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Evaluating machine utilization times for roadheaders used in coal mines: Multiple regression and artificial neural network analyses

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ABSTRACT

Roadheaders are extensively utilized for tunnel heading rock engineering applications all over the world. To create a work plan and calculate costs, it is critical to forecast roadheader performance as precisely as possible. Machine utilization time (MUT) is required for the calculation of daily advance rate of roadheaders. This paper investigates the values of MUT for roadheaders used in underground coal mines. The performance measurements were conducted on fifty different locations for axial machines and thirty-nine different locations for transverse machines. MUT values vary from 15 % to 37.5 % with an average of 26.3 % for axial roadheaders, and vary from 6.9 % to 37.9 % with an average of 18.4 % for transvers roadheaders. The average MUT is 25.4% for all measurements. The percentage of average support time approximately equals to the average MUT. Multiple regression and artificial neural network models were also developed for estimating MUT. Concluding remark is that the determined MUT values and the derived estimation models for roadheaders will be very useful for coal miners.

Keywords: *Coal mining, Roadheader, Machine utilization time*

Introduction

In rock engineering projects, rocks are excavated by drilling and blasting method or by mechanized excavation method. Mechanical cutting of rocks and coals has been increasing day by day in developed and developing countries. Roadheaders are commonly used in mining for gallery drivages and in civil engineering for tunnel excavations. It is essential to predict roadheader performance as accurately as possible for making a work schedule and estimating costs.

Different investigators have proposed several performance prediction equations for roadheaders (Gehring, 1989; Bilgin et al., 1990; Rostami et al., 1994; Copur et al., 1998; Thuro and Plinninger, 1999; Göktan and Güneş, 2005; Tumac et al., 2007; Ocak and Bilgin, 2010; Ebrahimabadi et al., 2011; Abdolreza and Yakhchali, 2013; Kahraman and Kahraman, 2016; Kahraman et al., 2019). Using these models, net cutting rate (NCR) is calculated. However, machine utilization time (MUT) is required for the calculation of daily advance rate (ARd) of roadheaders as shown in the following equations:

$$AR_d = V/A \quad (1)$$

$$V = NCR.MUT.WT_d \quad (2)$$

where, ARd, is daily advance rate (m/day), V is daily excavated volume (m^3/day), A is cross-section area of tunnel (m^2), NCR, net cutting rate (m^3/h), MUT is machine utilization time (%), and WTd is daily working time (h/day).

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MUT is the percentage of time used only for excavation during the entire shift or day. Several operational and organizational variables affect MUT. The remaining time from MUT consists of pauses such as support installation, muck haulage, breakdown, and maintenance. The correct selection of MUT is at least as important as the NCR estimation. Even if NCR is estimated correctly, if the MUT is selected incorrectly, the average advance rate and project duration will be incorrectly estimated. Therefore, often unrecoverable problems and large financial losses occur.

There is no detailed study in the literature on the MUT values of roadheaders. McFeat-Smith and Fowell (1979) evaluated roadheader performances in sandstone, mudstone and siltstone formations and observed that the MUT values ranged between 40 % and 60 %. Copur et al. (2001) stated that MUT ranged between 25 % and 50 %. MUT was measured as 47 % for the Küçüksu sewage tunnel (Bilgin et al., 2005) and as 28.2 % for the Kadıköy-Kartal metro tunnel (Ocak, 2008). It is quite remarkable that the MUT in Hereke tunnel, which is 38 % in straight excavations, decreases to 8 % in uphill excavations (Bilgin et al., 2004). Bilgin et al. (2014) explain that MUT varies from 20 % and 35 % for the tunnel excavation requiring steel supports, and varies from 30 % and 50 % for the tunnel excavation requiring rock bolts, shotcrete, and wire mesh.

According to literature data, MUT can vary in a wide range, from 8 % to 60 %. It is quite difficult to decide which value should be used in coal mining. This study investigates the range of MUT values for roadheaders used in coal mines. For this purpose, the performance measurements of roadheaders were conducted in seven different underground coal mines in Türkiye and the results were evaluated to determine the MUT values.

