SAGESH KUMAR M. R
P. S. PAUL
and
R. M. BHATTACHARJEE

Determinants of diesel particulate matter (DPM) concentration in underground metalliferous mines using multivariate regression analysis

The use of diesel engine powered equipment in underground mines across the globe has been increased considerably in the recent past to enhance the productivity and safety standards. However, the extensive use of diesel engine powered equipment caused severe health hazards because of the exposure to diesel particulate matter (DPM) and toxic gases discharged from the exhausts of these equipment. NIOH and IARC, USA, reported diesel exhausts including DPM are suspected as human carcinogen. The number of diesel equipment deployed in Indian underground mine has also increased exponentially, which resulted into significant level of DPM exposure. There have not been any comprehensive study on the exposure of DPM as well as any stipulation in the current mine safety legislation in India so far except a guideline from DGMS. The concentration of DPM depends upon many factors such as ventilation, engine designs, maintenance, types of fuel, condition of roadways, exhaust treatment arrangements etc. In the present study, field investigations were accomplished in the three underground metalliferous mines. Different parameters like quantity of air, power and life of engine and gradient of roadways were taken as independent variables to predict the concentration of DPM. Multivariate regression analysis was carried out for establishing the relation between DPM and these independent parameters, and a significant empirical equation has been derived. Thereafter, DPM values were measured by Airtec DPM monitoring instrument and the values predicted from the multivariate regression model and measured values from the instrument were validated through chi square test.

Keywords: *Diesel particulate matter; diesel-powered equipment; exhaust gases; health effects.*

1.0 Introduction

Diesel operated heavy-duty equipment are widely used for the mining activities in underground mines. The history of use of the heavy-duty equipment can be traced from early 1930s, the extensive deployment of diesel-powered trackless machines had commenced from 1960s (Mcginn, 1960). This equipment were initially deployed in Indian underground mines during early 1990's. Thereafter, this technology has globally become the backbone to enhance productivity of underground mines. At present, several metalliferous underground mines in India are fully mechanised with trackless mining equipment (Kumar et al, 2019). Deployment of trackless diesel equipment has also contributed significantly to enhance the productivity as well as safety standards of the underground mechanised mines.

Diesel powered trackless equipment operated in the belowground mines are generally categorized into light duty machines and heavy duty machines. Heavy duty equipment such as low-profile dump truck (LPDT), load haul dump (LHD), are engaged for the transportation of ore and waste. Similarly, light-duty machines are not made for normal production operation such as drill jumbos, electro hydraulic Simba (EHS), holters, utility trucks, lube trucks, personal carriers, etc. and there is an increasing trend of deployment of light duty vehicles. The population of diesel operated equipment in Indian metalliferous mines are illustrated in Table 1 (Kumar et al, 2019).

TABLE 1: DEPLOYMENT OF DIESEL POWERED TRACKLESS EQUIPMENT IN INDIA (YEAR 2017)

	Type of equipment	Total number (Approx.)	% of total equipment
1	LHDs (heavy duty)	115	31.5
2	LPDTs (heavy duty)	115	31.5
3	Drills jumbos, bolters and service equipment (light duty)	135	37.0

Though diesel operated machines have been instrumental in enhancing the production and productivity in underground mines, use of such machines have resulted into new health hazards for the mine environment. Noxious gases

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Mr. Sagesh Kumar M.R, Prof. P.S. Paul and Prof. R.M. Bhattacharjee, Department of Mining Engineering, Indian Institute of Technology, Indian School of Mines, Dhanbad 826004, India Email: sagesh123@rediffmail.com

like CO, CO_2, NO, NO_2, SO_2, Aldehydes etc., emitted along with the exhaust of diesel equipment poses severe health hazards to the persons deployed to such working environment (Grenier,2000 and Salvi et al,1999). In addition to this, diesel particulate matter (DPM) one of the prominent component is emitted in the exhaust. For the miners, the chance of getting overexposed from DPM and noxious gases from the diesel exhaust is much higher in the confined spaces and inadequately ventilated working faces of underground mines (Report on Carcinogens, 2000).

The vapour phase and associated respirable particles of diesel exhaust contains known mutagens and carcinogens. Diesel exhaust particles are identified as the possible contributor for the lung cancer in humans due to following reasons:

- The size of diesel exhaust particles are so small that, in all chance it will penetrate into the alveolar region in human lungs.
- Mutagenic and carcinogenic chemicals, consists of nitroarenes and polyaromatic hydrocarbons (PAHs), are extracted from the diesel exhaust particles with organic solvents or with a lipid part of human lung surfactant (Report on Carcinogens, 2000).

