Chapter 7
Energy-Efficient Loading and Hauling Operations

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Abstract Approximately, 40% of the total energy used in surface mines is related to diesel consumption. Truck haulage is responsible for a majority of this. This chapter introduces the principal equipment used to load and haul materials in mines, namely trucks, electric rope shovels, hydraulic excavators and crushing and conveying systems. The chapter discusses factors that contribute to the energy-efficient operation of such equipment. Based on gross weight hauled per unit weight of payload, belt conveyors appear to be the most energy-efficient means of transporting material in surface mines. However, a number of factors, including large upfront capital expenditure and limited ability to relocate and scale up belt capacities, currently restrict their widespread applicability.

Keywords Energy · Efficiency · Mining · Loading · Hauling

7.1 Introduction

In the 2012–2013 financial year, some 603 PJ of energy was consumed in the mining and quarrying industry in Australia. The three biggest consumers of energy in the Australian mining industry are as follows (in decreasing order) [1]:

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- Crushing and grinding (40.5%),
- Materials handling (20.6%), and
- Mine ventilation (10.1%)—underground mines only.

This chapter provides an overview of the current knowledge on energy used for materials handling during the extraction phase of mining operations and identifies opportunities to reduce energy consumption associated with these processes. The mining method (shovel/truck, conveyor, etc.) and associated equipment dictate the quantity of energy consumed in any mining operation. In the following, the discussion is organised based on the type equipment.

7.2 Haul Trucks

Approximately, 40% of the total energy used in surface mines relates to diesel consumption [2]. Truck haulage is responsible for a majority of this diesel consumption [3]. Haul trucks are used in combination with other equipment such as excavators, diggers and loaders, depending on the production capacity and site layout.

Trucks in surface mines are used to haul ore and overburden from the pit to a stockpile, dump site or the next stage of a mining process. Trucks are expensive to purchase, operate and maintain and use a major proportion of diesel in surface mines.

Many parameters, such as production rate, age and maintenance of the vehicle, operator practices, payload, speed, cycle time, mine layout, mine plan, idle time, tyre wear, rolling resistance, dumpsite design, engine operating, parameters and transmission shift patterns, affect the productivity of trucks in surface mining. This knowledge can be merged into mine plan costing and design procedures to improve effective process control. The major truck types used in surface mining are shown in Fig. 7.1.

7.2.1 Types of Trucks

There are three main types of trucks: rear, bottom and articulated dump trucks.

In rear dump trucks, the tray is mounted on the truck frame. Dumping is carried out by a hydraulic hoist system raising the tray. These are very flexible units capable of handling all types of material. They have good grade ability and are easily manoeuvred [5]. They are the most common haulage truck globally (see Fig. 7.2).

The standard rear dump haul truck has two axles with two wheels on the front axle and four wheels on the rear axle. The rear wheels are usually the only ones

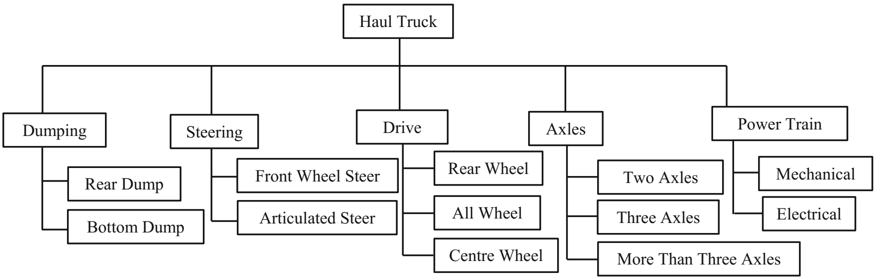

Fig. 7.1 Haul truck classifications [4]

Fig. 7.2 Rear dump truck

driven. Three-axle trucks are less common in mines but are used for on/off highway hauls.

Bottom dump trucks provide faster dump times and higher payload for the same engine horsepower, but at the cost of grade ability and manoeuvrability. This type of truck has three axles, two tyres in front, four drive tyres at the rear of the tractor, and four tyres on the rear of the trailer (see Fig. 7.3) [5].

In general, they are used in strip coal mines where the ramp gradients are kept at five percent or less.

Articulated dump trucks tend to be smaller and of lighter construction. Maximum size is in the order of 50 t (see Fig. 7.4).

The main application of this type of trucks is in wet and poor road conditions. Their lighter construction results in a shorter life [5].

Some advantages and disadvantages of the types of trucks mentioned above have been tabulated in Table 7.1.

Fig. 7.3 Bottom dump truck

Fig. 7.4 Articulated dump truck

7.2.2 Effective Parameters on Truck Productivity

Table 7.2 shows some parameters that influence haul truck productivity in mines.

7.2.3 Haul Truck Fuel Consumption

Haul truck fuel consumption is a function of various parameters, the most significant of which have been identified and categorised into six main groups (see Fig. 7.5).

Table 7.1 Advantages and disadvantages of popular mine haul trucks [4]

Truck type	Advantages	Disadvantages
Rear dump truck	• Mobile and flexible in moving to other working areas • Handle a range of material properties and sizes • Medium transport distance • Can effectively operate gradients up to 12%	• Require good road surface for efficient operation and tyre protection • Higher operating labour component (Compared to conveyors)
Bottom dump truck	• Higher speed on flat hauls • Mobile and flexible in moving around working area	• Better on flatter gradients <5% • Require good roads • Requires a drive over dump hopper to discharge • Suited to lighter and finer materials due to light trailer and dump doors (e.g. Coal, Bauxite)
Articulated dump truck	• Can handle difficult floor conditions—rough, boggy • Handle a range of material properties and sizes • Can handle steeper gradients	• May require higher maintenance • Try can roll sideways safety • Higher capital cost/capacity

Table 7.2 Effective parameters on haul truck productivity [4]

Parameter	Detail
Truck model and type	Each type and model of the truck has special characteristics, and these can affect haul truck productivity
Material	Material which is hauled
Bucket density	The density of the material being loaded
Swell factor	The swell factor is the volume increase after the material has been disturbed
Bucket load	Estimated bucket load that the loading unit can carry in BCM
Calculated passes to fill	Estimate of how many bucket loads (passes) is required to fill the truck to its nominal capacity
Calculated truck payload	Estimated average payload that the truck will carry after considering all the above factors
Load factor	Percentage of truck fill compared to its nominal or rated payload
Time per pass	Time taken for a loading unit to complete one pass
Load time	Time taken to load the truck
Spot time	The time during which the loading unit has the bucket in place to dump, but is waiting for the truck to move into position. Spot time will depend on the truck drivers' ability and the system of loading. Double-side loading should almost eliminate spot time

(continued)

Table 7.2 (continued)

