as the final level attained does not exceed 200 μg/m^3 of DPM (gravimetric mass equivalent) as an eight-hour-shift average. MSHA arrived at its DPM limit by taking into account economic as well as technical feasibility. In this manuscript, NIOSH, in contrast, focuses on estimating the DPM limit for metal and nonmetal mines based on technical feasibility alone.

To this end, an estimate of DPM concentration based on the use of technically feasible DPM control technology was made for underground metal and nonmetal mines using data available from the literature. The literature referenced includes the MSHA data (MSHA, 1999a, 1999b) on engines now being approved under existing regulations (Code of Federal Regulations, Title 30, Part 7), the recommendations from European studies to curtail DPM levels from diesel equipment used in tunneling (Mayer 1998a), filtration efficiencies of diesel exhaust filters found to be effective in that study (Mayer et al., 1999a) and prevailing ventilation rates for mines using diesel equipment (63 Fed. Reg. 58198-58205, 1998). Economic constraints and the variable of increasing ventilation rates (largely considered impractical as well as economically unfeasible) were not considered.

Filtration systems are becoming available for the range of vehicles used in underground mines, and a number of suppliers have the knowledge, skills and hardware to engineer and fabricate successful systems for the majority of the mine equipment used in underground metal and nonmetal mines.

Development of the estimate

The development of the estimate of the DPM level achievable considers only MSHA-approved engines, uses the MSHA ventilation-rate data on these engines, the achievable efficiency of exhaust control technology to reduce DPM and the prevailing ventilation rates in underground mines. The development of the estimate from these parameters is discussed below.

MSHA-approved engines. The calculations for the technically feasible DPM level achievable are based on the particulate index (PI) obtained and published by MSHA (1999a, 1999b) on each engine approved under the current regulations (30 CFR, Part 7, Subpart E). The current federal regulations for underground metal and nonmetal mines do not require the use of MSHA-approved engines (some state regulations do). The MSHA-proposed new Part 57.5067 (63 Federal Register 58221) specifies that any engine introduced into the subject mines after promulgation of the rule shall be approved by MSHA under the above-referenced section. (Existing engines are grandfathered and application of the control technology to these engines will result in DPM levels greater than the ones calculated here.) Mines that purchase or lease new vehicles or purchase replacement engines will, because of the long service life of an engine, select only MSHA-approved engines if possible.

The list of engines approved by MSHA provides the approval number, engine make and model, horsepower at rated speed, the gaseous or "nameplate" ventilation rate and the particulate index. As of Nov. 24, 1999, MSHA has issued 70 approvals covering more than 70 engines, which range from 10.4 to 484 kW (14 to 650 hp), for use in nonpermissible areas.

Because of existing or proposed rules, the only engines that will be permitted in underground mines in the future are those being approved under the current MSHA regulation. Thus, as its first parameter, the feasibility estimate only uses engines now being approved by MSHA.

MSHA ventilation rates. MSHA's engine-approval protocol is specified in 30 CFR 7, Subpart E, and is essentially identical to the internationally accepted test procedures for diesel engine emission testing specified in ISO 8178 (61 Federal Register 55418) and the MAPTEST used to evaluate engines and control system performance in Canada (CANMET, 1997). Under carefully controlled conditions, engine emissions are measured for eight different steady-state engine load and speed conditions or modes (Table 1), which is referred to in the MSHA-proposed rule as the "eight-point test cycle." At each test point, gaseous and DPM emissions are determined and used to obtain two ventilation rates — the gaseous ventilation rate and the particulate index.

The gaseous ventilation rate (Q_{gas}) (30 CFR 7.84(c)), often referred to as the "nameplate" ventilation rate, is the dilution air quantity required to reduce the highest concentration from among four specific (toxic) exhaust gases encountered using the MSHA eight-point test cycle to the following levels:

CO_2 = 5,000 ppm
CO = 50 ppm
NO = 25 ppm
NO_2 = 5 ppm.

The particulate index (PI) is the dilution air quantity (Q_{dpm}) needed to reduce exhaust DPM concentration to 1,000 $\mu g/m^3$ (30 CFR 7.89). The PI is determined from the weighted average of DPM mass obtained over the same test points used for determining Q_{gas} and can be obtained at the same time that the gaseous rate is determined. The eight engine operating points and the weighting factor for each engine condition are provided in Table 1.

