

# Rail Haulage Systems – Innovative use of the tried and tested

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## ABSTRACT

Rail haulage systems in mining have come a long way in the last centuries and especially in the last decades with AC electric drive systems and automation increasing safety, efficiency, reliability and thus productivity in large scale mines while cutting emissions. Nordic Minesteel Technologies (NMT) and Schalke Locomotives GmbH (Schalke) have been involved in the largest mining rail haulage projects in the last 30 years like CODELCO's El Teniente mine in Chile, LKAB's Kiruna 1365 level in Sweden and Freeport's Grasberg mine in Indonesia. All these mines benefit from innovations implemented in a tried and tested haulage system to achieve maximal productivity with minimal operational expenditures compared to other haulage solutions like trucks or conveyors.

## 1 INTRODUCTION

This paper provides an overview of how innovations brought the rail haulage method in mining into the 21<sup>st</sup> century and made it a serious option – not only for large scale mining – while showing its advantages and limitations compared with competing haulage methods.

### 1.1 *The tried and tested: A short history of rail haulage in mining*

The history of rail-based transportation in mining dates back to the 16<sup>th</sup> century and possibly earlier when carts with wooden wheels called “hunts” were pushed over wooden rails that provided less friction, guidance, and drastically increased the capacity compared to the former used baskets and normal pushcarts (Agricola, 2006). After being pushed by humans or pulled by horses (pit ponies) the invention of the steam engine in the 18<sup>th</sup> century offered a further increase in productivity by pulling the carts with ropes while the engine was stationary.

Improvements in the materials used for the wheels and rails from wood to cast iron to steel, had allowed higher loads and thus heavier carts. This resulted in the innovation from stationary steam engine to the first steam locomotives used in mines in Cornwall in the early 19<sup>th</sup> century.

However, locomotives powered by open fire were unsuitable for being used underground in coal mines due to the risk of exploding methane and coal dust. Therefore, locomotives with a very similar propulsion system using compressed air stored in tanks instead of steam boilers were utilized from the last half of the 19<sup>th</sup> century in explosive conditions. But those had significant issues regarding range due to the compressed air being stored at a relatively low pressure (Unknown, 1876).

Electric locomotives in mining started their success story in 1882 with Siemens building the first mining locomotive called “Dorothea” with an electric drive system being powered by an overhead catenary system (OCS) with direct current (DC) supply. Around ten years later first attempts with battery powered electric locomotives were made (Philippi, 1928).

Mining locomotives powered by internal combustion engines were the last to be invented and were first powered with petrol or alcohol before the diesel engine became predominant (Anglada, 1914). Common to all locomotives with internal combustion engines was the challenge to transfer the crankshaft's torque to the wheels. Besides pure mechanical transfer using a clutch and a gearbox also hydraulic

transfer with pumps and motors or torque converters as well as a transfer with generator and electric motors was established.

For mines with the risk of explosive conditions only battery locomotives and internal combustions powered locomotives with special exhaust treatment were suitable due to the risk of arcing when using an OCS.

While the development of locomotives is well documented, the evolution of the cart(s) from the “hunts” to currently used versions is lacking evidence. Size and thus capacity and weight has definitely increased over time with more tractive effort and stronger and more wear resistant raw materials being available. Big differences exist to this day in the methods to empty a loaded car. Smaller cars are often simply tipped over or rotated 360° around their longitudinal axis in special unloading stations (rotary dumps). This must be done for each cart individually, interrupting the train movement and increasing cycle times. Continuous unloading and thus train movement was made possible by cars that are emptied while being constantly pulled over an unloading station that with different methods opens the crate and tilts its floor to let the hauled material slide out. Some cars achieve this by opening a side wall and tilting the crate while the chassis stays on the rails (Granby car) whereas other car types like gravity bottom dump cars have their crate suspended by rollers enabling their whole floor including chassis to open on the unloading station while it is still hinged to the crate.

Rail haulage - with and without locomotives – has been the prevalent haulage method in mining until the 1970s when it was mostly superseded due to progress in decline access by alternative haulage methods like haul trucks and conveyors (Merchiers et al., 2015). Nevertheless, rail haulage is a system tried and tested over centuries. It has multiple advantages and lots of opportunities to overcome the majority of its drawbacks by technical innovations. It can establish itself as the haulage system of the future.