On the basis of adequate evidence of epidemiological and animal studies, IARC classified that DPM is carcinogenic for the humans (Group 1) in the year 2012 (Chang and Xu, 2017 and WHO, 2012). Moreover, the report published by National Institute for Occupational Safety and Health (NIOSH), stated that diesel exhausts are suspected to the occupational carcinogen.

In order to reduce the occupational health hazards due to DPM, the magnitude of DPM in the work environment should be maintained as per the acceptable standard. Globally, developed countries such as USA, Canada, Germany and Australia etc. had already framed the limiting values or standard for DPM exposure for mines in their respective countries. Likewise, in India, a guideline for deployment of diesel engines in underground mine was issued recently by the Directorate General of Mines Safety (DGMS). However, no further major field studies were carried out in Indian underground mines to determine the current level of DPM generation and exposure to the person employed.

The concentration of DPM at the work places depends upon many factors such as ventilation, diesel engine design, maintenance, type of fuel, condition of roadways, exhaust treatment arrangements etc. (Haney and Saseen 2000). During the mining operation where diesel operated equipment is used, it is very difficult to predict the concentration of DPM at the working place. Various studies on exhaust from diesel powered equipment in underground mines have been reported across the world (Zheng and Tien2008) studied the airflow pattern and diesel particulate matter (DPM) emission numerically for single heading in underground non-coal mines. The control technologies to minimise exposure of mine workers to DPM and monitoring instrumentations for DPM are evaluated by Mischler and Colinet (2009). Haney and Saseen (2000) formulated a model to estimate the exposures to DPM and to evaluate the effect of various controls methodologies on the DPM exposure in underground mines. For assessing the status of diesel exhaust emission at underground metaliferrous mines in India, three mechanised underground metal mines, in which trackless diesel operated equipment were prominently deployed for various mining activities were examined by using Airtec real time DPM monitoring instruments. The generation of DPM from diesel powered equipment deployed at these underground mines were studied in detail. During the field studies, detailed data of diesel operated equipment such as power of the engines, age of the engines were collected. Furthermore, gradient of the roadways, quantity of the air circulating the working area were also monitored, and consequently, generation of the DPM were also measured. In this paper, multivariate regression analysis has been done to evaluate the influence of these parameters on the concentration of DPM at the working faces.

2.0 Diesel exhaust and diesel particulate matter

Diesel engine exhausts are a complex combination of chemicals and particulates. They are generally categorized into vapour (gas) phase and particulate (solid) phase. Each of these vapour and particulate phase consists of both organic and inorganic components. The particulate phase of exhaust from diesel engine contains clusters of particles having sizes that can be inhaled into the lungs (respirable particle) These respirable particle mostly consists of carbon and are named as “diesel particulate matter” (DPM). The gas (vapour) phase mainly consists of carbon dioxide(CO_2), carbon monoxide (CO), sulphur dioxide (SO_2), oxides of nitrogen (NO_x), aldehydes, many polycyclic aromatic hydrocarbons (PAHs) and many urban hazardous air pollutants, such as acetaldehyde, acrolein, benzene, 1, 3-butadiene, formaldehyde and polycyclic aromatic hydrocarbons, etc. (Bugarski et al, 2011 and MSHA, 2014). The components of diesel exhaust are illustrated in Fig.1.

2.1 Diesel particulate matter (DPM)

DPM is a sub-micron aerosol, mostly comprises soot particles formed of carbon, sulfates, silicates, ash, metallic abrasion particles, etc. The solid core of these soot particles area are made of elemental carbon. Organic carbon compounds (aromatic hydrocarbons) and other substances are attached with the surface of the solid core. Furthermore, major part of hydrocarbons made from the un-burnt fuel, oils for lubricating and compounds created at the time of the combustion also got absorbed with the core of DPM due to its high surface area to volume ratios (DEEP Report, 2001). More than 90% of the particles in the DPM having diameters of <1mm, therefore DPM is a respirable particulate matter. In