1. Materials and methods

Underground coal mines located in different areas of Türkiye were visited for the field studies. Axial and transvers type roadheaders were observed during the excavation of roadways and comprehensive performance data for were collected for the analyses.

The overall performances of roadheaders for each coal mine was first evaluated using pie charts and MUT values were calculated for each case. Then, the data was evaluated using multiple regression and artificial neural network analyses. Multiple regression and artificial neural network models were also derived for the estimation of MUT values.

2. Performance measurements

Axial and transvers type roadheaders' performances were measured in seven different lignite collieries in Türkiye. The study covers one enterprise from Amasra and Dodurga region, two enterprises from Çayırhan region and three enterprises from the Soma region.

During the performance measurements, excavation time, support time, mucking time, maintenance time, machine breakdown time, electric break-down time, shift change time, other waiting time were recorded. The experience of operators, the age of machines, the experience of companies, the inclination of roadways, the cross-sectional areas of roadways were also noted.

Performance measurements were made in as many different conditions as possible. The measurements were carried out in fifty different locations for axial machines and thirty-nine different locations for tranverse machines.

3. Results and discussions

The summaries of the MUT values and the parameters affecting MUT are given in Table 1 and 2 for axial and transvers roadheaders, respectively. MUT values range from 15 % to 37.5 % with an average of 26.3% for axial roadheaders. For transvers roadheaders, MUT values vary from 6.9 % to 37.9 % with an average of 18.4 %. The values have wide ranges for the experience of operators, the age of machines, the experience of companies, the inclination of roadways, the cross-sectional area of roadways.

Table 1. *The parameters affecting MUT for axial roadheaders.*

Statistical parameter	Excavation time (MUT) (%)	Operator experience (years)	Machine age (years)	Company experience (years)	Roadway inclination (o)	Roadway cross- sectional area (m^2)
Number of observ.	50	50	50	50	50	50
Minimum	15.0	0.5	1.0	2.0	- 18.0	12.0
Maximum	37.5	23.0	32.0	20.0	+ 4.0	23.5
Average	26.3	8.3	18.0	13.4	-3.70	20.6
Standard deviation	± 6.2	± 8.1	± 13.8	± 8.0	± 7.9	± 3.9

Table 2. *The parameters affecting MUT for transvers roadheaders.*

Statistical parameter	Excavation time (MUT) (%)	Operator experience (years)	Machine age (years)	Company experience (years)	Roadway inclination (o)	Roadway cross-sectional area (m^2)
Number of observ.	39	39	39	39	39	39
Minimum	6.9	2.0	5.0	1.0	- 12.0	14.0
Maximum	37.9	15.0	39.0	15.0	+ 15.0	28.0
Average	18.4	5.6	23.2	9.0	1.6	20.0
Standard deviation	± 8.3	± 3.9	± 16.5	± 6.3	± 7.8	± 4.5

The summaries of the MUT values, the percentages of stoppages, and other job times are given in Table 3-9 for each company, respectively. The overall performances of roadheaders for each coal mine were plotted as shown in Fig. 1.

The MUT values vary from 17.7% to 56.2% with an average of 31.8% for coal mine A. Support work takes the most time (27.1%) after the MUT value. Since there is no electric break down during the performance measurements, the time for electric break down is zero.

For coal mine B, the average MUT value is 23.5%, with values ranging from 9.8% to 31.9%. Other waiting time is very high (35.8%) due to the breakdown of the main belt conveyor of the mine. Machine break downtime has the lowest value with 1.2%.

With an average of 26.0% for coal mine C, the MUT values range from 20.3% to 32.5%. The percentage of support time (29%) is higher than that of the MUT value. The mucking time is also relatively high (%17). The lowest waiting percentage is 2.9% for electric break downtime.

The average MUT value for coal mine D is 17.2%, with values ranging from 6.9% to 33.3%. Support time is too high (42.9%) due to the fact that mine operates in harsh conditions such as high depth, excessive water flow, and highly fractured formations. Electric breakdown time has the lowest percentage, 2.0%.

