Influence of Road Geometry and Surface Resistance on Heavy Vehicle Productivity: A Rimpull-Based Engineering Assessment

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ABSTRACT : *Road geometric design and surface conditions significantly influence heavy vehicle performance, particularly on unpaved industrial roads subjected to high axle loads. This study evaluates the influence of road geometry specifically grade and crossfall and surface resistance on heavy vehicle productivity using a rimpull-based engineering assessment. Total resistance was quantified by integrating grade resistance and rolling resistance to determine its impact on vehicle speed and cycle time. Field measurements were conducted to assess existing road conditions, followed by resistance modeling based on manufacturer rimpull performance curves. The results indicate that excessive grade and high rolling resistance substantially reduce effective rimpull utilization, leading to decreased travel speed and extended cycle time. After implementing road standardization measures, including geometric correction and surface improvement, total resistance was reduced, resulting in measurable productivity enhancement. The findings demonstrate that systematic road standardization based on resistance analysis can significantly improve heavy vehicle operational efficiency. This study provides a quantitative framework for integrating road engineering design parameters with vehicle performance modeling to optimize productivity.*

KEYWORDS – *Road Geometry ; Rolling Resistance ; Heavy Vehicle Productivity ; Rimpull Analysis*

I. INTRODUCTION

Road geometric design and surface conditions are critical determinants of heavy vehicle performance in transportation systems [1]. Longitudinal grade and cross-sectional elements significantly influence vehicle operating speed, traction demand, and overall operational efficiency. These effects become more pronounced on unpaved industrial roads subjected to high axle loads and repetitive haul cycles. Under such conditions, deviations from geometric standards and poor surface maintenance increase rolling resistance, thereby elevating total resistance acting against vehicle motion.

From a vehicle dynamics perspective, the resistance encountered by heavy vehicles during motion consists primarily of grade resistance and rolling resistance [2]. Grade resistance is governed by slope geometry, whereas rolling resistance is influenced by road surface roughness and material deformation characteristics [3]. Increased surface resistance substantially affects heavy vehicle operating costs, speed performance, and fuel efficiency, particularly on unpaved roads. When total resistance approaches available traction force, effective rimpull utilization declines, resulting in reduced travel speed and prolonged cycle time.

Although previous transportation engineering studies have investigated pavement roughness, geometric standards, and vehicle operating costs [4][5], limited research quantitatively integrates road geometric parameters with manufacturer-based rimpull performance curves to directly evaluate heavy-vehicle

productivity. In many industrial applications, productivity losses are often attributed to operational factors without systematically linking them to infrastructure-induced resistance through analytical modeling. This lack of integration represents a significant research gap in bridging road engineering design and heavy vehicle performance modeling.

Therefore, this study proposes a rimpull-based total resistance framework to quantitatively assess the influence of road geometry and surface resistance on heavy vehicle productivity. By integrating field-measured geometric data with resistance modeling and vehicle performance curves, this research establishes a direct analytical relationship between road standardization and measurable productivity improvement. The novelty of this study lies in positioning road standardization not merely as a maintenance practice, but as a quantifiable transportation engineering intervention that directly enhances heavy vehicle operational efficiency.

II. CONTRIBUTION

This study makes three principal contributions :

1) **Integrated framework linking road geometry and vehicle productivity.**
This research introduces an integrated analytical framework that links key road geometric parameters—particularly grade and crossfall—and surface-induced rolling resistance with heavy vehicle productivity through a rimpull-based total resistance model. Unlike conventional productivity assessments that primarily emphasize operational factors, this study explicitly quantifies the infrastructure–vehicle interaction mechanism.

2) **Application of rimpull performance curves in infrastructure evaluation.**
This study bridges a methodological gap by incorporating manufacturer-based rimpull performance curves into transportation infrastructure evaluation. By translating geometric deviations and surface conditions into measurable resistance increments and speed reductions, the framework establishes a direct analytical relationship between road standardization and vehicle performance.

