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Evaluation of Articulated CAT 745 Fuel Ratio Based on Haul Road Geometry at PT Hillconjaya Sakti Site PT Adhi Kartiko Pratama Tbk

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Abstract

The distance for transporting overburden at PT Hillconjaya Sakti reaches hundreds of meters. Based on actual conditions, Articulated CAT 745 queues often occur on specific haul road segments due to unsuitable haul road conditions. Hence, the fuel ratio value is in the low-performance category. This study aims to evaluate the fuel ratio value and provide recommendations for improving the geometry of haul roads to meet the established fuel ratio value standards. Multiple linear regression analysis using Eviews 12 VS software was used to determine the variables that significantly affect the fuel consumption of haulers based on haul road geometry. Road grade, total resistance, travel time, and speed of the hauler are independent variables, while fuel consumption is the dependent variable. Based on the data processing results, a fuel ratio value of 1.85 was obtained, and the parameters that significantly affected fuel consumption were total resistance and travel time. Improve haul road conditions based on ESDM Decree No. 1827 K/30/MEM/2018 and AASHTO Manual Rural High Way Design. The fuel ratio value after repairs decreased to 0.60 and was in the best performance category based on PT Hillconjaya Sakti's standard fuel ratio value.

Keywords: Fuel ratio; haul road geometry; load factor; multiple regression

1. Introduction

PT Hillconjaya Sakti uses an open mining system (surface mining) with a backfilling method, where the mine-out area will be used as a disposal area and will move in line with the direction of mining so that the distance to transport layers of soil reaches hundreds of meters. The geometry of the haul road is the main factor related to the activity of the haulage [1]. Road geometry that does not comply with standards and poor road surface conditions can increase the cycle time of the hauler, thereby reducing productivity and increasing fuel consumption. A good haul road design will significantly reduce equipment delivery time, use of fuel, tire costs, and freight costs per ton and establish a safe transportation system [2].

Based on actual conditions in the field, during the process of transporting overburden, there are often queues of Articulated CAT 745 on certain haul road segments, which cause delays and impact work efficiency. Delays that occur result in low productivity and increased fuel usage because the engine continues to work during delays, causing the fuel ratio value to exceed the standards set by the company. The optimal fuel ratio can be achieved if the Articulated CAT 745 is capable of maximum production with efficient fuel consumption. Several factors influence fuel consumption, namely road grade, total resistance, travel time, distance and speed. Road geometry that does not meet established standards, such as road slope and road width, will result in the transport equipment not being able to work optimally and will affect the cycle time of the hauler. The longer the cycle time of the hauler, the higher the fuel consumption rate. Similarly, a high total resistance coefficient will produce a high rolling resistance value so that the engine releases more energy and more force is required to pull the hauler. Therefore, a high rolling resistance value impacts excessive fuel use in the transport equipment. Multiple linear regression analysis is one way to predict factors that significantly influence Articulated CAT 745 fuel consumption. Evaluation of haul road geometry is carried out to determine the suitability of good haul road rules based on road standards and to become a benchmark in road improvements to reduce fuel consumption and meet the standard Articulated CAT 745 fuel ratio value at PT Hillconjaya Sakti as a contractor of PT Adhi Kartiko Pratama Tbk.

2. Methodology

The research was at the Makale Pit PT Hilconjaya Sakti project site PT Adhi Kartiko Pratama Tbk Lameruru

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Village, Lamanggiri District, North Konawe Regency, Southeast Sulawesi Province, Indonesia. The research stage begins by conducting a literature review from various references. The next stage is conducting field orientation and data collection. The data collected in this research are the topography of the mining area, nickel haul road coordinate data, haul road width, road subsidence depth, haul road conditions, haul cycle time, working hour data, and Articulated CAT 745 hauler specifications. The data that has been obtained is then processed through mathematical equations based on literature. Multiple linear regression analysis is carried out using the E-Views 12 VS software to analyze the influencing factors of CAT 745 fuel consumption, such as road grade, travel time, and total resistance, through multiple linear regression tests and carry out a comparative analysis between actual road geometry and theoretical road geometry standards.

Evaluation is carried out on the width and grade of the road by comparing the actual measurement data with the standard AASHTO road geometry measurements based on the Articulated CAT 745 specifications used by PT Hillconjaya Sakti so that it can be identified which haul road segments do not meet the standards. The evaluation and regression analysis results are used as a reference when making plans to improve road geometry. Road geometry improvements are based on parameters that have a significant effect on fuel consumption and productivity in an effort to achieve standard fuel ratio values.

3. Results and Discussion

3.1. Geometry of mine haul road

The mine haul road should be considered an important asset to a mining operation [2]. Haul road geometry is a calculation of the haulage road space used in transport activities. The road's geometry must match the hauler's dimensions so that the hauler can move freely at normal and safe speeds [3]. Haul roads are an important component of open-pit mining infrastructure because road performance directly impacts operational efficiency and work safety. Haul road geometry consists of many elements, including road width, maximum grade, road cross-grade, etc. The road's geometry must match the equipment's dimensions so that the transportation equipment can move freely at normal and safe speeds [4].

Overburden transportation activities are carried out via two routes. The first route is a hauler route for transporting overburden to disposal with a distance of 976.05 meters. The second route is the route for the hauler back to the mining front with a distance of 982.03 meters. The haul road on each route is divided into 11 segments to make it easier to interpret the condition and geometry of the haul road.

1. Width of haul road

   Determining the minimum haul road width for straight roads (Fig. 1) is based on the rule of thumb according to AASTHO (American Association of State Transportation Highway Officials) AND Minister of Energy and Mineral Resources Decree No 1827 K/30/MEM/2018 with Equation 1 [5].

