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Mine Road Design Feasibility and Its Impact on Overburden Hauling Productivity at PT PBT

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Abstract: *This study aims to analyze the feasibility of overburden (OB) hauling road design on production productivity and operational efficiency at PT PBT. The research employed a quantitative descriptive method through several stages, including preparation, data collection, data processing, data analysis, and conclusion formulation. Primary data were obtained through measurements of hauling road geometric parameters, including road width, grade, cross slope, superelevation, turning radius, cycle time, hauling equipment productivity, and fuel consumption. The results indicate that most road geometric parameters did not comply with technical standards, where the actual road width ranged from 17,1-19,1 m and the road grade reached 9%. These conditions increased operational resistance and hauling equipment cycle time. After the hauling road redesign was implemented, hauling equipment productivity increased from 108.34 BCM/hour to 130.69 BCM/hour, representing an improvement of 20.63%, while cycle time decreased from 13.45 minutes to 11.15 minutes. In addition, fuel consumption decreased by 10.21%, from 441.88 liters/hour to 396.74 liters/hour, resulting in significant operational cost savings. Therefore, improvements in hauling road geometry were proven to enhance mining productivity and operational efficiency.*

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INTRODUCTION

The mining industry is one of the strategic sectors that plays a vital role in supporting national economic development, particularly in providing energy resources and industrial raw materials. Mining activities contribute significantly to state revenue while also stimulating the growth of other industrial sectors that utilize mineral resources (Nawir et al., 2025). Therefore, the success of mining operations is highly dependent on the effectiveness and efficiency of each stage of the production process.

In general, mining activities consist of several main stages, including material excavation, loading, hauling, and stockpiling or material processing (Shoffan et al., 2024). One of the most widely applied mining methods is the open-pit mining system, a mining method carried out by removing the overlying soil or rock layers to extract mineral deposits located beneath the surface. This method enables the use of large-capacity heavy equipment, thereby allowing high production volumes to be achieved (Mochamad Ali Tamrin et al., 2025).

In open-pit mining operations, not all excavated materials possess economic value. The layer of soil or rock covering the mineral deposit is referred to as overburden (OB). This overburden material must first be removed before the main mineral resources can be extracted. The process of transporting materials, whether overburden or other mining materials, from the mining site to a designated location is known as hauling activity (Suryani J, 2025). Hauling operations generally utilize dump trucks operating continuously within the mining operational cycle (Nurul et al., 2024).

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The area where excavation activities take place is referred to as the front or loading point, namely the location where excavation equipment loads material into hauling equipment. The material is subsequently transported to a disposal area, which serves as a temporary or permanent dumping site for non-economic materials such as overburden. The smooth flow of operations from the front to the disposal area is one of the key factors in maintaining mining production continuity.

To ensure that hauling activities operate efficiently, supporting infrastructure in the form of mine roads or hauling roads is required. Hauling roads are specialized routes used by hauling equipment to transport materials from the front to the disposal area or other locations within the mining site. Ideally, hauling roads should be designed with careful consideration of technical and occupational safety aspects to support the optimal, safe, and efficient movement of hauling equipment. Well-designed roads allow hauling equipment to operate at stable speeds, achieve efficient travel times, and reduce fuel consumption (Simaremare et al., 2024a).

Mine roads must satisfy several technical parameters, including road width adjusted to the dimensions of hauling equipment, road gradient that does not exceed allowable limits, cross slope for drainage purposes, superelevation on curves, and minimum turning radius ((Mulyo et al., 2023)). These parameters are intended to ensure occupational safety while simultaneously improving the operational efficiency of hauling equipment. Accordingly, the ideal condition expected is a hauling road that complies with all applicable standards so that hauling equipment productivity can be optimized.

However, actual field conditions often reveal that hauling roads do not fully comply with established technical standards. Inadequate road geometric designs, such as insufficient road width, excessively steep gradients, and uneven road surfaces, may create obstacles in hauling operations. These conditions can result in reduced hauling equipment speed, increased cycle time, and higher fuel consumption due to the increased workload imposed on the equipment (Irfan et al., 2021).

Based on preliminary observations conducted on the overburden (OB) hauling road at PT Pusaka Bumi Transportasi (PBT), several road segments are suspected of not meeting the recommended geometric standards. This condition potentially hinders the smooth movement of hauling equipment from the front to the disposal area, thereby affecting hauling time efficiency and overall production productivity. Furthermore, suboptimal road conditions may also contribute to increased fuel consumption and higher mining operational costs (Simaremare et al., 2024b).

Several previous studies have demonstrated that mine road design significantly influences hauling equipment performance. Improvements in road geometry, such as adjustments to road width and gradient control, have been proven to increase hauling equipment speed, reduce cycle time, and improve productivity. In addition, better road conditions also contribute to lower fuel consumption and operational costs. Nevertheless, most previous studies have primarily focused on productivity aspects and have not comprehensively examined the interrelationship between road design feasibility, production productivity, fuel consumption, and operational costs (Faisal et al., 2025).

Based on the foregoing discussion, a gap exists between the ideal condition of hauling roads, which should comply with technical standards, and the actual field conditions, which are suspected of not being fully compliant. Therefore, a comprehensive study is required to evaluate the feasibility of hauling road design and analyze its influence on production productivity and operational efficiency.

This study is conducted using a mine road geometric analysis approach combined with an evaluation of hauling equipment performance. Through this approach, it is expected that the level of

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conformity between road conditions and applicable technical standards, as well as their impacts on hauling activities from the front to the disposal area, can be identified.

Although numerous previous studies have demonstrated that haul road geometry significantly influences hauling performance, most investigations have focused on individual technical parameters, such as road width, road grade, or rolling resistance, with productivity as the primary performance indicator (Hadiyansyah et al., 2025). Limited studies have comprehensively integrated technical feasibility assessment with operational performance and economic evaluation within a single analytical framework.

