Volume 21 | Issue 4 | August 2024

MINING & QUARRY WORLD

Volume 21 • Number 4 • August 2024

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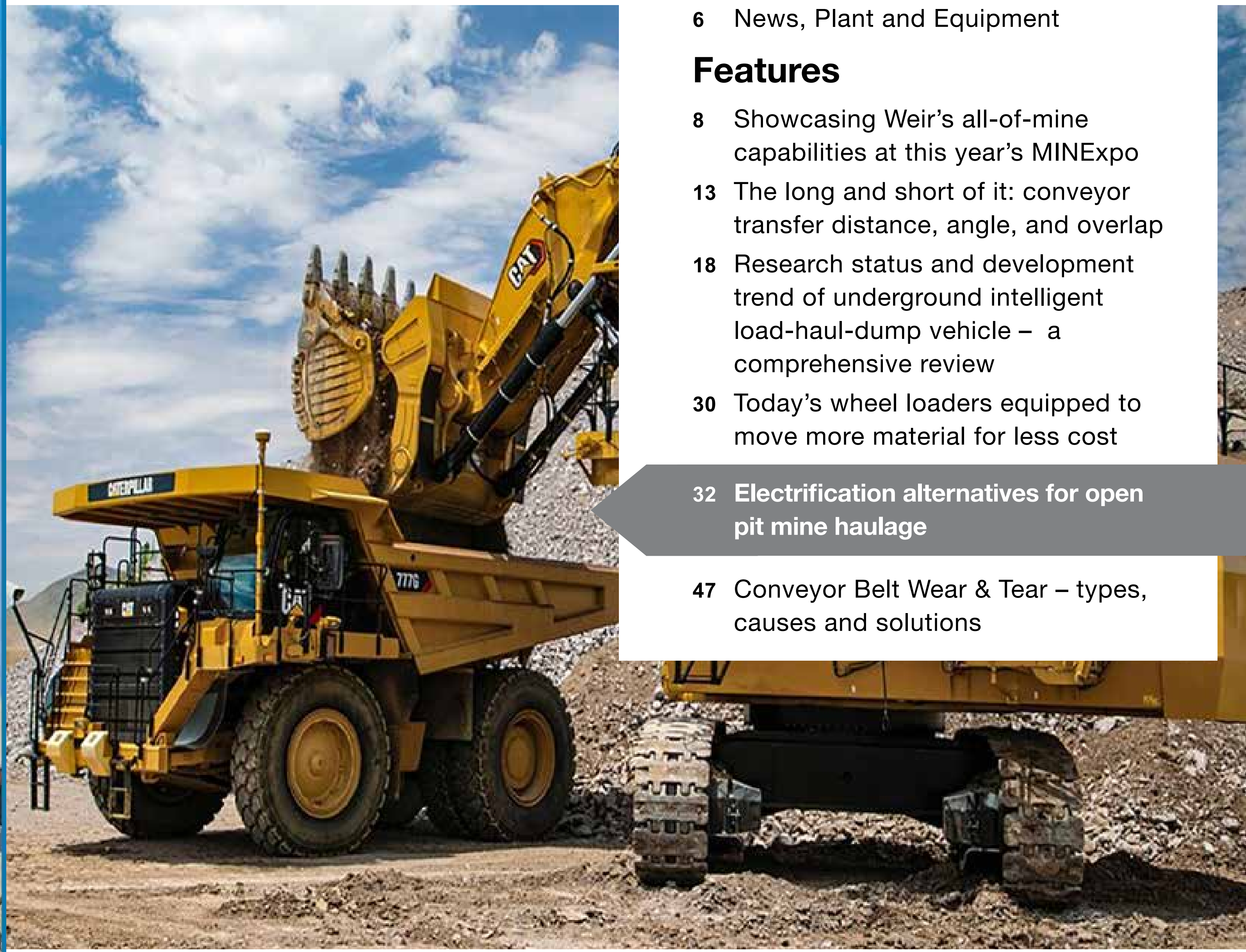

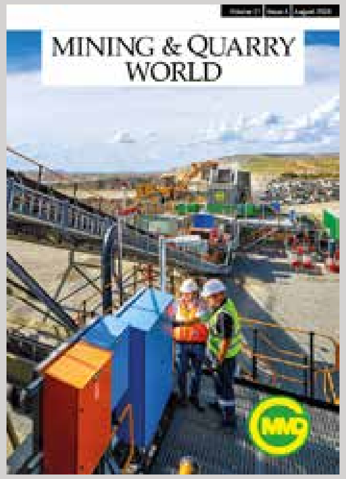

MMD Group is a global leader in the design and manufacture of Mineral Sizing and In-Pit Sizing and Conveying (IPSC) technology. The company's groundbreaking fixed, semi-mobile and fully mobile IPSC solutions are improving the performance and efficiency of numerous mines around the world by enhancing safety and reducing environmental impact, while delivering low operating and maintenance costs.
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E-mail: admin@mqworld.com
Web: www.mqworld.com

All subscriptions payable in advance.

Published 6 times per year, post free:
UK: £60.00 **Worldwide:** £70.00 | ISSN No: 2045-2578 | D-U-N-S No: 23-825-4721

Initial bids for Anglo's Australian coal mines next month, sources say

First-round bids for Anglo American's Australian metallurgical coal mines are due in September, two sources said recently, as CEO Duncan Wanblad takes initial steps to simplify the company after rejecting a takeover offer from BHP.

Anglo's mines for the steel-making ingredient include Grosvenor and Moranbah North as well as three smaller mines all in Queensland state, a package that broker Jefferies valued at $4.5-billion before a fire at Grosvenor in June. The mine remains shut and is unlikely to reopen before 2026, analysts say.

Wanblad is embarking on a strategy to shore up the miner with a focus centred on copper after rebuffing BHP's $49-billion takeover offer earlier in the year.

Anglo, which declined to comment, said it expected to reach a deal for the coal assets by early 2025.

Its restructuring plan also includes divesting its De Beers diamond assets and its nickel mines, as well as the demerger of its South African platinum unit. Standard Chartered has been appointed to run the nickel sale, according to one of the sources, who was not authorised to speak publicly about the matter. Standard Chartered did not immediately reply to an emailed request for comment.

Potential Buyers

Glencore, already a major supplier of Australian coal, is expected to make a bid for the assets, given its favourable view on the commodity and its strong balance sheet, according

to analysts.

The London-listed miner opted this month to keep its coal business, having considered spinning it off, as it completed its buyout of Teck Resources' Canadian coking coal assets. A Glencore spokesperson declined to comment.

Indonesian buyers are also expected to make an appearance.

A consortium including Golden Energy and Resources (GEAR), backed by Indonesia's Widjaja family and Australian privately owned company M Resources is considering making a bid, a source familiar with the matter told Reuters.

Indonesia's Delta Dunia Group, which runs its Buma coal mining services business in Australia, said last month it planned to grow through acquisitions.

Delta Dunia Group Director Iwan Fuad Salim told Reuters this month the company would continue to "look at opportunities when they arise as part of our growth strategy," but declined to elaborate further.

Yancoal, which operates several coal mines in Australia, "continues to look for high quality acquisition opportunities," it said in an earnings report.

Cat delivers on uptime, efficiency

A new engine has given the Cat 6020 hydraulic mining shovel a boost, delivering on high uptime and increased efficiency.

The engine has been replaced with a new Cat C23B to offer more reliable and durable operations. No additional hardware is required for the engine replacement, offering the same 776 kilowatts rated power as its predecessor.

A higher flow oil and baffles in the oil cooler keep the engine core cooled, while the new cylinder head maximises heat transfer.

In an effort to increase reliability, a thicker shim gasket reduces the risk of head-to-block oil leaks. More durable exhaust valves, especially when operating at high power, reduce the chance of exhaust valve failures.

"Hydraulic optimisation for the 6020 shovel dynamically assigns individual pumps or groups of pumps to deliver the exact flow and pressure required by each hydraulic function," Cat said.

"Reducing waste and excess heat buildup, hydraulic optimisation provides efficient use of the engine for greater productivity, less energy and fuel consumption, and reduced component wear.

"With its 22-tonne payload, the 6020 efficiently loads the Cat 775 truck in three passes, 777 in four passes, 785 in six passes and 789 in eight passes."

Designed for operator comfort, the next generation cab on the 6020 offers visibility for operating productively, safely and efficiently.

"Electronic-hydraulic servo joystick control delivers fast and precise machine movements with less operator fatigue, while five-circuit hydraulics allow for simultaneous control of two cylinder motions, two travel motions and swing," Cat said.

"The large 254mm high-definition colour touchscreen puts all vital machine and diagnostic data at the operators' fingertips."

Rome confirms promising tin mineralisation from early drilling in DRC

Rome Resources has struck visible tin mineralisation in several intervals in the first hole of its drilling campaign on the Bisie North projects, in the Democratic Republic of Congo (DRC).

The company will mobilise two drill rigs on site to maintain an aggressive drilling campaign.

The first drill hole was drilled down to a depth of 164.5 m at the Kalayi prospect. The mineralised zone was intersected about 60 m below the KBDD003 drillhole from Rome's 2023 drilling campaign which had reported 12.5 m of tin grading 1.03%, including 1 m of tin grading 2.78% and 1 m of tin grading 7.12%.

Visible coarse-grained cassiterite, or tin mineral, in the latest KBDD005 hole was intersected in three narrow zones associated with quartz veining and silica flooding at 88.5 m, 114 m and 125 m.

The presence of cassiterite was confirmed through Niton X-ray fluorescence analysis.

Rome reports that strong chlorite alteration, together with shearing and quartz veining, was noted throughout a 30 m interval from 84 m to 114 m. This has the potential to host fine grained disseminated cassiterite, which will be assessed in the quantitative analyses to be conducted by a laboratory.

Chlorite alteration is strongly associated with tin mineralisation at both Alphamin's Mpama North and South deposits, indicating a similar style of mineralisation at Kalayi.

The Bisie North projects comprise the Mont Agoma and Mont Agoma Northwest prospects in the North Kivu province of the DRC.

Europa touches down in the Pilbara

Fortescue's hydrogen-powered haul truck prototype, dubbed Europa, has arrived in the Pilbara to complete site-based testing.

Europa, a Liebherr T 264 haul truck, will be tested in a real-life mining environment at Fortescue's Christmas Creek green iron project, helping to inform the company's future fleet of zero emission haul trucks.

The truck will be refuelled with liquid hydrogen from a gaseous and liquid hydrogen plant on-site.

"It's fantastic to have our hydrogen-powered haul truck prototype now joining its battery electric equivalent, Roadrunner, up at site," Fortescue Metals chief executive officer Dino Otranto said.

"Europa integrates for the first time a Fortescue Zero battery into a Liebherr haul truck, marking a huge milestone in our partnership with Liebherr.

"Over the next five years we'll be working with Liebherr to develop a fleet of zero emission haul trucks, which will be progressively deployed across our sites from 2026."

Liebherr-Mining Equipment SAS executive vice president of research and development, engineering and production Oliver Weiss said both companies are aligned in the belief that hydrogen will play an important role in supporting the mine decarbonisation.

"What we learn from this hybrid truck will significantly shape and enhance our future development strategies for zero emission haulage," Weiss said.

"The integration of a Fortescue Zero battery into a Liebherr haul truck marks a huge milestone in the partnership between the two companies.

"It is fascinating to see how this cooperation helps to fast track our planned developments of new technology from ideas to demonstration and operation in the field."

Proposal to ban openpit mining advances in Mexican Congress

A committee in Mexico's lower house of Congress approved two constitutional reforms that would prohibit open-pit mining and fracking, as well as restrict the use of genetically modified corn.

The proposals, passed recently, will be taken up for discussion by the full lower house after lawmakers return to session in September.

The changes would also prevent the exploitation of water in areas with water scarcity, with the exception of extraction in populated areas for domestic use, according to a statement released.

The changes are part of a package of constitutional reforms presented in February by President Andres Manuel Lopez Obrador, which contains other proposals, including one to restructure the judiciary.

In Mexico, constitutional changes must be approved by a two-thirds vote in the plenary session of the both the lower house and the Senate, and by the majority of local congresses. In the June elections, Lopez Obrador's ruling Morena party and its allies achieved a qualified majority in the lower house and were just two seats short in the Senate.

Lopez Obrador has criticized the mining contracts with private companies signed by his predecessors and says that his administration has not granted any new private concessions in the sector.

The Mexican Mining Chamber (Camimex) opposes the ban on open-pit mining, saying such a prohibition would cause a 1% contraction in the country's GDP and threaten some 200,000 jobs.

Regarding the genetically modified corn, the proposal comes as Mexico and the United States have an ongoing dispute at a panel of the U.S.-Mexico-Canada Agreement. The lower house committee's reform would allow for the entry of genetically modified corn into Mexico only for non-human consumption and only if the grain does not have the capacity to germinate.

Weir, De Grey partner up

De Grey Mining has awarded Weir a contract to supply an Enduron high-pressure grinding roll (HPGR) for its Hemi gold project in the Pilbara.

The contract comes as Weir officially opens its Port Hedland Service Centre to further support its customers in the Pilbara.

De Grey Mining project director Peter Holmes said the company is looking forward to the partnership.

"De Grey Mining is pleased to partner with Weir on one of its key long lead items for its Hemi gold project and appreciates Weir having a local service facility to provide the required support to our site and the region," he said.

Weir Enduron HPGRs global product manager Bjorn Dierx echoed similar sentiments.

"Our partnership with De Grey Mining further expands our footprint in sustainable comminution," Dierx said.

"Our proven track record of developing highly engineered solutions for the industry, together with our capability to partner with our customers to bring projects to life, ensures that De Grey Mining will be in good hands to achieve its productivity, sustainability and project execution targets.

"Importantly, Enduron HPGRs also provide significant improvements versus traditional tumbling mill technology with energy savings of up to 40% and in turn, a lower carbon footprint. This will be the fifth, similar-sized Enduron HPGR in the Pilbara region alone, which is a testament to its credibility in high capacity, hard-rock grinding."

Weir regional managing director Kristen Walsh said the contract elevates Weir's sustainability goals.

"This win further underscores Weir's commitment to making mining more sustainable and demonstrates the substantial opportunity that can be made to CO_2 emissions reduction when choosing an energy-efficient technology in a large greenfield project," she said.

Metso locks in $333m order at Reko Diq

Metso has signed a comprehensive frame agreement with Reko Diq Mining, the owner of the Reko Diq copper-gold project, one of the largest undeveloped copper-gold deposits in the world.

Under the agreement, Metso will deliver crushing and grinding circuits that include Superior 6089 MKIII gyratory crushers, Nordberg MP1250 cone crushers and Premier ball mills with 51-megawatt installed power. These are equipped with gearless mill drive technology and Metso's failsafe polymer hydrostatic shoe bearing systems.

Reko Diq Mining has also placed orders for TankCell mechanical flotation cells, high-intensity Concorde Cell units, HRT thickeners, Vertimill and HIGmill regrind mills, mill reline equipment, concentrate filters and automation equipment, all of which are expected to be signed and booked in Metso's minerals segment order intake later this year and 2025.

The equipment packages under the framework agreement are valued at $EU200 million ($333 million).

"We are excited to work as a strategic partner with Reko Diq Mining in this major greenfield project which will ramp up global copper production required for energy transition," President of Metso's minerals business division and deputy chief executive officer (CEO) Markku Teräsvasara said.

"Metso will provide Reko Diq with advanced and sustainable technology for the production of copper and gold concentrates."

Reko Diq Mining is 50 per cent owned by Barrick Gold, 25 per cent owned by three federal state-owned enterprises, with the balance held by the Balochistan Government.

The Reko Diq project is expected to have a mine life of approximately 40 years as a truck-and-shovel open pit operation, with construction expected in two phases. This will provide a combined processing capacity of roughly 90 million tonnes per annum. First production is targeted for 2028.

"Reko Diq will substantially expand Barrick's strategically significant copper and gold portfolios and benefit all its Pakistani stakeholders for generations to come," Barrick president and CEO Mark Bristow said.

"We are pleased to partner with Metso in this project where sustainable concentrate processing is one of the key drivers for plant design and operation."





Showcasing Weir's all-of-mine capabilities at this year's MINExpo

Weir is a global leader in mining technology. It recognises that the planet's future depends on the transition to renewable energy, and that transition can only happen with the metals and minerals its mining customers deliver. Supporting the energy transition is at the core of its purpose, and Weir's integrated technologies and solutions play a critical role in supporting its customers in the efficient and sustainable extraction of these resources.

With all-of-mine capabilities – from extraction, through the mill and comminution circuits, to tailings solutions – Weir is uniquely positioned to leverage its world-class engineering, materials science expertise and global footprint to partner with miners to help them produce more valuable metal, while consuming less energy, using water wisely and generating less waste.

OPTIMISING EXTRACTION

Starting in the mining pit, Weir will be launching its newest GET system – the ESCO® NEXSYS™ GET and lip system for rope shovel dippers – at MINExpo. The new system extends service life due, in part, to its improved adapter protection, new rear wear cap and advanced tooth profile. The NEXSYS® optimised nose position and geometry extend adapter life, providing better penetration and loading. The new tooth system requires fewer point changes, while the single, sealed lock reduces impacted files for easier removal with an off-the-shelf hand tool.

Notably, mines have relied on ESCO® products for industry-leading lip and GET systems for nearly 100 years – and rope shovel dippers have been a mainstay for that entire period. Weir's experience when it comes to designing, manufacturing and optimising its ESCO® mining-class dippers ensures it delivers value and performance to its customers all over the world. It offers custom-engineered dippers for all OEM machines or, alternatively, it can create OEM direct replacement options with ESCO® Production Master® dipper features to improve performance and reduce maintenance.

Weir's precision engineering and manufacturing increases shovel availability, while its reliable, longer-lasting components eliminate unplanned downtime and reduce maintenance costs and improve safety.

Weir custom engineers each ESCO® Production Master® dipper to meet the mine's specific requirements. Scale model testing is used to maximise productivity and digging efficiency. Weir consults with mine personnel to address capacity, lip, GET, rope connection and wear package options to improve reliability and productivity.

ENGINEERING AND METALLURGICAL EXPERTISE

ESCO® ProFill® dragline buckets are manufactured using proprietary cast alloy construction, which have been developed over its 100 years as a manufacturer of premium steel castings. Weir's engineering and

WEIR MINING TECHNOLOGY



metallurgical expertise provides an optimised cast structure with a balance of strength, impact resistance and wear life. ESCO® dragline buckets are built to deliver superior productivity and maximum durability under the toughest digging conditions.

A proven performer, standard ProFill® buckets provide increased productivity and cost savings worldwide. Building on this success, Weir now offers the ProFill® Delta™ bucket, which combines proven performance and new, simplified rigging. The 164-yard ESCO® ProFill® bucket, which utilises a Nemisys® N5 lip system and 5-inch ESCO® ProSeries™ drag chain, is currently the world's largest operating dragline bucket.

Weir produces reliable, performance-driven wheel loader buckets built for the world's most demanding mine sites. ESCO® buckets are compatible with most 5m3 (6.5yd3) class and larger loaders. Engineered to deliver payloads meeting site production requirements, buckets are available in extra heavy-duty (XHD), heavy-duty (HD) and general purpose (GP) duty classes. Plate lip system options include best-in-class Nemisys® N65 and N70 or SV2® tooth system.

Their unsurpassed durability is the result of reducing stress points in beam shapes, weld-joint design and plate configuration, which are all optimised with advanced Finite Element Analysis (FEA). ESCO® mining wheel loader buckets are engineered to outlast with attachment lugs that wrap under the bucket to spread stress loads evenly and single-beam HD or triple-formed XHD beams that are engineered to meet application demands.

REDUCING DOWNTIME

With over 1000 installations worldwide, Weir's ESCO® Nemisys® lip and GET system is field proven to lower operating costs per tonne. The system features an integrated single-side lock for easier and faster removal to minimise machine downtime during maintenance cycles. The hammerless lock provides improved engagement with the nose to significantly reduce the chance of point loss and unplanned downtime.

The Nemisys® offering covers miners' GET needs for rope shovels, draglines, mining excavators and wheel loaders. No two sites are the same – equipment, application and customer requirements vary from operation to operation – and the ESCO® Nemisys® system provides flexibility with differentiated design segments to meet these various challenges.

AI AND COMPUTER VISION TECHNOLOGY

Complementing Weir's range of ESCO® products, MOTION METRICSTM AI and computer vision technology enhances sustainability and operational efficiency.

Weir's MOTION METRICSTM technology delivers accurate real-time particle size analysis throughout the mining process, from extraction to processing. These systems integrate seamlessly with shovels, loaders, conveyor belts and haul trucks, ensuring uninterrupted productivity. It helps mines minimise equipment downtime and enhances performance by precisely detecting missing GET, monitoring material volumes, analysing particle sizes and addressing oversized elements.

Weir introduces innovations like its tooth wear monitoring module and its advanced PayLoad Monitoring (PLM) system into one of its flagship digital products, ShovelMetrics™ Gen 3. Continuous monitoring of bucket teeth,lip shrouds, and the addition of wing shrouds releasing later this year – coupled with active tooth wear tracking – assists maintenance crews in anticipating change-outs. With PLM for ShovelMetrics™ Gen 3, operators can now accurately measure the weight of material bucket by bucket, overcoming challenges like overloading and underloading and maximising the efficiency of loading and hauling cycles.

Harnessing the power of AI, MOTION METRICSTM TruckMetrics™ uses AI-based stereoscopic cameras over hauling roads to monitor the material carried in mining trucks and then provides boulder alerts, while LoaderMetrics™ Gen 2 employs AI and thermal imaging for accurate detection of missing GET in mining loaders.

Delivering operational insights with technologies developed and designed to measure particle size, BeltMetrics™ Gen 2 analyses PSD and monitors bulk material on conveyor belts without the need for cuts, calibration or object scaling, while PortaMetrics™ Gen 2, which is a portable device, utilises image analysis technology to assess the PSD of blasted rock piles.

Flowsheet-based approach

Further upstream, Weir's new ENDURON® Elite screen is a double-deck banana screen, available in a range of sizes, the largest of which has a deck measuring 4.3m x 9.7m and weighs nearly 50 tonnes.

The ENDURON® Elite screens are driven by Weir's new ETX exciters. It's developed three new models – the ETX150, ETX200 and ETX250 – that can drive these large, high-capacity screens with just two exciters. There isn't another machine on the market that can do that. This delivers advantages in terms of efficiency, lowering energy consumption, as well as simplifying the maintenance requirements.

These screens, which are some of the biggest on the market, can be utilised in any screening duties within the mill circuit, including in HPGR discharge applications. Screening HPGR discharge typically requires a large screen because HPGR circuits operate with up to a 200% recirculation load, resulting in high screen feed rates. Moreover, because the cut size of typical HPGR screens range from 1-4mm, larger screens than those usually employed in typical mining application are required to ensure optimal performance.

Notably, the ENDURON® Elite screen complements Weir's commitment to deliver transformational flowsheets in which traditional tumbling mills are replaced by HPGRs and vertical stirred mills, potentially reducing energy consumption by up to 40%.

This flowsheet-based approach also informs Weir's tailings offering. Weir has developed a range of flowsheets for tailings management to help miners reduce, rethink, and repurpose their tailings. Weir recognises that its customers have different requirements and different constraints, and its flowsheet-based approach allows it to partner with miners to understand the advantages and disadvantages of each solution and provide a balanced assessment of each approach.

Weir realises that, as an OEM, its tailings management solutions cannot simply be dictated by its product portfolio; rather, through consultation, it comes to understand the constraints of each operation – for instance, water, energy, carbon, existing footprint, etc.– and develops a solution around these. The next stage focuses on designing and validating the best solution to combat these challenges and deliver operational and structural stability.

Essentially, the flowsheets Weir has developed provide a starting point to explore a full suite of tailings management options. They are all customisable, ensuring each operator can arrive at the optimal solution based on their needs and objectives.