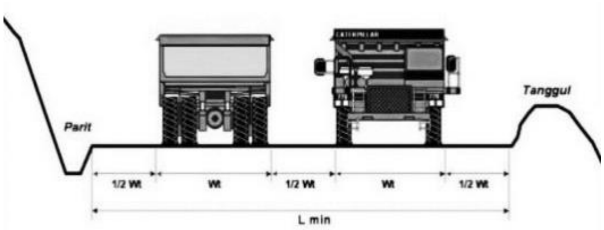

Figure 1. Straight haul road width

$$L = (n \times Wt) + (n + 1)(0.5 \times Wt) \quad (1)$$

where:
L = minimum width of straight haul roads (m)
n = number of lanes
Wt = total hauler width (m)

Calculation of the width of the haul road at curves or bends (Fig. 2) can be done using Equations 2 and 3 [5].

$$W = 2\,(U + Fa + Fb + Z) + C \quad (2)$$

$$C = Z = \frac{1}{2}\,(U + Fa + Fb) \quad (3)$$

where:
W = minimum haul road width at curves (m)
U = distance of vehicle wheel tracks (m)
Fa = front hanging width (m)
Fb = back drop width (m)
C = distance between two trucks that will intersect (m)
Z = distance from the outside of the truck to the edge of the road (m)

Articulated CAT 745 hauler equipment specification data required to determine the minimum carriageway width is presented in Table 1.
Based on Articulated CAT 745 specification data, the straight road width and minimum corner width are as follows.

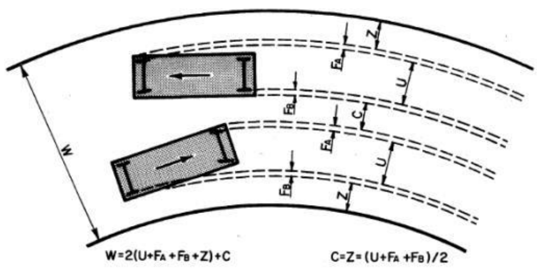

Figure 2. Width of haul road at bends

Table 1. Articulated CAT 745 specification data

Specification	Size
Width of hauler	3.801 m
Length of hauler	11.55 m
Distance between wheels	2.687 m
Front dangle	3.418 m
Back dangle	1.448 m
Wheel storage corner	45°
Fuel tank	550 L

a. Straight road width

$$L_{min}\ (1\ \text{lane}) = (1\times3.801) + (1+1) \times (\tfrac{1}{2}\times3.801) \quad (4)$$
$$= 7.60\ \text{m}$$
$$L_{min}\ (2\ \text{lane}) = (2\times3.801) + (2+1) \times (\tfrac{1}{2}\times3.801) \quad (5)$$
$$= 13.30\ \text{m}$$

b. Width of bend road

$$C = Z = 0.5(2{,}687+(3.418\times\sin 45) + (1.448\times \sin 45) \quad (6)$$
$$= 3.06\ \text{m}$$
$$L_{min}\ (1\ \text{lane}) = 1(2.687 + (3.48\ \text{x}\ \sin 45) + ((1.448\ \text{x}\ \sin 45)) + 3.06 \quad (7)$$
$$= 12.26\ \text{m}$$
$$L_{min}\ (2\ \text{lane}) = 2(2.687 + (3.48\ \text{x}\ \sin 45) + ((1.448\ \text{x}\ \sin 45)) + 3.06 \quad (8)$$
$$= 21.45\ \text{m}$$

The activity of transporting overburden is carried out via two routes, namely the route for transporting overburden to disposal and the route for hauler back to the front of the mine. The actual condition of the haul road route is 1 and 2 lanes, this is because the road construction is adjusted to the topography and geology. The actual road width measurement results for each segment of the loaded and unloaded routes can be seen in Table 2 and Table 3.

Based on Tables 2 and 3, road segments that meet the standards of Ministerial Decree No. 1827/K/30/MEN/2018 only segments E-F and J-K on loaded routes and segments K-J, G-F' and F'-E on unloaded routes

Table 2. Actual width of haul roads on loaded routes

Road Segment	Distance (m)	Number of Lanes	The width of the road (m)		Information
			Straight	Bend	
A-B	61.58	2	10.04	14.18	Not ideal
B-C	73.38	2	10.42	14.18	Not ideal
C-D	56.87	2	10.71	9.38	Not ideal
D-E	51.36	2	12.07	10.19	Not ideal
E-F	199.87	1	12.54	15.22	Ideal
F-G	78.08	1	6.62	11.84	Not ideal
G-H	99.24	2	9.40	16.13	Not ideal
H-I	174.89	2	7.87	-	Not ideal
I-J	97.06	2	11.01	15.50	Not ideal
J-K	68.75	2	16.92	-	Ideal
K-L	14.97	2	8.90	-	Not ideal
Amount	976.05				

Table 2. Width of haul roads unloaded routes

Road Segment	Distance (m)	Number of Lanes	The width of the road (m)		Information
			Straight	Bend	
L-K	14.97	2	8.90	-	Not ideal
K-J	68.75	2	16.92	-	Ideal
J-I	97.06	2	11.01	15.50	Not ideal
I-H	174.89	2	7,87	-	Not ideal
H-G	99.24	2	9.40	16.13	Not ideal
G-F'	139.88	1	9.80	12.50	Ideal
F'-E	144.06	1	6.95	12.87	Ideal
E-D	51.36	2	12.07	10.19	Not ideal
D-C	56.87	2	10.71	9.38	Not ideal
C-B	73.38	2	10.42	14.18	Not ideal
B-A	61.58	2	10.04	14.18	Not ideal
Amount	982.03				

2. Grade of haul road

The grade of the haul road is an important factor that must be observed in detail regarding the condition of the mine road. This is because the grade of the haul road is directly related to the ability of the haulage equipment (grade), both in braking and in overcoming hills. The grade of the haul road can be calculated using Equation 9 [6].

$$i = \frac{\Delta H}{\Delta x}\ x\ 100\% \quad (9)$$

where:

i = grade

ΔH = height difference between 2 measured points (m)

Δx = flat distance between two measured points (m)

Evaluation of the road grade based on the standards of Ministerial Decree No. 1827/K/30/MEN/2018 with a maximum value of mine road grade of 12%. The higher the grade of the road, the greater the fuel consumption [6]. A positive grade indicates the direction of movement of the hauler is upward (uphill), while a negative grade indicates the direction of movement of the hauler is downward (downhill). The road grade on each segment for the load route and the unloaded route is presented in Table 4 and Table 5, respectively.

