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Cycle Time Analysis of Open Pit Mining Dump Trucks

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Abstract

This study demonstrates a practical cycle time analysis of dump truck haulage system of "Ukhaa Khudag" open-pit coal mine located in Umnugobi Province, Mongolia. It examines the possibility of minimizing the cycle time of the haulage system as well as factors impacting the speed of the dump truck. The current study divides the open pit mine road for the dump trucks into five sections which are bench road, ramp, surface road, dump road uphill, and dump road. Meanwhile, it investigates the influence of the length, the grade, and the rolling resistance of the road section on the cycle time. The data is analyzed using mathematical regression methods via Microsoft Excel program. For each of the five road sections, we compare the statistical calculations of three regression models: linear, quadratic and exponential; thus, a total of thirty regression models are obtained in this research. Accordingly, the cycle time for each road section is predicted by the most accountable model. The loaded and empty direction of the movement is measured and calculated for each road section, and it appears that the difference between the calculated mean value and the actual cycle time of the models is 0.82 seconds with a relative error of 2.51 percent.

Keywords

Dump Truck, Cycle Time, Mine Haul Road, Regression Analysis

1. Introduction

Mining is one of the costly and complicated industries. Widespread studies have been conducted in relevant sections such as geology, canalization, and excavation planning and operation process [1]. Particularly, transportation costs amount to 50 to 60 percent of the total investment costs and 70 percent of the operation costs [2] [3] [4]. In open pit mining, the movement of raw materials is considered one of the most challenging tasks with the truck transportation representing the most influential factor of mining costs [5]. The deeper the open pit, the longer the open pit road is needed; thus leading to higher transportation cost. Accordingly, in order to reduce the transportation cost, it is necessary to investigate the potential strategies to improve the open-pit mine cycle time of the dump trucks.

The current study analyzes the dump truck haulage system of "Ukhaa Khudag" Open Pit Mine in Umnugobi Province, Mongolia which started its operations in 2009 and produced ten million tons of coals in 2018. Due to its potential growth and expected long life cycle, we aim to conduct a detailed survey on cycle time of the dump truck. The main contribution is to identify the potential opportunities to reduce the costs of dump truck systems by evaluating the mining road conditions in Mongolia which had not been rigorously studied. Specifically, this study surveys 13 trucks of CAT 785 model. Two main channels to improve the efficiency of the dump trucks are to increase truck capacity and to reduce cycle time [6]. As the movement time is the most important factor of overall cycle time, it is crucial to understand which factors significantly affect the speed of the movement so that we can optimize the speed and increase the efficiency of the dump truck [6]. To improve the efficiency of the dump truck, an optimal use regime for open-pit mining trucks should be established [7] [8]. The determinant of the optimal use regime includes the movement regime which is directly related to the speed of the dump truck.

The type of the road pavement and the grade of the road have a great influence on the speed of the dump truck [9] [10]. If the speed of the dump truck is accurately determined, the production amount as well as the number of trucks required will be calculated correctly [6] [2]. The speed of the dump truck can be controlled by optimizing the condition of each road section. Examining the effects of the open pit mine dump truck in the aspect of the movement regime can help us determine which parts bear the most cost and which strategies should be implemented to reduce the costs [7].

The road pavement expresses the direct rolling resistance of the road. Rolling resistance is a measure of the extra resistance to the motion that a haul truck experiences, and it is influenced by tyre flexibility, internal friction and most importantly, wheel load and road conditions [9].

Roger J. Thompson (2013) has thoroughly researched various mining road conditions and reported that the optimal overall road resistance of the dump truck is at 8 to 11 percent.

The current study employs regression technique. Our goal is that the equations resulting from our calculations are only applicable to this open pit mine.

2. Methods

2.1. Cycle Time of Dump Truck

Cycle time is defined as the time required for any equipment to complete one cycle of operation. For a truck, cycle time comprises the time to spot and load, travel to the dump site, maneuver, spot and dump, and drive back to the loading point, also inclusive of predictable delays and unpredictable waiting times (Lineberry, 1985) [11] [12].

Principally, cycle time is a direct measure of process and equipment performance in waste material transport for open-pit mining and other processes [13] [14].

Cycle time analysis was conducted starting with identification of the activities to be analyzed, for which the cycle times of seven activities were determined and recorded. In accordance with Samwel Victotmanyele (2017) [13], the total cycle time for the truck was appointed as per Equation

$$T_{ct} = t_q + t_{sp} + t_{ld} + t_{fh} + t_{dp} + t_{hg} + t_{eh} \quad (1)$$

where t_q: queuing time at the excavator, t_{sp}: spotting time, t_{ld}: loading time, t_{fh}: full haul time, t_{dp}: dumping time, t_{hg}: hanging time and t_{eh}: empty haul time.

2.2. Determine the Road Parameters and the Total Resistance

Road conditions affect the technical and economic performance of open pit mine dump truck. The road of the open-pit mine is classified by its character. Relevant characters include:

Structure: paved and unpaved;

Movement direction: one lanes, two or more lanes in traffic;

Time using: permanent and temporary;

Location: bench road, ramp, surface, dump road.

Rolling resistance is defined as the force required to maintain a vehicle at a steady speed on the ground level, and is a function of not only the gross vehicle mass and driving characteristics, but also the type and conditions of the tires and the road surface on which the vehicle is operated [9]. The characteristics of the road pavement are expressed as a coefficient of the rolling resistance.

Empirical estimations of the rolling resistance are based on tire penetration, and it turns out that 0.6 percent increase in rolling resistance per centimeter of tire penetration into the road typically result in 1.5 to 2 percent minimum resistance [9].

Figure 1 shows that rolling resistance for mine haul road depends on road conditions. Calculations of the rolling resistance are categorized as shown in **Table 1**.

According to B. Purevtogtokh (2018), the average value of the road rolling resistance in the direction of the load section *j* is defined as follow.

$$w_{lj} = \frac{l_1 * w_1 + l_2 * w_2 + \cdots + l_n * w_n}{l_1 + l_2 + \cdots + l_n} = \frac{\sum_{i=1}^{n} l_i * w_i}{\sum_{i=1}^{n} l_i}, \text{ N/kN} \quad (2)$$

The average value of the road rolling resistance in the direction of the empty section *j* is set as:

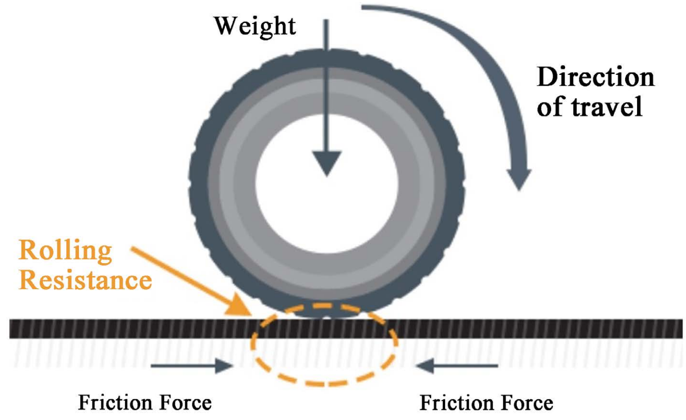

Figure 1. Rolling resistance.

