Assessment of environmental impact of digging and loading equipment in surface coal mining

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Abstract
This paper presents research on the environmental impact of digging and loading equipment used in surface coal mining. Environmental impact was assessed through the measurement of equipment exhaust and dust emissions, and sound level. In this study, exhaust emission refers to carbon dioxide (CO$_2$), carbon monoxide (CO), nitrogen oxides (NO$_x$), sulfur oxides (SO$_x$) and volatile organic compounds (VOCs). Dust generation refers to fine particles (PM$_{2.5}$), inhalable particles (PM$_{10}$) and total suspended particulate matter (TSP). Sound level refers to the sound pressure level at different distances from the equipment. Modeling of the environmental impact of digging and loading equipment was conducted using the Microsoft Visual Studio.NET software package. This research was a part of a broader project involving the development of a software system for the selection of productive, cost-efficient and ecofriendly mining systems, sponsored by the Appalachian Research Initiatives for Environmental Sciences (ARIES). This research may assist mining professionals in quantifying the environmental impact of digging and loading equipment, and developing strategies for reducing the overall impact of such equipment in surface mining.

Key words: Dust control, Exhaust emission, Noise exposure, Noise control, Surface mining, Digging and loading equipment


Introduction
Major environmental hazards in digging and loading operations in surface mining include exhaust emission, dust emission and noise exposure. The equipment used in this process not only contributes to a significant sound level in mining areas, but also accounts for a substantial fraction of the emissions of primary air pollutants, including dust and exhaust emissions.

Dust emission is categorized according to the size range of the component particles. Some dust particles are large, and others are so small that they can be detected only by a microscope. Inhalable particulate refers to the fraction of dust particles that can be breathed into the nose or mouth. Thoracic particulate refers to the fraction of particles that can penetrate the head airways and enter the airways of the lung. Respirable particulate refers to the fraction of inhaled airborne particles that can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs (Soderholm, 1989). Particles ranging in size from 0.1 micrometer to about 30 micrometer in diameter are referred to as total suspended particulate (TSP) matter. Particulate matters with a diameter of 10 micrometers collected with 50% efficiency by a PM$_{10}$ sampling collection device are called inhalable particles (PM$_{10}$). Fine particles (PM$_{2.5}$) are defined as particulate matters with a diameter of 2.5 micrometers collected with 50% efficiency by a PM$_{2.5}$ sampling collection device (EPA, 2012). In other words, TSP includes a broad range of particle sizes, including fine, coarse and super-coarse particles. The PM$_{10}$ includes coarse and fine inhalable particle sizes, and fine particles are called PM$_{2.5}$.

The U.S. Environmental Protection Agency (EPA) regulates fine and inhalable particles. The inhalable particles pose the greatest problems because they can get deep into lungs, and some may even enter into the bloodstream. Fine particles settle quite slowly in the atmosphere as compared to coarse and super-coarse particles. Normal weather patterns can keep PM$_{10}$ particles airborne from several hours to several days. The PM$_{2.5}$ particles can cause health problems due to their potentially long airborne retention time and the inability of the human respiratory system to defend itself against particles of this size (EPA, 2012). Dust particles can also be a safety hazard by impairing the equipment operator’s visibility (Reed and Organiscak, 2005). Although TSP is not regulated by the EPA, in some cases they may need to be reported for metals; thus, the TSP emission needs to be calculated to determine metal emissions (NPI, 2012).
Organisk and Reed (2004) described the average and instantaneous peak dust levels 30.5 m (100 ft) from haul roads. The authors also published the results of research related to the evaluation of safe following distance for equipment in order to avoid overexposure to respirable dust from lead trucks (Reed and Organisk, 2005). Colin et al. (2010) listed various available engineering controls that may help the mining industry reduce dust exposure. Reed et al. (2013) conducted research to compare dust sampling results from the model 1500-pDR, and provided a detailed sampling method. Reed (2004) also compared the performance of two dust dispersion models for haul trucks - dynamic component program (DCP) and industrial source complex (ISC3) model - developed by the EPA.