Based on the data in Table 4 and Table 5, there is a road grade that exceeds the standards of Ministerial Decree No. 1827/K/30/MEN/2018. Road grades exceeding 12% are found on road segments during load and unloaded routes. On the loaded route,

Table 3. Road grade on loaded routes

Road Segment	Distance (m)	Height Difference (m)	Grade (%)
A-B	61.58	-0.21	-0.37
B-C	73.38	1.68	2.93
C-D	56.87	7.62	13.38
D-E	51.36	3.74	6.54
E-F	199.87	4.23	7.39
F-G	78.08	2.93	5.12
G-H	99.24	5.26	9.20
H-I	174.89	3.84	6.71
I-J	97.06	8.29	14.57
J-K	68.75	5.70	9.98
K-L	14.97	5.81	10.17
Amount	976.05		

Table 4. Road grade on the unloaded routes

Road Segment	Distance (m)	Height Difference (m)	Grade (%)
L-K	14.97	-5.81	-10.17
K-J	68.75	-5.70	-9.98
J-I	97.06	-8.29	-14.57
I-H	174.89	-3.84	-6.71
H-G	99.24	-5.26	-9.20
G-F'	139.88	-5.79	-10.144
F'-E	144.06	-1.99	-3.48
E-D	51.36	-3.74	-6.54
D-C	56.87	-7.62	-13.38
C-B	73.38	-1.68	-2.93
B-A	61.58	0.21	0.37
Amount	982.03		

segments C-D and I-J for uphill conditions have grades of 13.38% and 14.57%, and on unloaded routes, segments, J-I and D-C for downhill conditions have grades of -14.57% and -13.38%.

3. Rolling resistance
   The surface conditions of the haul roads at PT Hillconjaya Sakti have two soil characteristics, namely smooth, hard, dry dirt, gravel, and well-maintained and soft unplowed dirt, poorly maintained so that tire subsidence easily forms in large sizes. The characteristics of smooth, hard, dry dirt, gravel, and well-maintained have a rolling resistance coefficient of 2%, and the characteristics of soft, unblown dirt, poorly maintained, have a rolling resistance coefficient of 4%.
   Rolling resistance is obtained based on subsidence data on each road segment through direct measurements in the field and the load of the Articulated CAT 745 hauler. Based on Table 6 and Table 7, the results of the rolling resistance calculation on the overburden load route obtained the largest resistance value on the D-E segment of 19,546.89 lbs, and on the unloaded route, the largest rolling resistance value was obtained on the same road segment, namely the E-D segment, of 10,155.16 lbs.
4. Grade resistance
   Road grade s that do not meet standards result in large grade resistance values. This causes the engine to work harder to withstand the grade resistance so that greater engine power is required at the rim at lower speeds, which results in longer cycle times and increased fuel usage. The results of grade resistance calculations are presented in Table 8.

Table 6. Rolling resistance on the loaded route

Road Segment	Vehicle Weight (Tons)	Rolling Resistance Coefficient (%)	Subsidence Data (Inches)	Rolling Resistance (lbs)
A-B	65.6	4	5.05	16,745.53
B-C		4	3.42	13,201.13
C-D		4	3.00	12,291.54
D-E		2	7.68	19,546.89
E-F		2	2.52	8,358.53
F-G		4	1.25	8,489.49
G-H		2	1.44	6,024.06
H-I		2	1.25	5,597.03
I-J		2	1.97	7,162.83
J-K		2	1.02	5,113.05
K-L		4	0.79	7,493.07

Table 7. Rolling resistance on unloaded routes

Road Segment	Vehicle Weight (Tons)	Rolling Resistance Coefficient (%)	Subsidence Data (Inches)	Rolling Resistance (lbs)
L-K	40	4	0.79	1,041.59
K-J		2	1.02	1,354.04
J-I		2	2.00	2,645.56
I-H		2	1.44	1,909.53
H-G		2	1.44	1,909.53
G-F		2	1.00	1,319.32
F-E		2	1.00	1,328.00
E-D		2	7.68	10,155.16
D-C		4	3.00	3,967.49
C-B		4	3.42	4,522.11
B-A		4	5.05	6,683.34

Table 5. Results of grade resistance calculations

Load Route			Unloaded Route		
Road Segment	*Grade* (%)	Grade Resistance (lbs)	Road Segment	*Grade* (%)	Grade Resistance (lbs)
A-B	-0.37	-489.38	L-K	-10.17	-8,137.60
B-C	2.93	3,837.60	K-J	-9.98	-7,982.40
C-D	13.38	17,557.18	J-I	-14.57	-11,658.40
D-E	6.54	8,576.54	I-H	-6.71	-5,366.40
E-F	7.39	9,700.93	H-G	-9.20	-7,363.20
F-G	5.12	6,712.19	G-F	-10.14	-8,115.20
G-H	9.20	12,075.65	F-E	-3.48	-2,783.20
H-I	6.71	8,800.90	E-D	-6.54	-5,229.60
I-J	14.57	19,119.78	D-C	-13.38	-10,705.60
J-K	9.98	13,091.14	C-B	-2.93	-2,340.00
K-L	10.17	13,345.66	B-A	0.37	298.40

The results of calculating grade resistance on the loaded route obtained the largest resistance value on the I-J segment of 19,199.78 lbs, while on the unloaded route, the largest grade resistance value was obtained on the same road segment, namely the J-I segment, of -11,658.40 lbs.

5. Total resistance
   Total resistance is the drag force between the wheels and the haul road conditions. The total resistance is obtained based on the rolling and tilt resistance values. Different road surface characteristics and road grades will influence the equipment's productivity level and fuel consumption of transportation equipment [7]. The results of calculating the total resistance value on the load and unloaded routes can be seen in Table 9 and Table 10, respectively.
   The total resistance on the unloaded route shows that the largest resistance value on the C-D road segment is 29,848.72 lbs. Based on Table 10, the largest total resistance value on the B-A road segment is 6,981.74 lbs.