## *1.2 Innovations bringing rail haulage to the 21<sup>st</sup> century*

Improvement through technical innovations for rail haulage systems in mining will be examined more in detail in the following chapters. This affects the locomotives and the rail haulage system as a whole.

Most of the electric mining locomotives – battery or OCS supplied – were equipped with DC motors in the last century. While all electric locomotives can make use of green energy when available and have no emissions except heat, DC motors have a low efficiency factor, hence emit more heat. Furthermore, they are expensive to maintain compared to asynchronous (AC) motors which have become predominant in the last decades. AC motors are controlled in speed and torque through inverters offering variable voltage and variable frequency (VVVFD) for the motor’s 3-phase supply. The first inverters were equipped with thyristors which had drawbacks regarding switching frequency and thus noise as well as not optimal efficiency due to resistance. For more than 20 years now, IGBT based inverters have overcome these drawbacks and offer great efficiency while providing sophisticated control over the complete speed range of the motor. This enables modern locomotives to use the drive system also as a wear free service brake down to standstill (Carroll, 1999).

The energy generated during braking can be dissipated as heat in brake resistors or reused by feeding back into the OCS or charging of lithium batteries, depending on the power supply or combinations thereof (hybrid locomotives) installed. In general, an electric drivetrain makes locomotives capable of utilizing different present and upcoming energy sources as long as they provide electricity with the required power. Schalke’s ModuTrac™ (Modu=modular, Trac=Traction) locomotives use a modular approach that standardizes the interface from energy source to locomotive enabling to even change the supply system on an existing locomotive already in operation. This is used to overcome the long-lasting disadvantage of rail haulage systems in terms of scalability.

Formerly rail haulage systems needed to have the whole infrastructure consisting of rails, loading and unloading stations and especially power supply like e.g. overhead catenary systems all in place before production could be started. Now it is possible to start production while parts of the mine are still in development with the infrastructure only partly installed and even the designated power supply system not being available at all. It is e.g. possible to start production with diesel powered locomotives and easily convert them to catenary or battery (or both) as soon as the corresponding infrastructure is available. As an example, the build-up of PT Freeport Indonesia (PTFI) Grasberg Block Cave mine (GBC) made use of this ModuTrac™ feature (see chapter 3.2).



**Figure 1 ModuTrac™ locomotive for PTFI's GBC mine.**

A further disadvantage of rail haulage systems that has been overcome is the intermittent operation caused by non-continuous loading and unloading processes of the cars and general interruptions due to the trains being operated by human drivers. The problematic points are specific waiting times for track clearance with the corresponding safety margins as well as breaks for rest periods or shift changes. A combination of fully automated operation and continuous unloading with the suitable car technology resolves these issues. Additionally, it leads to a fluid operation with maximum efficiency. Furthermore, fully automated and thus manless operation drastically increases safety since no personnel remains inside the risk areas. This not only refers to locomotive drivers but also to other workforces that usually operate on a non-automated haulage level. Generally,

access to an automated haulage level is blocked by gates which stop any movement when opened. Any activity that still has to be controlled manually (e.g. controlling loading chutes) can be performed via remote control.

Although all these improvements and innovations of rail haulage systems have been achieved, there are still some disadvantages attendant. On the one hand physical limitations, when driving up gradients, are unpreventable. On the other hand, despite the gained scalability with different ramp-up stages, a significant upfront capital expenditure (CAPEX) is present (see chapter 2.3).

## 2 COMPARING HAULAGE SOLUTIONS

The following chapter will compare advantages and disadvantages of the three most common hauling technologies in underground bulk mining with a main focus on their capabilities and key performance indicators (KPI) in horizontal haulage solutions.

### 2.1 Haul trucks

Haul trucks play an important role in today's mining industry. Although electrification through either batteries or catenary systems and also automation of modern haul trucks are becoming more and more prevalent, the manually driven diesel haul truck is often still the solution of choice. Truck haulage solutions are, aside from the infrastructure required for electric trucks, easily scalable following only a low upfront CAPEX to start production and generate revenue.

