Investigating the effect of different loading scenarios on the performance of wheel loaders: A case study on Can Lignite Enterprises

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Dates:
Received: 6 June 2023
Revised: 10 May 2024
Accepted: 12 Sep. 2024
Published: November 2024

How to cite:
Çelik, A. 2024. Investigating the effect of different loading scenarios on the performance of wheel loaders: A case study on Can Lignite Enterprises. *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 124, no.11, pp. 703–710

DOI:
http://dx.doi.org/10.17159/2411-9717/2840/2024

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Abstract

Wheel loaders are widely used in many sectors due to their mobility, operational flexibility, and low costs. The literature is mainly focused on improving the hydraulic, mechanical, and electronic subsystems of these machines in terms of efficiency or developing strategies for controlling these systems. In this study, the effects of the loader operator and different working conditions on the loading performance were investigated. The study was carried out at the Can Lignite Enterprise (CLI), which is a major coal producer in Turkey. In the study, which lasted approximately four months, a total of 808 measurements were performed to investigate seven different scenarios. The effect of a single parameter on loading performance was investigated in the first six scenarios. The results showed that the biggest impact on loading performance was caused by the operator's experience with 63.4%. On the other hand, the worst and most ideal working conditions determined from the first six scenarios were tested in the seventh scenario. It was tested as a script. The test results showed that the loading performance was 285.5% more effective under the most ideal operating conditions compared to the worst operating conditions. In addition, in the study, the loading performances of five loaders with four different capacities were examined in terms of energy efficiency and it was determined that the Kawasaki 115 work machine, which has a higher model and lower engine operating hours, was more advantageous. In the study, various suggestions were developed in parallel with the research results. The most prominent and easiest to implement of these suggestions is related to the selection of the loader operator.

Keywords

different loading scenario, loader operator, loading performance, short loading cycle, wheel loader

Introduction

The most popular machines that are preferred to transport a material from one place to another or load it on a suitable vehicle are wheel loaders (Zauner et al. 2020). The popularity of these machines is based on their mobility, operational flexibility, and relatively low capital costs (Hartman, 1992). Wheel loaders have loader attachments (buckets, grapples, forks, material handling arms, cutting aggregates) that make it possible to load materials with different properties (Filla, 2008). These attachments have made the use of loaders widespread in many sectors such as mining, quarrying, construction, substructure development, and agriculture, etc. (Dadhich, 2018).

Due to its versatility, differences in operating conditions and operator behaviour makes it difficult to optimize fuel efficiency and productivity when designing a wheel loader (Frank et al. 2018). Nezhadali et al. (2016) stated that among experienced operators, the change due to operator behaviour can reach 150% in fuel efficiency and 300% in productivity.

Wheel loaders can be thought of as an integrated system consisting of hydraulic, mechanical, and electronic subsystems (Roux, 2011). Strategies applied for the control of different subsystems include lifting and carrying tasks that affect the fuel consumption and production rates of the main system (Frank et al. 2018). Many researchers have carried out technical studies on subsystems and strategies for controlling subsystems for fuel efficiency and production efficiency (Blake et al. 2006; Filla, 2011; Nilsson et al. 2014; Oh et al. 2016; Liu et al. 2017; Chen et al. 2022; Cao et al. 2023; Eriksson and Ghabcheloo, 2023).

Another important issue in terms of fuel and production efficiency is the operating cycle of wheel loaders. This cycle, which is called the short loading cycle in the literature (Huang et al. 2021), refers to the cycle that a wheel loader follows to load a vehicle in the shortest time possible. As can be seen from Figure 1, in this cycle consisting of 6 moves; In the first move, the wheel loader moves towards the loading area, and in the second move, it fills the material to be loaded into the bucket. In the third and fourth moves, it moves with the full load towards the vehicle to be loaded. In the fifth move, it unloads the load into the vehicle and in the last move, it returns to its initial position. This cycle, which seems quite simple, is an important factor that separates experienced and inexperienced operators. Wrong cycle selections cause production to slow down and energy consumption to increase. Regarding the short loading cycle, Filla (2013) conducted a study on alternative routes for wheel loaders operating in short loading cycles and determined that alternative routes could be beneficial depending on the working conditions. Nezhadali et al. (2013), conducted a study on the optimal control of a wheel loader in the lift-handling portion of the short loading cycle. Nezhadali et al. (2016), analyzed the effect of the operator's steering ability in a short loading cycle and revealed that the development of autonomous vehicles can be envisaged, especially for repeated cycles.

