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DEVELOPMENT OF AIR QUANTITY ESTIMATOR (AQE 2.0) SOFTWARE FOR ESTIMATING AIRFLOW REQUIREMENTS FOR DILUTING DIESEL PARTICULATE MATTER

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ABSTRACT

Mine workers using diesel-powered equipment experience the highest occupational exposure to diesel particulate matter (DPM). This problem could be aggravated in underground stone mines due to their unique ventilation challenges with the large openings for airflow. Hence, adequate ventilation in these mines requires a combination of effective ventilation planning and delivering needed air quantities using auxiliary fans and stoppings. To meet this challenge, the National Institute for Occupational Safety and Health (NIOSH) developed the Air Quantity Estimator (AQE) software as a mine planning tool to help underground mine operators estimate the air requirements necessary to dilute DPM in the main air stream to statutory levels. The major parameters required for the calculations are the engine's horsepower, DPM emission rate, the percentage operating time, catalytic converter efficiency, and filter efficiency. In efforts to provide major updates to this software, this study describes the recent development of a revised version of the Air Quantity Estimator (AQE 2.0). With the revised version, users have access to a comprehensive database of over 40,000 pieces of equipment, can define their specific target DPM level, and can create specific equipment for a customized database, in addition to having an improved easy-to-use interface. The software output provides an estimated total airflow necessary to dilute DPM based on the projected emissions, and the user can generate a related results report. The results also provide the mine personnel with a tool to identify vehicles that are high DPM contributors and could further be used to optimize the ventilation requirement by making changes to the percentage operating time of the engine. This software provides the mine with a user-friendly tool that could help reduce the DPM exposure of workers.

INTRODUCTION

Diesel-powered engines are important to mining in the United States due to their durability, good-power performance, and efficiency. However, the exhaust from diesel engines contains harmful pollutants with both short- and long-term effects to workers' health. These exhausts are a complex mixture of gases and particulates [1], which consist of carbon ash, metallic abrasion particles, sulphates, and silicates. Ultrafine particles (<0.1 µm) and fine particles (<2.5 µm) from the diesel particulate matter (DPM) could pass through the nose and throat and into the lung tissue with toxic substances that obstruct the diffusion of oxygen into the bloodstream. These substances affect the cardiovascular and respiratory system, and the related hazards could include premature death, cancer, asthma, breathing difficulty, sudden infant death syndrome (SIDS), chronic obstructive pulmonary disease (COPD), coughing, pneumonia, chronic bronchitis, and stroke[2]. The National Institute for Occupational Safety and Health (NIOSH) identified the likely carcinogenic effects of DPM on human health [3], which is further confirmed by the International Agency for Research on Cancer (IARC) [4]. The problem with DPM is further aggravated in confined environments such as underground mines where workers are directly and continuously exposed. Studies have shown that workers in coal and noncoal mines using diesel-powered equipment experience the highest occupational exposure to DPM with a range of 10 µg/m^3 to 1,280 µg/m^3 [1]. Consequently, there are regulations to limit the exposure of mine workers to DPM. As stated in the 30 CFR § 57.5060 (b) standard, "Effective May 20, 2008, a miner's personal exposure to diesel particulate matter (DPM) in an underground mine must not exceed an average eight-hour equivalent full shift airborne concentration of 160 micrograms of total carbon per cubic meter of air (160TC µg/m^3)" [5]. Considering that natural ventilation has been used historically in most of the large-opening stone mines in the U.S., adequate ventilation planning is needed in large-opening stone mines to meet this requirement.

To ensure compliance with the DPM standard, mines must strategically plan the ventilation system by measures such as increasing ventilation airflow, using auxiliary fans, using stoppings to direct airflow, and decreasing engine DPM emissions by using filters and catalytic converters. To help with ventilation planning, this study focuses on the development of an updated version of the Air Quantity Estimator (AQE) [6] software for underground large-opening mines (40 ft – 50 ft wide by 20 ft – 30 ft high). The application is focused on stone mines even though it could be useful for other metal/nonmetal mines of similar dimensions. AQE was first developed by NIOSH in 2006 and provided stone mines with a tool for ventilation design [6]. The software estimates the airflow required to maintain appropriate levels of diesel particulate matter (DPM) in underground, large-opening mines. With this new software, users can input their target DPM limits, and the software will estimate the required airflow to achieve the set limit.