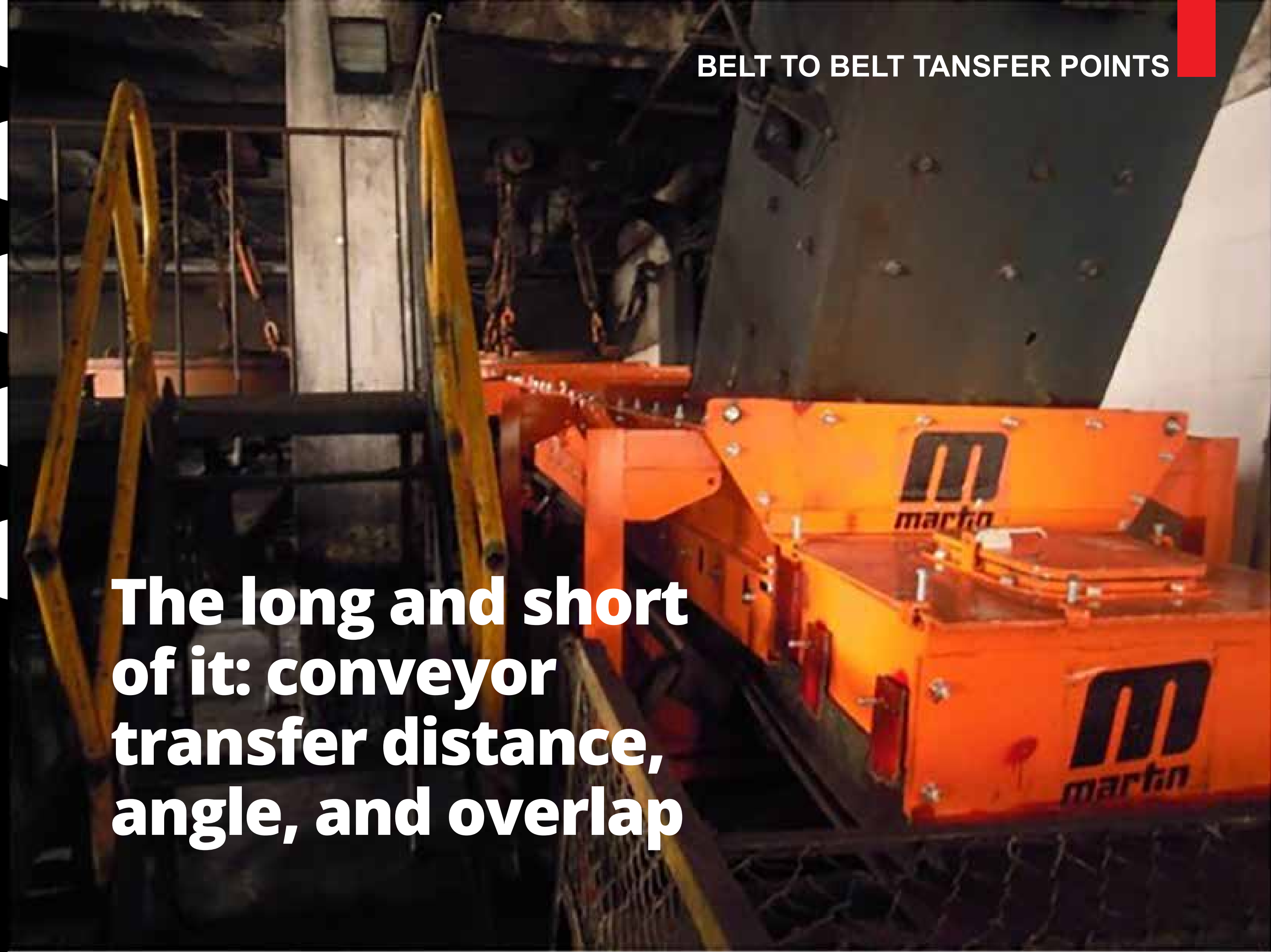
PROCESS OPTIMISATION

Further enhancing these solutions is Weir's digital capability. Weir provides an integrated system that can assess and then optimise individual equipment or processes. In other words, Weir's intelligent solutions have all the information needed about equipment – design, operational and service data. When combined with live performance data, Weir's data models and AI functionality, users benefit from valuable insight, recommendations and predictive capabilities.

It's also important that Weir is aligned with its customers, that it understands their objectives and how they want to harness digitalisation to help them meet their goals. Weir takes a very structured approach to this. It sits down with the customer at the outset, gets to know their operations and tailors a suite of digital solutions that target their operational objectives, whether that's reducing their energy consumption, improving equipment availability, optimising process efficiency or any number of other things.

One of the advantages Weir has over its competitors is that it has the largest service centre network in the industry, not only ensuring that its teams on-the-ground are well supported, but ikeeping them very close to customers, working with them every day, taking their feedback on-board and being a reliable partner.

Weir's booth will be in Central Hall, Booth #8833 where technical experts will be on hand ready to discuss the ways in which Weir's mining technology solutions help to accelerate the path to smart, efficient and sustainable mining.



The long and short of it: conveyor transfer distance, angle, and overlap

Modern retrofitted designs for transfer chutes can dramatically improve the efficiency of a conveyor system.

Bulk handling is not a surgical practice and nor should it be, but when it comes to conveyor systems, a few inches can make the difference between blissful efficiency and hours of frustrating and costly downtime. Efficiency is achieved when the conveyor transfer point can sustain production levels until the next scheduled shutdown without excessive hours of labor for cleaning up spillage, unscheduled downtime for maintenance of broken components and billowing clouds of dust.

The length of the conveyor transfer point varies according to the needs of the application and the allowable physical space. Consisting of a loading zone, a stilling zone and a settling zone, the general rule is that longer settling zones are better. However, in an attempt to save money, operators choose shorter transfer point designs just to find out that length is not the only thing it falls short of. It also fails to allow for settling dust, handle production demands, or – most importantly -- improve workplace safety.

IN-LINE TRANSITION

In an ideal world, all belt-to-belt transfers would be in-line and all the discharging and receiving belts would

Inline transfers may be an optimal configuration but can still have serious problems when "loading on the transition."

Changes in belt speeds or material properties can drastically impact the efficiency of a non-linear transfer point.

run in the same direction. In-line transfers reduce the length of the conveyor when drive power or tension is insufficient for a single belt. These transitions are often necessary to extend the length of the conveyor system or to accommodate mechanisms to blend, crush or separate the material. Transitioning in this manner also makes it relatively easy to place the material on the receiving belt with the load moving in the direction of the belt, reducing unnecessary wear and spillage.

Most inline transfers allow for sufficient belt overlap to avoid "loading on the transition". It may seem confusing because this doesn't mean the conveyor-to-conveyor transition, but instead, it means the belt trough angle transition where the belt goes from flat against the tail pulley to curving into a full trough angle equal to the angle of the cradles and idlers. Loading on the transition area is often an attempt by designers to reduce costs by saving a few meters of conveyor length. It is recognized that this practice creates numerous problems in loading, sealing and belt wear, and should be avoided.

If the belt has not fully transitioned into the trough angle, then the skirtboard and tail box are ineffective at sealing the loading zone. Due to the force and turbulence of the material hitting the belt, fugitive spillage and dust pour out of the openings. The dust permeates the area making visibility and maintenance difficult and may lead to a workplace violation. Spillage piles around the tail pulley, potentially fouling the pulley face, resulting in abrasive damage to the unprotected side of the belt and lowering its operational life. If spillage obstructs walkways and access, this too could pose a workplace violation due to slips, trips and falls, which consistently rank at the top of the list of the most common workplace injuries.

NON-LINEAR TRANSITION

Typically, a conveyor transition denotes a change in the direction of the cargo flow as one conveyor loads onto another, i.e., a "non-linear transfer." This may be required to divert material toward stockpiles or for separating the material.

Problems associated with non-linear transfer points include:

- Difficulty in maintaining the material's proper speed, trajectory, and angle.
- Problems controlling dust and spillage.
- Issues of increased wear on (and the resulting higher cost for replacement of) transfer-point components.

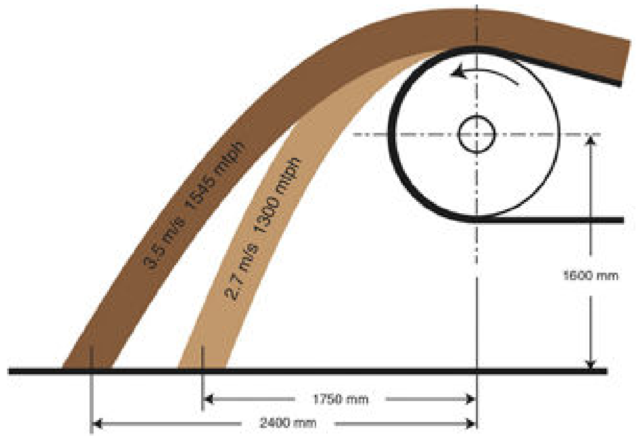
Off-centered loading puts constant abrasive pressure on one side of the loading zone causing uneven wear and mistracking.

If material is loaded on the belt in a direction that is not in line with the direction of the receiving belt, wear patterns may become visible on the inside of the chute. Corresponding to the splash pattern of course cargo as it bounces off the inside of the chute, the wear liner may also show increased deterioration on the area where the material adjusts to the direction and speed of the receiving belt. Ricocheting movement of the material within the transfer chute also accelerates wear on the skirtboard, belt and sealing systems.

HOW LOADING CAN CAUSE MISTRACKING

The force of the off-centered loading material may cause the belt to drift as the weight of the cargo pushes it out from under the skirting on one side. This allows the skirtboard to drop down, preventing the belt from returning to its centered position. The belt will attempt to return to its center as material loading changes, forcing the belt into contact with the sealing strip and cutting through the strip, resulting in substantial spillage opportunities.

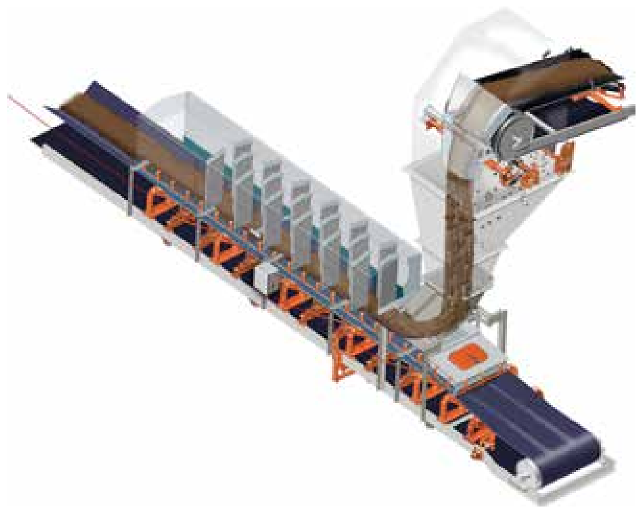
BELT TO BELT TANSFER POINTS



Due to air resistance, light materials and/or high belt speeds alter the upper and lower limits of the vertical and lateral spread.

If a significant weight remains on one side of the belt, it could cause tracking issues down the length of the system, leading to spillage, idler fouling and damage at the discharge zone. Fortunately, a number of strategies and components can be employed to guide the flow of material into the desired direction of travel and load it onto the center of the receiving belt.

Not providing enough overlap of the conveyors is a common mistake that results in mistracking. This leads to a loading on the transition situation, and in some cases, does not allow enough room for installing belt cleaners. Without attention to proper conveyor design, including sufficient overlap, the operation is burdened with a conveyor that will have excessive downtime and a higher cost of operation.



Spoon configuration: Controlling the trajectory of material flow has a direct impact on system health and equipment life.

CONVEYOR DISCHARGE TRAJECTORY

On a conveyor transfer system, to reduce the load absorption that can damage the belt and dust emissions caused by turbulence, drop height should be kept at a minimum. This is best accomplished by controlling the trajectory of the material. The "trajectory" is the path the bulk material takes as it is discharged from the delivery conveyor, which is affected by the speed of the belt, the angle of inclination of the discharging belt and the profile of the material on the belt.

The manual, *Belt Conveyors for Bulk Materials, Sixth Edition*, released by the Conveyor Equipment Manufacturer's Association (CEMA), maps the procedure to determine a constant trajectory path. "To plot the trajectory, a tangent line is drawn from the point at which the material leaves the pulley. At regular time intervals along this tangent line, vertical lines are projected down to fall distances. A curve is then drawn through these points to produce the centroid trajectory. The upper and lower trajectory limits can also be plotted by offsetting from the centroidal curve the distance to the belt and to the load height."

The most common mistake made at this stage of design is developing an initial material trajectory that fails to consider the effects of friction when plotting subsequent reflections of the material stream from the transfer chute walls. Modern transfer-chute designs control the stream of bulk material and do not allow it to free-fall from the discharge onto the receiving belt. With this controlled approach, the designer assumes the material cross-section does not fan out or open up significantly. If drop heights are minimized, then material degradation, dust creation and wear on the receiving belt are minimized.

This approach requires some knowledge of the friction values between the bulk material and transfer chute materials. To assess the effects of changing properties, such as the coefficient of friction, designers should consider using the Discrete Element Modeling (DEM) method. There are several DEM software packages on the market designed for this purpose.

TRANSFER CHUTE AND LOADING ZONE REDESIGN

Many conventional transfer-chute designs have the trajectory plotted as a starting point where the material stream will first impact the head chute wall. From there, the material stream is assumed to be reflected from other surfaces of the chute wall toward the receiving belt.

Engineered hood and spoon designs use gravity to maintain material flow speed but may require greater drop heights. A spoon configuration provides several benefits that should be considered as part of the original design or as part of the requirement of a future retrofit. Some of the benefits of a spoon design are:

- Centered loading for less mistracking.
- Reduced impact for less belt and idler damage.
- Less splash for longer wear liner and skirtboard life.
- Considerably less turbulence leading to dust and spillage.

MODULAR TRANSFER POINT

As important as the trajectory of the material is, the receiving belt needs to be housed in a sealed and well-

A well-designed loading, settling and stilling zone require safe components that protect the belt and the surrounding work environment.

designed environment. Martin Engineering developed a Modular Transfer Point Kit that is adaptable to the needs of bulk handlers of almost every industry. The kit is a heavy-duty horizontal enclosure for the loading zone which includes a loading zone, settling zone, or stilling zone.

The transfer point system accommodates belt widths of 18-72 in. (450-1800 mm) and an internal chute width of 9-59 in. (228-1498 mm). Each modular section is either 4 feet (1.21 meters) or 6 ft. (1.82 m) long and constructed of mild steel, 304 stainless steel or 316 stainless steel, with a thickness of 0.25 in. (6.35 mm), 0.5 in. (12.7 mm), or 0.75 (19.05 mm) to accommodate a wide variety of materials and conditions.

Once the kit is built, a series of integrated components such as impact cradles, slider cradles, dust curtains, external wear liners, and self-adjusting or dual-seal skirting can accompany the system to optimize efficiency, safety and maintenance. These components have been meticulously engineered and field-tested to provide optimum results.

CONCLUSION

The bulk handling environment is punishing on equipment and slight changes in the throughput can have unpredictable consequences. The dynamics of conveyor transitions can depend on changes in weather, material and production demands. To prevent dust emissions and spillage, conveyor transfers require a series of well-engineered components working in tandem to keep the environment sealed, however, they should also be graded above the existing production environment to accommodate these changes. Experts recommend that designers of conveyor transfers consider ease of maintenance, safety and logistics in their design by choosing a single reputable manufacturer for all of the integrated components.

Jerad Heitzler
Training Manager,
Martin Engineering

As program manager and lead instructor for Martin Engineering's FOUNDATIONS™ Training Workshops, Jerad Heitzler is a leader in helping the industry learn how to make the handling of bulk materials cleaner, safer, and more productive. He started with Martin Engineering as a Customer Development Representative in 2006. He soon realized his love for presentations and for teaching about conveyor systems, and so in 2010 took over management and development of the company's FOUNDATIONS™ Workshop program. Under his leadership the program has expanded to offer several levels of conveyor improvement workshops around the world.

Research status and development trend of underground intelligent load-haul-dump vehicle – a comprehensive review

The underground intelligent load-haul-dump vehicle (LHD) is a product of the deep integration of traditional LHD with information network technology, automatic controlling and artificial intelligence technology. It gathers the functions of environmental perception, autonomous driving and fault diagnosis in one machine and exhibits higher safety and greater efficiency than traditional LHD. Hence, it is a particularly important piece of underground mining equipment for building green, safe and smart mines. Taking the studies about intelligent LHD collected by CNKI and WOS databases from 1980 to 2022 as a sample data source, employing Citespace visual analysis software for key feature extraction from the documents, statistical analysis was conducted to clarify the current research progress and the frontier topics of the intelligent LHD academia in the past 40 years, in relation to the future development trends. The development history and application status of underground intelligent LHD was expounded in this article, summarizing the research status at home and abroad from four aspects: ore heap perception and modeling technology, trajectory planning method of bucket shoveling, autonomous navigation technology, real-time monitoring and intelligent fault diagnosis technology. The demerits and merits of the technologies were reviewed as well, with future developing and researching trends of the underground intelligent LHD concluded.

INTRODUCTION

Mining is a very important global industry, which is the foundation for industrial development. With the increasing demand of ore raw materials from all over the world and the depletion of shallow mineral resources, following thereupon, the mining scale of underground ore increases greatly[1].

Load-haul-dump vehicle (LHD) is an important and necessary piece of mining equipment, which plays a key role in the transportation of underground ores. Traditional LHD vehicles usually complete ore shoveling, transporting and unloading through manual operation[2-4]. However, the following problems always exist[5-8]. First of all, the production environment is quite harsh. Possible accidents by the underground roadway collapse and the hostile interspace with dust, humidity and noise seriously threaten the health and safety of LHD operators. Second, there are high safety risks upon the driver. Due to underground tunnels normally being narrow and with poor illumination, it is easy for the drivers to experience fatigue while driving, causing accidents. Third, high energy is consumed with low operating efficiency. Since the work efficiency of the LHD mainly depends on the proficiency of the driver, the operating stability of the LHD is unable to be guaranteed. Hence, in order to possibly minimize those issues, how to control and automate the LHDs intelligently have become the main developing trends in this field[9]. In recent years, a large amount of effort has been made on intelligent mining equipment for underground mines, by experts from industry to academia, both overseas and domestically in China. Developed countries, such as Canada, Finland and Sweden, deployed research and application about intelligent and unmanned mining early at the beginning of the 21st century[10]. Various autonomous controlling systems of underground LHDs have been developed successfully and tested in large industrial mines with good results. In China, smart mines have also been constructed gradually with strong technical and financial support from national institutions[11].

Intelligent LHD is a machine system upgraded from traditional LHD by artificial intelligence technology[12], robotic technology[13], information-physics-network technology and image processing technology[14]. It is multi-functionally integrated by remote control, intelligent autonomous operation, intelligent perception and diagnosis, etc. The rapid development of intelligent LHD has really benefitted a lot from the improvements in high-precision positioning and navigation technology. Furthermore, the continuous development and maturity of artificial intelligence (AI) technology also makes significant contributions to it. The intelligent LHD can continue learning new skills to optimize its performance and think like human beings with AI technology[15]. Currently, machine learning (ML) technology has gained wide attention as one of the research directions for artificial intelligence[16-18], which has been popularly used in image, speech and other patterns for recognition. Through combining AI technology with automatic control technology, a more effective intelligent trajectory control algorithm has been developed. In addition, the accumulated running data from a real LHD is also conducive to fault prediction and diagnosis.

This article reviewed the research and development status for intelligent LHDs systematically. Four main research directions, such as mine pile perception and modeling technology, bucket loading trajectory planning, autonomous navigation technology and real-time monitoring and fault diagnosis technology, were reviewed in detail separately. The mechanism, characteristics and shortcomings of each technology were discussed as well; the development trend of underground intelligent LHD for the future was also pointed out.

THE LITERATURE SOURCES AND STATISTICAL ANALYSIS

Data Source

The output English literature data were extracted from the Web of Science Core collection (WOSCC), while the Chinese data sample was obtained from China's largest academic journal indexing platform – China National Knowledge Infrastructure (CNKI). Both searches were performed on 17 May 2022 and the detailed data retrieval strategies are shown in **Table 1**. The valid sample data obtained are: 127 international articles and 158 Chinese articles. It can be seen that the number of articles in Chinese is even greater than that from the international WOSCC database; hence, it is quite important for statistical analysis. However, both source amounts are small, which indicates more attention and attempts should be paid to this topic by industry and researchers in related fields.

STATISTICAL METHOD AND RESULT

Data from the above-mentioned database were imported into and analyzed individually by CiteSpace (version 6.1.R2) software, which is a widely used tool for visual exploration of scientific literature provided by SOURCEFORGE software platform in San Diego, CA 92101, United States. The numbers of articles for valid sample data imported into the software were 125 and 142, respectively, as invalid ones were unformatted or information missed. Cluster and keyword co-occurrence analysis for articles in English and Chinese was performed individually and network maps were visually generated, to illustrate the development trend of key technologies and methods worldwide in the field of intelligent LHD as time went by. The results are shown in **Figures 1** and **2**, respectively. The keywords in the figures mainly come from both the original keywords of the literature and the those expanded based on the subject classification of the journal or database. The font size in the figure represents the occurrence frequency of the keywords. The larger the font, the higher the frequency of the keyword and the more research on it and vice versa. The horizontal position of the keyword represents the recorded year; the more left, the earlier it was paid attention to and studied. The words with a "#" symbol and serial number in the front are the cluster words; the smaller the number, the more keywords are included in the cluster.

Table 1. Data sources and collation results.

Region	Foreign	China
Retrieval date Database	17 May 2022 Web of Science Core Collection (WOS)	17 May 2022 CNKI
Retrieval method	TS = (autonomous OR automatic OR intelligent OR navigation OR location OR unmanned OR track OR remote OR route plan OR control OR shovel OR perception OR model OR underground mining OR sensors) AND TS = (load haul dump)	SU = ("intelligent" + "unmanned" + "autonomous" + "automatic" + "track" + "location" + "navigation" + "remote" + "control") × ("load haul dump")
Time span	1980-2022	1980-2022
Number of documents retrieved/article	127	449
Number of valid documents/article	127	158
imported into CiteSpace software	125	142

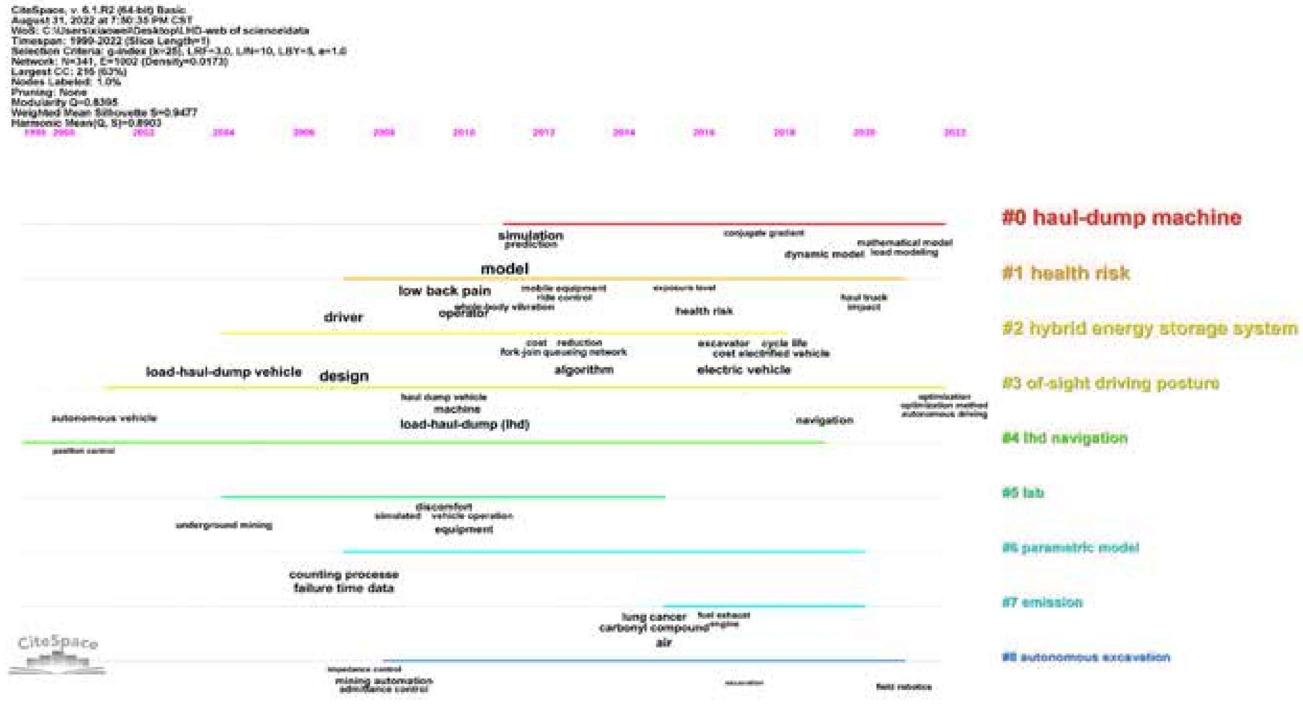


Figure 1: Keywords co-occurrence network map of English literature about intelligent LHD.