In recent years, studies on energy efficiency in all engineering disciplines have focused on designing existing systems/machines more efficiently in terms of energy and productivity with simulation methods (Filla, 2012, 2017; Yao et al. 2012; Oh et al. 2015; Xiong et al. 2019). This study focused on the operator and working conditions of the machine, rather than the machine's energy efficiency. In the study, the loading performance of a wheel loader operator working with a bucket was investigated under the following conditions:

➤ Monitoring/not monitoring the loader operator
➤ Experienced/inexperienced operator
➤ Daytime and night studies
➤ Sunny and rainy weather conditions
➤ Loading with and without bucket scale
➤ Compressed and free material loading
➤ The most ideal and worst working conditions.

In addition to the scenarios mentioned, the loading performances of wheel loaders with 4 different capacities under similar conditions were investigated.

Method

Field studies were evaluated in five parts. In the first part, the effect of monitoring/not monitoring the loader operator on loading performance is evaluated. In the second part, the loading performances of 7 different loader operators are examined. In the third part, the effects of different operating conditions on the loading performance of wheel loaders are investigated. In the fourth part, the effect of the ideal and worst working conditions on the loading performance is examined. In the fifth and last part, the loading performances of the loaders of different capacities used in CLI were evaluated.

In the study, performance data of wheel loaders were determined from field measurements. Field measurements were done in a classical V-cycle with equal orientation on both sides.

Loading time was taken into account as the main criterion in the performance analysis of wheel loaders. However, in the section where the effect of the loader bucket scale is examined, the amount of material loaded was also taken into account in addition to the loading time.

Furthermore, in the section where wheel loaders in CLI are compared in terms of energy efficiency, fuel consumption of wheel loaders was also taken into account in addition to loading times).

Determination of loading times

In the study, 40 measurements were made to determine the impact of each scenario. In each measurement, the loading of a single vehicle (approximately 26 tons-28 tons) was evaluated. The loading period started with the wheel loader moving to the loading area and stopped when the wheel loader reached the starting position after the material was loaded into the vehicle. Measurement times are expressed in seconds.

In the measurements where the effect of not monitoring the operator and the effect of the operators' experience on the results were investigated, the operator's short loading cycle was not intervened. In other measurements, the operator's short loading cycle was followed and measurements outside the cycle were cancelled.

Determination of the amount of loaded materials

In the section where the effect of the loader bucket scale on the loading performance is evaluated, the amount of material loaded as well as the loading times are taken into account. In the measurements made here, the amount of loaded material was found by weighing the loaded vehicles on vehicle scales.

Determination of the amount of fuel consumed

In the section where wheel loaders in CLI are compared with each other, the amount of fuel consumed was also taken into account in addition to loading times. Diesel fuel consumption (A_{DF}) of wheel loaders was calculated by Equation [1].

$$A_{DF} = \frac{T_{DM}}{3600} \times A_{ADF} \qquad [1]$$

In Equation [1], T_{DM} refers to the total duration of all measurements performed for a scenario. A_{ADF} is the hourly diesel fuel consumption of wheel loaders. This value was found by dividing the total amount of fuel consumed by the wheel loaders during their work in CLI in 2022 by their total working time. A_{ADF} values of wheel loaders are presented in Table I. The value 3,600 is a coefficient added to express T_{DM} in hours.

Wheel loader performance measurements

Performance measurements of the wheel loaders specified in Table I were made at Can Lignite Enterprise in Turkey (Figure 2).

In the study, attention was paid not to interrupt coal sales activities while providing working conditions. For this reason, field studies lasted for approximately 4 months, and a total of 808 measurements were taken, including 720 valid and 88 invalid

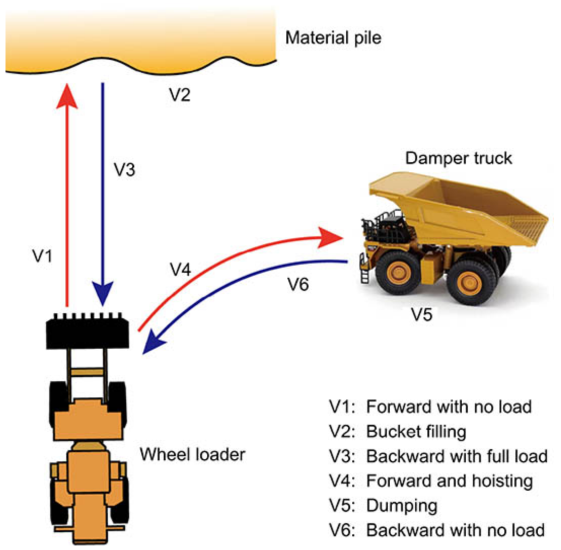

Figure 1—Short loading cycle (Huang et al. 2021)