The operational expenditures (OPEX) for a haul truck are very high compared with other haulage methods. This is due to the high maintenance costs and short working life of only 30,000 h. Main reasons for the high maintenance costs are tire wear and required service for the drivetrain and diesel engine if installed. Energy costs are a further contributor to the OPEX which are not only influenced by the chosen energy supply system but also by the unfavorable tare weight to payload ratio. When using diesel haul trucks underground the energy costs for ventilation are

also a factor that should not be neglected and can, depending on the depth of the mine/level, go up to 120 kW of installed ventilation power per 500 kW diesel engine running. For non-automated trucks the labor costs also must be included. Per tonne hauled material this leads to six times the OPEX required for a rail haulage system and double the OPEX of a conveyor system (Merchiers et al., 2015).

However, considering truck haulage having the lowest upfront CAPEX of all horizontal haulage methods compared here, it is still the preferable option for mines that aim at a constant production of less than 8,000 tonnes per day and/or at a very short mine life that renders the installation of a large infrastructure noneconomical. This is indicated by combining the CAPEX with the total OPEX in relation to the tonnage expected to be produced during the mine life leading to the total cost of ownership (TCO) (Merchiers et al., 2015).

Although this chapter compares horizontal haulage performance it should be mentioned that haul trucks are capable of negotiating considerably steeper inclines compared to adhesion rail haulage systems (see also chapter 2.3). So, in mines/levels with a suitable depth, haul trucks can be used for horizontal and vertical transport via a decline making an additional vertical haulage system like e.g. hoisting unnecessary. This has to be considered when calculating the TCO for the whole mine. More details on this can be obtained from reference (Brudek et al., 2016).

When a completely new mine or level is planned, the excavation costs for the drifts should also be included in the total CAPEX as well. The required drift size for usual haul trucks is higher compared to a rail haulage system due to a rail running gear being significantly smaller than the running gear with rubber tires commonly used on haul trucks.

## 2.2 Conveyor

Haulage via conveyor is the option in this comparison with a truly continuous flow of material which enables it to move high volumes. Although rail haulage with continuous loading

and unloading is uninterrupted, this can't be performed with the normal travel speed and the train must slow down significantly. More important, the travel time between loading and unloading has to be compensated by bunkers acting as buffers at both ends to achieve an actual constant flow of material for the following process. For a conveyor running at a constant speed this is not required. However, the demands of conveyor systems regarding rock size of the transported ore are more demanding. While haul trucks and rail haulage systems can handle rock sizes way over one meter directly from a grizzled ore pass, a conveyor requires the ore crushed down to a maximum size of approx. 100 mm. Hence a crusher is required at every loading point. For truck and rail this is usually only required at each unloading point. In a mine with multiple loading points this can drive up CAPEX and OPEX substantially (Ribeiro et al., 2016).

Due to being powered with electric motors, ecological aspects in terms of emissions are similar for conveyors compared with electric rail haulage systems and non-diesel haul trucks. All of them can be considered as zero-emission haulage methods since they only emit heat.

A major drawback of conveyor systems is their inflexibility because of the high effort required to relocate it or adapt its length. It is also almost impossible for a conveyor system to negotiate curves. For changing the direction of material movement, a transfer point from one belt to another is required. The belts are also the reason for most maintenance costs of conveyor systems. Despite achievements made regarding material characteristics and robustness, rubber belts are still prone to wear due to the abrasive nature of the hauled material in hard rock mining. In total this leads to OPEX per hauled tonne that are three times as high as required for a rail haulage system but only half the OPEX required for a haul truck system. Combined with the relatively high upfront CAPEX a conveyor system is suitable for mines that require a truly continuous haulage method due to their extraction methods and/or inability to buffer material for intermittent haulage methods (Merchiers et al., 2015; Ribeiro et al., 2016).

For conveyor systems that have no parallel backup, which would double the CAPEX and therefore are mostly not existing, breakdowns/malfunctions or even scheduled maintenances stop the complete haulage process often. This is a risk that must be considered during planning phase. Further risks for personnel are as low as they are for automated rail haulage systems because conveyors can also be considered as a manless haulage method. However, fire risks are higher due to the significant quantity of rubber being combined with a large quantity of rollers that can overheat due to bearing damage (Merchiers et al., 2015).

