

Cradle-to-Use Life Cycle Assessment of Diesel-Electric and Conventional Diesel Mining Haul Trucks: A Real-World Comparison of BELAZ 75135 and Komatsu HD785-7 in Indonesia

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Abstract : This study compares the cradle-to-use environmental impacts of a BELAZ 75135 diesel-electric haul truck and a Komatsu HD785-7 diesel-mechanical truck using actual operating data from an Indonesian open-pit coal mine. Life cycle assessment (LCA) was conducted using SimaPro 10.5, ecoinvent 3.12, and ReCiPe 2016 Midpoint (H), with 1 tonne-kilometre (tkm) as the functional unit. Manufacturing, transportation, and operational phases were assessed across four environmental impact categories. Based on January–June 2026 data, BELAZ generated higher global warming impacts (0.5178 versus 0.4320 kg CO₂-eq/tkm), energy consumption (4.924 versus 4.140 MJ/tkm), and lower transport productivity (524.6 versus 617.0 tkm/h). BELAZ also exhibited higher fine particulate matter formation (+19.91%), terrestrial acidification (+20.03%), and terrestrial ecotoxicity (+23.54%). The operational phase dominated most impacts, contributing approximately 97–98% to global warming, particulate formation, and acidification, and 85–88% to ecotoxicity. Manufacturing contributed more substantially to terrestrial ecotoxicity. These findings demonstrate that diesel-electric architecture does not necessarily reduce environmental impacts under actual mining conditions. Battery-related manufacturing impacts were excluded because the BELAZ configuration has no traction battery.

Keywords: Life Cycle Assessment, Mining Haul Truck, Diesel-Electric, BELAZ 75135, Komatsu HD785-7, Recipe 2016, Tonne-Kilometre

Abstrak : Penelitian ini membandingkan dampak lingkungan dari tahap produksi hingga penggunaan (cradle-to-use) antara truk angkut tambang BELAZ 75135 dengan sistem diesel-elektrik dan Komatsu HD785-7 dengan sistem diesel-mekanis berdasarkan data operasional aktual pada tambang batubara terbuka di Indonesia. Penilaian daur hidup (Life Cycle Assessment/LCA) dilakukan menggunakan SimaPro 10.5, ecoinvent 3.12, dan ReCiPe 2016 Midpoint (H), dengan unit fungsional 1 ton-kilometer (tkm). Tahap produksi, transportasi, dan operasional dianalisis berdasarkan empat kategori dampak lingkungan. Berdasarkan data Januari–Juni 2026, BELAZ menghasilkan dampak pemanasan global lebih tinggi (0,5178 dibandingkan 0,4320 kg CO₂-eq/tkm), konsumsi energi lebih besar (4,924 dibandingkan 4,140 MJ/tkm), serta produktivitas

pengangkutan lebih rendah (524,6 dibandingkan 617,0 tkm/jam). BELAZ juga menunjukkan dampak lebih tinggi terhadap pembentukan partikulat halus (+19,91%), asidifikasi terestrial (+20,03%), dan ekotoksisitas terestrial (+23,54%). Tahap operasional mendominasi sebagian besar dampak lingkungan, dengan kontribusi sekitar 97–98% terhadap pemanasan global, pembentukan partikulat, dan asidifikasi, serta 85–88% terhadap ekotoksisitas terestrial. Tahap produksi memberikan kontribusi relatif lebih besar terhadap ekotoksisitas terestrial. Temuan ini menunjukkan bahwa sistem diesel-elektrik tidak selalu menghasilkan dampak lingkungan yang lebih rendah dalam kondisi operasional pertambangan aktual. Dampak produksi baterai tidak diperhitungkan karena konfigurasi BELAZ yang diteliti tidak menggunakan baterai traksi.

Kata kunci: *Penilaian Daur Hidup, Truk Angkut Tambang, Diesel-Elektrik, BELAZ 75135, Komatsu HD785-7, Recipe 2016, Ton-Kilometer*

INTRODUCTION

Material loading and haulage are major energy- and emission-intensive activities in surface mining. Life-cycle studies of mining and mineral processing have shown that loading and hauling can make the largest contribution to greenhouse-gas emissions for several mined commodities (Norgate & Haque, 2010). At the equipment level, dump-truck fuel use is sensitive to payload, haul distance, elevation change, road gradient, cycle time, queueing, and other site-specific operating conditions (Dindarloo & Siami-Irdemoosa, 2016; Wang et al., 2021). Consequently, technology comparisons based only on rated engine power or nominal fuel consumption may not represent the environmental performance achieved in production. Decarbonization strategies for mine haulage increasingly include electrification, battery-electric trucks, trolley-assist systems, and diesel-electric drivetrains. Recent studies have demonstrated substantial decarbonization potential for electric mine fleets, while also emphasizing that the outcome depends on energy supply, road profile, truck duty cycle, and operational resilience (Balboa-Espinoza et al., 2023; Feng et al., 2022; Tokac et al., 2025). For heavy-duty vehicles more broadly, hybrid or electrified propulsion should not be presumed environmentally superior in all circumstances; life-cycle results vary by propulsion architecture, use-phase efficiency, and production burdens (Rial & Pérez, 2021).

