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Geometric Redesign and Cut-and-Fill Volume Estimation of a Non-Compliant Mine Haul Road at Pit Banko Tengah A, South Sumatra

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ABSTRACT

Mine haul roads must satisfy geometric standards to ensure safe and reliable heavy-equipment mobilization. This study evaluated the inactive Tesla haul road at Pit Banko Tengah A, South Sumatra, for reactivation using Komatsu HD-785 rigid dump trucks. Existing road geometry was assessed against operational standards, followed by 3D spatial redesign and cut-and-fill volume estimation in hilly terrain. The results showed that several straight segments require widening, with the largest correction reaching 7.93 m to meet the 24 m standard. Segment 5 also requires curve widening and superelevation correction, with actual superelevation of 0.064 m compared with the 1.223 m design requirement. Road grades remained within the 8% maximum limit. The redesign produced an excavation-dominant earthwork profile, consisting of 203.92 BCM of cut and 9.79 BCM of fill. These findings provide a practical basis for planning haul-road reactivation while aligning geometric compliance with earthwork requirements.

Keywords
Mine haul road geometry; geometric compliance; cut-and-fill volume; 3D spatial redesign; Komatsu HD-785.

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INTRODUCTION

In open-pit mining operations, haul roads function as the main logistical corridor connecting mining fronts, disposal areas, stockpiles, and other operational facilities. Their geometric condition directly affects the safety, continuity, and efficiency of heavy-equipment movement. For this reason, haul-road design cannot be treated merely as an access-road provision, but must comply with technical standards that regulate width, grade, turning radius, superelevation, cross fall, drainage, and safety protection. In Indonesia, mine-road safety and infrastructure compliance are guided by the Decree of the Minister of Energy and Mineral Resources No. 1827 K/30/MEM/2018, which provides the technical basis for implementing good mining engineering practices [1]. From an engineering perspective, haul-road design must also consider the interaction between road geometry, vehicle dimensions, rolling resistance, surface condition, and operational maintenance because these factors determine whether large haulage units can operate safely and consistently under mine-site conditions [2].

Pit Banko Tengah A, located in Muara Enim Regency, South Sumatra, contains an inactive haul road known as the Tesla road. This route is planned for reactivation to support overburden transportation using Komatsu HD-785 rigid dump trucks. Because the HD-785 is a large-capacity hauling unit, its operating width, turning requirement, and maneuvering clearance must become the basis for determining the minimum safe road geometry [3]. Preliminary observations indicate that the existing effective width of the Tesla road is approximately 16 m, which is below the 24 m minimum standard required for two-way HD-785 traffic at the site. Similar haul-road evaluations have shown that inadequate road width, poor curvature, and insufficient safety clearances can reduce operational safety and limit the reliability of hauling activities, particularly when large equipment operates on constrained road sections [4].

Previous studies have demonstrated that haul-road geometry is closely related to mine transportation performance. Road slope and total resistance have been linked to dump-truck fuel consumption, indicating that geometric deficiencies may increase the energy demand of hauling operations [5]. Other studies have reported that road-width and grade improvements can support the productivity of hauling equipment by reducing operational constraints along transport routes [6]. Beyond conventional field measurement, recent advances in remote sensing and digital monitoring have enabled more accurate mine-road assessment using unmanned aerial vehicles and deep-learning approaches [7]. Road-surface performance must also be considered because seasonal moisture variation can weaken stabilized mine haul roads and influence their bearing and service conditions [8]. In addition, geotechnical conditions around mine roads remain important because slope instability near road infrastructure may affect safety, access continuity, and the long-term reliability of the mining operation [9].

Although these studies provide important insights into haul-road geometry, productivity, monitoring, and stability, many of them still examine each component separately. Research on mine planning and scheduling has emphasized the importance of computer-based pit design, production sequence control, and operational planning [10]. More recent work has also integrated production scheduling with haulage-route planning in open-pit mines, showing that transportation routes are increasingly being treated as part of the broader mine-planning system [11]. A related MOTIVECTION study on mining-sequence compliance in South Sumatra also highlights that discrepancies between planned and actual field execution may be influenced by operational delays, equipment availability, weather, and haul-road geometry, thereby reinforcing the need to connect road design with production readiness [12]. However, a specific gap remains in the integration between geometric compliance redesign and the volumetric consequences of cut-and-fill work. In many cases, geometric studies identify non-compliant widths, grades, or curves, while earthwork studies estimate material volumes without explicitly linking those volumes to the correction of non-compliant haul-road parameters for a specific hauling fleet.