Like haul trucks, conveyors can also handle gradients and thus be used for horizontal and vertical haulage if economically feasible considering the depth of the mine/level and its total TCO. The manageable gradient of conveyor systems (20%) is steeper than the gradient of truck haulage systems (15%) (Merchiers et al., 2015). In regard to required drift size conveyor haulage has the lowest profile of all haulage systems compared and hence the lowest CAPEX in terms of excavation.

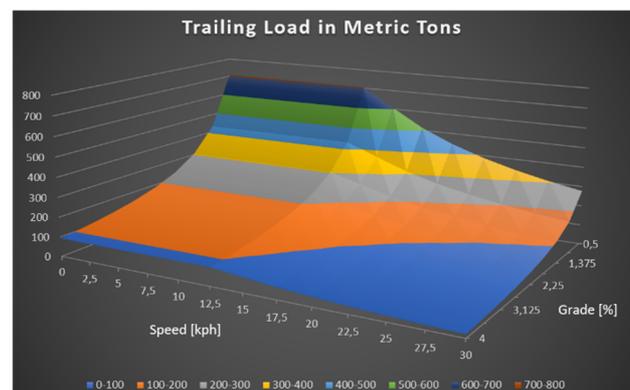
### 2.3 Rail

Out of all three compared haulage solutions, rail haulage is the method with by far the lowest OPEX with only a third of the OPEX required for conveyor systems and even only one sixth in comparison to haul trucks (Merchiers et al., 2015). The low maintenance costs for an overall very robust system are a main contributor to this. That is especially valid when a low maintenance AC traction system is used instead of outdated DC motors with high wear on carbon brushes and collector rings (see chapter 3.1.1). A further factor cutting OPEX is the efficiency of an AC traction system in combination with the low rolling resistance of steel wheels on steel rails with no rubber involved that has to be churned like in truck wheels or conveyor belts. This leads to an overall low energy consumption per hauled tonne and a high possible tare weight to payload ratio that can reach factors of more than 2.5. An example is shown in the equation.

$$\frac{1164 \text{ tonnes (payload)}}{444 \text{ tonnes (train + loco)}} = 2.62 \quad (1)$$

A further benefit of pairing steel wheels with steel rails is the comparable low wear, but it does not come without a drawback. The friction factor for the material combination steel/steel is way worse than for rubber/tarmac (truck) or rubber/steel (conveyor). This limits that traction force to be generated by a locomotive and can only be compensated by increasing the locomotive's weight. While mainline railways usually calculate with a friction factor of 0.33, assuming ideal conditions like clean and dry rails, the actual factor can go down to 0.14 due to moisture and dirt involved which is very likely in underground mining operations. That worst case must be considered when designing a rail haulage system, especially for braking performance.

In comparison to haul trucks and conveyors, this drastically limits a rail haulage system's ability to negotiate gradients. Figure 2 shows the possible trailing load (tare weight of cars + payload) for a fictional 40 tonne locomotive with 200kW of power at the wheels at a friction factor of 0.14 depending on the uphill gradient and target speed to be achieved.



**Figure 2** Achievable trailing load dependent on uphill gradient and target speed for an exemplary 40 tonne locomotive with 200kW of power at the wheels.

From an energy perspective it is an optimal solution if the geology allows for a slight downhill gradient from loading to unloading point. In this best case the locomotive can

generate power while braking to keep the loaded train at a constant speed going downhill and only requires minimal energy to move the empty train up the gradient.

Of all compared horizontal haulage solutions rail haulage is the method with the highest availability reaching up to 97% (Lara Moran et al., 2020). Especially in comparison to conveyors this is achieved by scheduled maintenance not interrupting the production since it is usually performed on spare locomotives and cars currently not in operation. These spare vehicles also greatly reduce breakdown hazards because they are simply swapped in case of a malfunction. If scheduled maintenance or malfunctions affect the infrastructure this is different but can be mitigated by installing redundancies in the rail network. This has to be considered during the planning phase and can increase upfront CAPEX if these redundancies are not utilized anyway for later expansion stages of the mine/level in terms of scalability.