Evidence from mine-haulage life-cycle studies also shows that the apparent benefit of electrification is strongly conditional on the energy carrier and on whether diesel combustion is actually displaced. Balboa-Espinoza et al. (2023) reported a greater global-warming impact for a diesel underground mining truck than for a battery-electric alternative, while identifying energy supply as the largest life-cycle contributor for both configurations and raw materials as an important burden for the electric truck. In a more recent open-pit modelling study, Tokac et al. (2025) estimated that replacing diesel haulage with battery-electric trucks could reduce greenhouse-gas emissions by approximately 50–92.6% under Canadian electricity scenarios. Those results are important benchmarks, but they cannot be transferred directly to an on-board diesel-electric truck because the BELAZ 75135 studied here does not replace diesel with grid electricity and does not contain a traction battery.

Operational variability provides a second reason why nominal powertrain labels are insufficient for environmental comparison. Dindarloo and Siami-Irdemoosa (2016), using more

than 5,000 material-transport cycles, showed that manufacturer fuel estimates could not capture the variability observed under site-specific mining conditions and identified empty-idle and queueing time as important avoidable fuel burdens. Wang et al. (2021) similarly identified lifting height, load, and haulage distance as key determinants of mine-truck fuel use. Golbasi and Kina (2022) further showed in a multi-route haulage network that precipitation conditions could change fuel consumption by approximately 15–25%. Sahoo et al. (2014) estimated that dump trucks can account for about 32% of total mine energy consumption and reported a 17% fuel-saving potential in their case study. Together, these studies indicate that operating conditions can produce differences large enough to alter the ranking of competing truck technologies.

A third consideration is the embedded burden of the vehicle itself. Wolff et al. (2020) developed a scalable component-based life-cycle inventory for heavy-duty vehicle production that explicitly represents steel, aluminium, copper, polymers, glass, and other materials. For electrified traction hardware, Nordelöf et al. (2019) showed that copper production can be important for toxicity-related impacts in traction-motor life cycles. These findings are relevant to the present comparison because the BELAZ has a larger reference mass and includes a traction generator and electric traction motors, even though it has no battery. A stage-resolved LCA is therefore needed to distinguish operational fuel effects from upstream manufacturing burdens. A key technical distinction is necessary in the present case. The BELAZ 75135 operated at the study site is commonly referred to operationally as a “hybrid” truck; however, OEM documentation identifies an AC/DC diesel-electric traction system in which the diesel engine drives a traction generator and the generated electrical power feeds traction motors. The vehicle does not contain a traction battery. During electrical braking, the traction motors operate in generator mode and the recovered electrical energy is dissipated through a dynamic resistor bank rather than stored for later propulsion. This architecture differs fundamentally from battery-hybrid or battery-electric mining trucks. Therefore, battery-manufacturing impacts and regenerative-energy-storage benefits should not be assigned to this specific BELAZ configuration.

Life cycle assessment is well suited to this comparison because it avoids evaluating only tailpipe or use-phase emissions. ReCiPe 2016 provides midpoint indicators that translate life-cycle inventory flows into environmental impact potentials, including climate change, fine particulate matter formation, terrestrial acidification, and terrestrial ecotoxicity (Huijbregts et al., 2017). A transport-work functional unit is particularly appropriate because BELAZ 75135 and Komatsu HD785-7 have different payload capacities; expressing results per tonne-kilometre normalizes the comparison to the same hauling service. This study therefore evaluates the cradle-to-use environmental performance of BELAZ 75135 diesel-electric and Komatsu HD785-7 diesel-mechanical haul trucks under real operating conditions in an Indonesian open-pit coal mine. The objective of the study is to compare four ReCiPe 2016 midpoint impacts per 1 tkm under actual operating performance and to quantify the contributions of vehicle manufacturing, transportation, and use phases in order to identify the dominant life-cycle hotspots. The analysis further examines whether the diesel-electric architecture delivers a lower impact when performance is normalized to actual transport work and whether any observed difference is driven primarily by operational energy intensity or by embedded upstream burdens.