Table 1. Calculation of rolling resistance for mine haul road.

Rolling resistance (%)	Road surface conditions (built from unbound gravel materials)
2	Strong layerworks and hard, compacted well-built and maintained road, no tire penetration/deflection discernable
2 - 3	Intermediate strength layerworks, compacted, well-built and frequently maintained road, with minimal (<25 mm) tire penetration/deflection
3 - 5	Weak layerworks or surfacing material, 25 - 50 mm tire penetration/deflection, rutted and poorly maintained
5 - 8	Weak layerworks or surfacing material, 50 - 100 mm tire penetration/deflection, rutted and poorly maintained

$$w_{ej} = w_{lj} * 1.25\text{, N/kN} \tag{3}$$

At the same time, the average slope of the road in the load and empty section *j* is specified as:

$$i_j = \frac{l_1 * i_1 + l_2 * i_2 + \cdots + l_n * i_n}{l_1 + l_2 + \cdots + l_n} = \frac{\sum_{i=1}^{n} l_i * i_i}{\sum_{i=1}^{n} l_i}\text{, ‰} \tag{4}$$

where

w_i: the rolling resistance of the road in the load of direction;

l_i: the length of the road section *i* for traffic *j*, km;

i_i: the slope of the road section *i* for traffic *j*, ‰.

Meanwhile, the total resistance of the movement is described as:

$$W_j = \frac{P_{l1}\left(w_{l1} + i_{l1}\right)\sum l_{l1} + P_{e1}\left(w_{e1} + i_{e1}\right)\sum l_{e1}}{L_1}\text{, N} \tag{5}$$

where: P_{l1}, P_{e1}: the weight of the dump truck in the load and empty direction, tons;

w_{l1}, w_{e1}: the rolling resistance of the road in the load and empty direction, N/kN;

l_{l1}, l_{e1}: the length of the road in the load and empty direction, km;

i_{l1}, i_{e1}: the slope of the road in the load and empty direction, ‰;

L_1: the total distance of road.

It is essential to develop a methodology to optimize the utilization regime in connection with the increase in the volume of transport. Consequently, a scientific assessment of the organizational level, operating conditions and quality characteristics should be conducted; otherwise it is impossible to maximize the efficiency of the dump truck.

2.3. Multiple Linear Regression

Multiple linear regression analysis is a statistical method used for determining a formula that explains the prediction of a dependent (unknown) variable by its relationship to a set of independent (known) variables. A weighting is assigned to each independent variable to reflect the portion of its impacts on the value of the dependent variable; thus, the weighting is referred to as the coefficient of the variable in the equations [15] [16].

Multiple R. Multiple R is the Correlation Coefficient, illustrating the strength of the linear relationship. For instance, a value of 1 signifies a perfectly positive relationship while a value of 0 expresses no relationship between a certain independent variable and the dependent variable. Multiple R is the square root of R squared.

R squared. R squared (r^2) is the Coefficient of Determination, representing the proportion of the variance for a dependent variable that is explained by the independent variables included in a regression model. For instance, R squared value of 80 %describes that 80 percent of the variations of the value of y fall on or closed to the regression line (the mean) are explained by the value of x; thus, implying that 80 percent of the values calculated are fit to the model.

Adjusted R square. Adjusted R-square (adjusted R^2) shows how well the data points fit the regression line, but adjusts for the number of terms in a regression model.

Standard Error of the Regression. Standard Error of the Regression is an estimate of the standard deviation of the error μ, which is *not* similar to the standard error in descriptive statistics. The standard error of the regression is the precision that the regression coefficient is measured; if the coefficient is large compared to the standard error, then the coefficient is probably different from 0.

Observations. Observations report the number of observations in the sample.

2.4. Simplification of the Road Scheme

In order to minimize the amount of road sections, a summary of the road parameter must be checked to ensure the road conditions for possible tractive forces, define the speed of movement and the time as well as the efficient usage frequency. Afterwards, the principle road scheme is simplified in accordance with associated parameters.

Before the road is simplified, following road conditions must be taken into account.

- Summarized roads must be a same type of road section (bench road, ramp, surface road, dump road).
- Pavement and structure of road must be the same.
- Road gradient and rolling resistance are nearby for dump trucks operating in the same regime.
- The speed of the dump truck is nearby.
- Safety conditions must be the same.

The *R* radius curved sections is converted to the slope of straight section. The curved sections of radius *R* are defined as the curve resistance according to the equation:

$$\Delta i_R = 30 * \frac{200 - R}{200}, ‰ \text{ (per mille)} \tag{6}$$

where: *R*: turn radius, m.

The radius *R* curve in section *j* is defined according to the equations:

$$i_j = i'_j + \Delta i_R, ‰ \tag{7}$$

where: i_j: slope of the *j* section curve converted into slope, ‰;

i'_j: Slope of the *j* section curve, ‰.

The road has to be subdivided into sections of the road, namely bench road (BR), ramp (R), surface road (SR), dump road uphill (DRU), and dump road (DR).

For each section of road, the average length, the average slope and the average rolling resistance are defined. In addition, the amount of charge is considered.

For example; weighted average length of the bench road:

$$L_{BR} = \frac{\sum L_{BRj} * Q_j}{\sum Q_j}, \text{ km} \tag{8}$$

Weighted average slope of the bench road:

$$i_{BR} = \frac{\sum L_{BRj} * i_{BRj}}{\sum L_{BRj}}, \text{ km} \tag{9}$$

Weighted average rolling resistance of the bench road:

$$w_{BR} = \frac{\sum L_{BRj} * w_{BRj}}{\sum L_{BRj}}, \text{ N/kN} \tag{10}$$

where; L_{BRj}: length of bench road in *j* section, km;

I_{BRj}: slope of bench road in *j* section, ‰;

Q_j: quantity of transport load by section *j*, tn/m^3;

W_{BR}: rolling resistance bench road in *j* section, N/kN (‰).

3. Practical Experiments of Transport Process

The test of dump truck regime determines the dimensions of the road and the speed (time) of each road section. Testing process consists of measuring chips in each dump truck and recording the cycle time. The determination of rolling resistance is based on the knowledge on the road surface and the current road defect. Meanwhile, road gradient and road length are determined by the measurement of the open-pit mine surface.

The road description from the excavation point to the discharge point is shown in Table 2.

Figure 2 exhibits the scheme of an open-pit mine road for a dump truck. Points 1, 2, 3, 4, 5 are loading positions and Point 12, 15, 18 are discharge positions.

Simplifying the Calculation of the Road Section

For the sake of simplicity, the same type of road is considered for this open pit mine. The road with five bench roads, three ramps, three surface roads, three dump uphill roads and three dump roads are combined and calculated for this open pit. The average length, average slope, and average rolling resistance of each road are calculated and the following equations are derived. The results of the simplified transport system calculations are shown in Table 3.

Weighted average length of the bench road:

$$L_{BR} = \frac{Q_1 * L_{1-6} + Q_2 * L_{2-7} + Q_3 * L_{3-8} + Q_4 * L_{5-8} + Q_5 * L_{4-7}}{\sum Q} = 0.26\text{ km} \quad (11)$$

Weighted average length of the ramp:

$$L_R = \frac{Q_1 * L_{6-7} + Q_2 * L_{7-8} + Q_4 * L_{8-9}}{\sum Q} = 0.358\text{ km} \quad (12)$$

Weighted average length of the surface road:

Table 2. Haulage systems description.