Table 6. Total resistance on the loaded route

Road Segment	Rolling Resistance (lbs)	Grade Resistance (lbs)	Total Resistance (lbs)
A-B	16.745,53	-489,38	16.256,15
B-C	12.204,71	3.837,60	16.042,31
C-D	12.291,54	17.557,18	29.848,72
D-E	9.582,70	8.576,54	18.159,25
E-F	8.358,53	9.700,93	18.059,46
F-G	8.489,49	6.712,19	15.201,68
G-H	6.024,06	12.075,65	18.099,71
H-I	5.597,03	8.800,90	14.397,92
I-J	7.162,83	19.119,78	26.282,60
J-K	5.113,05	13.091,14	18.204,19
K-L	7.493,07	13.345,66	20.838,73

Table 7. Total resistance on unloaded routes

Road Segment	Rolling Resistance (lbs)	Grade Resistance (lbs)	Total Resistance (lbs)
L-K	1.041,59	-8.137,60	-7.096,01
K-J	1.354,04	-7.982,40	-6.628,36
J-I	2.645,56	-11.658,40	-9.012,84
I-H	1.909,53	-5.366,40	-3.456,87
H-G	1.909,53	-7.363,20	-5.453,67
G-F'	1.319,32	-8.115,20	-6.795,88
F'-E	1.328,00	-2.783,20	-1.455,20
E-D	4.079,43	-5.229,60	-1.150,17
D-C	3.967,49	-10.705,60	-6.738,11
C-B	3.914,54	-2.340,00	1.574,54
B-A	6.683,34	298,40	6.981,74

Table 8. Rimpull of the Articulated CAT 745

Gear	*Horse Power* (HP)	Speed (mph)	*Rimpull* (lbs)
1st	504	3.8	42,276.32
2nd		5.0	32,130.00
3rd		7.0	22,950.00
4th		8.8	18,255.68
5th		11.6	13,849.14
6th		14.2	11,313.38

3.2. *Rimpull*

Rimpull is the amount of pulling force a machine tool can exert on the surface of a roadway [8]. House power and speed of each gear are obtained based on Articulated CAT 745 hauler specification data, while mechanical efficiency is assumed to be 85% (1-year unit). Rimpull is expressed in pounds (lbs) and is usually listed in the engine specifications. Rimpull for acceleration is the increase in speed of a moving hauler obtained from the acceleration force taken from the excess rimpull. The results of the rimpull calculation for each gear based on house power and hauler speed based on the Articulated CAT 745 specifications are presented in Table 11.

The maximum speed obtained in gear 1 is 42,276.32 lbs at a speed of 3.8 mph. The rimpull produced by the engine must be greater than the total resistance so that the hauler can accelerate. If the total resistance can be reduced, the operator can increase the speed to a higher gear by company operational standards at a safe speed. Optimal speed can speed up the cycle time so that there is a change from the actual cycle time condition to the cycle time based on rimpull.

3.3. *Load factor*

The load factor is a multiplying factor to obtain actual horsepower. Maximum power is not used continuously during the working period, so the load factor depends on the working conditions. The load factor can be calculated based on rimpull usage. Load factor can use Equation 10:

$$Load\ Factor = \frac{Rimpull\ used}{Maximum\ rimpull} \tag{10}$$

3.4. *Productivity of Hauler*

Productivity is calculated based on cycle time data, work efficiency, swell factor, and fill factor calculated using Equation 12.

$$\mathrm{C} = \mathrm{KB\ x\ FF\ x\ n} \tag{11}$$

$$\mathrm{Q} = \frac{\mathrm{C\ x\ 60\ x\ Ek\ x\ SF}}{\mathrm{Cta}} \tag{12}$$

where:

Q = production per hour hauler (m^3/hour)
n = number of excavator buckets to fill the hauler
KB = bucket capacity (m^3)
FF = *fill factor* (%)
SF = *swell factor*
Ek = hauler working time (%)
Cta = hauler cycle time (minutes)

The productivity of one Articulated CAT 745 unit is as follows:

$$\mathrm{Q} = \frac{\mathrm{16\ LCM\ x\ 45\%\ x\ 60\ minute/hour}}{\mathrm{18.60\ minute}} \tag{13}$$
$$= 23.22\ \mathrm{LCM/hour}$$

So the productivity of Articulated CAT 745 obtained is 23.22 LCM/hour.

3.5. *Fuel consumption*

Fuel consumption is the main parameter that is always considered when selecting a tool because it is the most significant contributor to operational costs [9]. The power required by a vehicle to drive the engine affects fuel consumption. Calculating the fuel requirements for a tool is very important to evaluate it in terms of fuel usage because fuel contributors have a significant influence on a company's finances. The size of a hauler's fuel consumption depends not only on the engine characteristics but is also influenced by the hauler's driving force, transport road conditions, speed, and power. The main variables in the vehicle's driving force are rolling resistance and grade resistance. The conditions of the haul road are the condition of the road surface and the grade of the road [10].

1. Fuel consumption (liters/hour)
   PT Hillconjaya Sakti uses 70% palm biodiesel (B30) fuel from PT Sinar Alam Duta Perdana II. Energy sources for haulers are transitioning to reduce emissions from fossil fuels and the resulting climate change [11]. Biodiesel is a form of new, renewable energy that reduces the use of fossil fuels. Palm biodiesel has a specific fuel consumption of 0.48 kg/kWh and a density of 7.06 lb/gallon [12]. Fuel consumption is the specific ratio of fuel entering the engine for one hour multiplied by the load factor and divided by the fuel density per liter. It is calculated using Equation 14 [10].

$$\mathrm{FC} = \frac{\mathrm{SFC\ x\ P\ x\ LF}}{\mathrm{FD}} \tag{14}$$

   where:
   FC = fuel consumption (liters/hour)
   SFC = specific fuel consumption (kg/kwH)
   LF = load factor
   FD = fuel density (kg/m^3)

   The results of calculating fuel consumption per hour have been summarized in Table 12. Based on the results of fuel consumption calculations in Table 12, the theoretically estimated fuel consumption of the Articulated CAT 745 on the loaded route is 62.98 liters/hour, while on the unloaded route, it is 41.66 liters/hour. The results of this calculation are then used to estimate actual fuel consumption based on the travel time of the hauler.