3) **Road standardization as a measurable engineering intervention.**
The study demonstrates that haul road standardization can be treated as a quantifiable engineering intervention rather than merely a maintenance activity. The proposed framework enables civil and transportation engineers to evaluate how geometric corrections and surface improvements reduce total resistance and improve heavy vehicle operational efficiency.

III. PROPOSED METHOD

This study applies a resistance-based vehicle–road interaction framework to quantify the influence of road geometry and surface resistance on heavy vehicle productivity. The methodological procedure consists of six sequential stages: (1) field data acquisition, (2) geometric standard evaluation, (3) resistance modeling, (4) rimpull–tractive performance analysis, (5) productivity estimation, and (6) sensitivity analysis.

3.1 Field Data Acquisition
Field measurements were conducted to obtain existing road and operational parameters, including:
- Longitudinal Grade (%)
- Crossfall (%)
- Segment Distance (m)
- Surface Condition Classification
- Vehicle Gross Weight (GVW)
- Actual Cycle Time Components

Geometric parameters were measured along representative haul segments. Surface condition was evaluated based on material type, loose layer thickness, and observable deformation affecting rolling resistance.

3.2 Geometric Design Standard Reference
To define a standardized road scenario, measured geometric parameters were evaluated against national heavy-duty road design guidelines specified in Keputusan Menteri ESDM Nomor 1827 K/30/MEM/2018 [6].
This regulation provides technical limits for :
- Maximum allowable longitudinal grade

- Recommended crossfall for drainage stability
- Minimum road width for heavy vehicle manueverability

In this study, these parameters were adopted as engineering benchmarks for geometric compliance. Deviations between field measurements and prescribed limits were quantified. Segments exceeding recommended grade or exhibiting inadequate crossfall were classified as non-standard and incorporated into resistance recalculation scenarios.

Although derived from national regulation, these geometric thresholds are consistent with general heavy vehicle roadway design principles in transportation engineering practice.

3.3 Total Resistance Modeling

- Total Resistance (TR) is defined as:
$$TR(\%) = GR(\%) + RR\,(\%)$$

- Grade Resistance
$$GR(\%) = G$$
Where G is the measured longitudinal grade

- Rolling Resistance
$$RR(\%) = Cr$$
Where Cr represents the rolling resistance coefficient determined by surface condition.
For unpaved roads, rolling resistance values typically range between 2–10% depending on compaction and roughness conditions.

- Conversion to Tractive Force
Resistance percentage is converted into force :
$$Fr = \frac{Tr}{100}\ x\ W$$

where : Fr = Required tractive force (kN)
W = Vehicle gross weight (kN)

3.4 Rimpull-Speed Performance Analysis

Available rimpull force is obtained from manufacturer performance curves provided in equipment performance manuals [7]. Vehicle operating speed is determined by the intersection between required tractive force and available rimpull:
$$R_{available} \geq F_r$$
If total resistance increases, the vehicle shifts to a lower gear, reducing attainable speed. This relationship establishes a direct link between geometric deviation and speed reduction.

3.5 Cycle Time and Productivity Estimation

- Travel time per segment:
$$T = \frac{D}{V}$$

- Total cyle time:
$$CT = T_{load} + T_{travel\ loaded} + T_{dump} + T_{travel\ empty}$$

- Productivity
$$P = Payload\ x\ \frac{60\ (minutes)}{CT\ (minutes)}$$

Road standardization scenarios were simulated by adjusting grade and rolling resistance to comply with geometric benchmarks. The resulting changes in speed and cycle time were recalculated to determine productivity improvement:
$$\Delta P(\%) = \frac{P_{std} - P_{actual}}{P_{actual}}\ x\ 100$$

3.6 Sensitivity Analysis

A parametric sensitivity analysis was conducted by varying:

- Grade ($\pm$ 1-3%)
- Rolling resistance coefficient ($\pm$ 1-3%)

The impact on:

- Required tractive force
- Travel speed
- Cycle time
- Productivity

Was evaluated to identify the dominant parameter influencing heavy vehicle performance.