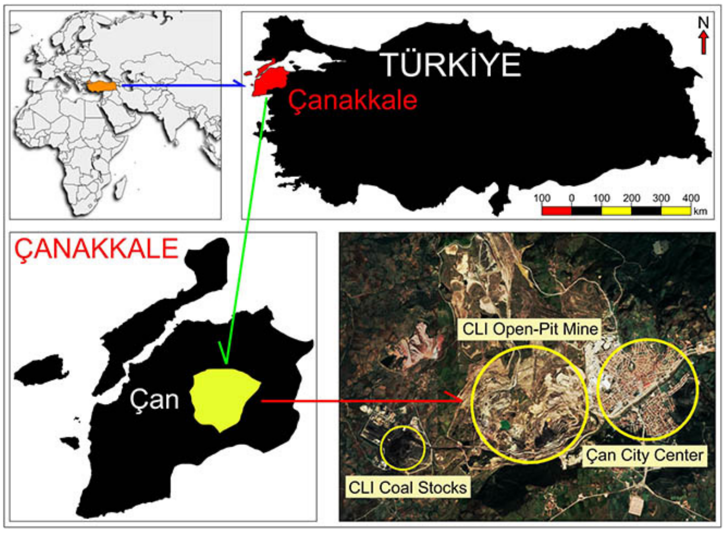

Figure 2—Location map

Table I

General information on wheel loaders

Wheel loader	Model	Power (hp)	Bucket capacity (yd3)	Machine weight (kg)	Working hours (hr)	*Diesel consumption (L/hr)
Cat 992K	2008	801	14.00	97,295	37,600	52.5
Komatsu WA800-3A	2004	826	14.39	101,900	46,000	67.6
Kawasaki 115 Z7	2020	538	10.46	55,200	11,300	35.2
Komatsu WA500-3	2007	235	6.54	28,220	24,400	32.2
Komatsu WA500-3	2007	235	6.54	28,220	28,000	33.8

*In the calculation of the AADF, the total working hours and total diesel consumption data of the loaders for the year 2022 are taken into account (Figure 3)

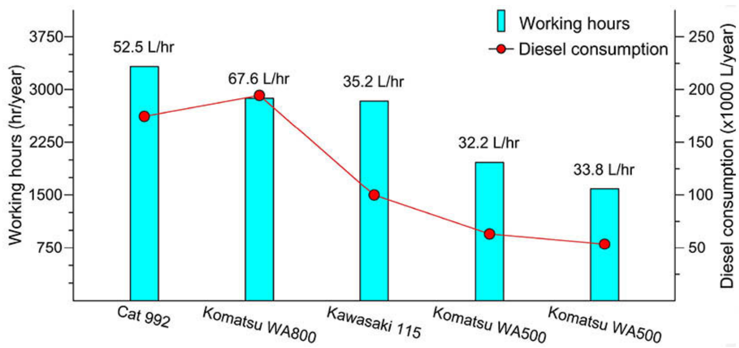

Figure 3—CLI loader working hours and diesel consumption data for 2022

measurements. In the study, the loaded trucks were weighed to determine the amount of coal loaded in each measurement. When the truck weights determined from each measurement are evaluated, the difference between the lowest weighing amount (26.5 tons) and the highest weighing (27.3 tons) amount was determined as 2.9%. Since the difference in weighing amounts is low, performance evaluations were made only on loading times. However, in the tests where the loader bucket scale was evaluated, the amount of material loaded was also taken into account.

