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Dump truck productivity enhancement through haul road geometry correction: a rimpull-based cycle time simulation

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ABSTRACT

This study aimed to evaluate haul road geometry on the overburden route of Pit B at a coal mining contractor in Sarolangun, Jambi, Indonesia, and to estimate dump truck cycle time and productivity after geometry correction. An observational-evaluative field design was applied: 48 cross-sections of a 523.82 m road were surveyed with a Total Station and assessed against the Indonesian good mining practice decree, 30 truck trips were timed, and the corrected condition was simulated with a rimpull-resistance model. Only 18.75% of cross-sections met the study design criterion for two-lane width, the steepest descent reached -21.68% against a 12% limit, 45.8% met the cross-slope range on a two-side mean basis, and all curve radii complied. Delays caused by narrow and steep sections made up 69.2% of total delay. Correcting grade and width was predicted to reduce the cycle time from 11.99 to 9.47 minutes (21.0%; 95% bootstrap interval 20.1–21.9%) and to raise truck productivity from 32.06 to 40.60 bank cubic metres per hour (26.6%). If only half of the assumed speed gains were realised, the reduction would fall to 14.7%. These are simulation-based predictions that require field validation after road correction.



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Introduction

Surface coal mining depends on an efficient material transport system, and the haul road is the most critical infrastructure supporting that system. In Indonesia, the Decree of the Minister of Energy and Mineral Resources No. 1827 K/30/MEM/2018 on good mining engineering practice requires haul roads to satisfy geometric requirements on road width, longitudinal grade, cross slope, curve radius and superelevation, adjusted to the dimensions and operating speed of the haul trucks (Kementerian Energi dan Sumber Daya Mineral [Kementerian ESDM], 2018). These requirements serve two purposes at once: they keep the haulage cycle efficient and they protect the personnel and equipment that operate on the road.

Geometry that falls below the standard affects truck performance directly. A road narrower than the minimum can force trucks to wait when passing, while a steep grade increases grade resistance and reduces attainable speed. These effects lengthen haulage cycle time and reduce productivity (Baek & Choi, 2017; Chanda & Gardiner, 2010; Maior et al., 2025). Studies in Indonesian mining have reported similar practical effects: Imammuti and Andas (2024) reported longer truck travel time on a road with non-ideal geometry. The present study extends this evidence by separating geometry-related delay from the travel-time component of the cycle.

International studies have quantified the link between road condition and haulage performance. Coffey et al. (2019) related haul-road pavement performance to truck energy consumption, while Golbasi and Kina (2022) and Tadubana et al. (2024) identified road, speed, payload and operating conditions as important factors in haul-truck fuel consumption, and Wang et al. (2021) modelled open-pit truck fuel consumption patterns from multi-dimensional features. Awuah-Offei (2016) and Sahoo et al. (2014) likewise showed that operating conditions, vehicle characteristics, payload, speed and mine gradient influence haulage energy efficiency. Liu and Chai (2019) optimised open-pit truck routes by minimising time-varying transport energy consumption, and Agosti et al. (2022) examined optimal slope profiles in relation to profitability and emissions. Siامي-Irdemoosa and Dindarloo (2015) further demonstrated the importance of travel and idle components in predicting dump-truck fuel consumption. Meneses and Sepúlveda (2023) used discrete-event simulation to show that progressive road deterioration reduces truck productivity, while Maior et al. (2025) quantified the combined influence of grade and rolling resistance on cycle time and productivity. Baek and Choi (2017) showed that truck speed decreases as grade rises. More recent work has expanded this line of research to road construction and maintenance effects (Dudek et al., 2025; Shakenov et al., 2026a, 2026b), fleet energy management (Mesa et al., 2025), and alternative haul-truck technologies (Nasirinezhad et al., 2025; Tokac et al., 2025; Vera-Burau et al., 2023). Studies on haul-road structural design have likewise compared design methods and stressed the role of the surface layer (Ercins & Bostancıoğlu, 2025; Gouda, Reddy, Srinivasan, & Butle, 2024).

PT Duta Karya Kontraktor operates as a mining contractor at the PT Sarwa Sembada Karya Bumi concession in Sarolangun Regency, Jambi Province. In Pit B, overburden is hauled by Shacman F3000 6×4 dump trucks from the loading front to an in-pit dump along a two-lane road about 524 m long, with a design speed of 20 km/h adopted for the analysis. A preliminary Total Station survey indicated that the road did not fully meet the standard: the average grade of the segment nearest the front reached -16.79%, well beyond the 12% maximum, and several sections appeared too narrow for two-lane traffic, so trucks often waited for each other when passing. In March 2026, the month of data collection, overburden removal reached only 78,715.84 BCM of a planned 117,074.12 BCM (67.23%). Although many operational factors contribute to such a shortfall, road geometry that lengthens truck travel time was suspected to be one of them.

Despite this body of work, three limitations remain. First, previous haul-road studies commonly evaluate geometry against design criteria or model the overall effect of road conditions on haulage performance, but fewer studies separate the cycle into travel and delay components (Baek & Choi, 2017; Chanda & Gardiner, 2010; Maior et al., 2025). Second, studies on truck loading, scheduling and dispatching have generally focused on fleet utilisation, waiting time, route allocation or production optimisation rather than isolating the delay caused by a lane-width deficit (Alarie & Gamache, 2002; Ataepour & Baafi, 1999; Chang et al., 2015; Icarte-Ahumada et al., 2026; Noriega et al., 2025; Osses Aguayo et al., 2022; Tapia et al., 2020; Wang et al., 2023). Third, recent simulation and field studies have demonstrated the importance of haul-road condition for productivity, energy use and cycle time, but the combined separation of width-related stopping delay and grade-related speed loss remains limited (Maior et al., 2025; Meneses & Sepúlveda, 2023; Shakenov et al., 2026a, 2026b). This study addresses that gap for the Pit B road of PT Duta Karya Kontraktor.