This study addresses that gap by integrating geometric compliance evaluation, equipment-specific haul-road redesign, and 3D cut-and-fill volume estimation for the reactivation of the Tesla haul road at Pit Banko Tengah A. The novelty of the study lies in its case-based integration of road-geometry correction with spatial earthwork quantification in hilly mine terrain. Rather than claiming direct improvement in productivity or fuel efficiency, this study provides a technical planning basis for determining which road sections require geometric correction and how much excavation and fill are needed to implement the proposed redesign. Therefore, this study aims to evaluate the existing haul-road geometry, formulate a compliant 3D redesign based on the operational requirements of Komatsu HD-785 units, and quantify the cut-and-fill volumes required to support road reactivation planning at Pit Banko Tengah A, South Sumatra.

METHOD

Study Area

This study was conducted at Pit Banko Tengah A, Tanjung Agung, Muara Enim Regency, South Sumatra. The research object was an approximately 1-km segment of the existing Tesla haul road, which is planned to be reactivated for overburden transportation using Komatsu HD-785 rigid dump trucks. Field data collection and topographical observation were conducted in March 2026. The location map in Figure 1 presents the spatial position of the research area, the observation point at Pit Banko Tengah A, the map scale, and the surrounding mining landscape used as the basis for defining the study boundary.

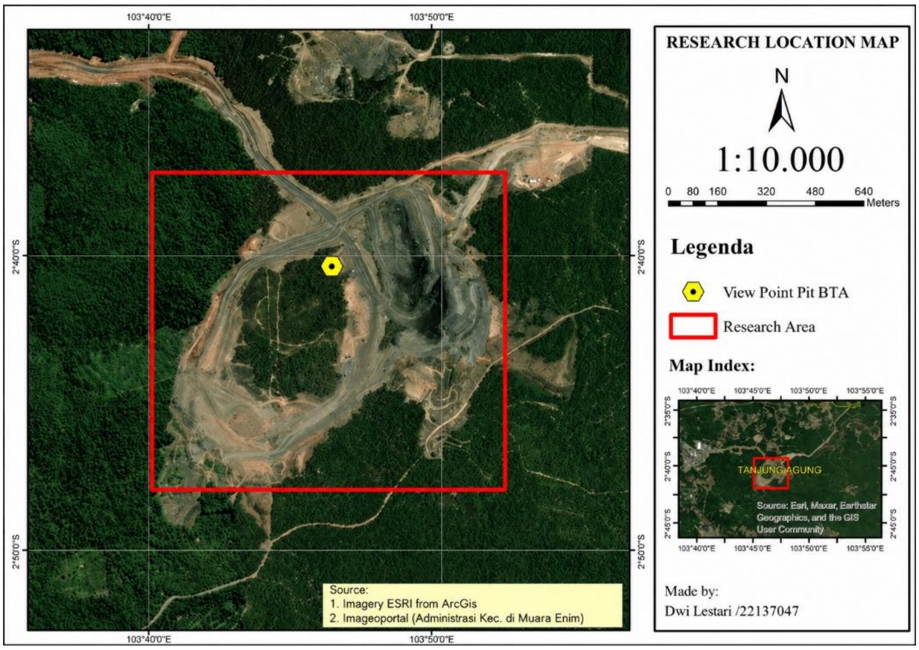

Figure 1. Research location map of Pit Banko Tengah A, South Sumatra.

Data Collection

This study used a technical-descriptive engineering approach by combining primary field data and secondary operational data. The primary data consisted of high-resolution orthophoto imagery and field observations of the existing Tesla haul road. Orthophoto-based spatial data were used to extract road alignment, identify existing geometric conditions, and support the delineation of the road segments evaluated in this study. The use of image-based spatial reconstruction and orthophoto interpretation requires careful ground control and field validation to reduce geometric distortion and improve positional reliability [13], [14]. Therefore, the spatial data were validated against established Ground Control Points (GCPs) using engineering design software and were cross-checked through direct ground-truthing in the field.

Secondary data were obtained from the company's engineering records. These data included topographic contour data, hauling equipment specifications, company road-geometry standards, and planned hauling speed. The topographic data were used to generate the terrain basis for road-grade calculation and cut-and-fill volume estimation. The Komatsu HD-785 specifications were used to determine the geometric design requirements because the largest operating equipment must be used as the controlling design vehicle in haul-road planning [2], [3]. The planned hauling speed was used in the calculation of turning radius and superelevation. The integration of terrain data, equipment specifications, and route planning is consistent with open-pit mine planning practice, where haulage-route design must be connected to operational feasibility and spatial constraints [11], [15].

Research Variables and Design Standards

The research variables were determined based on mine haul-road geometric parameters and cut-and-fill volume requirements. The evaluated variables consisted of straight road width, curve road width, turning radius, superelevation, road grade, cross fall, safety berm dimensions, and cut-and-fill volume. The evaluation was conducted by comparing the existing field geometry with the applicable technical standards, including the Decree of the Minister of Energy and Mineral Resources No. 1827 K/30/MEM/2018, AASHTO-based geometric design principles, company standard operating procedures, and the Indonesian National Standard for mine-road safety berms [1], [16], [17]. These standards were used as the technical basis for determining whether each road segment complied with the required operational geometry for Komatsu HD-785 movement.