IV. RESULTS AND DISCUSSION
4.1 Existing Road Geometric Condition

Figure 1. Existing Road Condition

Figure 1 illustrates the existing haul road alignment connecting the pit area to the disposal location. Based on field observation, several sections of the road show significant deviations from the geometric standards recommended in **Kepmen ESDM No. 1827 K/30/MEM/2018 [6]**, particularly regarding road gradient and structural stability.

In the first segment (Point 1), the road gradient reaches approximately 13%, exceeding the recommended maximum gradient for safe haul truck operations as commonly discussed in haul road engineering studies [8]. Excessive gradients increase engine load, reduce vehicle stability, and elevate the risk of braking failure during downhill travel, which are widely recognized issues in mine haul road design guidelines [9].

Furthermore, several locations along the haul road (Points 2, 4, and 5) experienced road collapse, indicating inadequate slope stability and insufficient road structural support. These failures disrupt haulage activities and pose safety hazards for heavy equipment operations.

At Point 3, the road segment presents a gradient of approximately **10%**, which is still relatively steep for large haul trucks operating under heavy loads. Such conditions may reduce hauling efficiency and increase fuel consumption.

Overall, the existing haul road geometry does not fully comply with the recommended technical standards, particularly in terms of maximum road gradient and structural integrity. These deviations potentially contribute to reduced haulage productivity, increased operational risk, and frequent road maintenance requirements.

4.2 Rimpull Analysis and Truck Travel Performance

Rimpull analysis was conducted to evaluate the effect of road resistance on the travel performance of the haul truck. The analysis uses the travel performance curve of the HD-785 haul truck to determine the achievable vehicle speed under different total resistance conditions.

Total resistance is defined as the sum of grade resistance and rolling resistance acting on the vehicle during operation. Variations in road geometry, surface condition, and slope significantly influence the total resistance experienced by the haul truck. When the resistance increases, the available rimpull must compensate for the additional force, which consequently reduces the attainable travel speed. In this study, two scenarios were analyzed: the planned road condition representing the recommended road geometry standard, and the actual road condition observed in the field. The comparison between these two conditions provides a quantitative evaluation of how deviations in road geometry affect truck performance.
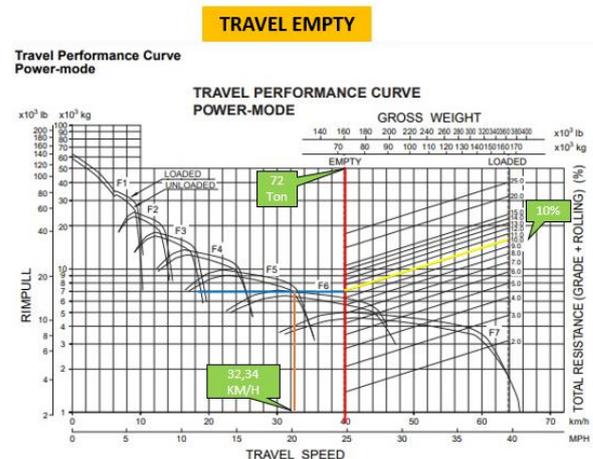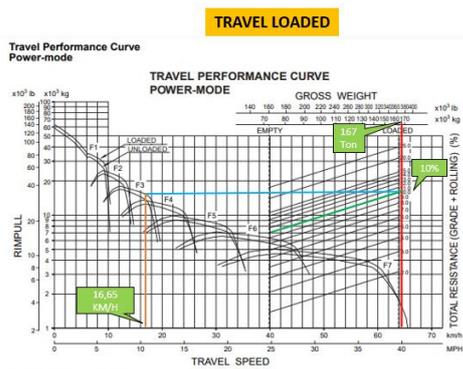
Figure 2. Rimpull Grafic Plan Speed

Figure 2. Travel performance curve of the HD-785 haul truck under planned road conditions with total resistance of approximately 10%. Under this condition, the truck can achieve a travel speed of about **32.34 km/h when traveling empty and 16.65 km/h when traveling loaded.**

Under the planned road condition, the total resistance is assumed to be approximately 10%, which represents the recommended road geometry and surface condition for haul road operation. Based on the rimpull curve analysis, the HD-785 haul truck can achieve a travel speed of approximately **32.34 km/h in empty travel conditions** with a vehicle weight of about **72 tons**.