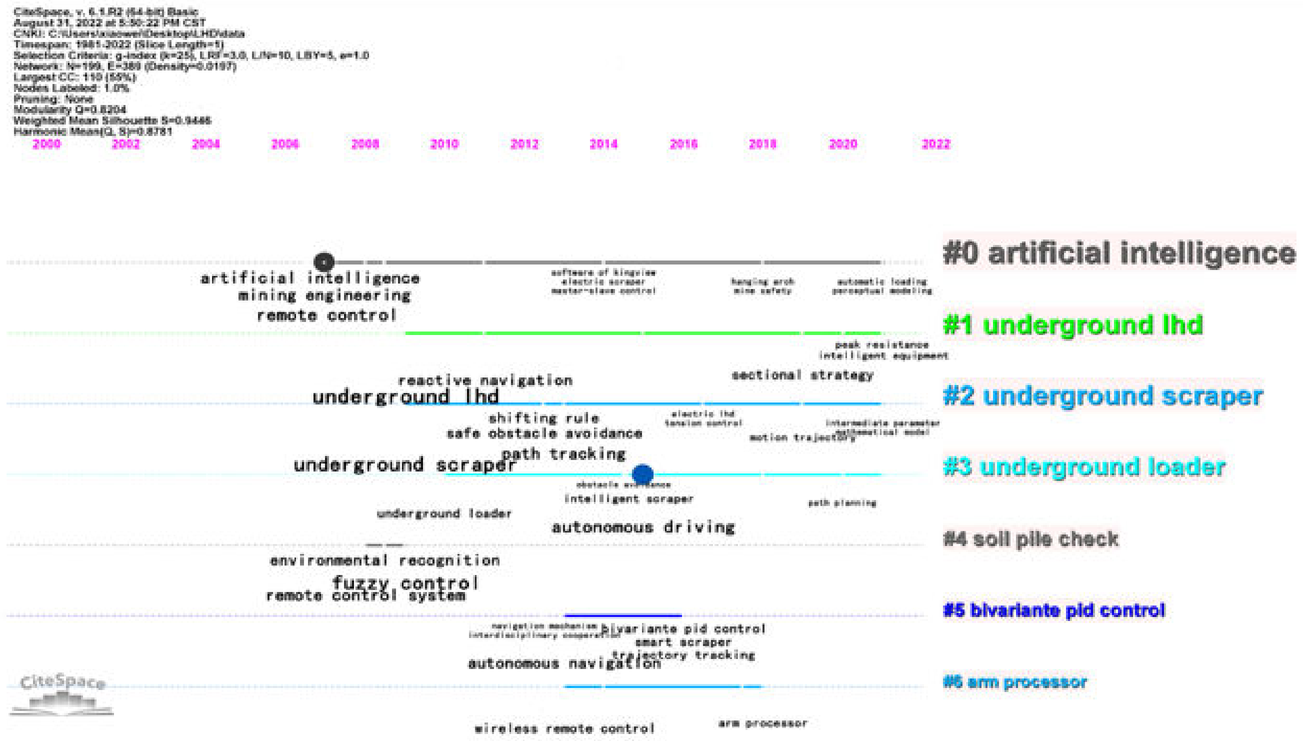


Figure 2: Keyword co-occurrence network map for Chinese literature about intelligent LHD.

The figures can be analyzed as follows:

1. As can be seen from **Figure 1**, the research in foreign countries about intelligent LHD could be traced back early to the 1990s and was mainly focused in 2007-2022. The keyword co-occurrence was not focused, shown as many scattered words with similar font sizes. If anything was summed up, the research topics about simulation prediction, dynamic model, algorithm, navigation and path tracking were relatively popular.
2. From **Figure 2**, the research about the intelligent LHD in domestic China was much later than that in foreign countries, beginning from about 2007 and mainly focused in 2009-2021, with hotspots mainly focused on key technologies, such as fuzzy control, remote control, autonomous driving, path tracking, environmental recognition, autonomous navigation and safe obstacle avoidance.

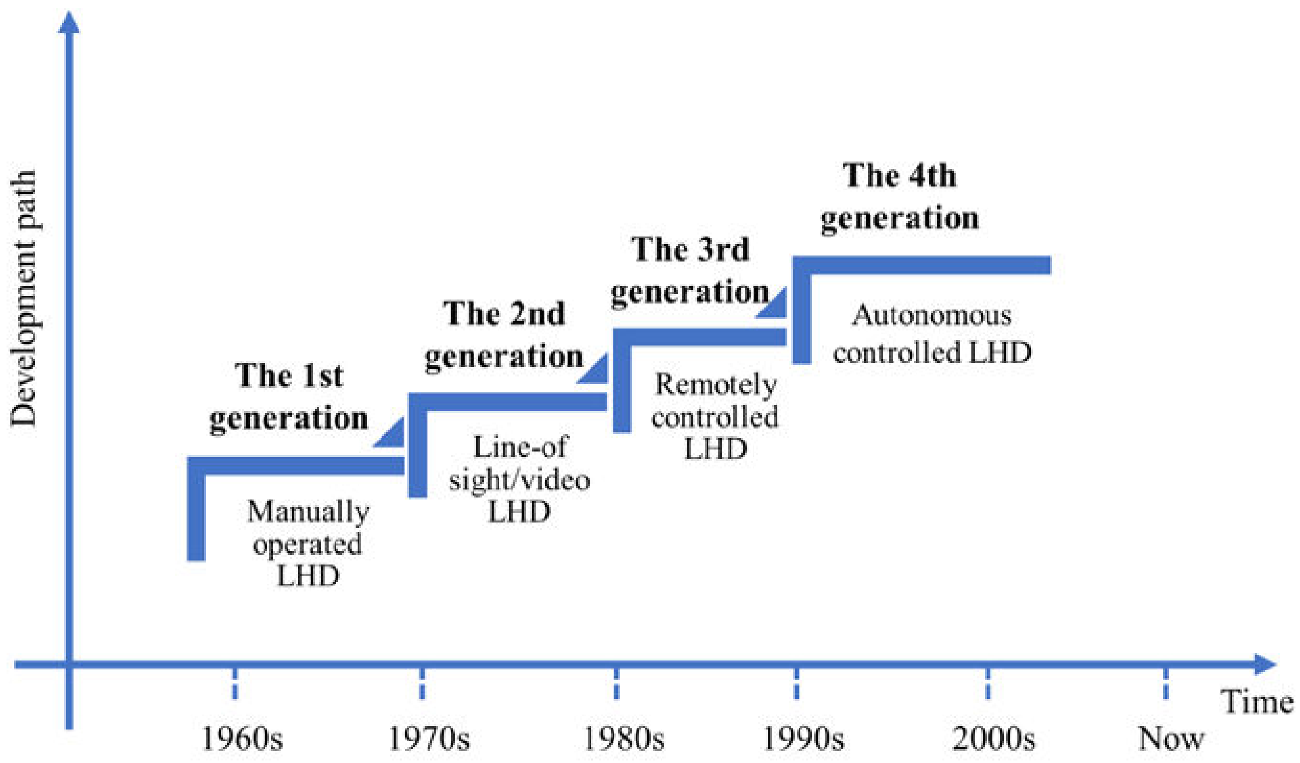


Figure 3: The development history of the LHD.

3. No matter whether at home or abroad, the research on intelligent LHD was scattered and not extensive. However, it is an undoubtedly important machine and would be one of the hotspots for the intelligent mining industry.

DEVELOPMENT AND APPLICATION STATUS OF INTELLIGENT LHD

The first LHD (version ST-5) was traced back to the 1960s, which was developed successfully in the Grandview Mine by the Wagner Company in the United States. Since then, the LHD has been widely used in underground mining around the world due to its high efficiency and flexibility. According to the level of automation control and development history, LHDs can be divided into four generations[19], as shown in **Figure 3**. At present, the underground LHD belongs to the fourth generation, with functions of intelligent and independent control[9].

Foreign research on intelligent LHDs began relatively earlier; hence, many companies invented LHD autonomous driving, uploading controlling systems with their own characteristics after long-term theoretical research and field tests, such as Sandvik in Sweden, Caterpillar in the United States, Atlas Copco in Sweden, etc.[9].

The Tamrock cooperation in Finland (acquired and owned by Sandvik now) was reported to be the first company in the world to exploit automated mining, which developed the AutoMine system with functions of integrated shoveling, transporting, unloading ores and fault diagnosis automatically[20]. The system was helpful for production increases and maintenance and operation cost decreases. The automatic mining yield of each LHD machine (version LH621) in Finland Pyhäsalmi Mine was improved greatly to 300,000 tons per year after being equipped with the AutoMine system. Both the utilization rate of equipment and the output of the entire mine increased significantly[21]. Canada Kidd Creek Mine extended the effective working time of four LH514 LHDs from 12 h to 15 h and increased the production capability by 50% accordingly, after being equipped with four sets of Sandvik company's single remote-controlling intelligent LHD system[9]. In 2018, Sandvik innovatively invented another new generation of unmanned underground LHDs, which made it possible to shovel, transport and unload ores totally automatically during the whole process. The machine passed through a complicated glass maze successfully with the help of equipped laser scanners, gyroscopes, odometers and angle sensors[22]. However, there has been no industrialization application yet[23]. The MINEGEM system was a new autonomous control system for a new generation of LHDs, jointly developed by Caterpillar and DAS in Australia in around 2004. Remotely controlling the LHDs on the ground to perform operations, such as shovel, transport or unload ore, could be attained with this system, through the cooperation of airborne computers, sensors, wireless networks, etc. This system was adopted by the Malmberget iron mine in Sweden and protected their operators from the dangerous underground environment with a remote ground comfortable operating room. Moreover, the system ran quickly and greatly improved the production efficiency by about 25%; the effective operating time was extended by 4~6 h as well[24,25]. In later years, Caterpillar further developed the ancillary software for this system, named Auto Dig, to automatically control the whole shoveling, transporting and unloading process. Through recoding a large amount of operation data by experienced drivers from a variety of buckets for a variety of given ores during loading cycles, the loading model could be established and optimized by computer and the fully autonomous operation was finally realized.

Atlas copco in Sweden is another famous company for intelligent underground LHD research and development. In 2006, it modified the ST. 1010 underground LHD with a reactive navigation system to an autonomous machine together with researchers from the University of Urebro, which was proved to be practical in the Kvarntorp Mine through automatic tests. At the end of 2007, its LHD automatic control system was applied to the ST-14 underground scraper and the automation experiment was carried out successfully in the Kemi mine in Finland[19]. The machine was equipped with three cameras, two in the front and one at the back. In addition, three additional cameras were reinstalled in the loading and unloading zones on the roadway as a supplement. Through scanning the way in the front roadway in 35 m by the laser mounted on each side of the vehicle, the real-time precise relative position of the ST-14 to the wall could be acquired[23]. After combining the ultra-precision steering algorithm and the speedometer, the operator could determine the precision potion of the machine in the roadway. Recently, Atlas company developed its own Scooptram automation technology, a semi-autonomous control system, with the goal of protecting human safety, improving machine performance and flexibility. The main advantage of the system is that the operation system could be maintained easily in control and integration with other systems without exposing the operator to the unsafe environment. Moreover, no other infrastructure support was needed and it could work even during blasting operation[26].

In addition to the main three companies mentioned above, there were also many other companies or research institutes investing finance and effort on this topic. A German manufacturing company of underground mining equipment called PAUS developed a new version (Tiger 300D) of underground LHD, based on the video remote control technology of the NAUTILUS company. Two cameras were set in front of the loader and another in the back. The cameras acquired and transmitted the image data to the display screen of the remote-control box firstly; the machine was automatically slowed down if someone was found standing on the road, even stopping if necessary. The device not only expanded the driver's vision, but also could be controlled through wider-range radio and was much safer. Furthermore, it could be either remote controlled automatically or manually controlled[27]. The Commonwealth Scientific and Industrial Research Organization (CSIRO) and the University of Sydney in Australia cooperated in the research on the special sensors for autonomous control of the LHD on the mount ISA. The sensors suitable for the underground environment were picked out through collecting a large amount of data from the sensors installed on the underground LHD[28]. Afterwards, CSIRO further researched the development of autonomous control of underground LHDs, with financial support from AMIRA, mainly focused on the positioning technology based on the dead reckoning method. The autonomous navigation system integrated from the underground electronic map data and the laser scanner sensor and, finally, the autonomous control of the driving process and identification of the signs and blocks on the road could be realized[29]. Vielle Montague in Sweden also developed a remotely operated and navigation-enabled

LHD; autonomous controlling tests were carried out in the Zinkgruvan zinc mine. The navigation and autonomous driving could be attained by tracking the white lines coated on the roadway roof with a camera. The maximum running speed was 8 km/h. During the 9-month test period, a total amount of 1200 buckets of ores was transported[30].

China's research on the autonomous control system of underground LHDs started relatively late and has gone through four stages of introducing from abroad, cooperative manufacturing, independently developing, innovatively creating and developing[31]. During the "Eleventh Five-Year" period (2006~2010), Beijing General Research Institute of Mining and Metallurgy conducted a research program on "Accurate Positioning Technology of the Underground Mining Equipment and Modeling Method for the Intelligent Unmanned Underground LHD" under the "863" goal-oriented project, together with the University of Science and Technology Beijing[32].

They constructed an underground electronic map through the vectorization of engineering drawings using GIS software and the position display and alarm of the scraper were basically realized by combined technologies of the laser scanner system[33], track estimation and beacon correction at the same time[34]. As a result, the underground LHD autonomous navigation and control technology were initially developed in China and the model for the unmanned underground LHD was established[35]. Later on from the "Twelfth Five-Year Plan" period, the two institutes cooperated continuously on the program on "Underground Intelligent LHD" under the "863" theme project. The program team explored and researched deeply the autonomous driving and unloading technologies of the LHD[36] and realized the field operation in the line of sight or by remote control in the Zhangzhuang Mine, Fankou Lead-Zinc Mine, Dayingezhuang Gold Mine, etc.[4,8,10].

At present, some underground mines in China are testing and promoting fourthgeneration underground fully automatically operated LHDs gradually, in order to realize unmanned mining operations[9].

AUTONOMOUS SHOVEL TECHNOLOGY

Rock Pile Identification and Modeling Technology

The underground intelligent LHD identifies the ore pile and obtains information, such as its shape and outline, through equipment, such as cameras or laser scanners, in the first step, creates a three-dimensional model of the ore pile secondly and then transmits it to the bucket excavation trajectory planning system to assist it in the process for planning of optimal mining trajectories. Therefore, the perception and modeling of the ore pile is a significantly decisive step to realize the autonomous shoveling and loading with the LHD[5,9].

There is extensive research on mine pile sensing technology at home and abroad, which can be mainly classified into two categories by sensing mechanisms: mine pile identification based on image sensors and that based on distance sensors[5].

Image Sensor-Based Rock Pile Identification

The image sensor is the core component in cameras. It converts an optical image on the photosensitive surface to electrical signals through photoelectric cells and obtains information consistent with human perception under good illumination conditions[37]. According to the number of cameras, the vehicle camera system can be divided into monocular camera, binocular camera, depth cameras (RGBD) and panoramic camera[38]. The utilization of monocular camera faces contradictions in ranging and distance. The wider the perspective view of the camera, the shorter the length of the accurate distance that can be detected and the narrower the angle of view, the longer the distance detected. As a result, when it is used on the scraper to perceive the ore pile, it can only obtain its information from a limited certain angle, which makes it difficult to construct the 3D model for the ore pile. The binocular camera system can cover different ranges of scenes through different cameras[39] and obtain comprehensive information about the ore pile. However, the process for comprehensively extracting information of the ore pile from multiple angles and multiple pictures is always extremely complicated to calculate, with high system requirements, which makes the 3D modeling construction quite difficult and slow.

The University of Southern Queensland produced an LHD model with a ratio of 1:5 to the physical machine. It is constituted with a CCD camera, a PC with image acquisition hardware and structured lighting form a vision system together and was successfully applied on 3D model establishment for rock piles[40]. The Western Mining Resource Center in the Colorado School of Mines in the United States conducted a project about LHD automation research. They collected mine production images with digital cameras, then filtered and interpolated the images and established a 3D curved surface model finally. This is helpful for the enhancement of the LHD's autonomous controlling and running capability as feedback. According to the experimental results, 3D models could be built even in a dark environment, but failed to be updated in real-time. An example to illustrate the image-sensor-based rock pile identification and 3D modeling process is shown in Figure 4. It proved that even for images obtained from pretty dark sites (**Figure 4a**), the 3D model was established successfully (**Figure 4b**)[41].

The advantage of a 3D ore pile model based on an image sensor is that, after obtaining the information of the ore pile through the image sensor as images, it can quickly build a 3D model through an image processing algorithm and update the model in real time. However, when the light is insufficient or the camera is blocked by dust, the image obtained would be not clear enough, possibly resulting in failure of the 3D mine pile model establishment through a single view[5].

Rock Pile Identification Based on Distance Sensor

The distance sensor mainly obtains the size information of the object by detecting the time interval from the light pulse emission to object reflection[42].

Carnegie Mellon University developed the first large-scale excavation and loading automatic system (Autonomous Loading System, ALS), which uses laser scanners to scan the to-be-excavated area for planning of the optimal excavation location. However, this system is mainly favorable for the excavation of soft-soil ore piles; no research has been carried out on the excavation of large hard ore piles[43].

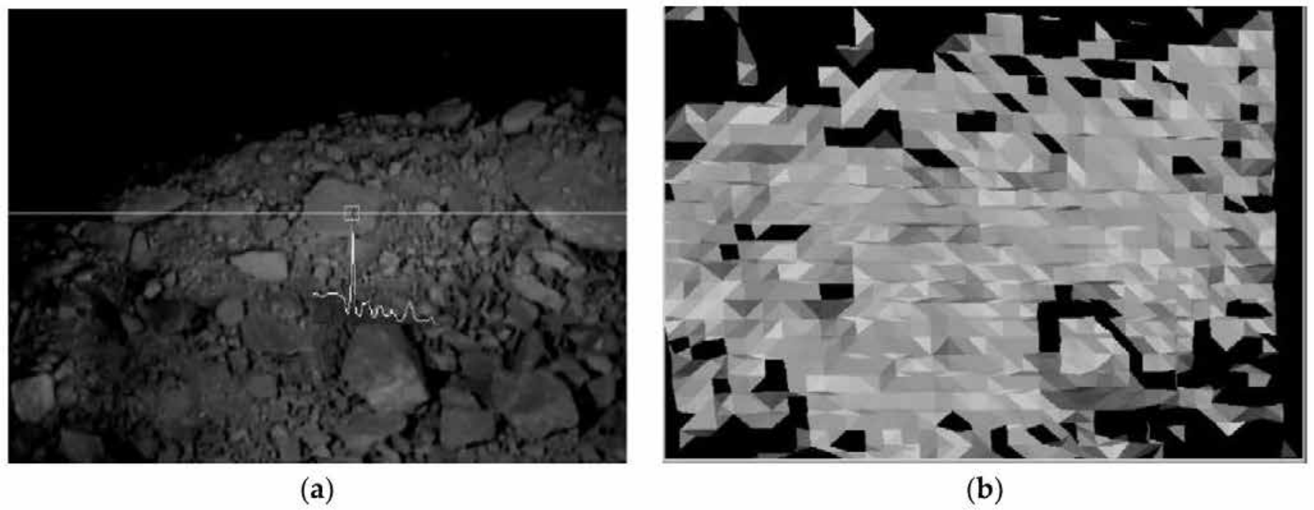


Figure 4: Construction of 3D model of ore pile. (a) The original map of the ore heap; (b) 3D model diagram[41].

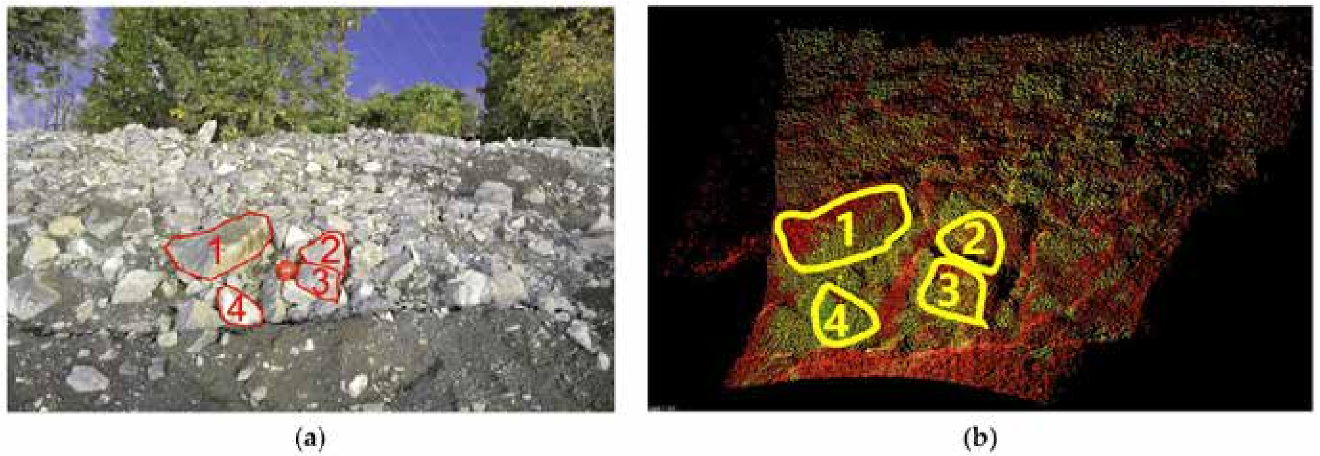


Figure 5: Point cloud processing of mine pile. (a) Mine pile original image; (b) mine pile point cloud image[47].

INTELLIGENT LOAD-HAUL-DUMP VEHICLES

The particles in the ore pile are always irregularly shaped without uniform sizes, since they are usually obtained after blasting the mine. Therefore, in order to avoid shovel loading failure or damage to the scraper, pretreatment must be performed first, meaning large ore blocks in the ore pile should be crushed or removed if they exist[44-46]. McKinnon C. *et al*. generated point cloud images with a rock pile recognition algorithm based on the images from the time-of-flight camera successfully. This technology realized good recognition of ore piles without the help of other sensors, which is beneficial for the extraction of bulk ores from irregular heap surfaces, as demonstrated in **Figure 5**. It can be seen that point cloud images could be generated based on the original photo by the camera, as expected. Moreover, the sampled lump ores, numbered as 1 to 4 in the point cloud image (**Figure 5b**), could be recognized clearly and matched quite well with those in the original one (**Figure 5a**)[47].

The advantage of mine pile identification based on distance sensors is that it can completely collect the mine environment information and create a 3D mine pile surface model quickly. However, only the surface information on the ore pile can be acquired through the distance sensor and the texture information of the surface is easy to lose[5]. Moreover, the modeling speed will be slowed down for high-density data processing, which is a result of ore pile scanning from multiple perspectives.

To sum up, a single type of mine pile identification based on either image sensors or distance sensors has its drawbacks. Therefore, the cooperation of both sensors on ore pile identification and modeling technology would be a considerable research direction for future underground intelligent LHDs. As the example, shown in Figure 6, both types of sensors are adopted as two sets of laser scanner and camera (one in the front and the other in the back) on the LHD to collect information of the ore piles. After data recognition and integration, the 3D heap model for even dark and dusty underground environments can be quickly established. The model can also be updated in real time with changes in the field conditions[48].

Shovel Trajectory Planning

After establishing an accurate three-dimensional ore pile model, the starting position for ore shovel loading will be independently determined and the optimal trajectory will be planned as well, theoretically based on the maximization of loading efficiency and minimization of energy consumption[50]. Based on the controlling model, bucket loading trajectory planning methods can be divided into the one determined by resistance force and the other directed by self-learning.