The software also provides the DPM emission rate of each piece of equipment and could be used to identify equipment that are a high source of DPM in the mine. After identifying the equipment, appropriate optimization strategies or engineering control methods could be implemented to reduce the DPM emissions. The updated software has a compilation of over 40,000 pieces of equipment from the Mine Safety and Health Administration (MSHA) and U.S. Environmental Protection Agency (US EPA) websites [7, 8]. Users of AQE 2.0 can import engine data from the database included in the software or create a customized database with their mine-specific equipment. The key parameters required for the calculations are the engine's horsepower, DPM emission rate, percentage of operating time, catalytic converter efficiency, and filter efficiency. The user has the option of creating multiple scenarios by creating cases where different engines are considered in specific shifts. Considering the assumptions used for the software development, this estimated value is a starting point and does not guarantee adequate mine face ventilation or compliance with personal exposure limit. The mine ventilation personnel must ensure that the airflow is effectively directed toward the mine working face to avoid accumulation of high DPM concentrations in the main air stream.

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RESEARCH APPROACH

The AQE 2.0 software is a user-friendly, stand-alone package that can be installed on any computer and does not depend on another program or the internet to function. Occasionally, the user can connect to the internet to check for updates on the database. For each scenario, the user can generate a pdf or html report. The user provides the equipment parameters, and the software estimates the required airflow to achieve the DPM limit set in the preferences. The calculations implemented in the software are described below and illustrated with a case study.

Software Calculations

The complete description of the method and assumptions used in the software are published by Robertson et al. (2004) [6]. The program assumes there is enough ventilation and a thorough mixing of ventilation air where equipment is operating. It assumes that the contaminants from all working faces or areas where the equipment is operating are eventually dumped into the main air stream of the mine and then exhausted out of the mine through one portal. It also assumes that a ventilation system is in place where there is little to no air recirculation in the mine and no air leakage across the main mine fans or stoppings. The equations are simplified and summarized below. The average vehicle DPM emission rate (g/min), $D_{A\epsilon}$, is calculated as:

$$D_{A\epsilon} = 1.67 \times 10^{-8}\, \text{Ђ}\, \text{Ɛ}\, \text{Ø}\, (100 - \Psi)(100 - \lambda). \tag{1}$$

In Equation 1, Ђ is the equipment horsepower (hp), Ɛ is the engine DPM emission rate (g/hp-hr.), Ø is the percentage of underground operating time that the equipment is used during a shift (%),Ψ is the catalytic converter efficiency of the equipment (%), and λ is the filter efficiency of the equipment (%). The air volume flow rate required to meet a target DPM level of 160_{TC} μg/m^3 standard ($\mathrm{A}_{₣160}$) (cfm) is calculated as:

$$\mathrm{A}_{₣160} = \frac{2.8269 \times 10^{7}}{160} \sum_{i=1}^{n} D_{A\epsilon_i} \tag{2}$$

In Equation 2, n is the total number of diesel equipment used for the shift. As a case study, two MSHA-approved engines are used to illustrate the application of the Equations 1 and 2.

Assuming that each piece of equipment is operated for 80% of a shift, the average DPM emission rate is calculated below:

For Cummins QSB-155C in Table 1,

$$D_{A\epsilon} = 1.67 \times 10^{-8} \times 155 \times 0.11 \times 80 \times (100 - 20) \times (100 - 72) = 0.0510\, g/min \tag{3}$$

For DEUTZ BF4M2012 in Table 1,

$$D_{A\epsilon} = 1.67 \times 10^{-8} \times 100 \times 0.08 \times 80 \times (100 - 20) \times (100 - 45) = 0.0470\, g/min \tag{4}$$

The total airflow required to meet the 160_{TC} μg/m^3 standard is estimated as:

$$A_{₣160} = 2.8269 \times 107 \times (0.0510 + 0.0470)\,/160 = 17{,}315\, cfm \tag{5}$$

Getting Started

AQE 2.0 is developed for a Microsoft Windows operating system and is available for download on the CDC NIOSH website: https://www.cdc.gov/niosh/mining/works/coversheet1809.html.

The software does not require any other software installation (such as Microsoft Excel) to function properly. After installing the software, the program could be started using the desktop shortcut or through the start menu. On the start menu, open the 'NIOSH' folder and click the 'Air Quantity Estimator' icon like any other software program normally installed on a Microsoft Windows operating system. After opening the software, an application metrics' page inquires if the user is willing to share the usage data with NIOSH (Figure 1). The metrics collected from AQE 2.0 allows NIOSH Mining Program researchers to gain a better measure of the software impact with interested parties. It also helps to identify if research results have been successfully implemented and transferred to industry. NIOSH does not collect any personally identifiable information, or any data imported into AQE. If the user decides to change their preference at any point, the metrics page can be accessed through the 'Usage Data' submenu on the 'Help' menu tab.

