Estimation of Diesel Particulate Concentrations in Underground Mines

by

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ABSTRACT

The Mine Safety and Health Administration has developed a model to estimate diesel particulate (dp) exposures in underground mines. The estimate uses either in-mine measured dp concentrations or engine manufacturers' standardized emission data and through a series of calculations estimates full shift dp concentrations by applying standard engineering principles of ventilation, control technology and work cycle. This model, in the form of a computer spreadsheet, provides the mining industry with a method to estimate diesel particulate levels and determine the impact of various diesel particulate controls on occupational exposure to dp in underground mines. A detailed description of the estimator and several examples demonstrating the results are provided.

INTRODUCTION

Many mining operations, both coal and metal and nonmetal, utilize diesel powered equipment in mining operations. Diesel powered equipment may be used for transport of personnel and supplies, to load and haul material, or to power various ancillary operations. The use of diesel powered equipment in confined spaces such as underground mines has caused concerns due to potential exposure to diesel exhaust. Because of the confined areas found in underground mines, workers in these areas can be exposed to diesel particulate concentrations far in excess of workers in other industries. Potential hazards from exposure to diesel exhaust range from eye and throat irritation to lung cancer. Many of these hazards are attributed to the fine particles in the engine exhaust. These particles have been referred to as soot or diesel particulate.

Depending on the amount and type of equipment in use, mining companies may consider it necessary to install controls to reduce diesel particulate exposures. In order to evaluate the effectiveness of these controls prior to their purchase or installation, the Mine Safety and Health Administration (MSHA) has developed a model to estimate the impact of control technology on diesel particulate exposures in underground mining operations.

Exposure to diesel particulate in mines is related to three primary factors. These factors are: quantity of exhaust emissions, efficiency of exhaust control technology, and in underground mines, ventilation. Because of the interrelation of the various control technologies on worker exposure, a combination of controls that best suits the mining operation can be used. In some cases, because of the number and size of the equipment, ventilation may be successfully used to reduce worker exposure to diesel particulate. In other cases, it may be necessary to reduce engine exhaust emissions by utilizing cleaner engines and/or after treatment devices.

Exposure to dp is inversely proportional to the ventilation rate. As ventilation increases, exposure to dp decreases and as ventilation decreases, the exposure to dp increases (Haney, 1992). Diesel exhaust after treatment can include the use of oxidation catalytic converters and filtration devices. Efficiencies of these devices can range from 50 to 95 percent. New engine designs which incorporate high pressure fuel injection, turbo charging and computerized fuel combustion, can also significantly reduce engine emissions. Other techniques have also been identified for reducing engine emissions and exposure to diesel particulate. These techniques include: the use of low sulfur fuel, fuel additives and alternative fuels; the use of enclosed cabs; engine maintenance; fleet management and work practices. (U.S. Department of Labor, 1997).

Through its studies in underground mines, MSHA has found mine dp levels of exposure to be related to:

1. Engine dp emission rates,
2. Engine horsepower,
3. Number of engines,
4. Engine operation time,
5. Length of work shift,
6. Quantity of ventilating air used,
7. Fuel properties, and
8. Efficiency of applied control technology.

Diesel particulate concentrations are directly proportional to changes in items 1 through 5; inversely proportional to airflow (item 6), and directly proportional to the percent of diesel particulate remaining after applications of controls (items 7 through 8). In order to facilitate the evaluation of control technology, MSHA has combined these relationships and developed a "Work Place Diesel Emission Control Estimator" model.

The model was developed to estimate diesel particulate exposures in production areas of underground mines where the highest exposures to diesel particulate have been measured. The model has been presented in the form of a computer spreadsheet. It provides a method to estimate diesel particulate levels and to determine the expected impact of instituting various control technologies on diesel particulate exposures. The model uses known diesel particulate exposure levels from a mine operation or established diesel engine emission rates in conjunction with mine operational information and control technology information to estimate diesel particulate levels.

The purpose of this paper is to describe the details of the diesel particulate estimator and to give examples of its use. Examples of the application of the model are presented for both coal and metal and nonmetal mining operations.

DESCRIPTION OF MODEL

Two different methods have been developed to estimate the impact of diesel particulate control technology. One method uses measured or estimated diesel particulate exposure data as the starting point. The other method uses engine emission output information derived from laboratory test data to estimate diesel particulate levels and the impact of control technology. Two columns of calculations are included so that the estimate of control effectiveness can be based on actual dp measurements or emission and operational data.