Parameter	Detail
Dump time	Time taken for the truck to manoeuvre and dump its load either at a crusher or dump
Fixed time	The sum of load, spot and dump time. It is called ‘fixed’ because it is essentially invariable for a truck and loading unit combination
Travel time	Time is taken to haul and return the load
Cycle time	Round trip time for the truck, it is the sum of fixed, travel and wait times
Efficiency	A measure of how much productive time is achieved in 1 h of operating time. The sort of activities that the efficiency factor includes is Clean-up by the loading unit or dozer, Crusher and dump slowdowns, Fuelling, Inspections, Loading unit movement, Operator experience, Under trucking, Unusual delays due to weather
Queue factor	Accounts for time lost due to queuing. It is another measure of wait time
Productivity	Tonnes of production hauled in an operating hour (t/h) Productivity = (Efficiency/Cycle time) × Truck payload × Queuing factor
Physical availability	Measure of time available to work divided by calendar time
Utilisation	Operating time divided by available time
Production	Hourly productivity × operating hours

Of these, the most significant factors affecting haul truck fuel consumption are as follows (see also Fig. 7.6):

- The gross vehicle weight (GVW), which is sum of the weight of an empty truck and the payload;
- The haul truck velocity (V);
- The total resistance (TR), which is equal to the sum of rolling resistance (RR) and the grade resistance (GR) when the truck is moving against the grade of haul road; and
- The rimpull force (RF), which is the force available between the tyre and the ground to propel the truck.

Figure 7.7 illustrates the variation of maximum truck velocity (V_{max}) and fuel consumption (FC) with GVW for six values of total resistance (TR). The results show that for all values of total resistance, truck velocity decreases and fuel consumption increases as the GVW increases. It should be noted that the rate of fuel consumption is calculated based on the best performance of the truck as recommended by the manufacturer (calculate at maximum achievable truck velocity and corresponding rimpull).

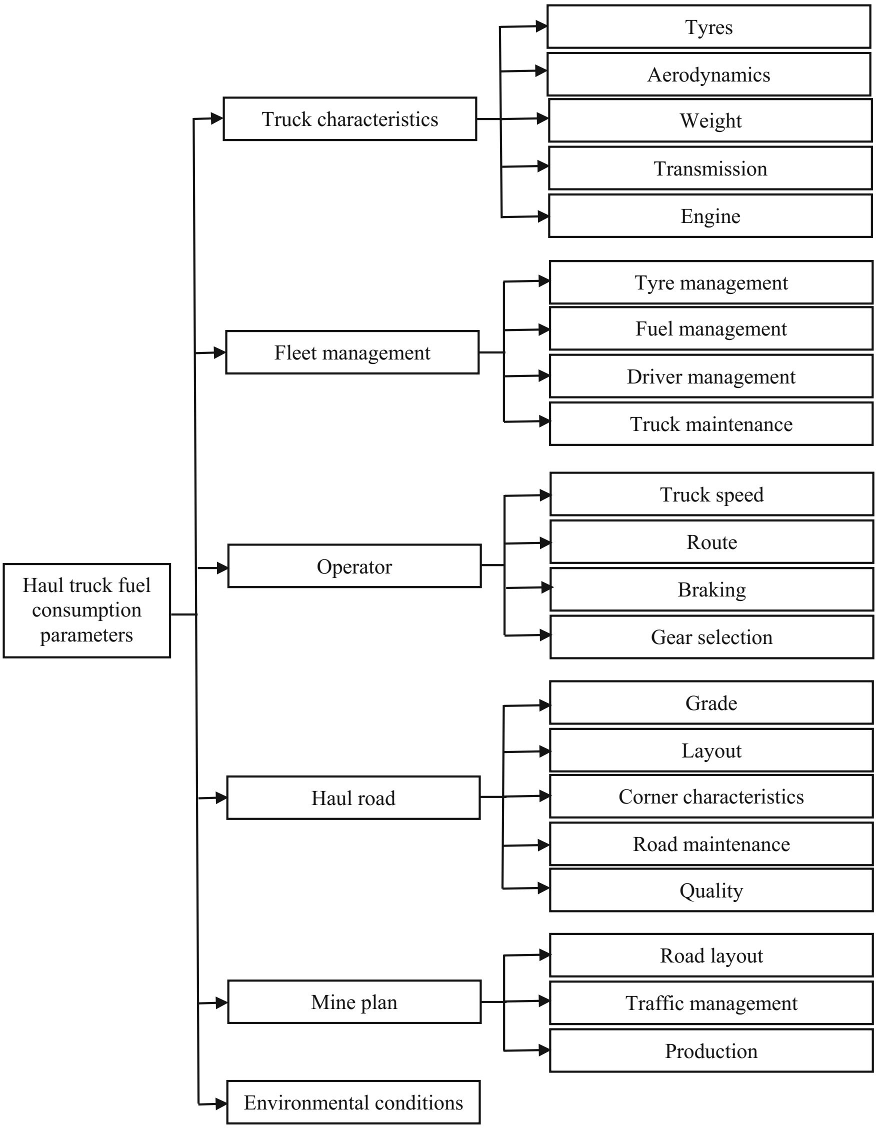

Fig. 7.5 Parameters affecting haul truck fuel consumption [6]

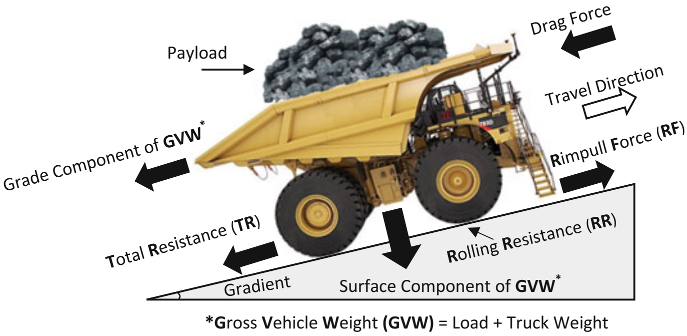

Fig. 7.6 Effective parameters on haul truck productivity and fuel consumption [6]

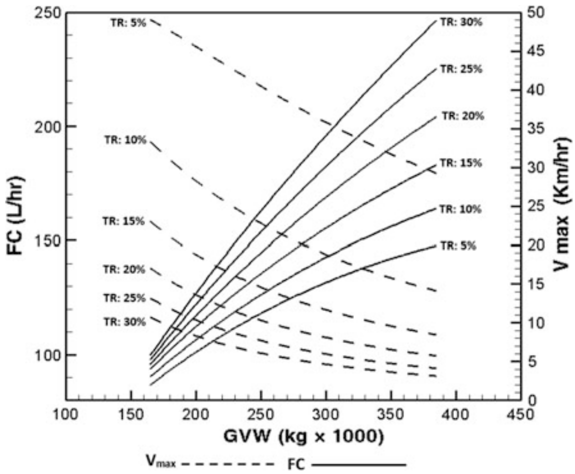

Fig. 7.7 Variation of $V_{\max}$ and FC with GVW for different TR (Caterpillar 793D) [4]