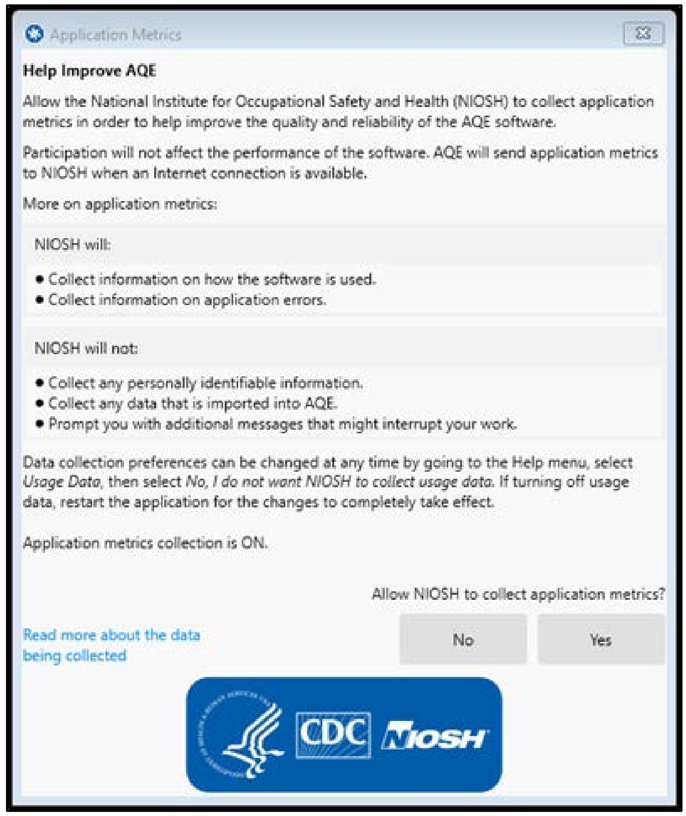

Figure 1. Usage data inquiry screen.

Input Parameters

The estimated airflow volume flow rate from the software is dependent on the input parameters as shown in Equation 1. Figure 2 (see APPENDIX) shows an illustration of the AQE software with the input parameters using sample equipment. The horsepower is the rated horsepower of the engine (hp), and the RPM is the revolution per minute corresponding to the horsepower. The percentage underground operating time is the percentage ratio of the duration the equipment is used during a shift divided by the duration of shift, and the range is a value between 0-100 %. As an illustration, 60% in Figure 2 implies that the equipment is used for 4 hrs 48 min during an 8-hr shift. The filter efficiency depends on the data available from the equipment manufacturer. In a scenario where this value is not available, 85% is a conservative estimate and should be entered as '85'. Similarly, if the equipment has a catalytic converter, 20% is a conservative efficiency that could be used as shown in Figure 1.

The last parameter required for each type of equipment is the DPM emission rate which could be challenging for the operators to estimate. However, the database included within the software could guide users if the equipment is not on the database. If this information is not available, the user could make an estimate on whether the engine is a New Direct, Old Direct, or Indirect injection engine. The DPM emission ranges from 0.1 to 0.4 g/hp-hr for a new direct injection engine, 0.5 to 0.9 g/hp-hr for an indirect injection engine, and 0.5 to 0.9 g/hp-hr for an old direct injection engine [9]. A new and well-maintained piece of equipment will have emission in the lower range for the estimate provided. Otherwise, higher values will provide a conservative estimated calculation. AQE 2.0 is developed with a comprehensive database of over 40,000 engines compiled from MSHA [8] and EPA databases [7]. The user can update the database by clicking the *'check for database update'* under the Equipment tab. NIOSH researchers will

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continue to update the database as new information is obtained or if any error is reported. In some cases, the user might not find the exact equipment used in the mine, but similar equipment on the database could guide the users toward defining the parameters of the equipment.