MATERIALS AND METHODS

The compared units were the BELAZ 75135 and Komatsu HD785-7. Their principal characteristics are summarized in Table 1. The BELAZ uses a diesel-electric AC/DC traction architecture without a traction battery, whereas the HD785-7 uses a conventional mechanical drivetrain with a torque converter and automatic planetary transmission. Both trucks have engines

of approximately 895 kW rated/gross power, but the BELAZ has a higher nominal payload and vehicle mass.

Table 1. Main technical characteristics of the compared haul trucks.

Parameter	BELAZ 75135	Komatsu HD785-7
Powertrain	Diesel-electric AC/DC	Diesel-mechanical
Engine	Cummins KTA38-C	Komatsu SAA12V140E-3
Engine power	895 kW	895 kW gross
Rated payload	110 t	91 t
Reference vehicle mass	100,100 kg (operation weight)	72,000 kg (empty weight)
Traction/transmission	Generator → electric traction motors	Torque converter → automatic planetary transmission
Traction battery	None	None

The study followed the attributional LCA framework of ISO 14040 and ISO 14044. The functional unit was defined as 1 tkm of material hauled, i.e., the transport service of moving one tonne of material over one kilometre. The cradle-to-use system boundary included (i) vehicle manufacturing, (ii) transportation of the completed vehicle from the manufacturing region to PT Bukit Asam, South Sumatra, Indonesia, and (iii) the use phase. End-of-life processes were excluded. The study used a 10-year service-life allocation basis. Annual operation was represented by 362.5 operating days per year and 13.6 h/day, corresponding to 49,300 operating hours over the assumed lifetime. Manufacturing and delivery burdens were allocated to lifetime transport work, so higher achieved tkm/h reduced the embedded vehicle burden per functional unit. For the actual scenario, transport-work rate was calculated as material productivity multiplied by loaded haul distance. BELAZ achieved 193.22 t/h over an average loaded distance of 2.715 km, corresponding to 524.6 tkm/h, whereas HD785-7 achieved 208.45 t/h over 2.960 km, corresponding to 617.0 tkm/h. Over the assumed 49,300 operating hours, these rates correspond to approximately 25.86 million lifetime tkm for BELAZ and 30.42 million lifetime tkm for HD785-7. Dividing the reference vehicle mass by lifetime transport work gives the delivered-vehicle allocations of 0.003870 and 0.002367 kg/tkm used in the foreground model. This normalization is essential because the two trucks do not deliver the same useful hauling output per operating hour. A comparison based only on litres per hour, engine power, or total manufacturing burden would therefore compare unequal transport services. Expressing both use-phase energy and embedded vehicle burdens per tonne-kilometre ensures that a truck producing more transport work spreads fixed manufacturing and delivery burdens across a larger functional output.

Foreground processes were built in SimaPro 10.5 and linked to ecoinvent 3.12 datasets using the allocation, cut-off by classification system model. The use phase employed the ecoinvent process “diesel, burned in building machine” to represent diesel combustion and its upstream supply chain. Electricity was not added to the BELAZ use phase because traction electricity is generated on-board by the diesel engine; adding grid electricity would double count energy supply. Direct tailpipe elementary flows were also not added manually because they are already represented in the selected combustion dataset. Manufacturing inventories were mass-balanced to the reference vehicle masses using OEM information where available and documented material proxies where a complete manufacturer bill of materials was unavailable. This limitation is addressed in Section 4.4. The main inventory values and use-phase inputs are shown in Table 2.

The resulting foreground inventory should be interpreted as a comparative engineering model rather than as an OEM bill of materials. Relative to HD785-7, the BELAZ reference vehicle mass is about 39.0% higher; in the harmonized inventory the modelled steel/iron mass is about 35.0% higher, aluminium 29.3% higher, copper 24.8% higher, rubber/elastomer 66.2% higher, and the other-material proxy 58.3% higher. These percentages describe the mass structure of the comparative LCI and are not intended to imply manufacturer-level composition accuracy. Their main purpose is to preserve mass balance and to test whether the larger diesel-electric vehicle carries a measurable embedded burden per unit of transport service. The BELAZ delivery scenario represented a longer international logistics chain than the HD785-7 scenario. Transport work for the completed truck was approximately 2.59×10^6 tkm for BELAZ and 5.12×10^5 tkm for HD785-7, using harmonized freight datasets for rail, sea, ferry/coastal transport, and heavy road freight where applicable. These routes are representative logistics scenarios rather than shipment-specific bills of lading. Although the representative BELAZ logistics chain is substantially longer than that of HD785-7, completed-vehicle transport remains a small contributor in the final results. This is methodologically useful because uncertainty in the representative route distances is unlikely to dominate the environmental ranking; the comparison is much more sensitive to use-phase energy intensity and, for toxicity-related indicators, to manufacturing.