7.2.3.1 The Effect of Payload on Haul Truck Fuel Consumption

The loading process in truck and shovel operations is often modelled as a stochastic process due to the high variability. An analysis of the haul truck payload data obtained from some mine sites around the world shows that the payload distribution can be estimated by a normal distribution [7]. The variance associated with haul truck payloads is typically large and depends on some parameters such as particle size distribution, swell factor, material density, truck–shovel matching, the number of shovel passes and the bucket fill factor. Many attempts have been made to reduce the payload variance by using technologies such as on-board truck payload measurement systems, shovel payload management systems and fleet monitoring systems. Also, to load a truck in an effective manner, the shovel operator should load the truck within optimal payload limits using the minimum number of passes. The optimal payload can be defined in different ways, but it is always designed so that

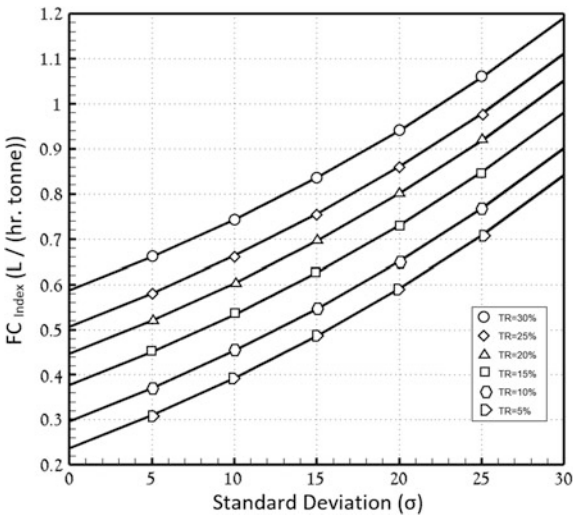

Fig. 7.8 The variation of FC_{Index} with standard deviation (σ) (CAT 793D) [9]

the haul truck will carry the greatest amount of material with lowest payload variance. The range of payload variance can be defined based on the capacity and power of truck. The payload variance in a surface mine fleet can significantly influence productivity due to truck congestion, or "bunching" phenomena,[1] in large surface mines [8].

The increasing of payload variance decreases the accuracy of a scheduled maintenance programme. This is because the rate of equipment wear is not predictable when the mine fleet faces a large payload variance. Minimising the variation of particle size distribution, swell factor, material density and fill factor can decrease the payload variance but it should be noted that it is not always possible to control all these parameters.

The effect of payload variance on haul truck fuel consumption in different haul road conditions is illustrated in Fig. 7.8.

In this chapter, we use the fuel consumption index (FC_{Index}) as a measure of haul truck fuel efficiency. This index represents the quantity of fuel burnt by a haul truck to move one tonne of mined material (ore or overburden) in an hour (L/(h tonnes)).

7.2.3.2 The Effect of Rolling Resistance on Haul Truck Fuel Consumption

The rolling resistance (RR) is a major component of total resistance (TR), and it is one of the main controllable effective parameters for haul truck fuel consumption.

[1]This is where trucks loaded at rated payloads are forced to travel slowly up ramp because they are stuck behind heavily loaded trucks which travel at low speeds.

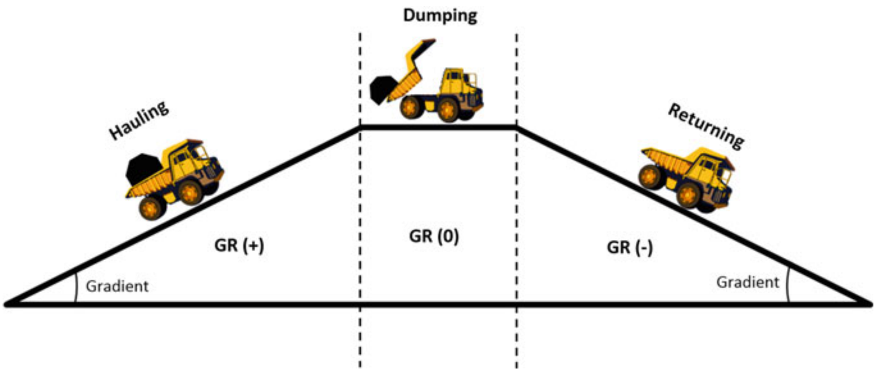

Fig. 7.9 Grade resistance [4]

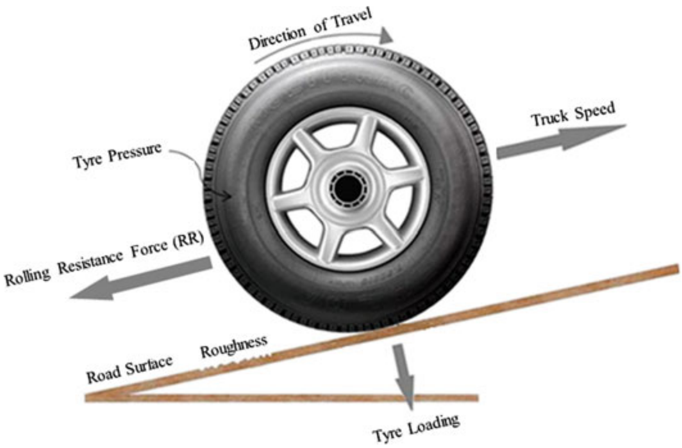

Fig. 7.10 Rolling resistance and the most influential parameters [10]

TR is equal to the sum of RR and grade resistance (GR) when the truck is moving against the grade of the haul road.

RR depends on the tyre and hauling road surface characteristics and is used to calculate the rolling friction force, which is the force that resists motion when the truck tyre rolls on the haul road. GR is the slope of the haul road, measured as a percentage and is calculated as the ratio between the rise of the road and the horizontal length (see Fig. 7.9).

GR is positive when the truck is travelling up the ramp, and it is negative when it travels down the ramp.

RR is defined as a measure of the force required to overcome the retarding effect between the tyre and road. This resistance is predominantly measured as a

Table 7.3 Influential parameters on rolling resistance

Rolling resistance	Group	Category[a]				Parameter
		D	C	O	M	
	Road	✓			✓	Roughness
		✓	✓		✓	Defects
		✓	✓		✓	Material density
				✓		Moisture content
					✓	Road maintenance
	Tyre	✓		✓	✓	Tyre penetration
		✓				Tyre diameter
				✓		Tyre pressure
			✓	✓	✓	Tyre condition
				✓		Tyre loading
				✓		Tyre temperature
	System			✓		Truck speed
				✓		Driver behaviour
	Weather			✓		Humidity
				✓		Precipitation
				✓		Ambient temperature

[a]D: Design C: Construction O: Operational M: Maintenance

percentage of the GVW, but can also be expressed as energy divided by a distance or force.

Tyre RR can also be characterised by a rolling resistance coefficient (RRC), a unit-less number. RR manifests itself predominantly in the form of hysteresis losses described as the energy lost, usually in the form of heat, when a section of vulcanised rubber is regularly deformed, such as during the operation of a haul truck.