For the particulate exposure data method, the effect of applying additional controls was estimated by using the measured dp concentration then proportionately reducing the measured concentration for increases in ventilation and decreases in engine emissions. The effect of after treatment or cabs is approximated by multiplying by the percent of emissions remaining after the after treatment or cab is applied.

When the dp has not been directly measured, the initial dp concentration is estimated from the engine emission rates, the engine horsepowers, the equipment operation times, the length of the shift, the section airflow and the intake (outby) dp level. The result of installing controls is approximated in the same manner as when the initial dp level is measured. This section of the spread sheet can also be used to evaluate the effect of reducing the amount of diesel equipment (fleet management), changing the size (horsepower) of the equipment and modifying the shift length.

The method that utilizes measured diesel particulate exposures would be the most reliable estimator of control technology effectiveness as the engine duty cycles are reflected in the diesel particulate measurements. The estimate obtained from the laboratory test data assumes that the laboratory duty cycle (ISO test cycle) represents the "in mine duty cycle" and that the average environmental concentration derived is representative of the workplace where miners work or travel.

As a result the estimate could be high or low depending on the specific engine duty cycles, state of engine maintenance, and time of operation. The Agency's experience is that the use of published engine emission rates from the ISO test provide a good estimate of particulate exposures when the engine is operated under heavy duty cycle conditions. For light duty cycle equipment, use of the published emission rates will generally overestimate the mine diesel particulate exposures.

DESCRIPTION OF THE OPERATION OF THE MODEL

Tables 1 and 2 show examples of the estimator spread sheet for a coal mine and a nonmetal mine, respectively. The spread sheet contains two columns of information. Column A is used when measurement data is known. Column B is used when equipment emission data is used. The estimator spreadsheet is divided into six sections. Table 3 gives the information that is needed for or is provided by each section of the model. The input and output units are also indicated in Table 3. Section 1, 2 and 3 contain the input data. Sections 4 and 6 provide an estimate shift diesel particulate exposure for the uncontrolled and controlled emissions. Section 5 allows the various controls to be applied to the engine emissions.

The datum input for Section 1 is an estimate of the diesel particulate level for a mining operation. This value is entered only when Column A of the Estimator is used. This level can be obtained in several ways. The first and most reliable method is to make an in mine measurement of the diesel particulate level. A second method of estimating dp concentration is to take a percentage of the respirable dust concentration. Studies have shown that the diesel particulate can range from 50 to 90 percent of the respirable dust concentration, depending on the specific operation, the size distribution of the dust and type of dp controls in place. The third method to estimate dp concentration would be to choose a value between 500 and 1500 $\mu g/m^3$. This corresponds to typical values found in underground mines. When making an estimate from engine emissions, section 1 data is skipped.

The data for Section 2 of the estimator include the diesel particulate emission rate of each vehicle, the operating time of each vehicle, the horsepower of each vehicle, and the shift length. These values must be entered when Column B of the Estimator is used and are optional when Column A of the Estimator is used.

Engine emission rates can be obtained from manufacturers' specifications. When manufacturers' specifications are not available, the typical range of values given for engine emissions in the spread sheet can be used. When the measurement method is used (Column A), engine emissions data only needs to be entered if a change in engine emissions is to be evaluated. In order to avoid a division by zero when the percent reduction in dp is calculated from new engine technology, a default value of 0.01 gm/hp-hr is used in the spread sheet when engine emissions are not used.

The horsepower for each engine is also obtained from manufacturers' ratings or estimated from the type of engines in use. Again, these values must be entered when Column B of the Estimator is used and are optional when Column A of the Estimator is used. When multiple engines of the same type are used, the estimator can be simplified by combining the horsepower of these engines. For example, two 97 hp, 0.5 gm/hp-hr engines can be entered as a one 194 hp, 0.5 gm/hp engine. However, if different controls are to be used for each engine, the data for each engine must be entered separately. In order to account for the duty cycle, the engine operating time for each piece of equipment and the length of shift are needed.

The data for Section 3 of the estimator include the intake diesel particulate level (dp resulting from diesel equipment use in travelways to the production areas) and the quantity of air being used to ventilate the work place. These values must be entered when either Column A or Column B of the Estimator is used. The estimator calculates the airflow per horsepower as an indication of ventilation system performance. The recommended airflow rate to control gaseous contaminants has been 100 to 200 cfm/horsepower. The particulate index (amount of air required to dilute emissions to 1 mg/m^3) generally ranges from 75 to 200 cfm/hp.