Therefore, the objective of this study was to measure the compliance of the Pit B haul road geometry with the decree, to quantify the share of the actual cycle time that is lost to geometry-related delay, and to estimate how cycle time and truck productivity would change if grade and width were corrected. Specifically, it addressed three questions: (1) to what extent does the actual road geometry comply with the standard in terms of width, grade, cross slope, curve radius and superelevation; (2) how much of the actual cycle time of the Shacman F3000 6×4 is lost to delays attributable to non-compliant geometry; and (3) how much would the cycle time and truck productivity change if grade and width were corrected? The study used an observational–evaluative design with three linked parts: a cross-sectional audit of the whole road, a time study of 30 truck trips, and a deterministic simulation of the corrected condition. This design was chosen because the corrected road had not been built, so a before–after comparison or a controlled intervention was not possible. Because the road was audited in full and the analysis is descriptive, a power analysis was not applicable; the adequacy of the cycle time sample was checked with a data sufficiency test instead (see Method). The working hypothesis was that correcting grade and width would remove the geometry-related delays and shorten the loaded and empty travel times, thereby reducing the cycle time and increasing truck productivity.

The novelty of this study is methodological and responds directly to the three limitations above. It links segment-level geometry evaluation, separate measurement of geometry-related delays (D1 and D2) and non-geometry delays (D3), and a rimpull–resistance simulation within a single field-based framework. Rather than relating geometry to productivity in aggregate, it isolates the delay components that geometry correction can remove and those it cannot, including the delay caused by a lane-width deficit, which gives a more realistic estimate of the attainable improvement, and it produces segment-specific design targets that the company can

adopt directly. Because the corrected geometry was not constructed during the study, the simulated improvement is a prediction that requires validation through repeated field measurement after road correction.

Method

This study employed an applied quantitative approach with an observational-evaluative design consisting of a cross-sectional audit of the road geometry, a time study of truck trips and a deterministic simulation of the corrected condition. Field measurements were used to characterise the actual road geometry and truck cycle time, which were then compared with the standard, and the cycle time after correction was simulated numerically. The study was conducted on the overburden haul road of Pit B, PT Duta Karya Kontraktor, Bukit Peranginan Village, Mandiangin District, Sarolangun Regency, Jambi Province (UTM Zone 48S), within the concession of PT Sarwa Sembada Karya Bumi. The population comprised the overburden haulage activities on this road; the full road length and one loading fleet, consisting of a Kobelco SK380XDLC excavator and three Shacman F3000 6×4 trucks (No. 24, 27 and 29), were purposively selected because they served the front and in-pit dump under study throughout the observation period. Because the study describes this specific route and fleet and does not test a hypothesis about a larger population, no power analysis was performed. Instead, the adequacy of the 30 observed trips (10 per truck) was assessed with a data sufficiency test and a between-truck comparison (see Results and Discussions), and the findings are limited to this fleet. Field data were collected in March 2026. The workflow is summarised in Figure 1.