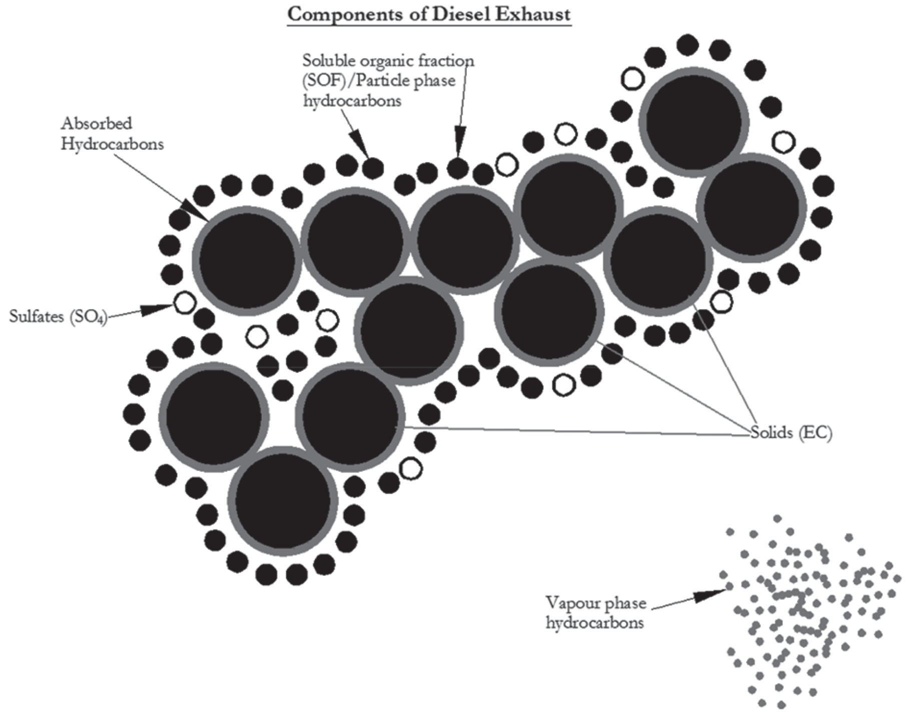

Fig.1: Components of diesel exhaust

addition to this, these respirable particulate matters penetrate to the alveoli part of the lungs, where the blood exchanges carbon dioxide and oxygen during the process of exhalation and inhalation, therefore, this causes a major concern (Chang and Xu, 2017). Another importance of the sub-micron size refers to that DPM will not settle to the floor easily under gravitational force, so it cannot be easily removed from the mine environment. Once it is generated, major part of particulate matter may remain suspended in the air from the generating place to the mine exhaust. Therefore it is evident that the DPM contaminates the working place where it is generated as well as the workplaces on the out-bye it. These hazardous properties of DPM necessitate the management of DPM at the generating point (DEEP Report, 2001).

2.2 HEALTH EFFECTS OF DPM

In underground mines, the confined spaces and insufficient ventilation increase the chances and severity of exposure of the miner to diesel particulate matter (DPM) and noxious gases present in the diesel exhaust. The recent epidemiological studies and studies conducted on animals revealed that short-term as well as long-term exposure to DPM might result in to health hazards (Chang and Xu, 2017).There are following hazardous health effects of DPM which are described below:

- Headache, dizziness, irritation of the eye, nose and throat occurred at many instances due to short duration exposure to high percentages of diesel exhaust (DE)/PM.
- Exposures to DE/DPM for long periods can intensify the risk of cardiovascular, cardiopulmonary and respiratory disease and lung cancer (Chang and Xu, 2017). In the year 1988, the National Institute for Occupational Safety and Health (NIOSH) published a report, stated that "diesel exhaust as a whole is a suspected occupational carcinogen" (Bugarski et al, 2011 and DEEP Report, 2001). U.S Environmental Protection Agency (EPA) categorised diesel exhaust as "likely to be carcinogenic" in the year 2002. In June, 2012, the International Agency for Cancer Research (IARC) classified diesel exhaust/DPM as a human carcinogen (Group 1) based on enough evidence that exposure to DPM is associated with an elevated risk for lung cancer (WHO, 2012).
- IARC further observed with limited evidence, a positive relation of enhanced risk of bladder cancer. The important finding by IARC was the likelihood of damage enhances with the increases in the exposure period to DPM (WHO, 2012 and Silverman, 2012).

