

Evaluation of the energy consumption of container diesel trucks in a container terminal: A case study at Klaipeda port

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Abstract

Introduction: In the paper, we examine the energy consumption efficiency of specialized container diesel trucks engaged in container transportation at a seaport terminal.

Objectives: Using the container terminal at Klaipėda in Lithuania as the background for the research, we produced an improved energy consumption model for measuring the theoretical energy consumption and regeneration of diesel trucks at the terminal and provide a comparative analysis.

Methods: We created a mathematical model which describes the instantaneous energy consumption of the diesel trucks, taking into account their dynamic properties and the overall geometry of their routes—“Ship-Truck-Stack-Ship”—using the superposition principle. We investigated other critical parameters relevant to the model and provide a statistical evaluation of the transportation process using data from a case study of Klaipėda port, where we collected measurements of container transportation parameters using georeferenced movement detection and logs from wireless equipment positioned on the diesel-powered container trucks.

Results: The modeling results showed that an instantaneous evaluation of energy consumption can reveal areas in the container transportation process which have the highest energy loss and require the introduction of new management and process control initiatives to address the regulations which are designed to decrease harmful industrial emissions and encourage novel technologies and thereby increase the eco-friendliness of existing systems.

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Conclusion: Based on the research results, the article can provide a reference for the estimation of diesel truck efficiency in seaport terminal operations.

Keywords

Container terminal, container truck, energy consumption, measurement, modeling, transportation

Introduction

The transport sector accounts for a quarter of the total greenhouse gas emissions produced by the European Union (EU), and this proportion is still growing as industry intensifies. To reduce the effect on the climate, it is necessary to eliminate emissions due to transport by 90% by 2050,¹ while also ensuring that on-site cargo handling services in the transport industry remain internationally competitive.² The most effective means of enhancing container handling operations at these terminals is in determining the most critical operations where energy loss is encountered,³ improving the existing systems through the replacement or improvement of infrastructure,⁴ and proposing complex solutions to maintain the sustainability of the transportation operations.⁵ However, multidimensional performance evaluation metrics such as these require a significant investment of time, effort, sectoral expertise, and holistic knowledge which are not suitable for instantaneous evaluations of separate container handling processes. CO₂ emission calculation methods have also been used to assess the efficiency of container handling terminals.⁶ Researchers⁷ have designed models to simulate the quantification of carbon emissions in which the energy consumption^{8–12} of container trucks is based on diesel consumption. However, these models only examine the overall efficiency of the terminal over a long period and do not provide an opportunity to examine the efficiency of individual container handling operations and infrastructure units. The tasks of scheduling container transportation routes, optimization, and synchronization of handling processes have been solved by various researchers. For example, Sha et al.¹³ proposed a novel integer programming model for the optimization of yard crane scheduling and their energy consumption at container terminals. This model considered key factors such as crane movement and turning distances and the practical operational rules directly related to total energy consumption. With the growing popularity of automated guided vehicles (AGVs) at container terminals, some previous studies have focused on integrated scheduling for the coordination of handling equipment and AGV routing,¹⁴ multi-AGV scheduling for conflict-free path planning,¹⁵ and optimization of strategies for yard truck scheduling at container terminals¹⁶ to minimize energy costs. Other studies^{17–22} have analyzed quay cranes (QCs) and related seaport infrastructure to improve transportation operations.

Previous studies have introduced models for the estimation of energy consumption in electric vehicles (EVs),²³ investigating energy recuperation capabilities and motor overload conditions. Recent literature contains energy modeling techniques for EV energy consumption in large-scale transportation networks.^{24,25} Some models provide simulations of the battery powered AGV systems used at automated

container terminals, evaluating their performance²⁶ according to parameters such as the number of AGVs, charging station configurations, recharging policies, etc. However, these models are not suitable for the estimation of energy consumption by container transportation at the terminal. Furthermore, diesel-powered container transportation currently prevails at seaport container terminals, and battery powered AGVs are still the machines of the future. It is therefore important to identify the energy needs to transport a container from ship to stack to minimize fuel consumption and CO₂ emissions and determine the potential energy savings through the deployment of battery powered AGVs.

In summary, previous studies have focused on the assessment of the general performance of container terminals over a long period but did not consider individual container transportation route analysis in terms of energy consumption; no specialized models for the estimation of instantaneous energy costs involved in transporting individual containers at a terminal are available. In the present article, we analyzed the technical efficiency of container handling equipment (i.e. diesel-powered container trucks) in terms of energy consumption per route (cycle)—“ship-truck-stack-ship”—using a model which evaluates instantaneous energy consumption. The results allow the total efficiency of container handling during truck operations to be increased through the use of the superposition principle. The model was verified with data collected from on-site measurements at the Klaipėda port container terminal.

Methods

In this section, we present a mathematical method which describes fuel and energy consumption based on the experimental data from on-site measurements. This method not only allows the total fuel consumption for the entire operational period to be evaluated but also the fuel consumption for each individually transported container. The model also allows a real-time estimation of the efficiency of the vehicle’s on-site movements.

Energy cost estimation model

The model calculates energy consumption according to the mass of the truck, its coordinates, and its acceleration values. Specific parameters were recorded for each point in 2D space (refer to Figure 1 for the model): traction force $F(t,C)$, which changes over time and depends on fuel consumption, truck velocity $v(t)$, total resistance force $F_T(t)$, and the tangent to the trajectory $\tau(t)$ intersecting at a single point of mass. The coordinates were calculated for each point of mass in the modeled body.