The MUT values vary from 2.3.7% to 37.9% with an average of 22.6% for coal mine E. The percentage of support time (22.8%) is the same as the MUT value. Electric breakdown time is also high (%15.1). Machine break downtime has the lowest value with 4.6%.

For coal mine F, the average MUT value is 31.2%, with values ranging from 15.6% to 41.6%. The percentage of support time (32.0%) is approximately the same as the MUT value.

The percentages of waiting times are zero for mucking time, maintenance time, machine break-down time, electric break-down time. However, this performance data only belongs to three measurements.

The average MUT value for coal mine G is 24.6%, with values ranging from 9.3% to 35.4%. Other waiting time is relatively high (21.2%) due to the breakdown of the main shaft haulage system of the mine. Maintenance time has the lowest value with 4.1%. However, this performance data consists of only three measurements.

The overall performances of roadheaders for all coal mines are listed in Table 10 and is plotted in Fig. 1h. The average MUT is 25.4%. The percentage of average support time (23.5%) is roughly equal to the average MUT. The percentage times of ucking, shift change, and other stoppages significantly affect the MUT value.

Table 3. *The summarized data for the MUT of roadheaders used in coal mine A.*

Statistical parameter	Excavation time (MUT) (%)	Support time (%)	Mucking time (%)	Maintenance time (%)	Machine break-down time (%)	Electric break-down time (%)	Shift change time (%)	Other waiting time (%)
Number of observ.	12	12	12	12	12	12	12	12
Minimum	17.7	12.5	0.0	6.2	0.0	0.0	12.5	0.0
Maximum	56.2	39.6	29.2	13.6	10.4	0.0	16.7	43.8
Average	31.8	27.1	11.9	8.4	1.0	0.0	12.8	6.9
Standard deviation	± 11.7	± 8.4	± 11.7	± 3.3	± 6.3	± 0.0	± 1.2	± 12.8

Table 4. *The summarized data for the MUT of roadheaders used in coal mine B.*

Statistical parameter	Excavation time (MUT) (%)	Support time (%)	Mucking time (%)	Mainte-nance time (%)	Machine break-down time (%)	Electric break-down time (%)	Shift change time (%)	Other waiting time (%)
Number of observ.	7	7	7	7	7	7	7	7
Minimum	9.8	3.1	0.0	0.0	0.0	0.0	6.3	0.0
Maximum	31.9	37.5	25.0	9.4	8.1	12.5	12.5	77.7
Average	23.5	17.5	7.8	4.0	1.2	3.0	7.2	35.8
Standard deviation	± 7.4	± 14.0	± 8.7	± 3.9	± 3.1	± 4.8	± 2.4	± 23.5

Table 5. *The summarized data for the MUT of roadheaders used in coal mine C.*

Statistical parameter	Excavation time (MUT) (%)	Support time (%)	Mucking time (%)	Mainte-nance time (%)	Machi-ne bre-ak-down time (%)	Electric break-down time (%)	Shift change time (%)	Other waiting time (%)
Number of observ.	17	17	17	17	17	17	17	17
Minimum	20.3	20.8	11.3	6.3	0.0	0.0	12.5	0.0
Maximum	32.5	38.2	24.0	6.5	8.3	6.3	12.5	9.3
Average	26.0	29.0	17.0	6.3	3.7	2.9	12.5	2.7
Standard deviation	± 3.4	± 6.8	± 4.6	± 0.1	± 2.9	± 3.2	± 0.0	± 3.4

Table 6. *The summarized data for the MUT of roadheaders used in coal mine D.*

Statistical parameter	Excavation time (MUT) (%)	Support time (%)	Mucking time (%)	Mainte-nance time (%)	Machine break-down time (%)	Electric break-down time (%)	Shift change time (%)	Other waiting time (%)
Number of observ.	25	25	25	25	25	25	25	25
Minimum	6.9	8.5	0.0	0.0	0.0	0.0	6.3	0.0
Maximum	33.3	76.3	53.8	15.6	31.3	14.6	12.5	27.5
Average	17.2	42.9	12.7	4.6	4.1	2.0	6.8	9.8
Standard deviation	± 7.0	± 20.9	± 11.9	± 5.3	± 9.1	± 4.1	± 1.7	± 9.0