The parameters affecting RR can be categorised into four groups: road, tyre, system and weather properties. Figure 7.10 illustrates the most influential parameters on RR.

The effective parameters on RR are also categorised into the design (D), construction (C), operational (O) or maintenance (M) parameters. Table 7.3 illustrates the parameters affecting RR, and their categories.

The surface material of the haul road is a major contributor to RR. Table 7.4 shows the RR associated with different surface types.

Estimating fuel consumption rate requires some assumptions. Figure 7.11 illustrates the relationship between the haulage operation parameters and truck fuel consumption.

The relationships between three main effective parameters on RR and FC_{Index} have been illustrated in Fig. 7.12.

Table 7.4 Surface type and associated rolling resistance [11]

Type of surface	Rolling resistance (%)
In situ clay till	4–6.7
Compacted gravel	2–2.7
Compacted clay gravel	3.9
Subsoil stockpile	4.4–8.3
Compacted clay till	4.1
Subsoil on mine spoil	7.3

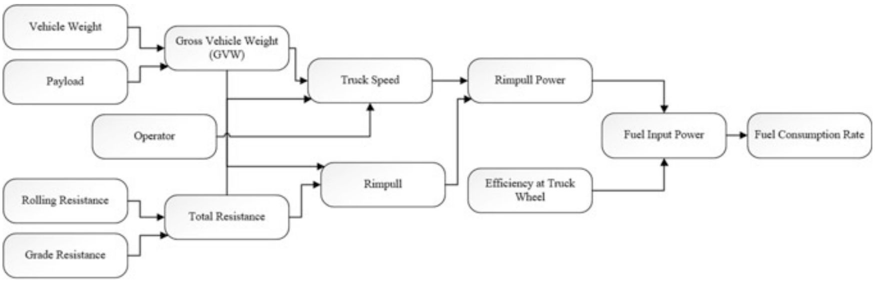

Fig. 7.11 Variable relationships required for truck fuel consumption estimation [4]

7.3 Loading Units

Loading equipments are applied to dig and load material in surface and underground mines. They are often regarded as critical equipment because there is typically no extra loader capacity contrary to trucks that tend to have excess capacity. Therefore, their availability and productivity can constrain production. Efficient loading process can lead to improved production, energy efficiency and decreased costs.

7.3.1 Operations of Major Loading Units

The major loading units are rope shovels, hydraulic excavators and front-end loaders (Fig. 7.13). Other loading equipment includes draglines, surface miners, dozers, scrapers and bucket wheel excavators.

Hydraulic excavators can be configured as either front (or shovel) or backhoe configurations. Face shovels allow for either front or bottom dumping. A backhoe's bucket is typically smaller in volume compared to that of a face shovel on a similar sized machine. Backhoe shovels are capable of loading trucks located either on the same bench level or at a lower bench (elevation) to the shovel.

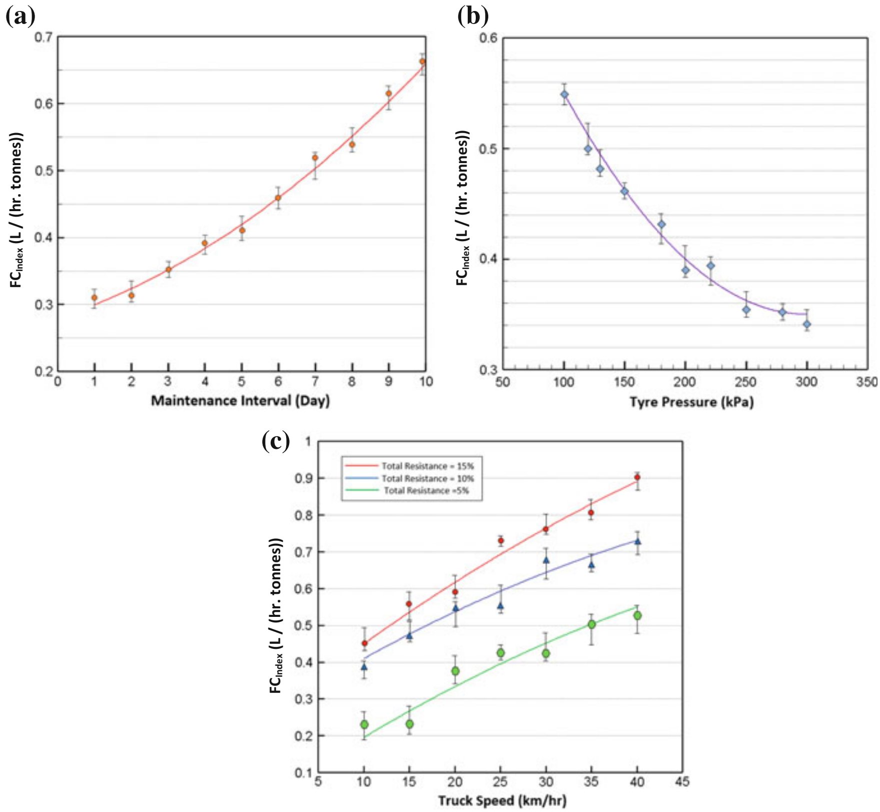

Fig. 7.12 **a** The relationship between maintenance interval and FC_{Index} (Caterpillar 793D) [4]. **b** The relationship between tyre pressure and FC_{Index} (Caterpillar 793D) [4]. **c** The relationship between truck speed and FC_{Index} (Caterpillar 793D) [4]

The hydraulic excavator uses diesel engines or electric motors to drive hydraulic pumps, motors and cylinders that in turn actuate the motions required to dig and load material and propel the machine (see Fig. 7.14).

The electric shovel uses electric motors, gear reducers, drums and wire rope to actuate the motions required for digging, loading and propelling (see Fig. 7.15).

The three primary parts of the hydraulic and electric shovel are the lower, upper and the attachment. A large electric mining shovel is capable of maximum propel speeds of nearly 1.6 km per h (1.0 mph) and a practical grade climbing capability of 20%. The average work cycle of electric mining shovel can take approximately 25–45 s depending on the machine, load, swing angle, bank conditions and operator proficiency [12].