2. Fuel Consumption (liters/rit)
   Articulated CAT 745 fuel consumption calculations are carried out to estimate the amount of fuel used per drive for each segment. The results of actual fuel consumption calculations can be seen in Table 13.

Table 9. Results of theoretical fuel consumption calculations

Loaded Route		Unloaded Route	
Road Segment	Fuel Consumption (liters/hour)	Road Segment	Fuel Consumption (liters/hour)
A-B	56.37	L-K	42.77
B-C	57.73	K-J	43.94
C-D	75.10	J-I	46.99
D-E	87.18	I-H	42.83
E-F	52.86	H-G	41.36
F-G	56.57	G-F'	42.85
G-H	56.09	F'-E	41.36
H-I	55.16	E-D	28.78
I-J	78.08	D-C	44.19
J-K	56.32	C-B	40.69
K-L	61.28	B-A	42.52
Average	62.98		41.66

Table 11. Results of actual fuel consumption calculations

Loaded Route			Unloaded Route		
Road Segment	Average Cycle Time (Seconds)	Fuel Consumption (Liters/Rit)	Road Segment	Average Cycle Time (Seconds)	Fuel Consumption (Liters/Rit)
A-B	35.59	0.62	L-K	28.04	0.32
B-C	30.48	0.53	K-J	36.80	0.43
C-D	93.93	1.64	J-I	75.32	0.87
D-E	22.54	0.39	I-H	27.36	0.32
E-F	25.18	0.44	H-G	17.30	0.20
F-G	16.51	0.29	G-F'	14.44	0.17
G-H	25.85	0.45	F'-E	18.49	0.21
H-I	19.99	0.35	E-D	32.79	0.38
I-J	75.54	1.32	D-C	93.15	1.08
J-K	47.03	0.82	C-B	32.25	0.37
K-L	21.82	0.38	B-A	43.24	0.50
Amount		7.25			4.85
		12.10			

The total fuel consumption of the Articulated CAT 745 on all haulage road segments during the load route and unloaded route for one hour is as follows.

$$\text{Fuel consumption} = 12.10\ (\text{liters/rit}) \times 3.23\ (\text{rit/hour}) = 39.03\ \text{liters/hour} \tag{15}$$

The condition of the hauler at idle time is around 10% of the total demand when the hauler is running [13], so the total fuel consumption of the Articulated CAT 745 is as follows.

$$\text{Total fuel consumption} = 39.03\ \text{liters/hour} + 39.03 \times 10\%) = 42.93\ \text{liters/hour} \tag{16}$$

So, the total fuel consumption of the Articulated CAT 745 on the load route and unloaded route is 42.93 liters/hour.

3.6. Actual fuel ratio

Fuel ratio is the amount of fuel (liters) released to obtain 1 BCM of overburden [14]. Factors that influence the fuel ratio value are fuel consumption (liters/hour) and equipment productivity (bcm/hour). The total productivity for one unit of Articulated CAT 745 is 23.22 LCM/hour, and the total fuel consumption used is 42.93 liters/hour, so the fuel ratio of the Articulated CAT 745 hauler is as follows.

Table 10. PT Hillconjaya Sakti standard fuel ratio

Performance Level	RF value
Low Performance	> 1.19
Average	1.00 – 1.19
Best Performance	< 1.00

$$\text{Fuel ratio} = \frac{42.93\ \text{liters/hour}}{23.22\ \text{LCM/hour}} = 1.85\ \text{liters/LCM} \tag{17}$$

The fuel ratio obtained is 1.85 liters/LCM, which is included in the low-performance category based on the standard fuel ratio value set by PT Hillconjaya Sakti in Table 14.

PT Hillconjaya Sakti can meet the standard fuel ratio values set by reducing fuel consumption and increasing the productivity of transportation equipment. The solution to reduce fuel consumption and increase productivity is to evaluate the condition of the haul roads used in overburden hauling activities at the Makale Pit.

3.7. Multiple linear regression analysis

Multiple linear regression analysis is a linear relationship between two or more independent variables and the dependent variable. This analysis is to measure the intensity of the relationship between two or more and make an approximate prediction of the value of Y over predict two or more predictor variables against the criterion variable. Equation 18 is a multiple linear regression equation [7].

$$Y = a + b_1X_1 + b_2X_2 + \cdots b_nX_n \tag{18}$$

where,
Y = dependent variable
X = independent variable
a = constant
b = independent variable regression coefficient

Prediction of fuel consumption on mining transportation equipment using the multiple regression method [15]. Classical assumptions are important for applying multiple regression, such as the assumptions of linearity, normality, non-multicollinearity, and homoscedasticity; if none of the assumptions are met, then the resulting output will be bad from the multiple regression variables [16].

Multiple regression variables I and multiple regression II are presented in Table 15, Table 16, Table 17, and Table 18.

The independent variables in multiple linear regression I are road grade (X1) and total resistance (X2) and the independent variables in multiple linear regression II are travel time (X1) and speed (X2). The dependent variable in this analysis is the fuel ratio (Y). Multiple regression analysis I and multiple regression II are differentiated based on the value of the independent variable which is fixed and can change under the same conditions. Road grade and total resistance are variables with fixed values under the same conditions used as independent variables in multiple regression I. Travel time and speed are variables with values that can change under the same conditions used as independent variables in multiple linear regression II.