Table 2. Key foreground inputs used for the actual cradle-to-use scenario.

Model element	BELAZ actual	HD785 actual
Delivered vehicle allocation (kg/tkm)	0.003870	0.002367
Diesel energy input (MJ/tkm)	4.924	4.140
Steel/iron in manufacturing model (kg/unit)	70,836.41	52,453.83
Aluminium (kg/unit)	7,214.69	5,578.45
Copper (kg/unit)	1,365.00	1,094.12
Rubber/elastomer (kg/unit)	6,514.20	3,919.80
Other-material proxy (kg/unit)	14,169.70	8,953.80

The operating scenario was based on aggregated field performance from January to June 2026. The transport productivity used in the lifetime allocation was 524.6 tkm/h for BELAZ and 617.0 tkm/h for HD785-7. The corresponding delivered-vehicle allocations were 0.003870 kg/tkm and 0.002367 kg/tkm, respectively. Actual diesel-energy inputs were 4.924 MJ/tkm for BELAZ and 4.140 MJ/tkm for HD785-7. These values were used consistently to represent the observed transport service within the cradle-to-use model. The actual diesel-energy input was therefore 18.94% higher for BELAZ on a transport-work basis (4.924 versus 4.140 MJ/tkm), while its achieved transport-work rate was 14.98% lower (524.6 versus 617.0 tkm/h). At the same time, the delivered-vehicle allocation was approximately 63.5% higher for BELAZ because its larger reference mass was distributed over a smaller lifetime transport-work denominator. These three indicators provide the operational and allocation context needed to interpret the subsequent LCIA results.

Impact assessment was performed using ReCiPe 2016 Midpoint (H) V1.13, World (2010) H. Four midpoint categories were selected: global warming (kg CO₂-eq), fine particulate matter

formation (kg PM_{2.5}-eq), terrestrial acidification (kg SO₂-eq), and terrestrial ecotoxicity (kg 1,4-DCB-eq). Results were calculated per 1 tkm. Infrastructure processes were retained, while long-term emissions were excluded consistently across scenarios. Stage contribution analysis grouped impacts into manufacturing, transportation, and use phase.

RESULTS AND DISCUSSION

Actual cradle-to-use environmental impacts

The actual operating scenario produced consistently higher impact scores for BELAZ 75135 than for Komatsu HD785-7 in all four selected categories (Table 3). The difference ranged from 19.87% for global warming to 23.54% for terrestrial ecotoxicity. The global warming result was 0.517813 kg CO₂-eq/tkm for BELAZ and 0.431968 kg CO₂-eq/tkm for HD785-7. The similar relative differences observed for particulate matter formation and terrestrial acidification indicate that the higher actual burden of BELAZ was not limited to climate change. Terrestrial ecotoxicity showed the largest relative gap, with BELAZ at 0.621575 kg 1,4-DCB-eq/tkm compared with 0.503117 kg 1,4-DCB-eq/tkm for HD785-7.

Table 3. ReCiPe 2016 Midpoint (H) results for the actual operating scenario (functional unit: 1 tkm).

Impact category	Unit	BELAZ 75135	HD785-7	BELAZ vs HD785
Global warming	kg CO ₂ -eq/tkm	0.517813	0.431968	+19.87%
Fine particulate matter formation	kg PM _{2.5} -eq/tkm	0.001235	0.001030	+19.91%
Terrestrial acidification	kg SO ₂ -eq/tkm	0.002356	0.001963	+20.03%
Terrestrial ecotoxicity	kg 1,4-DCB-eq/tkm	0.621575	0.503117	+23.54%