Whereas the gaseous ventilation rate is based on the worst-case emission rate and is meant to prevent acute exposures, the particulate index is a weighted average over the load and speed points that are assumed to be representative of an average shift emission rate. MSHA instituted the PI as a guide to facilitate choosing engines that emit less DPM when a choice is possible.

The analysis that follows assumes that the PI represents a reasonable estimate for well-maintained engines as deployed in the industry. A more accurate analysis would require determination of actual/representative duty cycles of the engines and the local ventilation conditions under which they operate.

A measure of the cleanliness of an engine is the amount of DPM emitted per horsepower or, in this discussion, the PI per engine horsepower (Q_{dpm}/hp). Figure 1 shows a plot of the PI per horsepower (normalized PI) in cfm/hp against engine horsepower. A careful study of the graph reveals two clusters of engines — those engines with a normalized PI below 70 cfm/hp and those with a normalized PI above this level. The graph also shows that engines below 149 kW (200 hp) vary widely in normalized PI; this group is composed of a mix of engines using both the older and modern fuel-management systems.

Two additional features can be noted:

- no engine more than 149 kW (200 hp) has a normalized PI above approximately 70 cfm/hp; and
- for any engine with a normalized PI above 70 cfm/hp, it is possible to find an engine of about the same horsepower with a normalized PI below 70.

This ability to select the cleaner of comparably powered engines is critical to determining the technically feasible DPM. For this estimate, it is assumed that it is possible to replace the higher PI engine with a lower PI engine of about the same horsepower by substitution or, at worst, by vehicle redesign. A detailed engineering review would be required to substantiate this assumption for all cases.

Based on the above observations, a second param-

TABLE 1

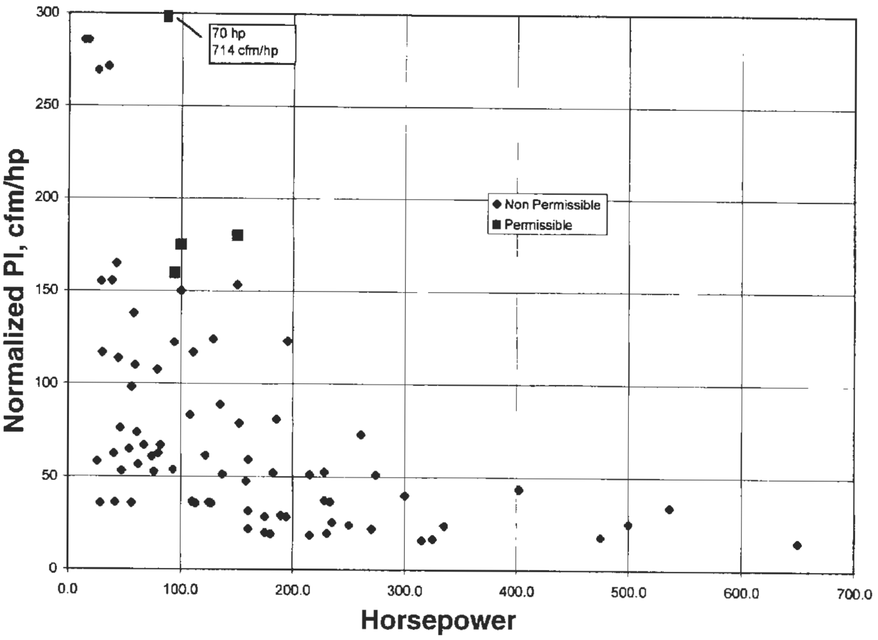
The MSHA eight-point test cycle and weighting factors for various engine conditions.

Speed category	**Rated speed[1]**		**Intermediate speed[2]**				**Low-idle speed[3]**	
Percent rated torque	100	75	50	10	100	75	50	0
Weighting factor	0.15	0.15	0.15	0.1	0.1	0.1	0.1	0.15

[1] The speed at which the rated power is delivered as specified by the engine manufacturer.
[2] The maximum torque speed if between 60% and 75% of rated speed, or else it is 75% or 60% of rated speed, whichever is closer to the manufacturer's specified maximum torque speed.
[3] The minimum no-load speed as specified by the manufacturer.