3.0 Indian standard for DPM from diesel powered equipment in underground mines

In recent years, the exponential growth in deployment of diesel engine powered equipment is happened in Indian underground mines. However, the statutory norms were framed by the regulatory agency, DGMS for exhaust gases and DPM based on the international standards as well as nature of deployment of diesel engines in Indian mines. The mine management shall take all necessary steps for minimising of emission of diesel particulate matter (DPM) from the diesel engine exhaust and for the dispersal and dilution of DPM which enters the air at any work place belowground and for ensuring that the exposure of workers to DPM is limited to an extent that is reasonably practicable but in any case not exceeding the limits described below:

(a) A miner's personal exposure to diesel particulate matter (DPM) in an underground mine shall not exceed an eight-hour time weighted average (TWA) airborne concentration of 100 micrograms of elemental carbon per cubic meter of air ($100_{EC}\mu g/m^3$).

Provided that the allowable limit of TWA of EC in DPM may be $120_{EC}\mu g/m^3$ for a period of one year from the date of coming into force of this standard.

(b) The airborne concentration of DPM shall not exceed 3 times the TWA value (i.e. $300_{EC}\mu g/m^3$) for more than 30 minutes and shall never exceed 5 times the TWA value (i.e, $500_{EC}\mu g/m^{3}$) at any place in an underground mine.

Likewise, additional quantity of air required for each diesel equipment and it shall not be lesser than $0.06 m^3/sec/kW$ of maximum rated engine output specified by manufacturer (DGMS, 2018).

4.0 Selection of input parameters and instrumentation work

In order to measure the concentration of DPM, the field studies were conducted in the three mechanized underground metalliferous mines where diesel-powered machines were deployed for the excavation of declines, drifts and ramps. Furthermore, four independent parameters quantity of air, power of diesel engine, life of engine and gradient of roadways were selected for establishing the relationship. However, other parameters such as quality of fuel, diesel-engine designs, speed of the vehicle, maintenance schedule also govern the generation and accumulation of DPM at a working face. The detailed data of selected independent parameters for the three mechanized mines are given in Table 2.

Quantity of air: Velocity of the air as well as quantity of air at the working area is an important parameter in the concentration of spot DPM readings. If quantity of air is circulated adequately, the accumulation of DPM will be less in the working area (Haney and Saseen, 2000).

Gradient of working area: Gradient of the working area also has a significant role in generation of the DPM as the engine of the vehicles consumes more fuel during the operation in the up-gradient. Hence, this may cause higher creation of exhaust particles.

Power of engine: For higher power of diesel engines, additional quantity of air will be required for combustion. In addition to this, quantity of DPM generation will be increased in higher power of diesel engines. Therefore, power of machine is also directly related to the quantity of DPM generated in confined atmosphere (Haney and Saseen, 2000 and Kurnia et al, 2014).

Life of machine: The age of diesel-engine also transmit impacts on the concentration of DPM and it is monitored during the sampling period. In general the machines are being maintained directly by the original equipment manufacturer (OEM) or under the direct supervision of the OEM engineers as per the specification of the OEM. The engines of the loaders and dumpers are overhauled after every 10000 hrs of operations. Therefore, the age of diesel-engines are considered since commissioning or last overhauling.

In the present study, the Airtec diesel particulate monitor was used to measure the concentration of DPM. This portable real time personal monitor is manufactured by FLIR systems to monitor the elemental carbon concentration in real-time. The Airtec DPM/EC monitor measures elemental carbon (EC) in the wearer's breathing zone, as shown in Fig.2. Air is sucked through a pre-filter at a controlled rate (Fig.3). The pre-filter is the same that is used in the NIOSH 5040 test. It consists of a cyclone and impact or to separate out all the dust particles more than 0.8 microns size. Particles measuring smaller than 0.8 microns pass through the particle size selector to a filter cassette, where laser sensor is used to monitor the optical transmittance of the filter. The optical transmittance is converted to an EC concentration using a factory calibration stored in the monitor (Noll and Janisko 2013) .