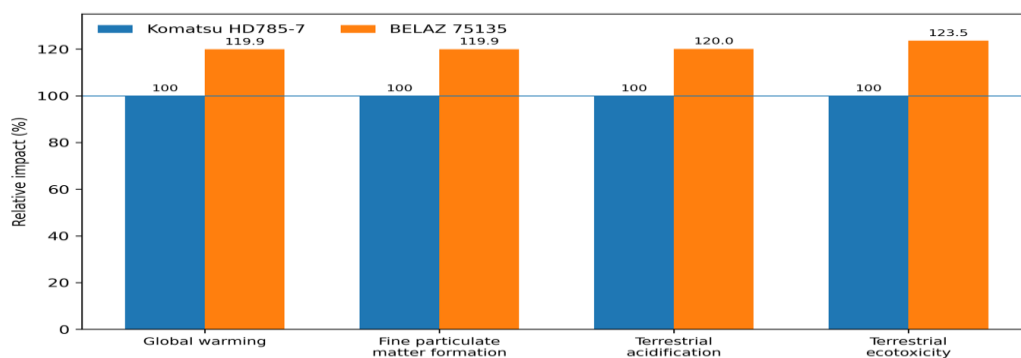


Figure 1. Relative environmental impacts under actual operation, with HD785-7 normalized to 100% in each category.

Operational basis of the impact difference

The relative difference in global warming closely follows the difference in actual diesel-energy intensity. BELAZ used 4.924 MJ/tkm compared with 4.140 MJ/tkm for HD785-7, a difference of 18.94%, while the global-warming result was 19.87% higher. Fine particulate matter formation and terrestrial acidification were likewise about 20% higher for BELAZ. The close correspondence indicates that use-phase diesel intensity is the principal mechanism behind the ranking for these three categories rather than a large difference in upstream manufacturing or

completed-vehicle transport. The transport-work denominator is equally important. BELAZ produced 524.6 tkm/h, 14.98% below the 617.0 tkm/h achieved by HD785-7, despite its larger rated payload. Consequently, both operational fuel use and one-time vehicle burdens are distributed over fewer tonne-kilometres. The delivered-vehicle allocation is 0.003870 kg/tkm for BELAZ versus 0.002367 kg/tkm for HD785-7, a 63.5% difference. The result should therefore be interpreted as a comparison of realized hauling systems at the study site, not as a controlled laboratory test isolating powertrain architecture from route, dispatch, payload, and cycle-time effects.

Life-cycle stage contribution

The use phase dominated most impacts for both trucks (Figure 2). For global warming, fine particulate matter formation, and terrestrial acidification, use-phase contributions were approximately 97–98%. Transportation of the completed truck contributed less than 1% in all selected categories. Manufacturing became more visible for terrestrial ecotoxicity, accounting for 14.49% of BELAZ and 11.65% of HD785-7 impacts. The dominance of the use phase is a central result of this study. For global warming, PM formation, and terrestrial acidification, approximately 97–98% of impacts were associated with operation. This pattern is consistent with Norgate and Haque (2010), who found loading and hauling to be major greenhouse-gas contributors in mining and mineral-processing systems. It also aligns with Balboa-Espinoza *et al.* (2023), whose mining-truck LCA showed energy supply to be a dominant life-cycle contributor for both diesel and battery-electric alternatives, although the specific technology and underground context of that study differ from the present case.

For the current diesel-based configurations, the practical implication is that reducing impact per tkm primarily requires lowering fuel-energy input per unit of useful hauling service. Technology selection alone is insufficient. Improvements in payload utilization, dispatching, queue reduction, haul-road condition, rolling resistance, gradient management, and cycle productivity can materially influence the realized environmental intensity. Sahoo *et al.* (2014) similarly showed that payload, speed, distance, and mine gradient affect benchmark fuel consumption, illustrating the value of site-specific operating optimization. The very small transportation share is notable because BELAZ was assigned the longer international delivery scenario. Even with this disadvantage, completed-vehicle transport contributed less than 1% of the selected impacts. This means that the observed 19.87–23.54% total-impact gap cannot be explained by the logistics assumption alone. Instead, the use phase dominates the climate, particulate-matter, and acidification results, while manufacturing becomes more important for terrestrial ecotoxicity.