Table 12. Multiple linear regression variable I on loaded routes

Theoretical Fuel (Y)	Grade (X_1)	Total Resistance (X_2)
56.37	0.37	16256.15
57.73	2.93	17038.73
75.10	13.38	29848.72
87.18	6.54	28123.43
52.86	7.39	18059.46
56.57	5.12	15201.68
56.09	9.20	18099.71
55.16	6.71	14397.92
78.08	14.57	26282.60
56.32	9.98	18204.19
61.28	10.17	20838.73

Table 13. Multiple linear regression variable I on unloaded routes

Theoretical Fuel (Y)	Grade (X_1)	Total Resistance (X_2)
42.77	10.17	7096.01
43.94	9.98	6628.36
46.99	14.57	9012.84
42.83	6.71	3456.87
41.36	9.20	5453.67
42.85	10.14	6795.88
41.36	3.48	1455.20
28.78	6.54	4925.56
44.19	13.38	6738.11
40.69	2.93	2182.11
42.52	0.37	6981.74

Table 14. Multiple linear regression variable II on loaded routes

Actual Fuel (Y)	Traveling time (X_1)	Speed (X_2)
0.62	35.59	1.73
0.53	30.48	2.41
1.64	93.93	0.61
0.39	22.54	2.28
0.44	25.18	7.94
0.29	16.51	4.73
0.45	25.85	3.84
0.35	19.99	8.75
1.32	75.54	1.28
0.82	47.03	1.46
0.38	21.82	0.69

Table 15. Multiple linear regression variable II on unloaded routes

Actual Fuel (Y)	Traveling time (X_1)	Speed (X_2)
0.32	28.04	0.53
0.43	36.80	1.87
0.87	75.32	1.29
0.32	27.36	6.39
0.20	17.30	5.74
0.17	14.44	9.69
0.21	18.49	7.79
0.38	32.79	1.57
1.08	93.15	0.61
0.37	32.25	2.28
0.50	43.24	1.42

1. Classic assumption test

   The classical assumption test must be fulfilled as a condition for multiple linear regression, namely that there is no heteroscedasticity and no multicollinearity, and it is normally distributed [17].

   a. Normality test

      The normality test aims to determine whether or not there is a normal distribution of residual values for the dependent variable and independent variables. Normality test results above α (0.05) support H0, which means the residuals are distributed normally and the assumptions are met.

      1) Multiple linear regression I

         a) Loaded route

            The test result has a sig value of 0.712646, which means the value is greater than 0.05, so it is concluded that the residual is normally distributed or passes the normality test.

         b) Unloaded route

            The test result has a sig value of 0.000009, which means the value is smaller than 0.05, so it can be concluded that the residuals are not normally distributed or do not pass the normality test. Data that is not normally distributed can be overcome using detection and eliminating outliers [16]. The test results have a sig value of 0.954511, which means the value is greater than 0.05, so it is concluded that the residuals are normally distributed or pass the normality test.

      2) Multiple linear regression II

         a) Loaded route

            The sig value test result is 0.796351, which means the value is greater than 0.05, so it is concluded that the residual is normally distributed or passes the normality test.

         b) Unloaded route

            The sig value test result is 0.882869, which means the value is greater than 0.05, so it is concluded that the residual is normally distributed or passes the normality test.

   b. Heteroscedasticity test

      The heteroscedasticity test was carried out to determine any deviations from the classical assumption requirements in the regression model. The regression model must meet the requirements, namely the absence of heteroscedasticity in the data used. One way to detect heteroscedasticity is if the independent variable significantly influences the dependent variable with a significance level below 5%.

      1) Multiple linear regression I

         a) Loaded route

            The sig value test result (Prob. Chi-Square on Obs*R-squared) is 0.0908, which means the value is greater than 0.05 so it is concluded that heteroscedasticity does not occur.

         b) Unloaded route

            The sig value test result (Prob. Chi-Square on Obs*R-squared) is 0.3741, which means the value is greater than 0.05 so it is concluded that heteroscedasticity does not occur.

      2) Multiple linear regression II

         a) Loaded route

            The test results show that the sig value (Prob. Chi-Square on Obs*R-squared) is 0.3773, which means the value is greater than 0.05 so it can be concluded that heteroscedasticity does not occur.

         b) Unloaded route

The test results show that the sig value (Prob. Chi-Square on Obs*R-squared) is 0.7418, which means the value is greater than 0.05 so it can be concluded that heteroscedasticity does not occur.

c. Multicollinearity test

The multicollinearity test occurs if the independent variables are strongly correlated with other independent variables.

1) Multiple linear regression I

a) Loaded route

The test results show that the variance inflation factor (VIF) value of the grade and total resistance is 1.676174, respectively, which means the value is less than 10, so it can be concluded that there is no multicollinearity.

b) Unloaded route

The test results show that the variance inflation factor (VIF) value of the road grade and total resistance is 1.706051 and 1.699240, respectively, which means the value is less than 10, so it is concluded that there is no multicollinearity.

2) Multiple linear regression II

a) Loaded route

The test results show that the variance inflation factor (VIF) value of the travel time and speed is 1.377563, respectively, which means the value is less than 10, so it can be concluded that there is no multicollinearity.

b) Unloaded route

The test results show that the variance inflation factor (VIF) value of the travel time and speed is 1.695555, respectively, which means the value is less than 10, so it is concluded that there is no multicollinearity.

2. Multiple linear regression model

The multiple linear regression equation model was obtained based on the coefficient values resulting from the analysis. The equation model consists of equations on the load and unloaded routes from each multiple regression I and multiple regression II.

a. Multiple linear regression I

1) Loaded route

Based on the results of multiple linear regression the model Equation 20 for the load route is obtained as follows:

$$Y = 21.98070 - 0.633917\ X_1 + 0.002274\ X_2$$

2) Unloaded route

The regression equation model for the unloaded route can be shown as follows:

$$Y = 39.58199 + 0.159428\ X_1 + 0.000372\ X_2$$

b. Multiple linear regression II

1) Loaded route

The results of multiple linear regression obtained the equation as follows.

$$Y = -0.003220 + 0.017495\ X_1 + 0.000400\ X_2$$

2) Unloaded route

Based on the results of multiple linear regression, the equation model for the unloaded route is:

$$Y = -0.003355 + 0.011620\ X_1 + 0.000409\ X_2$$

3. Significance test

The significance test in multiple linear regression consists of a simultaneous test, partial test, and coefficient of determination.

a. Simultaneous test (f-test)

The simultaneous test (F-test) aims to find out whether the independent variables (X_1 and X_2) together (simultaneously) significantly influence the dependent variable (Y).