Software Assumptions

The airflow estimated from this software is a starting value for ventilation planning at a mine level and does not guarantee the best possible value for adequate ventilation airflows for each working face. It is assumed that the ventilation air is thoroughly mixed in the locations where the engines are operated. It is also assumed that all contaminants in the mine are mixed with the main air stream and exhausted through one portal [6]. It is also assumed that there is no recirculation, and air leakages between the mine fans and stoppings are negligible. Finally, it is important to note that the air volume flow rate estimate from this software is highly dependent on the input parameters, and it is the responsibility of the user to ensure that this is as accurate as possible, even when values are obtained from the software database.

RESULT AND DISCUSSION

AQE 2.0 is an updated version of a software that has been previously validated in the mine [6]. Therefore, this version is validated by comparing the results from the previous validation study with the new software using the same conditions. The results summary from the software is displayed below the software interface as shown in Figure 2 showing the 'total equipment DPM', 'Total HP', and the 'Estimated air quantity required to meet the 160_{TC} μg/m^3 standard'. The user can generate a report of the scenario of the simulation by clicking the 'Generate report' tab. The report can be generated as 'HTML' or 'PDF' depending on the user's preference. Based on the results, it is possible to identify equipment that are contributing higher DPM to the mines compared to others. After identifying such equipment, measures such as improving filter efficiency or reducing the operating/idling time of such equipment could help to reduce DPM emission and optimize the airflow requirements. For the illustration in Figure 3 (see APPENDIX) , the equipment contributing the highest DPM is AD XX with an average DPM emission rate of 1.515 g/min. Based on this result, a simple optimization study is illustrated by improving the filter efficiency of AD XX (Figure 4) and reducing the operating time (Figure 5). Figure 5 shows the impact of the filter efficiency on the total airflow requirement. By improving the filter efficiency from 40% to 80%, the total airflow required reduced from 367,878 cfm to 189,427 cfm (≈ 48.5% decrease). This is a huge reduction in the overall airflow requirement and could potentially translate into a significant financial saving for the mine with regards to fans and electricity cost. Overall, this strategy also reduces the level of DPM released into the mine from 1.52 g/min to 0.51 g/min for the equipment. Further investigation in Figure 5 shows the plot of airflow required with a different operating time for Equipment AD XX. The required airflow reduced from 367,878 cfm to 278,652 cfm (≈ 24.3%) by reducing the operating time of AD XX from 90% to 60%. This is also a significant reduction in the airflow required and the diesel emission rate from the equipment (1.52 g/min to 1.01 g/min). These are some of the measures that could be implemented to reduce the DPM level in a mine, and AQE 2.0 provides a simplified method to identify the impact of these parameters. Reducing the underground operating time could be as simple as ensuring the equipment is not idling during a shift except when it is critical to the operation. It is important to note that the catalytic converter has a significant impact on the DPM emission rate. For example, if Equipment AD XX does not have a catalytic converter, the total airflow required for 160_{TC} μg/m^3 increases to 434,797 cfm. This is an increase of over 18% in the required airflow which suggests that mines could reduce the DPM emission or required airflow by using equipment with a catalytic converter.

CONCLUSIONS

This report presents the development of the updated version of the Air Quantity Estimator (AQE) software for estimating the airflow required to achieve a specified level of DPM level in underground large-opening stone mines. This easy-to-use software provides a starting point for airflow estimation and can be used to plan ventilation control strategies. The illustration presented in this study shows how the operator can identify equipment that are high DPM contributors. The results show that the potential airflow can be significantly optimized by increasing the filter efficiency of the equipment, reducing the equipment utilization duration by minimizing idling, and ensuring that equipment has a catalytic converter. These findings show that the software provides the mine operator with a tool for airflow optimization and could be used for ventilation planning.

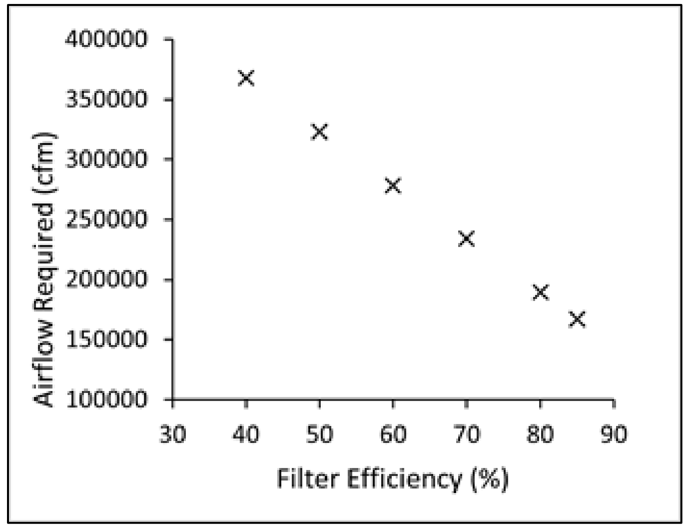

Figure 4. Airflow required with variation to filter efficiency for Equipment AD XX (highest DPM emitter).