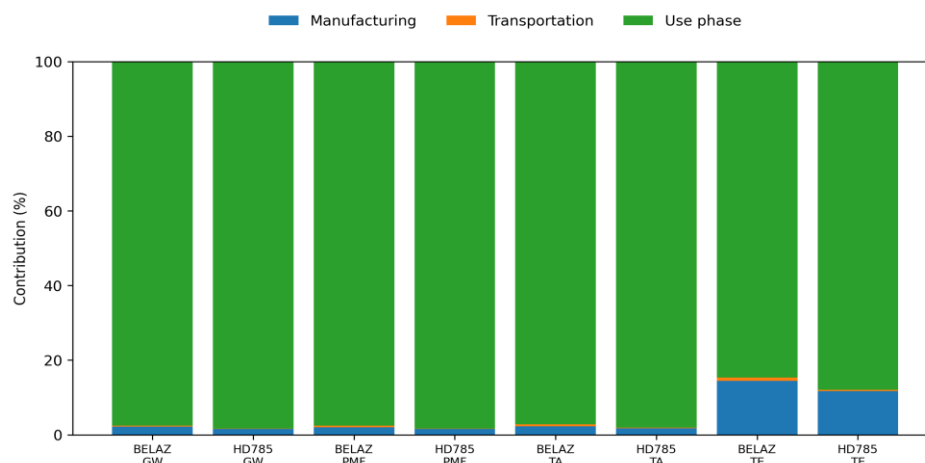


Figure 2. Contribution of manufacturing, transportation, and use phase to actual cradle-to-use impacts. GW = global warming; PMF = fine particulate matter formation; TA = terrestrial acidification; TE = terrestrial ecotoxicity.

Interpretation of actual diesel-electric performance

The results demonstrate that a diesel-electric drivetrain does not intrinsically guarantee lower life-cycle impacts per unit transport work. In the present case, both trucks ultimately rely on diesel as the primary energy source. The BELAZ architecture changes how power is transmitted from the engine to the wheels, but it does not eliminate combustion and it does not store braking energy for later propulsion. Therefore, any environmental advantage must emerge through improved conversion efficiency and/or higher productive transport output relative to fuel consumption. This interpretation is consistent with broader heavy-duty vehicle LCA evidence. Rial and Pérez (2021) reported that diesel-hybrid heavy-duty trucks were not always environmentally preferable to conventional diesel vehicles. Likewise, Feng et al. (2022) showed that the benefits of mining haul-truck powertrains depend strongly on the operating profile used for design and optimization. These studies support a conditional rather than categorical interpretation of “hybrid” or electrified powertrains.

Field operation further amplifies this conditionality. Wang et al. (2021) identified lifting height, load, haul distance, and cycle operation time as key determinants of mine-truck fuel consumption, while queueing fuel use was not negligible. Dindarloo and Siami-Irdemoosa (2016) likewise demonstrated substantial variability across material-transport cycles and identified idle and queue-related activities as avoidable fuel burdens. Awuah-Offei (2016) synthesized similar evidence, emphasizing that equipment efficiency interacts with operating conditions, mine design, and operator behaviour. Consequently, life-cycle impacts per unit of transport work should be interpreted in relation to the site-specific road, dispatch, payload, and cycle-time conditions under which the trucks actually operate. Bodziony and Patyk (2024) reached a compatible conclusion from a different perspective, showing that the technical condition of the mining operating environment affects both energy consumption and haulage availability. Awuah-Offei (2016) likewise emphasized the interaction between equipment technology, operators, mine design, and operating practice. The implication for the present study is that the 895 kW engine rating shared by the two trucks is a poor predictor of per-tkm environmental performance unless payload realization, road geometry, delays, and productive output are considered simultaneously.

Comparison with previous studies

The present results can be positioned more clearly by comparing the magnitude and direction of the findings with previous mining-haulage and heavy-duty-vehicle studies. Direct numerical equivalence is not always possible because the studies use different system boundaries, functional units, truck sizes, electricity mixes, and mine geometries. Table 4 therefore emphasizes reported findings that are methodologically relevant to the interpretation of the current 1 tkm results rather than treating unlike metrics as directly interchangeable.

Table 4. Comparison of the present findings with selected previous research.

Study	System / context	Selected reported result	Relation to the present study
Norgate & Haque (2010)	LCA of iron ore, bauxite, and copper mining/mineral processing	Loading and hauling were the largest GHG contributors for iron ore and bauxite.	Supports the present finding that haulage/use-stage energy can dominate climate impacts.