In general, scalability is an option to take advantage of the lowest OPEX of all compared horizontal haulage solutions and spread the relatively high CAPEX over different build up stages of the mine/level to generate early revenue and optimize cash flow. Combining the high CAPEX for a fully developed mine/level with the low OPEX leads to a TCO in regard to hauled tonnes that makes rail haulage systems a viable option for almost every mine above a certain size and essentially leaves no economical alternative if aiming for a daily production rate above 50,000 tonnes (Brudek et al., 2016).

The required upfront CAPEX for excavation is moderate since the required drift size is smaller than for haul trucks but larger in comparison to conveyor systems. It has to be considered that trains can't negotiate curves as good as haul trucks can. There is a minimum curve radius of 60m required for a train running on rails with the normal gauge of 1435mm to avoid excessive wear and increased resistance and thus lower train weights and production. Smaller gauges can slightly decrease the necessary minimum radius.

### 3 RAIL HAULAGE INNOVATIONS IN DETAIL

The innovations introduced in chapters 1.2 and 2.3 will be explained more in depth in the following.

#### 3.1 Modern electric drive system

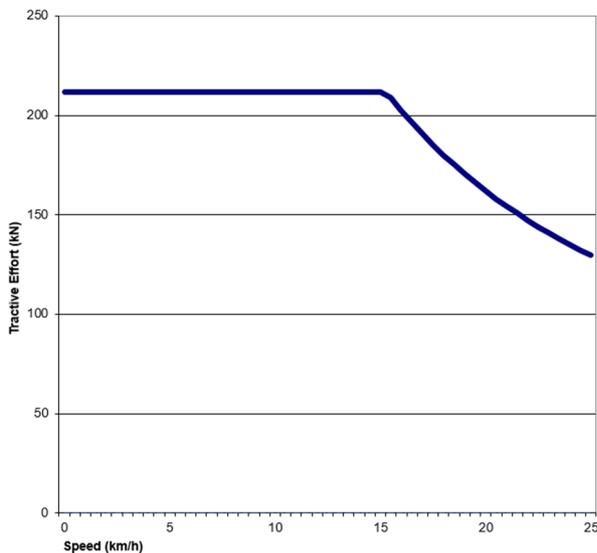
Electric drive systems with AC motors and state-of-the-art IGBT inverters provide an optimal control while being extremely efficient and requiring a minimum of maintenance. Modern energy supply and storage solutions enable an even more efficient drive system.

##### 3.1.1 From DC to AC motors

For a long time, drive systems with DC motors have been the primary choice for electric mining locomotives. This was the case due to their high starting torque, easy control and affordable price. Although generally robust, DC motors required regular maintenance due to wear on the carbon brushes and the corresponding collector ring. Control in power and torque was in the easiest way performed by resistors switched in series with the motor. This resulted in high losses of energy in the form of heat and thus an adverse efficiency, especially in lower speed ranges. The development of inverters with variable voltage and variable frequency, particularly with highly efficient IGBTs, made AC induction motors (squirrel cage motors) supersede the DC motor in every aspect except of initial costs. But this difference in initial cost is easily counter balanced by the AC motor's high efficiency and low maintenance cost due to not having any moving parts that have to transfer current (Banerjee, 1998).

A modern traction inverter offers sophisticated control over the AC induction motor's torque for every rotational speed. Therefore, the full nominal torque is available from standstill with a very high efficiency compared to DC motors. The torque control combined with a quick response time and adequate sensor technology offers slip- and slide-control enabling the locomotive to generate the maximal traction force from the friction factor available. These advantages are not only valid for propelling or

accelerating the locomotive but also for regenerative braking. This means that the motors work as generators, producing energy and generating negative torque to slow down the locomotive/train or maintain a constant speed on downhill gradients. Modern locomotives use this generative brake as the standard wear free service brake down to standstill and even to hold position when the locomotive/train is standing in a gradient. Having close to no wear on the mechanical brakes, which are still in place as a backup for safety reasons, cuts down the OPEX for modern locomotives even further. Figure 3 shows a typical traction diagram for a locomotive with AC induction motors indicating the achievable tractive effort dependent on speed.