FIGURE 1

Normalized particulate index for current MSHA-approved engines, including four permissible (coal mine) engines. Note that one engine approved for coal mines has a Q_{dpm} considerably above the range of the chart.



eter for the estimate of technically feasible DPM levels is that engines with a normalized PI below 70 can be used in metal and nonmetal mining applications.

Control technology availability and efficiency. From a practical viewpoint, most control technologies that can reduce engine DPM are not effective to the degree necessary to attain significant improvement of underground DPM levels (Mayer 1998a; Mayer et al., 1998). The exception is the diesel particulate filter (DPF), or trap, which is designed for engine exhaust streams not cooled by water baths or other means. The filtration elements consist of porous ceramic, silicon carbide, sintered metal or glass or ceramic fibers that are knitted, woven or otherwise configured. These filters reduce diesel particulate mass by at least 80% and solid particle numbers by 99% or more (Mayer et al., 1998; Mayer et al., 1999b). A list of DPFs resulting from the European tunneling study by VERT (Verminderung der Emissionen von Realmaschinen im Tunnelbau) is available (Mayer, 1998b). In addition, the Swiss have established a DPF certification procedure and have recently published a list of certified DPFs (Mayer 1999a; BUWAL/SUVA, 1999).

DPFs collect DPM in the filtration media at exhaust temperatures. When engine exhaust temperatures reach 550° to 600°C (1,022° to 1,112° F) (Houben 1994), the accumulated soot spontaneously combusts and is converted to CO_2. Catalyzing the DPF media or adding catalysts to the fuel can lower the soot combustion temperature to 300° C (572° F). In cases when exhaust temperatures do not reach the requisite temperature or are not sustained for a sufficient period, regeneration systems must be employed to remove the collected DPM. The regeneration systems can be either on-board or off-board the vehicle. The on-board systems use integral electric heaters or fuel combustion systems to raise the filter or exhaust gas temperature. These systems operate on demand by sensing the back pressure due to DPM accumulation or on a timed cycle. Off-board systems use an oven that is designed to burn off the collected DPM from a filter that is removed from the vehicle. If the vehicle must return to service, then a second filter is needed. Periodic exchange of loaded DPFs for regenerated ones is required. DPF capacities can be sized so that trap exchange occurs at convenient intervals, e.g., once per shift. The degree of trap loading can be detected by a rise in engine-exhaust back pressure.

Selecting a DPF for a particular vehicle involves selecting the correct filter size to handle the exhaust flow with acceptable back pressures and determining whether a regeneration system is required. The latter is determined by profiling exhaust temperatures (exhaust temperature vs. time) for several typical work scenarios by using data loggers placed on the equipment. The requisite application engineering is available either from the DPF vendor or from consultants. The DPF serves as a replacement muffler (exhaust silencer). DPF cost is determined by physical size, regeneration scheme and filter media.

In marginal cases of exhaust temperature and to avoid the use of or to increase the efficiency of an on-board regeneration system, fuel additives (Pt-, Fe- or Ce-based) can be used to lower the DPM combustion temperature to about 300° C (572° F). With diesel filters in place, the oxides of the additives are removed at high (95%) filtering efficiencies and DPM filtration performance improves as well. The additive's ash particles slowly accumulate in the filter, which reduces filter life and/or requires maintenance to remove the particles.

DPF systems are commercially available from US, Canadian and European manufacturers. The research and development thrust in Europe is a result of lowered workplace standards and demand for diesel-emission control in general.

The comprehensive testing program performed by VERT researchers for the tunneling project was instrumental in demonstrating the feasibility of the technology and setting performance standards. The final results of the VERT studies (Mayer et al, 1999a) claim that "traps (DPFs) are effective in the entire size range of diesel particulates, starting from primary particles of about 10 nm." Additionally, the study notes that: "Traps can be deployed for new engines. They can also be retrofitted to existing older engines. Hence, they are suitable for rapid and wide-spread application to reduce the particulate matter exposure." Trap evaluations for applicability and effectiveness are scheduled to start in Canada this year under the Diesel Emissions Evaluation Program (DEEP) (project descriptions are available at http://www.deep.org).