5.0 Monitoring of DPM at three mechanized underground mines

Three mechanized underground mines where trackless diesel-engine equipment extensively used were selected for this study. All the three mines A, B and C are underground metalliferous mines, where trackless diesel equipment are extensively used for more than two decades. The gradient of the decline is 1 in 7 for the access to the mines. These mines are being worked in different levels and working faces connected through ramps. Generally, cut and fill stoping method is used in these metalliferous mines, and development faces like as ramps, ore drives, haulage drives and cross-cuts are driven. In these mines, diesel powered equipment such as LHDs, LPDTs and drill-jumbos are used for the development and production mine activities. In addition to this, service equipment for transport of men and material, crane trucks,

TABLE 2: BACKGROUND DETAILS OF SELECTED INDEPENDENT PARAMETERS FOR THE MINES

Details	Mine A	Mine B	Mine C
kW of engine	136-415	136-379	295-567
Machine life	Overhauling after 10000hr	Overhauling after 10000hr	Overhauling after 10000hr
Maintenance	By the OEM	By the OEM	By the OEM
Quantity of air (m^3/min)	8.50 to 15.50	9.5 to 19.50	10.00 to 20.50
System of ventilation	Independent ventilation for working faces and exhaust type	Independent ventilation for working faces and exhaust type	Study done on the faces having independent ventilation and exhaust type
Gradient of roadway	1in 100 and 1in 8	1in 100 and 1in 8	1in 100 and 1in 7
Size of roadways	5m × 3m	5m × 3m	5m × 5
Type of fuel	Low sulfur diesel (<50PPM)	Low sulfur diesel (<50PPM)	Low sulfur diesel (<50PPM)

Fig.2: Airtec DPM/EC monitor instrument

lifting platforms, lube trucks etc. are deployed.

In the mine A, the general size of development faces are made in order of 5 m × 3 m. Meanwhile, the power of diesel-engine of LHDs and LPDTs up to 136kW and 279 kW are being deployed respectively. Total 125 data sets were collected from this mine. Out of which 113 of data sets were used for generation of model and rest of data sets were used for the testing of the model generated. Similarly, 85 and 84 data sets were collected from the mine B and mine C respectively. In the mine C, the general size of development headings are up to 5m × 5m, and consequently, higher power of LHDs (up to 352 kW) and LPDTs (up to 567 kW) are being deployed.

6.0 Statistical analysis

The concentrations of DPM in underground working areas are related to different influencing variables. In the present study, four independent parameters quantity of air, power of diesel-engine, life of engine, and gradient of the roadways were considered for establishing the role of these parameters in determining the DPM concentration. Furthermore, in order to examine the collective influence of this critical parameters on concentration of DPM, multivariate regression analysis was done. The beauty of multivariate regression is that it provides a platform where multiple variables will interact to each other while predicting one or more dependent variable(s).

6.1 Development of multivariate linear regression model

The study of residuals has very significant role in any statistical model. The fundamental assumptions in order to create significant model are: the residuals should be random and normally distributed and the degree of scattering should be same for the fitted values. Histogram plots are useful to detect the normality of residuals. The histogram plots should be in the form of normal bell-shaped distribution. The residuals plot should not indicate any kind of pattern. If the errors indicate any kind of pattern, then it is considered that the model is not well-fitted. For the correct working of the model, residuals should be random i.e. they should follow the normal distribution with zero mean and constant variance (Baxter et al, 2004, Chandrakar et al, 2021, Lokhande et al , Murthy 2014 and Roy et al, 2011).

The residuals plot for the multivariate linear regression model showed that it is a correct-fitted model, as the histogram plots of this model made a normal bell-shaped curve, as represented in Fig.4. Moreover, normal probability plot of regression standardized residual also followed straight-line plot, as illustrated in Fig.5. The coefficient of determination (R^2) value derived in multiple linear regression model is 0.84. F-value (342.362) and significant (P) value (< 0.05) obtained in the multivariate linear regression model are given in Tables 3 and 4. Furthermore, analysis of variance (ANOVA) was carried out, as illustrated in Table 5. The results indicate that this multiple linear regression model is statistically significant at 0.05 level. Based on the results of multivariate regression analysis, an empirical equation has been established as shown in Eq. (1).

$$\text{DPM spot EC in } \mu g/m^3 = -14.462\,Q + 0.408\,Kw + 0.008\,Hr + 93.660\,Gr + 353.446 \qquad \text{... (1)}$$

