Transportation Performance Measurement for Coal Mining: A Review and Framework

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Abstract

Industries including transportation companies depend on their assets and normally utilize them to maximize their productivity. To increase profitability, companies need to reduce their unit cost and improve productivity by utilizing their equipment effectively to gain more income. A typical measurement for equipment effectiveness is overall equipment effectiveness (OEE). The OEE concept has evolved and developed in the transportation sector, with different names and terms. Therefore, this study was conducted to review and analyze the evolution and development of OEE in the road transportation sector. It was also to modify existing transportation overall vehicle effectiveness (TOVE) which is an extended version of the OEE as an indicator to measure vehicle effectiveness in a coal mining transportation company. This study was able to identify the evolution of OEE in road transportation sector and also propose the new vehicle effectiveness indicators in coal mining transportation companies.

Keywords
Overall Equipment Effectiveness (OEE), Productivity, Transportation Overall Vehicle Effectiveness (TOVE), Vehicle, Performance.

1. Introduction
Companies need to improve their productivity and quality to compete in the market because an increase in operational costs and low productivity can reduce their profitability. This indicates there is a need to determine the appropriate strategies and methods to reduce costs as well as to improve quality and productivity. Moreover, high customer demand is also one of the reasons companies think of ways to make their products or services better, safer, and at competitive prices. This is also observed in coal transportation which is a capital-intensive business that maximizes its equipment such as trucks effectively to obtain an early return on investment. The effectiveness of equipment is important in industries and its major indicator is the Overall Equipment Effectiveness (OEE) which has been widely used in the manufacturing sector. The OEE concept has the ability to improve performance and assist the management in discovering hidden capacity, reducing overtime costs, and avoiding investing in new equipment. This means the indicator provides substantial and measurable financial benefits, contributes to the operational bottom-line improvement, and increases the company's competitiveness (Muchiri and Pintelon 2008). It is, however, important to note that several vital factors in transportation operations such as fuel consumption rate which is one of the main components in transportation costs are not accommodated in the OEE despite its usefulness and wide application. Meanwhile, the use of fuel consumption as in indicator is necessary in the transport sector because cost-effectiveness is the most important factor from the perspective of management. Hence, this present study makes efforts towards combining several essential factors in transportation, including fuel efficiency and safety rates, into the components used in measuring the effectiveness of transportation.

This study, therefore, focuses on summarizing existing publications on the evolution of OEE in the road transportation sector and improving the existing indicator to develop a new one to measure the effectiveness of transportation in the mining sector. The new measurement indicator which is considered to be more applicable to monitor the effectiveness of the operations in the coal transportation business.

2. Literature Review
The effort to increase efficiency is a critical aspect in the transportation sector and this is the reason OEE concept was used in this study due to its ability to optimize the performance of a company, assist the management to analyze and

identify losses and hidden capacity, and also avoid investing in new equipment. It has the ability to substantially provide financial benefits, contribute to bottom-line operations improvement, and increase company competitiveness (Muchiri & Pintelon, 2008). The implementation of improvement initiatives such as lean in the mining sector has been studied previously using lean tools such as kaizen, value stream mapping (VSM), total productive maintenance (TPM), and single minute exchange die (SMED). The focus of these studies was on the gold mining companies in Canada and the results showed a positive impact of the tools on productivity and work safety (Nemati et al. 2019). Another study also discussed the challenges in coal mining operations (Yu et al. 2016) and those observed to be prevalent include low productivity, low efficiency, safety, and environmental issues (Maunzagona and Telukdarie 2017). It was also discovered by (Dunstan et al. 2006) as well as (Maunzagona and Telukdarie 2017) that these challenges are strongly influenced by weather, geographical conditions, remote locations, and huge areas that require the team to spread out. This, therefore, indicates it is necessary to develop relevant indicators to increase the productivity and efficiency of coal mining companies through the application of the OEE concept.

The term "Overall Equipment Effectiveness (OEE)" was first introduced by (Nakajima 1988) as an indicator of manufacturing equipment productivity. It has been used to measure the success of implementing the total productive maintenance (TPM) program (Cheah et al. 2020) and also as a standard indicator to evaluate production productivity (Soltanali and Khojastehpour 2021; Chikwendu et al. 2020; Ng et al. 2020). OEE is normally calculated by multiplying availability (A), performance (P), and quality (Q) (Sohal et al. 2014; Cheah et al. 2020; Supriatna et al. 2020; Supriatna et al. 2019). It is important to note that availability (A) measures the total system downtime due to failure, setup, adjustment, and other stoppages in order to show the ratio of actual operating time to planned available time, performance (P) measures the actual time's deviation against the ideal time while the quality level (Q) shows the relationship between the number of units that meet the specifications and the total number of units produced. OEE has recently been used as a benchmark to determine the overall efficiency of a plant by comparing its present value to future targeted value in order to determine the factors to be improved to achieve the desired OEE level. A previous study considered 85% as the benchmark score and this value is suggested to be used as a reference (Nakajima 1988; Dal et al. 2000).