The operational performance of hauling equipment is strongly influenced by haul road geometry. Road width, longitudinal grade, cross slope, superelevation, and turning radius determine vehicle maneuverability, travel resistance, and operating speed. From a transportation engineering perspective, inadequate haul road geometry increases rolling resistance and grade resistance, forcing hauling equipment to operate under higher engine loads (Bao et al., 2024). Consequently, travel speed decreases, cycle time increases, fuel consumption becomes higher, and overall hauling productivity declines.

Conversely, haul roads designed according to recommended engineering standards reduce operational resistance, allowing hauling equipment to maintain more stable operating speeds and shorter travel times (Lotsu et al., 2026). These improvements directly enhance transportation efficiency, reduce fuel consumption, increase equipment productivity, and lower operating costs. Therefore, haul road geometry is considered one of the most important engineering factors affecting mine transportation efficiency (Rahma et al., 2024).

Therefore, this study addresses this research gap by integrating haul road geometric feasibility analysis with hauling equipment performance, fuel consumption, operational cost, and Benefit Cost Ratio (BCR) analysis. Unlike previous studies, this research not only evaluates compliance with technical haul road standards but also quantifies the operational and economic impacts of haul road redesign. This integrated framework provides a more comprehensive basis for decision-making in mine haul road planning and optimization.

Accordingly, the objective of this study is to analyze the conformity of the overburden (OB) hauling road design at PT PBT with applicable technical standards, evaluate its influence on production productivity, and examine its impact on fuel consumption and operational costs. The findings of this study are expected to provide practical technical recommendations for improving mine road design in order to enhance operational efficiency and productivity optimally.

RESEARCH METHOD

The study utilized both primary and secondary data sources. Primary data were collected through direct field observations and measurements of haul road geometric parameters, including road width, road grade, cross slope, superelevation, turning radius, hauling distance, travel speed, cycle time, and fuel consumption. Secondary data were obtained from company operational reports, equipment specifications, production records, road design documents, and relevant scientific literature related to mine haul road engineering and productivity analysis. The research variables consisted of independent and dependent variables. The independent variables included haul road geometric parameters, namely road width (m), grade (%), cross slope (%), superelevation (%), and turning radius (m). The dependent

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variables included hauling equipment performance indicators such as travel speed (km/h), cycle time (minutes), productivity (BCM/hour), fuel consumption (L/hour), and operational efficiency (%). These variables were selected to evaluate the relationship between haul road conditions and hauling performance.

The sampling technique employed was purposive sampling. Road segments were selected based on their operational significance and frequency of utilization by hauling equipment. A purposive sampling technique was employed to select representative haul road segments. Eight road segments were selected based on their operational importance, traffic intensity, and geometric characteristics, including straight sections, curved sections, uphill grades, and transition areas. These segments represent the overall hauling route used for overburden transportation at PT PBT.

The haul road was divided into several observation segments representing straight sections, curved sections, uphill grades, and downhill grades. Measurements were conducted on each segment to identify deviations from recommended design standards. Data collection was carried out through field surveys using measuring instruments, GPS devices, clinometers, and direct operational observations. Road width measurements were conducted at multiple points along each segment, while grade and cross slope values were measured using topographic survey equipment. Hauling equipment operational data, including cycle time, travel speed, and fuel consumption, were recorded during active production periods to represent actual operating conditions.

The research was conducted through several stages. The first stage involved preliminary preparation, including literature review, determination of research variables, preparation of survey instruments, and acquisition of company permits. The second stage consisted of field data collection through direct measurement and operational observations. The third stage involved data processing, including road segmentation, tabulation of measurement results, calculation of geometric parameters, and determination of hauling equipment productivity using standard productivity equations. The fourth stage comprised data analysis by comparing actual road conditions with haul road design standards recommended in mining engineering guidelines. The influence of haul road geometry on hauling performance was analyzed quantitatively through comparisons of productivity, cycle time, fuel consumption, and operational efficiency under existing conditions.

Productivity calculations were performed based on actual cycle time and hauling capacity data obtained during field observations. Furthermore, fuel consumption and operational efficiency analyses were conducted to identify the economic impact of non-compliant road geometric conditions. The results of the analysis were then interpreted to determine the feasibility level of each haul road segment and to formulate technical recommendations aimed at improving road geometry, reducing operational costs, increasing hauling productivity, and enhancing overall mine transportation efficiency.

To improve data reliability, field measurements were conducted repeatedly for each haul road segment, and the average values were used for subsequent analyses. Operational data, including hauling productivity, cycle time, and fuel consumption, were cross-checked with company production records to ensure consistency between field observations and actual operating conditions. This validation procedure improves the reliability and credibility of the analytical results.

Field measurements were conducted using standardized surveying procedures. Road width was measured at multiple locations within each segment to minimize measurement error. Road grade was determined from elevation differences and segment length using topographic surveying methods,

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while hauling equipment speed was measured using a speed gun under normal operating conditions. Cycle time observations were conducted repeatedly during regular production activities to represent actual operational performance.

The overall research framework consisted of six main stages: (1) research preparation, (2) literature review and determination of variables, (3) field data collection, (4) data processing and calculation, (5) data analysis and evaluation of haul road feasibility, and (6) formulation of conclusions and recommendations.