In Section 4, the diesel particulate concentration without control applications is calculated when the estimate is based on engine emissions. No calculation is given when a Section 1 estimate, based on a measurement is used.

The data for Section 5 of the estimator takes into account the effectiveness of control technology. Control technology includes increased ventilation, the use of oxidation catalytic converters (OCC's), the use of clean engine technology and the use of cabs and exhaust filters. Establishment of the ventilation rate should take into consideration the particulate index for all heavy duty engines in the area of the mine or 200 cfm/hp.

When OCC's are used, a dp reduction of up to 20 percent can be obtained. Low sulfur fuel must be used with OCC's to prevent contamination of the catalyst. Clean engine technology can be used to reduce emissions to between 0.1 and 0.2 gm/hp-hr. Environmental cabs can reduce equipment operator exposure by 50 to 80 percent; however, if all workers do not have cabs or if workers cannot remain inside the enclosure, cabs may have little effect on dp exposure. Exhaust filters capture dp at the engine exhaust. Depending on the type of filter, they can reduce emissions by 65 to 95 percent. When starting with a known concentration in the measurement method, the effect of existing controls are reflected in the measurement and would not be entered into the control technology section.

To obtain the output of Section 6, the effect of the control technology entered in Section 5 is applied to either the Section 1 or Section 4 dp concentration. This value provides an estimate of the diesel particulate concentration using the Section 5 controls. This value can be compared to the targeted concentration to determine if additional control technology is required.

RESULTS

Tables 1 and 2 show examples of the estimator. These examples are based on actual in-mine studies. Table 1 shows an example for a coal mine. Table 2 shows an example for a nonmetal mine. In-mine measurements were available in each example, however both the measurement and emissions based methods are shown for comparison.

The first example (Table 1) illustrates a one-section underground coal mine using a room and pillar mining system. Coal was mined using a continuous miner and was transported to a belt feeder by diesel-powered haulage vehicles. No other diesel equipment was used in the mine. Three 94-hp haulage vehicles (0.3 gm/hp-hr) were used to transport coal. The section airflow was approximately 45,000 cfm. The haulage vehicles operated for six hours of the eight hour shift. The in-mine measured diesel particulate concentration was 610 $\mu g/m^3$.

The estimator indicates an engine emission dp concentration of 879 $\mu g/m^3$ compared to the measured dp concentration of 610 $\mu g/m^3$. This difference (30%) was attributed to a lower actual in-mine emission rate and variation of the estimated work cycle. The section airflow was approximately the sum of the PI for each piece of equipment. With the addition of 95 percent exhaust filters the calculated dp would be 53 or 66 $\mu g/m^3$, based on the concentration measurement and the engine emission method, respectively.

The second example illustrates a single level underground limestone mine which operated two shifts per day. Production activities took place on the midnight shift. Support activities took place on the day shift. During the study the mine operated one mining unit, using a room and pillar mining system. On the production shift, a 315-hp loader was used to load two haul trucks having 250-hp and 330-hp diesel engines. These trucks transported the limestone to an underground crusher. The total airflow for the mining unit was approximately 155,000 cfm and most equipment was equipped with an OCC. The equipment was operated for eight hours of the nine hour shift. The in-mine measured diesel particulate concentration was 330 $\mu g/m^3$.

The results of the estimator for the production shift are given in Table 2. The estimator indicates a dp concentration of 551 $\mu g/m^3$ compared to the measured dp concentration of 330 $\mu g/m^3$. This difference (40 percent) was again attributed to a lower actual in-mine emission rate and variation of the estimated work cycle. The airflow for the units was approximately 173 cfm/hp. With the addition and proper use of cabs that reduce exposure by 60 percent, the calculated dp would decrease to 162 or 184 $\mu g/m^3$, based on the concentration measurement and the engine emission method, respectively. Cabs could be effective in this mine because all equipment operators could remain at the controls for the entire shift. If workers had been outside the equipment cabs, a combination of higher ventilation, low emission engines or exhaust filters would have to be used to reduce workers' exposures. Additionally, if further reductions are desired or needed these technologies could be applied in addition to the cabs.

SUMMARY

The Mine Safety and Health Administration has developed a model that can be used to estimate diesel particulate concentrations in underground mines. The model also enables dp levels to be estimated for available diesel particulate control technologies. The model allows for the interrelationship among different control technologies. Two methods have been developed to estimate the impact of diesel particulate control technology. One method uses diesel particulate measurement data as the starting point to derive an estimated diesel particulate concentrations after applying control technology. The other method uses engine emission information derived from laboratory test data to estimate diesel particulate levels and the impact of control technology.