Although hydraulic face shovels provide a high degree of flexibility and can generally produce high digging forces low in the bank, electric mining shovels are inherently more capable of consistently generating higher production rates through

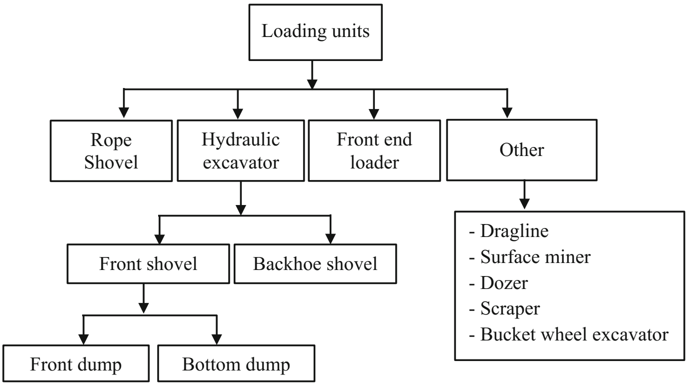

Fig. 7.13 Loading units' classifications

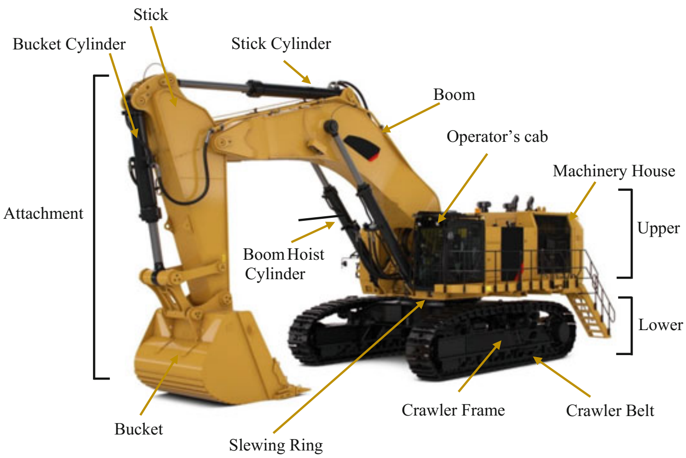

Fig. 7.14 Typical hydraulic mining shovel assemblies

a combination of consistent dig forces throughout the digging phase, high fill factors, low cycle time and reduced operator fatigue [12].

The four primary motions executed by the shovel are propelling, swinging, hoisting and crowding/retracting. In the cable shovel, the crowd and hoist motors attain the crowd/retract and hoist motions, respectively. The hoisting equipment on the cable shovel involves a rope drum which is reeled in or spooled out by the electric motor-driven hoist transmissions.

Figure 7.16 depicts a typical shovel dipper trajectory. The shovel cleans free material from the starting point (A) in the direction of the bench toe (B). Then the position of the shovel dipper teeth changes from (B) to the start point of the coasting phase (C). The task of moving the dipper into the final coasting phase (C–D) is to make the bank clear [13].

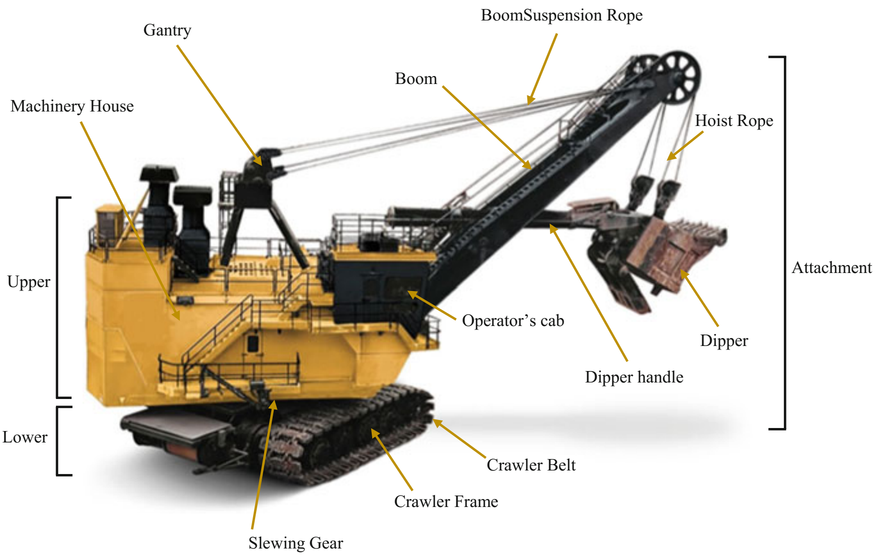

Fig. 7.15 Typical electric mining shovel assemblies

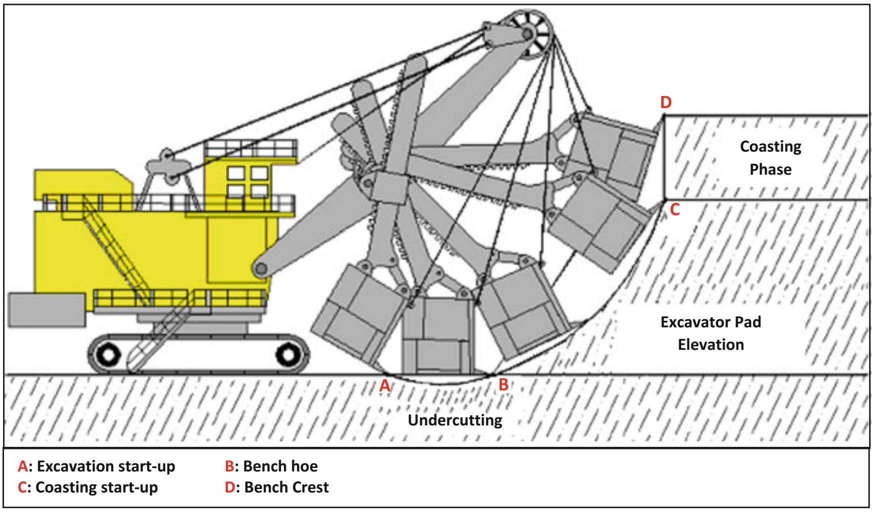

Fig. 7.16 The three separate digging phases accomplished by a cable shovel [14]

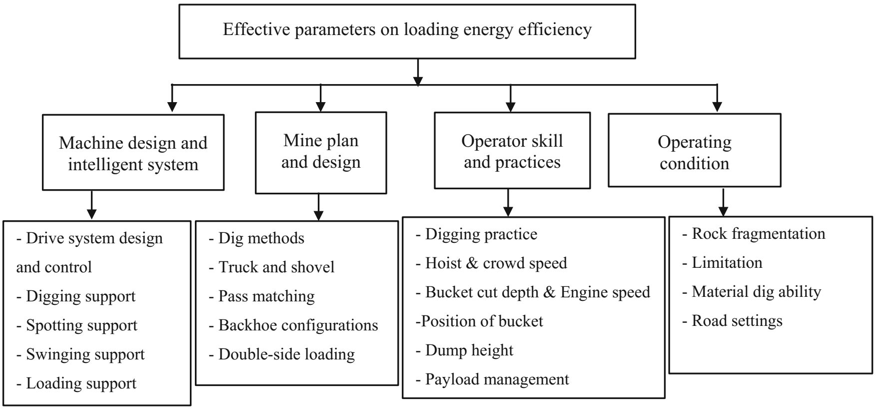

Fig. 7.17 Effective parameters on loading energy efficiency

7.3.2 *Effective Parameters on Loading Energy Efficiency*

Energy efficiency of loading operations can be improved by enhancing the equipment, ensuring better-operating conditions, selecting proper mine planning and design, and training the operator (Fig. 7.17).