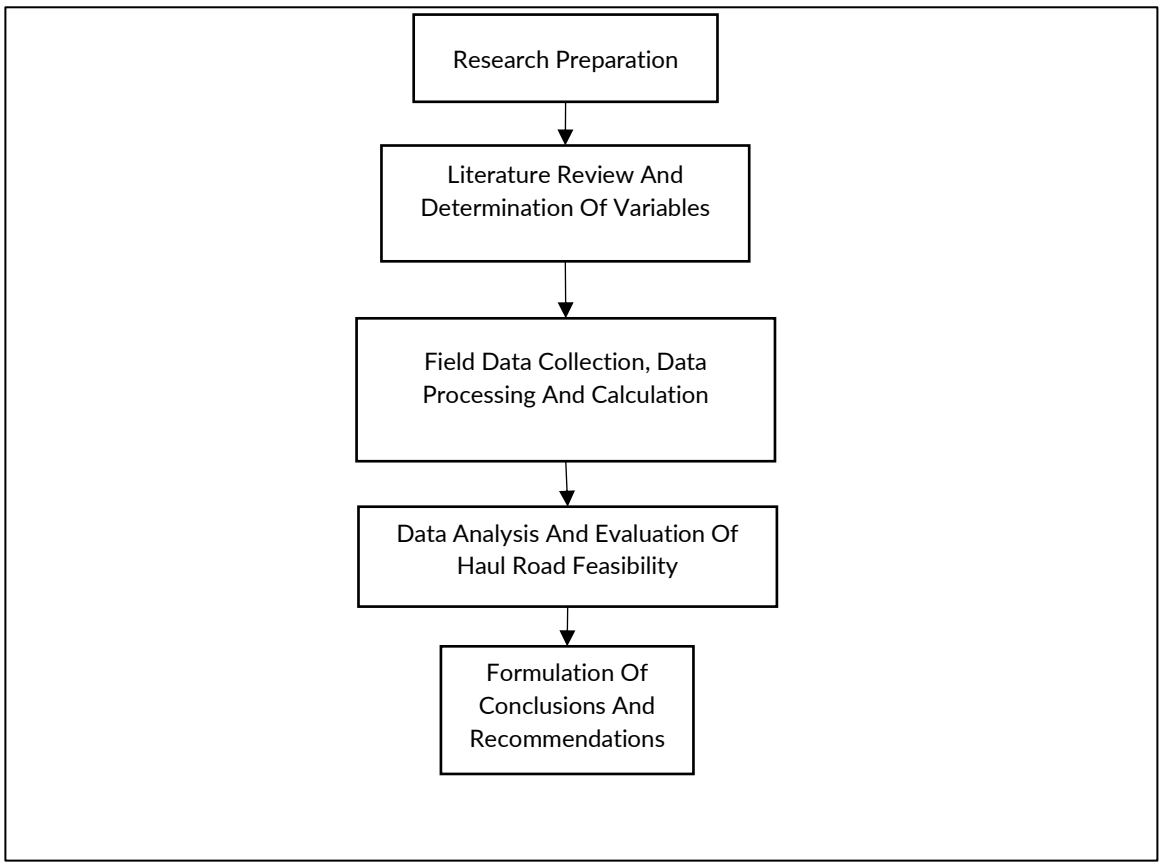

Figure 1. Flowchart Research Framework

The research was conducted through six sequential stages. The first stage involved a literature review to identify research gaps, define the research objectives, and establish the technical criteria for haul road evaluation. The second stage consisted of collecting primary and secondary data through field measurements, operational observations, and company records, including haul road geometry, hauling performance, and fuel consumption. Subsequently, the existing haul road geometry was evaluated by comparing field measurements with applicable mining engineering standards to identify deficiencies affecting hauling operations. Based on the evaluation results, a haul road redesign was developed by improving the geometric parameters in accordance with recommended engineering standards. The redesigned haul road was then analyzed by comparing hauling performance, fuel consumption, operational costs, and economic feasibility using the Benefit Cost Ratio (BCR) method. Finally, the results were interpreted to assess the effectiveness of the proposed redesign and to formulate technical recommendations for improving haul road performance and operational efficiency in open-pit mining.

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RESULTS AND DISCUSSION

Data Analysis

Table 1. Feasibility of Existing OB Hauling Road at PT PBT

Parameter	Standard	Research Result	Deviation (%)	Description
Straight Road Width	22.75	17.8 – 19.1	-16% s.d -22%	Unfeasible
Curve Width	23	17.1	-25.6 %	Unfeasible
Maximum Grade	≤ 12	≤ 9%	-	Acceptable
Superelevation	≤ 5	4.7%	-	Acceptable

The deviations found in the hauling road geometric parameters not only indicate non-compliance with technical standards but also represent the main factor contributing to the low operational efficiency under existing conditions. Based on the analysis results, the hauling road geometry that failed to meet the required standards, such as insufficient road width, relatively high grades, and the presence of curves, caused a reduction in hauling equipment speed. This condition resulted in an increase in cycle time to 13.45 minutes. In addition, operational conditions influenced by road factors led to a relatively low work efficiency of 0.34. Consequently, hauling equipment productivity only reached approximately 108.34 BCM/hour, while production productivity achieved 149,795.1 BCM/month. Therefore, improvements in work efficiency, reductions in cycle time, and enhancements in hauling road geometry conditions would directly contribute to increasing overall production performance.

Redesign of the PT PBT OB Hauling Road

Road Width Redesign

Based on the analysis of existing conditions, it was found that most hauling road segments did not meet the recommended minimum width standard. Therefore, a redesign of the hauling road width within the study area was conducted on February 9-11, 2026, to comply with the applicable technical standards.

This redesign aimed to improve the smooth movement of hauling equipment, particularly along two-way traffic routes, thereby reducing operational constraints and enhancing occupational safety aspects. In addition, the adjustment of road width was expected to increase hauling equipment speed and reduce cycle time.

Table 2. Redesign of the PT PBT OB Hauling Road Width

Segment	Road Width	Distance	Number of Lanes	Road Type
A-B	23	100 m	2	Curve
B-C	22,75	100 m	2	Straight
C-D	22,75	100 m	2	Straight
D-E	22,75	100 m	2	Straight
E-F	22,75	100 m	2	Straight
F-G	22,75	100 m	2	Straight
G-H	22,75	100 m	2	Straight
H-I	22,75	100 m	2	Straight

Based on the redesign results, the hauling road width dimensions were adjusted to comply with the minimum standards. For the curved segment A–B, the planned road width was 23 meters, while

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for the straight road segments (B–C to H–I), a road width of 22.75 meters was applied. All segments were designed as two-way roads with a segment length of 100 meters each.