Straight Road Width

The minimum width of a straight haul-road segment was calculated based on the number of lanes and the width of the hauling equipment. This calculation ensures that the road provides sufficient travel width and lateral clearance for two-way hauling operations. The minimum straight road width was calculated using Equation (1).

$$L_{\min} = (n \times W_t) + (n + 1)\left(\frac{1}{2} \times W_t\right) \quad (1)$$

where L_{min} is the minimum straight haul-road width (m), n is the number of traffic lanes, and W_t is the width of the hauling equipment (m). The calculated value was then compared with the company's minimum operational standard to identify road segments requiring widening.

Curve Road Width

Curve segments require a wider road width than straight segments because haul trucks need additional space during turning maneuvers. For two-way operation, the curve width must account for wheel track width, front overhang, rear overhang, lateral clearance between passing units, and edge clearance from the road boundaries. The required curve road width was calculated using Equations (2)–(6).

$$W_{\min} = n(U + F_a + F_b + Z) + C \quad (2)$$

$$F_a = A_d \sin\alpha \quad (3)$$

$$F_b = A_b \sin\alpha \quad (4)$$

$$C = Z = \frac{1}{2}(U + F_a + F_b) \quad (5)$$

$$\sin\alpha = \frac{W_b}{R} \quad (6)$$

where W_{min} is the minimum curve road width (m), U is the wheel track width (m), n is the number of lanes, F_a is the front overhang width during turning (m), F_b is the rear overhang width during turning (m), A_d is the distance from the front wheel to the front bumper (m), A_b is the distance from the rear wheel to the rear bumper (m), Z is the edge clearance (m), C is the lateral clearance between passing haulage units (m), α is the front-wheel steering angle (°), W_b is the wheelbase or distance between the front and rear wheels (m), and R is the turning radius (m). The calculated curve width was used to determine whether each curve segment was adequate for safe Komatsu HD-785 maneuvering.

Turning Radius and Friction Coefficient

Turning radius was evaluated to ensure that the haul road curve geometry could accommodate the turning movement of the design vehicle at the planned speed. In haul-road design, turning radius must be considered together with operating speed, friction, and superelevation because these parameters influence vehicle stability during cornering [2], [16]. The minimum turning radius was calculated using Equation (7).

$$R_{\min} = \frac{v^2}{127(e_m+f)} \tag{7}$$

where R_{min} is the minimum turning radius (m), v is the design speed of the hauling equipment (km/h), e_m is the maximum allowable superelevation, and f is the coefficient of friction between the tire and road surface. The coefficient of friction was determined based on the design speed using Equations (8) and (9).

$$f = (-0.00065 \times v) + 0.192, \quad v < 80 \text{ km/h} \tag{8}$$

$$f = (-0.00125 \times v) + 0.240, \quad v > 80 \text{ km/h} \tag{9}$$

The calculated R_min was used as the geometric constraint for evaluating curve adequacy and determining the corresponding superelevation requirement.

Superelevation

Superelevation is the transverse slope provided on a curve by raising the outer road edge relative to the inner edge. This geometric feature helps counterbalance lateral forces acting on a vehicle during turning and supports safer maneuvering on curved haul-road sections [2], [16]. In this study, the required superelevation was determined based on curve radius, design speed, friction coefficient, and the maximum allowable superelevation. The superelevation-related parameters were calculated using Equations (10)–(12).

$$e_{\min} = \left(\frac{D}{D_m}\right) \times e_m \tag{10}$$

$$D = \left(\frac{25}{2\pi R}\right) \times 360^\circ \tag{11}$$

$$D_m = \frac{181913.53(e_m+f)}{v^2} \tag{12}$$

where e_{min} is the minimum superelevation (%), e_m is the maximum allowable superelevation (%), D is the degree of curvature (°), D_m is the maximum degree of curvature (°), R is the turning radius (m), f is the friction coefficient, and v is the design speed (km/h). After the required superelevation was obtained, the physical elevation difference between the inner and outer sides of the curve was determined using Equations (13) and (14).

$$\tan \alpha = e \tag{13}$$

$$a = W_c \times \sin \alpha \tag{14}$$

where α is the transverse slope angle, e is the superelevation value, a is the required elevation difference (m), and W_c is the curve road width (m). The calculated elevation difference was then compared with the actual elevation difference measured in the field to identify curve segments requiring elevation correction.

Road Grade

Road grade was evaluated to determine whether the longitudinal slope of the haul road remained within the allowable operating limit for Komatsu HD-785 units. Road grade is an important design parameter because excessive gradients may affect braking performance during descent and tractive effort during ascent [2]. In this study, road grade was calculated from the elevation difference and horizontal distance between two measured points using Equation (15).

$$\text{Grade} = \left(\frac{\Delta h}{\Delta x}\right) \times 100\% \tag{15}$$

where Δh is the elevation difference between two measured points (m), and Δx is the horizontal distance between those points (m). The calculated grade value was compared with the maximum allowable road-grade standard used at the site.