Study	System / context	Selected reported result	Relation to the present study
Sahoo et al. (2014)	Opencast-mine dump-truck energy benchmarking	Dump trucks represented about 32% of mine energy use; the case study indicated about 17% fuel-saving potential and a minimum SFC of 89 g/t.	Shows that operational optimization can shift energy intensity by a magnitude comparable to the observed BELAZ-HD785 difference.
Dindarloo & Siami-Irdemoosa (2016)	>5,000 surface-mine transport cycles	Observed fuel consumption varied substantially from manufacturer estimates; empty-idle and queueing time were major avoidable burdens.	Supports use of field data and cautions against interpreting nominal truck specifications as realized environmental performance.
Wang et al. (2021)	Open-pit mine-truck fuel modelling using multidimensional features	Lifting height, load, and haulage distance were identified as key fuel-consumption factors.	Supports the interpretation that route and duty-cycle conditions can materially affect impact per tkm.
Golbasi & Kina (2022)	29 haul trucks, 15 routes, multi-mine cement network	Precipitation conditions produced about 15-25% variation in fuel consumption.	The magnitude is similar to the 18.94% BELAZ-HD785 energy-intensity gap, illustrating how operating environment can change comparative outcomes.
Rial & Pérez (2021)	LCA of four heavy-duty road-truck propulsion technologies	Alternative technologies reduced GHGs by about 5-6% overall, but diesel-hybrid trucks were not always environmentally preferable to diesel trucks.	Closely supports the present conclusion that a diesel-electric/hybrid label does not guarantee lower life-cycle impacts.
Balboa-Espinoza et al. (2023)	Battery-electric versus diesel underground mining trucks	The diesel truck had greater global-warming impact; energy supply was the largest life-cycle contributor for both trucks, while raw materials were important for the electric truck.	Contrasts with the present ranking because the studied BELAZ is not battery-electric and still derives traction energy from diesel.
Ibañez Noriega et al. (2024)	Energy and exergy assessment of heavy-duty mining trucks	Reducing engine heat losses was estimated to lower fuel use by 1.8-9.1%; adding a 12 t battery package could reduce truck productivity.	Highlights the trade-off between efficiency gains and vehicle mass/productivity, both relevant to per-tkm performance.

Study	System / context	Selected reported result	Relation to the present study
Tokac et al. (2025)	Diesel versus battery-electric open-pit haulage modelling	Battery-electric replacement was projected to reduce GHG emissions by about 50-92.6% in Canadian scenarios and operating costs by 40-62%.	Shows the much larger decarbonization potential when diesel is displaced by electricity rather than converted on board in a diesel-electric drivetrain.
Nordelöf et al. (2019)	LCA of permanent-magnet electric traction motors	Copper production was significant for toxicity and human-health impacts; manufacturing impacts were reported at 1.7-2.0 g CO ₂ -eq/km for the studied road-vehicle motors.	Supports the direction of the terrestrial-ecotoxicity interpretation, although the motor scale and functional unit are not directly comparable.

The present 18.94% difference in diesel-energy input per tkm is particularly important when viewed against the operational literature. Sahoo et al. (2014) reported a 17% fuel-saving opportunity from improved operating strategy, while Golbasi and Kina (2022) found a 15–25% fuel-consumption variation associated with precipitation conditions. These values do not demonstrate that either mechanism caused the BELAZ-HD785 difference at PTBA; rather, they show that realistic operating variability can be of the same order as the observed gap. This reinforces the need to interpret the current ranking as site-specific realized performance. The current result is also more directly comparable with Rial and Pérez (2021) than with studies of fully battery-electric mine trucks. Rial and Pérez found that diesel-hybrid heavy-duty trucks were not automatically environmentally superior to conventional diesel technology. By contrast, Balboa-Espinoza et al. (2023) and Tokac et al. (2025) examined configurations in which diesel use is replaced substantially by electricity. Their lower GHG results for electric alternatives therefore do not contradict the present finding: the BELAZ 75135 still burns diesel to produce all traction electricity, so it retains the dominant combustion-related use-phase burden.

The comparison also explains why the largest relative gap in the present study occurs for terrestrial ecotoxicity (+23.54%) rather than global warming (+19.87%). Operational energy remains dominant, but the heavier BELAZ material inventory and electric-traction hardware add an embedded contribution that becomes more visible in toxicity-related indicators. This pattern is consistent with Nordelöf et al. (2019), who identified copper as an important contributor to toxicity-related impacts in traction-motor life cycles, and with Wolff et al. (2020), whose heavy-duty-vehicle LCI demonstrates the importance of resolving multiple material categories instead of treating vehicle production as a single undifferentiated mass.

Manufacturing contribution and terrestrial ecotoxicity

Although manufacturing was a minor contributor to global warming, PM formation, and terrestrial acidification, it represented a larger share of terrestrial ecotoxicity: 14.49% for BELAZ and 11.65% for HD785-7. The greater manufacturing visibility for BELAZ is consistent with its larger reference mass and additional electric-traction hardware. Importantly, this burden should not be attributed to a traction battery because no such battery is installed in the studied BELAZ 75135. The influence of electrical-machine materials on toxicity-related impact categories has been noted in the literature. Nordelöf et al. (2019) found copper production to be significant for toxicity and human-health impacts in traction-motor LCAs. This supports the relevance of copper, electrical steel, structural materials, and other electric-drive components when interpreting the

manufacturing contribution of diesel-electric equipment. However, the present manufacturing inventory contains proxy-based material composition because an OEM bill of materials was not available; therefore, the material-level attribution is more uncertain than the stage-level result.