The results of the hauling road width redesign are presented in Table 8. Based on the table, it can be concluded that all hauling road segments after the redesign complied with the recommended road width standards.

Road Grade Redesign

During the redesign stage, adjustments were made to the hauling road alignment in order to control the road gradient so that it complied with the recommended technical standards. These adjustments were carried out through cut and fill activities on several road segments, resulting in a smoother and more uniform road profile (Jamaluddin, 2023).

The improvement of road grade was intended to enhance the operational performance of hauling equipment, as lower road gradients reduce grade resistance, allowing hauling equipment to operate at more stable and efficient speeds.

Table 3. Redesign of the PT PBT OB Hauling Road Grade

Segment	Elevation h1 (m)	Elevation h2 (m)	Elevation Difference (m)	Segment Length (m)	Actual Grade
A-B	81	86	5	100	5%
B-C	86	92	6	100	6%
C-D	92	97	5	100	5%
D-E	97	103	6	100	6%
E-F	103	108	5	100	5%
F-G	108	114	6	100	6%
G-H	114	119	5	100	5%
H-I	120	125	5	100	5%

Based on the redesign results of the PT PBT OB hauling road gradient, the road grade became more controlled compared to the existing condition. The redesign was carried out by adjusting the elevation difference between segments while maintaining a constant road length of 100 meters, resulting in grade variations ranging from 5% to 6%. Compared to the initial condition, where the grade reached up to 9%, the redesign demonstrates a significant reduction in road gradient. This improvement positively affected hauling equipment speed, reduced engine workload, and enhanced fuel consumption efficiency. The grade design was not entirely forced to follow ideal values, but rather adjusted according to topographical conditions and earthwork efficiency, thereby producing a design that was technically and economically optimal.

The evaluation of hauling road geometric conditions was conducted by comparing the existing condition and the redesign results with applicable technical standards. This comparison was used to assess the road feasibility level based on road width, grade, and superelevation parameters. The comparison results are presented in Table 4.

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Table 4. Feasibility of the PT PBT OB Hauling Road After Redesign

Parameter	Standard	Actual	Remarks	Redesign	Final Remarks
Straight Road Width	22.75	17.8 – 19.1	Not Suitable	22.75	Suitable
Curve Width	23	17.1	Not Suitable	23	Suitable
Maximum Grade	≤ 12 %	≤ 9%	Adequate	5% - 6%	Suitable
Superelevation	≤ 5	4.7%	Adequate	4.7%	Adequate

Based on Table 4, it can be observed that under existing conditions, most hauling road geometric parameters did not comply with the recommended technical standards. The primary non-conformity was found in the road width, both on straight and curved sections, which were all below the minimum standard and therefore categorized as unfeasible. Meanwhile, the grade and superelevation parameters under existing conditions were still within the allowable limits, although they were not yet optimal in supporting hauling equipment operational performance.

After the redesign was implemented, all road geometric parameters showed significant improvement. The road width on straight sections was adjusted to 22.75 meters, while the curve width was increased to 23 meters, thereby meeting the standards and being categorized as feasible. The road grade also became more controlled within the range of 5%–6%, which is more ideal compared to the previous condition. Meanwhile, the superelevation value remained at 4.7% and was still categorized as acceptable according to the applicable standards. These improvements indicate that the redesign successfully reduced deviations from technical standards and enhanced the overall feasibility of the hauling road.

Productivity Calculation Results After Redesign

Hauling Equipment Speed After Redesign

Following the improvement (redesign) of the hauling road geometry, hauling equipment speed measurements were conducted again to determine the effect of the road condition changes on operational performance. Speed measurements were carried out using a speed gun on each road segment, applying the same method used prior to the redesign so that the results could be directly compared.

Table 5. Hauling Equipment Speed After Redesign

Segment	Speed (km/hour)
A-B	20
B-C	23
C-D	25
D-E	26
E-F	25
F-G	23
G-H	23
H-I	22

Based on the measurement results, variations in hauling equipment speed were observed across each hauling road segment. The highest speed was recorded on segment D–E at 26 km/hour, followed by segments C–D and E–F at 25 km/hour each. Meanwhile, the lowest speed occurred on segment A–B at 20 km/hour, which represents a curved segment. Other segments, such as B–C, F–G, and G–

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H, exhibited relatively uniform speeds of 23 km/hour, while segment H–I recorded a speed of 22 km/hour.

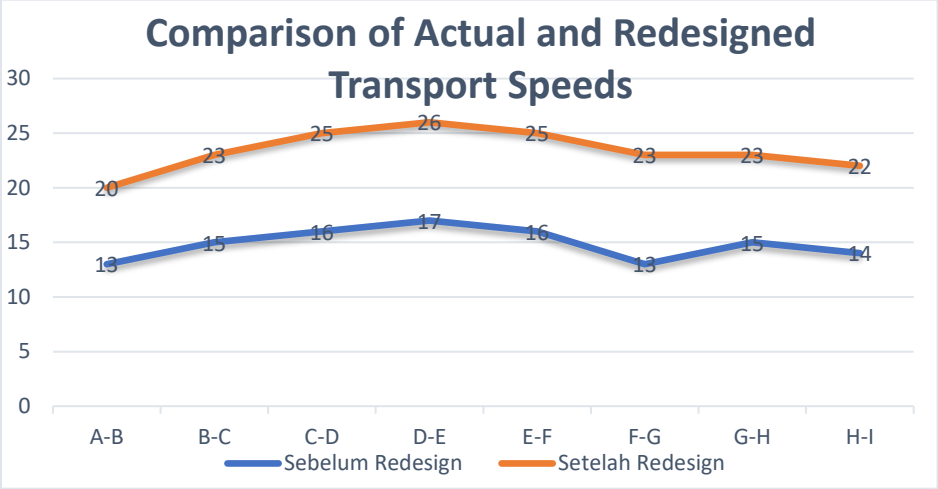

Figure 2. Graph Comparison of Actual and Redesign Hauling Equipment Speed

Compared to the condition prior to the redesign, an overall increase in speed occurred across all road segments. This improvement indicates that the enhancement of road geometry, particularly in terms of road width and grade control, had a positive impact on the smooth movement of hauling equipment.