Cross Fall

Cross fall was evaluated to determine whether the transverse slope of the road surface was sufficient to support surface-water runoff. In mine haul-road design, an appropriate cross fall helps direct water from the carriageway toward the drainage side and reduces the potential for water accumulation on the road surface [2]. The cross-fall geometry was assessed using the relationship between road width and the required vertical elevation difference, as shown in Equations (16) and (17).

$$a = \frac{1}{2} \times L \tag{16}$$

$$b = a \times 40 \text{ mm/m} \tag{17}$$

where a is half of the total road width (m), L is the total road width (m), and b is the required vertical elevation difference based on the cross-fall standard. The calculated cross-fall requirement was compared with the actual elevation differences measured at the Right Edge, Centre Point, and Left Edge of each road segment.

Safety Berm

Safety berms were evaluated as protective embankments installed along mine haul roads to reduce the risk of vehicle departure from the road edge. The berm dimensions were calculated using the tire diameter of the largest hauling equipment and the assumed berm cross-section geometry. Referring to the Indonesian National Standard for mine-road safety berms, the required berm height and base width were calculated using Equations (18) and (19) [17].

$$t = \frac{3}{4} \times d_{\text{tyre}} \tag{18}$$

$$b = a + 2t \cot \alpha \tag{19}$$

where t is the safety-berm height (m), d_{tyre} is the tire diameter of the hauling equipment (m), b is the safety-berm base width (m), a is the safety-berm top width (m), and α is the berm side-slope angle (°). The calculated berm dimensions were used as part of the proposed haul-road redesign.

Cut-and-Fill Volume Estimation

Cut-and-fill volumes were estimated through 3D spatial modeling using mine planning software. The modeling process compared the existing topographic surface with the proposed haul-road design surface. This approach follows the principle of open-pit mine planning, where design surfaces, route geometry, and terrain conditions are integrated to quantify the amount of material that must be excavated or placed during infrastructure construction [15]. The calculation boundary was limited to the planned haul-road corridor, including the required road width, safety berm dimensions, and side-slope configuration. The resulting cut-and-fill values were used to determine the earthwork demand required to implement the proposed geometric redesign. Because the purpose of the analysis was to quantify material movement, the resulting volume should be interpreted as an earthwork planning estimate rather than direct evidence of operational productivity improvement.

Data Analysis Procedure

The overall research procedure is summarized in Figure 2. The workflow begins with literature study and field observation, followed by problem identification and data collection. The collected data were divided into primary and secondary data. Primary data were used to evaluate the existing road condition, while secondary data were used to define the geometric standards, topographic basis, hauling speed, and equipment specifications. These datasets were then integrated into two main analytical stages: Tesla roadworthiness analysis and design-based cut-and-fill volume estimation.

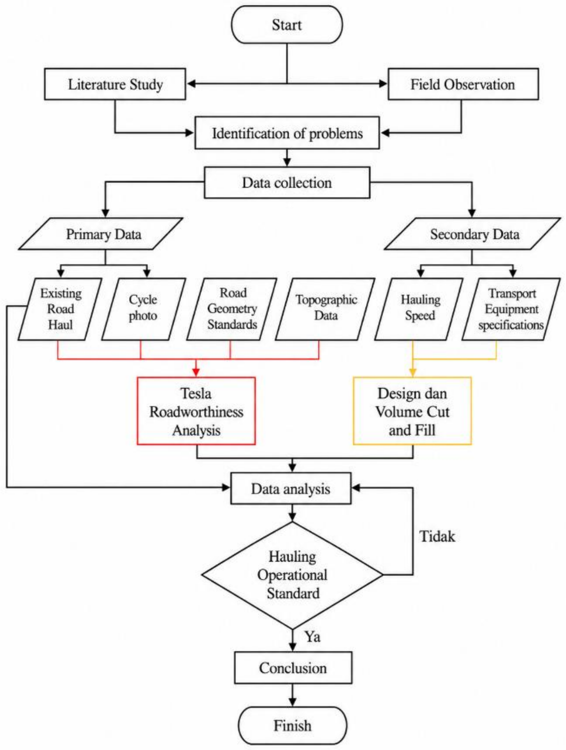

Figure 2. Research workflow for haul-road geometric evaluation and cut-and-fill volume estimation.

The data analysis was conducted chronologically in four stages. First, the orthophoto and field-observation data were processed to identify the existing road alignment and geometric conditions. Second, the extracted geometric parameters were compared with regulatory, technical, and company standards to determine compliant and non-compliant segments. Third, segments that did not meet the required standards were redesigned using engineering design and mine planning software. Fourth, the proposed design surface was intersected with the existing topographic surface to calculate the required cut-and-fill volumes. The final output of this procedure was a proposed 3D haul-road redesign based on the applicable geometric standards and a quantitative estimate of the earthwork volume required for road reactivation planning.