Diesel particulate filter systems with a minimum 80% efficiency in reducing DPM (mass) of engine exhausts are commercially available in Europe and North America. This is the third parameter used in the estimate calculation. From this point in the discussion, it will be assumed that all vehicles are equipped with diesel particulate filters.

Prevailing mine ventilation rates. A plot (shown in Fig. 2) of the normalized MSHA gaseous ventilation rate (Q_{gas} in cfm/hp) for MSHA-approved engines illustrates that the gaseous "nameplate" ventilation rarely exceeds 70 cfm/hp. For completeness, the four permissible coal mine engines are included in the figure.

The rule-of-thumb for establishing ventilation rates in metal/nonmetal mines is to provide between 100 and 200 cfm/hp (Haney, 1998). MSHA used rates between 127 and 173 cfm/hp in its estimator examples in the proposed rule (63 Federal Register 58198 – 58205). On average, to keep the gases below an action level of one-half the threshold limit value (TLV), ventilation rates need to be at least double the gaseous/nameplate ventilation rate. This coincides with about 150 cfm/hp and provides a safety factor by virtue of the fact that the gaseous ventilation rate is determined from the worst-case gas emission rate.

Thus, the final parameter used in this estimate is to assume a prevailing local ventilation rate of 150 cfm/hp.

Results

One can determine the resulting workplace DPM concentrations for each of the MSHA-approved engines by using the engine's PI, a prevailing ventilation rate of 150 cfm/hp and an estimated worst-case diesel particulate filter efficiency of 80%.

A plot of the resulting DPM concentration vs. engine horsepower for each MSHA-approved engine (Fig. 3) shows the two clusters described previously, with the lower PI engines achieving a 90-$\mu g/m^3$ DPM concentration or less. The DPM levels plotted represent levels that will prevail downstream of the vehicle operating under a local ventilation rate of 150 cfm/hp of uncontaminated air. When the upstream air already contains DPM, the DPM levels represent the additional concentration of DPM contributed to the downstream air by the corresponding engine.

Because mine operators are required to increase the ventilation air quantity in proportion to the combined

FIGURE 2

Normalized nameplate ventilation rate for MSHA-approved engines. All but five require ventilation rates below 70 cfm/hp.