Parameter/ Position	Bench road					Ramp			Surface road			Dump road uphill			Dump road		
	1_6	2_7	3_8	5_8	4_7	6_7	7_8	8_9	9_13	9_10	9_16	10_11	13_14	16_17	11_12	14_15	17_18
length, km	0.043	0.135	0.795	0.055	0.191	0.55	0.72	0.432	0.975	0.126	0.699	0.331	0.332	0.34	0.3	0.36	0.5
slope, ‰	0	13.5	0	−86	51	51	68.5	100	0	19	0	51	55	55	0	0	0
rolling resistance,‰	80	80	80	80	51	27.5	30	60	30	30	46.5	152	152	152	152	152	152
radius, m	0	0	0	0	80	0	0	100	0	0	0	80	0	0	0	0	0

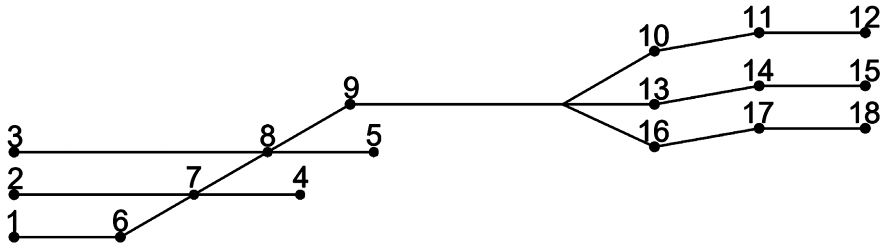

Figure 2. Scheme of the road section.

$$L_{SR} = \frac{\sum Q*\left(L_{9-13}+L_{9-10}+L_{9-16}\right)}{\sum Q} = 0.600 \text{ km} \quad (13)$$

Weighted average length of the dump road uphill:

$$L_{DRU} = \frac{\sum Q*\left(L_{10-11}+L_{13-14}+L_{16-17}\right)}{\sum Q} = 0.334 \text{ km} \quad (14)$$

Weighted average length of the dump road:

$$L_{DR} = \frac{\sum Q*\left(L_{11-12}+L_{14-15}+L_{17-18}\right)}{\sum Q} = 0.387 \text{ km} \quad (15)$$

Weighted average slope of the bench road:

$$i_{BR} = \frac{i_{1-6}*L_{1-6}+i_{2-7}*L_{2-7}+i_{3-8}*L_{3-8}+i_{5-8}*L_{5-8}+i_{4-7}*L_{4-7}}{\sum L} = 8.39\ ‰ \quad (16)$$

Weighted average slope of the ramp:

$$i_{R} = \frac{i_{6-7}*L_{6-7}+i_{7-8}*L_{7-8}+i_{8-9}*L_{8-9}}{\sum L} = 78.43\ ‰ \quad (17)$$

Weighted average slope of the surface road:

$$i_{SR} = \frac{i_{9-13}*L_{9-13}+i_{9-10}*L_{9-10}+i_{9-16}*L_{9-16}}{\sum L} = 1.33\ ‰ \quad (18)$$

Weighted average slope of the dump road uphill:

$$i_{DRU} = \frac{i_{10-11}*L_{10-11}+i_{13-14}*L_{13-14}+i_{16-17}*L_{16-17}}{\sum L} = 59.62\ ‰ \quad (19)$$

Weighted average rolling resistance of the bench road:

$$w_{BR} = \frac{\sum L_{BRj}*w_{BRj}}{\sum L_{BRj}} = 75.46\text{, N/kN} \quad (20)$$

Weighted average rolling resistance of the ramp:

$$w_{R} = \frac{\sum L_{Rj}*w_{Rj}}{\sum L_{Rj}} = 40.99\text{, N/kN} \quad (21)$$

Weighted average rolling resistance of the surface road:

$$w_{SR} = \frac{\sum L_{SRj}*w_{SRj}}{\sum L_{SRj}} = 36.41\text{, N/kN} \quad (22)$$

Weighted average rolling resistance of the dump road uphill:

$$w_{DRU} = \frac{\sum L_{DRUj}*w_{DRUj}}{\sum L_{DRUj}} = 152\text{, N/kN} \quad (23)$$

Weighted average rolling resistance of the dump road:

$$w_{DRU} = \frac{\sum L_{DRj}*w_{DRj}}{\sum L_{DRj}} = 152\text{, N/kN} \quad (24)$$

In this case, three roads have a curve radius and have been converted to a straight road gradient as illustrated in Table 4.

Figure 3 shows a simplified representation of road sections. Measured values of road are grouped into bench road, ramp, surface road and dump road.

4. Result and Discussion

4.1. Factors That Influence the Movement Process of Dump Trucks and the Mathematical Model

The current study observes every road section and dump truck movement. Subsequently, the data is analyzed via multiple mathematical regression models using mathematical statistical methods. The data regarding five bench roads, three ramps, three surface roads, three dump uphill roads and three dump roads are combined and calculated and accordingly the measurement of "UkhaaKhudag" open-pit mine has been summarized. The results show the estimated ranges obtained via Microsoft Excel application as outlined in Table 5.

The Microsoft Excel program compares statistical calculations with of regression models: linear, quadratic and exponential. Factors are validated by the F-test. Table 6 shows comparisons of road moving time regression models in each section in the loaded direction.

Table 3. Simplified Haulage systems description.

Direction	Road section	Grade, ‰	Rolling resistance, N/kN	Length, km	Average duration, seconds	Speed, km/hour
Loaded	Bench road	8.39	75.46	0.244	38.72	22.73
	Ramp	78.43	40.99	0.355	77.47	16.48
	Surface road	1.33	36.41	0.600	53.19	40.59
	Dump road uphill	59.62	152.00	0.334	53.23	22.61
	Dump road	0.00	152.00	0.387	62.12	22.41
Empty	Dump road	0.00	190.00	0.387	62.08	22.42
	Dump road uphill	−59.62	190.00	0.334	35.61	33.80
	Surface Road	−1.33	45.51	0.600	44.05	49.01
	Ramp	−78.43	51.24	0.355	44.04	28.98
	Bench Road	−8.39	94.32	0.244	30.86	28.51

Table 4. Converted slope for the curved sections of radius *R*.

Road section	Radius, m	Slope for *R*, ‰	Total slope, ‰
Bench road 4_7	80	18	69
Ramp 8_9	100	15	115
Dump road uphill 11_10	80	18	69

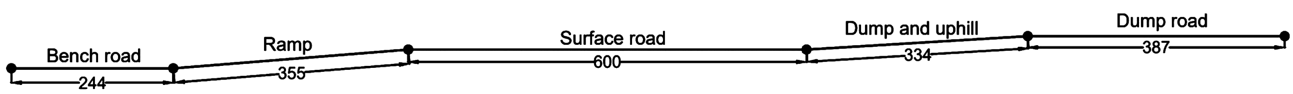

Figure 3. Simplified scheme for road sections.

Table 5. Descriptive statistics of road sections with duration of movement.