Where,

Q = Quantity of ventilating air in m^3/s

kW = Kilowatt of the equipment

Hr = Life of engine

Gr = Gradient of the roadways

Fig.3: Procedure for wearing the Airtec instrument for collecting DPM

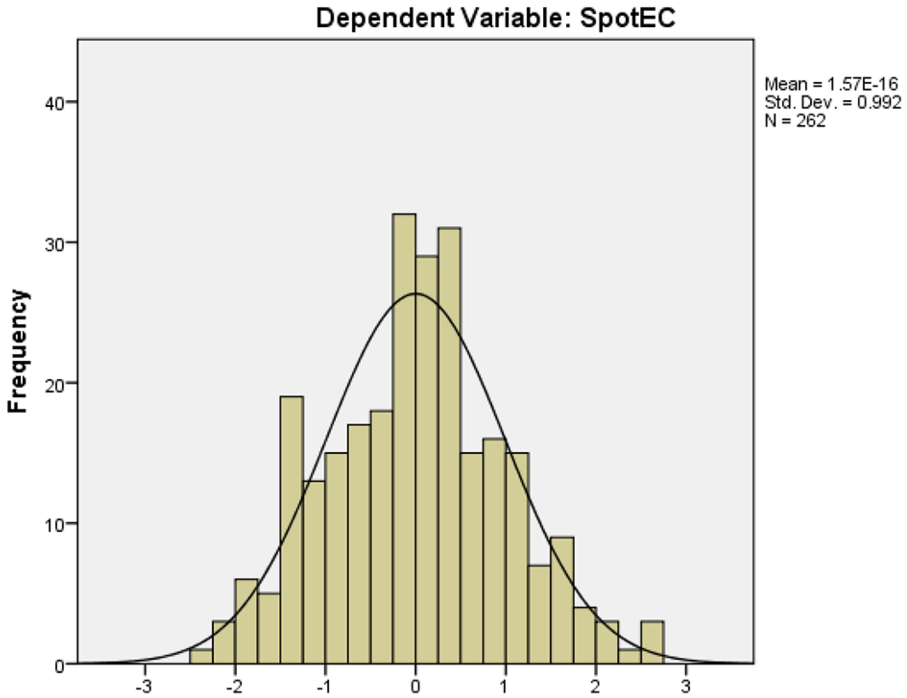

Fig.4: Standardised residual analysis (histogram plot) of DPM generation model.

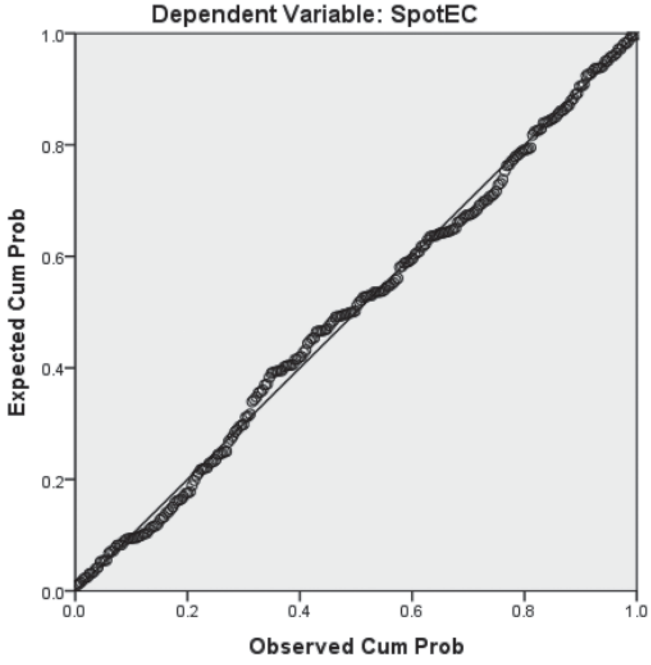

Fig.5: Normal probability plot of regression standardized residuals

6.2 Model validation

In order to validate the multivariate regression model, 32 data sets were taken from the three selected mines. Meanwhile, the concentrations of DPM were calculated from the empirical equation. In addition to this, correlation between predicted values of DPM from the empirical equation and measured values of DPM from the Airtec DPM/EC monitor were carried out, as shown in Fig.6. The coefficient of determination (R^2) value was found to be 0.94. Therefore, it can be considered that empirical equation will give the predicted values of DPM adequately.

Furthermore, chi-square test was carried out between expected frequencies (predicted values of DPM from the empirical equation) versus observed frequencies (measured values of DPM with the help of Airtec DPM/EC monitor). As a result, it was found that the calculated value of chi-square (χ^2_{cal}) is less than the tabular or critical value of chi-square (χ^2_{cri}) at 0.05 level of significance (α), as is shown in Table 6. The result of chi-square test revealed that null hypothesis (H_0) is accepted, and there is no such variation between predicted values of DPM from the empirical equation and measured values of DPM by Airtec DPM/EC monitor. Hence, the established multivariate linear regression model for predicting the concentration of DPM is statistically validated.