Resistance Force Determined Trajectory Planning Method

In a joint project by Russian scholar Mikhirev and the Minsk Machinery Research and Production Association, which was mainly about the development of the open-pit mining automatic loader, the calculation method of the effective trajectory for the excavator bucket was firstly studied based on mechanical control[51]. In order to shovel the materials better with the bucket, it is rather necessary to accurately predict the digging resistance from the obstacle. Obermayr *et al*.[52], from Kaiserslautern University of Technology, Germany, predicted the excavation resistance of a slab excavator in unbonded granular material, excavating using the discrete element simulation method and the accuracy of the results was verified by experiments. Coetzee, from Stellenbosch University in South Africa, simulated and

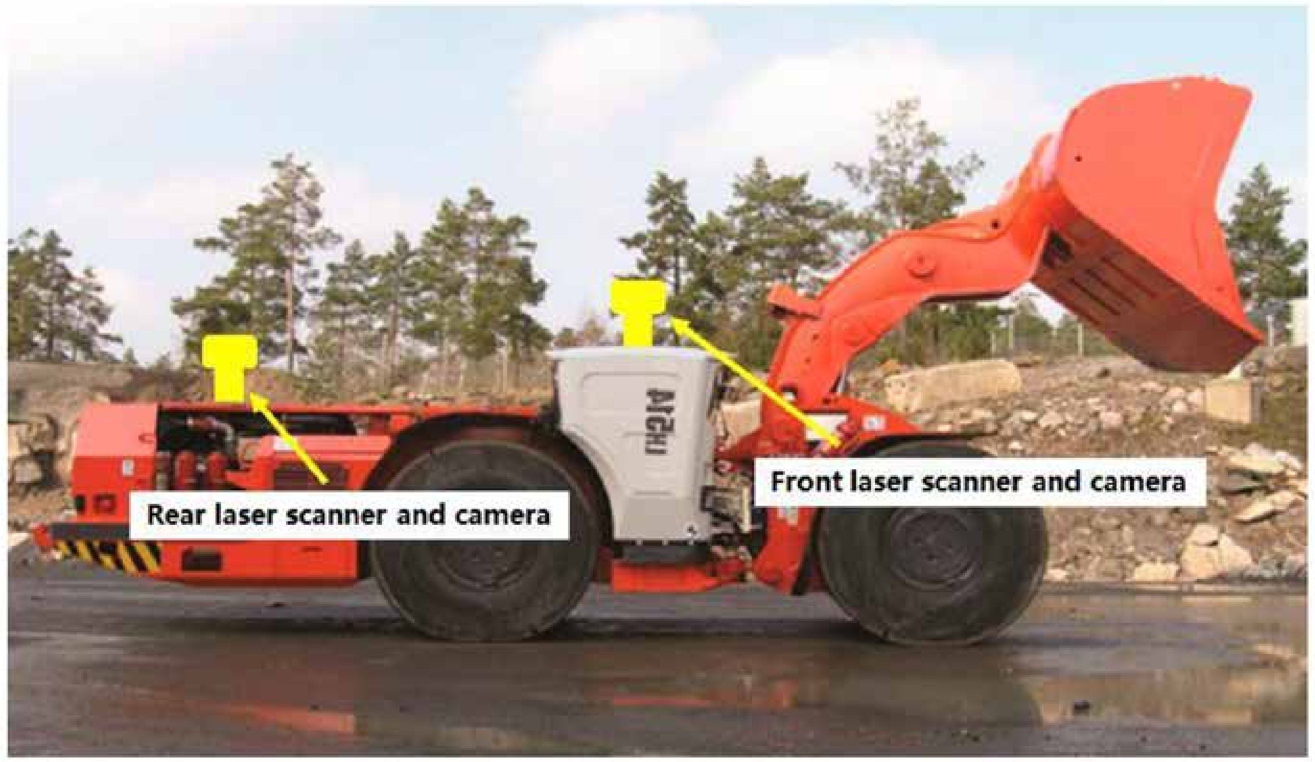


Figure 6: Schematic diagram for the installation location of the laser scanner and camera on the underground scraper[49].

analyzed the bucket excavation process using the discrete element method simulation platform, but the predicted excavation resistance was found to be smaller than the actual value from experiments. In addition, the excavation resistance changing trends were almost the same in the entire excavation time domain[53,54].

Since the shape and size of the ores are inconsistent after blasting, the resistance from the ore blocks on the scraper will change during the shovel loading process. Therefore, when establishing the resistance model, it is necessary to take the change in the shape and size of the ores into consideration. Guiyu Lin *et al.*[55], from Northeastern University, counted the rock materials with different particle sizes after blasting through discrete element and simulated their excavation process based on the actual prototype, then predicted the excavation resistance under several complex working conditions. It was found that the results from prediction were quite close with the resistances under actual situation. Xiaobang Wang[56], from Dalian University of Technology, established a rapid online excavation trajectory planning method for the mining shovel, based on a dynamic excavation resistance prediction model, especially for complex ore piles. The experimental results showed that the running accuracy of the trajectory planned by this method can be improved by more than 14%, compared with the traditional mining resistance model, and the energy consumption was reduced by 8.86%.

Although the excavation resistances predicted by the above method are close to those under actual conditions, it cannot be said that the predicted situation can fully explain the actual site, since the possible accidents, such as collapse or landslide, would happen during the actual excavation process. Hemani[57] believed that the material excavation could not be realized but only guided through the resistance model preset by the mathematical formula. Hence, he proposed to adjust the excavation trajectory according to the real-time magnitude of the resistance during the excavation process. W. Richardson-Little[58] presented a rheological method for simulating the interaction force between the soil and bucket. Then, under real conditions, the excavation trajectory of the excavator bucket could be controlled and adjusted through detecting the force on it. Meng Yu *et al.*[49] established a mechanics feedback model for the bucket based on Coulomb earth pressure theory. With 100% full bucket rate as the prerequisite, the insertion depth was optimized to minimize the energy consumption and the optimal bucket trajectory was finally determined. Marshall J.A. *et al.*[59], from Carlton University in Canada, proposed a velocity-based admittance controller for the first time according to the characteristics of the scraper hydraulic cylinder induction force during the excavation process. Field tests were also conducted on the Atlas Copco scraper and proved that the shovel loaded more efficiently than manual operation. Chaozhong Yin *et al.*[60], from University of Electronic Science and Technology of China, established a manipulator model system, which adopted the method of intelligent drag reduction, inserting a shovel on the basis of the minimum energy consumption trajectory. The bucket was stressed less, the energy consumption of the process was effectively reduced and the production was significantly improved under this planning method. The corresponding calculating formula for the uprise velocity for minimum energy consumed trajectory is listed below as **Equation 1**.

Equation 1

$$V_{pu} = -(l_1 + l_2)sin\beta_2\beta_2 + [r_5 \sin(\beta_2 + \beta_3) + r_6 \cos(\beta_2 + \beta_3)]\omega$$

in which, V_{pu} is the uprise velocity component of the bucket tooth point P, l_1 is the boom length, l_2 is the pull rod length, r_5 is the depth of the bucket, r_6 is the vertical distance between the tooth point and the bottom of the bucket, ω is angular velocity of the bucket and β_2 and β_3 are the second and third velocity vectors of motion pair, respectively. For a better understanding of those parameters, the manipulator model system is graphically described in **Figure 7**, in which the blue lines are a simple profile for the reverse six-bar linkage mechanism, with letters A-G representing the movable mechanical joints; the black lines are just for annotations.

Self-Learning-Guided Trajectory Planning Methods

With the development of artificial intelligence technology, many scholars have tried to solve the complex and changeable

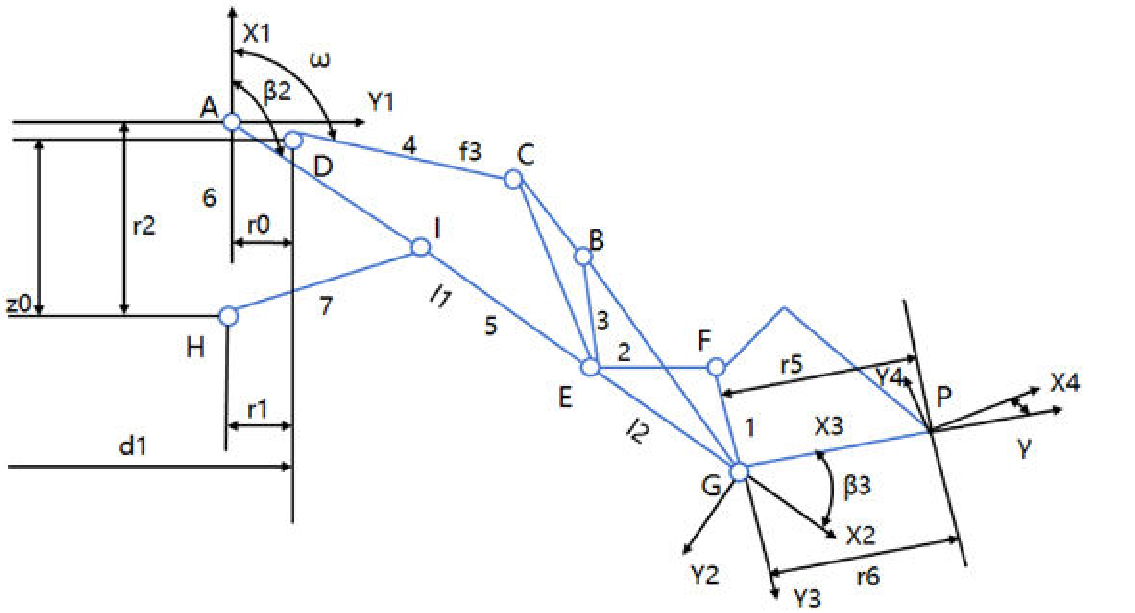


Figure 7: Manipulator model for reverse six-bar linkage mechanism: 1-bucket; 2-pull rod; 3-rocker arm; 4-bucket cylinder; 5-arm; 6-front frame; 7-boom cylinder.

INTELLIGENT LOAD-HAUL-DUMP VEHICLES

problems during the shovel loading process of LHD by applying learning methods. Scholars from the University of Arizona[61] applied fuzzy logic control to perform mechanical mining in unstructured and unpredictable environments for the first time and combined fuzzy logic with neural networks to simulate robotic autonomous mining experiments. Lever *et al.*[62] developed an automatic dig control system (ADCS) based on the combination of both a behavior-controlled and fuzzy-logic-controlled model. Tests were conducted on a Cutler wheel loader and found to excavate comparably to manual operation but required longer mining time. G. J. Maeda *et al.*[63] proposed an earthwork excavation control method for the excavator based on a combination control of iterative learning and impedance. Siddharth Dadhich *et al.*[64] proposed an autonomous mining method based on reinforcement learning (RL), which is suitable for the mining of different pile types and ore shapes. This method worked well with steady loading weight, cycle time and fuel efficiency[44]. Heshan Fernand *et al.*[65] advanced an iterative learning-based admittance control algorithm, which could automatically update the control parameters according to the target bucket filling weight. It was verified to be effective for both fragmented rock and gravel shoveling after field testing with a 14-ton scraper. In addition, the performance on the fragmented rock piles was better than that on gravel piles.

The self-learning-guided shovel trajectory planning method has obvious advantages when working in the uncertain underground roadway. Through interactive learning about the environment, the bucket trajectory planning can be better completed. However, a large amount of data and long time of study are required for training to implement good trajectory planning.

In general, the shovel loading trajectory needs to be planned according to the actual real-time loading conditions, either guided by resistance force or self-learning. The ultimate aim is to excavate successfully with optimized shovel time and energy consumption. If the loading trajectory is planned improperly, as shown in **Figure 8**, the shovel fails as the lump block is too big.

AUTONOMOUS NAVIGATION TECHNOLOGY

Autonomous navigation technology refers to the technology that the scraper can automatically identify the environment through its own various sensors under unmanned control after ore shoveling and then automatically plan and complete the best driving path in the roadway[66].

Positioning Technology

The positioning technology for the underground intelligent scraper refers to the determination of its position in a two-

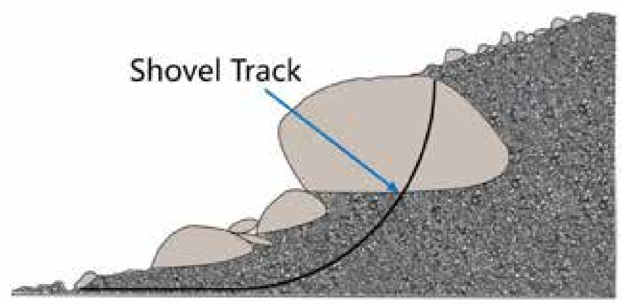


Figure 8: Example for improper shoveling trajectory planning[47].

dimensional coordinate system and its own attitude as well or it can also be expressed as the relative position of the scraper to the coordinate of a known location (beacon point) in the underground tunnel. Thus, positioning technology is the basis for autonomous navigation of LHD. GPS-based autonomous positioning technology is known to be popular in many fields, but as the GPS signal is too weak in the underground roadway, other methods need to be found for scraper positioning[67]. At present, there is much research on the LHD positioning technology at home and abroad, mainly as the dead reckoning method, inertial navigation technology, ultra-wide band (UWB) positioning technology, visual positioning technology and information fusion positioning technology, etc.[68-70].

1. Dead reckoning method

The basic principle of the dead reckoning method is with known initial coordinates of the scraper, collecting the information of heading angle, speed and time using the sensors installed on the scraper (such as heading gyro, speedometer, odometer, etc.) and calculating the data for the current position of the shovel[71]. This method has good accuracy and low cost for short-term positioning, but has accumulated errors for long-term positioning estimation, which need to be corrected by correction techniques[68,72].

2. Inertial navigation technology

The inertial navigation system is a completely independent system that does not rely on external information, but obtains the information of the speed, position and attitude of the vehicle by its own inertial components, such as gyroscopes and accelerometers[68]. Although the inertial navigation technology exhibits good concealment, it has advantages, such as being affected by neither natural, man-made factors nor external electromagnetic interference, and there will be inevitable accumulative errors after a long-time server. In order to improve the absolute accuracy of the system, other auxiliary positioning sensors are necessarily installed. To be specified, the cost for the equipment in this system is reported to be quite expensive[73,74].

3. UWB Positioning

UWB technology locates in real time the vehicle through building a base station in the roadway, obtaining signals between the base station and the vehicle tag, then attaining the real-time location information of the tag. This method is reviewed to be insensitive to channel fading, showing high positioning accuracy and low system complexity[75,76]. To position the accurate two-dimensional location of the vehicles, Chehri A. *et al.*[77] conducted tests to collect the distance signals and position the tags, especially for narrow-long underground coal mine roadways, through UWB technology and TOA algorithms, respectively. It was found that this method was proved to show higher positioning accuracy than regular methods in both visual and non-visual distance. However, in UWB positioning technology, the location information of at least three base stations needs to be received for calculation about the tags' location in the targeted area zone. Since the underground tunnels are always long and narrow, multiple base stations must be constructed and high cost would be consumed for higher positioning accuracy[67].

4. Visual Positioning

Visual positioning technology refers to collecting the surrounding environment of the roadway by cameras or other visual sensors, setting, identifying and tracking special route markers by the scraper, analyzing the signals

Table 2. Comparison of positioning technologies.

Positioning Method	Advantage	Disadvantage
Dead Reckoning	It can achieve high accuracy with low cost in short term	Errors will accumulate over a long period of time
Inertial Navigation	It is unaffected by external factors and shows good concealment	Errors will accumulate over time and the equipment are expensive
UWB Positioning	It is insensitive to channel fading, with simple system and high positioning accuracy	Multiple base stations are required, which is costly
Visual Positioning	It shows high positioning accuracy	Roadway dust, light intensity and other environmental factors affect the positioning easily
Information fusion positioning	It is extensively applied, with high positioning accuracy	The cost and calculating complexity increase

and finally obtain the location information of the scraper. Weiss L.E. *et al.*[78] proposed a form of visual serving control, which can overcome uncertainties in the calculation models (including robots, vision systems and environments) and improve the accuracy of visual positioning or tracking. Iu S. *et al.*[79] pointed out that estimating the target's moving direction and structure through the maximum likelihood estimation method was found to be quite accurate. Wu Di *et al.*[75] proposed a calculation method of minimizing the error of photometrics based on its weight of different texture areas, to improve the matching accuracy for images with dim and noisy points obtained from a dust-filled underground roadway.

In general, the visual positioning technology is accurate in location, but as the scraper works in unique underground scenes, it still faces challenging problems, such as environmental features being insufficient, roadways being too dusty and lighting conditions varying too much, etc. Hence, how to make the system operate stably and long term will be a key problem to be solved in the future.

5. Information Fusion and Location Technology

Single-positioning technology usually has certain limitations. Therefore, various information from different positioning technologies can be integrated to locate the scraper and improve the positioning accuracy. MaKel A.H. *et al.*[80] applied a positioning method combining dead reckoning and laser scanning positioning and determined the position and driving direction of the scraper by the articulation angle sensor, odometer and gyroscope. The result from dead reckoning was corrected by the scanning data of the roadway wall obtained through two laser scanners. The accumulated error was significantly improved compared to the ordinary dead reckoning method and the installation of other auxiliary equipment was avoided in the roadway. Wang B. *et al.*[81] optimized the location and navigation algorithm based on the combination of the dead reckoning positioning and laser scanning. The simulation results showed that this method can improve the accuracy and robustness of the operating system. Chi Hongpeng *et al.*[82] and Jiang Yong *et al.*[83] combined the information obtained from both the heading gyroscope and the laser rangefinder by Kalman filtering algorithm based on a multi-sensor information fusion model and the heading angle of the scraper was accordingly determined. Shi Xiaojie *et al.*[67] proposed a positioning system, which combined the UWB and laser ranging methods in the view of the long and narrow characteristics of underground tunnels and the high cost for UWB positioning systems. Skoczylas A. *et al.*[84] integrated the inertial measurement unit (IMU) and dynamic time warping (DTW) algorithms to locate the underground mine LHD and it was found to have good robust performance.

The characteristics of various positioning technologies are listed for better comparison in **Table 2**. To sum up from **Table 2** and the above-relevant text, each single-positioning method has its own advantages and disadvantages. Even

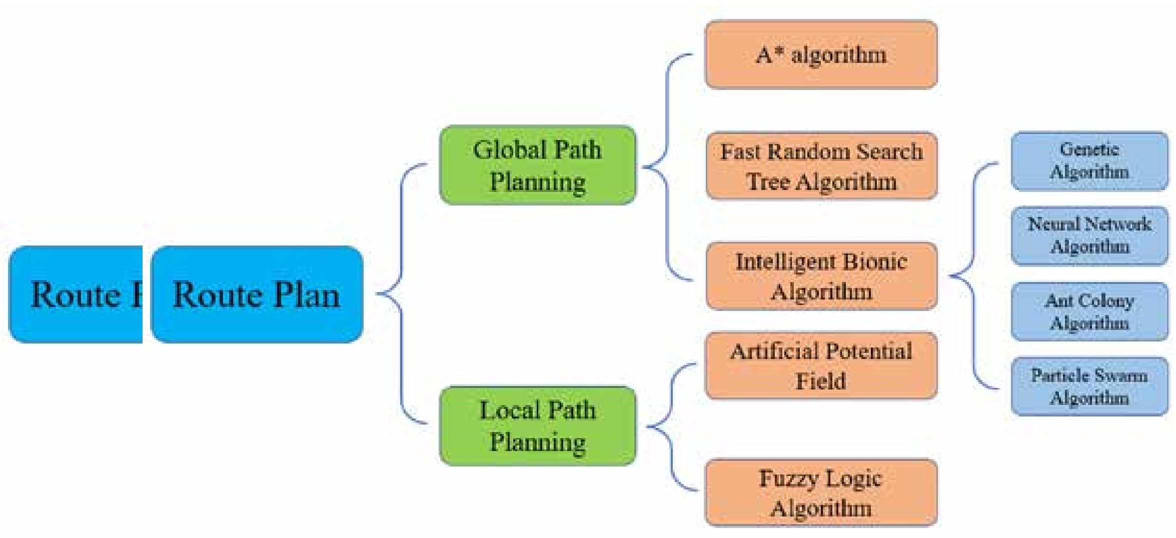


Figure 9. Path planning methods for underground intelligent LHD[12,85,86].

though the limitations of a single-positioning technology can be overcome and the positioning accuracy can also be improved to a certain extent when various technologies are jointly applicated in different ways, the technology still faces the problems of high cost for the equipment and complexity for the calculation. Hence, how to improve the adaptability of the positioning technologies and cut costs are the key scientific issues to be considered in future research at home and abroad.

Path Planning

Path planning technology is important for autonomous navigation of underground intelligent LHD[3]. When the scraper finishes shoveling the ores, there must be a planned collision-free path from the starting point to the destination, through which the distance is short, the transportation is efficient and energy is saved. According to the degree of access to environmental information, they can be divided into global path planning methods and local path planning methods[31], as shown in **Figure 9** in detail.

Global Path Planning

Global path planning means searching an optimal route between the origin and the terminal for the underground intelligent scraper to drive autonomously in a known environment.

1. A* algorithm

The A* algorithm is a heuristic search algorithm, which guides and determines the search direction, mainly through an evaluation function[86]. As long as the optimal distance from the node to the target point is determined, an optimal path must be obtained[87]. However, it is necessary to conduct a traversal search around the nodes on the path to optimize the path and save cost, resulting in large calculation amount, poor real-time performance and long operation time. Moreover, as the number of nodes increases, the algorithm search efficiency decreases[12]. In order to improve the efficiency for the optimal path searching and reduce the searching time, Zheng *et al.*[88] used a jumping point search method based on the A* algorithm and introduced the angle evaluation function into the cost function in the A* algorithm. The number of inflection points on the path obtained by the combined method was minimized compared with that by the original A* algorithm and quick optimal path search was achieved with speed faster than that of the traditional A* algorithm. Ma F. *et al*. [89] proposed a navigation path planning method for articulating underground LHD based on the improved A* algorithm, through introducing the collision treat cost into the evaluation function, in order to avoid the LHD from scraping the narrow roadway walls. According to the specific requirements of the path planning for unmanned underground LHD, Qi Yulong *et al.*[90] proposed an improved A* algorithm modeled with extended nodes and introduced the collision threat cost into the evaluation function to avoid the scraper from collision onto the tunnel walls. Simulation tests were also conducted and it was verified that the modified A* algorithm method could enhance the search process, improve the safety of the scraper and prevent collisions.

2. Fast Random Search Tree Algorithm

The fast search random tree algorithm is an incremental search algorithm based on probability sampled data. The basic idea is to take the starting point of the automatic LHD as the root node of the random tree, then find a tree node closest to the root one and expand a step length. If collision occurs, the node is discarded and a new expanding direction is set randomly from the current tree node to find the next tree node. The cycle is repeated until a new direction is found. The advantages of this method include high search efficiency, strong search ability, wide search range and no specific requirements for the scene. However, it faces the following shortcomings: nonautonomous search, low utilization rate for the evenly allocated random sampling points, irregular and time-consuming planned path and easily falling into dead zones and causing local minima for searches in complex maps[12,86].

3. Bioinspired Intelligent Algorithm

Compared with traditional algorithms, the advantages of bioinspired intelligent algorithms are mainly reflected in the ability to solve multi-objective optimization problems effectively, anti-interference strongly, obtain the global optimal value quickly without limitation of local optimal value and the initial value, etc.[91]. It can be mainly divided into genetic algorithm, particle swarm algorithm, ant colony algorithm, etc.[85].

a. *Genetic Algorithm*

Genetic algorithm is an intelligent optimized algorithm based on biological genetic evolution theory in nature. It is the mainstream of robot path planning research and has great research prospects[92]. This algorithm shows good compatibility with other intelligent algorithms, attributed to easy improvement and excellent iterative evolution. The method is flexible in search with the generation of initial population and introduction of crossover and mutation operators and also capable for global optimal path determination. However, at the same time, the calculation speed is slowed down with relative low searching efficiency. In addition, too many inflection points in the path result in the generation of some meaningless populations during iterative evolution of the algorithm, which slows down the subsequent calculation process. Thus, this method is not suitable for online path planning.

b. *Neural Network Algorithm*

Neural networks are intelligent systems composed of many simple but highly interconnected processing elements that transmit information through dynamic responses to external inputs[93]. Neural networks have the characteristics of high fault tolerance, distributed representation, extensive parallelism and generalization. Afifi *et al.*[94] proposed a multi-level system built with a deep reinforcement policy gradient algorithm, which can collaboratively plan multi-vehicle collision-free travel paths through motion planning. Luviano *et al.*[95] proposed a multi-agent reinforcement learning algorithm to solve the problem that unmanned vehicles learn slowly or even fail to learn in a completely unknown environment. By ensuring the corresponding reward methods and completing the training process, the optimal path can be found. Pang Ke *et al.*[96] reported a route search strategy for unmanned vehicles that integrates the reinforcement learning algorithm and the deep learning algorithm. It determines the driving path by driving comfort constraints together with the function about reward and punishment of obstacle information and traffic regulations.

c. *Ant Colony Algorithm*

The ant colony algorithm has good comprehensive performance and strong global optimization ability, which can complete the scraper path planning in complex mining environments, but it is easy to reach a stalemate of only local optimal. Long Zhizhuo *et al.*[97] proposed global path planning for underground intelligent LHD through an improved ant colony algorithm to solve the problems of slow convergence speed and easy stagnation due to local optimum in the traditional ant colony algorithm.

d. Particle Swarm Algorithm
Particle swarm optimization is also a probabilistic global path planning algorithm. Because of its multi-possibility of the iteration, it is much more possible to cover the global map during the path searching process with this algorithm. Correspondingly, the global optimal solution is easier to be obtained[98]. The particles adapt well to complex situations through the interconnection of information. Hence, this method is highly adaptable, even in a high-dimensional environment.