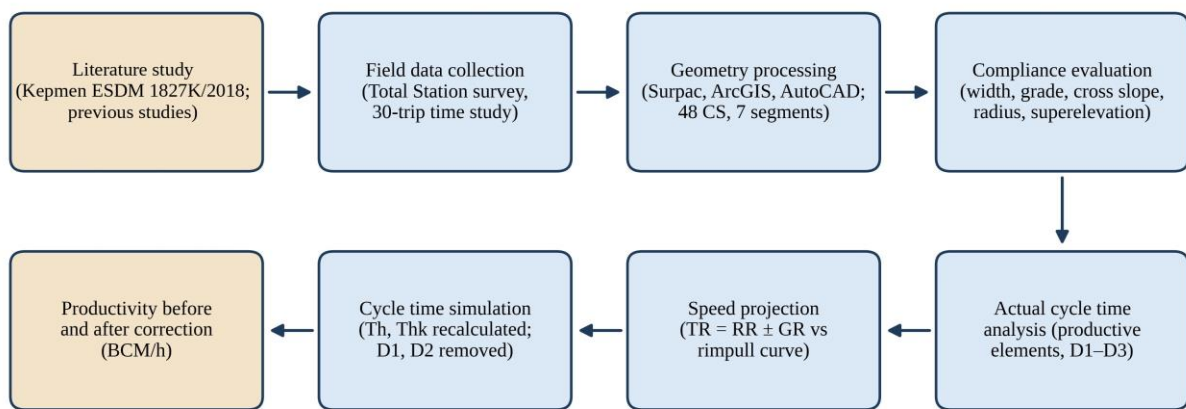


Figure 1. Research workflow

The object of the geometry survey was the entire road from the loading front to the in-pit dump. A Total Station recorded 227 three-dimensional points along the road. After cleaning, 47 points were removed: 46 lay on side branches or ramps outside the main haul route, identified by re-checking the two-dimensional layout, and one was an unpaired right-edge point without its centre-line and left-edge partners. Because the removed points are not part of the road under study, their removal cannot bias the geometric parameters of the main route, and all of them were retained in the data file for audit. The remaining 180 points formed 48 complete cross-sections (CS) over a centre-line length of 523.82 m, with one survey gap of 30.81 m between CS 20 and CS 21. The points were measured with an EFIX ETSR4 total station in prism mode, whose nominal accuracy according to the manufacturer's specification (EFIX Geomatics Co., Ltd., 2023) is 2" for angles and 2 mm + 2 ppm for distances measured with a single prism. The company calibrates the instrument once a year, but the calibration record was not available to the authors and the repeated-measurement precision of the instrument was not recorded, so the actual measurement error could not be estimated statistically; the robustness of the findings to measurement error was instead examined through a sensitivity analysis (see Results and Discussions). The road was divided into seven segments (SG1–SG7) at changes in cumulative azimuth along the chainage. A minimum segment length of 50 m was adopted as a methodological criterion set by the authors, not as a standard value. It was justified by the survey data: the mean spacing between cross-sections was 11.15 m, so 50 m gives about four to five cross-section intervals per segment for a stable average, equals about 5.6 truck lengths (8.967 m), and is travelled in about 9 s at the design speed of 20 km/h. A sensitivity test of the threshold from 0 to 90 m showed that the number of segments stayed at seven for thresholds of 35–55 m, so the segmentation is stable around the adopted value. SG3 contains only three cross-sections because of the survey gap noted above. Because segment averaging smooths short bends, the local curve radius was also checked at cross-section level from three consecutive centre-line points. The coordinates were processed in Surpac, ArcGIS and AutoCAD, and the calculations were performed in Microsoft Excel. Secondary data comprised the specifications of the

Shacman F3000 6×4 truck and the Kobelco SK380XDLC excavator, the Pit B map, and the March 2026 working-hour records of trucks No. 24, 27 and 29 from the company's maintenance dashboard.

The maximum road grade of 12% was adopted from Kepmen ESDM No. 1827 K/30/MEM/2018, while the minimum two-way haul road width was calculated based on the regulation's requirement of 3.5 times the width of the largest haul truck. Other geometric parameters, including the design width for straight and curved sections, cross slope, curve radius, and superelevation, were determined using applicable study and design criteria. For the Shacman F3000 6×4 with a width of 3.469 m, the regulatory width requirement gives 12.14 m (Kementerian ESDM, 2018). For a more detailed geometric assessment, this study also applied AASHTO-based design formulas using the truck dimensions, as applied by Imammuti and Andas (2024) and Baek and Choi (2017). The minimum width of a straight two-lane road was calculated with Equation 1 and the minimum width on curves with Equation 2, where n is the number of lanes (2), Wt is the truck width (3.469 m), U is the wheel track (1.99 m), Fa and Fb are the front and rear overhang widths (1.255 m and 2.95 m), Z is the edge clearance and C is the clearance between passing trucks, both taken as half of $(U + Fa + Fb)$, or 3.098 m. These calculations gave study design criteria of 16.23 m for straight segments and 21.68 m for curves. The 12.14 m value from the decree was retained as a less-demanding regulatory reference in the sensitivity check.

$$Lmin = n \cdot Wt + (n + 1) \cdot C \quad (1)$$

$$Wmin = n \cdot (U + Fa + Fb + Z) + C, \text{ with } C = Z = 0.5 \cdot (U + Fa + Fb) \quad (2)$$

Grade was calculated with Equation 3, where Δh is the elevation difference and Δx is the horizontal distance between two points, and was evaluated by its absolute value. The decree requires a cross fall of at least 2%; for the detailed evaluation, this study adopted a 2–4% design range, and each side of the road was assessed separately because each side drains independently and an average can conceal a non-compliant side. The minimum curve radius was calculated with Equation 4 using the 20 km/h design speed adopted for this analysis, a maximum superelevation $emax = 0.08$ and a friction coefficient from the AASHTO-based relationship $f = -0.00065V + 0.192 = 0.179$, which gave $Rmin = 12.16$ m. The theoretical superelevation was calculated as $e = V^2/(127R)$, and the actual superelevation was judged adequate if it reached the theoretical value without exceeding the 8% maximum (Imammuti & Andas, 2024). Where the actual superelevation fell short, the speed at which the curve remains safe was checked as $V = [127R(e + f)]^{0.5}$.

$$Grade (\%) = (\Delta h / \Delta x) \times 100 \quad (3)$$

$$Rmin = V^2 / [127 \times (emax + f)] \quad (4)$$

The cycle time was observed with a stopwatch over 30 trips under normal operating conditions, 10 trips each for trucks No. 24, 27 and 29. The actual cycle time (CT) was calculated with Equation 5 (Mnzool et al., 2024), where Tml is manoeuvre loading, Tl loading, Th loaded hauling, Tmd manoeuvre dumping, Td dumping and Thk empty return. Three delay components were recorded separately: D1, queuing because the road was too narrow for passing; D2, holding speed on the steep SG1 descent; and D3, queuing at the loading point. Data uniformity was checked with the coefficient of variation (CV), and elements with CV below 15% were considered uniform.

$$CT = Tml + Tl + Th + Tmd + Td + Thk \quad (5)$$

The cycle time after correction was simulated by recalculating Th and Thk . For each segment, the total resistance was calculated with Equation 6 for the actual grade and for the corrected grade, where RR is rolling resistance and GR is grade resistance (Alegre et al., 2021; Maior et al., 2025). Each total resistance was matched against the manufacturer's rimpull–speed curve of the Shacman F3000 6×4 to obtain the attainable speed. Travel time was then calculated with Equation 7, where d is the segment length (km) and v is the projected speed (km/h) (Mnzool et al., 2024). Delays D1 and D2 were set to zero in the corrected condition because they arise from road width and grade, whereas D3 was retained because it depends on loading-point management rather than road geometry. Manoeuvre, loading and dumping times were held at their observed means because they do not depend on road geometry.