The equipment defines how the machines transform energy efficiently into useful work in specified circumstances, although difficult operating conditions such as sub-optimal rock fragmentation, material digability and road settings lead to considerably higher energy input per unit of useful work. The mine plan and design (which defines in how equipment is organised) have influenced on the operating conditions, relations between equipment components, and how efficiently the equipment is used. The combination of all of these parameters can either improve or diminish the energy efficiency. Last but not least, operator skill and practices have a substantial impact on energy efficiency. Research evidence exists to demonstrate that this parameter significantly affects energy efficiency independently of the influence of other factors [14].

7.3.2.1 Machine Design and Intelligent System

To enhance the energy efficiency of loading operations, intelligent automated digging, spotting, swinging and loading support should be considered.

Typically, for the shovel, three aspects can improve cycle time: greater pull torque, greater peak power and increased speed to swing and to move the dipper. The shovel operator should have greater power and the capability to go faster from side to side in the bank. Therefore, enhancing excavating equipment can lead to machines that more efficiently transform energy into useful work.

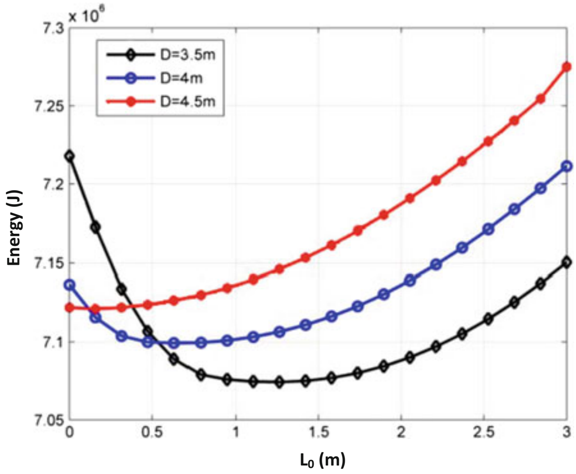

Fig. 7.18 Energy consumption with different starting points [17]

The digging torque has a significant influence on the hoist and crowd movements during the excavation period. Critical energy savings can be reached using regenerative AC drives in mining shovels. Particularly in the swing and hoist movement, the regenerated energy increases to 80 and 22%, respectively. The overall energy savings attained by implementing regenerative AC drives in comparison with non-regenerative drives is approximately 26% [15].

Moreover, it is necessary to raise the torque and horsepower for the propel task to avoid getting stuck. Since the same motors carry out hoist and propel tasks, a structure which reduces hoist–propel switchover time would improve the energy efficiency. The propel task and digging operation of the shovel influence cycle times [16].

Trajectory of the bucket (Digging Trajectory)

When it comes to the digging trajectory, both defining the optimum starting point and choosing the appropriate type of trajectory curves can increase the energy efficiency.

The three curves shown in Fig. 7.18 illustrate the difference in energy consumption with various starting points and consequently three digging distances: D = 3.5, 4 and 4.5 m. L_0 is the distance between the new starting point and the end of the soil pile. For every digging distance, energy consumption changes and there is an ideal starting point which minimises energy consumption.

Swing trajectory

It is essential to optimise the position of the shovel in relation to the truck. Large swing angles extend shovel cycle time and waste swing energy, while small swing angle cause swing cycles to become hoist dependent [18]. With the better coordination of the shovel's hoist and crowd tasks, the cycle time could be decreased through the loading period. Passing through the bank and filling the bucket rapidly would be desired, but not so quick that the hoist motors get blocked and halted. In other words, the hoist and crowd tasks should be controlled, simultaneously.

Control the hoist and crowd functions together
During the digging process, the shovel operator retracts the crowd before the hoist motors stall and then crowds as hard as possible against the bank to fill the dipper. If the shovel's hoist and crowd functions are better coordinated, the cycle time could be reduced during the loading phase. The aim would be passing through the bank and filling the bucket quickly, but not so fast that the hoist motors stall. Mines need a system that combines these two motions and can be controlled together. We suggest that further research should be conducted to develop algorithms that could control hoist and crowd together during digging. When the hoist speed falls off, it retracts until hoist speed picks up again [16].

Collision-free trajectory
A semi-automated load assistance system (Auto Load) and a collision avoidance system (Truck Shield) are two sample technologies based on three self-reliant approaches which estimate the position of the haul truck corresponding to the shovel, initially assisted by global positioning system (GPS), ultra-wideband (UWB) ranging receivers and 3D scanning LIDAR [18, 19].

Shovel load assist program (SLAP) technology has numerous benefits such as shovel safety, accessibility, efficiency and lower maintenance as well as faster shovel cycle times, lower machine duty, enhanced material delivery in trucks, fewer influences between truck and shovel and lower operator workload. SLAP is developing equipment that will assist operators of electric mining shovels to load trucks with higher productivity and safety.

An appropriate organisation for supporting the operator of an electric mining excavator to avoid collisions with identified obstacles within the workspace of the excavator is essential. This can be achieved by applying a receding horizon avoidance filter. In this technology, the command provided by the operator is adjusted for collision avoidance. The receding horizon avoidance filter computes the filtered command using a receding horizon control framework. A collision-free trajectory, which is the lowest variation from the operator's proposed trajectory, is considered, and the first command from the trajectory converts the filtered command [20].

7.3.2.2 Mine Plan and Design

The mine plan and design have an impact on the operating conditions, relations between equipment components, and well-organised practice of equipment. This combination either improves or deteriorates energy efficiency. For example, research results show that higher production is achievable by double, rather than single, benching. Similarly, double-side loading is proved to be slightly more complicated than single-side loading but more productive [16]. Although double-sided loading requires additional care to keep safety criteria, it is possible to excavate more material per shift and to increase truck efficiency. For instance, spotting times in trucks loaded with double-sided loading are frequently around 35 s compared to 65 s with single-sided loading. A 30-s decrease in truck cycle time has a non-negligible impact on production rate [21].

Truck and shovel pass matching has a critical influence on loading efficiency. Shovels and buckets should be sized so as to fill a truck tray within 3–4 passes. Each pass beyond this waste cycle time and energy. Cycle times for backhoe configurations can be marginally faster in comparison to front–shovel configurations [16].

7.3.2.3 Operator Skill and Practice

The operator influences vital factors and consequently defines the production rate and energy consumption, for example, bucket fill factor and cycle time. Significant energy inefficiency in loading operations is as a result of operator practices. The best operators use 40% less energy per tonne of production in comparison with the other operators. Probably, extra savings could be achieved since there is nothing that assures that the best operator operates at the optimum energy efficiency [12]. Operator practices have an excessive influence on shovel performance; consequently, operator practices should be optimal. The result of the best operator practice is a greater proportion of cycles in the lower digging energy classifications while keeping an appropriate loading ratio. Digging energy is a function of both muck pile digging states and primarily digging practice. It has been observed that the operator with the lower hoist speed and higher crowd speed accomplishes dipper cuts in the bank and consumes greater energy during digging.