The work of each truck is defined by a cycle: the truck moves from the ship to the stack and back again. During the cycle, the mass of the modeled body changes. In the model, the total mass m_1 comprises the mass of the truck plus the mass of the container it carries, and mass m_2 is the mass of the truck alone. The total mass

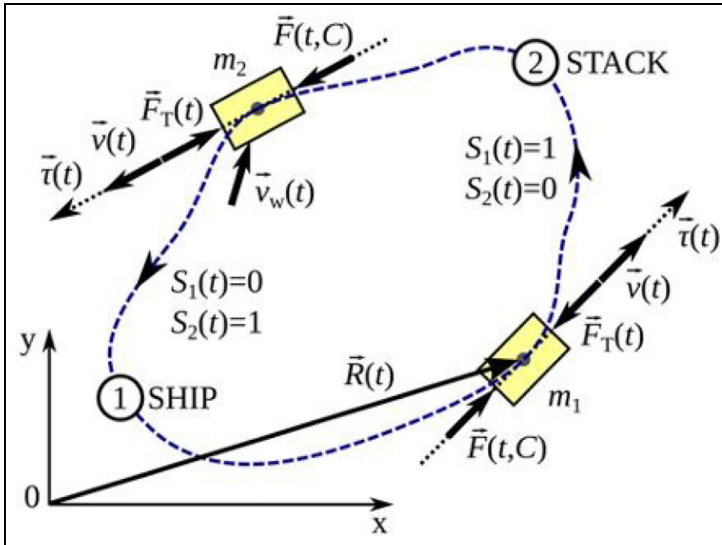


Figure 1. Representation of truck dynamics and container transportation in the port.

changes over time as different containers are transported. At some point in time, two containers may be placed on the truck (TEU containers). The image below (Figure 2) demonstrates the changes in total mass over a single cycle of the diesel truck at the terminal.

Figure 2 indicates that the truck waited for the crane operation for up to 300 s (in the presented case study). Two 20-foot containers were loaded at the 320th second. The first 20-foot container was unloaded from the truck into the stack by the end of the 440th second. The second 20-foot container was unloaded from the truck by the end of the 640th second, and the truck returned to the crane by the end of the 800th second, concluding the full cycle.

Evaluation of the cycle included the energy consumption model, which is necessary for the estimation of energy loss during these full cycles at the terminal. To calculate these coefficients, additional measurements were conducted with the truck and the measuring equipment during the experimental phase. An explanation of the methods applied in these experiments is presented in detail in sub-section IV.

We examined three different movement modes in the container trucks to estimate their fuel consumption: 1—acceleration; 2—movement with inertia; 3—braking process. The first mode was calculated when the truck's acceleration was positive: $\frac{da}{dt} > 0$, $a(t) > 0$. The second mode was calculated when the truck moves with inertia: $\frac{da}{dt} < 0$, $a(t) > 0$. The third mode was calculated when the truck decelerates using brakes: $\frac{da}{dt} < 0$, $a(t) \leq 0$. To calculate the energy and fuel consumption, only the first and second modes were considered. To calculate the energy and fuel consumption for the third mode, only the minimum acceleration values were used $-a(t)m_i$. These modes can be used to evaluate the movement and fuel

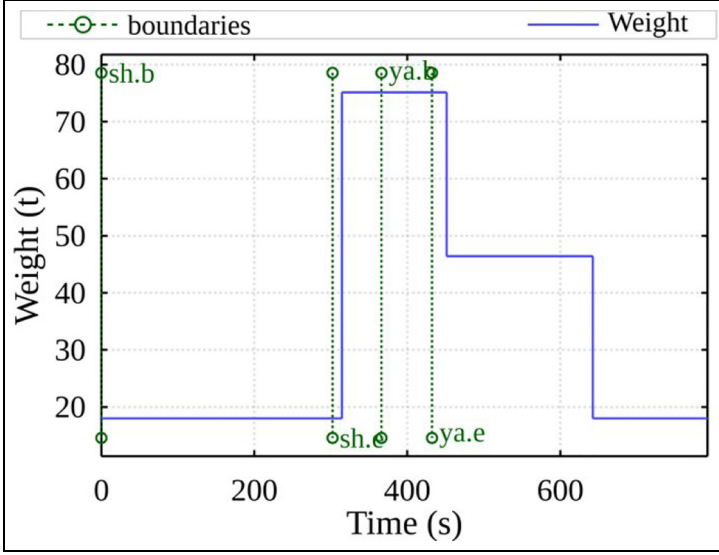


Figure 2. Example of the change in mass during a single transportation cycle at the terminal.

consumption of both loaded and unloaded trucks and present an opportunity to decrease consumption in all cycles. Therefore, the movement mode can be described according to energy consumption criteria (power).

