

Autonomous Mining Trucks: A Review of Deployment, Technology Architecture, Operational Benefits and Emerging Challenges

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Abstract: Autonomous mining trucks are driverless haul vehicles that transport ore, waste rock and overburden without an onboard operator. They have become one of the most consequential technology transitions in modern surface and underground mining. This paper reviews the current state of autonomous haulage systems (AHS), with attention to deployment growth, functional architecture, sensing and perception stacks, path planning and fleet management strategies, and demonstrated operational outcomes. Global adoption has accelerated sharply: the operating fleet on surface mines rose from roughly 2,080 units in mid 2024 to more than 3,830 units by July 2025, an 84% increase in twelve months, led by iron ore, copper, coal and oil sands operations across Australia, Chile, Peru, Canada and China. Reported gains include productivity improvements of up to 30%, operating cost reductions of about 20%, safety related incident reductions of approximately 50%, and utilization improvements of up to 20% relative to conventional manned fleets. Rio Tinto autonomous trucks operate approximately 700 hours per year more than conventional units and are associated with load and haul cost reductions on the order of 15%. Beyond these gains, the paper examines outstanding challenges in perception under dust, fog and non line of sight (NLOS) conditions, cybersecurity of highly connected cyber physical systems, workforce transitions, and the integration of autonomy with the emerging generation of battery electric and trolley assisted haul trucks. The review synthesizes evidence from peer reviewed journals, industry publications, corporate disclosures on autonomous mining technologies, and identifies interoperability, ecosystem level intelligence, cyber secure V2X communications and human-robot collaboration as the priority research directions for the next decade of automation in mining.

Keywords: Autonomous Mining Trucks, Autonomous Haulage System (AHS), Open Pit Mining, LiDAR, Sensor Fusion, Fleet Management, Mine Safety, Battery Electric Haul Trucks.

INTRODUCTION

Haulage is the single largest cost center in most surface mining operations and one of the most hazardous activities in underground mines. Autonomous mining trucks, also referred to as Autonomous Haulage Systems (AHS) or Autonomous Haulage Trucks (AHTs) are driverless haul vehicles that transport ore, waste rock and overburden without an onboard operator (Gaber, *et al.*, 2021). They rely on satellite positioning (GNSS/GPS), high resolution maps, onboard perception (LiDAR, radar and cameras), wireless communications and centralized fleet management software to plan and execute haulage cycles under supervisory control from a remote operations center (Wang, *et al.*, 2022; Mining Technology, 2024).

The transition from conventional to autonomous haulage has moved from pilot projects to industrial scale production remarkably quickly. Two Caterpillar prototype trucks were placed in service in the United States in 1994, and Komatsu conducted its first unmanned mining truck trial in a Japanese quarry the following year (Wang, *et al.*, 2022). Commercial deployments began in Chile in the mid-2000s where CODELCO opened the first autonomous copper mine at Gabriela Mistral in

2008 (Gaber, *et al.*, 2021) and were followed by rapid expansion in the Pilbara iron ore province, where Rio Tinto has operated autonomous trucks since 2008 (Attarbo, 2025). By April 2019, Komatsu's FrontRunner AHS had transported more than 2 billion tonnes of material across 10 mines in four countries, and Caterpillar Command equipped vehicles had covered 67.6 million kilometers without a fatality (Wang, *et al.*, 2022).

Growth has since accelerated further. According to industry analysts, more than 3,830 autonomous haul trucks were operating on surface mines globally by July 2025, up from 2,080 units a year earlier which is an 84% increase in twelve months and a near sevenfold expansion since 2019 (Figure 1) (Range Strategy Consulting, 2025; Mining Technology, 2025). The 300th autonomous truck was delivered to Rio Tinto's Pilbara operations in 2024, where the autonomous fleet now supports approximately 80% of daily production capacity across 10 mine sites (Pertama Partners, 2024). Chinese operators lead the world by fleet size, with CHN Energy Investment Group running 509 autonomous trucks and Guanghui Energy running 420 (Mining Technology, 2025).