Figure 7.19 illustrates the optimization problem with the objective function being energy per unit loading rate. The objective function reduces when the hoist

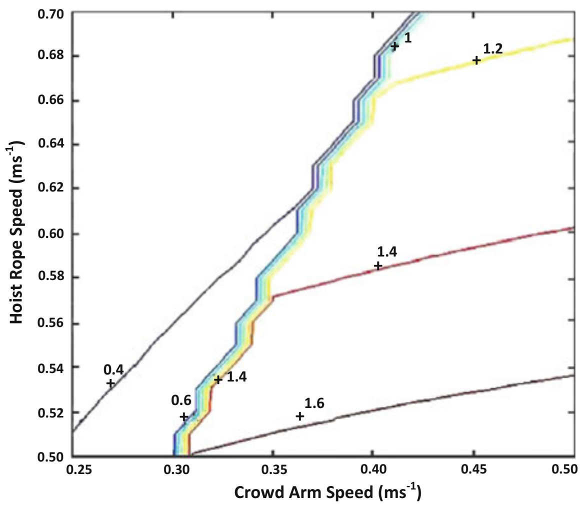

Fig. 7.19 Energy per unit loading rate (kJ s per kg) [23]

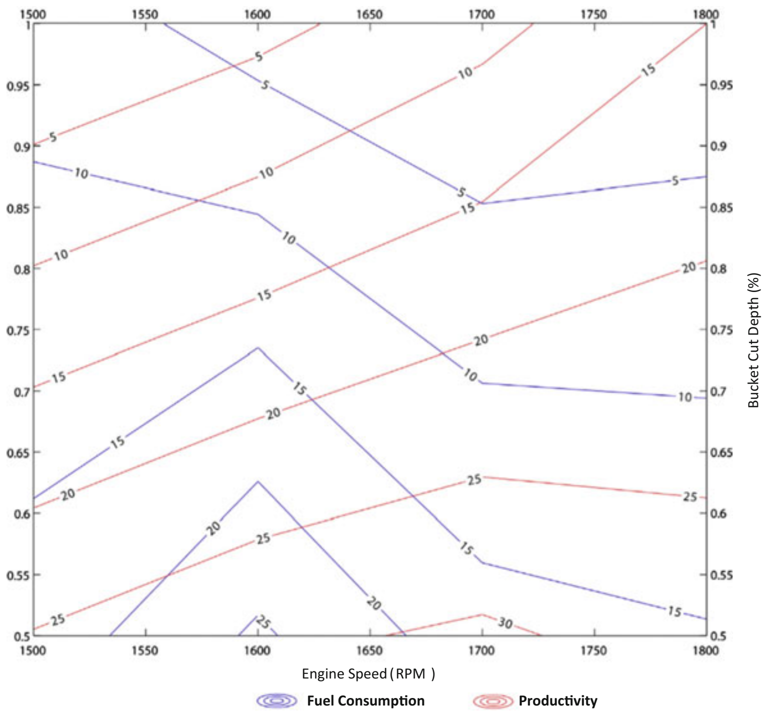

Fig. 7.20 The productivity and fuel consumption [25]

speed increases and crowd speed decreases. The primary inference obtained from Fig. 7.19 is that the best operator practice is accomplished when the dipper is moved at low crowd speeds and high hoist speeds [22].

For draglines, research has suggested that the most effective factors that cause variation in the energy efficiency of operators include dump height and engagement/disengagement position of the bucket. Cycle time, payload and swing in time are the less efficient parameters which lead to variation in operator energy efficiency [23].

It has been observed that engine speed and bucket cut depth (BCD) arrangements have an impact on fuel efficiency and productivity of a hydraulic excavator.

By applying the map showing the influence of RPMs and BCDs on productivity and fuel consumption, manufacturers can provide operators support with an automated system built into the excavator. Thus, the system is enabled to adjust the engine speed and the bucket dig depth during excavating, automatically.

Figure 7.20 demonstrates the result of engine speed and bucket cut depths (BCD) on cycle time, fuel consumption and output. To make the map simpler, cycle time and output were joint into one unit: productivity (m^3/h). The fuel consumption design is laid over productivity to clarify the unexplored correlation between these variables. The *x*-axis and *y*-axis depict the engine speeds, BCDs (in percentage), respectively, and *z*-axis shows two variables, fuel consumption (litres) and productivity (m^3/h). The dependent variables are presented as a percentage gain in 5% intervals. The behavioural configuration of the dependent variables is described with two various coloured lines on the map. Fuel consumption (litres) is characterised in blue and productivity (m^3/h) in red. This map can be implemented as a supportive database in automation process of an excavator. The engine speed and the bucket dig depth during excavating can be arranged. To accomplish the best likely productivity and fuel consumption rate, engine speed and BCD should be adjusted to 1660 RPM and 50%, respectively. However, the operator will have to consciously select between low fuel consumption and high productivity excavation strategies [24].

Payload controlling, or filling the dipper to the proper weight, also affects the digging cycle time. If the shovel operator could know the weight of the material in the bucket throughout the digging procedure, then he/she could stop loading after the desired point, and the break-out and load phase of the cycle could begin. Some digging plans that try to minimise cycle time have a tendency to fill the bucket to only 80% of capacity which results in more passes that would be essential if the bucket was always filled to 100% [16].

7.3.2.4 Operating Condition

Excavator performance is significantly affected by material digability, which depends on blasting. Material digability can be measured by excavator dig time, which is defined as the period from when the bucket engages the muck pile to when it begins to swing the boom across to the truck. Material digability can be influenced by the equipment operator, material characteristics (rill properties, looseness, fragmentation, etc.) and excavator type. It has been reported that a 7–58% improvement in excavator dig time is possible from improvements to the muck pile characteristic and operator skill [26–28].

7.4 Conveyor Transport

Conveyors are a very efficient, low-cost means of transporting sized materials in high volumes. The most common type of conveyor used in mining is the trough conveyor, which consists of a head pulley, drive motor and torque coupling, a take-up mechanism, a belt constructed as a rubber ply structure or using embedded steel cords, a set of troughs with carry and return idlers, and a tail pulley plus transfer chutes to channel material onto and off the belt. Belts can be up to 2 m in width, a few kilometres long and run up to 7 m/s in speed. This enables transport capacities of up to 20,000 tonnes per h, typical of the large German lignite mines.

Fig. 7.21 Semi-mobile IPCC system in an Australian mine

There are many different types of conveyor systems used in mining applications. Conveyors typically handle materials sized below 300 mm, so it is necessary to employ a crusher at the feed end of the conveyor. At the discharge end of the conveyor, there is a need to employ either a stacker or spreader. In between, the feed and discharge stations, a variety of bench, ramp and overland conveyors are employed (Fig. 7.21).