Truck movement power P_{mov} is calculated according to:

$$\begin{aligned} P_{mov} &= v\vec{\tau}^T(m_t\vec{a} + \vec{\tau}F(t, C_t(t)) - \vec{\tau}F_T(t)) \cdot H(\vec{\tau}^T\vec{a}) \\ &= v(m_t a + F(t, C_t(t)) - F_T(t, v)) \cdot H(\vec{\tau}^T\vec{a}), \end{aligned} \quad (1)$$

Where $F(t, C_t(t))$ is the traction force, $C_t(t)$ is the fuel consumption, $v(t)$ is the velocity of the total mass body at time t , τ is the unit vector tangent to the trajectory, $F_T(t, v)$ is the resistance force, $H(\vec{\tau}^T\vec{a})$ is the Heaviside function, and $a(t)$ is the acceleration value of the body mass m_t . The total mass of the body is described as:

$$m_t = (m_{truck} + m_{cont.})S_1(t) + m_{truck}S_2(t) = m_1S_1(t) + m_2S_2(t), \quad (2)$$

Where $m_1 = (m_{truck} + m_{cont.})$ as the mass of the truck and the container, and $m_2 = m_{truck}$ as the mass of the truck. $S_1(t) \cdot S_2(t)$ are the step-functions which describe the path from the ship to the stack ($S_1(t) = 1, S_1(t) = 0$) and the path from the stack to ship ($S_1(t) = 0, S_1(t) = 1$).

The total movement resistance force $F_T(t, v)$ of the body is calculated for each point in time t according to:

$$F_T(t, v) = F_{air}(t, v) + F_{roll}(t, v) + m_t a(t), \quad (3)$$

This force depends on the rolling resistance force $F_{roll}(t)$ and air drag force:

$$F_{air}(t, v) = \frac{1}{2} C_a A \rho (v - \vec{\tau}^T \vec{v}_w)^2 \text{sign}(v - \vec{\tau}^T v_w), \quad (4)$$

where $F_{air}(t, v)$ is the air drag force, C_a is the truck drag coefficient, \vec{v}_w is the wind vector, ρ is the air density; A is the frontal cross-sectional area of the truck calculated according to:

$$A = A_1 S_1(t) + A_2 S_2(t), \quad (5)$$

where $S_1(t) = 0$, A_1 is the frontal area of a loaded truck and A_2 is the frontal area of the unloaded truck such that $A_1 > A_2$.

The rolling resistance force $F_{roll}(t)$ which acts on the moving truck at the specified time is calculated expressed by:

$$F_{roll}(t, v) = m_1 g f_{r1}(v) S_1(t) + m_2 g f_{r2}(v) S_2(t), \quad (6)$$

where $f_{r1}(v)$ is the rolling resistance coefficient with body mass body m_1 , $f_{r2}(v)$ is the rolling resistance coefficient with body mass body m_2 , and g is the acceleration due to gravity (9.81 m/s^2).

The power which is lost when the truck brakes is calculated according to:

$$P_{BR}(t) = v(t) F_T(t, v) H(\vec{\tau}^T \vec{a}(t)) H(-\vec{\tau}^T \frac{d\vec{a}(t)}{dt}) + v(t) m_i |a_{av}| H(-\vec{\tau}^T \frac{d\vec{a}(t)}{dt}), \quad (7)$$

The first member of equation (7) represents the power in the second mode, and the second member represents the power in the third mode (Figure 3), where:

$$a_{av} = 1/(t_2 - t_1) \int_{t_1}^{t_2} a(t) dt, \quad (8)$$

where the interval $t_j - t_i$ acceleration is negative, $a(t) < 0$ (braking in progress).

Energy consumption was calculated by numerical integration using the trapezoidal method. The integration step was determined by the data recording time-step, which was 10 ms.

Fuel consumption evaluation method

In the fuel consumption calculation, we assumed that the fuel consumption of a truck involved two components: fixed, to maintain the efficiency of the truck, and variable, to overcome the forces which resist movement during acceleration or maintaining a constant velocity. Variable fuel consumption has a linear relationship between the power supplied to the truck wheels and the fuel consumption of the engine at that time.

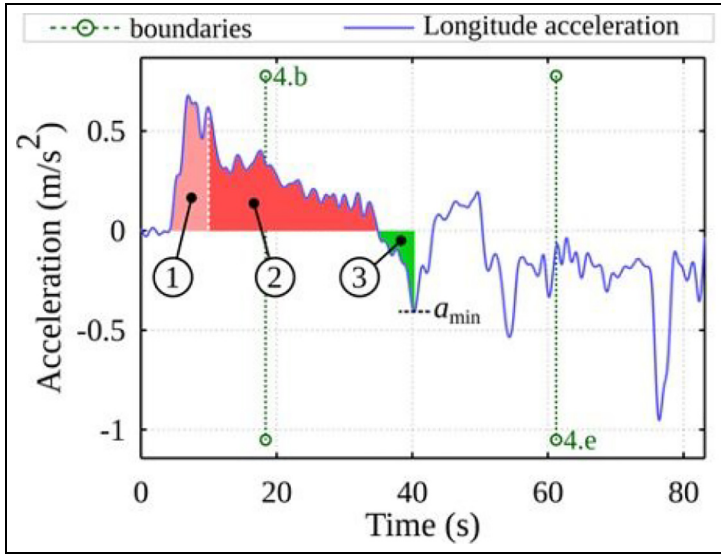


Figure 3. Container truck movement mode: 1—acceleration; 2—movement with inertia; 3—deceleration (braking process).