Parameters	Bench road		Ramp		Surface road		Dump road uphill		Dump road	
	loaded	empty	loaded	empty	loaded	empty	loaded	empty	loaded	empty
Mean	38.71	30.86	77.47	44.04	53.19	44.05	53.23	35.61	62.11	62.08
Standard error	3.51	2.95	4.83	2.24	4.63	3.85	1.81	0.58	1.34	0.76
Median	24.90	18.79	80	47.5	73	60	58	36	63	62.5
Mode	3.28	5.36	30	19	10.63	9.26	60	38	65	65
Standard Deviation	39.53	29.81	32.76	15.21	34.71	28.82	10.56	3.39	7.86	4.46
Sample Variance	1563.2	889.1	1073.5	231.3	1205.2	831.1	111.6	11.51	61.8	19.9
Kurtosis	−0.128	0.219	−0.956	−0.685	−1.834	−1.819	−0.882	−1.146	−0.343	−0.524
Skewness	1.195	1.340	−0.278	−0.502	−0.374	−0.362	−0.863	0.004	−0.222	−0.338
Range	127.20	110.70	109	54	82.47	71.58	31	11	33	17
Minimum	2.02	4.31	23	16	10.52	8.12	34	30	45	52
Maximum	129.22	115.02	132	70	93	79.70	65	41	78	69
Sum	3949	3148	3564	2026	2978.9	2467	1810	1211	2112	2111
Count	102	102	46	46	56	56	34	34	34	34
Largest	129.22	115.02	132	70	93	79.70	65	41	78	69
Smallest	2.02	4.31	23	16	10.52	8.12	34	30	45	52
Confidence Level (95.0%)	0.76	0.85	0.73	0.51	0.29	0.72	0.68	0.18	0.74	0.55

Table 6. Comparisons of the moving times regression model of the road in each section (loaded).

	Notice	Mark	Linear	Quadratic	Exponential
Bench road					
1	Multiple R	R	0.9905451	0.9900295	0.989893331
2	R Square	R^2	0.981179595	0.98015841	0.979888807
3	Standard Error	E	3.506487648	3.65390383	3.692186238
4	Observations	n	102	102	102
5	Regression model	T	$T = 21.12 + 140.50 * L + 0.043 * i - 279.68 * w$	$T = 6.53 + 39.96 * L^2 - 0.02 * D^2 + 22.04 * L * D - 69.01 * L - 1.05 * D$	$T = -64251.68 + 90.61 * e^L + 1.85 * e^i + 59226.97 * e^w$
Ramp					
1	Multiple R	R	0.986360259	0.986317476	0.986356668
2	R Square	R^2	0.97290656	0.972822164	0.972899477
3	Standard Error	E	3.582549638	3.591237708	3.583279283
4	Observations	n	46	46	46
5	Regression model	T	$T = -36.99 + 134.67 * L + 0.79 * i + 121.69 * w$	$T = -569.25 - 0.91 * D^2 - 88.52 * L * D + 994.92 * L + 68.97 * D$	$T = -171.48 + 77.32 * e^L + 0.0005 * e^i + 114.91 * e^w$

Continued

Surface road					
1	Multiple R	R	0.994184897	0.993602695	0.99419007
2	R Square	R^2	0.988403609	0.987246315	0.988413895
3	Standard Error	E	3.844788064	4.032076969	3.84308244
4	Observations	n	56	56	56
5	Regression model	T	$T = 24.43 + 53.73 * L - 1.45 * i + 247.3 * w$	$T = -0.71 - 39.8 * L^2 + 0.02 * D^2 + 7.43 * L * D + 107.31 * L - 1.3 * D$	$T = -217.12 + 23.23 * e^L - 6.67 * e^i + 239.17 * e^w$
Dump road uphill					
1	Multiple R	R	0.901037479	0.901422382	0.901034437
2	R Square	R^2	0.811868539	0.812562311	0.811863057
3	Standard Error	E	4.806587274	4.797716463	4.806657299
4	Observations	n	34	34	34
5	Regression model	T	$T = 257.62 + 90.9 * L - 1.38 * i - 1000.9 * w$	$T = -25287.04 - 256924.76 * L^2 - 1.03 * D^2 + 570.85 * L * D + 160942.16 * L - 156.76 * D$	$T = 976.09 + 64.96 * e^L - 0.02 * e^i - 859.8 * e^w$
Dump road					
1	Multiple R	R	0.807370366	0.795962535	0.803396018
2	R Square	R^2	0.651846908	0.633556357	0.645445161
3	Standart Error	E	4.785962235	4.910070586	4.829763306
4	Observations	n	34	34	34
5	Regression model	T	$T = 254.87 + 72.88 * L - 1457.53 * w$	$T = 6385.91 - 212.3 * L^2 + 250973.44 * W^2 - 762.51 * L + 6645.97 * L * W - 80170.28 * W$	$T = 1461.95 + 48.11 * e^L - 1264.04 * e^w$

Table 7. Comparisons of the moving times regression model of the road in each section (empty).

Notice		Mark	Linear	Quadratic	Exponential
Bench road					
1	Multiple R	R	0.978383333	0.971925706	0.978418247
2	R Square	R^2	0.957233945	0.944639578	0.957302266
3	Standard Error	E	3.259765985	4.122102196	3.254763857
4	Observations	n	102	102	102
5	Regression model	T	$T = 23.47 + 107.44 * L + 0.059 * i - 238.17 * w$	$T = 42.88 + 39.7 * L^2 + 0.18 * D^2 + 18.13 * L * D - 109.44 * L - 5.82 * D$	$T = 101.37 + 66.31 * e^L + 0.0004 * e^i - 147.25 * e^w$
Ramp					
1	Multiple R	R	0.948316493	0.924445685	0.948314643

Continued

2	R Square	R^2	0.899304171	0.854599825	0.899300661
3	Standard Error	E	3.99627532	4.003756713	3.996362388
4	Observations	n	46	46	46
5	Regression model	T	$T=-5+64.74*L$ $-0.29*i+52.44*w$	$T=232.49-584.97*L^2$ $+2.34*D^2-136.72*L$ $*D+84.1*D$	$T=-100.56+70.26*e^L$ $-4064.02*e^i+49.23*e^w$
Surface					
1	Multiple R	R	0.993477756	0.991812291	0.993478402
2	R Square	R^2	0.986998051	0.98369162	0.986999336
3	Standard Error	E	3.380615642	3.786142721	3.380448564
4	Observations	n	56	56	56
5	Regression model	T	$T=28.7+39.94*L$ $-1.42*i+65.22*w$	$T=-21.46-45.38*L^2$ $-0.48*D^2+1.62*L*D$ $+117.98*L+5.45*D$	$T=-34.25+17.25*e^L$ $-6.12*e^i+62.36*e^w$
Dump road downhill					
1	Multiple R	R	0.794361298	0.80374	0.794363088
2	R Square	R^2	0.631009871	0.646002716	0.631012716
3	Standard Error	E	2.161998317	2.154490499	2.161989982
4	Observations	n	34	34	34
5	Regression model	T	$T=-214.9+818.18*L$ $-0.29*i-213.16*w$	$T=+578.552-13619.0271*L^2$ $-0.168448*D^2+288.4464*L*D$ $+2913.8509*L-95.6335*D$	$T=-510.78+584.69*e^L$ $-1334.16*e^i-228.95*e^w$
Dump road					
1	Multiple R	R	0.534138299	0.570484006	0.549175541
2	R Square	R^2	0.285303722	0.325452001	0.301593775
3	Standard Error	E	3.891124185	3.780252076	3.84652343
4	Observations	n	34	34	34
5	Regression model	T	$T=90.43+27.75*L$ $-206.13*w$	$T=-1040.43+448.69*L^2$ $-16221.3*W^2+1304.72*L$ $-8663.95*L*W+9209.55*W$	$T=251.1+18.93*e^L$ $-179.52*e^w$

Table 7 shows comparisons of road moving time regression models in each section in the empty direction.