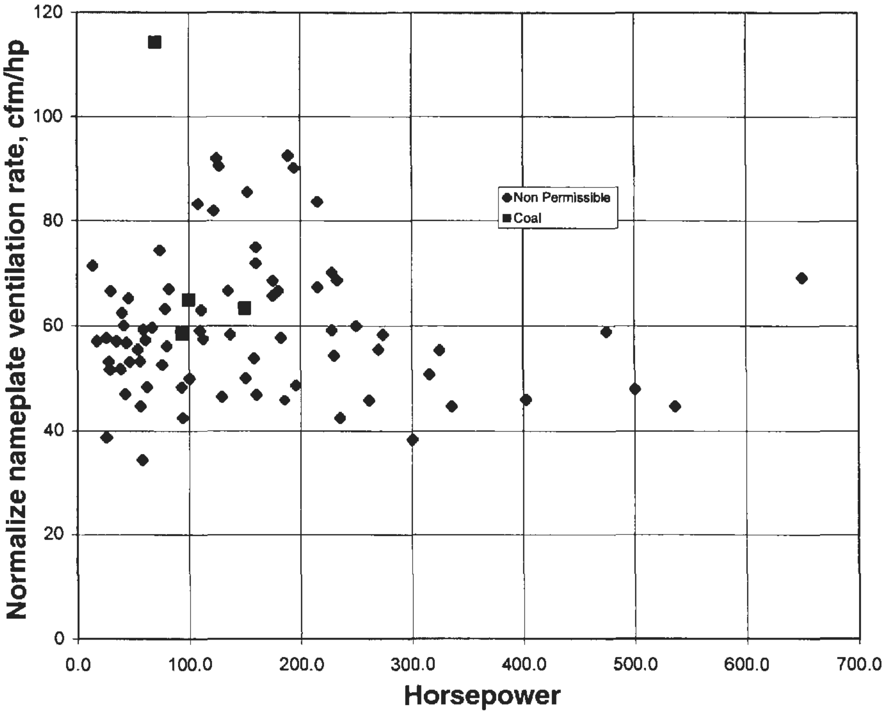
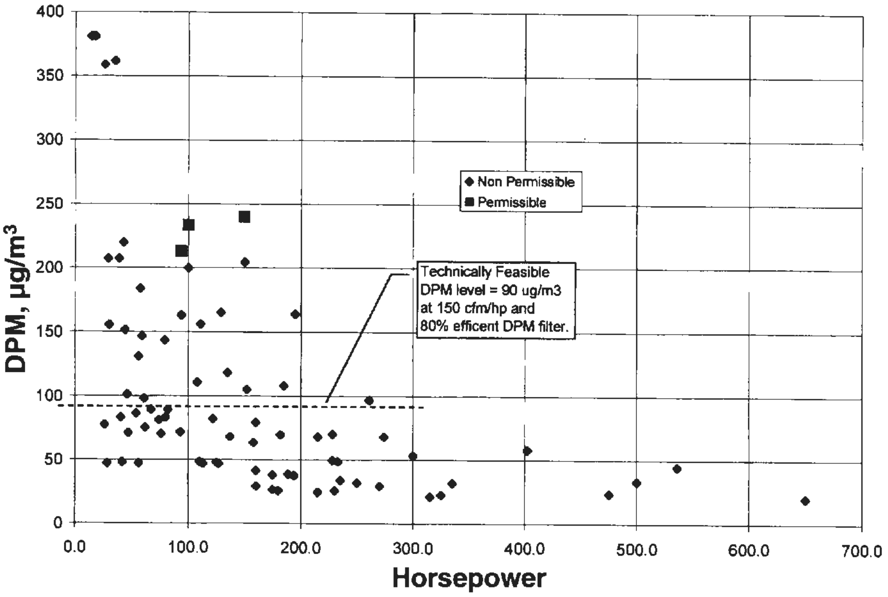


FIGURE 3

Estimated DPM concentrations from currently MSHA-approved diesel engines at nominal ventilation rates of 150 cfm/hp and equipped with a diesel filter with 80% efficiency in removing DPM as mass. For every engine of 30 kW (40 hp) or greater that produces a DPM concentration more than 90 µg/m³, one can find an engine that produces DPM concentration of 90 µg/m³ or less. This, then, defines the technologically feasible DPM concentration.



horsepower of the vehicles operating in the same split of air (see Eq. (2) below), the use of additional vehicles on the same air split does not significantly affect the estimated DPM concentration at the end of the split.

The assumption that every vehicle in the mine is using a diesel particulate filter, including the low-horsepower utility vehicles, assures this. For example, assuming that each vehicle contributes DPM concentrations of 90 µg/m³/hp at a ventilation rate of 150 cfm/hp, a mine section using a 37-kW (50-hp) diesel vehicle and a 74-kW (100-hp) diesel vehicle would require 10.4 m³/sec (22,500 cfm) of air. The first diesel vehicle in the series would create a concentration of 30 µg/m³ downstream, and the second would contribute 60 µg/m³, bringing the downstream DPM concentration to 90 µg/m³.

The addition of a third vehicle downstream of the other two lowers the concentration contributions of the upstream vehicles (because of the increased ventilation rate) and produces a final downstream DPM concentration of 90 µg/m³. Note that for the larger MSHA-approved engines, the attainable DPM concentration is much lower, on the order of 60 µg/m³ or less. Vehicles with these larger engines, which are also the ones that a mine would most likely select first to be equipped with diesel filters, are also the ones most likely to be used in dead-end drifts, where studies (CANMET, 1997) found up to twice the concentration of pollutants that were found in the return air immediately downstream. Thus, it would be expected that the DPM level actually achieved would be greater than 60 µg/m³.