Constant fuel consumption at a specific point in time is expressed as:

$$C_0(t) = p_0 b(t), \quad (9)$$

where p_0 is the constant coefficient. The factor $b(t)$ is determined by:

$$b(t) = \begin{cases} 1, & \text{when } da(t)dt > 0 \\ 0, & \text{when } da(t)dt \leq 0 \end{cases} \quad (10)$$

Variable fuel consumption at a particular point in time is expressed as:

$$C_d(t) = p_d P_{mov}(t), \quad (11)$$

where p_d is the coefficient and fuel consumption at a specific point in time. The total fuel consumption at any given time is obtained from:

$$C_i(t) = C_0(t) + C_d(t). \quad (12)$$

Each component's factors are calculated from the truck's measurement data: mass, acceleration, velocity, and total fuel consumption $C_i(t)$ during the measurement period.

By integrating (12) during the measurement period (from time t_s to time t_e) for each cycle, we obtain total fuel consumption (13). The fuel consumption after the N^{th} cycle is equal to:

$$\sum_{k=1}^{N_{\text{cycle}}} \int_{t_{sk}}^{t_{ek}} C_{0k}(t)dt + \sum_{k=1}^{N_{\text{cycle}}} \int_{t_{sk}}^{t_{ek}} C_{dk}(t)dt = \sum_{k=1}^{N_{\text{cycle}}} \int_{t_{sk}}^{t_{ek}} C_{tk}(t)dt, \quad (13)$$

Equation (13) can be rewritten as:

$$ap_0 + bp_d = c, \quad (14)$$

where a , b , c are the coefficients:

$$\begin{aligned} a &= \sum_{k=1}^{N_{\text{cycle}}} \int_{t_{sk}}^{t_{ek}} C_{0k}(t)dt \\ b &= \sum_{k=1}^{N_{\text{cycle}}} \int_{t_{sk}}^{t_{ek}} C_{dk}(t)dt, \\ c &= \sum_{k=1}^{N_{\text{cycle}}} \int_{t_{sk}}^{t_{ek}} C_{tk}(t)dt \end{aligned} \quad (15)$$

The fuel consumption coefficients are determined after the N^{th} cycle by minimizing the objective function:

$$\min \Phi = (ap_0 + bp_d - c)^2, \quad (16)$$

We introduce the variables vector $\vec{x}^T = [p_0, p_d]$. Minimization of the objective function is performed using the method of iterations, when each iteration k solves the following equation:

$$[I_k]^T [I_k] \Delta \vec{x}_k = - [I_k]^T \Phi_k, \quad (17)$$

where the Jacobi matrix:

$$[I_k] = \left[\frac{d\Phi(x_k)}{d\vec{x}} \right]. \quad (18)$$

After solving (17), we obtain the improved variable vector:

$$\vec{x}_{k+1} = \vec{x}_k + \Delta \vec{x}_k, \quad (19)$$

where k is the iteration number.

To calculate fuel and energy consumption, it is necessary to know the components which resist movement of the truck. The calculation method of these components is presented in sub-section III. To find these components, experimental measurements were performed in the field to determine the necessary data for the calculations.

Method of estimation of the air and rolling resistance coefficients

To calculate the energy expended in transporting the container, it is necessary to assess the aerodynamic coefficients and total resistance to the movement of the truck. The method for determining these coefficients experimentally is given below.

The coefficient of the total rolling resistance is estimated for each period such that $t = t_{i+1} - t_i$. This allows evaluation of the fuel consumption of a truck with a cargo load during movement, where $S_1(t) = 1$, and without a load, where $S_2(t) = 1$. This improvement in the rolling resistance coefficient is necessary because it allows us to estimate the vertical strain on each truck wheel. This method can be applied up to velocities of $v_{al} = 30$ km/h, which is suitable for the studied case since truck speed in the terminal is restricted up to 30 km/h.

The total rolling resistance coefficient during the period $t = t_{i+1} - t_i$ is calculated from the equation:

$$f_{rk,i,i+1} = \frac{28.2 \cdot (a_{i+1} \cdot v_i^2 - a_i \cdot v_{i+1}^2)}{1000 \cdot (v_i^2 - v_{i+1}^2)}, \quad (20)$$

where $k = 1$ when $S_i(t) = 1$, and $k = 2$ when $S_i(t) = 2$; $a_i = a(t_i)$ and $a_{i+1} = a(t_i + t)$; $v_i = v(t_i)$ and $v_{i+1} = v(t_i + t)$ for the movement velocities of periods t_i and t_{i+1} .

The movement velocity v_{i+1} is determined by using the acceleration values a_i and a_{i+1} according to:

$$v_{i+1} = v_i + \frac{t}{2}(a_i + a_{i+1}), \quad (21)$$

Determining the aerodynamic drag coefficient C_a applies the same procedures as determining the rolling resistance. The drag coefficient C_a in the period $t = t_{i+1} - t_i$ is calculated according to the expression:

$$c_{k,i,i+1} = \frac{6 \cdot m_t \cdot (a_i - a_{i+1})}{A \cdot (v_i^2 - v_{i+1}^2)}, \quad (22)$$

such that $v_i^2 - v_{i+1}^2 \neq 0$; where A is the frontal area of the truck determined from (5), m_t is the total mass of the truck calculated from (2) for $k = 1$ when $S_1(t) = 1, S_2(t) = 0$, and $k = 2$ when $S_1(t) = 0, S_2(t) = 1$.

Using these methods, we conducted a field experiment to determine the rolling resistance and air drag coefficients, which were then applied in the momentary energy (fuel) consumption model and energy (fuel) consumption calculation.