This paper reviews the deployment, technology architecture, operational benefits and emerging challenges of autonomous mining trucks. The review draws primarily on peer reviewed articles and complements them with industry publications, OEM technical materials and corporate disclosures where those provide the most current deployment data. Because copper porphyry systems are also the leading global source of byproduct gold, the economics of automated copper haulage carry directly into precious metal production (Effah, *et al.*, 2025b).

GLOBAL DEPLOYMENT OF AUTONOMOUS MINING TRUCKS

Historical Trajectory and Current Fleet

The commercial trajectory of autonomous mining trucks reflects three overlapping phases: prototype testing (1994–2005), controlled commercial deployment (2005–2015) and industrial scale

scaling (2015–present). The first commercial AHS system was developed in Chile in 2005 (Gaber, *et al.*, 2021). Commercial launch of Caterpillar's Command for hauling followed in 2013, and by April 2020 the platform had moved 2 billion tonnes of material; the same platform surpassed 2.5 billion tonnes with more than 350 Cat Command trucks operating at over nine sites worldwide (Mining Technology, 2024).

Recent industry tracking places the global operating fleet at more than 3,830 units by July 2025, an 84% year on year rise (Figure 1) (Range Strategy Consulting, 2025). Fleet leadership has diversified: CHN Energy (509 units), Guanghui Energy (420 units), BHP (360 units), Rio Tinto (approximately 300 Pilbara units) and Fortescue (approximately 190 units) are the largest single owner autonomous fleets reported through 2024–2025 (Figure 4) (Mining Technology, 2025).

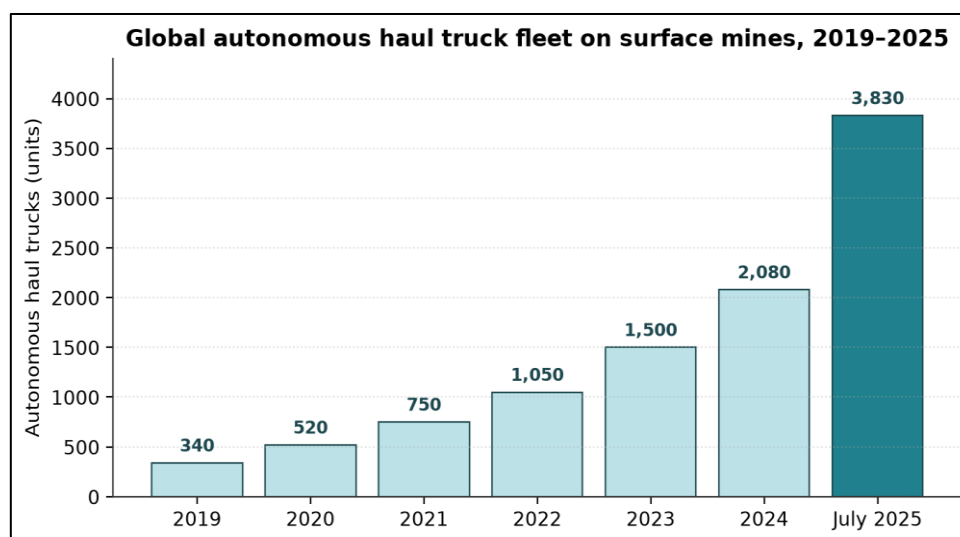


Figure 1: Global autonomous haul truck fleet on surface mines, 2019–July 2025. Fleet counts compiled from Range Strategy Consulting (2025) and Mining Technology (2025).

Original Equipment Manufacturers

Two OEMs dominate the AHS market. Komatsu's FrontRunner and Caterpillar's Command are the two production grade platforms operating at scale (Gaber, *et al.*, 2021; Mining Technology, 2024). Additional AHS suppliers active in the mining sector include Hitachi, Scania, Volvo and Sandvik (Mining Technology, 2024). Komatsu's systems are typically integrated with 830E, 930E and, more recently, autonomous trolley ready electric drive trucks; Caterpillar's Command supports the 789D, 793D, 793F and 797F, and the newly introduced 794 AC electric drive autonomous truck offering a 320 t payload and 40% more retarding power than earlier models (Mining Technology, 2024).