OEE has been widely used as a performance measurement tool in the manufacturing sector due to its ability to integrate several performance factors including availability, performance, and quality into a single globally recognized tool (Garza-Reyes 2015). Previous studies proved the ability of OEE to improve production performance for manufacturing companies (Cheah et al. 2020; Tsarouhas 2020). It was reported to be particularly appropriate for high-volume processes where capacity utilization is a priority and downtime is very expensive due to capacity loss (Garza-Reyes et al. 2010). Moreover, the use of OEE is critical in capital-intensive industries because the managers usually want to use their equipment as effectively as possible to obtain an early return on their investment (Jeong and Philips 2001). It is also important to note that capacity utilization is highly needed in the mining transportation sector because it is capital-intensive and the equipment used is expensive.

The adoption of OEE as a method to measure the effectiveness of public transportation was investigated by (Muñoz-Villamizar et al. 2018) using a mathematical model which succeeded in optimizing the method by making adjustments and modifications to the classical OEE as indicated in the following Table 1.

Table 1. Definition of OEE with Modified Losses

	Classic OEE Losses	Road Transportation Losses
Quality losses	Defects	Order not delivered within time windows
	Start-up	Order not delivered within time windows
Performance losses	Reduced speed	Reduced speed
	Abnormal production	Traffic jams
	Minor stop losses	
Availability losses	Process failures	Unloading times
	Equipment breakdown	Waiting time to delivery within time windows
	Setup /adjust	

Source: (Muñoz-Villamizar et al. 2018)

The increase in the popularity of OEE has led to its adaptation to meet industry-specific needs as indicated by the modification of its term in some literature as well as the creation of another equivalent term in others (Muchiri and Pintelon 2008). This signifies the OEE concept used in the manufacturing sector can also be applied in the transportation sector as the key performance indicator (KPI) to measure performance considering the fact that the current conditions need to be evaluated to improve performance. Moreover, transportation KPI is a tool to evaluate the transportation process and it has been used by companies to determine their current performance, competitiveness, and also to analyze current industry trends (Hunedoara et al. 2017).

Simons et al. (2004) showed that the indicators to measure the effectiveness of transportation need to be simple, easy to understand, applicable to the road transport industry, and designed to measure the effectiveness and productivity of transportation. This led to the development of Overall Vehicle Effectiveness (OVE) which uses OEE principles to measure the effectiveness of vehicles and tractors in the transportation industry and was observed to have been applied by the U.K. government to measure transport efficiency. It was also designed to be calculated by multiplying availability, performance efficiency, and quality rates and five losses in transportation identified include driver break, excess load time, fill loss, speed loss, and quality delay. Initially, OVE did not consider the energy efficiency while making the route selection in cases where deliveries or collections were made to/from a significant number of destinations but this was solved through the introduction of a new component that considers route effectiveness into the equation. It is important to note that the OVE value was discovered to be high on inefficient routes due to its inability to identify the losses when the vehicle made deliveries to multiple addresses or destinations. Moreover, the OVE was modified by (San et al. 2003) by dividing the performance factor into two components which include the route and time efficiency in order to reflect the efficiency of the route. The new measure was called modified overall vehicle effectiveness (MOVE) which is calculated by multiplying vehicle utilization, route efficiency, time efficiency, and quality rate. The vehicle utilization was determined based on the delivery requirements and utilization of backhauling and fleet management, route and time efficiency were used to measure traveling performance, and the quality rate was obtained from handling performance. Another measurement indicator named overall transportation effectiveness (OTE) was also introduced by (Dalmolen et al. 2013) and it is similar to OVE but calculates availability, performance, and quality in more detail as indicated by its ability to measure the efficiency of transportation by calculating the level of CO2 for each truck.