$$TR = RR \pm GR \quad (6)$$

$$t = (d / v) \times 60 \quad (7)$$

Truck productivity was calculated with Equation 8 (Chanda & Gardiner, 2010), where Q is productivity (BCM/h), CT is cycle time (minutes), n is the number of bucket passes, Kb is bucket capacity, Eff is job efficiency, SF is the swell factor and FF is the fill factor. The parameters were held constant: $n = 7$ from field observation; $Kb = 1.6$ m³, the midpoint of the manufacturer's 1.40–1.80 m³ range for the Kobelco SK380XDLC, because the bucket of the operating unit was not verified individually; $Eff = 87.18\%$, the average of the three

trucks in March 2026; and SF = 81% and FF = 81%, both treated as fixed assumptions for the wet-clay operating condition because actual material swell and bucket fill were not measured. These assumptions were held constant between the observed and simulated cases; therefore, the comparison isolates the effect of cycle-time change, while the absolute productivity value remains dependent on these assumptions. Holding these parameters constant meant that any change in productivity reflected only the change in cycle time.

$$Q = (60 / CT) \times n \times Kb \times Eff \times SF \times FF \quad (8)$$

Two assumptions limit the method. The projected speeds were derived analytically from the rimpull–resistance relationship rather than measured on a corrected road, and other operating conditions, such as fleet size and traffic management, were assumed unchanged. Geotechnical stability, drainage design, fuel consumption and road construction cost were outside the scope of the study. Accordingly, the analysis was primarily descriptive and evaluative. Descriptive statistics, 95% confidence intervals (Student's *t* for means and Wilson for proportions) and, for road width only, a one-sample *t*-test and a Wilcoxon signed-rank test of the width deficit against the required minimum were used to show how strongly the measured values depart from the standard. Because adjacent cross-sections along one road are spatially correlated, these *p*-values are indicative rather than confirmatory. Robustness to measurement error was assessed by shifting widths by ± 0.50 m and grades by ± 1 and ± 2 percentage points and recounting the non-compliant sections. The adequacy of the cycle time sample was tested with the data sufficiency formula $N' = [(k/s) \cdot \sqrt{(N\sum x^2 - (\sum x)^2)/\sum x}]^2$, with $k = 2$ (95% confidence) and $s = 5\%$ precision, and homogeneity among the three trucks was tested with one-way ANOVA. Uncertainty of the simulated cycle time was expressed in two ways: a 95% percentile bootstrap interval from 10,000 resamples of the 30 trips, which reflects sampling variation only, and a scenario analysis in which the speed gains assumed in the simulation were realised at 100%, 75%, 50% and 0% (removal of delays D1 and D2 only), which reflects uncertainty in the model assumption. The sample size for the proposed field validation was estimated for a two-sample comparison of cycle time ($\alpha = 0.05$, power 80%) with the observed standard deviation. The simulated cycle time and productivity are interpreted as predicted improvement rather than field-validated results.

Results and Discussions

The 48 cross-sections formed seven segments, five curves and two straights, as shown in Figure 2. SG1 lies at the north-eastern end near the loading front and SG7 at the western end near the in-pit dump. The geometric characteristics of each segment are summarised in Table 1 and plotted against the applicable criteria in Figure 3.

Table 1. Geometric characteristics of the haul road segments

Segment	Type	Length (m)	Arc radius (m)	Avg. width (m)	Study width criterion (m)	Grade (%)
SG1	Curve	78.47	53.45	8.21	21.68	–16.79
SG2	Curve	59.09	63.50	14.67	21.68	–3.89
SG3	Curve	57.63	44.79	28.10	21.68	1.34
SG4	Straight	64.46	740.10	14.20	16.23	1.13
SG5	Curve	87.14	62.63	11.05	21.68	1.91
SG6	Straight	106.83	238.48	16.05	16.23	–0.38
SG7	Curve	70.20	89.21	11.83	21.68	7.99
Total / mean	–	523.82	–	12.97	–	–

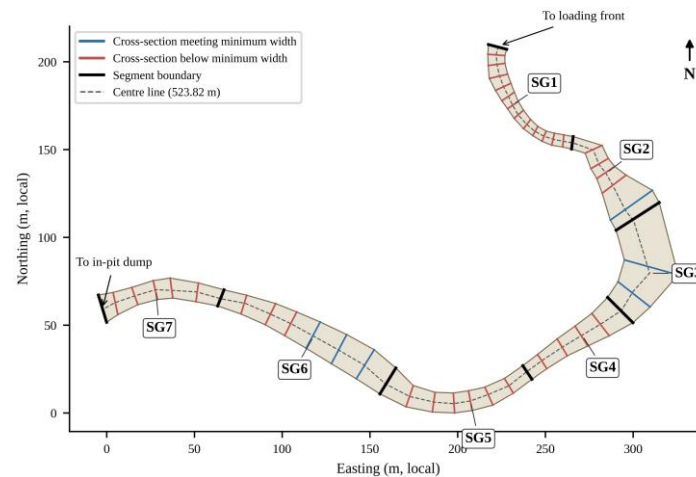


Figure 2. Plan view of the Pit B haul road drawn from the Total Station survey, showing the seven segments and the width compliance of each cross-section