Setup of experimental equipment

This section describes the experimental conditions, measured parameters, and evaluated factors. Based on the presented methods, the equations can be applied to calculate the energy consumption required to transport a container at the container

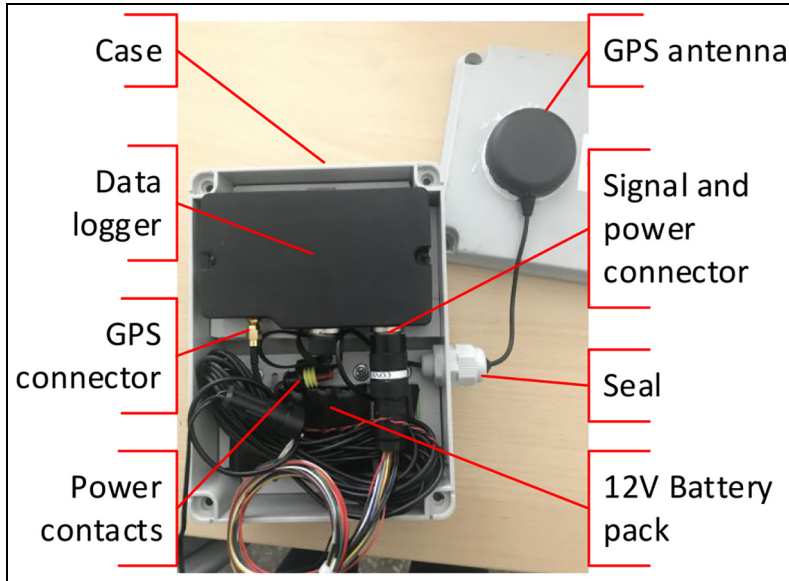


Figure 4. The measurement equipment is used to acquire the position of the truck and sensory data.

terminal using a diesel truck. We performed experimental studies to determine the coefficients of the resistances required for the calculations.

We used the measurement equipment shown in Figure 4 to acquire statistical data on the movement of diesel trucks at the Klaipėda port.

Using magnets, we mounted the equipment on the roof of a truck. The mounting position is shown in Figure 5.

At the start of the experiment, the fuel level was observed and recorded. The fuel level was then checked every half hour for the duration of the experiment. After an undefined period of operations, the vehicle was re-filled with fuel.

The operators checked the fuel levels before and after refueling, observing the amount of fuel displayed on the fuel pumps for more accurate results.

Results

Statistical analysis of the experimental data

Using modern instruments, we conducted experimental measurements of non-autonomous container handling in the port area. The movements of trucks and their container loads between the ship and container stacks were recorded. We analyzed 160 full cycles of the truck. The comparative results of the diesel truck route distance and travel time are presented in Figure 6.



Figure 5. Example of the trucks used in the experiment and the selected mounting point on the vehicle.

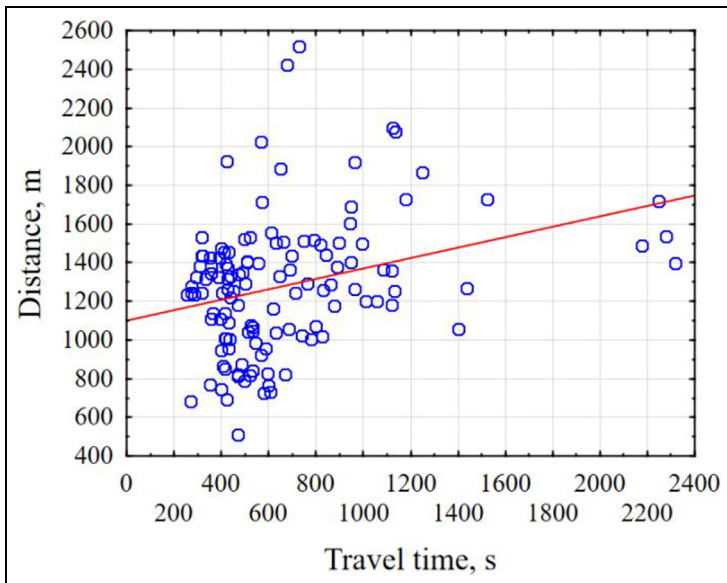


Figure 6. Relationship between the duration of a truck cycle in the port area and the distance traveled.

Linear equations can be written as $y = 1198 + 0.14x$, where y is the travel distance in meters and x is the time required to travel in seconds. The value of correlation coefficient r is 0.32. Figure 6 shows that the truck traveled a distance of 1200–1400 m in 200–1200 s. The time required can vary 10-fold.