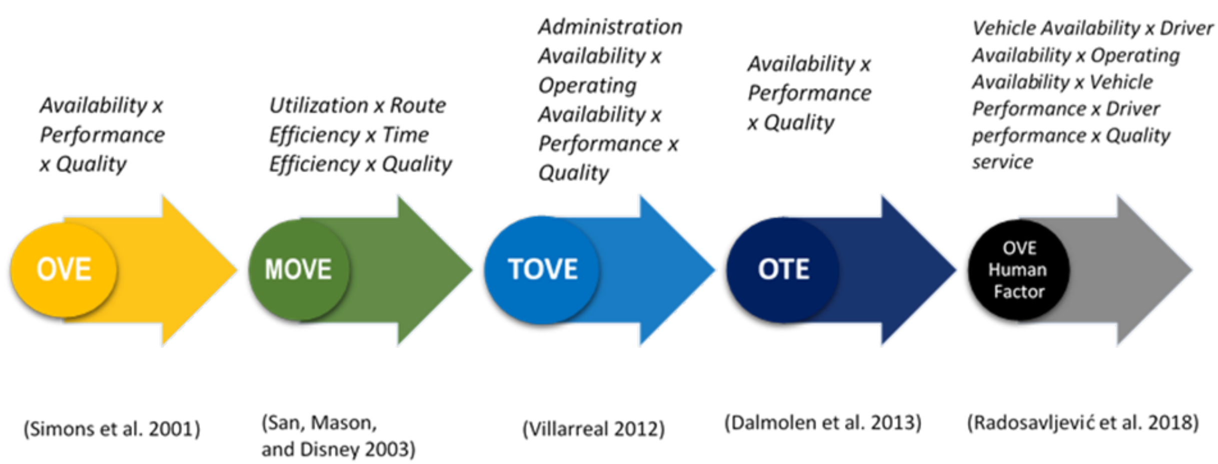

Figure 1. OEE Evolution in Road Transportation Sector

Another specific indicator was also introduced for the overall effectiveness of the transport process. This is due to the importance associated with vehicle utilization rate because of the high capital investment in procuring the vehicle. Companies with fleets of vehicles need to calculate the OVE indicator based on the total calendar time in order to enhance utilization and this was observed to have led to the creation of a new term known as the Total Overall Vehicle Effectiveness (TOVE). It is important to note that a lower availability utilization rate usually leads to a higher transportation cost. This method was developed to evaluate the effectiveness of transportation equipment using four components which include (1) administrative or strategic availability, (2) operating availability, (3) performance, and (4) quality rates (Garza-Reyes et al. 2016). The incorporation of the efficiency concept in the availability of vehicle administration is essential due to its significant impact on the total efficiency of the vehicle as a whole. This implies TOVE can be used to control and monitor transportation operations and to determine improvement priorities (Garza-Reyes et al. 2016). The TOVE method was further researched to improve route efficiency and also combined with transportation value stream mapping to identify waste (Villarreal 2012). Moreover, the efforts to enhance road transportation operation based on lean thinking and to reduce the seven extended wastes in transportation have been studied by (Villarreal et al. 2016).

Another indicator of the effectiveness of transportation was also introduced as OVE Human Factor using a mathematical model which includes vehicle availability, driver availability, and energy as resources affecting the effectiveness of the process (Radosavljević et al. 2018). The study found that the influences of specific energy consumption on overall vehicle effectiveness depend on both the payload capacity utilization rate and mileage utilization rate. The formula for the OVE Human Factor is based on determining the availability utilization rates of vehicles and drivers, performances of vehicles and drivers, transport process quality which consists of quality of supplied service to the customer, vehicle fleet energy efficiency, and quality of services rendered. The evolution of the OEE in the road transportation sector is, therefore, described in Figure 1.

3. Methodology

Transportation efficiency is important to the enhancement of transportation performance and the three main costs usually incurred by the service providers are fuel, labor, and vehicles (Simons et al. 2004). Therefore, this study proposes a new indicator which was named MTOVE or mining transportation overall vehicle effectiveness to evaluate the transportation effectiveness in coal mining transportation. This indicator represents an expression involving vehicle utilization, vehicle availability, vessel capacity, fuel consumption, and safety as factors influencing transport process effectiveness. Moreover, the evaluation process depends on the utilization rates, physical availability, performances rate, quality rate, and vehicle fleet safety level. It is also important to note that vehicle effectiveness is influenced by the following factors:

- Availability utilization
- Vehicle physical availability
- Vehicle performance in terms of vessel capacity and fuel consumption
- Transport process quality in terms of safety

The coal mining transportation process which is known as the hauling process involves transporting coal from the mining pit to port using a truck. The detailed activity includes loading coal into the truck, the truck travels to the port, unloads the coal into the stockpile, and returns to the mining pit.