Recent deployment announcements underscore the pace of expansion. Komatsu's autonomous 930E fleet went into service at Vale's Salobo copper mine in August 2026 (International Mining, 2026a), and Southern Copper's Tia Maria project became Peru's first Komatsu AHS site (International Mining, 2026b). BHP contracted Komatsu for 41 additional autonomous trucks for its South Flank operation in Western Australia (Australian Mining, 2025). Caterpillar has publicly targeted more than 2,000 autonomous mining trucks in service by 2030 (International Mining, 2025).

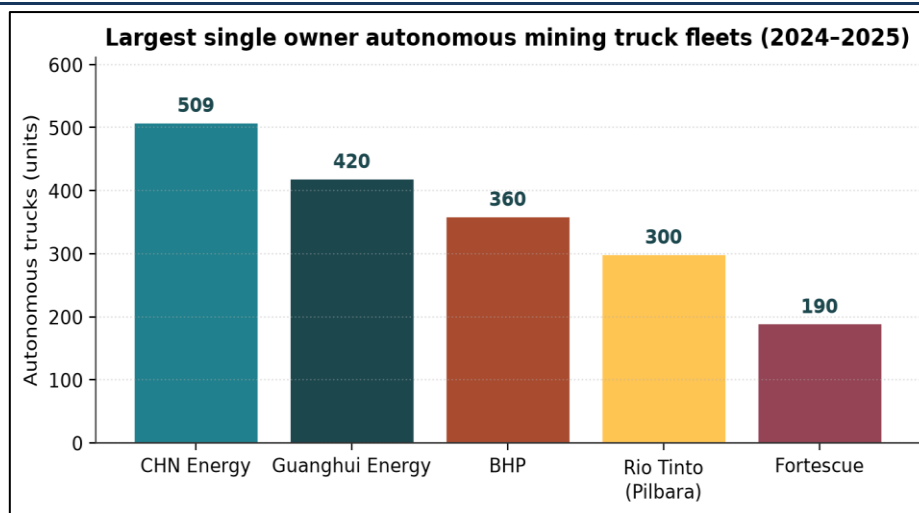


Figure 4: Largest single owner autonomous mining truck fleets reported through 2024–2025. Data compiled from Mining Technology (2025) and Pertama Partners (2024).

TECHNOLOGY ARCHITECTURE OF AUTONOMOUS HAULAGE SYSTEMS

AHS are best understood as safety critical cyber physical systems (CPS) that integrate five interdependent functional layers: perception,

localization, decision and planning, vehicle control and fleet level supervision, all connected by a vehicle to everything (V2X) communications backbone (Figure 2) (Gaber, *et al.*, 2021; Wang, *et al.*, 2022; Ma, *et al.*, 2025).

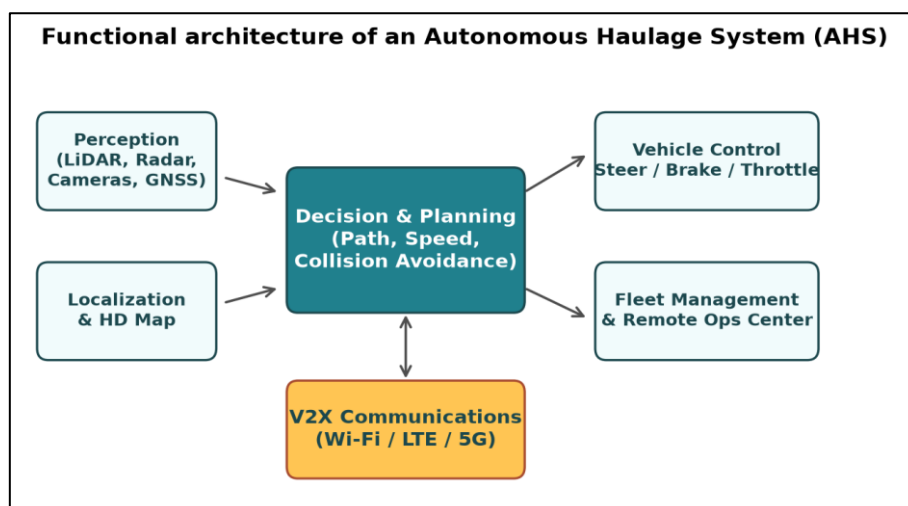


Figure 2: Functional architecture of a mine grade Autonomous Haulage System. Adapted from Wang *et al.* (2022) and Gaber *et al.* (2021); redrawn by the authors.