Table 7. *The summarized data for the MUT of roadheaders used in coal mine E.*

Statistical parameter	Excavation time (MUT) (%)	Support time (%)	Mucking time (%)	Mainte-nance time (%)	Machine break-down time (%)	Electric break-down time (%)	Shift change time (%)	Other waiting time (%)
Number of observ.	31	31	31	31	31	31	31	31
Minimum	2.3	0.0	0.0	0.0	0.0	0.0	2.1	0.0
Maximum	37.9	59.4	81.0	39.6	18.8	73.8	9.4	75.0
Average	22.6	22.8	14.0	4.8	4.6	15.1	5.8	10.3
Standard deviation	± 10.9	± 13.4	± 17.0	± 7.2	± 6.8	± 17.0	± 1.5	± 14.7

Table 8. *The summarized data for the MUT of roadheaders used in coal mine F.*

Statistical parameter	Excavation time (MUT) (%)	Support time (%)	Mucking time (%)	Mainte-nance time (%)	Machine break-down time (%)	Electric break-down time (%)	Shift change time (%)	Other waiting time (%)
Number of observ.	3	3	3	3	3	3	3	3
Minimum	15.6	9.4	0.0	0.0	0.0	0.0	17.7	0.0
Maximum	41.6	45.8	0.0	0.0	0.0	0.0	17.7	57.3
Average	31.2	32.0	0.0	0.0	0.0	0.0	17.7	19.1
Standard deviation	± 13.8	± 19.7	± 0.0	± 0.0	± 0.0	± 0.0	± 0.0	± 33.1

Table 9. *The summarized data for the MUT of roadheaders used in coal mine G.*

Statistical parameter	Excavation time (MUT) (%)	Support time (%)	Mucking time (%)	Mainte-nance time (%)	Machine break-down time (%)	Electric break-down time (%)	Shift change time (%)	Other waiting time (%)
Number of observ.	3	3	3	3	3	3	3	3
Minimum	9.3	24.0	12.5	0.0	0.0	0.0	12.5	13.6
Maximum	35.4	26.0	12.5	6.2	0.0	0.0	12.5	35.5
Average	24.6	25.0	12.5	4.1	0.0	0.0	12.5	21.2
Standard deviation	± 13.6	± 1.0	± 0.0	± 3.6	± 0.0	± 0.0	± 0.0	12.4

Table 10. *The summarized data for the MUT of roadheaders used in all coal mines.*

Coal mine	Average excavation time (MUT) (%)	Support time (%)	Mucking time (%)	Mainte-nance time (%)	Machine break-down time (%)	Electric break-down time (%)	Shift change time (%)	Other waiting time (%)
A	31.8	27.1	11.9	8.4	1.0	0.0	12.8	6.9
B	23.5	17.5	7.8	4.0	1.2	3.0	7.2	35.8
C	26.0	29.0	17.0	6.3	3.7	2.9	12.5	2.7
D	17.2	42.9	12.7	4.6	4.1	2.0	6.8	9.8
E	22.6	22.8	14.0	4.8	4.6	15.1	5.8	10.3
F	31.2	32.0	0.0	0.0	0.0	0.0	17.7	19.1
G	24.6	25.0	12.5	4.1	0.0	0.0	12.5	21.2
Average	25.3	23.5	10.8	4.6	2.1	5.8	10.9	12.4