RESULTS AND DISCUSSION

Hauling Equipment Specifications

The hauling equipment used as the controlling design vehicle in this study was the Komatsu HD-785 rigid dump truck. The main dimensional parameters applied in the haul-road geometric calculations included an overall operating width (Wt) of 6.885 m, a front overhang of 1.075 m, a rear overhang of 1.595 m, and a minimum turning radius of 10.1 m. These dimensions were used to determine the required straight road width, curve road width, turning clearance, and geometric correction requirements for the Tesla haul road.

Straight Road Width

The required straight road width for the Tesla haul road was set at 24.0 m based on the operational standard for the design vehicle. Field measurements showed that the existing straight road widths varied across segments. As presented in Table 1, only Segment 2 met the required standard, while Segments 1, 3, 4, 6, and 7 required widening. The largest required widening was identified in Segment 1, with an additional width of 7.93 m.

Table 1. Existing and Required Straight Road Widths

No.	Segment	Width (m)	Standard (m)	Condition	Required Improvement (m)
1	1	16.07	24	Non-compliant	7.93
2	2	29.058	24	Compliant	—
3	3	20.633	24	Non-compliant	3.367
4	4	18.286	24	Non-compliant	5.714
5	6	21.637	24	Non-compliant	2.363
6	7	23.427	24	Non-compliant	0.573

Note : Segments 5 and 8 were evaluated separately as curve sections and are therefore not included in the straight-road width assessment.

Curve Road Width

The required curve road width was set at 25.0 m. The field measurement results in Table 2 show that Segment 5 had an existing curve width of 16.197 m, which did not meet the required standard and therefore required widening of 8.803 m. In contrast, Segment 8 had an existing width of 30.191 m and already met the required curve-road width standard.

Table 2. Existing and Required Curve Road Widths

No.	Segment	Width (m)	Standard (m)	Condition	Required Improvement (m)
1	5	16.197	25	Non-compliant	8.803
2	8	30.191	25	Compliant	—

Road Grade

The road-grade evaluation was conducted for eight road segments using the elevation difference and horizontal distance between the measured section points. As shown in Table 3, all evaluated road grades remained below the maximum allowable standard of 8%. The highest positive grade was recorded in Segment 1 at 4.687%, while the steepest negative grade was recorded in Segment 7 at -7.746%. Based on these values, no segment exceeded the allowable grade standard.

Table 3. Road Grade Evaluation Based on Start and End Point Coordinates

segment	Start Point (X, Y, Z)	End Point (X, Y, Z)	Δx (m)	Δh (m)	Grade (%)	Standard (%)	Condition
1	A (371054.907, 9575556.253, 115.000)	B (370791.757, 9575495.488, 102.341)	270.075	12.659	4.687	8	Compliant
2	B (370791.757, 9575495.488, 102.341)	C (370669.720, 9575436.284, 97.285)	135.64	5.056	3.728	8	Compliant
3	C (370669.720, 9575436.284, 97.285)	D (370598.338, 9575376.791, 95.000)	92.924	2.285	2.459	8	Compliant
4	D (370598.338, 9575376.791, 95.000)	E (370546.015, 9575331.935, 95.000)	68.918	0	0	8	Compliant
5	E (370546.015, 9575331.935, 95.000)	F (370493.109, 9575258.608, 93.000)	90.421	2	2.212	8	Compliant
6	F (370493.109, 9575258.608, 93.000)	G (370454.050, 9575147.993, 96.995)	117.308	-3.995	-3.406	8	Compliant
7	G (370454.050, 9575147.993, 96.995)	H (370371.938, 9575022.248, 108.628)	150.181	-11.633	-7.746	8	Compliant
8	H (370371.938, 9575022.248, 108.628)	I (370277.850, 9574969.645, 111.267)	107.794	-2.639	-2.448	8	Compliant

Note: Coordinates are presented as (X, Y, Z). The Δh value follows the elevation-difference convention used in the road-grade calculation.

Superelevation

The superelevation evaluation was conducted for the curve segments of the Tesla haul road. The required superelevation standard was 1.223 m for the planned design condition. As presented in Table 4, Segment 5 had an actual superelevation of 0.064 m and therefore required an additional elevation difference of 1.159 m. Segment 8 had an actual superelevation of 1.682 m and was categorized as compliant with the required standard.

Table 4. Superelevation Evaluation

No.	Segment	Width (m)	Δh (m)	Standard (m)	Condition	Required Δh Addition (m)
1	5	16.197	0.064	1.223	Non-compliant	1.159
2	8	30.191	1.682	1.223	Compliant	—

Cross Fall

Cross-fall evaluation was conducted by comparing the actual elevation differences at the Right Edge, Centre Point, and Left Edge of each segment with the required standard of 0.482 m. Table 5 shows that several measured points did not meet the required cross-fall condition. The largest required correction was recorded at Segment 2 on the Right Edge, where the actual elevation difference was -1.039 m and the required elevation addition was 1.521 m.