The effect of monitoring/non-monitoring of the operator on loading performance

One of the important parameters in loading performance is the loading trajectory applied by the loader operator. Although the operators were instructed to use a classical V-cycle before the study, it is known from field experience that the operators will not fully comply with this cycle. For this reason, before starting the tests, the test was carried out to check whether the operators complied with the short loading cycle and the results were evaluated. In the conducted study, the loader operator's loading cycle (loading

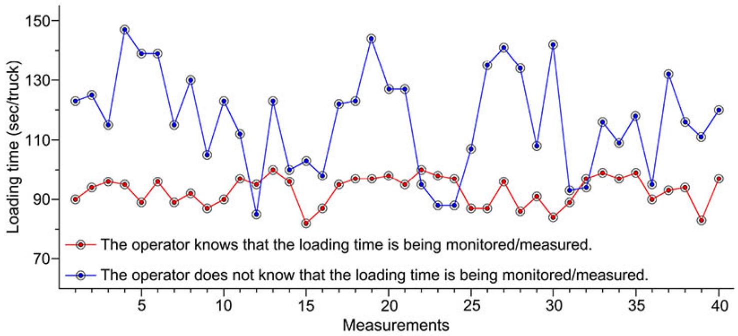

Figure 4—Effect of monitoring/not monitoring of the loader operator on loading performance

Table II

Effect of loader operator's experience on loading performance

Parameters		Operator No						
		1	2	3	4	5	6	7
Data		40	40	40	40	40	40	40
Range		79-90	84-95	84-99	82-100	86-104	90-104	129-156
Mean		86.1	89.6	89.8	93.0	97.2	98.9	140.8
Standard deviation		3.26	2.19	2.72	4.96	5.33	3.29	6.03
Variance		10.6	4.81	7.4	24.6	28.4	10.8	36.4
Experience	In CLI	8	7	6	4	3	3	<1
(Years)	Total	8	22	15	6	4	7	2

cycle is associated with loading time) was first measured by remote monitoring without the operator's knowledge. The loading performance of the operator, who was then informed that the measurement would be made, was measured closely. A Kawasaki 115 wheel loader was used in the measurements. The operator with 7 years of experience in CLI used the loader. Measurements were made in sunny weather and compressed material. The bucket scale of the loader was not used in the loading process. A total of 80 measurements were made during the measurements that lasted 8 days. The measurement results are given in Figure 4.

When Figure 4 is examined, the following important conclusions/observations are made.

➤ When the operator did not know he was being monitored (initial case), the operator's time to load a truck was measured between 85 to147 seconds (Data: 40; Mean: 116.7; Standard deviation: 17.1; Variance: 290,4). The main reason for the significant 65-second difference here is the variability of the operator's loading cycle
➤ When the operator knew he was being monitored (second case), the operator's time to load a truck was measured between 82 to100 seconds (Data: 40; Mean: 93.0; Standard deviation: 4.9; Variance: 24.6). The main reason for the 18-second difference here is the variation in the loading difficulty of the compressed material
➤ When the two conditions are evaluated, it is determined that if the operator knows that he is being monitored, he can improve the average loading time by 20.3%.

After it was determined that the monitoring of the operator caused a significant difference in the results, measurements were carried out by closely monitoring the operators in all other scenario and measurements outside the short loading cycle were cancelled.

The effect of loader operator's experience on loading performance

In the energy efficiency of the loader, the experience and ability of the operator who uses the machine are as important as the machine design. Within the scope of the study, the loading performances of 7 different wheel loader operators working in the enterprise were monitored. A Kawasaki 115 loader was used in performance measurements. Measurements were made in sunny weather and compressed material. The bucket scale of the loader was not used in the loading process. For each operator, 40 measurements were made. The results of the measurements completed in 26 days are presented in Table II.

When Table II is examined, the following important conclusions/observations were made.

➤ In the measurements, the highest loading time was determined from operator number 7. This operator has 3 months of experience in CLI and his total operator experience is 2 years
➤ In the measurements, the lowest loading time was determined from operator number 1. This operator started his career as an operator at CLI and has 8 years of operator experience
➤ It has been determined that, as the experience of the operators increases, the distribution of loading times becomes more balanced, in other words, the standard deviation values of the measurements decrease
➤ A difference of 63.4% was detected between the operators with the highest and lowest loading time. This difference showed that operator experience has a very significant effect on loading performance. In addition, the difference between the loading times of operators who have been working at CLI for

more than 6 years was determined to be 4.3%. This difference showed that similar experiences had little impact on loading performance.