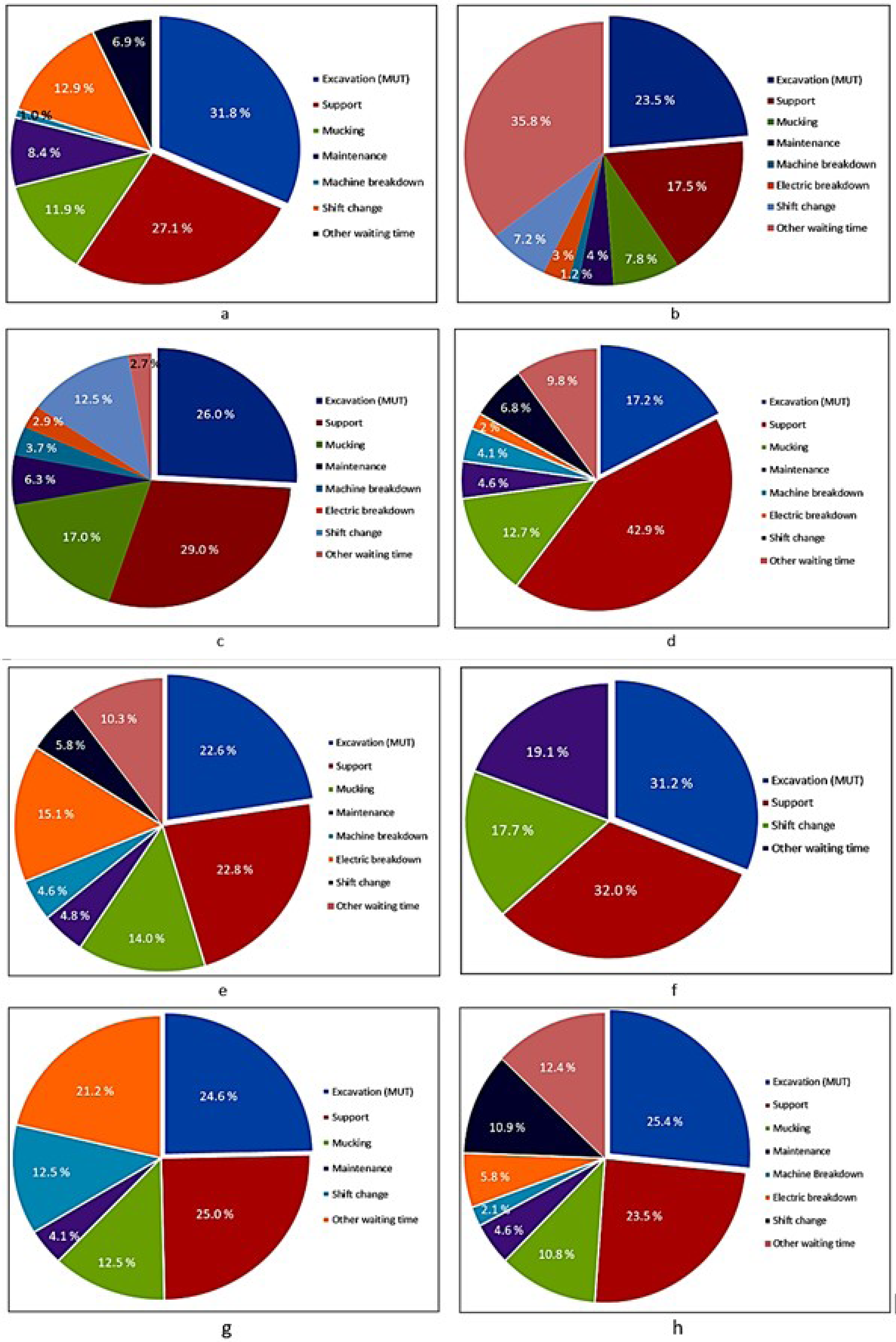

Figure 1. *The overall performances of roadheaders for coal mine A (a), coal mine B (b), coal mine C (c), coal mine D (d), coal mine E (e), coal mine F (f), coal mine G (g), and all coal mines (h).*

3.1. Multiple regression analysis

The results were also evaluated for the development of the estimation models for MUT. MUT is influenced by a variety of factors; hence it cannot be studied using simple regression models. The analysis must therefore be performed using multiple regression techniques. The experience of operators, the age of machines, the experience of companies, the inclination of roadways, and the cross-sectional area of roadways were all added to the multiple regression analysis as independent variables. The derived equations and the correlation coefficients (r) are as follows:

$MUT_a=-0.21E_o-0.31A_m+0.80E_c+0.40\alpha-0.85A+41.92$
r = 0.78 (3)

$MUT_t=0.26E_o-0.12A_m+1.95E_c-0.43\alpha+2.38A-44.61$
r = 0.76 (4)

where MUT_a is the machine utilization of axial roadheaders (%), MUTa is the machine utilization of transvers roadheaders (%), E_o is the experience of operator (years), A_m is the age of machine (years), E_c is the experience of company (years), α is the inclination of roadway (°), A is the cross-sectional area of roadway (m^2).