**Figure 3 Typical traction diagram for a locomotive with AC induction motors.**

### 3.1.2 Lithium batteries and alternative power sources

A standardized interface between locomotive and installed energy supply module(s) enables ModuTrac™ locomotives to basically use every possible source of electric energy as long as it can deliver the required power. This can be a diesel-generator module, a lead-acid-battery module, a module with lithium-ion-batteries, a module with a pantograph for catenary systems or a module with any electric energy source that is yet to come like e.g. hydrogen fuel cells. Combinations of different modules on one

locomotive are also possible to create all sorts of hybrid vehicles. The standardized interface enables the modules to be changed within less than one hour, even on existing locomotives that are already in operation for years, and thus ensures ModuTrac™ locomotives to be future-proof. So it is easy for the locomotive to adapt to upcoming green and emission-free forms of energy with minimal downtime and thus production loss. Only swapping the form of energy supply and not the whole locomotive ensures a sustainable and modern vehicle over its total lifetime of 30-40 years while keeping future CAPEX low.

Although the majority of existing hybrid or multi-system mining locomotives are still equipped with lead-acid-batteries, lithium-ion-batteries have come a long way in the last years making them a viable option for future mining locomotive applications. Especially for acting as the only or major energy supply system on a locomotive, lithium-ion-batteries have huge advantages over lead-acid-batteries. These are the higher energy densities in terms of energy stored per volume and specific weight per energy quantity as well as a generally longer life due to bearing a lot more charging cycles. Yet the most important advantage is the capability of lithium-ion-batteries to not only provide high currents and thus high power but also handle high charging currents. This cuts charging times to a fraction of what is required for lead-acid-batteries. The exact parameters for cycle times as well as charging and discharging characteristics differ depending on the used cell chemistry, but this topic alone would fill another paper (Nitta et al., 2015).

A highly sustainable future use case would be to have a pure lithium-ion-battery locomotive on a rail haulage system with geological conditions or track parameters as described in chapter 2.3. The energy generated while driving a loaded train downhill towards the unloading point could be completely stored in the battery and used to drive the empty train back uphill to the loading point. With the right conditions in terms of tare weight to payload ratio and gradient, this could lead to a haulage solution requiring no or only minimal external energy.

From an initial CAPEX point of view, lithium-ion-batteries are still more expensive than lead-acid-batteries for the same capacity. But their reduced OPEX due to longer lifetime through more charging cycles and general capability of handling high charging- and discharging currents outweighs that easily. Since safety and fire risk is a common concern regarding lithium-ion-batteries, this is handled by different manufacturers through intrinsically safe cell chemistry and/or encapsulating the cells in fire- and pressure-proof enclosures. Furthermore, modern battery management systems incl. temperature control are preventing overheating, thus fire cases.

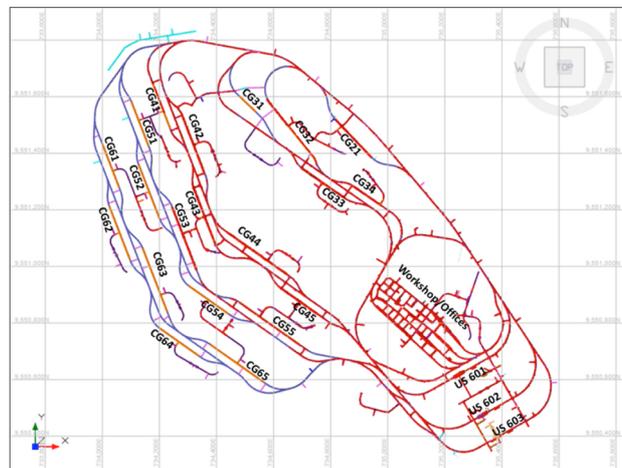
### 3.2 Scalability

As introduced in chapters 1.2 and 2.3, rail haulage systems have a comparable disadvantage regarding their required upfront CAPEX to acquire not only the locomotives and cars but especially the infrastructure consisting of the rail network, power supply systems like e.g. OCS as well as control, automation and communication systems. Loading, unloading and crushing will be neglected here since they are necessary for all haulage methods, although in different amounts and characteristics.