By comparing the regression models described in each road section, the models with greater correlation coefficient and smaller standard errors are selected; therefore the prediction models are acquired.

For the modeling variables: L: the length of the section on the road, km;

i: the grade of the section on the road (‰);

w: rolling resistance of the section on the road, N/mN (m-mega).

4.2. Demonstrating the Model of Each Road Section

Bench road in loaded direction

$$T = 21.12 + 140.50 * L + 0.043 * i - 279.68 * w \quad (25)$$

Road length and grade have a direct effect on moving time of cycle whereas rolling resistance has an indirect effect.

Figure 4 and Figure 5 prove that the regression model described in the direction of the bench road is similar to the value of the actual measurement.

Bench road in empty direction

$$T = 101.37 + 66.31 * e^{L} + 0.0004 * e^{i} - 147.25 * e^{w} \quad (26)$$

The model indicates that an increase of 179.7 seconds movement time results

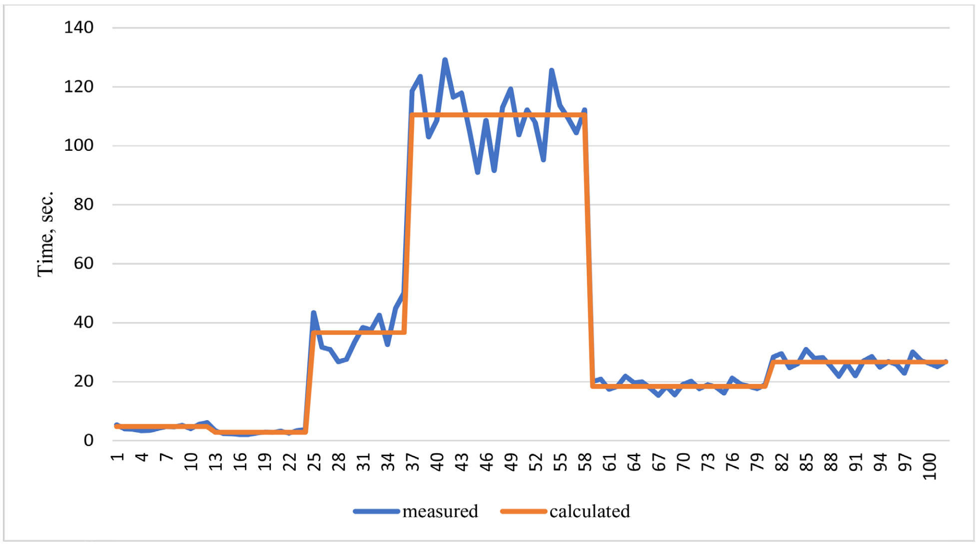

Figure 4. Comparison of measured time and calculated time of bench road loaded direction.

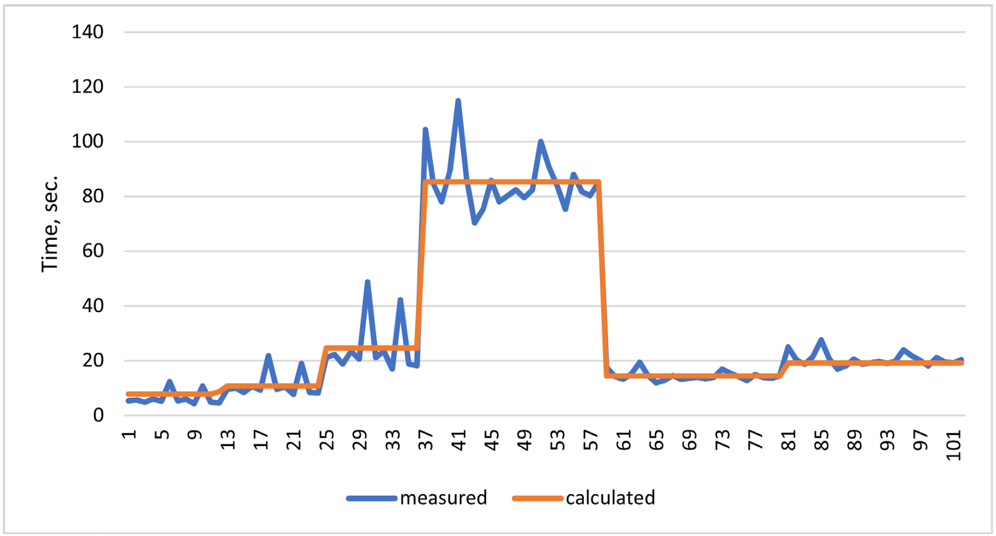

Figure 5. Comparison of measured time and calculated time of bench road empty direction.

in one unit increase of the road length. Furthermore, one unit increase of pavement road leads to a decrease of 399 seconds movement time.

Ramp in loaded direction

$$T = -36.99 + 134.67 * L + 0.79 * i + 121.69 * w \quad (27)$$

The regression model reveals that one unit increase of the rolling resistance causes an increase of 121.69 seconds movement time. One kilometer increase of the road length contributes to an increase of 134.67 seconds movement time. In the meantime, one unit increase of the road slope per mille conduces to an increase of 0.79 seconds movement time.

In summary, three factors included in this model significantly impact the cycle time.

Figure 6 reflects the similarities between the regression model described in the direction of ramp and the value of the actual measurement.

Ramp in empty direction

$$T = -5 + 64.74 * L - 0.29 * i + 52.44 * w \quad (28)$$

The regression model demonstrates that one unit increase of the rolling resistance and the length of the road lead to the increase of the movement time for 52.44 and 64.74 seconds respectively.

As evidenced in Figure 7, the differences in the values of the errors have a higher value compared with the other figures.