7.0 Results and discussions

In the present study, the measured values of DPM were collected by using Airtec diesel particulate monitor, and those working areas were selected, where LHDs and LPDTs were being operated. The concentration of DPM in the working environment is influenced by number of parameters and each one of these parameters has different degree of influence. However, the four independent parameters, quantity of air, power of diesel-engine, life of engine, and gradient of the roadways are considered as critical parameters. Furthermore, multivariate regression analysis was done to derive an empirical formula for the prediction of DPM generated.

On the basis of above statistical analysis, four independent parameters quantity of air, power of diesel-engine, life of engine, and gradient of the roadways were found to be influencing parameters for the amount of DPM in underground mines. The negative correlation was found between quantity of ventilating air (Q) and generation of DPM, which implies that concentration of DPM can be effectively reduced by improving the ventilation. Furthermore, it was found that power of diesel-engine and life of machine played a prominent role on generation of DPM. The concentration of DPM may be increased for higher power of diesel-engine. Similarly, the concentration of DPM was influenced by gradient of the roadway due to higher amount of fuels were consumed by the diesel-engine on inclined roadways. Therefore, generation of DPM will be increased by

TABLE 3: DETAILS OF SIGNIFICANT VALUE OF MULTIVARIATE LINEAR REGRESSION MODEL

Model	Predictors	Unstandardized coefficients		Standardized coefficients	T	Significance
		B	Std. Error	Beta		
1	(Constant)	353.446	17.863		19.787	.000
	Quantity (Q)	-14.462	.837	-.480	-17.277	.000
	Machine power (kW)	.408	.024	.495	17.098	.000
	Time (hr)	.008	.001	.186	6.190	.000
	Gradient (Gr)	93.660	46.302	.051	2.023	.044

TABLE 4: DATA SETS FOR VALIDATION OF MULTIVARIATE LINEAR REGRESSION MODEL

	M/C	Location	DPM predicted	DPM measured	Quantity	M/C power	M/C Hr	Gradient	χ^2 Value
1	LHD	Mine-A	268.08	251.24	15.50	206	6722	0.01	1.058
2	LPDT	Mine-A	274.61	263.68	15.05	206	6725	0.01	0.435
3	LPDT	Mine-A	304.63	335.77	13.02	279	3085	0.01	3.184
4	LPDT	Mine-A	280.61	288.94	13.65	224	4027	0.01	0.247
5	LHD	Mine-A	285.82	268.96	12.50	136	5212	0.17	0.995
6	LHD	Mine-A	277.16	261.57	13.10	136	5215	0.17	0.878
7	LHD+LPDT	Mine-A	288.23	301.76	15.40	281	5235	0.01	0.636
8	LPDT	Mine-A	297.09	312.73	13.50	206	6733	0.01	0.824
9	LHD+LPDT	Mine-A	330.99	352.16	15.15	342	7018	0.01	1.353
10	LHD	Mine-A	257.38	237.37	13.44	136	5231	0.01	1.555
11	LPDT	Mine-A	302.54	288.43	14.15	206	6715	0.17	0.658
12	LPDT	Mine-A	285.48	308.32	14.35	279	3096	0.01	1.827
13	LPDT	Mine-B	242.67	255.78	15.50	242	1710	0.01	0.709
14	LPDT	Mine-B	212.34	225.32	19.50	242	5150	0.01	0.793
15	LHD	Mine-B	265.48	248.27	14.50	136	8160	0.01	1.116
16	LHD	Mine-B	236.57	229.62	16.50	136	8162	0.01	0.204
17	LHD+LPDT	Mine-B	393.77	412.86	12.53	379	8242	0.01	0.926
18	LHD+LPDT	Mine-B	325.65	308.54	15.54	379	5168	0.01	0.899
19	LPDT	Mine-B	222.51	232.42	18.80	242	5156	0.01	0.441
20	LHD	Mine-B	212.72	199.10	16.50	136	5180	0.01	0.872
21	LHD+LPDT	Mine-B	305.29	313.05	14.80	379	1285	0.01	0.198
22	LPDT	Mine-B	284.83	270.00	14.50	242	5172	0.01	0.772
23	LHD	Mine-C	337.57	341.77	14.05	295	8248	0.01	0.052
24	LHD	Mine-C	345.82	362.09	13.48	295	8250	0.01	0.765
25	LHD	Mine-C	353.13	379.13	14.55	352	8191	0.01	1.913
26	LHD	Mine-C	295.73	326.56	18.52	352	8192	0.01	3.214
27	LPDT	Mine-C	469.39	505.04	13.21	567	9336	0.01	2.707
28	LPDT	Mine-C	398.07	421.35	14.50	429	8197	0.14	1.361
29	LHD	Mine-C	353.48	363.29	14.53	352	8198	0.01	0.272
30	LHD	Mine-C	367.40	335.16	13.57	352	8202	0.01	2.829
31	LPDT	Mine-C	386.09	409.52	14.45	429	8203	0.01	1.422
32	LPDT	Mine-C	435.64	452.04	15.55	567	9347	0.01	0.618
								χ^2 Total	35.73