For mine operators or investors with a strict focus on cash flow and thus aiming to generate revenue quickly, the high upfront CAPEX might be deterrent. This can be attenuated by the scaling abilities that modern rail haulage solutions offer. Infrastructure and vehicles can be purchased and installed in a small quantity to get the production started. Later on, the infrastructure can be gradually extended and additional train sets can be added with almost no interference regarding the already operational production. With ModuTrac™ locomotives it is even possible to extend this scalability to the energy supply system. It is e.g. possible to start production with diesel or battery powered locomotives and convert them to catenary supply (or a hybrid) as soon as an OCS is available in later stages of mine/level expansion.

PTFI's GBC mine made great use of this opportunity by building their project in a total of five stages. Each stage consisted of a certain

amount of additional loading points arranged in chute galleries (CG), the corresponding track with infrastructure like OCS and control/automation systems and in some stages additional unloading stations (US) and rectifier stations for the OCS. This enabled PTFI to not only spread the CAPEX but gave them the flexibility to react to updated rock quality information made during excavation/caving by alternating the track design and the scope between the stages. The amount of ModuTrac™ locomotives has been gradually extended to 15 as of now. Figure 4 shows PTFI's GBC mine's approved level life-of-mine (LOM) design as well as the as-builts of June 2020 (in red) (Lara Moran et al., 2020)



**Figure 4 GBC haulage level, LOM and as-builts, 2020** (Lara Moran et al., 2020)

### 3.3 Continuous operation through automation

Although rail haulage never was and never will be a haulage system with truly continuous flow of material from extraction point to the subsequent processing, modern state-of-the-art loading and unloading techniques in combination with automation can bring it to an equal state.

#### 3.3.1 Continuous operation

While old train haulage systems had to be stopped regularly to load or unload the cars, modern solutions enable the train to be moving constantly. For loading, this is achieved by a combination of the latest loading chutes with specially designed cars. The chutes offer a fast,

steady and safe control of the rock/ore flowing from the ore pass above the chute down to the car. To increase safety on automated rail haulage systems the chutes are able to be controlled completely remote, also from surface. A special design of the car's crate with an overlapping apron from on car to the next and general perfect match with the chute's geometry ensures constant train movement while loading with minimal spillage.

Unloading of the cars is performed utilizing continuous gravity discharge of materials over the specially designed unloading stations. These unloading stations are designed to carry and unload the complete train. Travel speed and discharge rate is controlled via the propulsion drives and scroll beam, speed during discharging is fixed at a preset km/h rate whether pulling or braking of the train, this allows for smooth and complete emptying of the cars and at the same time reduces dynamic forces applied to locomotive, cars and station structure for minimum wear and maintenance requirements. These specially designed unloading stations and cars allows for bi-directional travel and unloading depending on track layout and locations of ore passes. This is accomplished utilizing an End Hinged system or Side Hinged system.

- End Hinged System only allows the cars to discharge material in one direction but can reverse back through the unload station empty.
- Side Hinged System allows the cars to discharge material in both directions.

Figure 5 shows a typical unloading station for an End Hinged system.



**Figure 5** Typical unloading station.

A constant flow of material can be important for the extraction process upstream of the haulage system as well as for the following process which is often crushing and hoisting. Despite the train being in constant movement due to the improvements described, there is a certain travel time from loading to unloading depending on distance and speed. This inconsistency can be compensated by buffering material in the ore passes above the chutes as well as the ore bins under the unloading stations which are usually placed above a crusher. The required buffer capacity heavily depends on the distances between and amount of loading and unloading points. It has to be examined for each application in detail but is usually the size of 2-3 full train loads. Automation can drastically increase process stability of the actual train movement.

### 3.3.2 Automation

Today's automation systems are capable of bringing rail haulage systems to a whole new level. There is far more to it than simply replacing the driver with a computer that can accelerate and brake a locomotive. A central computer controls all train movements on the network giving trains driving permission and stopping them if required. Safety margins are controlled by the moving or fixed block technology. This means for the moving block technology, that the safe headway that a train has to keep to another train or a switching point is determined dynamically by its required braking distance that depends on the train's current speed and weight as well as the local track parameters such as curves and gradients. The central computer has to obtain and evaluate all of this information. Communication between the train(s) and the central computer is usually performed wireless via WiFi or 5G. In case of a communication failure each locomotive is equipped with a backup system that frequently synchronizes its position on the network via passive tag points and triggers an emergency brake if communication is not restored within a certain time (Brudek et al., 2016).