It can be said that the correlation coefficients of Eqs. (3 and 4) is strong. The scatter graphs of measured and predicted MUT values were also plotted for checking the prediction capability of the derived equations. The data points should ideally be scattered around 1:1 diagonal straight line on the plot of measured versus predicted value. A systematic deviation from this line may show that larger errors tend to accompany larger predictions, suggesting non-linearity in one or more variables. As illustrated in Figs. 2 and 3, the data points are scattered almost evenly around the 1:1 line. Therefore, it can be said that the models are valid. It can be said that the equations can be used reliably for the estimation of MUT values of roadheaders.

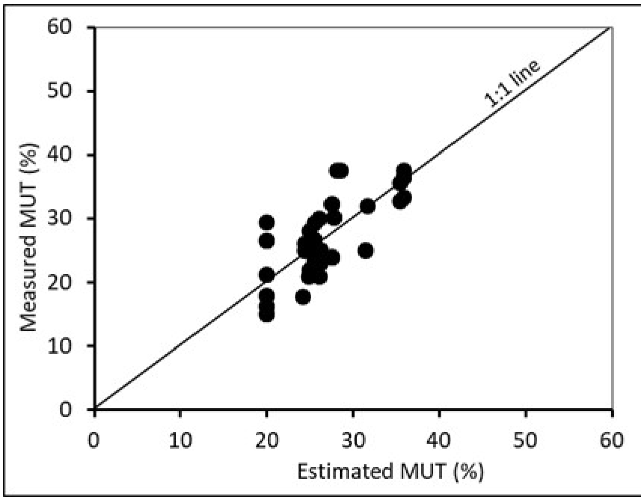

Figure 2. *Predicted versus measured MUT for Eq. (3).*

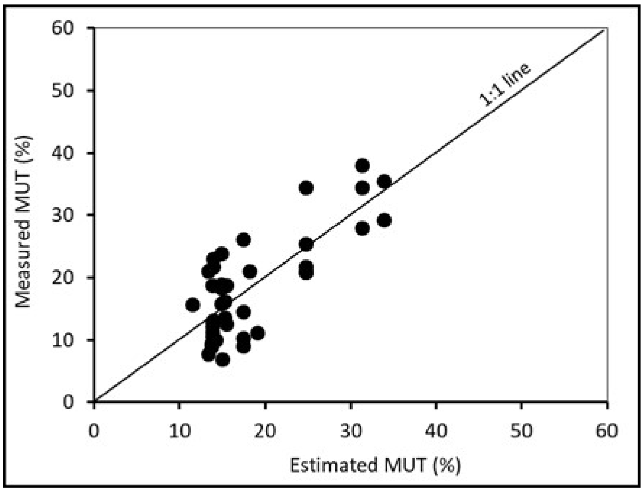

Figure 3. *Predicted versus measured MUT for Eq. (4).*

3.2. Artificial neural network analysis

Artificial neural network (ANN) analyses were also performed in MATLAB environment for the expectation of more reliable models than the multiple regression models. ANNs are incredibly simplified representations of the neural systems seen in the human brain. These models are made up of a networked assemblage of neurons, which are basic processing units, arranged in layers. Every neuron in one layer is linked to the neurons in the next layer, and so on. In this research, a Multi Layered Perception neural network was utilized (MLP).

For axial type roadheaders, a total of 50 data were used. The first data set, which had 34 data, was utilized to train the network for Model I. For the validation and testing of Model I, 8 data sets were utilized, respectively. For transverse type roadheaders, a total of 39 data were used. The network was trained using the first data set, which had 25 data. Model II was validated and tested using 7 data sets, respectively. While constructing the models, trial-and-error procedure was used to find good models. Table 11 displays the structures and algorithm used throughout the training phase. The training progresses were also given in Table 12 and 13.