1) Multiple linear regression I

a) Loaded route

The results of multiple linear regression estimation on loaded routes have test results that show a prob value (F-statistic) of 0.000291, which is smaller than 0.05 so that the independent variables simultaneously have a significant effect on the dependent variable.

b) Unloaded route

The results of multiple linear regression estimation on the unload route have test results that show a prob value (F-statistic) of 0.000041, which is smaller than 0.05 so that the independent variables simultaneously have a significant effect on the dependent variable.

2) Multiple linear regression II

a) Loaded route

The results of the multiple linear regression estimation on the loaded route have test results that show a prob value (F-statistic) value of 0.000000 is smaller than 0.05 so that the independent variable simultaneously has a significant effect on the dependent variable.

b) Unloaded route

The results of multiple linear regression estimates on unloaded routes have test results that show a prob value (F-statistic) value of 0.000000 is smaller than 0.05 so that the independent variables simultaneously have a significant effect on the dependent variable.

b. Partial test (t-test)

The partial test (t-test) aims to determine the effect of each independent variable individually on the dependent variable.

1) Multiple linear regression I

a) Loaded route

Based on the results of multiple linear regression estimates on loaded routes, the following results are obtained.

- Prob value. on the road grade variable (X_1) of 0.1984 is greater than the significance level of 0.05. This indicates that the road grade variable (X_1) has no significant effect on fuel consumption (Y).

- Prob value. the total resistance variable (X_2) of 0.0002, it is smaller than the significance level of 0.05; this shows that the total resistance variable (X_2) has a significant effect on fuel consumption (Y).

b) Unloaded Route

The results of multiple linear regression estimates on the unloaded route are:

- Prob value. on the road grade variable (X_1) of 0.1835, which is greater than the significance level of 0.05; this shows that the road grade variable (X_1) has no significant effect on fuel consumption (Y).
- Prob value. on the total resistance variable (X_2) of 0.1135, which is greater than the significance level of 0.05; this shows that the total resistance variable (X_2) has no significant effect on fuel consumption (Y).

2) Multiple linear regression II

a) Loaded route

Estimation results of multiple linear regression on loaded routes obtain:

- Prob value. in the travel time variable (X_1) of 0.0000 is smaller than the significance level of 0.05, this indicates that the travel time variable (X_1) has a significant effect on fuel consumption (Y).
- Prob value. on the speed variable (X_2) of 0.0554, which is greater than the significance level of 0.05; this indicates that the speed variable (X_2) has no significant effect on fuel consumption (Y).

b) Unloaded route

The results based on multiple linear regression estimates on the unloaded route are:

- Prob value. in the travel time variable (X_1) of 0.0000 is smaller than the significance level of 0.05, this indicates that the travel time variable (X_1) has a significant effect on fuel consumption (Y).
- Prob value. on the speed variable (X_2) of 0.3377, which is greater than the significance level of 0.05; this shows that the speed variable (X_2) has no significant effect on fuel consumption (Y).

c. Coefficient of determination

The coefficient of determination explains the variation in the influence of the independent variables on the dependent variable or can also be said to be the proportion of the influence of all independent variables on the dependent variable. The value of the coefficient of determination of multiple linear regression can be measured by the Adjusted R-Square value, namely when the number of independent variables is more than one [18].

1) Multiple linear regression I

a) Loaded route

It is found from the loaded route equation that the correlation coefficient (Adjusted R-Square) was 0.836677 or had a contribution effect of 83.6677% on fuel consumption and the other 16.3323% was influenced by other factors but not included in the calculation. So, the grade of the road (X_1) and total resistance (X_2) strongly influence the increase in fuel consumption.

b) Unloaded route

Based on the estimation results in the multiple linear regression model on the unloaded route, the correlation coefficient (Adjusted R-Square) value is 0.937048 or has a contribution effect of 93.7048% on fuel consumption, and other factors influence the other 6.2952% but not included in the calculation. The grade of the road (X_1) and total resistance (X_2) have a very high influence on the increase in fuel consumption.

2) Multiple linear regression II

a) Loaded route

Based on the estimation results in the multiple linear regression model on the loaded route, it is known that the correlation coefficient (Adjusted R-Square) was 0.999990 or had a contribution effect of 99.9990% on fuel consumption, and other factors influenced the other 0.001% but not included in the calculation. Thus, travel time (X_1) and speed (X_2) have a very high influence on the increase in fuel consumption.

b) Unloaded route

The estimation results in the multiple linear regression model on unloaded routes show that the correlation coefficient (Adjusted R-Square) was 0.999879 or had a contribution effect of 99.9904% on fuel consumption and other factors influenced the other 0.0096% but not included in the calculation. Thus, travel time (X_1) and speed (X_2) have a very high influence on the increase in fuel consumption.

The variables that significantly affect fuel consumption are total resistance (on the loaded route) and travel time (on the unloaded route). The effect of total resistance and travel time on fuel consumption has a positive relationship where the lower the value of these parameters, the lower the fuel consumption.

3.8. Road geometry improvement plan

The parameters that have a significant effect on fuel consumption are total resistance and speed. The plan to improve the haul road's geometry regarding the haul road's width and the road's grade, respectively, can be shown in Table 19 and Table 20.

Evaluation of the haul road geometry is carried out on the width of the haul road following the minimum road width based on the Articulated CAT 745 specifications. The width of the road must match the dimensions of the equipment used by PT Hillconjaya Sakti so that the hauler can move freely and safely, increasing the speed of transportation equipment and avoiding delays. In this way, the cycle time of the hauler will decrease, thereby reducing fuel consumption and increasing the productivity of the Articulated CAT 745.