In addition to particulate matter, the EPA has adopted National Ambient Air Quality Standards for five other principal pollutants, referred to as criteria pollutants; these include nitrogen dioxide (NO₂), carbon monoxide (CO), sulfur dioxides (SO₂), ozone (O₃) and lead (Pb) (EPA, 2013). Volatile organic compounds (VOCs) are other pollutants emitted from mining equipment. Exposure to VOCs causes eye, nose and throat irritation; headache; loss of coordination; nausea; and damage to the liver, kidney and central nervous system (Davis, 2007). The EPA exempts coal extraction activities from VOC reporting requirements (EPA, 2000).

A number of studies have been conducted to analyze emissions of mining and construction equipment. Lewis et al. (2009) described governmental regulations that limit emission of air pollutants. The authors also identified construction equipment emission sources and compared their data with data obtained from various sources. Sharrard et al. (2007) conducted research on the environmental and energy implications in the construction industry and concluded that equipment fuel consumption is almost twice the level indicated in various governmental reports; and accordingly, that the impact of emission is 30% greater for particulate matter and almost twice the levels for NOₓ and VOCs. Kean et al. (2000) conducted a study to determine emissions of NOₓ and PM₁₀ for off-road diesel equipment based on diesel fuel consumption. Gautam et al. (2002) used an in-field testing method to determine emission factors for diesel powered off-road engines, including excavator, front-end loader, dozer and street sweeper. Bogunovic and Kecojevic (2009) conducted research to measure surface mining equipment CO₂ emission. Lewis (2009) estimated fuel consumption, exhaust and dust emissions of excavators, track loaders, wheel loaders, backhoes, dozers, off-road trucks and motor graders. Frey et al. (2010) used a portable emission monitoring system to gather data from excavators, backhoes, dozers, track type loaders, wheel loaders, graders, generators and off-road trucks. Dallmann and Harley (2010) conducted research to measure exhaust emissions for NOₓ and fine particulate matter from mobile sources using a fuel-based methodology. Kecojevic and Komljenovic (2010) determined the quantity of CO₂ emitted by haul trucks and the associated cost that may arise from potential CO₂ legislation.

The term noise applies to annoying and undesired auditory sensations (Bise, 2001). The U.S. Mine Safety and Health Administration (MSHA) regulates noise in mines regardless of mining method (MSHA, 2012). The action level is defined by MSHA as an eight-hour time-weighted average sound level of 85 dBA, integrating all sound levels from 80 dBA to at least 130 dBA. MSHA also defines the permissible exposure level as an eight-hour time-weighted average sound pressure level of 90 dBA, integrating all sound levels from at least 90 dBA to at least 140 dBA. If noise exposure of mine workers exceeds the permissible exposure level during any workshift, regulations require mine operators to enroll workers in a hearing conservation program and use all feasible engineering and administrative controls to reduce workers’ noise exposure to the permissible level.

According to Kovalchik et al. (2009), many health hazards associated with mining operations have improved, with the exception of hearing loss. Bolt, Baranek and Newman, Inc. (1971) established empirically based relationships of heavy equipment sound exposure as a function of horsepower. In 1982, the U.S. Federal Highway Administration (FHWA) (Bowlby and Cohn, 1982) published a standardized construction sound model called highway construction noise model (HICNOM). More recently, a number of models have been developed for the prediction of sound exposure in construction projects, such as CadnaA, SoundPLAN and the Environmental Noise Model (FHWA, 2006). In these models, equipment sound data is expressed as a sound pressure level at a reference distance, or sound power level. Noise impacts and exposures may be categorized relative to operator, other employees working around the equipment and the community. Much work has been done relating to use of operator cabs and sound absorbing materials to decrease equipment operators’ noise exposure. Bealko (2009) examined noise exposure inside haul truck cabs during a typical workday with normal operator practices, the effect of noise-reduction features inside the cab, the consequence of disabling noise controls (unnecessary open doors/windows) and the significance of haul truck and cab maintenance factors. Bauer and Babich (2007) conducted research on noise assessment of stone/aggregate mines for three surface and three underground mines. The surveys consisted of sound level measurements conducted around various equipment and machinery.