Table 11. *The structures of the ANN models for the prediction of differential stress.*

Model no	Number of input neurons	Number of hidden neurons	Number of output neurons	Network type	Transfer function	Training algorithm
I	5	6	1	Feed-forward back propagation	Tanjant sigmoid	Levenberg-Marquardt backpropagation algorithm (trainlm)
II	5	5	1	Feed-forward back propagation	Tanjant sigmoid	Levenberg-Marquardt backpropagation algorithm (trainlm)

Table. 12. *The training progress for Model I.*

Unit	Initial Value	Stopped value	Target Value
Epoch	0	11	1000
Elapsed Time	-	00:00:00	-
Performance	169	9.99	0
Gradient	269	7.03e-08	1e-07
Mu	0.001	1e-05	1e+10
Validation Checks	0	6	6

Table. 13. *The training progress for Model II.*

Unit	Initial Value	Stopped value	Target Value
Epoch	0	32	1000
Elapsed Time	-	00:00:00	-
Performance	224	20.9	0
Gradient	649	20.4	1e-07
Mu	0.001	0.1	1e+10
Validation Checks	0	6	6

The scatter diagrams of observed and estimated values can be presented in order to examine the estimating capabilities of the developed models. On a plot of estimated vs observed data, the points should ideally be dispersed over the 1:1 diagonal straight line. A point that lies on the line denotes a precise estimate. A systematic deviation from this line may reveal, for instance, that higher errors go along with larger estimations, which suggests that one or more variables are not linear. The plots for predicted vs. measured MUT are indicated in Figs. 4 and 5, respectively for the Model I, and II. The fact that the points are distributed consistently around the diagonal line in the graphs suggests that the models are valid.

The values of mean square error (MSE) and correlation coefficient (r) are listed in Table 14 for the ANN models. MSE values are low and r values are generally too high. Therefore, it can be said that ANN models are reasonable. In comparison to multiple regression models, ANN models' r values are noticeably greater.

Table. 14. *MSE and r values for the developed ANN models.*

	Model I	Model II		
	MSE	r	MSE	r
Training	10.83	0.83	23.72	0.81
Validation	6.01	0.97	13.26	0.93
Test	8.99	0.93	16.06	0.90