Technically, this increase in speed was caused by the reduction of operational constraints, such as narrow road widths and non-optimal gradients, enabling hauling equipment to operate more stably and efficiently. Nevertheless, the speed on the curved segment (A–B) remained lower than on straight segments due to safety considerations and vehicle maneuvering limitations within curved areas.

Hauling Equipment Cycle Time After Redesign

The calculation of cycle time after the hauling road redesign was based on changes in road geometry conditions that affected hauling equipment speed and travel time. The time components used in the calculation included a loading time of 3 minutes, hauling time based on measurements for each segment, a dumping time of 3 minutes, and a return time of 2.09 minutes. In this calculation, delay time was not directly included, as it had already been accommodated within the work efficiency factor. The travel time details for each segment are presented in Table 6.

Table 6. Hauling Time per Segment After Redesign

Segment	Speed (km/hour)	Hauling Time (minutes)
A-B	20	0.30
B-C	23	0.26
C-D	25	0.24
D-E	26	0.23
E-F	25	0.24
F-G	23	0.26
G-H	23	0.27
H-I	22	0.27
Total		2.06

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Subsequently, the total cycle time was calculated as follows:

$$CT = 3 + 2.06 + 3 + 2.09 = 11.15 \text{ minutes}$$

Based on these results, the cycle time obtained was 11.15 minutes. This value indicates a reduction in cycle time compared to the condition prior to the redesign. The reduction was influenced by the increase in hauling equipment speed across each road segment, which ranged from 20 km/hour to 26 km/hour. The highest speed occurred on segment D–E at 26 km/hour, indicating relatively more optimal road conditions, particularly in terms of road grade and width. Conversely, the lowest speed occurred on segment A–B at 20 km/hour, which was a curved segment where vehicles tended to reduce speed to maintain safety.

These variations in speed directly affected the travel time for each segment. The shortest travel time was recorded on segment D–E at 0.23 minutes, while the longest travel time occurred on segment A–B at 0.30 minutes. This demonstrates that road geometric conditions, both in terms of grade and road type (straight or curved), had a significant influence on hauling equipment travel time.

With the increase in speed and reduction in travel time, the overall cycle time became lower. This condition indicates that improvements in road geometry through redesign played an important role in increasing cycle time efficiency, which ultimately contributed to enhanced hauling equipment productivity.

Production Productivity After Redesign

Under the post-redesign condition, with a hauling road efficiency value of 0.34, the hauling equipment productivity was calculated as follows:

$$Q = \frac{71.43 \times 60 \times 0.34}{11.15}$$
$$Q = 130.69 \text{ BCM/hour}$$

Using this efficiency value, the hauling equipment production was obtained at 130.69 BCM/hour. Furthermore, the production productivity after redesign was calculated as follows:

$$Q = 130.69 \times 6 \times 8.23 = 6{,}453.38 \text{ BCM/day}$$
$$Q = 6{,}453.38 \times 7 = 45{,}173.64 \text{ BCM/week}$$
$$Q = 6{,}453.38 \times 28 = 180{,}694.6 \text{ BCM/month}$$

Thus, the total production under the redesigned condition reached 180,694.6 BCM/month.

Productivity Improvement Analysis

This analysis is important because production productivity represents one of the main indicators of mining operational success. Compared to the condition before redesign, where hauling equipment productivity was 108.34 BCM/hour, the following increase was obtained:

$$\Delta Q = 130.69 - 108.34 = 22.35 \text{ BCM/hour}$$
$$\% \text{ Increase} = \frac{22.35}{108.34} \times 100\% = 20.63\%$$

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This increase also had a direct impact on daily production, where production increased from 5,349.83 BCM/day to 6,453.38 BCM/day, representing an increase of:

$$6{,}453.38 - 5{,}349.83 = 1{,}103.55 \text{ BCM/day}$$

The increase in hauling equipment productivity from 108.34 BCM/hour to 130.69 BCM/hour indicates a performance improvement of 20.63% following the hauling road redesign. This improvement directly affected production productivity, which also experienced the same percentage increase on daily, weekly, and monthly scales.

Following the improvement of hauling road geometry through redesign, an evaluation of hauling equipment performance was conducted to determine the impact of road condition changes on productivity and operational efficiency. This evaluation was carried out by comparing several key parameters before and after redesign, including hauling equipment productivity, speed, cycle time, total resistance, and overall road conditions. The comparison results of hauling equipment performance are presented in Table 7.

Table 7. Comparison of Actual and Redesigned Hauling Equipment Performance

Parameter	Actual Condition	Redesign Condition	Change	Description
Productivity	108.34 BCM/hour	130.69 BCM/hour	+20.63%	Increased
Equipment Speed	Lower	Higher	↑	Increased
Cycle Time	Longer	Faster	↓	More Efficient
Total Resistance	High	Lower	↓	Reduced
Road Condition	Below Standard	Meets Standard	-	Improved

Based on Table 7, it can be observed that improvements in hauling road geometry had a positive impact on all hauling equipment performance parameters. Hauling equipment productivity increased from 108.34 BCM/hour to 130.69 BCM/hour, representing an improvement of 20.63%. This increase indicates that road conditions complying more closely with technical standards were able to enhance the effectiveness of the hauling process.

In addition, hauling equipment speed after the redesign increased compared to the previous condition. This increase in speed was directly proportional to the reduction in cycle time, resulting in a faster and more efficient hauling process.