The overall objective of this research project was to develop an integrated software tool for the selection of productive, cost-effective and ecofriendly mining systems, a tool that will be used by surface mining operations in the Appalachian region. This paper presents a part of that software that relates to determining the environmental impact of digging and loading equipment, including hydraulic backhoe and rope shovels, and front-end wheel loaders for a specific surface coal mining operation in the Appalachian region. Draglines, which are used for removing overburden, was also considered. In this study, exhaust emission refers to carbon dioxide (CO₂), carbon monoxide (CO), nitrogen oxides (NOₓ), sulfur oxides (SO₂) and volatile organic compounds (VOCs). Dust refers to fine particles (PM₂.₅), inhalable particles (PM₁₀) and total suspended particulate matter (TSP). Sound level refers to sound pressure level at different distances from the equipment.

**Method**

Data for this project was collected from an operating surface coal mine in West Virginia that has been active since the early 1970s. The geologic formations in the mine consist of sandstone overburden with some shale streaks, and include five coal seams of varying thicknesses interspersed between layers of interburden. The mine produces approximately 2.5 Mt (2.8 million st) of coal and about 32 Mm³ (42 million cu yd) of overburden per year. The operation uses diverse mining equipment, including: a dragline, a rope shovel, drills, bull-dozers, backhoe shovel, graders, haul trucks, front-end wheel loaders, water trucks and auxiliary equipment.

Data on fuel and electricity consumption, number of working hours and production rate for digging and loading equipment is displayed in an Excel spreadsheet. Data is classified for a backhoe shovel, nine front-end wheel loaders, a rope shovel and a dragline. The backhoe shovel and two wheel loaders...
are used for digging and loading the coal, while the dragline, rope shovel and seven wheel loaders are used for overburden material. Exhaust, dust emissions and sound levels were considered for the backhoe shovel and front-end wheel loaders, while dust and sound levels were considered for rope shovel and dragline. For the purpose of this project, modeling of the environmental impact of digging and loading equipment was conducted using the Microsoft Visual Studio.NET software package. What follows provides a mathematical interpretation that is used for the determination of exhaust and dust emissions and sound level.

There are several estimation methods that can be used to determine the exhaust emissions of mining equipment. These include: direct measurement or sampling, mass balance, fuel analysis and emission factors (NPI, 2008). Direct measurement uses continuous emission monitoring or sampling data from the working area. In the mass balance method, the difference between the amount of a specific substance in output and input of the system is used to calculate the emission of a specific pollutant. The fuel analysis method is based on chemical or physical properties of a substance (e.g., ideal gas law) and application of the set of mathematical relationships. The emission factors method is commonly used for determination of exhaust emissions. This method is based on multiplication of the activity rate (in units of weight, volume, distance or duration per unit of time) by the appropriate emission factors. These factors are expressed as the emission rate when a unit of equipment is operated in an average manner. Emission factors are usually mass-based and stated in mass per unit of fuel consumed, mass per unit of activity (e.g., pound per horsepower hour), or mass per mile traveled. The latter method is applied in this study.

The exhaust emission of digging and loading equipment (CO, NOx, SOx, VOC and CO2) was determined as follows:

\[ E_i = EF_i \cdot HFC \cdot H \]

where \( E_i \) is annual emission of the substance \( i \) (lb/yr), \( EF_i \) is emission factor of substance \( i \) (lb/gallon), \( HFC \) is hourly diesel fuel consumption (gallon/hr) and \( H \) is the number of operating hours per year (hr/year). Values of emission factors are adopted from NPI (2002) and EPA (1985).

In this study, dust emission was determined as follows:

\[ E_i = A \cdot EF_i \cdot (1 - CE_i/100) \]

where \( E_i \) is emission rate of pollutant \( i \) (lb/year), \( A \) is production rate (t/yr), \( EF_i \) is uncontrolled emission factor of pollutant \( i \) (lb/ton), \( CE_i \) is overall emission reduction efficiency of pollutant \( i \) (%), and TSP, PM\textsubscript{10} and PM\textsubscript{2.5} are pollutants \( i \).