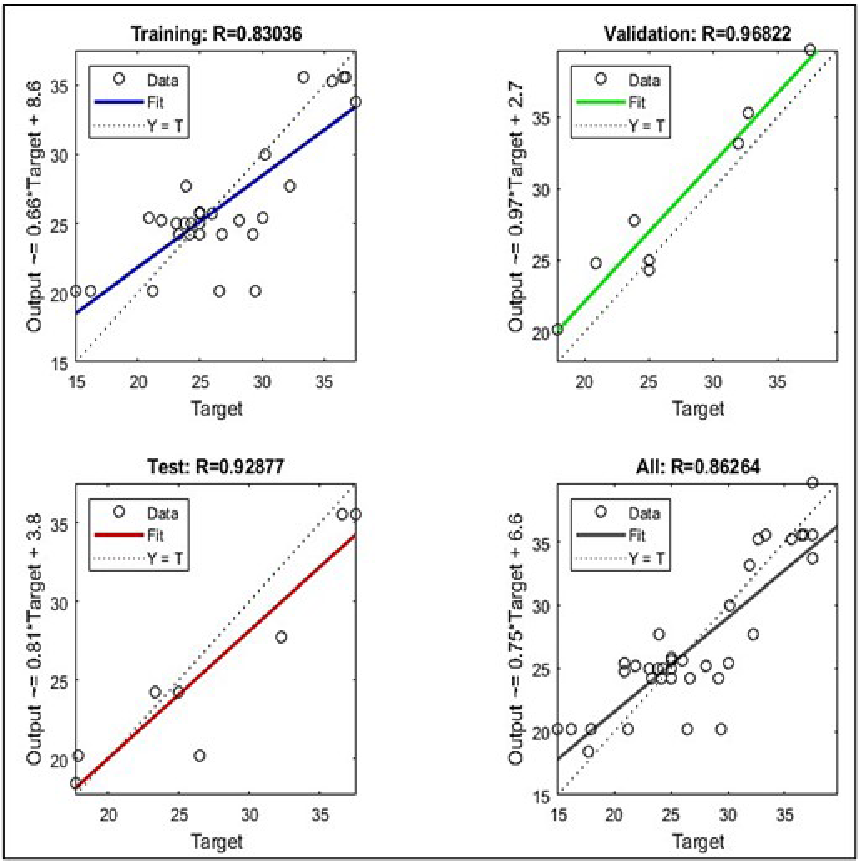

Figure 4. *Predicted vs. measured MUT values for ANN Model I.*

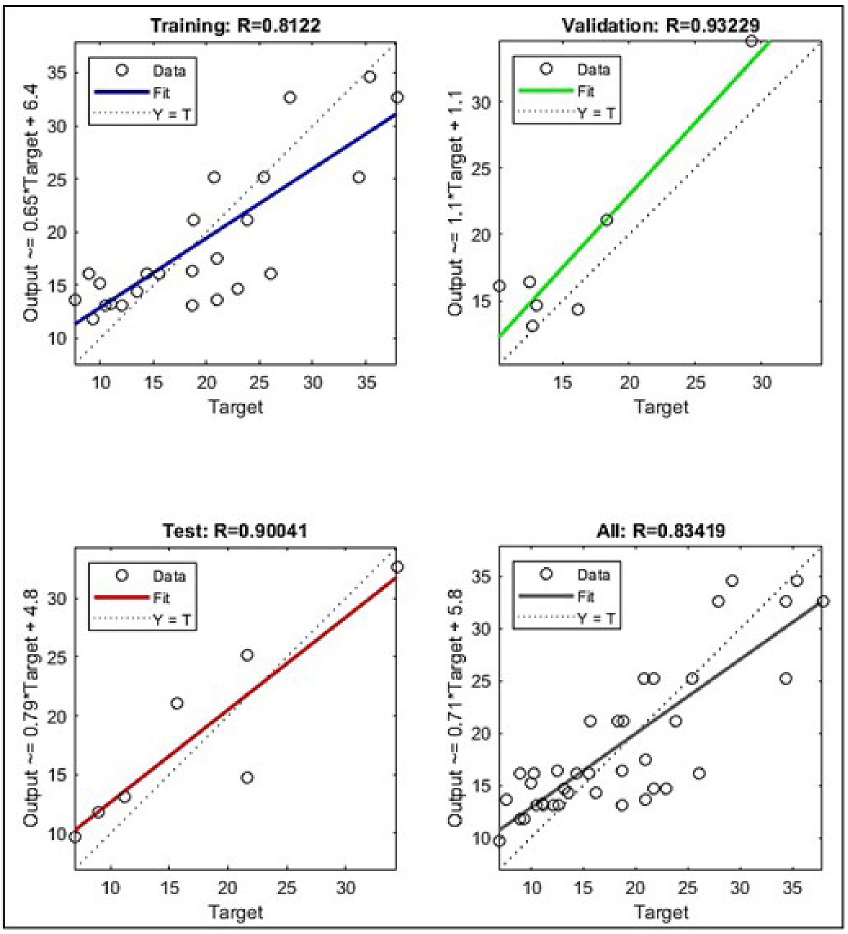

Figure 5. *Predicted vs. measured MUT values for ANN Model II.*

4.Conclusions

The MUT values of roadheaders used in underground coal mines were assessed. The study's findings can be summarized as follows:

The average MUT value is 26.3% for axial roadheaders, and 18.4% for transvers roadheaders.

The average MUT is 25.4% for both type of machines and all measurements.

The average support time percentage is approximately equal to the average MUT.

The derived multiple regression equations can be used for estimating MUT values

Since the correlation coefficients of the ANN models are quite high compared to the multiple regression models, these models can be preferred for more reliable estimation.

It can be concluded that the determined MUT values and the developed estimation models for roadheaders will be very helpful for coal miners.

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