Local Path Planning

Local path planning refers to obtaining real-time environmental obstacle information in an unknown or partially known environment according to various sensors and planning correspondingly to ensure that no collision happens between the outer contour of the vehicle body and the roadway wall or obstacles.

1. **Artificial Potential Field Method**
The artificial potential field (APF) method regards the task area as a charged potential field. The target point will generate a gravitational field for the underground intelligent scraper, while the obstacles will generate a repulsive field adversely; both fields together compose the potential field distribution. In the mission area, the underground intelligent LHD moves in the direction of combined potential field force, to reach the destination without collision with the obstacles[99-101]. Gu Qing *et al.*[102] proposed a real-time trajectory planning method based on two-dimensional search, which mainly focused on the difficulties in underground turning for intelligent LHD. It was demonstrated that the scraper could turn steadily in a short time.

2. **Fuzzy Logic Algorithm**
The fuzzy logic algorithm takes the environmental information obtained by the sensor as the input data, carries out the path planning through the fuzzy reasoning and outputs the calculated accurate result. This method can overcome the problems of uncertainty and ambiguity in the data processing process, eliminate noise and errors and can quickly and accurately plan the local path for even unknown or dynamic situations. Thus, it can perform well in real time. However, the rules for fuzzy control are mainly formulated by human experience. Once the rules are determined, it is difficult to adjust them online in real time and they are inadaptable to the changes in the roadway. Moreover, local minimum value would be attained as it responds rapidly to the input local information[70]. The characteristics of the above-mentioned path planning methods are summarized in **Table 3**.

In a word, both the global path planning and the local path planning methods have certain defects. How to quickly find a method that can plan a path in the shortest time, be real-time adjustable to the environmental information and can avoid obstacles make up the main research direction in the future.

REAL-TIME MONITORING AND FAULT DIAGNOSIS TECHNOLOGY

By monitoring the operating status of the scraper in real time, possible faults can be predicted, so that proper solutions can be prepared to reduce the rate of failure, ensuring efficient, safe and reliable operation of the scraper.

Real-Time Monitoring

Condition-based maintenance (CBM), which can grasp the working conditions of equipment in real time, is welcomed by more and more manufacturers [103]. The Optimine system in the Sandvik company collects the real-time operating information of the scraper and integrates all the data into one platform to make them visualized and under control. The intelligent monitoring system for an underground LHD with bucket volume of 8 m3, which was developed by the Jinchuan Group in China, could achieve the operation status monitoring in real time and record, save and transmit the running data as well. Moreover, it was also reported to have the functions of fault alarming and maintenance prompting[104]. Academically, Loughborough University's NG *et al.*[105] monitored the dynamic data in the hydraulic system for mobile machinery through embedded particle pollution sensors academically and determined the wear and tear degree of the machine and corresponding locations according to the size and shape of metal particles in the hydraulic oil. Pawel Stefaniak *et al.*[106] proposed an algorithm for detecting the technical state change in the scraper based on temperature data. It was proved by tests that the algorithm can describe the condition of the scraper's cooling system well and is suitable for various types of LHD.

Failure Prediction and Diagnosis

With the rapid development of computer technology, big data and artificial intelligence technology, the fault prediction and diagnosis technology of mechanical equipment is also developing in the direction of intelligence. Huan Shuangyu *et al.*[107] proposed a method combining the least square support vector machine (LSSVM) and hidden Markov model (HMM) into an artificial fish swarm algorithm for fault prediction, in order to solve the problem that the fault of the LHD electrical system cannot be predicted accurately by the single traditional diagnosis method. It was found that the accuracy rate of the new combined method could reach 91.1%, accurately predicting the failure and the change trend in the electrical system for the hybrid scraper. Caterpillar's intelligent information system (Cat productlink) could help the customers monitor and manage the equipment in real time and also predict potential faults by collecting key performance indicators and running data from the excavators. The Clear Sky system in JLG of America could accurately find the fault point, guiding the maintenance man to go directly to the site. It also had the ability to enter the monitoring system to find and eliminate faults, effectively shortening the maintenance time and costs.

To sum up, the technology of real-time monitoring and fault diagnosis for the underground intelligent LHD still faces the following problems:

1. The data for the underground LHD real-time status are not fully utilized. Excavation on the collected data is not deep enough for fault prediction and diagnosis.
2. Fault prediction and diagnosis are mainly targeted on the engine and hydraulic system of the scraper and few studies have been conducted on other systems.
3. Even deep learning has attracted the attention of many researchers as a new method in the field of intelligent fault diagnosis, though few studies have been conducted on fault diagnosis for LHD to date.

Table 3: Characteristics of path planning methods.

Algorithm	Advantage	Disadvantage
A* algorithm	It responds quickly to the environment	It has large amount of computation, poor real-time performance and long operation time
Fast Random Search Tree Algorithm	The search is highly efficient and is adaptable to different scenes	It is nonautonomous and time consuming for the path planning
Genetic Algorithm	Easy to plan for the global optimal path	The calculating speed is slow with low search efficiency
Neural Network Algorithm	high fault tolerated and generalization ability	Huge training data is required and there may be some unexpected data which is difficult to be handled
Ant Colony Algorithm	The optimal path can be searched at multiple points in the global area at the same time	Easy to fall into local optimum and slow convergence
Particle Swarm Algorithm	Fast search speed and good environment adaptability	Easy to result in local optimum and low convergence accuracy
Artificial Potential Field	Simple structure, convenient for bottom real-time control	Easy to simply obtain a local optimal solution and "chattering" phenomenon would occur
Fuzzy Logic Algorithm	The uncertainty and ambiguity for data processing can be overcame, exhibiting good real-time performance	It is expert in experience and requires large amount of calculation for complicated situations

SUMMARY

This paper is a systematic description and review on the research status and development of underground intelligent LHD, based on the relevant literature collected by the mainstream literature database in domestic and foreign countries. Through the literature statistics, it is found that the research history for the reviewed vehicle has been over 20 years. Foreign countries kept ahead in either industry or theory, while China started late and developed slowly. Through arranging and reviewing the mainstream technologies from four aspects as the mine pile perception and modeling technology, bucket loading trajectory planning methods, autonomous navigation technology, real-time monitoring and fault diagnosis technology, it can be concluded that even though those technologies for underground intelligent LHD have developed rapidly in recent years, there still needs to be further progress both domestically and overseas; the research directions can be proposed as follows:

1. For better mile pile perception in the future, how to complement and optimize the information of multi sensors in a multi-level and multi-dimensional manner, improve the data processing speed and establish the three-dimensional model would be the critical scientific issues, as a single sensor perceives poorly for the heaps in underground roadways that are dark, dusty and face field interference.

2. In the research for bucket shovel loading trajectory plan and optimization, the planning method based on reinforcement learning will be one of the mainstream directions under the background of artificial intelligence, big data and cloud computing in the future, while how to complete the shoveling most efficiently with the least energy consumption is the key goal for this method.

3. As for autonomous navigation technology, it is one of the key researched technologies for underground intelligent LHD, both at home and abroad, and it directly determines whether the transport of the ore will succeed or not. Thus, the research on multisensing information fusion technology and the positioning accuracy improvement and speeding should be focused on. The combination of the global path planning with the local path planning methods to plan a travel path, which is without collision and has shortest time consumption, will be the mainstream direction in the future.

4. With the introduction of digital twin technology into the intelligent mine construction field, synchronous mapping and real-time interaction between physical equipment and virtual equipment can be achieved. By building digital twin models for the intelligent LHDs in the coming future, remote monitoring, fault diagnosis, control optimization and health prediction for the physical machine are expected to be attained through modeling on the extracted feature from the faults and the corresponding process and analyzing the interference factors.

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INTELLIGENT LOAD-HAUL-DUMP VEHICLES

Today's wheel loaders equipped to move more material for less cost

The quest for increased loading efficiency is never ending. Mining operations look to OEMs to push the envelope of machine design and leverage the latest technologies to increase wheel loader efficiency and payload while using less fuel to drive down the cost-per-ton of material moved.

And OEMs are responding. As the wheel loader market evolves, machine design and integration of technology are driving loader productivity and efficiency higher than yesterday's models. For instance, the recently commercialized Cat® 995 wheel loader is the same size as its predecessor, the 994K. However, it offers a higher rated payload and bucket capacity range of 17.2 to 43.6 m^3 (22.3 to 57 yd^3), so it can load more material in fewer passes and burn less fuel.

The 995 offers up to a one-pass reduction compared to the 994K when loading Cat 785, 789 and 793 trucks. This results in up to 33% increased production and efficiency for mining operations when loading the 785, up to 25% when loading the 789 and up to 20% with the 793. Specifically looking at loading 240-tonne (265-ton) trucks, the 995 delivered 21% higher efficiency and 24% more production than its predecessor in equal operation mode because of the higher rated payload and 6% increase in hydraulic force.

These results are through upgrades to machine design alone. Newer technologies integrated with loader electronics are being introduced to further boost productivity of both machine and operator.

LEVERAGING TECHNOLOGIES

Newer technologies introduced with today's wheel loaders not only increase productivity, but they can also assist in reducing stresses on machine components to increase longevity. In the case of the 995 wheel loader, new tire slip prevention and tire set features help to improve tire life, productivity and efficiency through automating the most difficult parts of the digging cycle.

Tire slip prevention automatically reduces rimpull when there is less downforce on the tire and increases rimpull with more tire downforce, supplying maximum rimpull when it's needed. Tire set detects contact with the pile and automatically lifts against the pile to set the tires and increase available traction, discouraging premature racking and allowing for an increase in usable rimpull.

Keeping the lift motion without excessive use of the impeller clutch is another way to improve loader productivity and efficiency. The 995's standard lift stall prevention feature automatically applies the impeller clutch when necessary to prevent hydraulic stall when lifting through the face. Combined with tire slip prevention, this fully automates the impeller clutch while digging, which allows for bucket fill without the use of the pedal impeller clutch.

Today, onboard interactive training tools are available to help boost operator confidence, skills and productivity. The new Cat loader can be equipped with operator coaching to measure and report individual operator behaviors that impact efficiency, production and component life. Among the techniques monitored include tire rotation reduction, unracking in-dig, leveling the bucket when entering the pile, excessive impeller clutch usage, dump height and kickout usage. Instructional videos provide training on these measured behaviors, showing both the incorrect and recommended behaviors.

Selecting a large enough bucket to achieve target pass-match loading of the truck across a range of material density is critical to reaching productivity targets. Look for machines with payload overload prevention technology to help give operators the confidence to use a large bucket without the risk of overload. With adjustable overload values based on target payload, overload prevention can

be configured to either stop or slow the lift arms when the established overload value is exceeded.

EFFICIENT OPERATION

By design, today's engines powering wheel loaders that meet EU Stage V / U.S. EPA Tier 4 Final standards reduce two primary exhaust pollutants – particulate matter (PM) and nitrous oxide (NOx). Many also offer different engine settings to lower fuel consumption, and, in turn, GHG emissions.

The 995 wheel loader offers engine idle shutdown as well as on-demand throttle and enhanced economy modes. Engine idle shutdown avoids unnecessary idling to save fuel by automatically shutting down the machine when the loader is not utilized for a preselected time length.

Saving up to 8% fuel per hour and improving efficiency by up to 5% compared to horsepower plus operation, on-demand throttle on the 995 allows operators to maintain normal operation with the left pedal and implements, while the machine manages engine speed. Further reducing fuel consumption and CO_2 emissions, the loader's enhanced economy mode offers up to 8% greater efficiency and up to 13% lower fuel consumption per hour compared to horsepower plus. Comparing it to the 994K's throttle lock operating mode, enhanced economy mode has demonstrated a 30% increase in efficiency and an 11% reduction in hourly fuel consumption, which translates to 23% less CO2 per unit of material moved.

Pump control of the hydraulic system has also been optimized to boost efficiency on the 995 with its positive flow control hydraulic system through concurrent pump and valve control. Hydraulic oil flow is proportionate to implement lever movement, and fast, productive cycles are enabled by four electronically controlled, variable piston pumps. The system increases bucket feel and control and delivers consistent performance and efficiency with lower system heat.

MULTIPLE LIVES

From machine components to the hydraulic system to the entire wheel loader, mining companies can lower overall machine owning and operating costs while maintaining the like-new efficiencies through rebuilding. Plus, the machine can achieve higher levels of performance and fuel efficiency by upgrading or retrofitting the wheel loader with new features, technologies and options that may not have been available when originally purchased. Programs like Cat Certified Rebuild increase the machine's lifespan, providing miners with product updates at a fraction of the cost of buying a new machine.

Raw materials can be further preserved, while conserving energy and reducing emissions through using remanufactured parts. Caterpillar offers the Cat Reman program that returns end-of-life components to like-new condition. The program has been shown to contribute to 65-87% less GHG emissions, use 80-90% less new materials by weight, and consume 65-87% less energy when compared to manufacturing new engines and components.

Electrification alternatives for open pit mine haulage

Truck-Shovel (TS) systems are the most common mining system currently used in large surface mines. They offer high productivity combined with the flexibility to be rapidly relocated and to adjust load/haul capacity and capital expenditure according to market conditions. As the world moves to decarbonise as part of the transition to net zero emission targets, it is relevant to examine options for decarbonising the haulage systems in large surface mines. In-Pit Crushing and Conveying (IPCC) systems offer a smaller environmental footprint regarding emissions, but they are associated with a number of limitations related to high initial capital expenditure, capacity limits, mine planning and inflexibility during mine operation. Among the emerging technological options, innovative Trolley Assist (TA) technology promises to reduce energy consumption for lower carbon footprint mining systems. TA systems have demonstrated outstanding potential for emission reduction from their application cases. Battery and energy recovery technology advancements are shaping the evolution of TAs from diesel-electric truck-based patterns toward purely electrified BT ones. Battery Trolley (BT) systems combined with autonomous battery-electric trucks and Energy Recovery Systems (ERSs) are novel and capable of achieving further significant emission cuts for surface mining operations associated with safety, energy saving and operational improvements. This article reviews and compares electrification alternatives for large surface mines, including IPCC, TA and BT systems. These emerging technologies provide opportunities for mining companies and associated industries to adopt zero-emission solutions and help transition to an intelligent electric mining future.

INTRODUCTION

The current effects of climate change have created a worldwide consensus on the need for decarbonisation[1]. In order to achieve the 2030 emission reduction task announced by governments, more specific technology measures will need to be applied to achieve measurable decarbonization. As an energy-intense sector, the mining industry is more dependent on fossil fuel energy than others. To date, Truck-Shovel (TS) systems are still the dominant open-pit mining haulage system, while In-Pit Crushing and Conveying (IPCC) has become an option to overcome long-distance transport in deep open pit mines. As a proven technology, Trolley Assist (TA) has shown excellent performance in saving diesel fuel and reducing emissions. With significant volatility in fuel markets, stricter environmental and social requirements, and the further advance of technologies, Battery Trolley (BT) systems are likely to guide an electrification revolution to create the first zero-emission truck fleet, which is a transition from the current diesel-electric trolley operation to battery-electric trolley haulage.

This paper investigates the current world energy outlook in carbon emissions, Australian mining sector emissions projection, renewable energy development, decarbonization technology trends and mining challenges to conclude that equipment electrification is a potential zero-emission direction. Except for conventional TS systems, there are several electrification alternatives for open pit haulage: IPCC systems, TA systems and future conceptual BT systems. At the time of this writing, due to hydrogen storage, infrastructure and logistic challenges, there is no hydrogen-power alternatives discussion in this paper. In these systems, conventional diesel-powered TS systems belong to a high-emission haulage alternative, while Fixed IPCC, Semi-Fixed IPCC, Semi-Mobile IPCC and TA systems belong to low-emission haulage alternatives. Furthermore, Fully mobile IPCC and BT systems belong to zero-emission haulage alternatives. This paper introduces all these haulage alternatives' configurations, operations, characters, and pros and cons. As an electrification revolution to create the first zero-emission truck fleet solution, BT systems combinate several state-of-the-art technologies, including autonomous trucks, battery-electric power drivetrains, TA and energy recovery technologies. Like IPCC systems, BT systems have various configurations according to charging methods, whether to build a battery station and energy recovery approaches on the downhill ramp, which are:

1. Dynamic charging BT systems;
2. Stationary charging BT systems;
3. Dual trolley BT systems.

According to mining haulage systems' requirements, there is a comparison between diesel TS, IPCC, TA and BT systems from perspectives such as flexibility, energy efficiency, CAPEX, OPEX, and others.

This paper introduces the background of worldwide decarbonization targets and mining challenges, and presents evaluation parameters to compare all mining haulage systems' pros and cons. It reviews conventional TS systems' operating processes and characteristics, and introduces current electrification alternatives for open pit mine haulage. This paper reviews IPCC and TA systems' advantages and disadvantages compared with the TS system and presents the conceptual BT systems' theory, operating process and configurations. Finally, it compares the parameters between diesel TS, Semi-Fixed/Mobile IPCC, Full-Mobile IPCC, TA, Dynamic Charging BT, Stationary Charging BT and Dual Trolley BT.

DECARBONISATION AND MINING CHALLENGES

World Energy Outlook in Carbon Emissions

Figure 1 shows CO2 emissions in the World Energy Outlook. The Stated Policies Scenario (STEPS) takes account only of specific policies that are in place or have been announced by governments[2]. The Announced Pledges Case (APC) assumes that all announced national net zero pledges are achieved in full and on time, whether or not they are currently underpinned by specific policies[2]. The "implementation gap" between reported lowered emissions commitments and the regulatory frameworks and particular actions they need is highlighted by the 2.6 Gt difference in emissions between the STEPS and the APS in 2030. Pledges must be supported by robust, reliable policies and long-term strategies to become a reality[3]. In addition to underlining the need for specific policies and immediate measures necessary for long-term net-zero commitments, the divergence in trends between the APC and the STEPS demonstrates the potential effect of existing net-zero pledges. The APC shows, however, that existing net-zero pledges, even if fully achieved, fall well short of what is required to achieve net-zero global emissions by 2050[2]. It clarifies what further steps must be taken to move beyond these proclaimed commitments and onto a path with a high probability of avoiding the worst impacts of climate change[3].

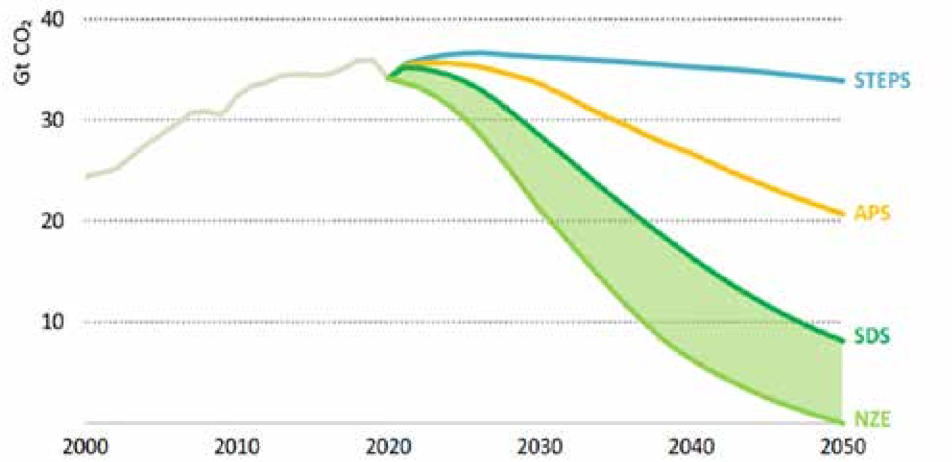


Figure 1: CO_2 emissions in the World Energy Outlook – 2021 scenario over time (Source: International Energy Agency (IEA). World Energy Outlook 2021) Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050 Scenario.

Australian Mining Sector Emissions

Figure 2 from the Australian Department of Industry, Science, Energy and Resources indicates that from 1990 to 2020, Australian stationary energy emissions increased at an average annual rate of 1.5%. As more decarbonization measures were implemented in 2020, emissions are expected to increase more slowly, at an average rate of less than 0.1% annually. The leading causes of growing global GHG levels are emissions from transportation, electricity generation, and industrial expansion, which have pressured many industry sectors to come up with strategies to cut emissions drastically in the future. Energy efficiency, electrification equipment, and replacing fossil fuels with low-emission alternatives in the electricity generation process are essential to achieving the APC pledges, particularly over the period to 2030[2].

Corresponding to the mining industry, a large mining base, fossil-fuel reliance, and increasing truck fleet size are the key contributors to rising CO_2 emissions[4]. The emissions from the mining subsector as whole are projected to increase from 19 Mt CO_2-e in 2020 to 21 Mt CO_2-e in 2030 because of mining needs. This increase is slowed due to technological advancements, including superior engine technology, increasing automation, and the electrification of

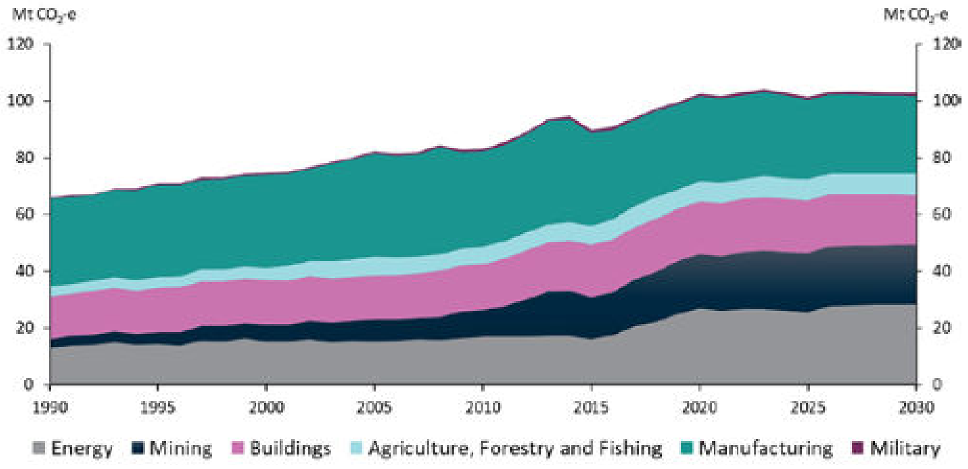


Figure 2: Australian stationary energy emissions, 1990 to 2030, Mt CO2-e (Source: Department of Industry, Science, Energy and Resources).

mining equipment. Along with emissions reductions, these technological advancements also offer operating benefits such as fuel savings and productivity improvements[5].

Renewable Energy Development

The energy transition from fossil fuels to renewable energy resources is now one of the main challenges in achieving sustainable development goals[6]. Due to more significant widespread deployment, there have been considerable technological breakthroughs and cost reductions in wind and solar PV production during the last ten years[4]. From the most current developments in energy storage and renewable generation are reviewed, due to the growing price of fossil fuels, the adoption of carbon tax policies in some areas, and the falling capital costs of renewable generation and energy storage technology, renewables are becoming more cost-competitive[4].

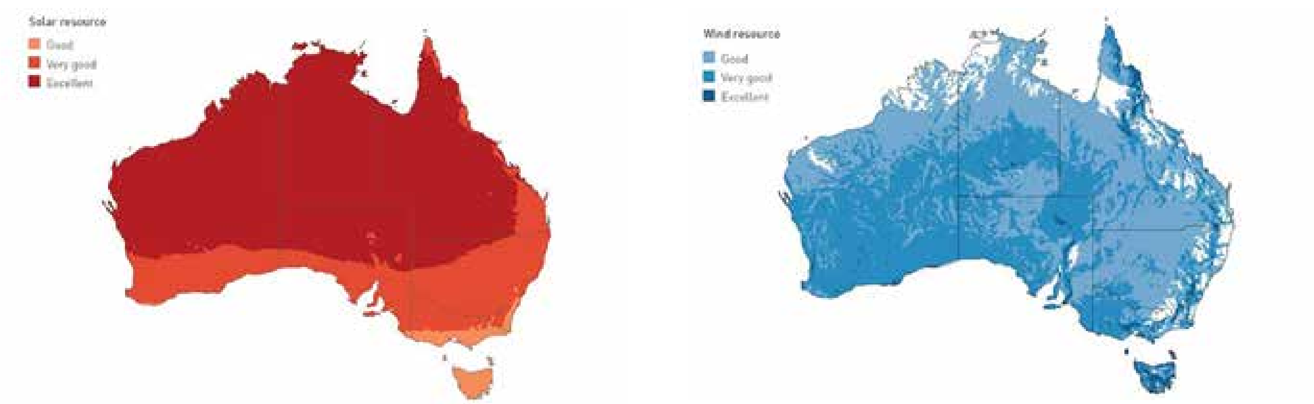
A vast landmass and abundant sunshine and wind make Australia one of the world's most renewable energy-rich nations[7]. In Australia, solar and wind resources are plentiful enough to supply renewable energy needs. **Figures 3** and **4** show the Australian solar and wind source maps[8]. In these figures: solar availability (good 1200-1600 MWh/m^2, very good 1600–2000 MWh/m^2, and excellent 2000-2400 MWh/m^2); wind availability (good 6-7 m/s, very good 7-8 m/s, and excellent 8-9 m/s, wind speed measured at 100 m). Solar power was the primary thermal-displacing electricity source in Queensland and South Australia. In Tasmania, a mix of wind power and hydroelectricity, and in Western Australia, New South Wales and Victoria, a mixture of solar and wind power[9].