Table 5. Cross-Fall Evaluation Based on Road-Edge and Centre-Point Elevations

Segment	Elevation (m)	Point	Δh (m)	Standard (m)	Kondisi	Required Δh Addition (m)	Conclution
1	110	Right Edge	1	0.482	Standard	-	Non-Standard
	111	Centre Point				-	
	111	LE	0		Non-Standard	0.482	
2	100.31	Right Edge	-1.039	0.482	Non-Standard	1.521	Non-Standard
	99.271	Centre Point				-	
	99.943	Left Edge	-0.672		Non-Standard	1.154	
3	96.179	Right Edge	0.318	0.482	Non-Standard	0.164	Non-Standard
	96.497	Centre Point				-	
	96.686	Left Edge	-0.189		Non-Standard	0.671	
4	95	Right Edge	0	0.482	Non-Standard	0.482	Non-Standard
	95	Centre Point				-	
	95	Left Edge	0		Non-Standard	0.482	
6	94	Right Edge	-0.107	0.482	Non-Standard	0.589	Non-Standard
	93.893	Centre Point				-	
	93.794	Left Edge	0.099		Standard	-	
7	102.907	Right Edge	0.332	0.482	Non-Standard	0.150	Non-Standard
	103.239	Centre Point				-	
	103.754	Left Edge	-0.515		Non-Standard	0.997	

Safety Berm

The safety-berm calculation was based on the tire diameter of the Komatsu HD-785, which was 2.616 m. The calculation also used a berm top width of 1.0 m and a side-slope angle of 45°. Based on these parameters, the required safety-berm height was 1.962 m, while the required base width was 4.924 m. These dimensions were then incorporated into the proposed haul-road redesign.

Haul Road Design

The proposed haul-road redesign was developed based on the geometric correction requirements identified from the straight width, curve width, grade, superelevation, cross-fall, and safety-berm evaluations. Figure 3 presents the planned haul-road trajectory and segment delineation. The redesign divides the Tesla haul road into eight segments to support the evaluation of straight and curved sections and to provide the basis for subsequent cut-and-fill volume estimation.

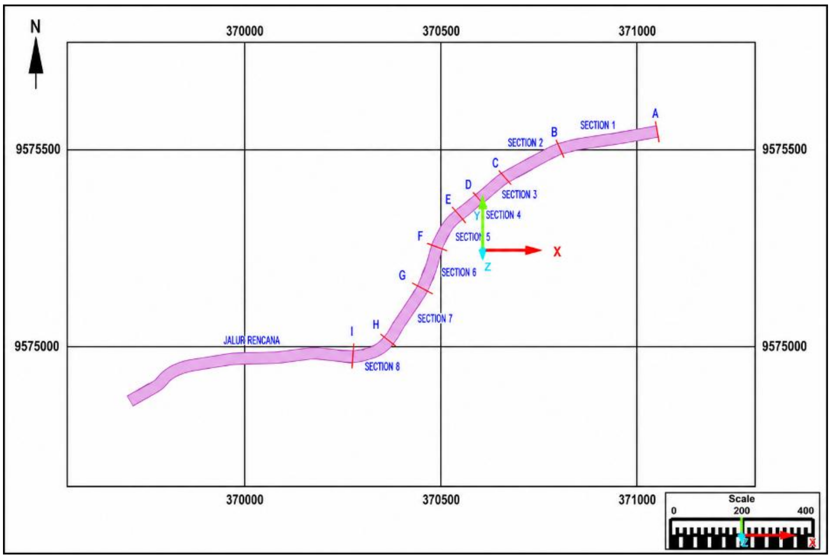

Figure 3. Planned haul-road redesign and segment delineation.

Figure 4 shows the proposed road alignment plotted over the existing hilly topography. The spatial relationship between the planned road surface and the existing terrain was used to identify the sections requiring excavation or fill during the redesign process.