Both methods provide a valuable tool for estimating what technology should be used to obtain various concentrations. Comparison of results obtained with each method indicate that estimates will be within 40 percent of each other. Several examples have been prepared to illustrate the use of the model in both underground coal and metal and nonmetal mines. These examples are based on actual in mine studies.

A variety of control strategies are available to reduce miners' exposure to diesel particulate. The use of the model provides the mine operator the opportunity to evaluate control strategies prior to their implementation. The examples given illustrate that the proper application of dp control technology can significantly reduce exposure to dp in underground mining operations.

REFERENCES

Haney, R.A., and Fields, K.G., "Diesel Particulate Exposures in the Mining Industry," MINExpo International '96, Las Vegas, NV, September 10, 1996. (National Safety Council, Orlando FL, October 30, 1996)

Haney, R.A., Fields, K.G., and Vail, S.G., 1997, "Evaluation of Diesel Particulate Exposures and Control Technology in a Nonmetal Mine," Proceedings of the Sixth International Mine Ventilation Congress, Pittsburgh, PA.

Haney, R.A., Saseen, G.P., and Waytulonis, R.W., "An Overview of Diesel Particulate Exposures and Control Technology in the U. S. Mining Industry," Proceedings of the Second International Conference on the Health of Miners, Pittsburgh, PA, November, 1995.

U.S. Department of Labor, Mine Safety and Health Administration, 1996, 30 CFR, Part 7, Subparts E and F. Approval Exhaust Gas Monitoring and Safety Requirements for the Use of Diesel Powered Equipment in Underground Coal Mines; Final Rule.

U.S. Department of Labor, Mine Safety and Health Administration, 1997, “Practical Ways to Reduce Exposure to Diesel Exhaust in Mining -- A Toolbox” (Draft).

Table 1. Example of Estimator Spreadsheet Results for a Coal Mine

Work Place Diesel Emissions Control Estimator					
Mine Name:		Coal Mine			
		Column A		Column B	
1. Measured or Estimated In Mine DP Level (Fg/m3)		610		---	
2. Vehicle Emission Data					
Emissions Output (gm/hp-hr)					
Vehicle 1	Indirect Injection 0.3-0.5 gm/hp-hr	0.3	gm/hp-hr	0.3	gm/hp-hr
Vehicle 2	Old Direct Injection 0.5-0.9 gm/hp-hr	0.3	gm/hp-hr	0.3	gm/hp-hr
Vehicle 3	New Direct Injection 0.1-0.4 gm/hp-hr	0.3	gm/hp-hr	0.3	gm/hp-hr
Vehicle 4		0.0	gm/hp-hr	0.0	gm/hp-hr
Vehicle Operating Time (hours)					
Vehicle 1		6	hours	6	hours
Vehicle 2		6	hours	6	hours
Vehicle 3		6	hours	6	hours
Vehicle 4		0		0	hours
Vehicle Horsepower (hp)					
Vehicle 1		94	hp	94	hp
Vehicle 2		94	hp	94	hp
Vehicle 3		94	hp	94	hp
Vehicle 4		0	hp	0	hp
Shift Duration (hours)		8	hours	8	hours
Average Total Shift Particulate Output (gm)		0.20	gm/hp-hr	0.22	gm/hp-hr
3. Mine Ventilation Data					
Full Shift Intake Particulate Concentration		25	Fg/m3	25	Fg/m3
Section Air Quantity		45000	cfm	45000	cfm
Airflow Per Horsepower		160	cfm/hp	160	cfm/hp
4. Calculated SWA DP Concentration Without Controls		---		879	Fg/m3
5. Adjustments For Emission Control Technology					
Adjusted Section Air Quantity		45000	cfm	45000	cfm
Ventilation Factor (Initial cfm/final cfm)		1.00		1.00	
Airflow Per Horsepower		160	cfm/hp	160	cfm/hp
Oxidation Catalytic Converter Reduction (%)					
Vehicle 1		0	%	0	%
Vehicle 2	If Used Enter 0-20%	0	%	0	%
Vehicle 3		0	%	0	%
Vehicle 4		0	%	0	%
New Engine Emission Rate (gm/hp-hr)					
Vehicle 1		0.3	gm/hp-hr	0.3	gm/hp-hr
Vehicle 2	Enter New Engine Emission (gm/hp-hr)	0.3	gm/hp-hr	0.3	gm/hp-hr
Vehicle 3		0.3	gm/hp-hr	0.3	gm/hp-hr
Vehicle 4		0.0	gm/hp-hr	0.0	gm/hp-hr
After Filter or Cab Efficiency (%)					
Vehicle 1	Afterfilters	95	%	95	%
Vehicle 2	Use 65-95% For After Filters	95	%	95	%
Vehicle 3	Use 50-80% For Cabs	95	%	95	%
Vehicle 4		0	%	0	%
6. Estimated Full Shift DP Concentrations		53	Fg/m3	66	Fg/m3