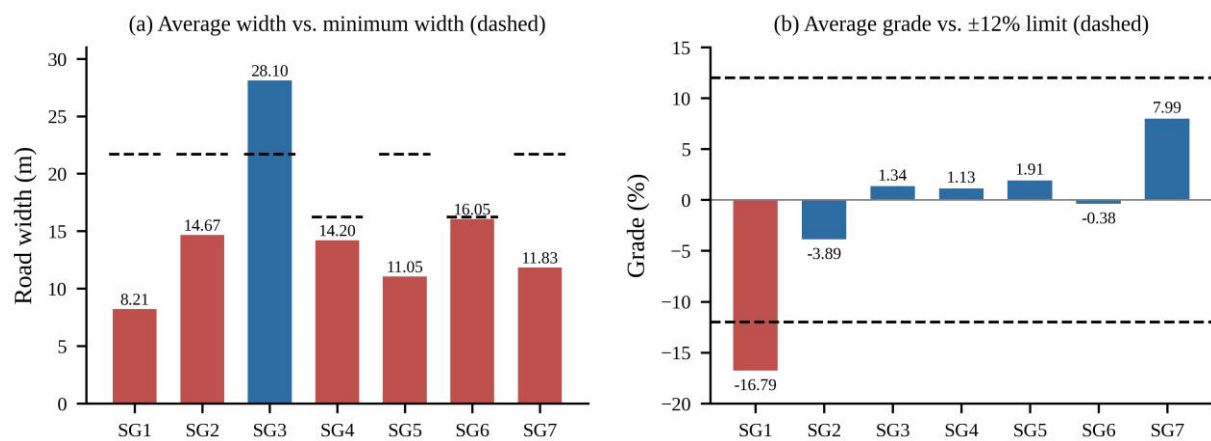


Figure 3. Average width (a) and average grade (b) of each segment against the applicable criteria; red bars do not comply

The average width of the whole road was only 12.97 m, below the study design criteria of 16.23 m for straight segments and 21.68 m for curves. SG1 was the most critical segment: its average width of 8.21 m was only 38% of the curve requirement, and its average grade of -16.79% exceeded the 12% limit. Within SG1, ten consecutive sub-segments exceeded the limit with an average of -18.31%, and the steepest point reached -21.68%. SG3 met the width requirement on average, but only because the road widens at a junction (CS 19–22); the normal carriageway there is narrower. SG6 came close to the straight-road minimum (16.05 m against 16.23 m). Across the 48 cross-sections the mean width was 12.97 m (SD 5.93 m; 95% CI 11.25–14.69 m), and the mean deficit against the applicable minimum was 7.35 m (95% CI 5.35–9.35 m; one-sample t-test, $t(47) = -7.40$, $p < 0.001$; Wilcoxon signed-rank, $p < 0.001$). Widths ranged from 6.02 m to 31.84 m, and three cross-sections in SG1 (CS 9–11) were narrower than two truck widths side by side (6.94 m), where passing is physically impossible. Table 2 summarises compliance at cross-section level.

Table 2. Compliance of haul road geometry with the applicable regulatory and study criteria at cross-section level ($n = 48$)

Parameter	Actual value	Applicable criterion	Compliant CS	Remark
Road width	Mean 12.97 m	≥ 16.23 m (straight); ≥ 21.68 m (curve)	9 (18.75%)	Most sections below two-lane minimum
Grade	-16.79% to 7.99% (segment means)	$\leq 12\%$ (absolute)	10 SG1 sub-segments exceed	Steepest point -21.68% in SG1
Cross slope	Mean 3.05%	$\geq 2\%$ regulatory minimum; 2–4% study range, each side	22 (45.8%) by two-side mean; 4 (8.3%) on both sides	Uneven cross fall

Parameter	Actual value	Applicable criterion	Compliant CS	Remark
Curve radius	44.79–89.21 m	≥ 12.16 m	48 (100%)	All above minimum
Superelevation	2.4–4.1% (curve means)	$\geq$ theoretical (3.5–7.0%); $\leq 8\%$	1 of 5 curves (SG7)	Below theoretical, but safe at operating speed (SG3 safe to ≈ 34 km/h)

Road width was the parameter with the lowest compliance against the study design criteria: only 9 of the 48 cross-sections (18.75%; 95% CI 10.2–31.9%) met the two-lane minimum. Cross slope was the second weakest parameter, with 22 cross-sections (45.8%; 95% CI 32.6–59.7%) having a two-side mean within the 2–4% range; only four cross-sections had both sides within the range, and the 26 cross-sections outside it were evenly split between too flat (13) and too steep (13), so drainage across the road surface was uneven. Every curve radius exceeded the 12.16 m minimum. Because segment averaging smooths short bends, local radii were also checked: nine cross-sections had local radii below 36.5 m (three times the minimum), and the smallest, 12.70 m at CS 15, exceeded the minimum by only 0.54 m. Superelevation reached the theoretical value for the 20 km/h design speed only at SG7; at the other four curves the actual values (2.4–2.9%) were below the theoretical values (5.0–7.0%). These curves are nevertheless safe at the observed operating speed of 10–14 km/h: even the tightest curve, SG3 with a radius of 44.79 m, remains safe up to about 34 km/h. Superelevation and radius therefore did not constrain truck speed, and superelevation was not included in the cycle time simulation. During the survey, safety berms were also found missing at 30 cross-sections, mostly in SG4–SG7. Although berms were outside the scope of the cycle time analysis, this finding is relevant to the company's safety obligations.