The distribution of travel time is presented in Figure 8. In the case of non-autonomous loading, the data shows that the duration of transportation at the quay can vary from 253 to 2600 s. We can also see that the travel route is often

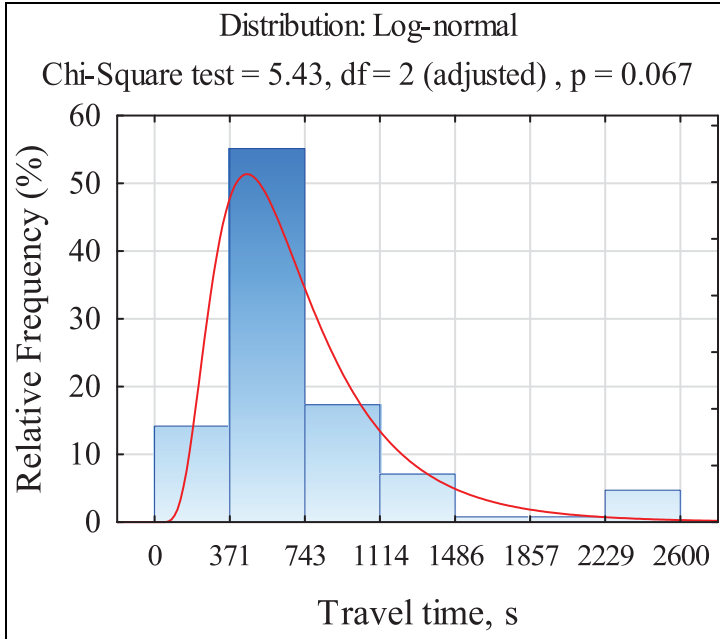


Figure 7. Distribution of the duration of truck movement in the port area.

longer than necessary, therefore, in general, managing the data and overall data flow between the loading process and transport equipment could optimize the travel time required for transportation, thereby reducing the required energy. We performed a statistical analysis of the measurement data using the Chi-Square method and found that the total driving time for “crane-stack-crane” movement is described by a lognormal distribution.

Statistical analysis of the measured travel times (Figure 7) showed that over 67% of the travel times did not last more than 743 s. However, approximately 35% of the travel times continued for more than 763 s as a result of interruptions, causing inefficient use of energy.

The travel distances measured in the port area are presented in Figure 8. The data for travel distance and duration indicated a very high scatter. The average travel distance was 1289 m, with a standard deviation of approximately 347 m. The largest distance traveled values was 2889 m, indicating that the vehicle traveled an inefficient trajectory (Figure 8).

The time taken for transportation in the port area could be reduced by synchronizing the work of vehicles and automating the port’s entire loading and transportation process, thereby using energy resources more efficiently and producing less pollution. This would be especially significant for ports located in urban areas.

The next section of the article provides detailed measurements of truck movements in the port to identify transport interruptions and truck or crane downtime

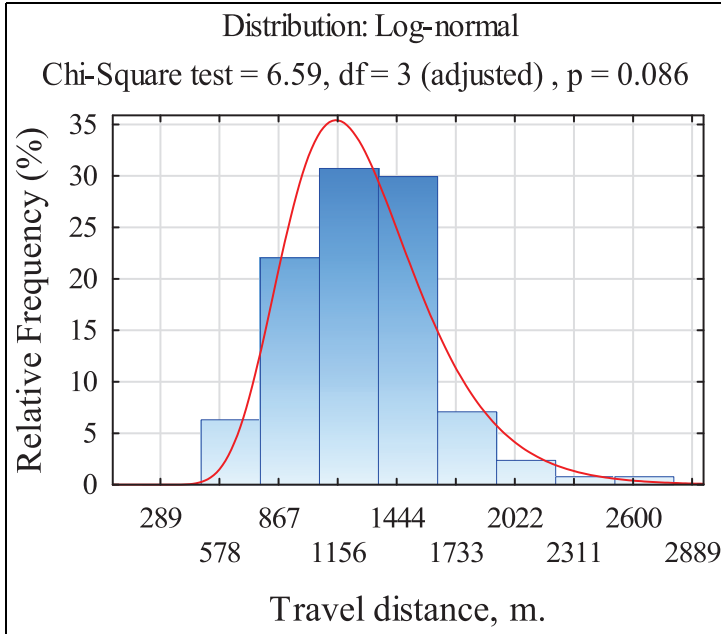


Figure 8. Distribution of the distance traveled in the port territory.

due to lack of coordination between the operational modes in the loading equipment.

Study of a single “ship-truck-stack-ship” cycle

The most common length of trajectory traveled by a truck is shown in Figure 9.

After receiving a container from the ship, the truck moved from the ship toward a designated stack to unload the container, then returned to the container loading area near the ship. Figure 9 shows the sections of the trajectory curve are marked with start “b” and end “e.”

As mentioned above, the truck’s position was measured using GPS equipment. Since the GPS information was transmitted by radio signal and the working environment at the port contained many metal structures, the experiment was exposed to a large amount of interference and the trajectory measurements were distorted.

Figure 10 shows the change of mass during a single route cycle of a truck loaded with a container.

Figure 11 graphs the measured velocities during the truck route cycle. The truck velocity was non-uniform and changed radically at each new turn.

Figure 12 shows the sudden and uneven changes in acceleration along the truck route (longitudinal acceleration). This unevenness may be a possible reason for the

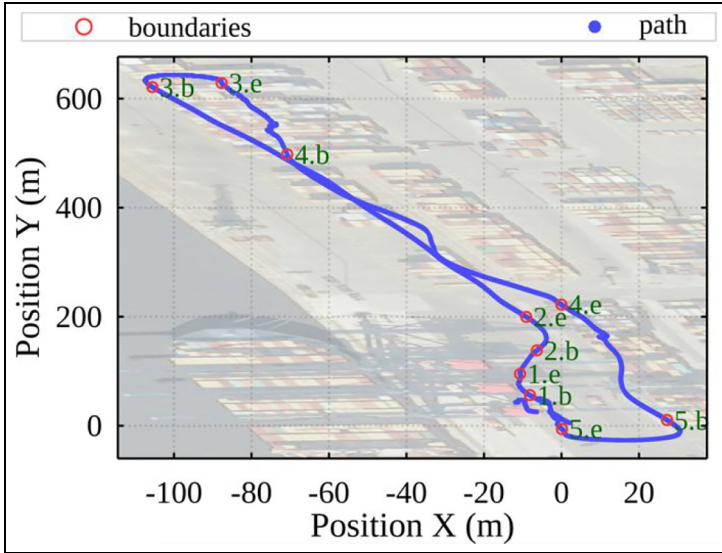


Figure 9. Trajectory of a truck at the terminal.
e: end; s: start.