Various pollutant emission control technologies, such as wording, the use of chemical wetting agents, fabric filters, electrostatic precipitators and wet scrubbers are usually used to decrease the concentration of dust emitted into the air. In cases where emission abatement tools have been used, the efficiency of dust collection of the abatement device needs to be considered.

According to the EPA (2006), dust emission factors for digging and loading equipment working on overburden material can be determined as follows:

\[ EF_i = K_i \cdot 0.0032 \cdot \left( \frac{U}{5} \right)^{1.3} \cdot \left( \frac{M}{2} \right)^{1.4} \]

where \( U \) is mean wind speed (mph) and \( M \) is moisture content (% by weight). The factor \( K_i \) for TSP, PM\textsubscript{10} and PM\textsubscript{2.5} is equal to 0.74, 0.35 and 0.053, respectively.

The TSP emission factor for digging and loading equipment working on coal extraction can be determined as follows (EPA, 1998):

\[ EF_{TSP} = 1.16/ \frac{M^{1.2}}{Q} \]

The PM\textsubscript{10} emission factor is determined as follows:

\[ EF_{PM_{10}} = 0.089/ \frac{M^{0.9}}{Q} \]

The PM\textsubscript{2.5} emission factor is determined as follows:

\[ EF_{PM_{2.5}} = 0.022/ \frac{M^{1.2}}{Q} \]

In the absence of onsite specific data on wind speed and moisture content, the single-value emission factors derived from the EPA (1998) can be used. Emission factors for TSP, PM\textsubscript{10} and PM\textsubscript{2.5} at digging and loading operations in overburden material are 0.0185, 0.00875 and 0.001325 kg/t (0.037, 0.0175 and 0.00265 lb/st), respectively, and for digging and loading operations in coal, these values are 0.017, 0.003 and 0.0009 kg/t (0.034, 0.006 and 0.0018 lb/st), respectively. In the developed software forms, these values are presented as default values, although there are two more options for users. The first, to directly adjust emission factors based on the values from measurement of dust in mining area, or second, to input moisture content and wind speed to calculate the values based on EPA equations.

The sound pressure level is the level of sound, i.e., the sound exposure at the measuring point. Therefore, the sound produced by equipment can be expressed by specifying the measurement distance along with sound pressure level (\( L_p \)). The \( L_p \) can be expressed as follows (Mollenhauer and Tschoeke, 2010):

\[ L_p = 20 \cdot \log_{10} \left( \frac{P}{P_0} \right) \]

where \( P \) is sound pressure (Pa), and \( P_0 \) is the reference sound pressure (\( P_0 = 2 \times 10^{-5} \) Pa).

An alternative way to describe sound produced by a machine is the sound power level (\( L_w \)):

\[ L_w = 10 \cdot \log_{10} \left( \frac{W}{W_0} \right) \]

where \( W \) is sound power emitted by the source (watts) and \( W_0 \) is reference sound power level (\( W_0 = 10^{-12} \) watts).

The relation between sound pressure level and sound power level is as follows (Berger et al., 2003):

\[ L_p = L_w + 10 \cdot \log_{10} \left( \frac{Q}{4 \pi r^2} + \frac{4}{R} \right) + k + CF \]

where \( CF \) is a correction factor, in decibels, for atmospheric temperature and pressure; \( k \) is a constant that is 10.5 dB for English units (0 for SI units); \( R \) is an enclosed area constant, \( Q \) is a directivity factor, and \( r \) is the distance from the source. The correction factor \( CF \) at or near standard conditions, which is 20° C (68° F) and 101 KPa (14.7 psi), is usually negligible. The enclosed area factor \( R \) for open areas would be a very large number. \( Q \) for areas above a reflecting plane, such as the ground, is 2. Therefore, the simplified relation between sound pressure level and sound power level for loading equipment is as follows:
Sound power level and sound pressure level are defined on a logarithmic scale, called the decibel (dB). The decibel is a useful way of handling very small or very large scalar values, defined as follows:

\[ \text{dB} = 10 \cdot \log_{10} \left( \frac{\text{quantity measured}}{\text{reference level}} \right) \]  

It should be noted that decibels defined for sound power and sound pressure level are completely different, because the reference level for sound pressure level is \( P_0 = 2 \times 10^{-5} \text{ Pa} \), while the reference level for sound power level is \( W_0 = 10^{-12} \text{ watts} \). It is a means to compare two sounds that can be defined by comparing the sound level with a reference sound.