Perception and Localization

Current AHS trucks fuse LiDAR, radar, stereo cameras and satellite positioning (typically multi constellation GNSS with real time kinematic corrections) to build a 3D representation of the immediate haul environment and to localize the vehicle on a high definition mine map (Xu, *et al.*, 2025; Yang, *et al.*, 2026). Object detection under mining specific conditions like dust, fog, precipitation, low textured haul roads and nonstandard obstacles such as boulders, berms and other equipment remains a research frontier. Xu *et al.* (2025) present MBFILNet, a YOLOv8 based

multi branch detection network for autonomous mining trucks operating in dusty environments, reporting a mean average precision (mAP) of 72.0% on their DOM dataset (a 2.0 percentage point improvement over the baseline) and 55.8% on the DAWN benchmark (3.7 points above baseline). Under complete LiDAR occlusion, Yang *et al.* (2026) show that a Blind Spot Complementary Fusion (BSCF) framework integrating 3D LiDAR with 4D millimeter wave radar can extract high confidence risk cues for hidden obstacles in unloading areas of open pit coal mines (Figure 5).

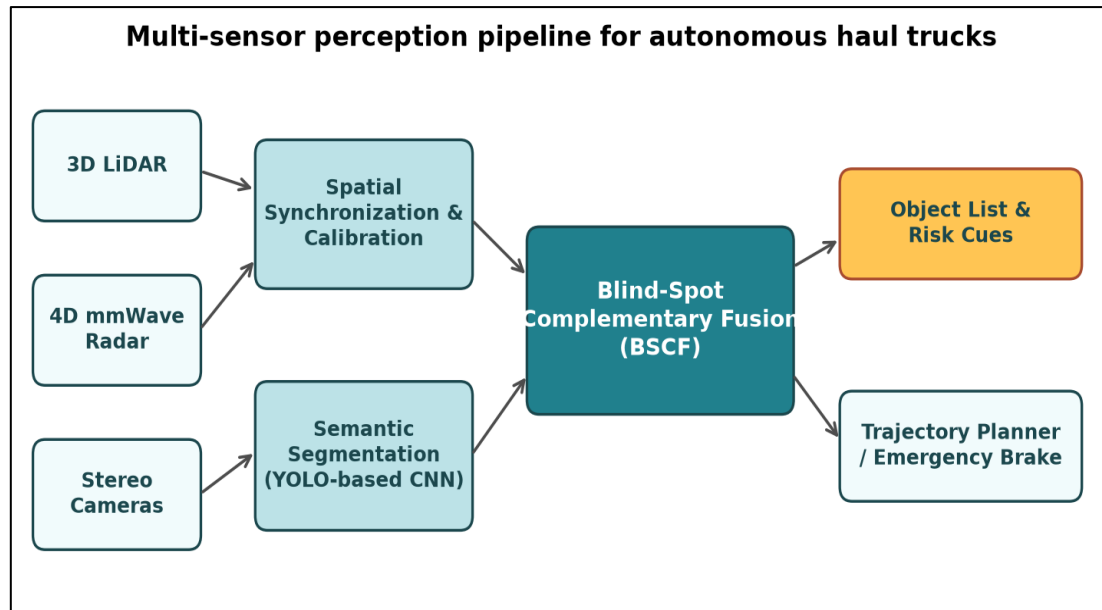


Figure 5: Multi sensor perception pipeline for an autonomous haul truck. The Blind Spot Complementary Fusion (BSCF) block is adapted from Yang *et al.* (2026); semantic segmentation stage informed by Xu *et al.* (2025).