From the perspective of operational constraints, the total resistance value decreased after the redesign was implemented. This indicates that improvements in road geometry, particularly regarding road grade and width, were able to reduce the workload imposed on hauling equipment during transportation activities.

Overall, the hauling road condition after redesign experienced significant improvement, changing from a condition that previously did not meet technical standards to one that more closely complied with the recommended standards. These improvements directly contributed to enhanced hauling equipment performance in terms of productivity, speed, and operational efficiency.

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Therefore, it can be concluded that improvements in hauling road geometry had a significant influence on enhancing hauling equipment performance, as reflected in the increased productivity and overall efficiency of the hauling system.

Analysis of Fuel Consumption Efficiency and Operational Costs

Fuel Consumption

Fuel consumption is one of the primary components of hauling equipment operational costs. Improvements in hauling road design are expected to reduce fuel consumption, thereby increasing the overall efficiency of production costs.

Based on the results of fuel usage data collection during February, operational conditions were divided into three phases: before redesign, during the redesign process, and after redesign. In the first week (early February), the hauling road remained in its existing condition prior to any design improvements. Subsequently, on February 9-11, 2026, which fell within the second week, the hauling road redesign activities commenced. During this phase, the road condition was still undergoing adjustments; therefore, the impact on fuel consumption had not yet shown significant changes (Anwar, 2021).

More noticeable changes began to appear during the third and fourth weeks, when the hauling road condition had already been improved in accordance with the planned design. During this period, hauling equipment fuel consumption showed a decreasing trend compared to the condition before redesign. The reduction in fuel consumption indicates an improvement in operational efficiency, influenced by enhancements in road geometric parameters such as the reduction of extreme grades, improvement of road surface conditions, and smoother hauling equipment movement (Suhendik et al., 2022).

In detail, the daily fuel consumption data during February are presented in Appendix 2. These data served as the basis for analyzing the magnitude of fuel consumption savings achieved after the hauling road redesign was implemented.

Therefore, the comparison of fuel consumption before and after redesign will be further analyzed to determine the level of efficiency achieved and its contribution to reducing hauling equipment operational costs.

Table 8. Average Fuel Consumption of 6 Hauling Units

	Week1	Week2	Week3	Week4	Total
Plan	420	420	420	420	1680
Act	441,88	426,01	407,77	396,74	1672,40

Based on field sampling results, the fuel consumption for one hauling unit was determined to be 70 liters/hour. With a total of six hauling units in operation, the planned fuel consumption was theoretically calculated at 420 liters/hour. This value was used as a reference for comparing the actual fuel consumption during operational activities.

However, based on the actual data presented in Table 8, fuel consumption did not consistently correspond to the planned value. In the first week, the actual fuel consumption reached 441.88 liters/hour, which was higher than the planned value. This indicates that the actual hauling road condition prior to redesign was still suboptimal, resulting in less efficient hauling equipment performance and consequently increasing fuel consumption (Ersan et al., 2025).

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Entering the second week, fuel consumption began to decrease to 426.01 liters/hour, although it still remained above the planned value. During this period, the hauling road redesign process had already commenced; however, road conditions had not yet become fully stable, so operational efficiency had not been maximized (Odeyar et al., 2022).

More significant changes were observed during the third and fourth weeks, where actual fuel consumption decreased to 407.77 liters/hour and 396.74 liters/hour, respectively, both of which were lower than the initial actual value of 441.88 liters/hour. Therefore, the reduction in fuel consumption was calculated as follows:

$$441.88 - 396.74 = 45.14 \text{ liters/hour}$$

$$\frac{45.14}{441.88} \times 100\% = 10.21\%$$

Thus, the hauling road redesign resulted in a fuel consumption reduction of 10.21%.

Table 9. Fuel Consumption Efficiency After Redesign

Parameter	Actual Condition	Redesign Condition	Savings	Description
Fuel Consumption	441.88 Liters	396.74 Liters	45.14 Liters	More Efficient
Efficiency Percentage	-	-	10.21%	Reduction
Equipment Workload	High	Lighter	↓	Improved
Operating Condition	Not Optimal	Optimal	-	Improved

The reduction in fuel consumption from the actual condition to the post-redesign condition by 10.21% indicates an improvement in fuel usage efficiency following the hauling road redesign. These improvements contributed to smoother hauling equipment movement, reduced operational resistance, and more stable operating speeds. This demonstrates that the hauling road redesign had a positive impact on fuel consumption efficiency, although inefficiencies still occurred during the initial period due to road conditions that had not yet become fully optimal.

Fuel Ratio

To evaluate fuel usage efficiency in hauling activities, the researcher also analyzed the ratio between fuel consumption and the amount of production generated. Therefore, the fuel ratio parameter was used to express the amount of fuel required to produce one unit volume of material. The fuel ratio calculation was conducted using Equation (12).

Table 10. Comparison of Actual and Redesign Fuel Ratio

	Actual	Redesign
Fuel Ratio	0,082	0,06

This parameter was used to determine the level of fuel usage efficiency, where a lower fuel ratio value indicates more efficient fuel consumption during hauling operations.

Based on the calculation results, the fuel ratio under the condition before redesign was 0.082 L/BCM, while after redesign the value decreased to 0.06 L/BCM. This reduction in fuel ratio indicates an improvement in fuel efficiency per unit of production.

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Technically, this efficiency improvement was influenced by enhancements in hauling road geometry conditions, such as reduced road grade and adjusted road width, which minimized operational resistance experienced by hauling equipment (Erlan et al., 2024). With more optimal road conditions, hauling equipment was able to operate at more stable speeds and shorter travel times, resulting in more efficient fuel consumption relative to the volume of material transported.

Operational Cost Calculation (Fuel Cost)

The industrial fuel price used in PT PBT operational activities was IDR 14,000 per liter. Based on the fuel consumption data analyzed under both actual and redesigned conditions, an operational cost calculation focused on fuel cost was conducted. The comparison of fuel costs before and after redesign is presented in Table 11.