Based on the report given by the British Standards Institution (BSI, 2009), the permissible sound power levels of the dragline and shovels are calculated as follows:

\[
L_{SW} = \begin{cases} 
103 & P \leq 55 \text{kW} < 73.76 \text{ hp} \\
84 + 11 \cdot \log_{10} P & P > 55 \text{kW} \geq 73.76 \text{ hp} 
\end{cases}
\]  

and for wheel loaders:

\[
L_{w} = \begin{cases} 
101 & P \leq 55\text{kW} \leq 73.76 \text{ hp} \\
82 + 11 \cdot \log_{10} P & P > 55 \text{kW} = 73.76 \text{ hp} 
\end{cases}
\]

where \( P \) is engine power (kW).

Therefore, the sound pressure limit measuring at the distance of \( r \) from the dragline and shovel will be:

\[
L_{p} = \begin{cases} 
105.5 - 20 \cdot \log_{10}(r) & P \leq 55\text{kW} \leq 73.76 \text{ hp} \\
86.5 + 11 \cdot \log_{10}(P) - 20 \cdot \log_{10}(r) & P > 55 \text{kW} \geq 73.76 \text{ hp} 
\end{cases}
\]

and for wheel loaders:

\[
L_{p} = \begin{cases} 
103.5 - 20 \cdot \log_{10}(r) & P \leq 55\text{kW} \leq 73.76 \text{ hp} \\
84.5 + 11 \cdot \log_{10}(P) - 20 \cdot \log_{10}(r) & P > 55 \text{kW} \geq 73.76 \text{ hp} 
\end{cases}
\]

It should be noted that the exact value of sound pressure level for mining equipment should be determined by onsite measurements, since the level of sound pressure produced by each type of equipment varies widely and there are many issues that affect the sound pressure level (FHWA, 2006). Values presented in the above equations only represent the maximum level of allowed sound pressure for different equipment based on the BSI (2009).

**Results and discussion**

Software forms for the determination of the environmental impact of the front-end wheel loader, backhoe shovel and rope shovel are shown in Figs. 1, 2 and 3. The user interface
consists of three major tabs: Production, Cost and Environmental Impact. Data on annual production rate, number of operating hours per year, engine power and fuel consumption originate from the Production tab. Values of emission factors are presented as default values in the Environmental Impact tab. For example, Fig. 1 shows exhaust and dust emissions for a wheel loader working on overburden removal using default values of emission factors. The zero values for overall control efficiency factors indicate that no dust emission control method has been used in the loading operation by this specific wheel loader. The user can directly adjust/change these factors and the overall control efficiency factor, based on data from the specific surface coal mining operation.

Dust emissions have been presented for three different particle sizes: PM$_{2.5}$, PM$_{10}$ and TSP. Exhaust emissions include CO$_2$, CO, NO$_x$, SO$_x$ and VOCs. Dust and exhaust emissions have been presented on hourly (lbs/hr), annual (lbs/year) and unit of volume (lbs/cu yd) levels. Sound pressure level at a distance of 15.2 m (50 ft) from the equipment has been presented in dBA.

For example, the data in Fig. 1 shows that the wheel loader generates 77,665 kg (171,221 lbs) of TSP per year. The amount of annual PM$_{10}$ and PM$_{2.5}$ emissions are 36,733 and 5,562 kg/year (80,983 and 12,263 lbs/year), respectively. The PM$_{2.5}$/PM$_{10}$ and PM$_{10}$/TSP fractions are 0.15 and 0.47, respectively. Annual CO$_2$, CO, NO$_x$, SO$_x$ and VOCs emissions of this wheel loader are 798,788; 3,523; 11,473; 1,114 and 1,541 lbs/year (1,761,027; 7,768; 25,293; 2,457 and 3,398 lbs/year), respectively. The sound pressure at 15.2 m (50 ft) from the equipment is 81 dBA, which is less than both action level and permissible exposure level defined by MSHA.