Although the attainable DPM concentration is much lower for the larger engines, the highest level is chosen because all engine sizes must be accounted for in making a feasibility estimate, and to try at this stage to apportion the relative contributions of individual vehicles to the DPM burden is beyond present resources.

The results indicate that, under the stated assumptions, 90 µg/m³ is the technically feasible DPM concentration expected. This level makes allowances for mines whose use of diesels may be solely in the lower horsepower range and presumes that all engines used are of the lowest PI of the current MSHA-approved engines in their horsepower range.

Additional comments

Estimate formula. The following formulas calculate the DPM concentration increase in the downstream air over that of the upstream air, resulting from one or more vehicles operating on the same split of air, to a first approximation (ignoring duty-cycle and operating-time effects)

$$[DPM] = 1{,}000\frac{(1-\eta)}{Q}\sum_i \mathrm{PI}_i \qquad (1)$$

where $Q = 150\ _{\mathrm{i}}\ \mathrm{Hpi}$ (2)

In these formulas,

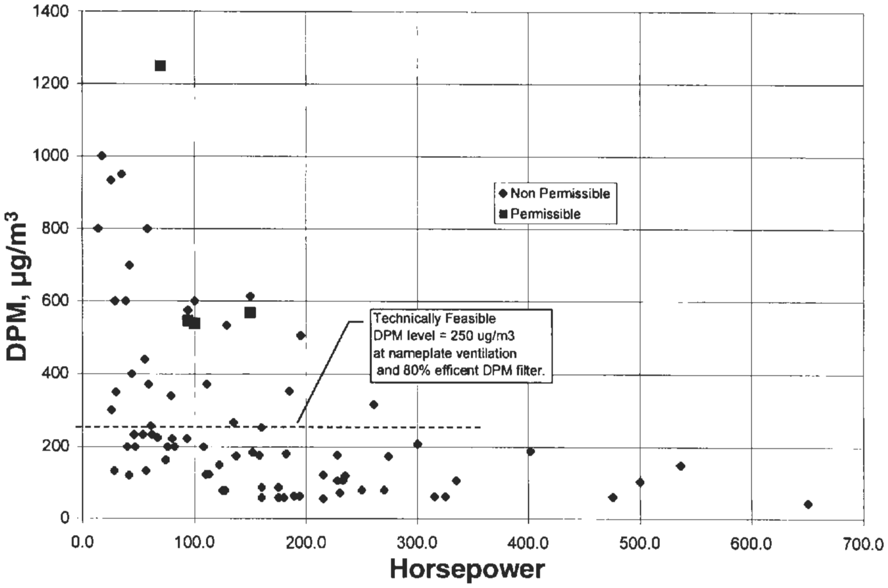
$[DPM]$ is the estimated DPM concentration in micrograms per cubic meter (µg/m³);

the assumed filtration efficiency (0.8 in this calculation);

PI_i is the particulate index for engine *i*, with a horsepower rating of Hp*i*;

FIGURE 4

DPM concentrations when the prevailing air quantity equals the MSHA-approval plate air quantity and when a DPM filter with an efficiency of 80% is used.



150 is the "rule-of-thumb" ventilation rate in cubic feet per minute per horsepower (cfm/hp); and

Q is the total ventilation air quantity for the split in cfm.

These formulas ignore duty-cycle and operating-time effects.

Estimate validity. The estimate of technically feasible DPM levels is an aggregate estimate. It provides the DPM concentration expected after the contribution of the last vehicle in a serially ventilated air split. Nevertheless, it also provides valid estimates for local conditions as well.

It is simplistic and naive to assume that vehicles upstream of the last one will be operating in excess "air." Except for utility vehicles operating in the main air course, it is common to find production vehicles operating in dead-end drifts ventilated by auxiliary fans. In these cases, the local effective ventilation rate may be closer to the 150 cfm/hp or even less. Thus, in many cases, the estimate is valid for the local ventilation conditions as well. Operation of a vehicle with and against local air currents can also drastically affect local (vehicle operator) DPM concentrations.