The width finding should be interpreted against two levels of criterion. The decree requires at least 12.14 m for a two-way road for the 3.469 m-wide truck, whereas the 16.23 m straight-road and 21.68 m curve values are the additional geometric design criteria used in this study. Even under the less demanding 12.14 m regulatory criterion, 30 of the 48 cross-sections (62.5%) remained below the minimum. Under the study design criteria, 9 of 48 cross-sections (18.75%) complied. Other Indonesian studies adopted different minimum widths for their own fleets, so compliance rates are not directly comparable without considering truck dimensions and the formula used. Under the 12.14 m criterion, SG1 (all 13 cross-sections) and SG5 (6 of 7) remained narrow. The result is also robust to measurement error: shifting every width by ± 0.50 m changed the number of cross-sections compliant with the study design criteria from 9 to at most 17.

The deviations also carry safety implications beyond cycle time, which are inferred here from the geometry and are not based on incident records. In SG1, the average width of 8.21 m (6.02–10.76 m) leaves little clearance between two 3.469 m wide trucks, and at CS 9–11 passing is not physically possible, so one truck must stop, which is the D1 delay. Where two trucks do pass in the remaining narrow stretches, the lateral clearance is small enough to raise the risk of side contact or head-on conflict, which is the operational reason for the two-lane minimum. The same segment combines an average descent of -16.79% (steepest sub-segment -21.68%) with a curve of 53.45 m radius, so grade resistance, braking demand and limited lateral clearance coincide. Because a loaded truck on a long descent relies on its retarding and service brakes while also steering through the curve, any loss of speed control there would leave little room to avoid an oncoming truck; this collision risk is inferred from the geometry and was not observed in the study. Maior et al. (2025), citing Thompson and co-workers, report a recommended maximum longitudinal gradient of 10% that ensures safe trafficability and note that inconsistent gradients require frequent gear shifts that affect vehicle speed, and Shakenov et al. (2026a) use braking instability and grade severity, together with fuel-use burden, to rank the criticality of haul road segments; a mean descent about 1.4 times the 12% limit therefore potentially raises braking demand and reduces the margin for error. SG5 and SG7 are only about 11–12 m wide on average, roughly half of the 21.68 m curve requirement, and they lie within the SG4–SG7 stretch where safety berms were missing at most cross-sections. Baek and Choi (2017) describe the berm as the structure that prevents trucks from running over the edge and helps drivers recognise the lane. The decree requires a berm of at least three-quarters of the tyre height (0.84 m for the 12.00R20 tyre, nominal diameter 1.122 m), yet only 9 of the 18 cross-sections that had a berm reached it. Narrow carriageways with missing or low berms thus represent a potential run-off hazard that the cycle time analysis does not capture, and the cross-slope deviations, with 13 cross-sections too flat to drain and 13 steeper than 4%, add a drainage concern.

The remaining non-compliant segments carry lower but still relevant risks. SG2 is a curve of 63.50 m radius with an average width of 14.67 m (68% of the 21.68 m requirement) and a gentle descent of -3.89% , so the shortfall mainly reduces clearance between opposing trucks on a bend where sight distance is potentially limited, and it contributes to the queuing recorded as D1. SG4 is a straight section 64.46 m long with an average width of 14.20 m against 16.23 m (87%) and a nearly flat grade (1.13%), so the risk is limited to reduced passing clearance and not to braking demand. SG6 falls short by only 0.18 m (16.05 m against 16.23 m) on a gentle

grade (−0.38%) and poses the smallest hazard, which agrees with the minor widening recommended for it. SG3 complies with the width requirement (28.10 m), but its 44.79 m radius is the tightest curve on the road, so it should be maintained as a transition area.

The pattern of non-compliance is consistent with the mechanism reported in the literature. Imammuti and Andas (2024) measured substantial grade deviation on an Indonesian haul road, while Chanda and Gardiner (2010) and Maior et al. (2025) showed that road characteristics, grade and rolling resistance affect truck cycle time and productivity. The Pit B road differs in the severity of the SG1 descent and in the share of narrow cross-sections. Moreover, unlike evaluations that stop at compliance or aggregate travel time, the present analysis separates geometry-related delay from the delay that is not caused by road geometry.

The elements of the actual cycle time are given in Table 3. All six productive elements had a CV below 15%, so the 30 trips were uniform. Loading was the longest element (191.64 s), followed by hauling (181.99 s) and return (135.16 s). Beyond these productive elements, the three delay components averaged 31.80 s for D1, 27.83 s for D2 and 26.56 s for D3. The resulting actual cycle time was 719.27 s (SD 48.75 s; 95% CI 701.06–737.47 s), or 11.99 minutes per trip (95% CI 11.68–12.29 minutes). The data sufficiency test (95% confidence, 5% precision) required at most 8 trips for loading, hauling, return and the total cycle time, and 29, 32 and 34 trips for loader manoeuvre, dumper manoeuvre and dumping. The last two slightly exceed the 30 observed trips, but these elements do not depend on road geometry and were left unchanged in the simulation; at 10% precision every element needed at most 9 trips. Cycle times did not differ among the three trucks (one-way ANOVA, $F = 0.37$, $p = 0.70$), which supports treating them as representative of this route, although the conclusions remain limited to this fleet.