The effect of different operating conditions on loading performance

In field experiences, it has been observed that weather conditions, loading zone, and loader bucket scale have an effect on loading performance and the degree of influence of these parameters has been measured within the scope of the study. In the performance measurements, the Kawasaki 115 loader was used by operator number 2, indicated in Table II. Measurements were completed in 16 days. Measurement results are given in Figure 5 and statistical analyses are given in Table III.

When Figure 5 and Table III are examined, the following important conclusions/observations are made.

- ➤ The average loading time of the wheel loader is 93 seconds in sunny weather and 99.3 seconds in rainy weather. Based on these values, it was calculated that the loading time of the wheel loader increased by 6.74% in rainy weather compared to sunny weather. The main reason for the difference here is that the operator increases the maneuver time in order to reduce the risk of work accidents that may occur due to slippery ground and reduced visibility. In other words, the operator works safer by reducing the machine speed. The loading in this scenario was carried out during the daytime and without using the loader bucket scale
- ➤ The average loading time of the wheel loader is determined as 93 and 96 seconds, respectively, during daytime and night operations. Based on these values, it was calculated that the loading time of the wheel loader increased by 3.41% at night compared to daytime. The loading in this scenario was carried out in compacted material and without the use of a loader bucket scale
- ➤ The mine-out coal in the CLI stock areas are stacked in layers and during this process, the coal stacks filled in each floor are compressed by machines (dozer, grader, cylinder). In order to determine the effect of this situation on the loading performance, some of the coal coming to the stock area was poured freely on the stock floor and was not compressed. In the performance measurements, the average loading time of the wheel loader was determined as 93 and 78 seconds in compressed and free material, respectively. Based on these values, it was determined that the loading time of the wheel loader increased by 19.3% in the compressed material compared to the free material. The loading in this scenario was carried out during the daytime and without using the loader bucket scale
- ➤ Bucket scales are used to load the desired quantities of coal to trucks. In the field observations, it was observed that the loading performance of the loader operators decreased considerably when bucket scales were used. In

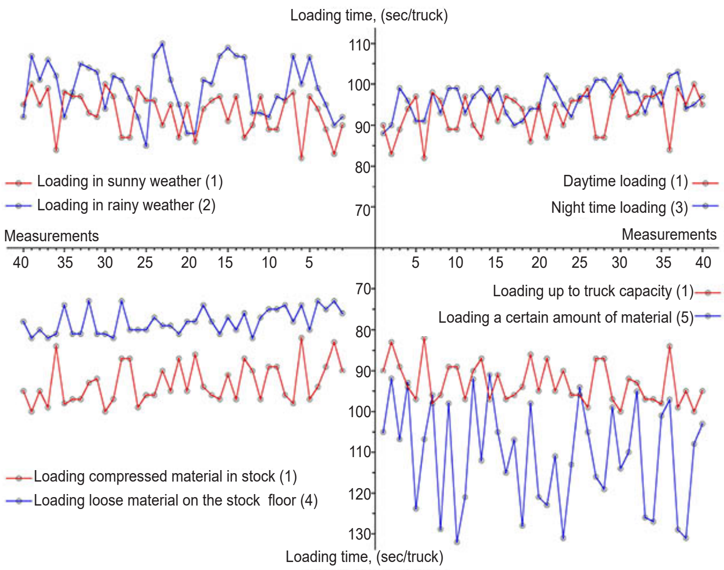

Figure 5—Effect of different operating conditions on loading performance

Table III
Statistical analysis of measurement results

Parameters	*Scenario No				
	1	2	3	4	5
Data	40	40	40	40	40
Range	82-100	85-110	88-103	73-82	91-132
Mean	93.0	99.3	96.2	78.0	111.7
Standard deviation	4.96	6.79	3.81	3.01	12.9
Variance	24.6	46.1	14.5	9.1	166.9

*Indicated in Figure 5

the performance measurements made on this situation, the average loading time determined in the case of using the bucket scale is 111.7 seconds, while the average loading time determined in the case of not using the bucket scale is 93 seconds. Based on these values, it was calculated that the use of bucket scales in the loading process increased the loading time by 18.92%. In addition, in the measurements carried out, the amount of loaded material is 5.28% less in the case of using a bucket scale. When evaluated in terms of energy efficiency, less material (5.28%) was loaded in a longer time (18.92%). The energy loss here is calculated as 25.2%. The loading process in this study was carried out during the daytime and in compressed material

➤ When the 40 measurements for each parameter were evaluated, the most consistent measurements (standard deviation: 3.01) were determined from scenario No. 4, where free material was loaded. On the other hand, the most inconsistent measurements (standard deviation: 12.9) were detected from scenario number 5, where the loader bucket scale was used. The results of the study show that as loading conditions become easier, operators' loading times become more consistent

➤ When the study results were evaluated in terms of loading times and the consistency of these times, the ranking of the scenarios from best to worst was evaluated as 4-1-3-2-5.