The effectiveness of coal transportation in this study using the Mining Transportation Overall Vehicle Effectiveness which was abbreviated as MTOVE. This method was adopted from the Transportation Overall Vehicle Effectiveness TOVE concept developed by (Villarreal 2012) combined with the Overall Vehicle Effectiveness Human Factor (OVE Human Factor) by (Radosavljević et al. 2018) with some adjustments made to ensure it is applicable in the coal mining transportation process. Its measurement is based on the calendar time considering the fact that the mining sector works throughout the year except for special holidays as well as 24 working hours a day which is suitable due to the fact that the sector is capital-intensive and requires optimal use of equipment for high volume production within a short time. It is important to note that the existing TOVE method does not accommodate important factors in coal trucks such as fuel consumption efficiency and safety issue which have a direct cost effect on the coal mining transportation and they need to be included as trucking performances components in coal hauling due to their significant importance.

The Overall Vehicle Effectiveness Human Factor (OVE Human Factor) considers specific energy consumption which is usually obtained based on scenarios and assumptions instead of actual data and measured in terms of MJ/ton-kilometer. It is difficult for the operation team to understand this variable and use it in the calculation, thereby, leading to the use of fuel consumption measured in liter/ton-kilometer and obtained from actual data in order to make sure the calculation for the transportation efficiency is simple and easy to understand according to (Simons et al. 2004). The vehicle availability in the OVE Human Factor was calculated based on the number of units ready to operate compared to the number of units available per day. This indicates the truck availability is calculated daily, meanwhile, the hauling availability in coal mining is normally evaluated hourly (truck working hour). It is also important to note that the availability in the OVE Human Factor was calculated by dividing the number of operating units by the available units on a particular day but it is better to conduct this measurement based on the working hours available for each unit. This is necessary because there is a possibility that one unit truck is unavailable only for several hours in a day, for example, when a truck breaks down and starts working again after one or two hours of repair and maintenance, it is categorized as being available after repairs and ready to be used for the rest of the day. Practically, a truck with a minor breakdown usually requires only a few hours to repair and this is categorized as "not available" in the OVE Human Factor since the vehicle availability calculation is based on the number of units operating per day.

The MTOVE framework developed in this study is described in Figure 2, to be a combination of several factors from the existing TOVE such as availability utilization and vehicle performance as well as others from OVE Human Factors such as specific energy consumption and quality of service, in this case specific energy consumption replaced with fuel consumption. Moreover, safety which is a crucial factor in mining is also included to calculate the quality rate which is the ability of the truck driver to operate without any accident or safety issues and to deliver the cargo safely.

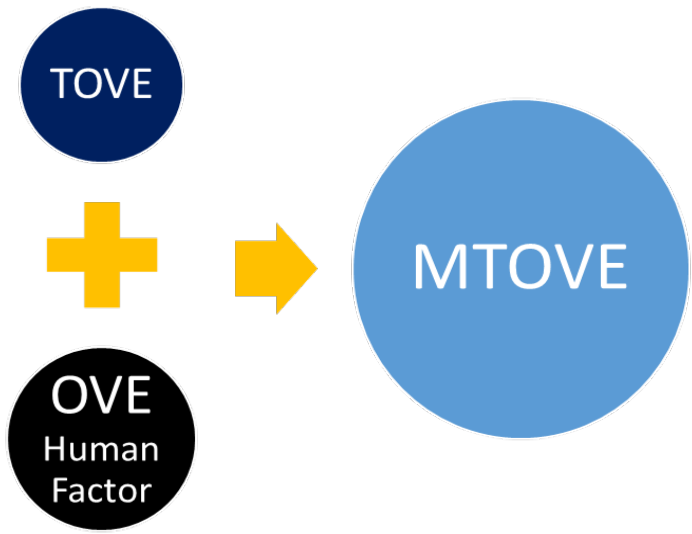

Figure 2. MTOVE Framework

The formula used to calculate MTOVE is presented as follows (1):

$$\text{MTOVE} = \text{PA (\%) x UA (\%) x PE (\%) x QR (\%)} \quad (1)$$

$$\text{Physical Availability (PA)} = \frac{\text{Uptime (hrs)}}{\text{Total Available Time (hrs)}} \text{ x } 100\% \quad (2)$$

$$\text{Use of Availability (UA)} = \frac{\text{Operation Time (hrs)}}{\text{Uptime (hrs)}} \text{ x } 100 \quad (3)$$

$$\text{Performance Efficiency (PE)} = \text{CP (\%) x FP (\%) x VP (\%)}$$

$$\text{Capacity Performance (CP)} = \frac{\text{Actual Volume Transported (metric ton)}}{\text{Standard Volume Vessel (metric ton)}} \; x \; 100\% \quad (4)$$

$$\text{Fuel Performance (FP)} = \frac{\text{Actual Fuel Rate } (\frac{\text{ltr}}{\text{ton}}.\text{km})}{\text{Standard Fuel Rate } (\frac{\text{ltr}}{\text{ton}}.\text{km})} \; x \; 100\% \quad (5)$$

$$\text{Vehicle Performance (VP)} = \frac{\text{Actual Cycle Time (metric ton)}}{\text{Standard Cycle Time (metric ton)}} \text{ x } 100\% \quad (6)$$

$$\text{Quality Rate (QR)} = \frac{\text{Total Accident or Insident}}{\text{Total Trip}} \text{ x } 100\% \quad (7)$$