DPM measurement. The above calculations predict the workplace mass concentration of DPM. Using the guidelines in the literature (Cantrell et al., 1998; Grenier et al., 1998) for total carbon (TC) (80% to 90% of DPM mass) and elemental carbon (EC) (40% to 60% of TC), the technically feasible DPM limit becomes approximately 72 to 81 $\mu g/m^3$ as TC and approximately 32 to 50 $\mu g/m^3$ as EC.

It should be noted that, when diesel particulate filters are used to control diesel exhaust, the relationship noted above between TC and EC (both of diesel origin) may change. It was reported (Mayer et al., 1998; 1999b) that particulate filters are more than 95% effective at removing solid core elemental carbon and only 80% effective at removing total DPM mass, which is comprised also of volatile organic materials. With the five-fold drop in TC from the use of DPFs, the airborne TC from sources other than DPM may become a more significant quantity and thus potentially become a greater source of error in estimating diesel DPM from TC alone.

Whether nondiesel, carbonaceous sources of TC become a greater source of error depends, however, on their size distribution and the type of sampling done to analyze for DPM.

Effect of uncontrolled light-duty vehicles. If the incidental, light-duty, low-horsepower utility vehicles are not equipped with exhaust filters, then, from MSHA's assumptions in the proposed rule, the incoming air to a working section may contain about 50 $\mu g/m^3$ DPM (the contribution from these upstream engines being highly diluted). Under these conditions, the estimated local or aggregate DPM would be expected to be about 140 $\mu g/m^3$ (90 plus 50). This is quite close to MSHA's proposed 200 $\mu g/m^3$, which was based on the assumption that it would be impractical and economically infeasible to place DPFs on every diesel engine operating underground. In coal mine entries, the upstream presence of light-duty vehicles places a lower limit on the DPM concentrations attainable in permissible areas if the proposed rule mandating filters with 95% efficiency only on permissible diesels is implemented.

Estimated DPM for engine nameplate ventilation rate. The current coal mine regulation states that the minimum air quantity for single or multiple units operating off the same air split shall be the sum of the approval plate ventilation air quantities (30 CFR 75.325 (g)). Neither the existing MSHA regulation nor the proposed rule states a policy concerning ventilation rates for diesel engines per se, except that toxic gases must be below the

1973 ACGIH TLV (30 CFR 57.5001) and, of course, the DPM limit in the proposed rule. Thus, it seems appropriate to plot the estimated DPM for each engine using its individual nameplate air quantity as the prevailing ventilation rate (the "150" in Eq. (2) is replaced by each engine's individual nameplate air quantity) and using an 80%-efficient DPM filter.

The result is shown in Fig. 4. Under these conditions and by using the lower PI engines when a choice is available, the expected DPM levels would be approximately 250 $\mu g/m^3$.

DPM estimates for different ventilation and control parameters. As was done in this manuscript, a spreadsheet can be designed to utilize MSHA's approval list and Eqs. (1) and (2) to generate data that can be plotted. The MSHA-approved engine list can be imported into a spreadsheet program to create the rows. The engine horsepower needs to be entered into a separate column to the right of the engine approval data. Eqs. (1) and (2) can be combined into one cell formula and entered in another column, with the variables referencing the appropriate data for engine PI and horsepower. Both the prevailing ventilation rate (the "150" in Eq. (2)) and the DPM control (filter) efficiency (η) can be made a named parameter and each referenced in the formula. Thus, the resulting DPM levels for the individual engines can be generated for varying ventilation conditions and DPM filter efficiencies.

Summary

The following parameters were used to provide an estimate of the expected workplace concentration of DPM mass of 90 $\mu g/m^3$:

- the particulate index provided by MSHA's engine-approval procedure,
- the assumption that all underground diesel engines have the lowest PI at their horsepower rating and are equipped with an diesel particulate filter that is at least 80% efficient at removing DPM mass and
- a prevailing ventilation rate of 150 cfm/hp.

The limitations of this estimate include an assumption that lower PI engines can replace higher PI engines of equivalent power in the required service application and that the MSHA PI is representative of real-world DPM emission rates, which are duty-cycle dependent. The general formulas for calculating the local DPM from an engine using MSHA's PI are provided, as well as the formula for converting the PI to a DPM mass emission rate for use in MSHA's estimator model as outlined in the MSHA-proposed DPM rule. ■

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