The material differences in the present foreground model are directionally consistent with this interpretation. BELAZ is 39.0% heavier than HD785-7 and contains larger modelled quantities of every reported material group. Because the terrestrial-ecotoxicity characterization is especially sensitive to metal-related upstream processes, the combination of greater structural mass and explicit electric-drive copper can increase the manufacturing share even when manufacturing remains a minor contributor to global warming. Nevertheless, the study does not attribute the full ecotoxicity difference to copper alone; the inventory is proxy-based and the result reflects the combined upstream supply chains of all modelled materials.

Limitations and transferability

Several limitations should be considered. First, the manufacturing inventory combines OEM mass information with literature-based material proxies because a complete manufacturer bill of materials was not available. The absolute manufacturing scores are therefore less certain than the directly operation-driven use-phase comparison. The proxy inventory is suitable for stage-level comparison and mass balance, but component-level interpretations should not be read as an environmental product declaration for either manufacturer. Second, international vehicle-delivery routes are representative logistics scenarios rather than shipment-specific transport records. This limitation has limited influence on the overall ranking because transportation contributed less than 1% of the four selected impacts. Even so, future work could replace the representative routes with verified bills of lading or supplier logistics records and test alternative freight geographies in a sensitivity analysis.

Third, the January–June 2026 operating dataset represents realized performance at one mine and is not a controlled paired experiment in which both truck models travel identical routes with identical payload, road, weather, queue, and maintenance conditions. The comparison therefore answers which system produced the lower impact per tkm under the observed operating conditions; it does not isolate a pure causal effect of diesel-electric versus mechanical transmission. This distinction is important because prior studies show that road gradient, lifting height, haul distance, precipitation, queueing, and operator practice can each affect fuel consumption. Fourth, the use phase relies on theecoinvent 'diesel, burned in building machine' process to represent combustion and upstream diesel supply. Direct truck-specific exhaust measurements were not available, and detailed maintenance, replacement parts, tyre replacement, lubricants, and component overhaul were outside the boundary. These omissions should be addressed in future cradle-to-grave work, particularly if the analysis is extended to longer service lives or alternative end-of-life and recycling scenarios.

The study also uses a cradle-to-use boundary; end-of-life and recycling were intentionally excluded from the reported results. Future work should integrate longer operational datasets, uncertainty and sensitivity analysis, maintenance and tyre replacement, direct emissions measurements where available, and route-level statistical analysis. A useful next step is to evaluate whether adding end-of-life treatment and material recovery changes the relative importance of the heavier BELAZ manufacturing inventory. Another priority is to separate route and dispatch effects from powertrain effects using matched-cycle or controlled-route data so that the technological contribution can be quantified more directly.

CONCLUSION

This cradle-to-use LCA compared a BELAZ 75135 diesel-electric mining haul truck with a Komatsu HD785-7 conventional diesel-mechanical truck using a functional unit of 1 tkm. Under

actual January–June 2026 operating performance, BELAZ generated higher impacts in all four selected ReCiPe 2016 midpoint categories: 19.87% higher global warming, 19.91% higher fine particulate matter formation, 20.03% higher terrestrial acidification, and 23.54% higher terrestrial ecotoxicity. The use phase dominated global warming, particulate matter formation, and terrestrial acidification at approximately 97–98%, and remained dominant for terrestrial ecotoxicity at approximately 85–88%. Manufacturing was more visible for terrestrial ecotoxicity, while completed-vehicle transportation remained below 1%. The environmental ranking is consistent with the actual transport-work and energy data: BELAZ used 18.94% more diesel energy per tkm and achieved 14.98% lower transport-work productivity than HD785-7. Comparison with previous research shows that this result is not anomalous; heavy-duty diesel-hybrid systems are not always environmentally superior, and mine-truck fuel consumption is highly sensitive to route, payload, queueing, weather, and operating conditions. The result should also not be interpreted as evidence against battery-electric haulage, because the studied BELAZ has no traction battery and all traction electricity is generated from diesel on board. For mine operators, the principal implication is that technology selection should be evaluated using actual transport work and stage-resolved life-cycle performance rather than rated power or powertrain terminology alone. For the studied systems, reducing fuel energy per tkm through higher productive output, improved dispatching, road-condition management, and lower delay remains the most direct pathway to lower cradle-to-use impacts. Future cradle-to-grave and matched-route analyses can determine whether end-of-life recovery or controlled operating conditions materially alter this conclusion.

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