Summarizing the data for all digging and loading equipment in the mine, it was determined that hourly CO, NO$_x$, SO$_x$ and VOC emissions for all wheel loaders were 8.5, 27.7, 2.7 and 3.7 kg/hr (18.76, 61.09, 5.93 and 8.21 lbs/hr), respectively, while these values for backhoe shovel are 0.12, 0.48, 0.04 and 0.057 kg/hr (0.256, 1.05, 0.096 and 0.125 lbs/hr), respectively.

The annual fuel consumption for all wheel loaders and the backhoe shovel in the mine was 3,045,623 and 14,494 L (804,571 and 3,829 gal), respectively. The annual CO, NO$_x$, SO$_x$ and VOCs emissions for all nine wheel loaders and backhoe shovels in the mine are shown in Figs. 4 and 5, respectively. The total annual

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**Figure 4** — Annual CO, NO$_x$, SO$_x$ and VOC emissions for all wheel loaders in the mine (lbs/year).

**Figure 5** — Annual CO, NO$_x$, SO$_x$ and VOC emissions for the backhoe shovel (lbs/year).

**Figure 6** — Annual dust emissions for digging and loading equipment.

**Figure 7** — Sound pressure level for digging and loading equipment.

**Figure 8** — Sound pressure level at various distances from the equipment.
CO₂ emissions of all wheel loaders and the backhoe shovel in the mine were determined to be 8,162,431 and 38,845 kg (17,994,778 and 85,638 lbs), respectively.

There are many empirical models with a range of values for the cost of CO₂ emission based on potential CO₂ legislation. The Massachusetts Institute of Technology’s Emissions Prediction and Policy Analysis (EPPIA) model and the U.S. Energy Information Agency’s National Energy Modeling System (NEMS) model are two of the most recognized models. These models consider the cost of CO₂ as ranging from $17 to $50 per ton of CO₂ emitted (Aziz and Kecojevic, 2008). Assuming the minimum cost of $17 per ton, the annual cost of CO₂ emissions would be $153,683 per year.

Figure 6 shows the annual amount of dust emission for dragline, rope shovel, nine wheel loaders and backhoe shovel. It can be seen that the dragline produced the highest level of TSP, PM₁₀ and PM₂.⁵, emissions, respectively, at 677,061 kg, 293,461 kg and 44,019 kg (1,492,666 lb, 646,970 lb and 97,045 lb), respectively.

Figure 7 shows the sound pressure levels for the backhoe shovel, rope shovel, wheel loaders and dragline at a distance of 15.2 m (50 ft). It can be seen that the sound pressure level of the backhoe shovel 181 kW (242 hp) was 77 decibels, while the sound pressure levels for the rope shovel 3,674 kW (4,925 hp) and dragline 7,460 kW (10,000 hp) were 92 and 95 decibels, respectively. It was determined that values of sound pressure level for three different wheel loaders of 414, 656 and 783 kW (555, 880 and 1,050 hp) were 79, 81 and 82 dBA, respectively.

Conclusion

The objective of this research was to develop software to enable mine operators to determine the environmental impact of digging and loading equipment. The wheel loaders, rope shovel and backhoe shovel contributed 39%, 19% and less than 1% of total dust emission. The major portion of exhaust emissions was generated by nine wheel loaders, and the backhoe shovel contributed to minimal exhaust emissions. The noise pressure level at 15.2 m (50 ft) from the cable shovel and dragline was more than 90 dBA, while the wheel loaders and backhoe shovel noise pressure level was lower than the MSHA action level. The research presented here may be used by mining professionals to track the environmental impact and aid in quantifying the environmental effect of digging and loading equipment, and to determine strategies for reducing its overall impact.

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