Table 3. Actual cycle time elements and data uniformity (30 trips)

Element	Mean (s)	Standard deviation (s)	CV (%)	Uniformity
Manoeuvre loading (Tml)	44.82	6.11	13.64	Uniform
Loading (Tl)	191.64	10.51	5.49	Uniform
Hauling (Th)	181.99	6.81	3.74	Uniform
Manoeuvre dumping (Tmd)	39.36	5.64	14.34	Uniform
Dumping (Td)	40.11	5.91	14.73	Uniform
Return (Thk)	135.16	5.88	4.35	Uniform

Delays D1 and D2 can be traced directly to the geometric deficiencies. D2 occurred because drivers had to hold the loaded and empty trucks at low speed on the SG1 descent, which is steeper than the 12% limit. D1 occurred because, at cross-sections narrower than the two-lane minimum, one truck had to stop and wait while the other passed. Together, D1 and D2 accounted for 59.63 s of the 86.19 s total delay (69.2%). D3, queuing at the loading point, is a matter of loader–truck management rather than road geometry. Thus, non-compliant grade and width were the direct cause of most of the delay that lengthened the cycle time, consistent with the established influence of road geometry, resistance and truck operating conditions on cycle time (Alegre et al., 2021; Baek & Choi, 2017; Maior et al., 2025). On the basis of this evaluation, a target geometry was set for each segment, focusing on width and grade because these two parameters affect travel time directly (Table 4).

Table 4. Recommended geometry targets for each segment

Segment	Type	Actual width (m)	Target width (m)	Actual grade (%)	Width status	Priority
SG1	Curve	8.21	21.68	−16.79 (min −21.68)	Non-compliant	High – grade and width
SG2	Curve	14.67	21.68	−3.89	Non-compliant	Medium – width
SG3	Curve	28.10 ^a	21.68	1.34	Compliant	Low – maintain
SG4	Straight	14.20	16.23	1.13	Non-compliant	Medium – width
SG5	Curve	11.05	21.68	1.91	Non-compliant	High – width
SG6	Straight	16.05	16.23	−0.38	Non-compliant	Low – minor widening
SG7	Curve	11.83	21.68	7.99	Non-compliant	High – width

^a Widened by a junction (CS 19–22); the normal carriageway is narrower.

SG1 received the highest priority because it is the only segment that fails both grade and width. SG5 and SG7 were also ranked high because their widths are about half of the curve requirement. SG3 should be maintained as a transition area, and SG6 needs only minor widening. In the simulation, the rimpull–resistance matching showed that reducing the SG1 grade to 12% or less would raise the loaded truck speed on that segment from 8 km/h to 15 km/h. On SG2–SG5, where the normal carriageway is narrower than two lanes (including

SG3 outside the junction), meeting the two-lane width would raise the speed from 13 km/h to 18 km/h, since trucks would no longer need to slow down or stop for oncoming traffic. T_h and T_{hk} were then recalculated with Equation 7. Table 5 and Figure 4 compare the cycle time and productivity before and after the simulated correction.

Table 5. Cycle time and productivity before (actual) and after (simulated) geometry correction

Element	Actual	Simulated	Difference	Change (%)
Manoeuvre loading (s)	44.82	44.82	0.00	0
Loading (s)	191.64	191.64	0.00	0
Hauling (s)	181.99	125.21	-56.78	-31.2
Manoeuvre dumping (s)	39.36	39.36	0.00	0
Dumping (s)	40.11	40.11	0.00	0
Return (s)	135.16	100.32	-34.84	-25.8
Subtotal productive (s)	633.08	541.46	-91.62	-14.5
D1 – queuing on narrow road (s)	31.80	0.00	-31.80	-100
D2 – holding on steep SG1 (s)	27.83	0.00	-27.83	-100
D3 – queuing at loading point (s)	26.56	26.56	0.00	0
Total delay (s)	86.19	26.56	-59.63	-69.2
Cycle time (s)	719.27	568.02	-151.25	-21.0
Cycle time (min)	11.99	9.47	-2.52	-21.0
Productivity (BCM/h)	32.06	40.60	+8.54	+26.6

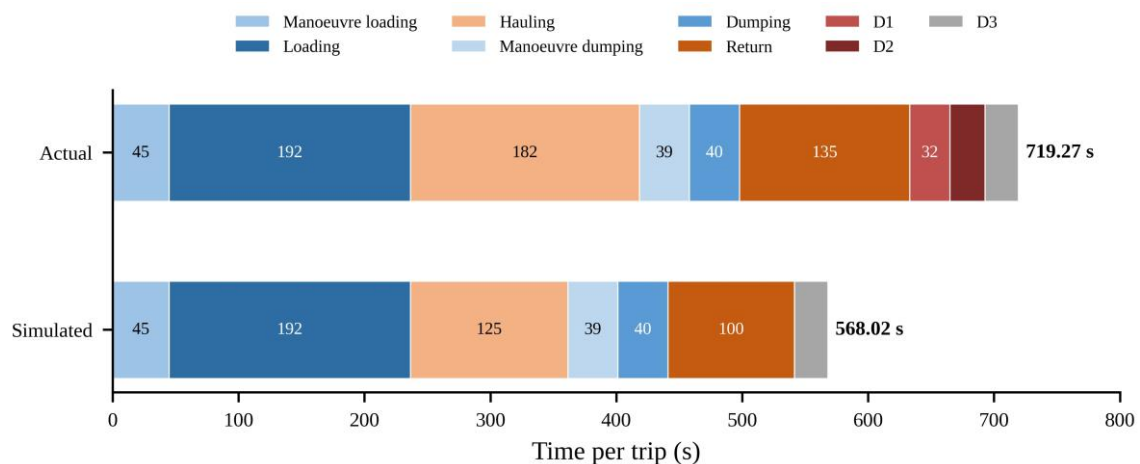


Figure 4. Composition of the cycle time per trip before and after the simulated geometry correction

The simulated correction reduced the cycle time from 719.27 s (11.99 minutes) to 568.02 s (9.47 minutes) per trip, a reduction of 151.25 s or 21.0%. The saving came from three sources: the removal of D1 and D2 (59.63 s), the shorter hauling time (-56.78 s, -31.2%) and the shorter return time (-34.84 s, -25.8%). Because the elements at the loading and dumping points were unaffected, the whole saving lies in the travel components between the front and the dump. With all other productivity parameters held constant, the shorter cycle time raised truck productivity from 32.06 to 40.60 BCM/h, an increase of 26.6%.