TABLE 5: DETAILS OF ANALYSIS OF VARIANCE (ANOVA)

Model		Sum of squares	Df	Mean square	F-value	Significant value (P)
1	Regression	1691277.065	4	422819.266	342.362	$.000^b$
	Residual	317396.660	257	1235.006		
	Total	2008673.725	261			

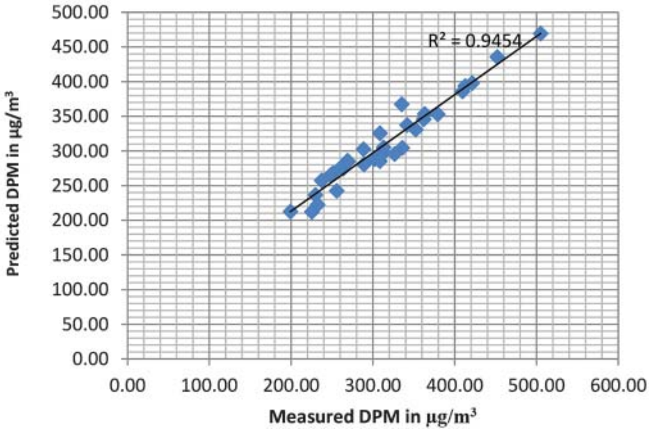

Fig.6: Correlation between predicted values and measured values of DPM

TABLE 6: DETAILS OF CHI-SQUARE TEST

Degree of freedom (DF)	Calculated value of χ^2	Tabular or critical value of χ^2	Results
31	35.73	43.77	Null hypothesis (H_0) is accepted

using heavy-duty equipment on inclined roadways rather than levelled roadways.

Taking into account all these influencing parameters, an empirical equation has been established for predicting the concentration of DPM. This established empirical equation will be useful to obtain the concentration of DPM at the working areas in underground mechanized mines, where diesel operated equipment are widely deployed.

8.0 Conclusions

Exposure to diesel particulate matter (DPM) is highly injurious to health due to the carcinogenic in nature of it. In the underground mechanized mines, heavy-duty diesel equipment such as LHDs and LPDTs contribute about 70% of the total vehicle population. Larger deployment of diesel machines in confined work atmosphere of underground workings requires dealing with the exposure hazard to ensure risk from such hazard to an acceptable level. Global standards have been developed and enforced for maximum exposure, short term exposure and maximum exposure limits. In India also, through a recent guideline, DGMS has stipulated such limits of DPM exposure. It is essential now to make assessment of DPM exposure level while deploying such machines in underground workings.

The multivariate regression model developed in order to predict of the concentration of DPM in the working areas will be useful to the mining industry, particularly for the underground metaliferrous mines, where numerous diesel-powered equipment are being used. Result of the present field study will help in predicting the concentration of DPM and relative contribution of different parameters in total concentration of elemental carbon. This prediction model can be utilised for planning of ventilation requirement to the specific power of engines and vice versa. Consequently, number and types of equipment can be framed at different working faces. Ultimately, the health and safety standards of mine will be improved by controlling the concentration of DPM at the working faces in Indian underground mines. The practicing mining managers and engineers should identify suitable mitigating measures like using fuel efficient diesel engines (Tire VI), proper maintenance of diesel machines, use of suitable oil and lubricants, use of diesel filters, good driving practices etc. on top of proper ventilation circuit and adequate quantity of ventilating air to ensure the concentration of DPM and the time weighted average (TWA) DPM exposure within the stipulated limits.

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