When the truck operates under loaded conditions with a gross vehicle weight of approximately **167 tons**, the achievable travel speed decreases to around **16.65 km/h**. These speeds represent the expected operational performance when the haul road geometry complies with recommended design standards.

The results indicate that under proper road conditions, the available rimpull is sufficient to maintain relatively stable travel speeds for both empty and loaded travel segments.
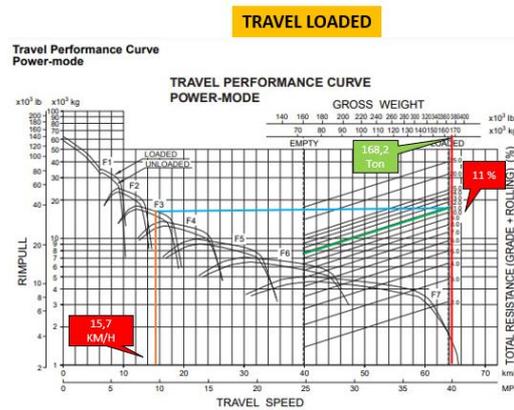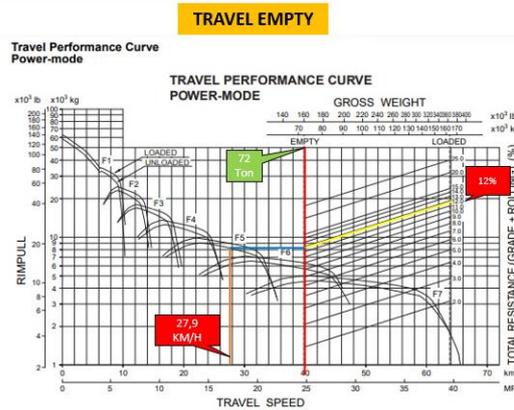

Figure 3. Rimpull Grafic Actual Speed

Figure 3. Travel performance curve of the HD-785 haul truck under actual road conditions where total resistance increases to **11–12%** due to steeper gradients and deteriorated road surfaces. Under these conditions, the achievable speed decreases to **27.9 km/h for empty travel** and **15.7 km/h for loaded travel**.

Field observations show that the existing road geometry produces higher resistance values than the planned condition. The presence of steeper gradients and surface deterioration increases the total resistance to approximately **11–12%**.

Based on the rimpull analysis, this increase in resistance reduces the achievable travel speed of the HD-785 haul truck. Under empty travel conditions, the speed decreases from **32.34 km/h to approximately 27.9 km/h**. Similarly, under loaded travel conditions, the speed decreases from **16.65 km/h to approximately 15.7 km/h**.

Although the increase in total resistance appears relatively small, the results demonstrate that it significantly affects truck travel performance. Reduced travel speed directly increases cycle time, which ultimately leads to lower hauling productivity, a relationship widely reported in haul truck productivity studies [11].

These findings confirm that deviations from the recommended road geometry standards have a measurable impact on haulage performance through increased total resistance and reduced vehicle speed.

Table 1. Relationship between total resistance and achievable travel speed of the HD-785 haul truck based on rimpull analysis.

Total Resistance	Empty Speed	Loaded Speed
10%	32,34 km/h	16,65 km/h
11-12%	27,9 km/h	15,7 km/h

Table 1

Based on the identified deviations in road geometry and the results of the rimpull analysis, haul road improvements were carried out to reduce excessive gradients and improve surface conditions. The effectiveness of these improvements was then evaluated by comparing truck travel performance and hauling productivity before and after the improvement.