Table 17. Results of the plan to improve the width of the haul road

Freight Road Segment	Width (m)		Freight Road Segment	Width (m)	
	Straight ahead	Bend		Straight ahead	Bend
A-B	13.30	21.45	L-K	13.30	-
B-C	13.30	21.45	K-J	16.92	-
C-D	13.30	21.45	J-I	13.30	21.45
D-E	13.30	21.45	I-H	13.30	-
E-F	7.60	12.26	H-G	13.30	21.45
F-G	7.60	12.26	G-F'	9.80	12.26
G-H	13.30	21.45	F'-E	7.60	21.45
H-I	13.30	-	E-D	13.30	21.45
I-J	13.30	21.45	D-C	13.30	21.45
J-K	16.92	-	C-B	13.30	21.45
K-L	13.30	-	B-A	13.30	21.45

Table 18. Results of the plan to improve the grade of the haul road

Freight Road Segment	Grade (%)	Unloaded Road Segment	Grade (%)
A-B	-0.37	L-K	-10.00
B-C	2.93	K-J	-9.00
C-D	12.00	J-I	-12.00
D-E	6.54	I-H	-6.71
E-F	7.39	H-G	-8.00
F-G	5.12	G-F'	-10.00
G-H	8.00	F'-E	-3.48
H-I	6.71	E-D	-6.54
I-J	1.00	D-C	-12.00
J-K	9.00	C-B	-2.93
K-L	10.00	B-A	0.37

The haul road geometry evaluation plan carried out is that the haul road grade that exceeds the standard is evaluated based on Ministerial Decree No. 1827/K/30/MEN/2018 standards to reduce the grade resistance value. Maintaining the condition of haul road materials, such as adding soil hardening material to prevent tire subsidence, thereby reducing the rolling resistance value. Reducing the rolling resistance and tilt resistance values will directly reduce the total resistance as a parameter, significantly affecting fuel consumption.

3.5 Fuel ratio results recommendations for improvement

The fuel consumption calculation (liters/hour) is based on the load factor obtained from the haul road geometry improvement plan results. The results of the calculation of liter/hour fuel consumption are shown in Table 21.

Calculation of fuel consumption as an example of the A-B segment is:

Table 16. Results of fuel consumption calculations (liters/hour) based on the haul road geometry improvement plan

Loaded Route		Unloaded Route	
Road Segment	Fuel Consumption (liters/hour)	Road Segment	Fuel Consumption (liters/hour)
A-B	57.81	L-K	43.06
B-C	58.81	K-J	42.22
C-D	72.55	J-I	43.05
D-E	72.74	I-H	42.83
E-F	56.35	H-G	45.11
F-G	56.21	G-F'	44.06
G-H	58.03	F'-E	41.36
H-I	55.16	E-D	41.99
I-J	64.87	D-C	41.75
J-K	58.55	C-B	42.16
K-L	61.26	B-A	43.11
Average	61.12		42.79

$$\text{Fuel consumption} = \frac{33.82 \text{ sec/rit}}{3.600 \text{ sec/h}} \times 61.12 \text{ liters/hour} = 0.57 \text{ liters/rit} \quad (19)$$

The fuel consumption (liters/rit) of each segment can be seen in Table 22.

The total fuel consumption of the Articulated CAT 745 on all haulage road segments during the load route and unloaded route for one hour is as follows:

$$\text{Fuel consumption (liters/hour)} = 10.86 \text{ (liters/rit)} \times 3.48 \text{ (rit/hour)} = 37.76 \text{ liters/hour} \quad (20)$$

The condition of the hauler at the idle time is around 10% of the total demand when the hauler is running [12], so the total fuel consumption of the Articulated CAT 745 is:

$$\text{Total fuel consumption (liters/hour)} = 37.76 + (37.76 \times 10\%) = 41.54 \text{ liters/hour} \quad (21)$$

So, the total fuel consumption of the Articulated CAT 745 on the loaded and unloaded routes is 41.54 liters/hour. The total fuel consumption of the Articulated CAT 745 on the loaded and unloaded routes is 40.28 liters/hour, so the fuel ratio value resulting from recommendations for improving the haul road geometry is as follows.

$$\text{Fuel ratio} = \frac{41.54 \text{ liters/hour}}{25.03 \text{ LCM/hour}} = 0.60 \text{ liters/LCM} \quad (22)$$

Table 19. Results of actual fuel consumption calculations

Loaded Route			Unloaded Route		
Road Segment	Average Cycle Time (Seconds)	Fuel Consumption (Liters/Rit)	Road Segment	Average Cycle Time (Seconds)	Fuel Consumption (Liters/Rit)
A-B	33.82	0.57	L-K	27.74	0.33
B-C	30.06	0.51	K-J	36.80	0.44
C-D	93.93	1.59	J-I	73.61	0.87
D-E	22.54	0.38	I-H	18.40	0.22
E-F	15.03	0.26	H-G	16.56	0.20
F-G	13.15	0.22	G-F'	12.88	0.15
G-H	16.91	0.29	F'-E	14.72	0.17
H-I	18.79	0.32	E-D	22.08	0.26
I-J	75.14	1.28	D-C	92.01	1.09
J-K	37.57	0.64	C-B	29.44	0.35
K-L	18.79	0.32	B-A	33.12	0.39
Amount		6.38			4.49
			10.86		

The fuel ratio is influenced by two factors, namely, the amount of fuel consumed and the productivity of the tool. The lower the fuel consumption and the greater the productivity of the tool achieved, the lower the fuel ratio value will be. The optimum fuel ratio value is the target to achieve large profits. The optimum fuel ratio obtained based on road repair recommendations is 0.60 liters/LCM. These results have met the standard fuel ratio value expected by PT Hillconjaya Sakti (<1.00 liters/LCM) because it is in the best performance category. The decrease from the actual fuel ratio value was 1.25 liters/LCM.

4. Conclusions

The parameters that significantly affect the fuel consumption of Articulated CAT 745 are total resistance and travel time. Total resistance affects fuel consumption with a probability value (p-value) of 0.0002, and travel time affects fuel consumption at a p-value of 0.0000. Both total resistance and travel time significantly affect fuel consumption because their p-values are much smaller than 0.05. Travel time has the strongest effect, as indicated by the small p-value (close to 0). These results suggest that optimizing travel time and managing total resistance can effectively reduce fuel consumption in the Articulated CAT 745. The estimated optimum of fuel ratio obtained based on the haul road geometry improvement plan is 0.60 liters/LCM.

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