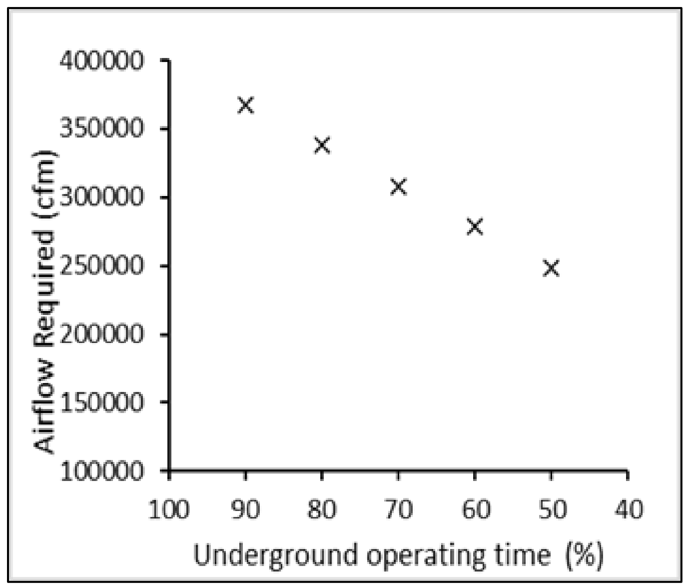

Figure 5. Airflow required with changes in underground operating time for Equipment AD XX (highest DPM emitter).

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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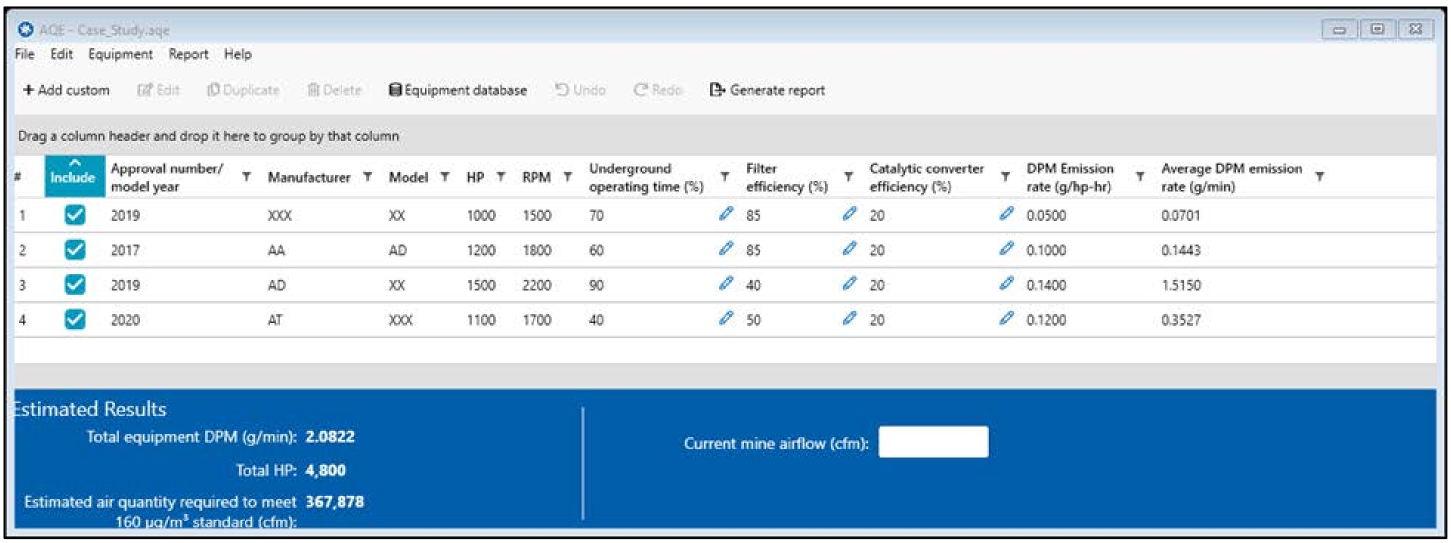
APPENDIX

Table 1. Summary of Equipment used for Illustration.