Decision, Path Planning and Vehicle Control

Once the environment has been perceived, path planning and trajectory tracking translate mission level commands from the fleet management system into steering, braking and throttle commands. Model predictive control (MPC) and nonlinear MPC are the dominant control families for articulated and rigid mining trucks (Zhang, *et al.*, 2019; Ma, *et al.*, 2025). Ma *et al.* (2025) propose a model free adaptive MPC (MPC-MFAC) that improves trajectory tracking accuracy for autonomous mining trucks in complex open pit environments. At the mission planning layer, Fang and Peng (2023) develop a micro factors aware metaheuristic scheduler for multiple autonomous open pit trucks, reporting 0.78% lower energy consumption and 5.04% shorter task completion time when temporal factors are embedded directly in the cost function. Collaborative trajectory planning that treats groups of autonomous trucks as coordinated agents rather than independent vehicles is an active area of research (Zhang, *et al.*, 2023).

V2X Communications and Remote Operations

Because current AHS trucks operate as SAE Level 4 systems within tightly defined operational design domains such as geofenced pits, presurveyed haul roads, centrally dispatched loading and dump points which are reliable low latency communications are a load bearing element of the system (Yang, Y., *et al.*, 2026 in Sensors 26/13 [Vehicle Autonomy to Ecosystem Intelligence review]). Modern deployments use combinations of Wi-Fi, LTE and private 5G networks to support V2V and V2I data flows and to enable remote operations centers to supervise fleets in real time (Gaber, *et al.*, 2021).

OPERATIONAL BENEFITS

The consolidated business case for autonomous mining trucks rests on four benefit categories: productivity, cost, safety and utilization (Figure 3). Caterpillar reports that its Command system reduces mine operating costs by 20%, improves productivity by 30% and reduces safety related incidents by 50% (Mining Technology, 2024). Independent reviews of AHS deployments during the late 2000s report performance gains of up to 20% relative to conventional systems (Yang, Y., *et al.*, 2026 [Sensors 26/13]).

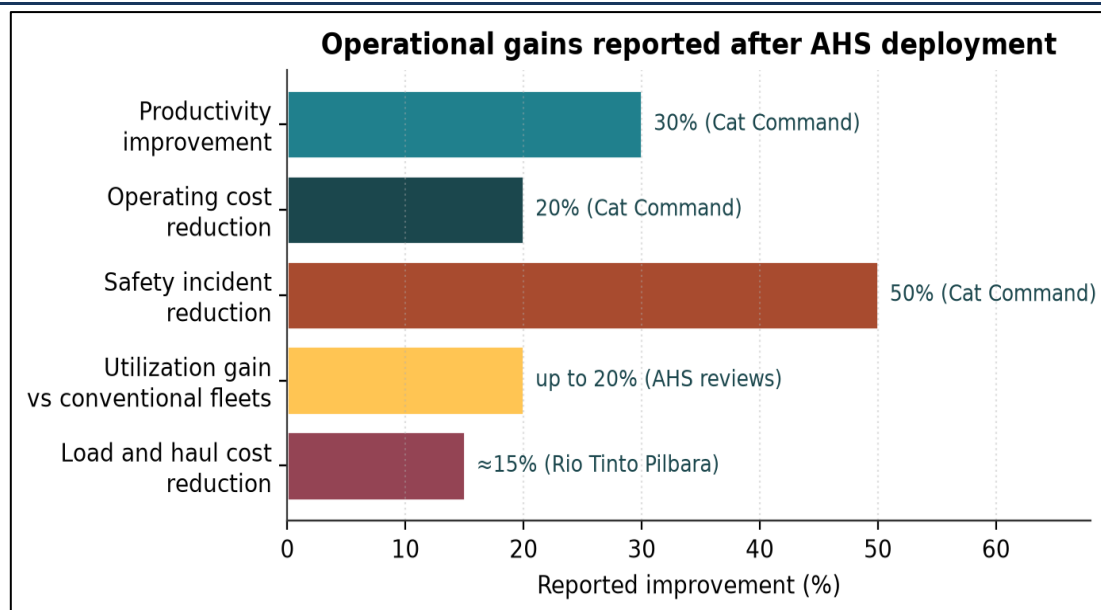


Figure 3: Operational gains reported after AHS deployment. Data compiled from Caterpillar corporate disclosures (Mining Technology, 2024), Rio Tinto operational data (Djanetey *et al.*, 2025) and MDPI systematic review evidence (Yang, Y., *et al.*, 2026).