Implementing modern automation into a rail haulage system not only boosts productivity by erasing possible human error and general

interruptions due to rest periods and shift changes. It also increases safety by keeping personnel out of risk areas which can be extended to the complete mine/level when processes that still require manual intervention are remote controlled. A true 24/7 operation is possible and by integrating process information like fill levels of ore passes and ore bins, production can be optimized even further.

#### 4 EXAMPLES FOR INNOVATIVE RAIL HAULAGE IN TODAY'S BULK MINING

Modern and innovative automated rail haulage systems are not a theoretical construct but have proven their abilities in some of the largest mines in the world.

##### 4.1 LKAB's KIJ 1365 level, Sweden

LKAB's current production level in Kiruna is KIJ 1365. It is operated as a fully automated rail haulage system with Schalko Locomotives and NMT cars, unloading stations and loading chutes.

Key figures:

- 25 kilometers of track
- 9 locomotives, each with 108 tonnes, 900 kW of power and supplied with overhead and side catenary as well as batteries (triple-mode power supply)
- 163 17m<sup>3</sup> bottom dumping cars
- Train consists of 1 locomotive with 21 cars
- 39 loading chutes
- 4 unloading stations
- Daily production: up to 110,000 tonnes



**Figure 6 Train in operation on LKAB'S KIJ 1365 level.**

##### 4.2 PTFI's Grasberg Block Cave (GBC) mine, Indonesia

With being located 2760m above sea level, PTFI's Grasberg Block Cave mine is a challenging environment. It is operated as a fully automated rail haulage system with Schalko locomotives and NMT cars, loading stations (chutes) and unloading stations. As a peculiarity, the weight of the locomotives has been increased from 40 to 45 tonnes and the power from 270 to 320 kW. Both upgrades lead to the possibility to attach more cars to a train and thus boost production. This was also performed on locomotives already in operation by means of retrofit kits.

Key figures:

- 23 kilometers of track
- 15 locomotives, each with 45 tonnes, 320 kW of power and supplied with overhead catenary as well as batteries
- 168 20m<sup>3</sup> bottom dumping cars
- Train consists of 1 locomotive with 11 cars
- 117 loading chutes
- 3 unloading stations
- Daily production: up to 160,000 tonnes



**Figure 7 Train on unloading station in PTFI's GBC mine.**

### 4.3 KPIs from various studies

NMT and Schalke are also jointly conducting feasibility and pre-feasibility studies for mining companies interested in rail haulage systems. These detailed studies simulate train movements resulting cycles times, energy consumption and production rates. Combined with further energy, maintenance and labor costs, these studies give a detailed forecast of the OPEX to expect per hauled tonne of material. Furthermore, a detailed CAPEX calculation for all equipment and installation, if required also in different stages, is provided to demonstrate the total TCO of a project. The following two examples show some key performance indicators (KPIs) of already finished studies without project details to keep confidentiality. Currencies are converted to Euros to ensure comparability.

#### 4.3.1 Project 1

KPIs:

- Daily production: approx. 31,000 tonnes
- Distance for one full cycle: approx. 1.6 km
- Cycle time: approx. 10 minutes
- Trains in operation: 1
- Energy consumption per tonne: 0.078 kWh
- Total OPEX (calculated over 10 years): 0.21 €/tonne

#### 4.3.2 Project 2

KPIs:

- Daily production: approx. 192,000 tonnes
- Distance for one full cycle: approx. 44 km
- Cycle time: approx. 67 minutes
- Trains in operation: 9
- Energy consumption per tonne: 1.47 kWh\*
- Total OPEX (calculated over 10 years): 0.18 €/tonne

\* Result of loaded train uphill movement over a long distance.

## 5 CONCLUSIONS

This paper has demonstrated that rail haulage, while being by far the oldest haulage method in mining, is capable of being the haulage system

of the future by consequently implementing technical innovations that increase productivity, efficiency, availability and safety.

Its drawbacks in terms of upfront CAPEX are quickly surpassed by its low OPEX, especially considering a designed equipment lifetime of 30 years and more. On the world's way to a sustainable future, electric rail haulage systems can contribute to a zero-emission ecological footprint by utilizing green energy while saving resources through their low required maintenance.

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