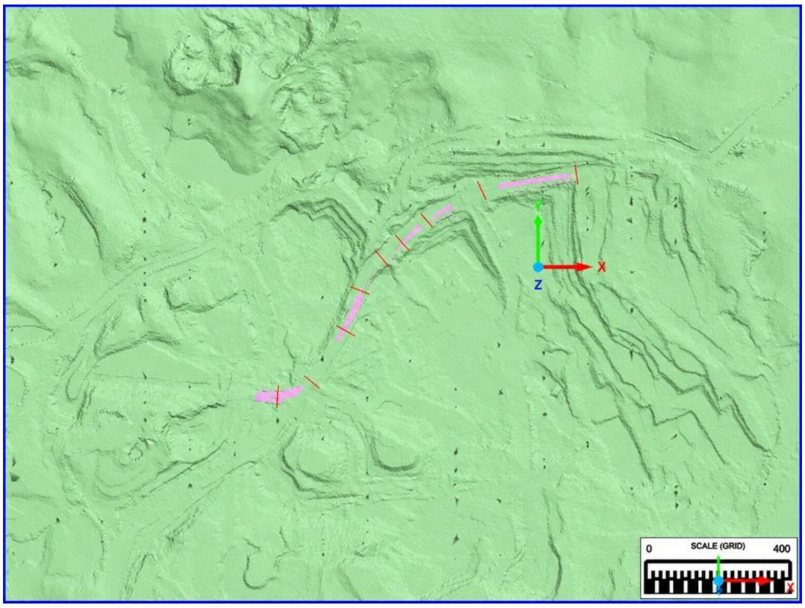

Figure 4. Planned road alignment over existing topography.

Cut-and-Fill Volume

The cut-and-fill volume was calculated by comparing the existing topographic surface with the proposed haul-road design surface within the planned road corridor. The calculation included the required road width, safety-berm dimensions, and side-slope configuration. As summarized in Table 6, the redesign resulted in a total cut volume of 203.92 BCM and a total fill volume of 9.79 BCM. The largest cut volume was recorded in the Planned Road section, with 183.38 BCM of cut and 1.61 BCM of fill. Overall, the earthwork requirement was dominated by excavation.

Table 6. Cut-and-Fill Volume

No.	Segment	Cut (BCM)	Fill (BCM)
1	1	2.69	4.08
2	2	2.56	0.68
3	3	1.14	0.09
4	4	1.17	0.07
5	5	4.07	0.27
6	6	0.93	1.95
7	7	5.43	0.06
8	8	2.55	0.98
9	Planned Road	183.38	1.61
	Total	**203.92**	**9.79**

Discussion

The results indicate that the main limitation of the existing Tesla haul road is not associated with longitudinal grade, but with horizontal and transverse geometric non-compliance. Based on Table 1, five straight segments require widening to satisfy the 24 m operational standard, with the largest deficiency found in Segment 1. Table 2 further shows that Segment 5 is also non-compliant in terms of curve width, requiring an additional 8.803 m of lateral widening. These findings confirm that the reactivation of the Tesla haul road must be controlled by the dimensional requirements of the Komatsu HD-785 as the design vehicle. In haul-road design practice, road width and curve geometry must be derived from the largest operating equipment, including its operating width, turning path, and lateral clearance requirements [2], [3], [16]. This result is also in line with recent open-pit road-design research, which emphasizes that road width must be treated as an equipment-dependent geometric parameter rather than a fixed access-road dimension [18]. Therefore, the width correction identified in this study is not merely a dimensional adjustment, but a necessary geometric requirement for allowing the planned fleet to operate within the design envelope.

In contrast to the width and curve deficiencies, the road-grade results in Table 3 show that all evaluated segments remain below the 8% maximum standard. This finding suggests that the existing longitudinal alignment does not constitute the primary geometric constraint for road reactivation. However, this result should not be interpreted as direct evidence that the road will automatically improve hauling productivity or reduce fuel consumption, because this study did not measure actual cycle time, truck speed, payload movement, or fuel use. Previous studies have shown that hauling cycle time and fuel consumption are affected by multiple operational factors, including road slope, rolling resistance, loading-dumping delay, equipment interaction, and road-surface condition [5], [19], [20]. In surface-mine truck haulage, the broader operating environment may also influence energy consumption and technical availability, especially when road quality and operating resistance vary along the haulage route [21]. Thus, the compliant grade condition in this study should be interpreted more cautiously as the elimination of one geometric constraint, while the remaining non-compliant width, superelevation, and cross-fall parameters still require correction before operational readiness can be inferred.

The transverse geometry results provide another important interpretation. Table 4 shows that Segment 5 has an actual superelevation of only 0.064 m, whereas the design requirement is 1.223 m. This condition indicates that the existing curve geometry does not yet provide the required transverse elevation difference for the planned design speed. Table 5 further shows that several cross-fall points are below the required 0.482 m standard, including a negative value of -1.039 m at the Right Edge of Segment 2. A negative cross-fall value is technically important because it may indicate an inverted drainage direction or localized surface depression. In mine haul-road design, cross fall is not only a road-surface shape parameter, but also a functional drainage component that helps remove surface water from the carriageway [2]. This interpretation is supported by recent work showing that seasonal moisture variation can weaken stabilized mine haul roads and reduce service performance when surface-water control is inadequate [8]. Therefore, the cross-fall correction identified in Table 5 is more directly related to drainage reliability and surface-condition control than to productivity improvement itself. Similarly, the safety-berm dimensions calculated from the design vehicle should be interpreted as preliminary geometric requirements based on the adopted standard [17]. Recent full-scale and numerical research on edge protection along mine haul roads shows that berm performance depends not only on height, but also on berm geometry, material behavior, vehicle type, speed, and impact condition [22]. Therefore, the safety-berm result in this study provides a necessary design input, but it does not yet verify actual containment performance under dynamic impact conditions.