Productivity and Utilization

Rio Tinto's Pilbara autonomous fleet, running Komatsu FrontRunner AHS, operates approximately 700 hours per year more than each conventional haul truck and reduces load and haul costs by approximately 15%; Rio Tinto has reported operating cost reductions of about 13% attributable to AHS adoption (Djanetey, *et al.*, 2025). Continuous 24/7 operation, the elimination of shift changes and reduced idle time between cycles account for most of the utilization gain (Djanetey, *et al.*, 2025; Mining Technology, 2024). The 300 truck Pilbara fleet now delivers approximately 80% of Rio Tinto's daily production capacity across 10 mine sites (Pertama Partners, 2024).

Safety

Powered haulage is one of the leading causes of fatalities and lost time injuries in surface mining (Attarbo, 2025). By removing operators from hazardous cabs and high traffic loading and dump zones, AHS directly reduces exposure to the equipment related hazards responsible for a large share of mining fatalities (Djanetey, *et al.*, 2025; Amuah, *et al.*, 2025). Caterpillar's Command equipped vehicles had accumulated 67.6 million kilometers without a fatality by 2022 (Wang, *et al.*, 2022). Djanetey *et al.* (2025) further note that autonomous haulage complements other autonomous technologies with drilling, loading and ventilation in reducing worker exposure across the underground mining production cycle.

Fuel and Emissions

Automated haulage improves fuel efficiency by reducing idle time, smoothing acceleration and braking cycles, and enabling optimized routing (Djanetey, *et al.*, 2025; Mining Technology, 2024). When combined with electrification, the emissions dividend is much larger. Fortescue and Liebherr have unveiled the world's first self driving battery electric mining truck (Mining.com, 2025). BHP and Rio Tinto have begun trials of 240 t class electric haul trucks (Electrek, 2025), and Komatsu has demonstrated autonomous trolley operation with a battery ready electric drive truck (Komatsu, 2025). Shishkin *et al.* (2025) model an autonomous electric dump truck used in coal mine reclamation and show that the operating cycle can become net energy generating at payloads above roughly 110 t on a 13% descent grade, converting reclamation from a cost center into a potentially energy positive activity. The rising demand for lithium ion batteries that power these electric haul truck fleets is in turn driving new interest in hard rock lithium sources, particularly LCT igneous pegmatites, as reviewed by Effah *et al.* (2025a).

CHALLENGES AND OPEN RESEARCH QUESTIONS

Perception in Adverse Mining Conditions

Even mature AHS deployments struggle with dust, precipitation, low visibility conditions and non line of sight (NLOS) obstacles at loading and dump points (Xu, *et al.*, 2025; Yang, *et al.*, 2026). LiDAR cannot penetrate solid obstacles, and single

LiDAR systems can miss hidden targets entirely under close range occlusion, potentially leading to collisions (Yang, *et al.*, 2026). Radar and LiDAR fusion, cooperative perception between vehicles and infrastructure, and domain adaptive training pipelines that transfer simulated data to real mine environments are all active countermeasures (Xu, *et al.*, 2025).

Cybersecurity of Connected Haul Fleets

AHS trucks are, in effect, servers on wheels: a modern autonomous 400 t haul truck can generate and consume terabytes of data per shift and is continuously networked to a fleet management system, a remote operations center and a mine wide V2X backbone (Gaber, *et al.*, 2021). Gaber *et al.* (2021) show that the very features that make AHS commercially attractive are always on wireless, cloud connectivity, standardized interfaces that expand the attack surface materially. Attarbo (2025) similarly identifies cybersecurity as one of the principal management challenges of AHS deployment. The mining industry has responded with dedicated risk frameworks and secure deployment guidance (Labbé, 2022), but standardized, mine wide cybersecurity architectures for AHS remain immature.