Table 2. Example of Estimator Spreadsheet Results for a Nonmetal Mine

			Work Place Diesel Emissions Control Estimator						
				Mine Name:	Underground Metal and Nonmetal Mine				
						Column A		Column B	
1. Measured or Eestimated In Mine DP Level (Fg/m3)						330	Fg/m3	---	
2. Vehicle Emission Data									
Emissions Output (gm/hp-hr)									
Vehicle 1		Indirect Injection 0.3-0.5 gm/hp-hr			FEL	0.1	gm/hp-hr	0.1	gm/hp-hr
Vehicle 2		Old Direct Injection 0.5-0.9 gm/hp-hr			Truck 1	0.2	gm/hp-hr	0.2	gm/hp-hr
Vehicle 3		New Direct Injection 0.1-0.4 gm/hp-hr			Truck 2	0.1	gm/hp-hr	0.1	gm/hp-hr
Vehicle 4						0.0		0.0	gm/hp-hr
Vehicle Operating Time (hours)									
Vehicle 1					FEL	9	hours	9	hours
Vehicle 2					Truck 1	9	hours	9	hours
Vehicle 3					Truck 2	9	hours	9	hours
Vehicle 4						0		0	hours
Vehicle Horsepower (hp)									
Vehicle 1					FEL	315	hp	315	hp
Vehicle 2					Truck 1	250	hp	250	hp
Vehicle 3					Truck 2	330	hp	330	hp
Vehicle 4						0	hp	0	hp
Shift Duration (hours)						10	hours	10	hours
Average Total Shift Particulate Output (gm)						0.09	gm/hp-hr	0.12	gm/hp-hr
3. Mine Ventilation Data									
Full Shift Intake Diesel Particulate Concentration						50	Fg/m3	50	Fg/m3
Section Air Quantity						155000	cfm	155000	cfm
Airflow Per Horsepower						173	cfm/hp	173	cfm/hp
4. Calculated SWA DP Concentration Without Controls						---		551	Fg/m3
5. Adjustments For Emission Control Technology									
Adjusted Section Air Quantity						155000	cfm	155000	cfm
Ventilation Factor (Initial cfm/final cfm)						1.00		1.00	
Airflow Per Horsepower						173	cfm/hp	173	cfm/hp
Oxidation Catalytic Converter Reduction (%)									
Vehicle 1						0	%	20	%
Vehicle 2		If Used Enter 0-20%				0	%	20	%
Vehicle 3						0	%	0	%
Vehicle 4						0	%	0	%
New Engine Emission Rate (gm/hp-hr)									
Vehicle 1						0.1	gm/hp-hr	0.1	gm/hp-hr
Vehicle 2		Enter New Engine Emission (gm/hp-hr)				0.2	gm/hp-hr	0.2	gm/hp-hr
Vehicle 3						0.1	gm/hp-hr	0.1	gm/hp-hr
Vehicle 4						0.0	gm/hp-hr	0.0	gm/hp-hr
After Filter or Cab Efficiency (%)									
Vehicle 1					Cabs	60	%	60	%
Vehicle 2		Use 65-95% For After Filters				60	%	60	%
Vehicle 3		Use 50-80% For Cabs				60	%	60	%
Vehicle 4						0	%	0	%
6. Estimated Full Shift DP Concentration						162	Fg/m3	184	Fg/m3

Table 3. Information needed for or provided by each section of the model

Spreadsheet Section	Input/Output	Mine Information
Section 1	Input	Measured or Estimated DP Level, µg/m^3
Section 2	Input	Engine Emissions, gm/hp-hr Engine Horsepower, hp Operation Times, hr Shift Duration., hr
Section 3	Input	Section Airflow, cfm Intake DP Level, µg/m^3
Section 4	Output	Current DP Level, µg/m^3
Section 5	Input	DP Controls: Airflow, cfm Oxidation Catalytic Converter, percent Engine Emissions, gm/hp-hr After Filters, percent Cabs, percent
Section 6	Output	Projected DP Level, µg/m^3