Table 11. Comparison of Actual and Redesign Operational Cost Calculation

	Aktual	**Redesign**
Fuel Consumption	441,88	396,74
Fuel Cost	IDR 6,186,320/hour	IDR 5,554,360/hour

Based on Table 17, the fuel consumption under actual conditions of 441.88 liters/hour resulted in an operational cost of IDR 6,186,320 per hour. After the redesign, fuel consumption decreased to 396.74 liters/hour, resulting in a reduction in operational cost to IDR 5,554,360 per hour.
Therefore, the fuel cost savings obtained were as follows:

$$\text{IDR } 6{,}186{,}320 - \text{IDR } 5{,}554{,}360 = \text{IDR } 631{,}960/\text{hour}$$

When converted into operational time scales, the savings were calculated as follows:

$$\text{IDR } 631{,}960 \times 24 = \text{IDR } 15{,}167{,}040/\text{day}$$
$$\text{IDR } 15{,}167{,}040 \times 28 = \text{IDR } 424{,}677{,}120/\text{month}$$

Based on these results, it can be concluded that fuel operational cost savings of IDR 424,677,120 per month were achieved after the hauling road redesign.

Technically, this reduction in cost was influenced by decreased fuel consumption resulting from improvements in road geometry, particularly in terms of road width and grade control. More optimal road conditions were able to reduce operational resistance encountered by hauling equipment, thereby reducing engine workload and improving fuel efficiency.

Furthermore, the gradual decline in fuel consumption from the first week to the fourth week indicates that the redesign implementation had a sustained positive impact on operational efficiency. Therefore, the hauling road redesign not only improved the technical performance of hauling equipment but also provided significant economic benefits through reductions in fuel operational costs.

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Table 12. Comparison of Actual and Redesign Operational Cost per BCM

Condition	Fuel Consumption (L/hour)	Production Productivity (BCM/hour)	Operational Cost (IDR/hour)	Operational Cost per BCM (IDR/BCM)
Actual	441.88	108.34	6,186,320	57,100
Redesign	396.74	130.69	5,554,360	42,500

To determine the level of operational cost efficiency more comprehensively, a comparative analysis was conducted between fuel consumption, hauling equipment productivity, and operational cost per unit of production (cost per BCM) before and after the hauling road redesign (Xiao et al., 2016).

Based on Table 18, fuel consumption decreased from 441.88 liters/hour to 396.74 liters/hour. On the other hand, hauling equipment productivity increased from 108.34 BCM/hour to 130.69 BCM/hour. These changes had a significant impact on operational costs per unit of production.

The operational cost per BCM (cost per BCM) prior to the redesign was IDR 57,100/BCM, while after the redesign it decreased to IDR 42,500/BCM. Therefore, the cost savings can be calculated as follows:

$$57{,}100 - 42{,}500 = \text{IDR } 14{,}600/\text{BCM} \Rightarrow \frac{14{,}600}{57{,}100} \times 100\% = 25.57\%$$

The reduction in operational cost per unit of production indicates that the hauling system became more efficient after the hauling road redesign. Technically, this efficiency improvement was influenced by the combination of reduced fuel consumption and increased hauling equipment productivity. Improvements in road geometry, such as road width adjustment and grade control, were able to reduce operational resistance, enabling hauling equipment to operate more optimally.

In addition to increasing productivity, improvements in road geometry also affected the fuel consumption of hauling equipment. The fuel efficiency evaluation was carried out by comparing conditions before and after the redesign, as presented in Table 12.

Benefit Cost Ratio (BCR) Analysis

Calculation of Redesign Work Volume

The calculation of redesign work volume was conducted to determine the total material handled during the widening and geometric improvement process of the hauling road. The work volume was obtained based on the excavator productivity and the total working time during the redesign process. Based on the research data, the excavator used had a productivity of 450 BCM/hour with a redesign working duration of 5 shifts. Each shift consisted of 8 working hours, so the total equipment working time was calculated as follows:

$$V = 450 \times 5 \times 8 = 18{,}000 \text{ BCM}$$

The calculation results show that the redesign work volume for the hauling road widening and geometric improvement process was 18,000 BCM.

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Equipment Operational Costs

Equipment operational costs are expenses incurred during the operation of heavy equipment in the hauling road redesign activities. These costs are influenced by equipment operating duration and hourly operational costs (Rizky et al., 2024). In this study, one excavator unit and one bulldozer unit were used during the redesign process. The excavator rental cost was Rp 2,300,000/hour, while the bulldozer rental cost was Rp 1,500,000/hour, with a total operating duration of 40 hours. Therefore, the operational cost calculations were as follows:

$$\text{EOC (Excavator)} = 40 \text{ hours} \times Rp\ 2{,}300{,}000/\text{hour} = Rp\ 92{,}000{,}000$$
$$\text{EOC (Bulldozer)} = 40 \text{ hours} \times Rp\ 1{,}500{,}000/\text{hour} = Rp\ 60{,}000{,}000$$
$$\text{Total EOC} = Rp\ 92{,}000{,}000 + Rp\ 60{,}000{,}000 = Rp\ 152{,}000{,}000$$

The total equipment operational cost was Rp 152,000,000.

Fuel Costs

In addition to operational costs, fuel costs were also included as one of the cost components during the hauling road redesign process. Fuel consumption was influenced by the duration of equipment operation during the redesign activities. Fuel usage for the excavator was 900 liters/shift, while the bulldozer consumed 400 liters/shift. The fuel cost calculations were as follows:

$$\text{Fuel Cost (Excavator)} = 900 \text{ liters} \times 5 \times Rp\ 14{,}000 = Rp\ 63{,}000{,}000$$
$$\text{Fuel Cost (Bulldozer)} = 400 \text{ liters} \times 5 \times Rp\ 14{,}000 = Rp\ 28{,}000{,}000$$
$$\text{Total Fuel Cost} = Rp\ 63{,}000{,}000 + Rp\ 28{,}000{,}000 = Rp\ 91{,}000{,}000$$

The total fuel cost was Rp 91,000,000.