Australian National Electricity Market (NEM) renewables are projected to supply over 30% of electricity in 2021 and 55% in 2030. Emissions in the NEM will decline by more than 26% below 2005 levels by 2022[5].

Technology Trends

All sectors of society must support decarbonization. The mining sector must encourage the use of renewable energy technology and other cost-effective low-emission technologies as a means of combating climate change[8]. It is possible to become competitive with and replace high-emission incumbents by making the electrification of mining equipment a priority technology[5]. Through the development of electrification and battery technologies, diesel-powered equipment at mining sites and transportation may be gradually replaced with a combination of electricity-power and energy storage technology. The mining sector will likely place more emphasis on electricity generation and battery storage as a result of the switch to an "all-electric" mine[8].

Transportation is crucial in reducing emissions associated with mining operations, particularly the mining truck fleet[4]. The mining sector is replacing fossil fuels by using renewable electricity to reduce the influence of fuel price volatility and decarbonization. Especially for remote mines that rely heavily on diesel generation on-site, renewable electricity generation and zero-emission truck fleets are critical to achieving a considerable emission reduction in the total mining facility emissions[4].



(a) (b)

Figure 3: (a) Australian solar source map, (b) Australian wind source map. (Source: Australian Renewable Energy Agency; The Australian Government Bureau of Meteorology Average daily solar exposure dataset; the CSIRO DATA61 Mesoscale Wind Atlas Data dataset).

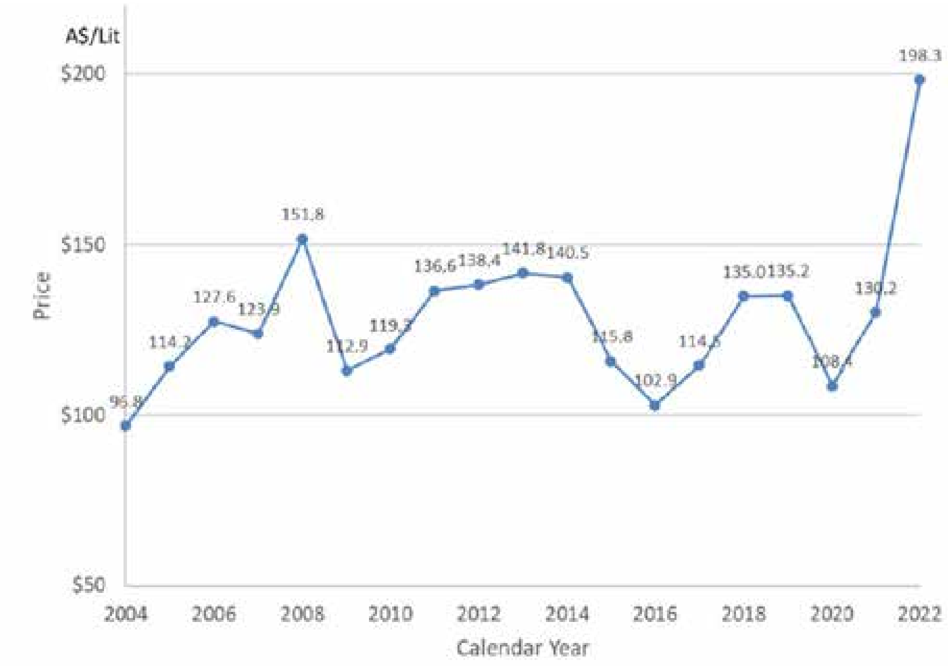


Figure 4: Historical Australia Diesel TGP Data (Source: AIP-Australian Institute of Petroleum).

Mining Challenges

With the strong demand for minerals and the depletion of high-quality resources, there are many challenges facing the mining sector. These include:

1. **Greater depths and lower grades:** Open pit mining depths have significantly expanded over the last two decades. Some open pit mines go down more than 1000 m in depth[10]. It is worth noting that future deposit extraction will inevitably be conducted at greater depths and lower grades compared to current practices, and this tendency is anticipated to continue[11,12].

2. **High operating cost:** As mines become deeper and stripping ratios increase with a lower grade, more waste material needs to be extracted. The haulage truck fleet grows correspondingly, requiring more operators and maintenance staff and a subsequent increase in diesel consumption[12-14]. In addition, as copper ore grades decline, more ore needs to be processed to attain similar metal production. A decrease in copper ore grade between 0.2% to 0.4% requires seven times more energy than present-day operations[15,16]. Reducing the cost of truck haulage, which makes up about half of the operating expenses of a mining operation, is now more essential than ever[17].

3. **Fuel price volatility:** Fossil fuel price volatility significantly impacts mining viability but is outside the control of most miners[9]. **Figure 4** shows historical Australia diesel Terminal Gate Price (TGP) data. In the short term, the price of fossil fuels shows a propensity towards volatility, while it shows a significant rise from the long-term perspective.

METHODOLOGY

TS and IPCC systems have been widely deployed in existing open pit mines. TA systems have been proven in several mine sites and will spread to more current operating mines, while BT is still largely a conceptual decarbonization mining system, which will be put to the test in pilot mine sites. For the purpose of evaluating the selection of a mining haulage system, it is necessary to compare all these mining systems from many mining metric points, which are beneficial for mining decision-makers to select an optimum mining operating system for their mine sites. This paper adopts a mining system evaluation approach by analysing systems' operations, configurations, and characteristics to measure their reasonable implementation scopes, pros and cons from mining haulage requirements perspectives. The following is the mining haulage system evaluation important parameters:

1. Safety and productivity are indicators to measure system implementation scenarios.
2. Energy efficiency, CAPEX, OPEX, maintenance requirements, service life, additional infrastructure requirements and heat generation are system financial metrics.
3. Emissions and environmental footprint (noise/dust/DPM/vibration) are system environmental parameters.
4. Flexibility, Capacity, Scalability, Refuelling/Recharging/Swapping methods are system productivity parameters.

CONVENTIONAL TRUCK-SHOVEL SYSTEMS

Conventional Truck-Shovel System Operating Process

Conventional TS systems continue to dominate open pit mines because diesel-powered trucks are extremely flexible in handling various materials with good grade capabilities and easy manoeuvrability[18]. The classic TS system consists of various operating processes, including manoeuvres and queues to the load point, spotting, loading, hauling the material, manoeuvres and queues to the offload point, spotting, dumping, exit tipping point, returning[19-21], which has been shown in **Figure 5**. To date, TS systems are the most viable, flexible and widely used mining system, and autonomous trucks have further enhanced their safety and effectiveness[19,22].

Truck-Shovel Systems' Characteristics

Truck-Shovel system continues to be the predominant mining hauling system of choice for surface mines because of its ease of implementation, high flexibility, and high scalability.

1. Ease of implementation
   The majority upfront expenditures of TS systems are trucks and loaders (e.g., excavators and electric shovels). A greenfield project mine may begin operations with a relatively small truck-shovel fleet and expand production capacity by purchasing larger units as the mine matures[18]. In terms of mining design and layout, several hauling segments with suitable road design, such as grade and road width, are required to complete the transport cycle. From the commencement of mines, trucks and loaders are a very predictable

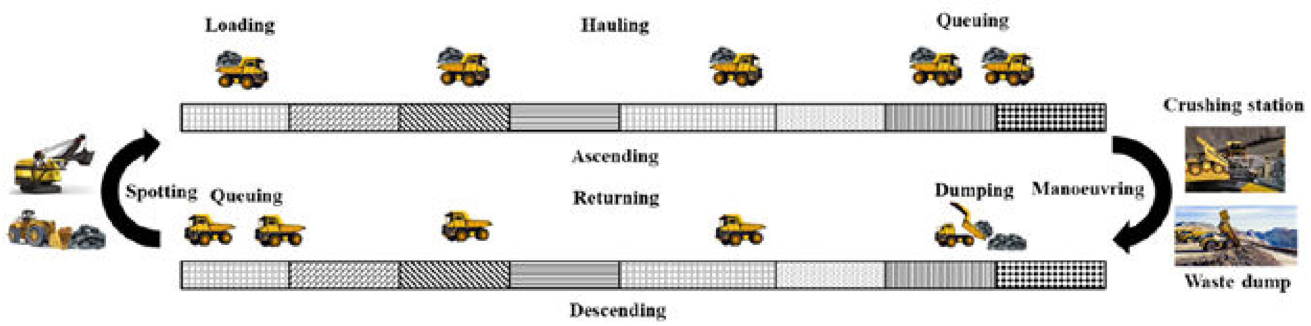


Figure 5: Conventional TS systems operating process.

and controllable means of haulage from economic and operational points of view[17].

2. High flexibility
   TS systems' high flexibility that they have become the dominant system in surface mining[23]. As TS systems are comprised of discrete elements, mine operators can dispatch each unit to a tailored working face to fulfil mine production requirements. Due to fewer mine design limitations and no infrastructure relocation, it's easy to change the truck fleet deployment schedule and mining tasks. Most importantly, trucks are capable of adapting to different orebody shapes and geology conditions to adapt to unforeseen changes in an open pit mine.

3. High scalability
   As a mine matures, additional trucks will be added to accommodate longer haul cycles, and larger trucks and shovels will be used to take advantage of economies of scale[24].

Additionally, the number and type of trucks and loaders used can be readily adjusted to change the production rate[17].

However, there are plenty of challenges with conventional TS system:

1. High operating costs
   Approximately 40–60% (depending on the combination of hauling equipment) of operating costs are attributable to haulage and material handling, notably TS operations[20,25,26]. The transportation distance starts to grow as mines become deeper, which dramatically reduces truck productivity. In order to reach the nominal mine production rate, the number of trucks in deployment needs to be increased. The demand for operating costs, including capital expenditures, fuel consumption, workforce, haul road size, maintenance, and repair service centres, all grow as the number of trucks increases[17].

2. CO_2 and diesel particular emissions
   Diesel-powered trucks emit a considerable amount of gas emissions and unique toxic materials caused by diesel engines[27]. According to ABB statistics, a single mining truck emits up to 1000 tonnes of CO_2 annually. It would take 46,000 trees to absorb[28].

3. Labour force shortage
   It is estimated that a conventional truck requires approximately seven people to operate (including operating and maintenance)[24]. A two 12-h-shift-day roster consists of 4.4 operators (0.4 to account for covering vacations and absences) and 2.7 maintenance workers[11], which makes it difficult for a remote mine to recruit enough people to meet its more significant truck fleet needs.

4. Fuel price volatility
   Fuel energy cost is one of the most significant expenditures in the mining sector, accounting for 15 to 40% (depending on mining system components) of total mine operating costs on average[15]. The classic TS system is susceptible to the volatility of the fossil fuel market since a significant portion of its energy derives from diesel fuel. Energy consumption, chiefly by diesel-powered truck operations, is anticipated to increase further as mining activity expands and demand for clean energy transformation metals rises[15].

5. Safety risks
   As the most prevalent kind of transportation equipment, haul trucks are involved in many accidents at operating mine sites, inspiring research interest in high potential incidents and serious accidents[29]. According to a report, approximately one-third of the deaths in Australian open pit mines are attributed to vehicle collisions[18].

6. Maintenance
   Internal combustion trucks are complex, requiring highly skilled mechanics and high maintenance costs for diesel-based engines. Another high cost is off-highway tyres because tyre wear will be severe as increasing truck units. In the meantime, ancillary equipment (e.g., grader, water truck and dozer) are applied to keep haul road and reduce environmental footprint with a good maintenance condition to support TS system performance. The maintenance cost of a conventional TS system is a significant portion of the hauling operating expenditure.

Leveraging the economies of scale over the past two decades, mines prefer to use larger trucks to increase productivity and reduce operating costs. However, larger trucks cannot eliminate TS disadvantages, and they have other negative impacts on downstream processes (crushing and milling). High benches and larger blasting patterns make it more difficult to separate ore from waste and cause uncontrollable dilution. Consequently, a substantial portion of ore material that meets the cut-off grade requirement becomes waste or marginal due to dilution. Again, a larger proportion of oversize material would make the comminution stage of the crushing and milling process more costly. From the whole mine-to-mill perspective, as feed grade is decreased, the processing recovery will result in a greater percentage of valuable input materials being transferred into waste[17,30].

Large open pit mines have increasingly invested in Autonomous Haulage Trucks (AHTs). A significant reduction in collision risks has been achieved with AHTs, along with high levels of productivity and tire performance[31]. While autonomous technologies can mitigate operator costs and improve energy efficiency, which is a significant portion of the haulage cost, they require a higher investment compared to conventional trucks with the same capacity[32]. Even with this sophistication, including the necessary hardware and software, these AHTs cannot overcome the many problems with increased travel distance[17]. More importantly, although AHTs are more fuel efficient, they cannot achieve the actual decarbonization of the mining industry.

Truck-Shovel Systems' Energy Consumption

The science of measuring the performance (productivity and energy consumption) of mining equipment has evolved and reached maturity in terms of the truck haul cycle. During ramp climbs, Siemens (2009)[33] estimates that 70-80%% of diesel fuel is consumed during haul operations. For an ultra-class dump truck, more than 40% of total energy is consumed to return the vehicle's mass to the ramp's top[33].

ELECTRIFICATION ALTERNATIVES FOR OPEN PIT MINE HAULAGE

In-Pit Crushing and Conveying Systems

IPCC Systems' Configurations

IPCC systems were first used in open pit mining operations in 1956 as an alternative to the classic TS haulage technique[34]. Using a continuous mining operation method often overcomes many of the drawbacks of the TS system. More specifically, compared to the conventional transportation system, it is possible to reduce the labour force, fuel consumption, and material size[14,28,35,36]. While most IPCC systems were used for coal and ore materials in the past, which is beneficial for downstream processes, it is seen as an unnecessary operating cost for overburden waste materials[18]. To date, however, IPCC systems have been increasingly introduced for stripping waste operations in response to the increasing hauling distance and stripping workload.

IPCC systems consist of crushers, in-pit conveyors (fully mobile), stationary conveyors, conveyor crossings, tripper car spreaders (waste), slewing spreaders (waste) and radial stackers (mineralized material). There are a variety of IPCC system alternatives available. In general, there are four distinct sorts of IPCC systems, each with unique characteristics. The four broad categories are: Fixed, Semi-Fixed, Semi-Mobile, and Fully Mobile systems[11,13,24,37] and each characteristic shows in Table 1.

Not common in deep hard rock mines -waste or ore

1. Fixed In-pit Crushing and Conveying systems (F-IPCC)
   In F-IPCC systems, the crusher is installed at a fixed location during the lifetime of the mine with rarely relocated, usually near the pit rim and the crest of the pit. Within the pit, the material is transported from the working face to the crusher unit using conventional truck haulage. After being crushed, the material is fed into a conveying system that moves it to either a spreader (waste material) or a stacker (mineralised material). F-IPCC system has its best application in deep, pre-existing pits, with low vertical advance rates, where a single crusher location can service the operation for an extended period.

2. Semi-Fixed In-pit Crushing and Conveying systems (SF-IPCC)
   In SF-IPCC systems, the crusher is fixed at a strategic junction point in the pit stage for a certain period (usually 3 to 5 years). Truck haulage is also used within the pit to move material between the working face and the crushing unit, just like with F-IPCC. The differences are: SF-IPCC is designed to decrease the haulage distance to the crusher much more than F-IPCC, and in order to relocate SF-IPCC, the entire crusher station must be disassembled into multiple parts or modules.

3. Semi-Mobile In-pit Crushing and Conveying systems (SM-IPCC)
   SM-IPCC is designed with a modular architecture to allow for the periodic movement of the crusher every 6 to 18 months as the working face deepens, where the crusher is operating near the mine working face (**Figure 6**). As the mine matures and increases in depth, the crusher is relocated deeper into the pit approximately every two to five benches (depending on the vertical advance rate) to maintain a short transport distance for the truck portion. Trucks feed crushing units, and dozers can directly push materials to feed crushers with a considerable cost reduction. Due to the continuous usage of trucks and the possibility of deploying the crusher at appropriate locations, SM-IPCC systems are the most easily accessible for current conventional hauling operations, which is also why SM-IPCC is the most flexible hauling system of all types of IPCC. Most importantly, by leveraging dozers or transport crawlers, the crusher can be relocated in hours without disassembling it, significantly reducing unproductive downtime.

Table 1: IPCC systems' characteristics.

IPCC Systems Type	Fixed IPCC	Semi-Fixed IPCC	Semi-Mobile IPCC	Fully Mobile IPCC
Crusher Type	Gyratory or jaw	Gyratory or jaw	Twin roll or sizer	Twin roll or sizer
Locations	Near the pit rim and crest	A strategic junction point in the pit	Near the operational level	Bench level in production
Relocations Time	Rarely or never relocated	Relocations every 3 to 5 years	Relocations every 6 to 18 months	Relocations as required to follow the shovel
Feed Systems	Shovel-Trucks	Shovel-Trucks	Shovel-Trucks and/or dozers	Shovels
Use	Deep hard rock mines-ore	Deep hard rock mines -waste or ore	Not common in deep hard rock mines -waste or ore	Not common in deep hard rock mines -waste or ore

Figure 6: Semi-Mobile In-pit Crushing and Conveying systems *(Source: Sandvik Mining and Construction).*

FULLY MOBILE IN-PIT CRUSHING AND CONVEYING SYSTEMS (FM-IPCC)

This system is distinguished by the loading unit dumping straight into the hopper of a fully mobile crusher that follows it (**Figure 7**). Once crushed, the material is transported straight from the working face to its destination through a network of conveyors. Utilizing a comprehensive continuous mining system and eliminating the requirement for truck haulage during steady state operation can dramatically save operational expenditure. However, as FMIPCC's flexibility is drastically constrained, the mine design must suit the system's requirements. In the meantime, truck haulage may still be required during each sinking phase of a mine because FMIPCC needs to be capable of completing mining tasks in complex geological conditions.

IPCC Systems' Characteristics

According to the literature review and mine site production experience, IPCC systems offer the following benefits compared to TS alternatives. The advantages of the IPCC are:

1. Operational expenditure
   As a mine's activity grows, the pit deepens and the size of the waste dumps increases, leading to a longer truck haul cycle and the need for more trucks to meet production requirements. Compared to IPCC methods, truck haulage is often thought to be more costly as distance and elevation increase[33]. With savings opportunities arising from energy saving, workforce reduction, weight efficiency and maintenance, it is possible to significantly reduce material transport operating expenses (OPEX) by using an IPCC system compared to a truck haulage system. When other unit operations are considered, such as drilling, blasting, loading and ancillary services, estimates prepared at the University of Queensland put total mining costs at around 24% less in comparison to equivalent TS operations[14].

Figure 7: Full-Mobile In-pit Crushing and Conveying systems[38] *(Source: McCarthy, 2013).*

2. CO_2 emissions
   IPCC systems are capable of a substantial reduction in CO_2 emissions because of fuel switching. An iron ore mine in Brazil with two installed FM-IPCC systems with a combined capacity of 7800 t/h, resulting in an expected decrease in diesel use of 60 million litres per year (ML/a), is an example of IPCC practice[11]. Reduced diesel consumption directly translates into reduced CO_2 emissions on site. In the same Brazilian mine, diesel savings of 60 ML/a equate to an approximate reduction of 130,000 t/a of CO_2. Considering that the average passenger vehicle emits approximately 3.552 t of CO_2 equivalent per year (Commonwealth of Australia, 2012), this is equivalent to taking more than 36,000 cars off the road per year[14]. The IPCC study[16] shows that when only fossil fuel-based energy was used, the CO_2 emissions per tonne of ore for the IPCC system were 67 kg CO_2 e/t as opposed to the TS system's 70 kg CO_2 e/t, a 3 kg decrease. It is possible to reduce greenhouse gas emissions by 14 kg CO_2 e/t ore using power generated from natural gas[17]. With renewable energy, e.g., solar-based and wind-based electricity, IPCC can be regarded as a decarbonization transport mining system.

3. Energy saving
   Conveyor haulage naturally uses less energy per unit weight of material transported than truck haulage. Another important aspect is that conveyors use more (81%) of the consumed energy for the transportation of the payload in comparison to trucks (39%)[11]. More precisely, during a truck cycle, only 39% of the energy is used to move the payload; the other 61% is needed to move the truck's weight. Because the conveyor's upper and lower portions weigh much less than the overall amount of material for each metre of its length, just 19% of the energy used to move the material is wasted[17,39]. On the other hand, IPCC can reduce a mine's dependency on diesel fuel due to electricity-based[40].

4. Production efficiency
   For the purpose of moving ore or waste to the appropriate areas, IPCC offers a continuous transportation system method, which typically improves production rates[36]. Conveyor haulage provides superior production efficiency on comprehensive metrics of assessing equipment performance, according to a comparison of the two systems (TS/IPCC) based on utilized time, operating time, and valuable operating time metrics[33]. While the truck fleet enables much higher available time and utilisation time, IPCC achieves higher operating time and valuable operating time, which means higher production efficiency compared to the truck fleet[33].

5. Environmental footprint (noise and dust)
   Since conveyors operate at a lower decibel level than conventional diesel-powered trucks, IPCC systems may help minimize noise pollution. Reducing the number of trucks on the road may significantly reduce the source of dust emissions, while some water will still be needed in conveyor systems to suppress dust at transfer points[11]. In other words, IPCC creates a better mining environment for the workforce from both noise and dust perspectives.

6. Maintenance
   IPCC usage decreases reliance on large off-highway tyres, which account for a large portion of the truck fleet cost. Large off-highway tyre shortages will significantly impact truck fleet availability and mining production rate. In addition to reducing haul truck numbers, conveyors have been reported to reduce the need for ancillary equipment (graders, dozers and water trucks) by 25-30%[11].

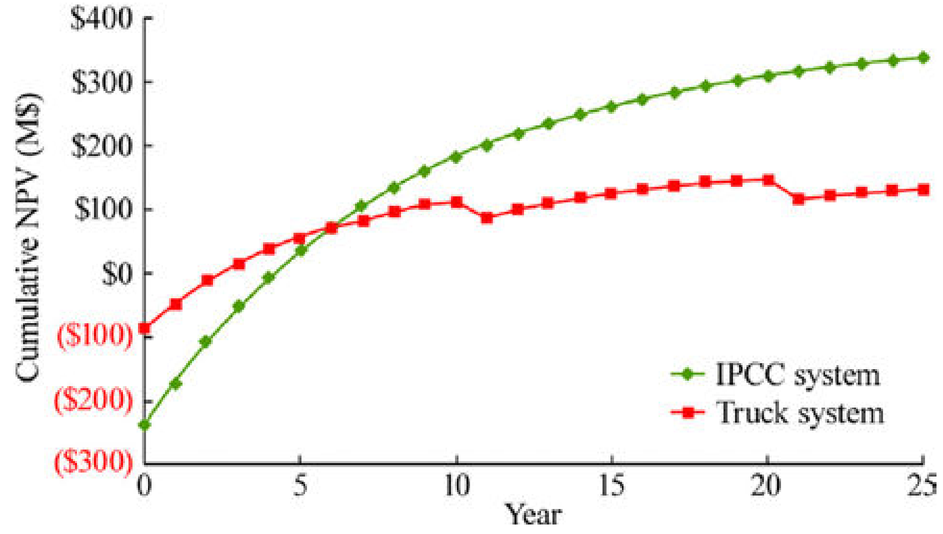


Figure 8: The cumulative net present value comparison of TS and IPCC systems[11]

7. Workforce reduction
   IPCC offers more opportunities to remote open pit mines with limited labour availability and high workforce cost, in some cases, as low as one operator for each major component (crusher, conveyor, spreader/stacker), with minimal maintenance staff[24]. For example, a FM-IPCC system has a total workforce requirement of around 80 people[37], including operators and maintenance personnel. The exact staffing numbers will depend on the number and installed length of conveyors. In comparison, it is estimated that a large ultra-class mining truck requires staffing of 7 people per year. Thus, from a workforce point of view, an IPCC system becomes an attractive alternative if it can replace approximately 12 trucks[14].