Surface road in loaded direction

$$T = -217.12 + 23.23 * e^{L} - 6.67 * e^{i} + 239.17 * e^{w} \quad (29)$$

Surface road in empty direction

$$T = -34.25 + 17.25 * e^{L} - 6.12 * e^{i} + 62.36 * e^{w} \quad (30)$$

The regression models shown in Figure 8 and Figure 9 are drawn from

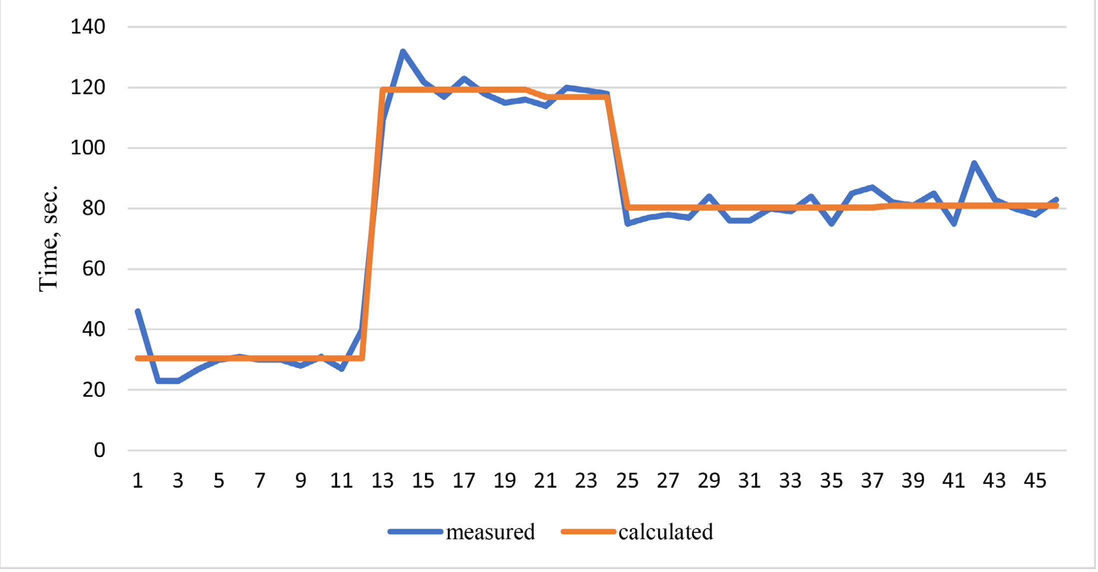

Figure 6. Comparison of measured time and calculated time of ramp loaded direction.

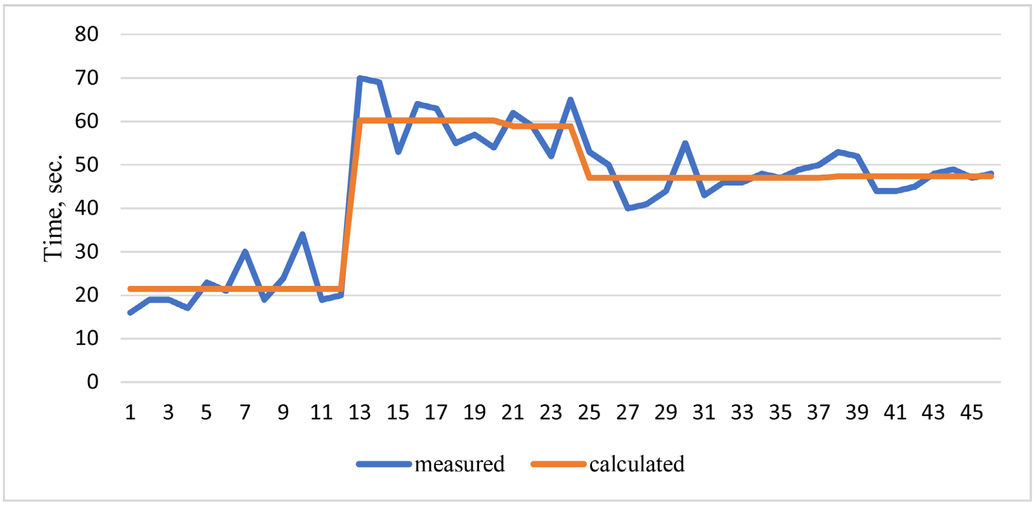

Figure 7. Comparison of measured time and calculated time of ramp empty direction.

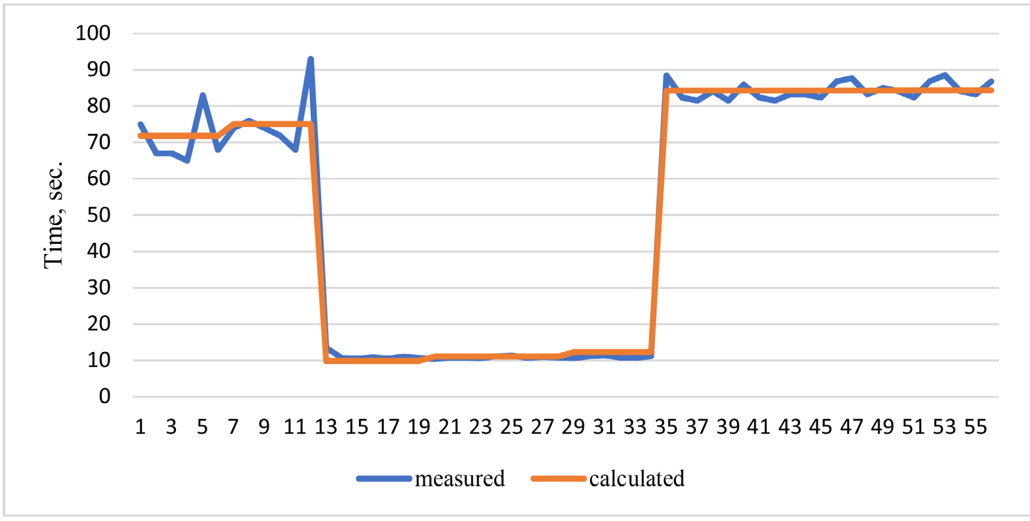

Figure 8. Comparison of measured time and calculated time of surface road in loaded direction.

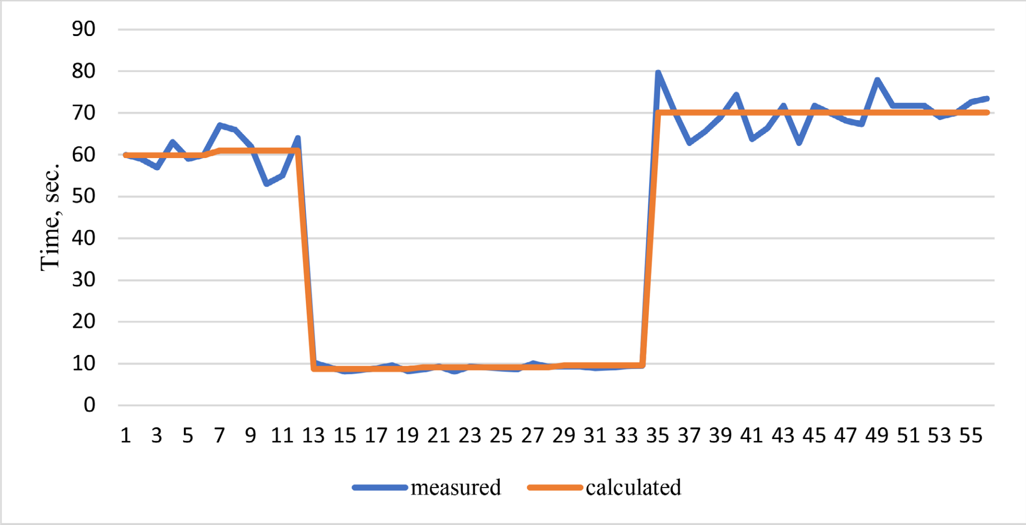

Figure 9. Comparison of measured time and calculated time of surface road in empty direction.

related exponential functions. It is obvious that the road pavement has larger influence on the movement time. Hence, the pavement should be highly considered as the surface road length increases.