Operator Labor Costs

Operator labor costs were one of the expense components incurred during the hauling road redesign process. In this study, operators were assumed to be vendor workers assigned specifically for the redesign activities, so labor costs were calculated based on the total working hours during the project. Wage calculations referred to Government Regulation Number 35 of 2021 concerning Fixed-Term Employment Agreements, Outsourcing, Working Hours and Rest Periods, and Employment Termination, where hourly wages are calculated as 1/173 of the monthly wage. Based on the research data, the Regional Minimum Wage (UMK) of Muara Enim Regency in 2026 was Rp 4,159,781/month, so the hourly operator wage was calculated as follows:

$$Uw = \frac{Rp\ 4{,}159{,}781}{173} = Rp\ 24{,}045/\text{hour}$$

During the hauling road redesign process, 8 operators worked for 5 shifts with a total working duration of 12 hours per shift, resulting in:

$$LC = Rp\ 24{,}045/\text{hour} \times 12 \text{ hours} \times 8 \times 5 = Rp\ 11{,}541{,}600$$

The total operator labor cost was Rp 11,541,600.

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Worker Consumption Costs

Worker consumption costs were additional expenses incurred during the redesign work. The calculation was based on the number of workers, number of shifts, and meal cost per worker. In this study, the meal cost was Rp 18,000/box for 8 workers over 5 shifts, resulting in:

$$\text{Consumption Cost} = 8 \times 5 \times Rp\ 18{,}000 = Rp\ 720{,}000$$

The total operator consumption cost was Rp 720,000.

Total Redesign Cost

The total redesign cost was obtained by summing all expenses incurred during the redesign process, including equipment operational costs, operator overtime costs, and worker consumption costs. The calculation was as follows:

$$\text{Total Cost} = Rp\ 152{,}000{,}000 + Rp\ 91{,}000{,}000 + Rp\ 11{,}541{,}600 + Rp\ 720{,}000$$
$$= Rp\ 254{,}261{,}600$$

Thus, the total redesign cost was Rp 254,261,600.

Table 13. Redesign Cost of OB PBT Hauling Road

No.	Redesign Cost Component	Total Cost
1	Excavator Operational Cost	Rp 92,000,000
2	Bulldozer Operational Cost	Rp 60,000,000
3	Excavator Fuel Cost	Rp 63,000,000
4	Bulldozer Fuel Cost	Rp 28,000,000
5	Operator Labor Cost	Rp 11,541,600
6	Worker Consumption Cost	Rp 720,000
Total Redesign Cost		Rp 254,261,600

A Benefit Cost Ratio (BCR) analysis was conducted to determine the economic feasibility of redesigning the overburden hauling road geometry at PT PBT. This analysis aims to compare the benefits obtained after the road redesign against the costs incurred during the redesign process. Based on the analysis results, it is known that the hauling road redesign provides operational cost savings of Rp 424,677,120 with a total redesign cost of Rp 159,933,500. The Benefit Cost Ratio value is calculated as follows:

$$\text{BCR} = \frac{Rp\ 424.677.120}{Rp 254.261.600} = 1{,}67$$

The calculation results show that the Benefit Cost Ratio (BCR) value is 1.67. This value indicates that the hauling road redesign is feasible to implement because the benefits obtained are greater than the redesign costs incurred. Redesigning the hauling road geometry can improve the operational efficiency of hauling equipment by reducing operational costs, increasing transport productivity, and improving the condition of the hauling road for overburden transport activities at PT PBT.

This study provides a practical evaluation framework that integrates haul road geometric assessment with hauling equipment performance and economic feasibility analysis. The proposed approach enables mining companies to prioritize haul road improvements based on both engineering

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performance and economic return, thereby supporting more effective operational decision-making (Dimas et al., 2024).

From an academic perspective, this study extends previous mine haul road research by integrating technical feasibility, operational performance, fuel efficiency, and economic evaluation into a single analytical framework (Arif et al., 2024). This integrated approach contributes to a more comprehensive understanding of the relationships among haul road geometry, hauling productivity, fuel consumption, and operational cost in open-pit mining operations.

CONCLUSION

Based on the results of the study, the following conclusions can be drawn: Based on the evaluation of the geometric parameters of the OB hauling road at PT PBT, it was found that most parameters did not meet the applicable technical standards. The actual straight road width ranged from 17.8–19.1 m, which was below the standard requirement of 22.75 m, while the curve width of 17.1 m was also below the required standard of 23 m. The road grade reached 9%, exceeding the ideal operational limit of 8%, whereas the superelevation value of 4.7% still complied with the standard (≤ 5%). These non-conforming conditions increased hauling resistance, thereby reducing hauling equipment speed and increasing cycle time. Improvements to road geometry through redesign were proven to enhance hauling equipment performance and production productivity. Hauling equipment productivity increased from 108.34 BCM/hour to 130.69 BCM/hour, representing an increase of 20.63%. This improvement also affected daily production productivity, which increased from 5,349.83 BCM/day to 6,453.38 BCM/day, or by 1,103.55 BCM/day. On a monthly basis, production increased from 149,795.1 BCM/month to 180,694.60 BCM/month. This increase was influenced by the reduction in cycle time from 13.45 minutes to 11.15 minutes as a result of improved road width and more optimal grade control. Fuel consumption has a direct influence on operational costs and the efficiency of the hauling system. The results of the study indicate that fuel consumption decreased from 441.88 liters/hour to 396.74 liters/hour, representing a reduction of 10.21%. This reduction resulted in fuel operational cost savings of IDR 631,960/hour, equivalent to IDR 15,167,040/day and IDR 424,677,120/month. These findings demonstrate that improved road conditions can reduce engine workload, enhance fuel efficiency, and significantly lower operational costs.

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