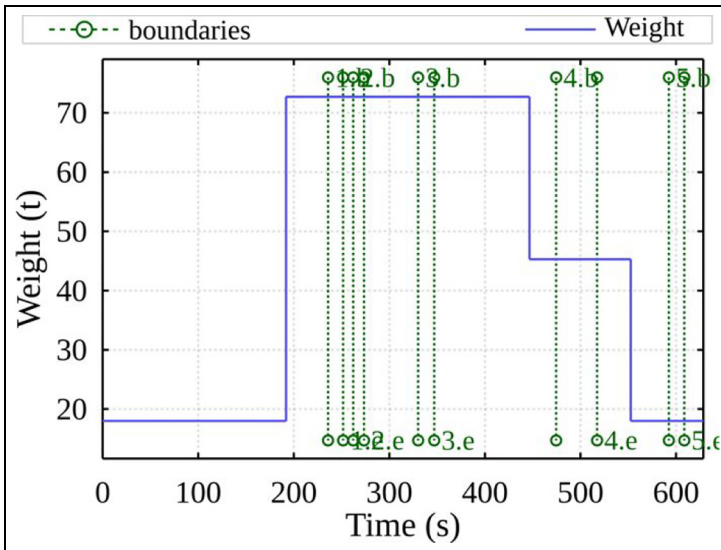


Figure 10. Variation of mass during the container transportation cycle.

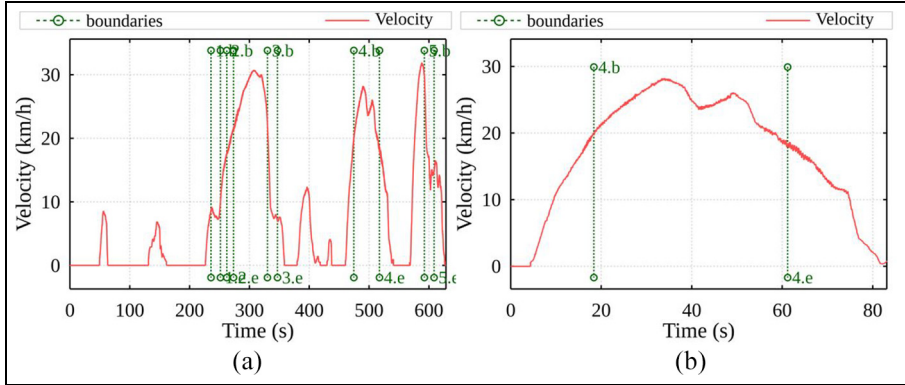


Figure 11. Truck velocity during a single transportation cycle: (a) full cycle and (b) period from 450 to 535 s.

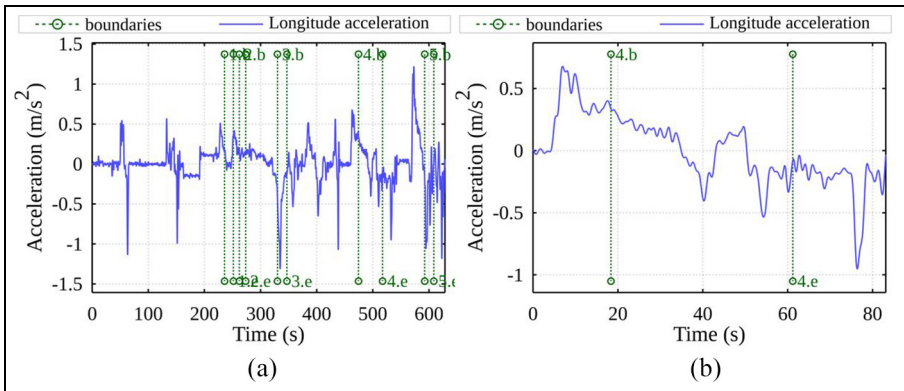


Figure 12. Changes in acceleration along the truck route (longitudinal acceleration: (a) full cycle and (b) period from 450 to 535 s.

high fuel consumption. The maximum variation in acceleration occurred during truck acceleration and deceleration.

Figure 13 shows the sudden and uneven changes in accelerations perpendicular to the truck route (lateral acceleration). The maximum accelerations occurred during a change in the truck movement direction. The vibrations (high spikes of lateral acceleration) also occurred because of insufficient fixation of the container. This acted on the driving performance and stability of the truck during the execution of a turn.