The redesign shown in Figure 3 and Figure 4 demonstrates the spatial consequence of correcting non-compliant geometry within hilly terrain. Figure 3 indicates how the planned haul-road alignment is divided into operational segments, while Figure 4 shows the relationship between the proposed road body and the existing topographic surface. This topographic relationship explains why the earthwork result in Table 6 is excavation-dominant. The total cut volume reaches 203.92 BCM, whereas the total fill volume is only 9.79 BCM. The largest cut volume is concentrated in the Planned Road section, with 183.38 BCM of cut and only 1.61 BCM of fill. This pattern indicates that the proposed geometric correction requires substantial excavation rather than a balanced cut-and-fill configuration. Similar earthwork-volume studies show that 3D terrain models, UAV-derived surfaces, and software-based cut-and-fill calculations can support construction and mining volume estimation, but the resulting values remain sensitive to surface generation, boundary definition, data accuracy, and the computational method used [23], [24]. Therefore, the cut-and-fill values in this study should be treated as a technical planning estimate for earthwork preparation, not as a final construction quantity unless further field verification and detailed engineering validation are conducted.

From a mine-planning perspective, the integration of geometric redesign and cut-and-fill estimation is the main contribution of this study. Previous optimization and scheduling studies have increasingly emphasized that haulage routes should be considered as part of open-pit production planning, rather than as isolated infrastructure elements [11], [25], [26]. The present study extends that perspective at the road-segment scale by showing how geometric compliance requirements directly generate measurable earthwork demands. In this case, correcting the Tesla haul road to meet the operating requirements of Komatsu HD-785 units does not only involve widening and elevation correction; it also creates a large excavation surplus that must be considered in material handling, disposal planning, and construction sequencing. This finding is important because a geometrically compliant design may still be difficult to implement if the earthwork logistics are not evaluated early in the planning process.

The findings also have practical implications for operational readiness. The non-compliant straight width in Table 1, the curve deficiency in Table 2, the superelevation deficiency in Table 4, and the cross-fall deficiencies in Table 5 collectively indicate that the road should not be reactivated solely on the basis of route availability. Instead, reactivation should be preceded by targeted geometric correction and earthwork planning. This interpretation is consistent with recent mining-sequence research in South Sumatra, which indicates that haul-road adequacy can influence production continuity when operational delays and field constraints are not controlled [12]. Studies on loading-hauling productivity and equipment availability also show that equipment performance is affected by the interaction between route condition, equipment readiness, and operational delay factors [27], [28]. However, the present study does not directly measure productivity, fuel consumption, speed, or equipment availability. Its contribution is therefore more appropriately framed as a technical basis for road reactivation planning. In addition, because earthwork-volume reporting can differ between survey-based and truck-count-based approaches, the cut-and-fill estimates produced in this study should be supported by periodic field verification during implementation [29].

Overall, the discussion of the results demonstrates that the Tesla haul-road problem is multidimensional. The road-grade condition is acceptable, but the road is still constrained by insufficient width, inadequate curve geometry, insufficient superelevation, non-compliant cross fall, and an excavation-dominant earthwork profile. The integration of Tables 1–6 with Figures 3 and 4 confirms that geometric compliance and earthwork volume cannot be evaluated separately in hilly mine-road reactivation. The proposed redesign provides a clearer planning basis for identifying which segments require correction and how much cut-and-fill work is needed. Nevertheless, the findings remain limited to geometric and spatial-volume evaluation. Further work is required to test whether the proposed redesign improves actual hauling cycle time, fuel consumption, equipment stability, road maintenance frequency, and overall fleet productivity after implementation.

CONCLUSION

This study concludes that the existing Tesla haul road at Pit Banko Tengah A requires targeted geometric correction before reactivation for Komatsu HD-785 operation. The evaluation shows that the longitudinal grades remain within the allowable standard, whereas several road sections still require improvement in straight road width, curve width, superelevation, and cross fall. The proposed 3D redesign provides a technical basis for correcting these non-compliant parameters and estimating the earthwork required for implementation. The redesign results in an excavation-dominant earthwork profile, with a total cut volume of 203.92 BCM and a total fill volume of 9.79 BCM. These findings indicate that haul-road reactivation planning should not only consider geometric compliance, but also the logistical management of excess excavated material. The main limitation of this study is that it focuses on geometric evaluation and spatial volume estimation without measuring post-redesign operational performance. Future research should evaluate the implemented redesign through actual hauling cycle time, fuel consumption, road maintenance frequency, and fleet productivity measurements.

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