The precision of these predictions is limited by two sources. Sampling variation among the 30 trips is small: the 95% bootstrap interval was 20.1–21.9% for the cycle time reduction (post-correction cycle time 9.22–9.72 minutes) and 40.14–41.06 BCM/h for productivity (an increase of 25.2–28.1%). The larger uncertainty lies in the assumed speed gains (8 to 15 km/h on SG1 and 13 to 18 km/h on SG2–SG5), which come from rimpull–resistance matching and not from observation. When these gains were reduced to 75% and 50% of their assumed values, the cycle time reduction fell to 17.8% and 14.7% (9.85 and 10.23 minutes) and productivity rose to 39.03 and 37.57 BCM/h (+21.7% and +17.2%). If no speed gain occurred and only delays D1 and D2 were removed, the reduction was 8.3% (10.99 minutes) and productivity rose to 34.96 BCM/h (+9.0%). The predicted improvement therefore ranges from about 8% to 21% of the cycle time, and the headline figures of 21.0% and 26.6% are the upper end of this range, contingent on the assumed speeds. They are predictions and not field-validated results. For the proposed field validation, the observed standard deviation of the cycle time (48.75 s) implies that a two-sample comparison ($\alpha = 0.05$, power 80%) would need about 3, 5 and 12 trips per condition to detect reductions of 151.25 s (full speed gain), 105.7 s (50% of the speed gain) and 59.63 s (removal of delays

D1 and D2 only), respectively. At least 12 trips per condition, spread over all three trucks, are therefore recommended, and more would be needed if the variability after correction proved larger.

These results support the mechanism described in the literature. A steep grade adds grade resistance and reduces attainable speed, while insufficient width can introduce stopping or deceleration during passing (Alegre et al., 2021; Baek & Choi, 2017; Maior et al., 2025). Once the total resistance falls to the level allowed by a compliant geometry, the rimpull curve permits a higher speed. The 21.0% reduction found here is larger than the 15% reported by Maior et al. (2025) for grade and rolling-resistance optimisation, and the 26.6% productivity gain is larger than their 17%. A plausible explanation is that the Pit B road combines a grade well beyond the limit with a width deficit along most of its length, so the delays removed by correction made up a large share of the original cycle. The present result also illustrates why isolating delay components can give a different attainable improvement from estimates based only on aggregate travel time.

The mechanism is also consistent with international evidence. Baek and Choi (2017) showed that truck speed falls as grade rises, and Mnzool et al. (2024) confirmed that hauling time is governed by distance and speed, which explains why raising the loaded speed on SG1 from 8 to 15 km/h shortens T_h so strongly in the simulation. Meneses and Sepúlveda (2023) showed that progressive road deterioration reduces truck productivity, while Shakenov et al. (2026a, 2026b) associated haul-road degradation and maintenance with transport-cycle stability, cycle time and fuel consumption. Bodziony and Patyk (2024) and Bodziony et al. (2025) likewise demonstrated that road conditions influence truck operating time, energy consumption and reliability. Coffey et al. (2019), Sahoo et al. (2014), Golbasi and Kina (2022), Tadubana et al. (2024), Vera-Burau et al. (2023) and Mesa et al. (2025) further support the importance of road, speed, payload and operating conditions in haulage-energy performance. Fuel was outside the scope of this study, but correcting SG1 may provide a fuel benefit in addition to the time saving. The present analysis focuses instead on the directly observed cycle-time mechanisms and does not infer fuel savings from the simulation.

The productivity gain should be read in context. The values of 32.06 and 40.60 BCM/h apply to an individual Shacman F3000 6×4 truck in the studied fleet of one Kobelco SK380XDLC excavator and three trucks. The 67.23% achievement of the March 2026 overburden target is a company-wide figure that also depends on weather, equipment downtime and the number of operating units. The gain is therefore a real contribution of geometry correction to haulage performance, but not the only factor needed to close the gap to the production target. Two limitations also apply. The projected speeds come from an analytical rimpull–resistance relationship rather than from measurements on a corrected road, so actual speeds may differ with operator skill and weather. The cycle times also come from three trucks of one fleet observed during one month, and the Total Station calibration and precision were not recorded, so the results describe this road and fleet and should not be generalised without repeat measurement. In addition, the simulation assumes that fleet size and traffic management stay the same, so the result represents the potential effect of geometry alone. Further research should verify the speeds and cycle time after the correction is built and extend the analysis to the match factor between the excavator and the truck fleet.

Conclusions

The Pit B overburden haul road did not fully meet the applicable geometric criteria, with the main deficiencies occurring in two-lane width and grade near the loading front. Curve radii were adequate, while the observed superelevation remained sufficient for the truck operating speeds even though several curves did not reach the theoretical value for the adopted design speed. The evaluation showed that width-related queuing and speed holding on the steep descent were the main geometry-related sources of delay. The rimpull–resistance simulation indicated that correcting grade and width could improve haulage performance, but the magnitude of the improvement remained dependent on the assumed speed gains. The segment-specific targets therefore provide a basis for prioritising road correction, beginning with the steep and narrow section near the loading front. Because the corrected geometry was not constructed during the study, the simulated improvement should be verified through field measurements after the road correction is implemented.

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