The effect of the best and worst working conditions on loading performance

In this section, the effect of the best and worst operating conditions determined from the study and specified in Table IV on the loading performance is evaluated.

Table IV

The best and worst working conditions

Parameters	The best	The worst
Operator	Experienced (Operator no. 1)	Inexperienced (Operator no. 7)
Monitoring of the operator	The operator knows	The operator does not know
Weather conditions	Sunny	Rainy and night
Material	Free	Compressed
Bucket scale	Not being used	Being used

Measurements carried out with the working conditions specified in Table IV were completed on 2 different days. The results of the study, in which a total of 80 measurements were carried out, are given in Figure 6.

When Figure 6 is examined, the following important conclusions/observations were made.

➤ Loading time was found to be between 69-80 seconds in the best conditions and 169-249 seconds in the worst conditions

➤ When the averages of the measurement results were evaluated, it was determined that the loading time in the worst working conditions was 285.5% longer than in the best working conditions

➤ It has been observed that in the worst conditions, the operator with little experience has difficulty in using the loader bucket scale. This is the most important reason for the inconsistency of measurement times, in other words, the high standard deviation amount.

Evaluation of loading performances of loaders of different capacities

A total of 200 measurements were carried out to determine the most advantageous wheel loader used in CLI in terms of energy efficiency. In the measurements, the loaders specified in Table I were used by operator number 2 specified in Table II. Measurements were carried out on compressed material in sunny weather. Bucket scales of the loaders were not used in the measurements. The results of the measurements, which took 18 days in total, are given in Figure 7.

When Figure 7 is examined, the following important conclusions/observations were made.

➤ Among the loaders, Komatsu WA500 loaders with the lowest bucket capacity have the longest loading times depending on bucket capacity

➤ The lowest average loading times for loading a truck belong to Komatsu WA800 (70.6 seconds) and Cat 992K (70.9 seconds) loaders

➤ Komatsu loaders have the highest energy consumption (>1.3 L/truck), while the Kawasaki 115 has the lowest (0.91 L/truck)

➤ Komatsu WA500s have the most ideal fuel consumption in terms of average diesel consumption per unit time (32–34 lt/h) as shown Table I. However, when the fuel consumption is evaluated together with the material loaded (1.3–1.4 L/truck), it is determined that the machines have high energy consumption

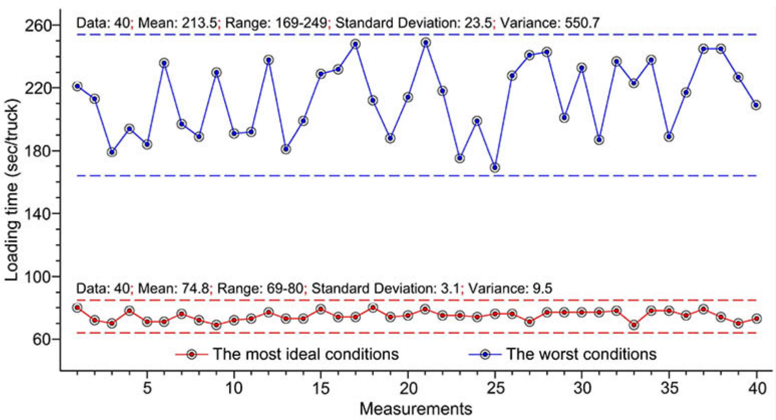

Figure 6—The effect of the best and worst conditions on loading performance

- ➤ The Cat 992K and Komatsu WA800 have similar power, bucket capacity, and machine weight as shown in Table I. Considering the energy consumption of these machines, of which the average loading times are very close to each other, Cat 992K is 22.7% more advantageous than Kawasaki WA800.

Although the Kawasaki 115 loader is preferably used in CLI due to energy efficiency, Cat 992 and Komatsu WA800 wheel loaders are needed due to the loading time advantage and increased workload. Additionally, Komatsu WA500 wheel loaders are generally operated at facility feed points due to their low fuel consumption per unit time.