Dump road uphill in loaded direction

$$T = -25287.04 - 256924.76 * L^2 - 1.03 * D^2 + 570.85 * L * D + 160942.16 * L - 156.76 * D \tag{31}$$

Dump road uphill in empty direction

$$T = +578.552 - 13619.027 * L^2 - 0.1684488 * D^2 - 288.4464 * L * D + 2913.8509 * L - 95.6335 * D \tag{32}$$

The regression models portray the values of the slope while main resistance factors on the road are expressed in the term of *D*;

$$D = (i + w)/10 \tag{33}$$

where: *i*: the grade of the section on the road (‰);

w: the rolling resistance of the section on the road, N/kN.

Figure 10 and **Figure 11** manifest that the difference between the calculations and actual measured values varies from 0.32 to 0.55 in the loaded direction and 0.34 to 0.52 in the empty direction; however, the proportion is comparatively small.

Dump road in loaded direction

$$T = 254.87 + 72.88 * L - 1457.53 * w \tag{34}$$

Dump road in empty direction

$$T = -1040.43 + 448.69 * L^2 - 16221.3 * w^2 + 1304.72 * L - 8663.95 * L * w + 9209.55 * w \tag{35}$$

The turning radius and the slope of the dump road are relatively small, for this

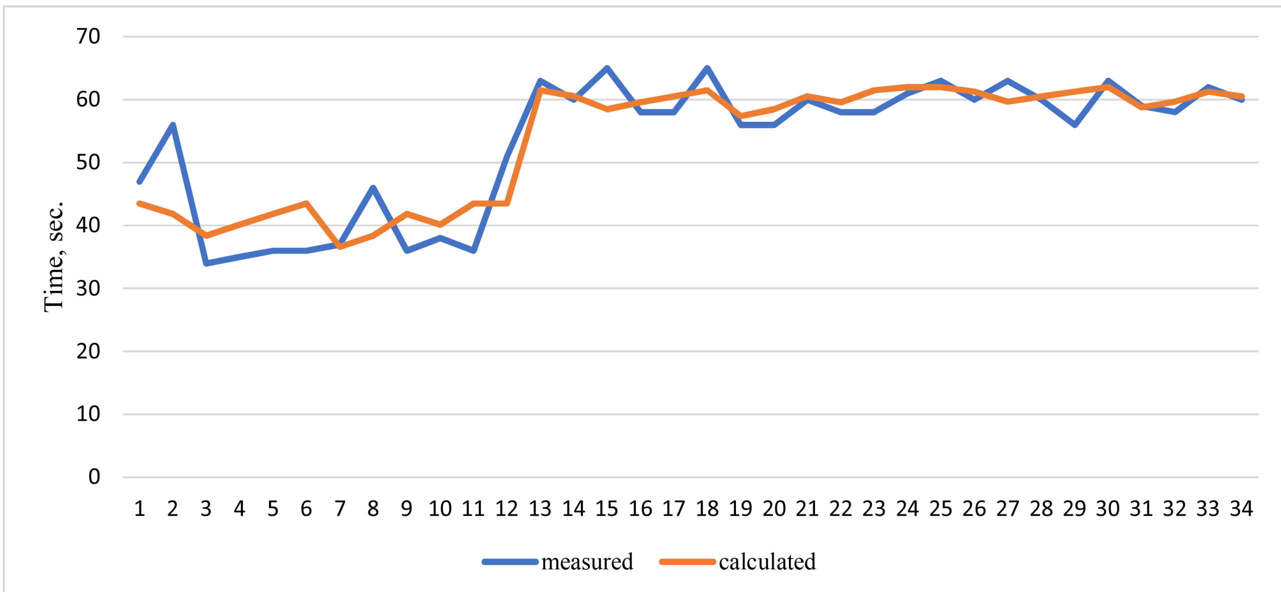

Figure 10. Comparison of measured time and calculated time of dump uphill road in loaded direction.

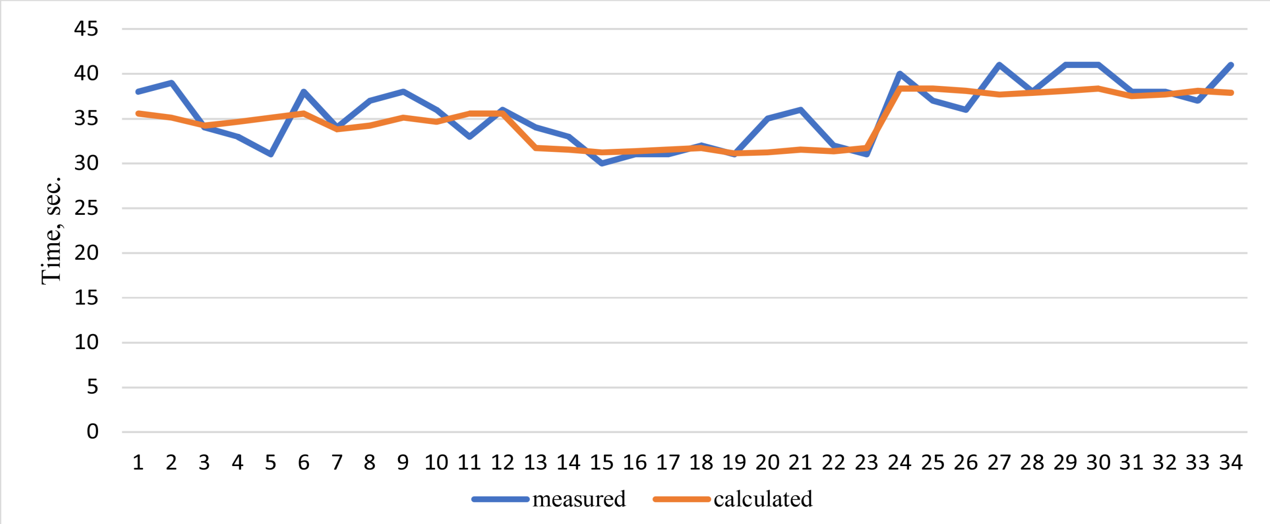

Figure 11. Comparison of measured time and calculated time of dump uphill road in empty direction.