4.3 Impact of Road Standardization on Haul Truck Performance and Productivity

Haul road geometry and surface conditions play an important role in determining the travel performance of haul trucks, particularly through their influence on rolling resistance and vehicle vibration [12]. Improvements in road geometry are expected to reduce total resistance, thereby increasing truck travel speed and improving hauling productivity.

Following the identification of geometric deviations and excessive resistance in the existing road conditions, improvement measures were implemented to align the haul road with recommended design standards. The effectiveness of these improvements was evaluated through rimpull analysis and operational performance monitoring.
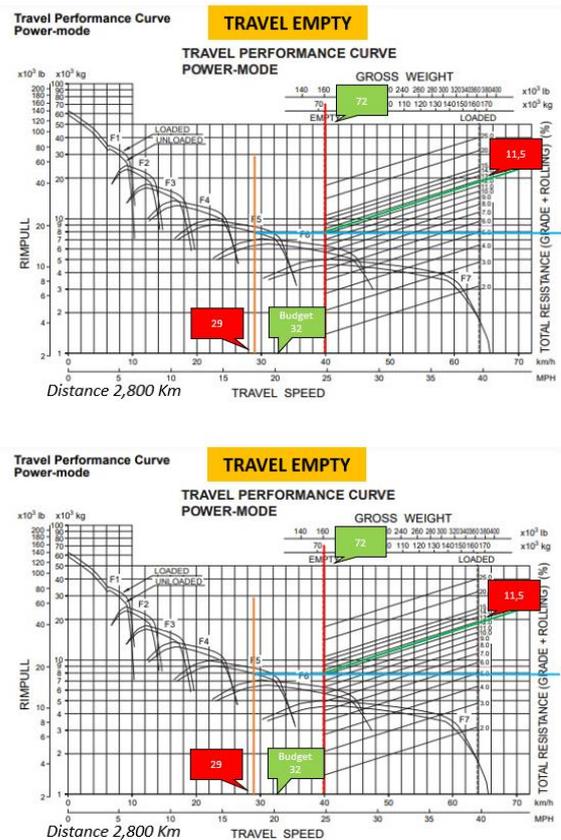

Figure 4. Rimpull Grafic Actual Speed After Improvement

Figure 4. Travel performance curve of the HD-785 haul truck after haul road improvement. Under the improved road condition with total resistance of approximately **10–11.5%**, the achievable travel speed is around **29 km/h for empty travel** and **16.32 km/h for loaded travel** along the 2.8 km hauling segment.

The rimpull analysis results indicate that the improved road condition reduces the total resistance experienced by the haul truck. As a result, the predicted travel speeds approach the planned operational target.

For empty travel conditions, the predicted speed reaches approximately **29 km/h**, while under loaded conditions the achievable speed is approximately **16.32 km/h**. These values are consistent with the

expected performance of the HD-785 haul truck under a total resistance close to the recommended operational range.

The results suggest that improving road geometry and surface conditions can effectively reduce resistance and enhance truck travel performance.
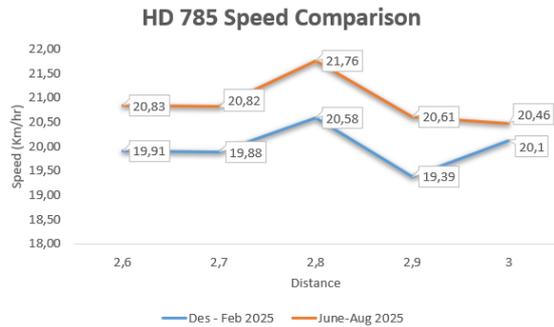

Figure 5. Before and After Speed Comparation

Figure 5. Comparison of average HD-785 haul truck speeds before and after haul road improvement along the 2.6–3.0 km hauling segment.

Operational data collected from the field further validate the results of the rimpull analysis. As shown in Figure 4.4, the average truck speed increased after the road improvement was implemented.