8. Safety
   Abbaspour[29] demonstrated that these transportation systems behave differently in terms of safety and social metrics by creating a simulation model over the whole mine life, including TS and four types of IPCC systems. In conclusion, FM-IPCC stood first in terms of safety, while the TS system was ranked fifth. A reduced truck fleet size will reduce the possibility of vehicle collisions, which is a leading cause of safety incidents in surface mining operations[14]. Because TS systems work in collaboration to feed fixed, semi-fixed and semi-mobile IPCC systems[18], FM-IPCC is able to arrive at the lowest safety risk indicator by eliminating the truck fleet.

9. Total cost operation over the mine life
   In 2012, the typical capital expenditure for an IPCC system was between USD180 million and USD250 million (depending on the types of IPCC, the number was estimated to be and installed length of conveyors)[41]. For a 360-ton haul truck, the cost in 2009 was around USD5 million[42]. It can be seen from **Figure 9** that IPCC requires more significant capital investment. The considerable gap causes plenty of greenfield project mines to embrace the TS system when they hope to recover capital as quickly as possible. However, the IPCC's accessories, such as the crusher and conveyor, are generally replaced every 20 to 25 years (about 150,000 h), whereas the economic replacement age for trucks is around seven to ten years of operation (between 45,000 and 60,000 h). This indicates that two truck fleet replacements will be required for a mining project that is 25 years old (i.e., where the red line drops in **Figure 8**). The conveyor system will require a lower total cost operation over the mine life[17]. It is estimated that the operating expenses (OPEX) of conveyor haulage are around one-third that of a comparable TS system. However, when capital expenditure (CAPEX) is considered, the reduction in the total cost of operation over the mine life is around 50%[14].

In the meantime, there are several disadvantages to IPCC versus TS:

1. Flexibility
   Its flexibility is the most significant factor that hinders the commercial take-up of IPCC systems when a mine considers an available mining system. Of the four types of IPCC systems, SM-IPCC shows the best flexibility, while FM-IPCC is the worst. Mine design, relocation and capability are limiting IPCC application.

   (a) Mine design limitation. The decision-makers must cater to the installation requirements of the IPCC systems when they design the mine layout. Take FM-IPCC as an example, the optimization of ultimate pit limit (UPL), considering the geometric constraints connected with the installation of FM-IPCC systems, is one study field that requires substantial further investigation[11]. Throughout each sinking phase of a mine, truck haulage may still be required, but the distance of the haul may be decreased by deploying and scheduling the trucks to dump into the fully mobile crusher close to the mining activity[14].
   (b) Relocation limitations. The IPCC has its specific extraction sequence. It is crucial to design its optimal location and relocation strategy to minimize operating costs. Mine designers need to trade-off large bench widths against production for an optimal location and relocation strategy[37]. For instance, because FM-IPCC systems are better suited to flat or gently dipping applications such as coal overburden or iron ore mining, it reduces the ability of a mine to switch mining to a different zone to adapt to unforeseen changes in market conditions or geology[14].

(c) Capacity limitations. Compared with the TS system, IPCC systems cannot be scaled up or down as mining requirements change[38]. This is because IPCC's major components (crusher, conveyor, spreader/stacker) have their own capacity limitations. An IPCC system also has a rated capacity, which reduces the ability to scale mining rates up or down according to market conditions.

2. Reliability
As IPCC systems are a series of connected systems, an unplanned delay or maintenance outage in one piece of equipment will affect the throughput of the entire system[14]. The availability of the whole IPCC system depends not only on the availability of the crusher but on the availability of each of the conveyors that comprise the whole system; the more components there are, the lower the reliability of IPCC systems[24].

3. Material requirements
The material requirements of IPCC transportation focus on material size and material properties. In order to transport material via conveyor, particle size distribution should be such that the largest material does not exceed approximately one-third of the belt width[14]. On the material properties side, the ability to sustain high throughput rates (4000–10,000 t/h) through a mobile crusher is key to IPCC system performance. Comprehensive knowledge of the material characteristics of the deposit and waste rock is required to specify the correct crusher type[14].

4. Contractual constraints
IPCC systems are not available as off-the-shelf solutions. The current approach for acquiring IPCC systems is via engineering, procurement, construction and management contract, which adds cost and delay to a mining project. This procedure will likely change once IPCC technology matures and gains greater acceptance[14].

Overall, the comparison results indicated that the IPCC system is superior for mining activities requiring strict environmental management, long lifespan, high production rate, and long-haul distances[17]. Generally speaking, the use of an IPCC continuous mining system will lower the energy consumption and significant emissions in the haulage sector of a mine, as well as reduce the cost of the haulage mine sector as a whole by millions of dollars, which will ultimately boost the mining sustainability and economy[13].

Trolley Assist Systems

Theory of Trolley Assist

After the oil supply crisis in the mid-1970s, the surface mining industry turned its attention to this fuel-saving technology. Several surface mines equipped with large off-highway electric trucks considered introducing TA into their operations. The overall view of the TA system is shown in **Figure 9**. As a solution that is a practical first step on the path to low-emission mine sites, TA is a proven technology capable of providing external electrical power to diesel-electric equipment. Recent advances in electric control technology have made this type of haulage an attractive alternative to conventional diesel-electric haulage[43].

The objective of mine decision-makers is to transport the highest volume of payload per hour while minimizing operating costs over one haul cycle of the trucks within acceptable risk boundaries[44]. Therefore, the power supply module which produces power from a diesel engine may be integrated with overhead trolley electricity to achieve further fuel savings[45,46]. The TA system is the most cost-effective on the ramps, where the majority of the total energy is used[44].

As **Figure 10** shows, after operators manoeuvre diesel-electric trucks leaving the workface to arrive at the trolley ramp, operators determine the most appropriate time and approach speed to enter trolley mode to raise the pantograph. The truck switches to trolley electricity when the pantograph is activated and connected to the overhead power lines. Additionally, the truck's diesel engine enters idle mode, significantly saving fuel energy and reducing CO_2 emissions[45]. Because the electric wheel motor power commonly exceeds engine power, the electric wheel motors' full power capacity can achieve accelerating speed in trolley mode[47]. From a power aspect, with pantographs, diesel-electric hauling trucks could draw power from an overhead trolley line. However, diesel-electric power is still required in the pit, surrounding the loader/crusher, during hauling level segments, and on return travel[44].

Configuration of Trolley Assist

Trolley Assist systems supplement the power requirements of diesel-electric haul trucks via an external power source. Diesel-electric haul trucks are powered by a diesel engine generating an Alternative Current (AC) that powers the rear wheel motors to deliver torque to the wheels. Under Trolley Assist, the wheel motors are powered by an external Direct

(a)

(b)

Figure 9: (a)The overall view of Trolley Assist system (source: ABB). (b) The detail of Trolley Assist on the ramp.

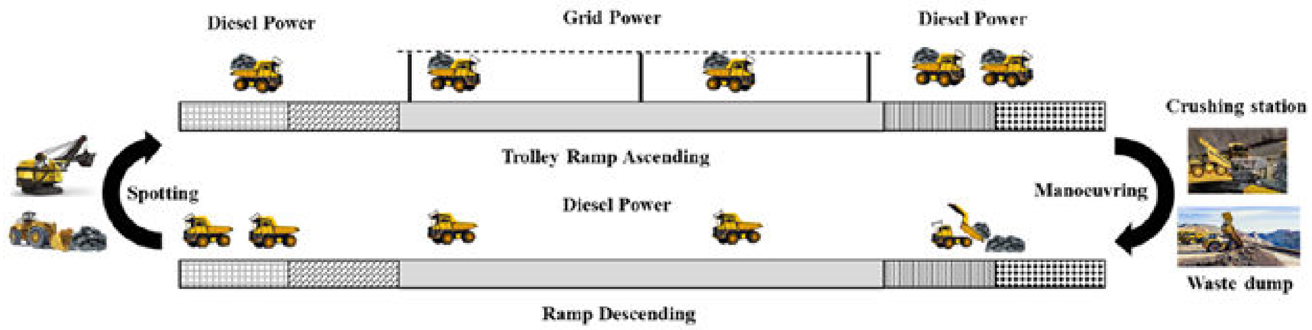


Figure 10: A schematic of a typical TA operation and power process.

Current (DC) power source, commonly an overhead power distribution system. TA systems consist of three subsystems: power supply to the pit, overhead power distribution, and trucks with TA capability (**Figure 11**)[48].

1. Power Supply to the Pit
Transmission lines from a utility source deliver AC power to strategically positioned rectifier substations, providing DC power to the trolley line along the haul road. Rectifier substations should be skid-mounted for mobility to accommodate changes in the haul route[48]. The rectifier substations deliver power to the overhead power distribution system along the haul route.

2. Overhead Power Distribution
Overhead power distribution is achieved by a catenary system that supplies electrical power along the haul road. The catenary system allows the trucks to drive underneath and connect to the DC power. The voltage supplied by the catenary system depends on the wheel motors in the trucks using TA[49]. The catenary system is supported by poles spaced approximately 20-30m along the haul road. The supporting poles' actual design and spacing depend on the haul road characteristics.

3. Trucks with Trolley Assist Capability
Figure 12 illustrates a truck operating under TA. The truck conversion was required in trolley mode when Trolley Assist systems were implemented, which in some cases required rewiring the wheel motor circuit to operate in series during TA. A pantograph system was required to connect the truck's electrical circuit to the overhead power, which operators determine the most appropriate times to raise or lower.

Advantages and Disadvantages of Trolley Assist System

In each of the TA applications, there was widespread publicity of various benefits resulting from the conversion to TA. The performance estimates of the TA system were derived from an analysis of several South African fleets that had used the technology in the past[48]. According to available reports and mine site production experience, TA systems offer the following benefits compared to TS alternatives. The advantages of TA are:

1. Reduced Emissions
The most crucial advantage is significantly reducing truck fleet CO_2 emissions[49]. According to ABB statistics, a single mining truck emits around 1000 tons of CO_2 per year[28]. Trolley Assist systems are most effective on the ramps, where most diesel energy is consumed, and the emissions are emitted.

2. Reduced diesel fuel consumption
A substantial saving in diesel fuel is made possible on the ramp with the use of a TA. According to a study case, the usage of TA decreases diesel consumption for ramp haulage by 19 litres per kilometre per truck[50]. The value of the resulting savings depends on the relative pricing of diesel fuel versus electricity. Indeed, relatively inexpensive electricity is more popular than diesel, and fossil fuel prices have continued to rise in the past few years. On the other hand, it is interesting to note that the several mines converted to TA systems are located in southern Africa, where the region faced the most severe oil supply problems during the 1970s. Reduced diesel fuel consumption can relieve the pressure on remote mines with oil supply problems[51].

3. Productivity improvements
Electric motors also offer more torque at low speeds than traditional combustion engines[52], which means electrified trucks are able to accelerate faster and provide better speed

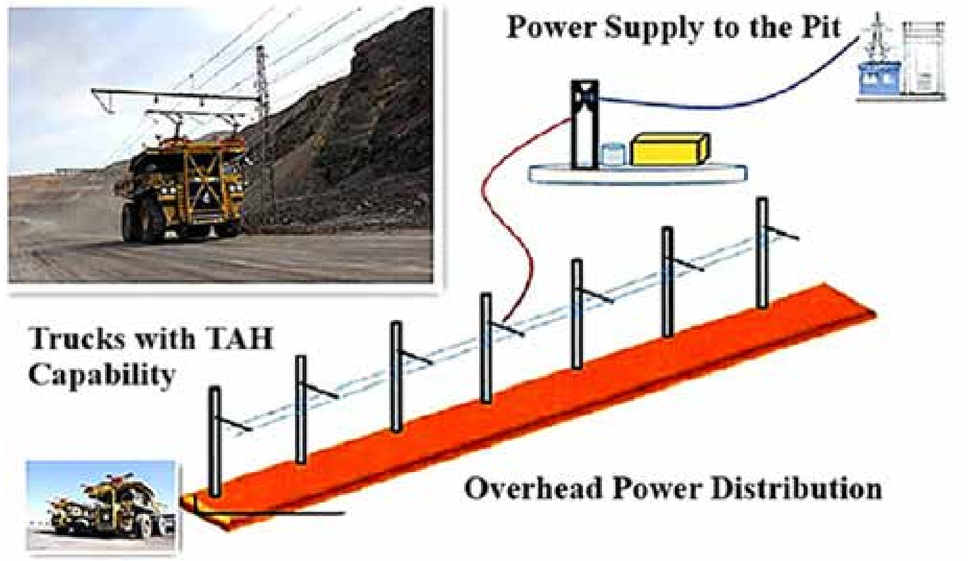


Figure 11: System design of TA.

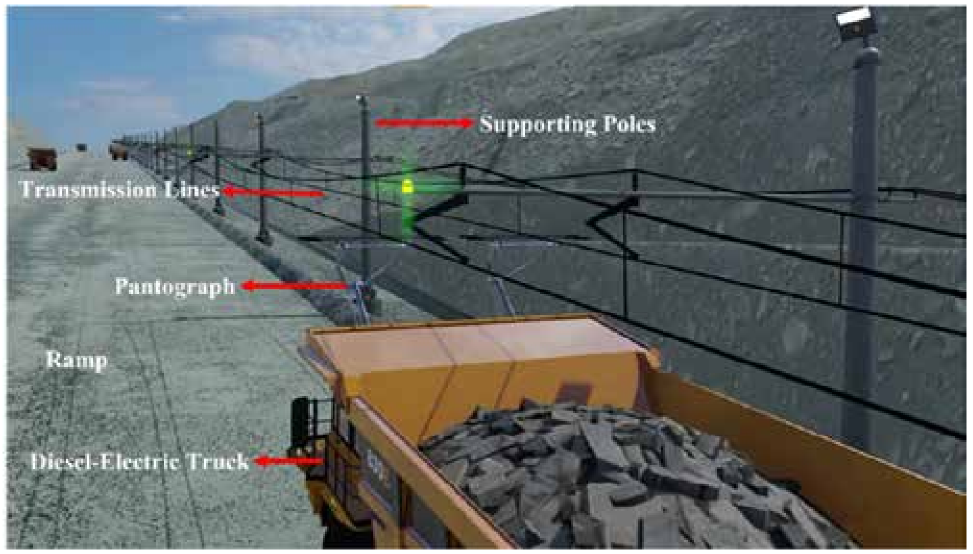


Figure 12: Truck with Trolley Assist capability operating on ramp (Source: ABB).

performance on a ramp[49]. Due to the trucks' higher gradient capability while operating under grid power, the TA system makes it simpler to access the deeper portions of the mine as mining depth increases. The use of TA on uphill hauls usually increases haulage system productivity. The report shows the resulting benefits are truck speed increases on a ramp from 13 km/h to 27 km/h[48]. The overall increase in truck productivity depends on the relative length and road grade of the uphill ramps in the haul cycle, and this productivity increase favours the use of TA for long uphill hauls.

4. Increase engine and wheel motor life
   All the mines with TA systems have reported a substantial increase in engine and wheel motor life cycles and running time. Increased speed on ramps results in shorter times during which the wheel motors are at the full load; thus, motor overheating is less likely to occur. With the same motors, longer ramps may be negotiated without undue wheel motor wear, thus improving the haulage system for deep pit capacity.

5. Reduced fleet size
   In a TA system, a single truck can complete one cycle in a shorter time due to its higher speed, which means the TA fleet can transport the higher possible payload per hour. Therefore, reducing the number of required trucks is likely to achieve production requirements. Fewer trucks lead to reduced maintenance and workforce costs, plus reduced capital expenditure.

6. Lower maintenance cost
   Under TA haulage, a truck's diesel engine idling reduces the duty on the engine and increases the engine life. From a single truck perspective, trolley trucks need less maintenance than conventional diesel trucks because of reduced truck engine maintenance and fewer overhauls. On the downside, it is considered that the savings would be offset by the increased cost of electric wheel maintenance and trolley system maintenance[50].

7. Lower overall operating cost
   Due to infrastructure and truck retrofit costs, although the TA system requires high upfront capital expenditure, the overall operating cost can be lower than conventional diesel trucks because TA is capable of reducing emissions (depending on carbon tax policy), energy consumption, the number of trucks, and maintenance costs.

In the meantime, there are several disadvantages to TA versus T:

1. High upfront capital outlay
   The TA system is more complex than the conventional TS system with respect to the infrastructure of power supply to the pit, overhead power distribution, and the retrofit of trucks with TA capability, which means a high upfront capital outlay. According to research, the infrastructure cost per truck for adaptive measures and TA systems, which need an overhead cable, is around 75% of the overall truck price[53].

2. Mine design and planning restriction
   The most significant advantages of off-highway haulage are its flexibility to mine schedule and ease of adjustment to a specific feature of the mined deposit. The installation of a TA system has imposed several restrictions on the flexibility of mine design and planning. While the trolley lines can be relocated, the relocation requires a skilled workforce, specialised equipment, and time. Time lost during critical stages of mining operations may have severe financial consequences. The cost and restrictions associated with the trolley shifting operation are likely to discourage frequent haul road relocations and restrict traffic patterns. Trolley shifting is another challenge in trolley ramp structural design, which affects trolley system performance. While not all the restrictions may apply to each mining situation, the associated costs for those that do apply should be evaluated and accounted for. More importantly, the TA system still preserves the majority of benefits in flexibility by using diesel-electric trucks. Although TA system flexibility is less than the conventional TS system, it is higher than IPCC systems.

3. Trolley Assist system maintenance
   The reported experience with the existing TA system indicates that the distance between the trolley wire and the haul road surface must be closely controlled[54]. The need to maintain smooth haul routes and tight tolerances between the haul road surface and overhead lines is currently experienced with trucks operating under a TA system where wheel path wander is minimal due to the requirement to position the pantograph under the power lines. In this case, more ancillary equipment is necessary to maintain road quality. In addition, the maintenance costs include infrastructure maintenance and inventory of related spare parts and materials.

4. System capacity
   The trolley sections have a limited capacity and are only able to accommodate a given number of trucks due to grid power limitations. When this number is on the section, the next truck cannot be accepted, and it must wait or travel powered by its diesel engine. Furthermore, slow-moving equipment, such as water trucks and graders, may slow the Trolley Assisted truck down. Truck schedules need to balance production tasks and maintenance requirements while considering TA technology's capacity. Bunching of trucks frequently occurs in TA operations, resulting in potential productivity loss. Therefore, considering system capacity limitations, the TA fleet needs a more effective dispatch strategy.

5. Access to Electricity
   Installation of a TA system will require additional electrical power capacity. The TA system becomes an option for mine sites that can increase their electrical power capacity (i.e., readily available power or excess capacity). The adoption of the truck haulage system outside South Africa indicates that TA may be economically feasible in situations without very high diesel-to-electricity cost ratios. For remote mines, renewable energy sources, such as wind turbines and solar PV, may be used as alternatives to fulfil the electrical power requirement of the TA system, which will be driven by decarbonization.

6. Operator requirement
   Operator training is essential to the truck haulage system because operators determine the most appropriate times to raise or lower the pantograph. The higher truck speeds combined with narrower steer paths demand more excellent skill and concentration from an operator. Greater awareness of the truck's dimensions is required to avoid collision with the catenary system supporting poles. If the truck loses contact with the trolley wire on the ramp due to erroneous driving, it will cause a severe bunching phenomenon because of lower speed and loss of potential productivity.

In most cases, a permanent, long-haul route with TA on the ramp out of the pit will result in the best economic benefit for Trolley Assist. The TA system's economic feasibility depends on several factors, including the availability of alternative electricity, diesel fuel and electricity costs, the cost of employing operators, and resulting maintenance requirements.

Battery Trolley Systems

Theory of Battery Trolley

The mining industry is working on a series of projects to achieve zero-emissions fleet requirements. Battery Trolley deployment is one such option[4,46]. Battery Trolley aims to offer a haulage mining system using the full source of electrical power as a decarbonization technology through autonomous high-intensity battery-electric trucks, TA systems and energy recovery systems.

Technology Uptake

It is advanced technology development that gives BT a chance to be a reality. Battery-electric power, autonomous deployment, TA and energy recovery technologies are the critical drivers for the BT to achieve the decarbonization pathway, which are core components in the future plans for deeper phases[31].

1. Battery-electric power technology
   Electromobility, defined as the development and usage of electric-powered vehicles, is an industry-wide technical trend[31]. BEVs are one of the choices available to accomplish ambitious decarbonization goals. New battery designs with superior usage performance and lower cost will boost BEVs' competitiveness in the mining sector. Battery electric trucks have fewer mechanical systems and control logic than conventional hybrid ones, which results in reduced failure rates and more straightforward maintenance[45]. Nevertheless, battery size, energy density, battery swapping and charging, battery health and management are challenges facing the mining sector when thinking about applying battery-powered trucks.

2. Autonomous technology
   According to statistics collected by GlobalData, by May 2022, there were 1068 autonomous haul trucks operating worldwide, a 39% yearly growth. Caterpillar and Komatsu supply 86.5% of the trucks monitored by the Mining Intelligence Centre, with the 793F and 930E being the two OEMs' most popular models, respectively[55]. That is because autonomous solutions can improve safety, equipment availability, and overall productivity on any mine site without machine operators sitting in the cab. As for the BT, determining the most appropriate times by leveraging autonomous technology to raise or lower the pantograph is the best option. BT systems are capable of taking advantage of autonomous trucks from both safety and productivity perspectives.

3. Trolley Assist technology
   Battery electric vehicles are one option for mining trucks. However, in order to overcome battery size and energy density defects, mining trucks need TA technology to provide ascending energy on an uphill where the most energy is consumed. TA technology makes BT available by offering electric power to battery trucks, which enables battery trucks to haul for a long time.

4. Energy recovery system
   The BT is able to leverage an energy recovery system to recuperate braking energy, which is used to charge the onboard battery when returning downhill[47]. The depth alterations connected with mining development bring significant variations in haul cycles and recoverable potential energy per cycle[56].

Battery Trolley Advantages and Disadvantages

Battery Trolley makes it possible to achieve the first zero-emissions truck fleet as a green solution, which is available to remove the reliance on fossil fuels by using battery-electric power in mining haulage systems. Except for decarbonization, reducing energy costs and TA's advantages, the BT can achieve lower maintenance costs for a single truck without a diesel engine. Additionally, from the overall mine operating life, the operating costs of BT are less than the conventional diesel truck fleet because of using electricity as end-use energy, which is similar to IPCC.

In spite of the advantages associated with BT, decision-makers may be reluctant to use it for some reasons. From diesel-electric to battery-electric power, this transition would significantly increase the mine's electricity cost and demand, as well as the power infrastructure and station capital expenditure. Additionally, the battery truck fleet has to face many challenges, such as battery size and performance, high upfront capital outlay, feasibility, availability, capability, truck fleet dispatching, mine design restrictions, and ancillary equipment maintenance schedule arrangement.

EMERGING TECHNOLOGIES IN HAULAGE

Battery Trolley Systems Configurations

Like IPCC systems, there are three possible configurations for BT. Each type has its pros and cons, which can be used in unique mining situations.

1. Dynamic charging BT configuration
   Dynamic charging technology enables the ability for grid power to be used to power the electric drive motors and charge the onboard vehicle battery simultaneously. The dynamic charging BT consists of the battery-electric truck, the TA systems and dynamic charging technology.

Figures 13 and **14** are, respectively, the dynamic charging BT systems operational process and power source. Battery-electric trucks load and haul with battery power, switching to trolley mode after arriving at the trolley ramp. The battery consumes energy at a much lower rate for cooling and idling. At the same time, the grid power is simultaneously used to charge the on-board battery and provide the wheel motors output power on the trolley ramp. When the battery-electric truck comes onto an ex-pit flat road, it returns to battery power mode to complete hauling, queueing, dumping and returning manoeuvres. The battery-electric truck then enters energy recovery mode on the downhill ramp. The energy recovery system transforms truck braking power into electric energy that can be stored on the battery. The battery-electric truck then reuses battery power to return to the loading point.

STATIONARY CHARGING BT CONFIGURATION

In stationary charging method, a battery station is necessary for battery charging/ swapping. As for choosing charging method or swapping method, it depends on charging C-rate and swapping time. The location of battery station is selected on the crest of pit for providing enough permanent room to build infrastructure and park trucks. The stationary charging Battery Trolley consists of the battery-electric truck, the TA systems and battery station.