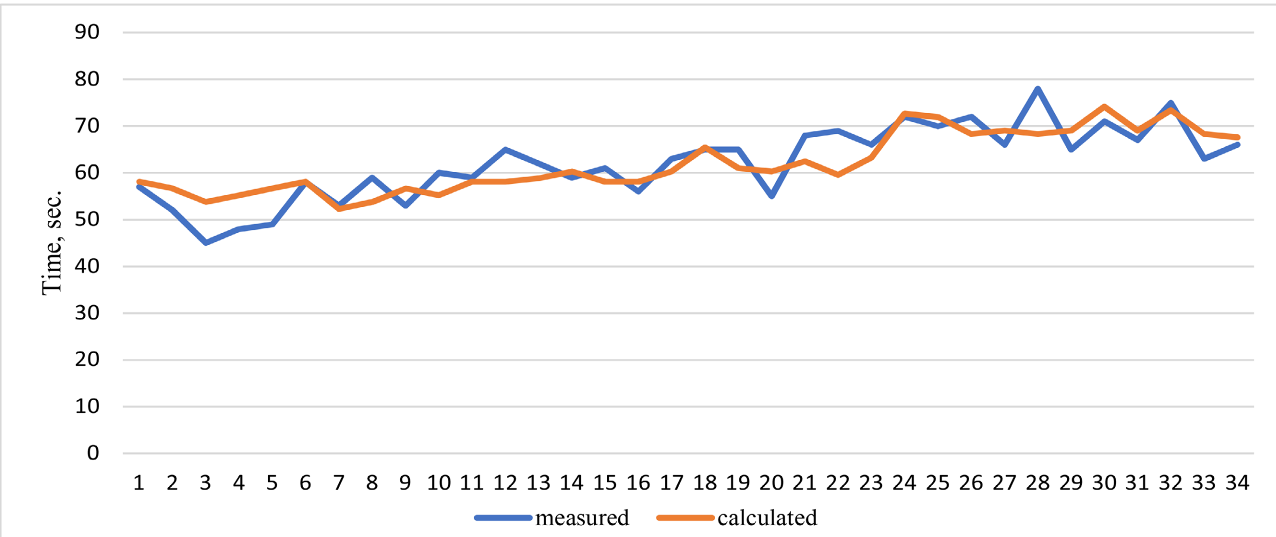

Figure 12. Comparison of measured time and calculated time of dump road in loaded direction.

reason, the regression model should be determined by including only two variables: rolling resistance and the road length.

The regression models emphasize that one unit increase of rolling resistance is attributed to a reduction of 1457.53 seconds movement time in loaded direction. Simultaneously, one kilometer increase of the road length is the cause of an increase in the movement time for 72.88 seconds and 36.25 seconds in the loaded direction and the empty direction respectively. As a result, it is necessary to define the road exactly as the length increases. Figure 12 and Figure 13 show the comparison of the calculated and measured values of the defined models in the loaded and empty direction.

4.3. Research of the Dump Truck Stop Times

This section measures the waiting time of the excavator, spotting time, loading

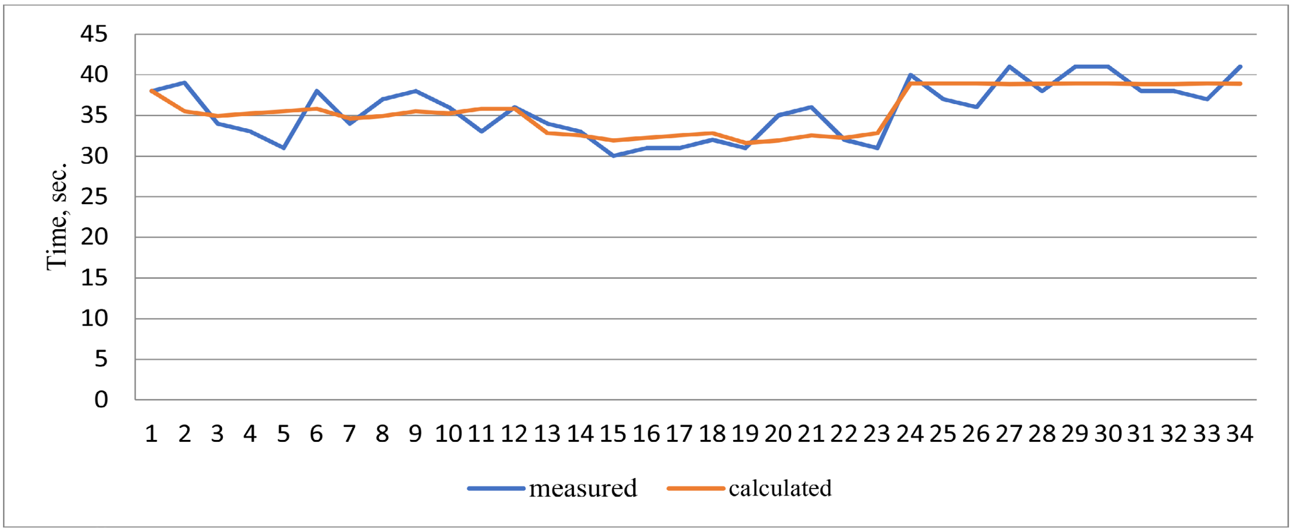

Figure 13. Comparison of measured time and calculated time of dump road in empty direction.

Table 8. Load and dump time of dump trucks (seconds).

Parameters	average	min	max
Waiting time	64.61	0	279
Load spot time	29.45	8	68
Loading time	127.38	81	165
Dumping spot time	26.6	10	56
Dumping time	52.5	22	70

time, dumping time, and dumping spot time. The experimental measurement exemplifies the combination of Excavator R9250 and Truck CAT785, and the results are displayed in Table 8.

It is affirmed that waiting usually takes longer time than most of the other processes. Moreover, the difference between the minimum and the maximum records of the waiting time appears extremely large. Thereby, it is necessary to optimize the combination of trucks and shovels.

Corresponding to Table 9, the difference between the actual and mathematical model of the mean time is 0.82 seconds. Regarding the errors, the absolute error of 0.82 seconds with the relative error of 2.51 percent confirms the probability value of the mathematical models. Table 10 shows the total cycle times of the dump trucks.

5. Conclusion

- The results of the study on movement duration reveal that it is possible to increase the productivity by 34.19 percent according to the comparison between the maximum duration and average duration. Regarding the practical experiments, the regression equations are derived and can be used for defining the movement time of both loaded and empty direction for each road section.

Table 9. Comparison of actual and calculated time for road section (seconds).

Road section	Actual	Calculated	Error	
			Absolute	Relative
Bench road loaded	38.72	38.72	0	0
Bench road empty	30.86	30.76	0.1	0.3240
Ramp loaded	77.48	77.45	0.03	0.0387
Ramp empty	44.04	43.77	0.27	0.6131
Surface road loaded	53.2	53.22	−0.02	−0.0376
Surface road empty	44.05	44.08	−0.03	−0.0681
Dump road uphill loaded	53.24	53.58	−0.34	−0.6386
Dump road uphill empty	35.62	34.8	0.82	2.3021
Dump road loaded	62.12	62.13	−0.01	−0.0161
Dump road empty	62.09	62.09	0	0.0000
Total	**501.42**	**500.6**	**0.82**	**2.5175**

Table 10. Cycle time of dump trucks (seconds).

№	Component		Minimum	Average	Maximum
1	Loading time		81	127.38	165
2	Moving time		445.9975	501.42	580.7639
3	Dumping time		22	52.5	70
4	Waiting time		0	64.61	279
5	Spotting time	Loading	8	29.45	68
		Dumping	10	26.6	56
6	Total cycle time		566.9975	801.96	1218.7639

- Experimental results disclose that it is feasible to reduce the waiting time while emphasizing the advancement of spotting method and the combination of trucks and shovels.
- The mathematical models developed during the current study can be utilized for future open pit mine planning of which the key factors generally include the type of pavement, the slope of the road, and the cycle time.
- In general, improvement of the road increases the speed; however, for mining, the roads are usually for temporary use so that not much investment is dedicated to road construction. As reported by this study, it is crucial to pay attention the road built by focusing on its expected life cycle.
- Specifically, the equations obtained via the regression analysis clearly identify which road sections significantly influence the speed of the trucks.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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