Mining systems are referred to as either in-pit or ex-pit systems, dependent on the crusher location. If the crusher station is located within the pit, there are some alternatives: fixed in-pit crushing and conveying systems (FIPCC), semi-mobile in-pit crushing and conveying systems (SMIPCC) or fully mobile in-pit crushing and conveying (FMIPCC) systems. Fixed crusher stations are designed to be a permanent fixture in the life of mine. Semi-mobile crusher plants are designed in modular architecture so that they can be periodically relocated (at intervals of say, every 3–5 years) as a mine deepens. Truck–shovel systems work in collaboration to feed both fixed and semi-mobile IPCC systems. In fully mobile IPCC systems, the shovel directly feeds a mobile system comprised of a hopper, apron feeder and low-profile crusher, commonly a hybrid roll crusher or sizer. The mobile crusher then feeds a bench conveyor via a stinger conveyor connected to a hopper car, mounted on rails or tracks above a relocatable bench conveyor.

The material is conveyed ex-pit via a ramp conveyor. Dependent on material characteristics, including size distribution, bulk density and moisture content, a ramp conveyor can manage inclinations of between 15° and 18°. This is substantially more than a truck haul road, which averages only 10% gradient. Other than a dedicated conveyor ramp, other pit exit strategies include construction of a dedicated conveyor decline, shared conveyor access via widening an existing truck haulage route, the use of a slot conveyor in the cusp of two of the pit walls or the use of a high angle conveyor. The latter type of conveyor consists of novel pipe or sandwich design and are capable of transporting materials up the slope of around 35°. To date, however, they have been restricted to lower capacity systems not exceeding 3000 tonnes per h.

Once outside of the pit, the material will usually be transferred to an overland (fixed) conveyor. If it is a valuable mineral or energy material, it will proceed to a stacker discharge station that feeds the mill or handling and preparation plant. If it is waste material, it will proceed to the waste dump, where it will be transferred to a bench conveyor linked to a tripper car feeding a spreader. The tripper car provides a variable off-loading point along the length of the bench conveyor, thus enabling the spreader to travel along a waste pad systematically filling using both up-cast and down-cast spreadings.

7.4.1 Power Efficiency

A mining truck with a 327-tonne payload capacity has an empty vehicle mass of around 246 tonnes, dependent on the tray wear packages installed. As part of its duty cycle, the truck needs to expend energy to vertically lift its empty vehicle mass plus payload out of a mine and then to return the empty vehicle weight back into the mine in preparation for the next loading cycle. This means that the total mass moved in one round trip is approximately $2 \times 246 + 327 = 819$ tonnes. Thus the ratio of moved material to total weight moved is 1:2.7, or only 38% efficient.

A troughing conveyor that has a capacity of 10,800 tonnes/h and a belt speed of 5 m per s must deliver 3 tonnes of material per second. These 3 tonnes are distributed over a belt length of 5 m. The mass of 5 m of the belt, plus a 5 m section of the return belt, is around 600 kg. Thus, the ratio of moved material to belt mass for the conveyor is just 1:1.2 or 81%. To this, we can add the fact that the conveyor belt is driven by electric motors, which are around 95% energy efficient.

Belt conveyor power is measured as a function of belt velocity multiplied by equal force. The latter is made up of the sum of main resistances, secondary resistances, slope resistance, special main resistances and special secondary resistances. Of these, the first three are the most important. Main resistances refer to the indentation and rolling resistance of the belt; the flexure resistance of the belt and the rotational resistance of the idlers and bearings. Secondary resistances refer to inertial and frictional resistances due to accelerating material at the loading point and resistance due to friction at the side walls of chutes, pulley bearing resistance and resistance due to the wrap of belts around the pulleys. Slope resistance refers to the potential energy required to lift the load up an inclined slope.

7.4.2 Conveyor Belt Applications in Mining

Apparently, then, conveyor belts offer a more energy-efficient means of transporting bulk materials. Belt conveyor operation also enhances mine safety, as around one-third of all fatalities in Australian surface mines are related to vehicle collisions. Truck operations require a significant logistics chain to supply fuel, tyres and spare parts to a mine. Fewer supply trucks are necessary to support conveyor belt operations, which can be beneficial for mines operating in areas with sensitive community concerns.

With all of the advantages offered by conveying systems, why do we not see them in use more frequently in mining operations? The answer to this question has to do with

- Material type and sizing;
- Upfront capital expenditure;
- Flexibility (mine design limitations, ability to relocate and scale up or down); and
- System reliability.

First, for material to be transported by conveyor belt, it must be sized to below 300 mm. While this is financially viable for ore which needs to be crushed anyway before processing, it is regarded as an unnecessary cost for waste materials.

Second, IPCC systems require significant upfront capital investment. Total system cost can amount to around US$80 million for systems with capacities of up to 10,000 tonnes per h. A crusher station costs around US$15 million, and a typical 10,000 tonnes per h system might employ two such crusher stations at the cost of some US$30 million. A spreader will cost around US$16 million. The remainder of the system costs is then divided between bench, ramp, overland and dump conveyors plus the ancillary hopper and tripper cars. This upfront capital investment has a significant influence on project Net Present Value (NPV), despite IPCC systems offering significantly reduced operational expenditure (in the order of between 15 and 25% less total mining cost, dependent on SMIPCC or FMIPCC system type). Truck systems have the advantage of being able to be scaled up as mining pits grow.

Thus, a mine can begin operations with a relatively small truck–shovel fleet and purchase additional units to add capacity as the mine progresses. Over the life of mine, due to shovel and truck fleet replacements, total capital expenditure is roughly similar to that of the IPCC system. However, for truck–shovel systems expenditure is distributed over the mine life which can lead to an NPV advantage. Financial analysis shows that the NPV of IPCC systems wins out in the case of long life deposits.

Third, IPCC systems require significant changes to be made to a mine plan in comparison to a plan employing truck–shovel systems. For a start, a viable conveyor exit strategy is required. If a ramp conveyor is used, then the wall on which this conveyor is located must be relatively immobile over the life of mine; this is not always the case. Frequent movements of the bench (and dump) conveyors consume large quantities of productive time, and so the optimal mine design for FMIPCC systems will employ long linear benches. This does not suit all deposit types. The capacity of installed IPCC systems is fixed and cannot easily be scaled up or down to suit prevailing economic conditions (unlike truck–shovel operations, for example, where a time of low commodity prices equipment can simply be parked up to save money).

Finally, IPCC systems are complex series connected systems. Downtime any of the system components will cause a system outage and stop material movement. This includes both availability losses due to maintenance and utilisation losses due to the bench or dump conveyor relocations. It is estimated that FMIPCC-effective utilisation is around 64%, equivalent to 5600 productive hours per year [29]. Of this, about one-third of the system losses are due to maintenance or repairs. The remaining losses are utilisation losses.

7.5 Conclusions/Summary

As a result of these limitations, truck–shovel systems continue to be a predominant system of choice for most surface mines. However, around the world, most notably at the Technical University of Freiberg, Germany and at The University of Queensland, Australia, research efforts are underway to address the limitations identified above. In a world becoming more fossil fuel constrained, solving such issues is imperative to continue the level of supply of minerals and energy commodities that the world currently enjoys.

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