Model Year/ Approval Number	Manufacturer	Model	HP	Rated RPM	Steady-State Discrete Modal Test Results (g/hp-hr.)	Filter Efficiency (%)	Catalytic Converter Efficiency (%)
07-ENA040001	CUMMINS	QSB-155C	155	2500	0.11	72	20
07-ENA040002	DEUTZ	BF4M2012	100	2500	0.08	45	20



AQE - Case_Study.aqe
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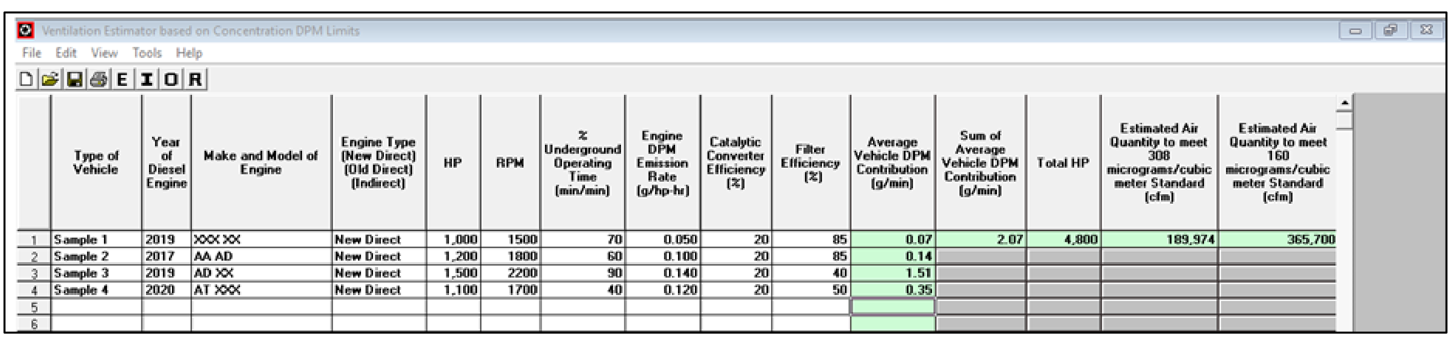
#	Include	Approval number/ model year	Manufacturer	Model	HP	RPM	Underground operating time (%)	Filter efficiency (%)	Catalytic converter efficiency (%)	DPM Emission rate (g/hp-hr)	Average DPM emission rate (g/min)
1	✓	2019	XXX	XX	1000	1500	70	85	20	0.0500	0.0701
2	✓	2017	AA	AD	1200	1800	60	85	20	0.1000	0.1443
3	✓	2019	AD	XX	1500	2200	90	40	20	0.1400	1.5150
4	✓	2020	AT	XXX	1100	1700	40	50	20	0.1200	0.3527

Estimated Results
Total equipment DPM (g/min): **2.0822**
Total HP: **4,800**
Estimated air quantity required to meet 160 μg/m³ standard (cfm): **367,878**
Current mine airflow (cfm):

Figure 2. AQE 2.0: Demonstration of software output.



Ventilation Estimator based on Concentration DPM Limits
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	Type of Vehicle	Year of Diesel Engine	Make and Model of Engine	Engine Type (New Direct) (Old Direct) (Indirect)	HP	RPM	% Underground Operating Time (min/min)	Engine DPM Emission Rate (g/hp-hr)	Catalytic Converter Efficiency (%)	Filter Efficiency (%)	Average Vehicle DPM Contribution (g/min)	Sum of Average Vehicle DPM Contribution (g/min)	Total HP	Estimated Air Quantity to meet 308 micrograms/cubic meter Standard (cfm)	Estimated Air Quantity to meet 160 micrograms/cubic meter Standard (cfm)
1	Sample 1	2019	XXX XX	New Direct	1,000	1500	70	0.050	20	85	0.07	2.07	4,800	189,974	365,700
2	Sample 2	2017	AA AD	New Direct	1,200	1800	60	0.100	20	85	0.14				
3	Sample 3	2019	AD XX	New Direct	1,500	2200	90	0.140	20	40	1.51				
4	Sample 4	2020	AT XXX	New Direct	1,100	1700	40	0.120	20	50	0.35				
5															
6															

Figure 3. Results from the old AQE software validated with field studies.

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