The comparison performed in this section involves the loaders used in the CLI. For example, it would be misleading to generalize that the Cat 992K loader is a more advantageous machine than the Komatsu WA800 loader as a result of this study. The main reason for this is that the models, technologies, engine hours, and maintenance and repair processes of the compared machines are quite different from each other.

Conclusions

The important conclusions drawn from the study, which investigated the effects of different operating conditions and operator differences on wheel loader loading performance, are listed below.

- ➤ It has been found that when loader operators realize that they are being monitored or their performance is being monitored by an observer/researcher/manager, they can reduce the loading time of a truck by 20.3%
- ➤ It has been determined that the most important effect on the loading performance of the wheel loader is the experience of the operator. In the study, the loading efficiency of 7 operators, 6 of whom are experienced and 1 of them inexperienced, were investigated. As a result, it was determined that the loading time of the inexperienced operator was 63.4% more than the experienced operators
- ➤ It has been observed that operators move more carefully and therefore slower, due to the slipperiness of the loading zone in rainy weather. As a result of the study carried out to determine the effect of this situation on the loading time, it was determined that the loading time increases by 6.74% in rainy weather
- ➤ As in rainy weather, the loading performance of the operator decreases depending on the clarity of vision during night work. During the measurements carried out to determine the effect of the decrease in loading performance, it was determined that the loading time increased by 3.41% in night studies compared to daytime studies
- ➤ In field observations, it was observed that the operators had difficulty in loading the compacted material. In the measurements carried out to determine the loading difficulty between the compressed material and the free material, it was determined that the loading time increased by 19.3% when the compressed material was loaded
- ➤ Another scenario measured detected that, in field observations the use of bucket scales for wheel loaders is implemented. Bucket scales for wheel loaders are used in order not to exceed the legal load allowed for trucks in coal sales. On-site observations determined that the efforts of the operators to adjust the desired load reduced the loading efficiency. In the measurements carried out to reveal the effect of this situation, it was revealed that the use of the loader bucket scale increased the loading time by 18.92%
- ➤ The measurements carried out to determine the effect of the best and worst working conditions on the loading performance, showed that the loading time of the inexperienced operator tested under the worst conditions was 285.5% longer than the experienced operator tested under the best conditions.

Within the scope of the study, the performances of 5 wheel loaders in CLI were also investigated. Research results showed that the most advantageous loader in terms of energy consumption is the Kawasaki 115 (0.91 L/truck). Kawasaki 115 has more advantages than other loaders in terms of model, engine hours, technology and maintenance-repair processes. When all these processes were evaluated, it was expected that the Kawasaki 115 would be the most advantageous loader. This result of the study actually showed how important machine renewal is in terms of fuel consumption and loading performance.

Recommendations

In parallel with the study results, the following recommendations were developed:

- ➤ The loader operator has the most significant impact on loading performance. It is recommended to implement social and economic improvements to increase the job commitment of experienced operators
- ➤ The use of a loader bucket scale increases loading time and the inconsistency of loading times. For this reason, it is recommended to investigate alternative options to the loader bucket scale along with cost analysis
- ➤ In CLI, it is recommended that wheel loaders that have reached the end of their useful life are replaced with new ones for energy efficiency.

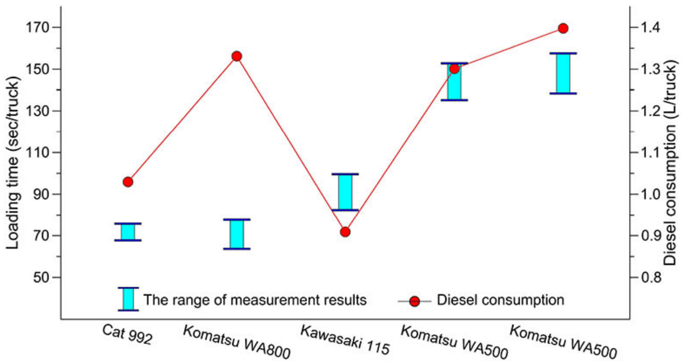

Figure 7—Loading performance and energy consumption of loaders of different capacities

Acknowledgement

The authors would like to thank the staff of Can Lignite Enterprises.

Credit Author Statement

AC: Conceptualization, methodology, investigation, validation, formal analysis, resources, writing.

Declaration of Competing Interest

The author declares that there is no conflict of interest.

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