Workforce Transition and Human–Robot Collaboration

Automation displaces some traditional mining occupations while creating new demand for remote operations technicians, AHS data engineers, network specialists and reliability engineers (Attarbo, 2025). Amuah *et al.* (2025) argue that the future of mine safety lies in AI- and IoT enabled human–robot collaboration rather than the outright replacement of human labor, with autonomous trucks working alongside human operated auxiliary equipment and inspection robots. Djanetey *et al.* (2025) reaches a similar conclusion for underground haulage, where narrow drifts, limited maneuvering room and rapidly changing geometry make full autonomy considerably more difficult than in open pit environments.

Capital Cost, Interoperability and Infrastructure

AHS deployments require substantial capital investment in high precision GNSS, communications infrastructure, high-definition mine mapping and command centers, and this cost has slowed adoption in smaller and underground operations (Djanetey, *et al.*, 2025). Interoperability between OEMs is limited: fleets are typically

single vendor because control protocols and fleet management interfaces are proprietary. Tage Zhixing has demonstrated mixed marshalling operation of trucks from different manufacturers and tonnages at Bayan Obo (Wang, *et al.*, 2022), but industry wide interoperability standards for autonomous mining trucks remain absent.

Environmental and Climate Resilience

Autonomous fleets operate on infrastructure such as haul road networks, waste rock dumps, tailings storage whose stability is increasingly stressed by climate change (Armah, *et al.*, 2025). Integrated AI/GIS platforms of the kind proposed by Amuah *et al.* (2025) for predictive water quality monitoring in copper mining regions and the AI/IoT hazard detection framework of Amuah *et al.* (2025b) point to a natural fusion between AHS perception data and mine wide environmental monitoring, in which autonomous trucks act as mobile sensor platforms as well as production assets.

CONCLUSIONS

Autonomous mining trucks have moved decisively from demonstration to industrial scale production. The global operating fleet has passed 3,830 units on surface mines and continues to grow at more than 80% per year (Range Strategy Consulting, 2025). Reported operational benefits are substantial and consistent across independent studies and OEM disclosures: productivity gains of the order of 30%, operating cost reductions of about 20%, safety incident reductions of about 50%, and utilization improvements of up to 20% relative to conventional manned fleets, together with material reductions in load and haul cost and additional operating hours per truck per year at Rio Tinto's Pilbara operations (Djanetey, *et al.*, 2025; Mining Technology, 2024).

At the same time, the review highlights four priority research directions. First, perception under dust, fog and NLOS conditions must improve, and multi sensor fusion architectures such as those proposed by Yang *et al.* (2026) and Xu *et al.* (2025) are the most credible near term path. Second, cybersecurity architectures for AHS need to keep pace with the expanding data footprint of connected haul trucks (Gaber, *et al.*, 2021; Attarbo, 2025). Third, the industry must accelerate interoperability standards so that mixed OEM fleets and hybrid manned/autonomous operations become the default rather than the exception. Fourth, the convergence of autonomy with battery electric propulsion, trolley assist and regenerative

braking cycles points to a genuinely low emission haulage paradigm (Shishkin, *et al.*, 2025; Komatsu, 2025). Delivered together, these advances would justify the current investment in autonomous mining trucks and would extend their operational envelope from a handful of well capitalized open pit iron ore and copper operations to a much broader set of underground, mid tier and emerging market sites.

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Source of support: Nil; **Conflict of interest:** Nil.

Cite this article as:

Whajah, J., Effah, B. B., Whajah, J., Djanetey, G. E. "Autonomous Mining Trucks: A Review of Deployment, Technology Architecture, Operational Benefits and Emerging Challenges" *Sarcouncil Journal of Engineering and Computer Sciences* 5.10 (2026): pp 1-8.