Figures 15 and **16** are, respectively the stationary charging BT systems operational process and power source. Battery-electric trucks load and haul with battery power, switching to trolley mode after arriving at the trolley ramp. The battery consumes energy at a much lower rate for cooling and idling. At the same time, the grid power is capable of providing the max wheel motors output power to operate in a faster speed on the trolley ramp. When the battery-electric truck comes onto an ex-pit flat road, it returns to battery power mode to complete hauling, queueing, dumping and returning manoeuvres. According to on-board battery size design and energy consumption, the battery-electric truck needs to charging/swapping battery within each cycle or every two/three cycles. The battery-electric truck then enters energy recovery mode on the downhill ramp. The energy recovery system transforms truck braking power into electric energy that can be stored on the battery. The battery-electric truck then reuses battery power to return to the loading point.

DUAL TROLLEY BT CONFIGURATION

Research shows that for downhill hauls, a bidirectional substation enables energy feedback to the grid[44]. It is reasonable to install a dual trolley system for better energy capture performance in a BT system: the uphill ramp trolley enables the ability for grid power to be used to power the electric drive motors while the downhill ramp trolley captures braking energy and returns it to the grid. The dual trolley BT consists of battery-electric trucks and a double trolley system.

Figures 17 and **18** are, respectively, the dual trolley BT systems operational process and power source. Battery-electric trucks load and haul with battery power, switching to trolley mode after arriving at the trolley ramp. The battery consumes energy at a much lower rate for cooling and idling. At the same time, the grid power is capable of providing the max wheel motors output power

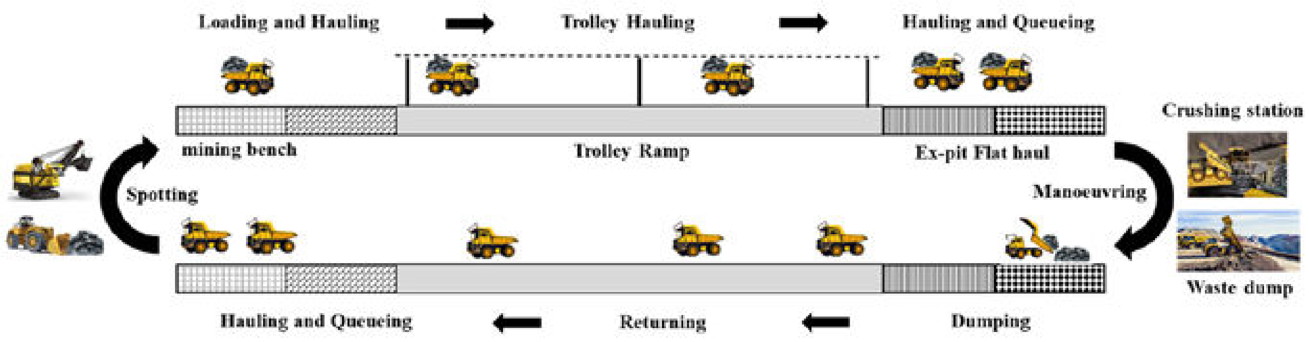


Figure 13: A schematic of dynamic charging BT systems operational process.

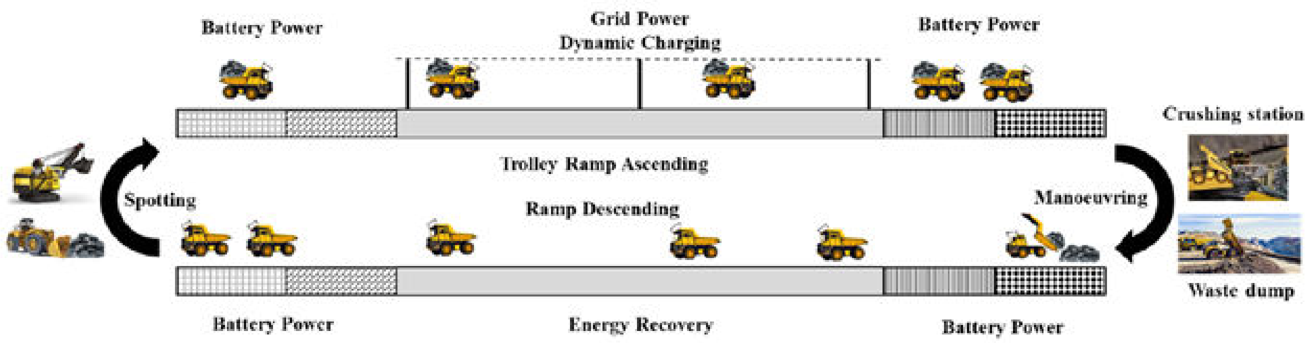


Figure 14: A schematic of dynamic charging BT systems power source.

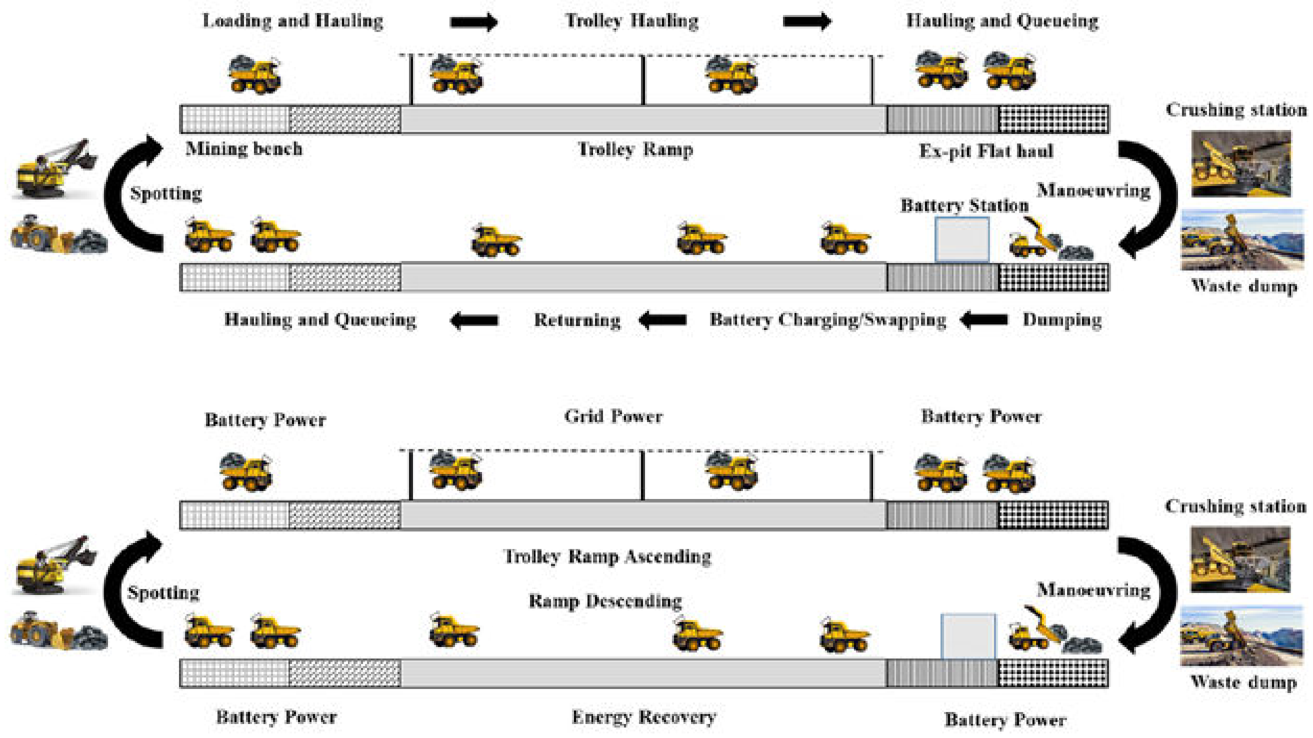


Figure 16: A schematic of a typical BT systems power source.

to operate in a faster speed on the trolley ramp. When the battery-electric truck comes onto an ex-pit flat road, it returns to battery power mode to complete hauling, queueing and dumping manoeuvres. According to on-board battery size design and energy consumption, the battery-electric truck needs to charging/swapping battery within each cycle or every two/three cycles. The battery-electric truck needs to charging/swapping batteries on returning travel when it passes a battery station located on the pit's crest. The battery-electric truck then enters energy recovery mode downhill by engaging the trolley line, which captures braking energy back to the grid. The battery-electric truck then reuses battery power to return to the loading point.

DISCUSSIONS

In order to achieve optimum make-decision in mining haulage systems, it is necessary to use the mining system analysis method for evaluating each mining system parameter in **Table 2**.

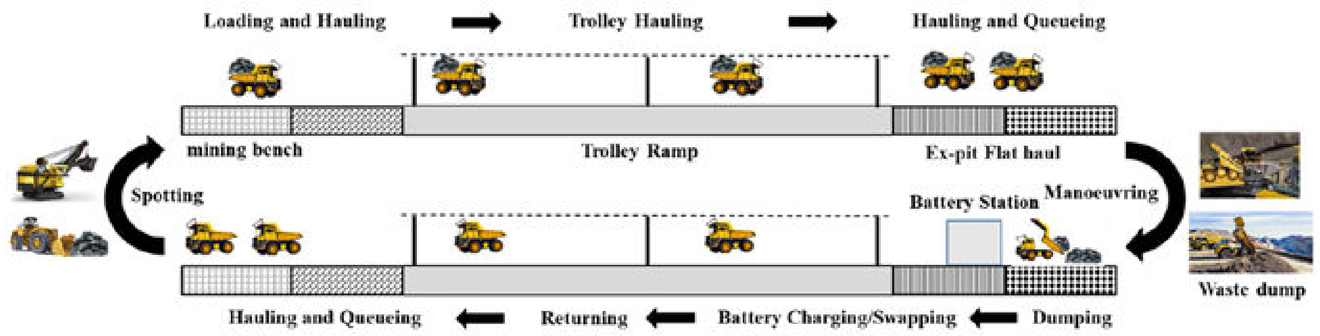


Figure 17: A schematic of dual trolley BT systems operational process.

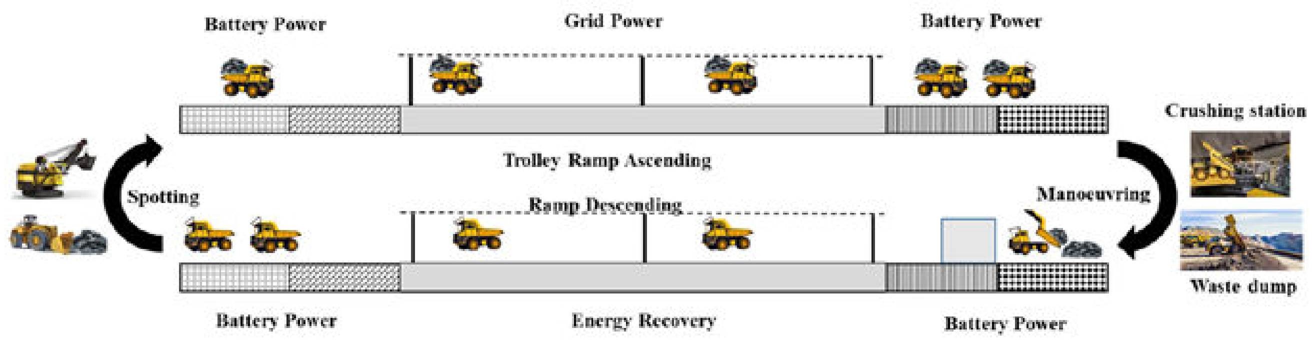


Figure 18: A schematic of dual trolley BT systems power source.

Table 2: Comparison between diesel TS, IPCC, TA and BT.

Parameter	Diesel TS	SF/M IPCC	FM-IPCC	TA	Dynamic Charging BT	Stationary Charging BT	Dual Trolley BT
Flexibility	High	Medium	Low	Medium	Low	Medium	Medium
Energy Efficiency	Low	Medium	High	Medium	High	High	High
CAPEX	Low	High	High	High	High	High	High
OPEX	High	Medium	Low	Low	Low	Low	Low
Maintenance Requirements	High	Medium	Low	Medium	Medium	Medium	High
Service Life	Short	Medium	Long	Long	Long	Long	Long
Additional Infrastructure	No	No	No	Yes	Yes	Yes	Yes
Refuelling/Recharging/Swapping	Fast	None	None	Fast	None	Low	Low
Emissions	High	Low	None	Low	None	None	None
Heat Generation	High	Medium	Low	Medium	Low	Low	Low
Environmental Footprint (Noise/ Dust/DPM/Vibration)	High	Medium	Low	Medium	Low	Low	Low
Reliability	High	Medium	Low	Medium	Low	Medium	Low
Scalability	High	Low	Low	Medium	Low	Medium	Low
Capability	No	Yes	Yes	Yes	Yes	Yes	Yes
Safety	Low	Low	Medium	Low	Medium	Medium	Medium

According to **Table 2**, diesel TS shows the best performances in flexibility, CAPEX, refuelling, reliability, scalability, and capability, which explains why classic TS are prevalent in all kinds of greenfield and brownfield mining projects. IPCC is capable of mitigating the TS disadvantages from energy efficiency, maintenance, refuelling, emissions, heat generation, and environmental footprint points. However, flexibility, CAPEX, reliability, scalability, and capability characteristics are the constraints for IPCC, especially FM-IPCC, to large-scale applications in mine sites. Due to diesel-electric power and trolley limitations, TA shows medium performance in almost all parameters. In the dynamic charging alternative, because the onboard battery energy source is from grid charging uphill and energy capture downhill, the battery-electric trucks cannot complete one haul cycle without enough trolley lines charging. Therefore, dynamic charging BT has lower flexibility, reliability, scalability and capability compared with stationary charging BT, while no recharging/swapping battery need in the battery station is the most significant merit for dynamic charging BT systems. Because of flexibility limitations and considerable capital outlays, dual trolley BT is unlikely to be popular in large-scale BT deployment. However, dual trolley BT is suitable for some unique mine site conditions like super-depth copper mines.

CONCLUSIONS

The mining industry is now at a crossroads with surface mining fleets as it works to meet interim reduced emissions and final net-zero targets. A big part of that is moving away from diesel to electricity alternatives. This paper depicts the various haulage systems from diesel-based power trucks to electric-based power IPCC, diesel-electric power TA systems and battery-electric power BT systems. IPCC and TA are ramping up due to reasonable economic and emission reduction, whilst trucks operating in conjunction with a conceptual BT system could decarbonise haulage mining systems in open pit mines. All these haulage systems are interrelated and complementary. They cannot be determined in isolation, which requires further comparison and analysis of their mine sites' practice performance, whereby all advantages and disadvantages are considered simultaneously. Large open pit mines may require a combination of different systems, e.g., SM-IPCC and BT systems, to achieve the decarbonization haulage system.

ABBREVIATIONS

TS	Truck-Shovel
IPCC	In-pit Crushing and Conveying TATrolley Assist
BT	Battery Trolley
ERSs	Energy Recovery Systems
CAPEX	Capital Expenditures
OPEX	Operating Expenses
STEPS	Stated Policies Scenario
APC	Announced Pledges Case
SDS	Sustainable Development Scenario
NZE	Net Zero Emissions
IEA	International Energy Agency
GHG	Greenhouse Gas
PV	Photovoltaic
NEM	National Electricity Market
TGP	Terminal Gate Price
DPM	Diesel Particulate Matter
AHTs	Autonomous Haulage Trucks
FIPCC	Fixed In-pit Crushing and Conveying
SFIPCC	Semi-Fixed In-pit Crushing and Conveying
SMIPCC	Semi-Mobile In-pit Crushing and Conveying
FMIPCC	Fully Mobile In-pit Crushing and Conveying
UPL	Ultimate Pit Limit
AC	Alternative Current
DC	Direct Current
BEVs	Battery-electric vehicles

REFERENCES

For further references and reading please use the link:
https://www.mdpi.com/2673-6489/3/1/1

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Conveyor Belt Wear & Tear – types, causes and solutions

The wear resistant qualities of the outer covers of a conveyor belt are the biggest single influence on the working life of the belt and consequently its 'whole life' cost. Here, conveyor specialist Leslie David looks at the question of durability and resilience and how it determines the working life and ultimately the true cost of your conveyor belts.

WHAT IS WEAR AND TEAR?

'Wear and tear' is an umbrella term used to encompass a number of different kinds of action that progressively damages and wears out industrial conveyor belts, eventually necessitating their replacement. These are abrasion, cutting & gouging and rubber degradation. A fourth kind of damage is ripping & tearing. Although more usually associated with more catastrophic damage affecting both the inner carcass as well as the outer covers, ripping and tearing of the rubber covers can dramatically shorten the operational lifetime of the belt. Different causes of wear and tear require rubber compounds that have very specific properties. The overriding solution to literally every kind of wear and tear lies in the quality of the rubber.

ABRASIVE WEAR

As a general rule, 80% of conveyor belt surface wear occurs on the top cover of the belt and approximately 20% of the wear on the bottom cover. Wear on the top cover is primarily caused by the abrasive action of the materials being carried, especially at the loading point or 'station' where the belt is exposed to impact by material landing on it. In almost all cases, the shorter the belt then the faster the wear rate because they pass the loading and discharge points at more frequent intervals. The selection of the correct type of cover quality (grade) for shorter length belts therefore becomes even more important than usual.

Unclean environments and damaged rollers can accelerate wear.

ISO 4649 / DIN 53516 abrasion testing.

Wear on the bottom cover of the belt is mainly caused by the friction contact with the drum surface and idlers. The rate and uniformity of this type of wear can be adversely affected by many other factors such as misaligned or worn drums and idlers set at incorrect angles. Unclean environments where there is a build up of waste material and damaged idlers and rollers also accelerate wear. Belt cleaning systems, especially steel edged scrapers, can be another cause of wear to the top cover if not kept correctly adjusted.

TESTING

The test method for resistance to abrasive wear (ISO 4649 / DIN 53516) is measured by moving a test piece of rubber across the surface of an abrasive sheet mounted on a revolving drum and is expressed as volume loss in cubic millimeters (mm^3).

The most important thing to remember when comparing abrasion test results is that higher figures represent a greater loss of surface rubber and therefore a lower a lower resistance to abrasion. Conversely, the lower the figure the better the resistance to abrasive wear. A belt with good abrasion resistance can often run for longer than the combined working life of two or even three or more lower grade ‘economy’ belts.

QUALITY STANDARDS

There are two internationally recognised sets of standards for abrasion, EN ISO 14890 (H, D, and L) and DIN 22102 (Y, W, and X). The longer-established DIN standards are usually the preferred reference in Europe. Generally speaking, DIN Y relates to ‘normal’ service conditions and is the most commonly used, with a maximum volume

More than 50% of conveyor belts are significantly below the minimum standards claimed by the manufactuer.

CONVEYOR BELTING

Surface cuts can propogate and link up with other areas of damage, causing pieces of rubber to detach completely if low grade rubber is used.

loss of 150 mm^3. Strangely, there is no direct equivalent ISO standard. The nearest is ISO 14890 L, but in several respects, it is a much lower cover class than DIN Y. In other words, if you want a belt that meets DIN Y standards then do not accept ISO 14890 L.

DIN X (ISO 14890 H), with a maximum volume loss standard of 120 mm^3, is a little more versatile because in addition to resisting abrasive wear it also incorporates good resistance to cutting, impact (from high drop heights) and the gouging that is often caused by heavy, sharp materials. However, as far as abrasive wear is concerned, the highest grade is DIN W (ISO 14890 D), with a maximum volume loss standard of 90 mm^3.

REALITY VERSUS PROMISES

It is important to bear in mind that DIN and ISO standards are only the minimum benchmark of acceptability. Even then, although signified as being a certain grade on the manufacturer’s technical datasheet, laboratory tests consistently reveal that more than 50% of conveyor belts are found to be significantly below those minimum standards.

And even if a belt does marginally meet the required standard, manufacturers using higher quality rubber compounds can produce a significantly better resistance to abrasive action. So much so, in fact, that one manufacturer’s DIN Y grade belt can outperform another manufacturer’s allegedly superior DIN X grade belt by a considerable margin.

With one unique exception, belt manufacturers only show the claimed test standards applicable rather than the actual performance achieved during the test on their technical datasheets. The welcome exception is Netherlands-based Fenner Dunlop, who show the average test results extracted from their routine quality control testing against each applicable property. They have done this for many years, with the regularly updated averages shown alongside the minimum required standard data. At least in this way their customers can better compare and have more of an indication of the level of performance they can expect rather than just promises of what should be.

CUTTING AND GOUGING

Belts that transport heavy and/or sharp rocks, that cause cutting and gouging of the belt surface need different resistance properties compared to belts carrying ‘fine’ materials such as aggregate, sand and gravel. If the material being conveyed is particularly sharp, such as dolerite or granite rock for example, then a DIN X (ISO 14890 H) belt with a rubber compound that is more resilient to cutting is probably the best option. Another cause of surface cutting and gouging are stones and rocks that become trapped between rotating components such as drums and the belt. Good quality DIN Y (ISO 14890 L) abrasion resistant rubber should be able to cope up to a point but marginal or low quality rubber is quickly compromised, requiring all too frequent patch repairs and resultant loss of output due to stoppages. In all cases, good quality belt should not suffer from surface cuts that propogate and link up with other areas of damage, causing pieces of rubber to detach completely.

Cracking up. Without ozone and UV resistant covers, wear and tear is accelerated.

It's all about the quality of the rubber.

Each manufacturer uses its own mix of polymers to create cover compounds with specific wear resistance qualities. The main polymers are SBR (Styrene-Butadiene-Rubber), which is a synthetic rubber and NR (Natural Rubber). In basic terms, SBR has good general resistance to abrasion while natural rubber has better resistance to cutting and gouging. Consequently, natural rubber should be a major part of the mix used to create DIN X grade rubber. Unfortunately, it is appreciably more expensive. As a result, many manufacturers try to avoid or at least minimise the amount of natural rubber used in order to achieve low prices, despite the reduced protection of the inner carcass, higher level of repairs and, ultimately, a shorter operational lifetime.

Surface ripping and tearing effectively falls into the same category of cutting and gouging but is simply more destructive. The size, weight and sharpness of the material being conveyed is the key factor, especially when heavy and sharp objects fall from height onto the belt surface. The damage this can cause goes beyond normal wear and tear because the cover can be punctured and expose the inner carcass. Depending on the severity, DIN X (ISO 14890 H) grade belt is certainly a good option but a belt specifically engineered and proven to handle severe conditions (impact, rip & tear) that has DIN W (ISO 14890 D) covers is most likely the best choice.

HOW OZONE & ULTRAVIOLET LIGHT CONTRIBUTE TO RAPID WEAR

There is absolutely no question that ALL rubber conveyor belts should be fully resistant to the damaging effects of ozone (O3) and ultraviolet light (UV). This is because ozone becomes a pollutant at ground level. Exposure, which is unavoidable, increases the acidity of carbon black surfaces and causes reactions to take place within the molecular structure of the rubber. Known as ozonolysis has several consequences such as surface cracking and a marked decrease in the tensile strength of the rubber.

Likewise, ultraviolet light from sunlight and artificial (fluorescent) lighting also accelerates deterioration. This is because it produces photochemical reactions that promote the oxidation of the surface of the rubber resulting in a loss in mechanical strength. In both cases, this kind of degradation causes an acceleration of the wear and tear process.

Rubber belts that are not fully resistant to ozone and UV can start to show signs of degradation even before they have been fitted simply by being exposed to open air and daylight. Sadly, despite its crucial importance in terms of operational lifetime, laboratory testing has revealed that some 90% of belt sold in Europe, the MiddleEast and Africa are not ozone and UV resistant. This is because the antiozonants needed to create that resistance are seen as an avoidable cost. My advice is to always make a guarantee of ozone & UV resistance compulsory when selecting any rubber conveyor belt.

IT'S ALL ABOUT THE QUALITY OF THE RUBBER

Ultimately, resilience to wear and tear is all about the quality of the rubber. Ironically, it is the size of the difference in selling price that is invariably the best indicator of that quality because rubber constitutes at least 50% of the cost of making a conveyor belt.

Consequently, it is the single biggest opportunity for manufacturers to cut corners in order to compete for orders on price. When it comes to the true cost of a conveyor belt, time will always tell.

ABOUT THE AUTHOR

After spending 23 years in logistics management, Leslie David has specialised in conveyor belting for over 17 years. During that time, he has become one of the most published authors on conveyor belt technology in the world.

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