The physical availability of the asset is reduced when there is a breakdown in the unit due to component failure. Therefore, there is a need to ensure regular maintenance to prevent failure and also to extend component lifetime. It is important to reiterate that the vehicle utilization concept used in the coal transportation sector originated from TOVE developed by (Villarreal 2012) with due consideration for the calendar time in the maximization of the truck. This is due to the fact that the working hours are usually maximized in the mining operation throughout the year except for special holidays such as Christmas, new year, and Independence Day. It is important to note that some of these days are also not considered a holiday in some cases due to the effort of the company to improve truck utilization and production volume. The working hours used in this study to calculate truck utilization are 24 hours a day and seven days a week except for the seventh day when there is one day off to change shifts. This is necessary because the crew works in two workgroups and are divided into day and night shift. Moreover, the two types of factors observed to be affecting the use of availability (UA) of trucks are external and internal factors. The external aspect is focused on the situation when the truck is ready for use but does not operate due to weather conditions such as rain which has the ability to cause slippery and unsafe road conditions while the internal aspect includes rest, mealtime, and change in shift. Meanwhile, the factors discovered to be affecting the trucks' physical availability (PA) are the time for scheduled maintenance and breakdown time during operation.

The vehicle performance has 3 components which include capacity, vehicle, and fuel. Capacity performance is the actual volume transported compared to the standard vessel volume. The truck capacity is usually measured and included in performance calculation because lack of capacity is categorized as loss considering the fact that the contractor is normally paid based on the volume transported. Moreover, vehicle performance is normally used to compare the actual cycle time with the standard cycle time for one trip and the situation where the actual cycle time is longer than the standard cycle time indicates a reduction in the truck performance. These cycle times vary based on the hauling distance from the loading point which moves continuously based on the mining sequence. Fuel performance is based on the actual fuel consumption for each truck compared to the standard fuel consumption rate of the truck per hour. It is important to note that the standard fuel consumption is normally determined by the truck manufacturer in liters/ton.km and a low rate indicates high-performance efficiency. Furthermore, the quality rate compares the number of trucks that fail to transport coal to the designated point known as the port stockpile due to accident or breakdown along the journey which leads to its inability to deliver the coal cargo to the stockpile safely and requiring another truck to complete the delivery.

This method was developed to determine the existing performance and potential improvements in coal transportation processes and measure the effects of the action implemented. Therefore, the values of the MTOVE will be calculated, closely monitored, analyzed, and compared to the company objectives in order to allow the transport manager to observe the level of vehicle utilization, vehicle availability, and quality in the realization of the transportation process. Moreover, appropriate corrective action need to be applied to increase vehicle effectiveness in order to ultimately enhance the transportation performance and subsequently improve productivity.

4. Results and Discussion

There is a need for a company to improve the productivity of its asset and this led to the modification of the existing TOVE to create a new indicator, MTOVE, which is expected to enable mining hauling contractors to measure, monitor, evaluate, and improve their operational performance. The proposed indicator will be used to improve operation performance by ensure less idling and stop time, minimize breakdown, maintain cycle time, maintain standard loading time, maintain truck volume following its standard capacity, reduce fuel consumption, and increase operation safety. The essential factors in coal hauling operation were also identified and included in the calculation, and this new indicator reflects the transportation overall vehicle performance.

5. Conclusion

This study describes the evolution of OEE in the road transportation sector and also demonstrates the introduction of a new indicator to improve the effectiveness of vehicles in coal mining transportation. It was discovered that transport process effectiveness depends on effective utilization, physical availability, vehicle performance, and the quality rate described by the safety level, and these were used to propose a new methodology in the form of MTOVE as an improvement on the original TOVE indicator to ensure it is suitable for the mining hauling industry application. This new calculation method incorporates the crucial factors in the coal transportation business. It is, therefore, recommended that further study ensures the real-life application of MTOVE in the coal mining transportation operation using real data from the mining operation.

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