Prior to the improvement, the average travel speed ranged from **19.39 km/h to 20.58 km/h**. After the road geometry and surface condition improvements were applied, the average speed increased to **20.46 km/h to 21.76 km/h**.

Although the increase in speed appears relatively moderate, it significantly contributes to improving the overall efficiency of the haulage cycle and overall fleet productivity [13].
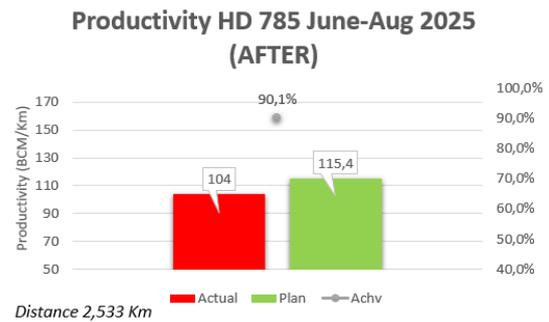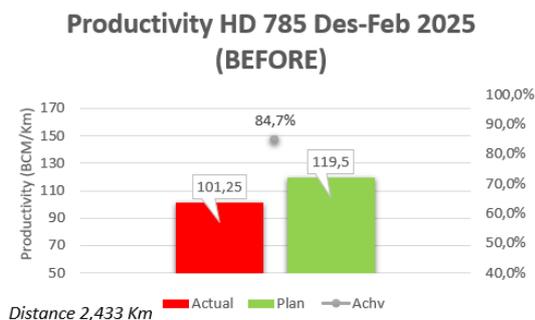

Figure 6. Comparison Productivity Haul Truck

Figure 6. Improvement in haulage productivity performance before and after haul road improvement.

The improvement in haul road conditions also had a direct impact on overall hauling productivity. Based on operational performance data, the productivity achievement level increased significantly after the road improvement measures were implemented.

During the period **December–February 2025**, the average productivity achievement was **84.7%** of the production target. After the road improvement program was implemented, the productivity achievement increased to **90.1% during the June–August 2025 period**.

This improvement indicates that better road geometry and reduced resistance contribute not only to increased truck travel speed but also to improved operational efficiency and higher productivity performance.

These findings demonstrate that haul road standardization plays an important role in optimizing haul truck performance and achieving production targets in mining transportation operations.

V. CONCLUSION

This study evaluated the influence of haul road geometry and surface resistance on heavy vehicle productivity using a rimpull-based engineering assessment. The analysis identified that several segments of the existing haul road exhibited excessive gradients and surface deterioration, resulting in increased total resistance that negatively affected truck travel performance.

The rimpull analysis demonstrated that deviations in road conditions increased the total resistance from the planned value of approximately 10% to 11–12%. This increase reduced the achievable travel speed of the HD-785 haul truck from 32.34 km/h to 27.9 km/h under empty travel conditions and from 16.65 km/h to 15.7 km/h under loaded travel conditions. These findings confirm that even small increases in road resistance can significantly influence haul truck travel performance.

After haul road improvement and standardization, the operational performance of the haul trucks showed measurable improvement. Field monitoring indicated an increase in average truck speed along the haul route, while productivity achievement improved from 84.7% during the December–February 2025 period to 90.1% during the June–August 2025 period. These results demonstrate that proper haul road geometry and surface conditions play an important role in improving transportation efficiency and supporting production targets.

The findings of this study highlight the importance of integrating engineering-based road design evaluation with operational performance monitoring in haul road management. The rimpull-based approach provides a practical method for assessing the impact of road resistance on heavy vehicle productivity and can be applied in other large-scale hauling operations. However, this study is limited to the evaluation of road resistance and vehicle performance on a specific haul route segment. Future studies may incorporate additional variables such as traffic interaction, haul road maintenance strategies, and longer operational monitoring periods to provide a more comprehensive assessment of haul road performance.

VI. Acknowledgements

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