The instantaneous power calculated using the energy consumption model described in the above sections are shown in Figure 14. The presented results show

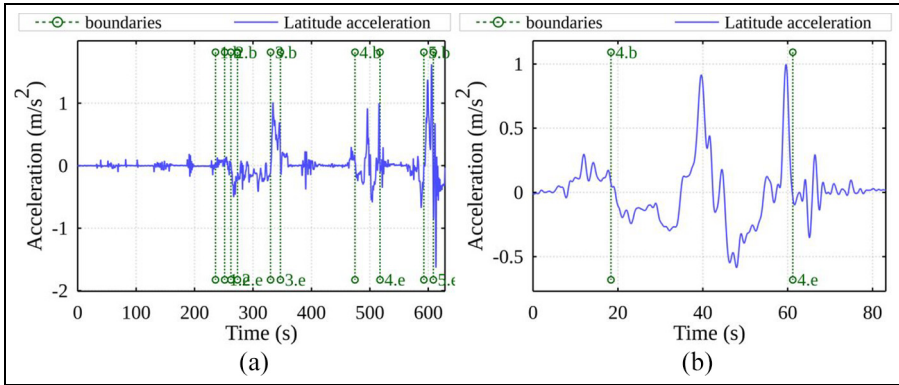


Figure 13. Changes in accelerations perpendicular to the truck route (lateral acceleration): (a) full cycle and (b) period from 450 to 535 s.

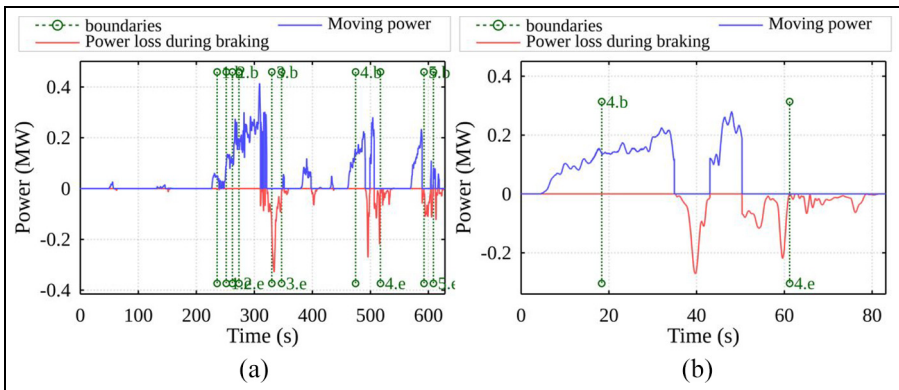


Figure 14. Instantaneous truck movement power (acceleration and continuous power for driving) and braking power: (a) full cycle and (b) period from 450 to 535 s.

an exaggerated velocity increase at several moments: a source of increased fuel consumption.

If the electric autonomous guided vehicle (AGV) ran on the same profile, its electric motor-generator would be rather powerful (>100kW) and have a battery power capacity capable of absorbing the energy which is recoverable during the braking. The red line shows the power during active braking of the truck. In the case of an internal combustion engine, the braking energy is converted into heat, but with the installation of an electric motor-generator, it can be recovered as electrical energy.

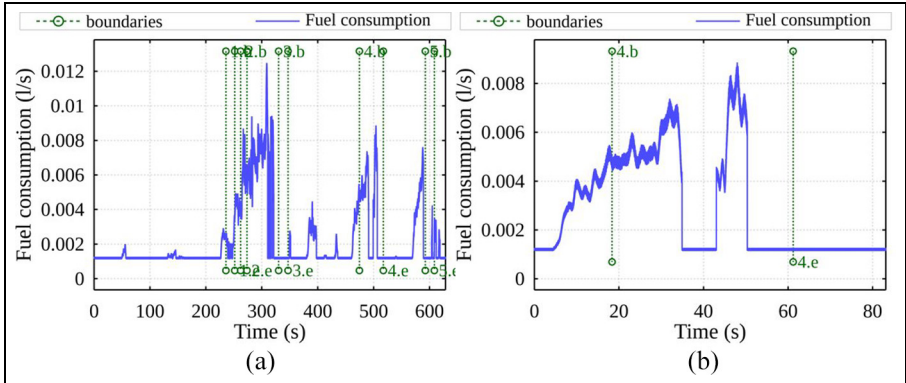


Figure 15. Fuel consumption during a single drive cycle of a loaded truck: (a) full cycle and (b) period from 450 to 535 s.

Figure 15 shows the fuel consumption required to accelerate or maintain a constant truck velocity. Fuel consumption was calculated according to the method presented in Section IV Part B.

Figure 15 indicates that during acceleration, fuel consumption momentarily exceeded 0.004 l/s. Also, during downtime (periods of 0–90 s, 130–200 s, etc.), fuel consumption in the truck reached significant values of >0.001 l/s. We can assume that sudden increases in truck velocity such as these increase overall fuel consumption. We can also observe from this investigated cycle that the downtimes when the truck was not moving could be partially eliminated by synchronizing the operations with other machinery on-site. During this cycle, energy resources can be conserved through the application of adjustments to the driving and acceleration characteristics.

Energy calculations

By using the presented methods for the estimation of fuel consumption, we can estimate the losses of energy for each mode for each period t . If we know the exact amount of energy lost, we can analyze the non-obvious reasons for this loss.

The energy consumption for one cycle is described according to:

$$E_{mov} = \int_{t_s}^{t_e} (P_{mov}(t) + P_{BR}(t))dt, \quad (23)$$

where t_s is the starting time point t of the truck work cycle (ship-stack-ship), t_e is the ending time point t of the truck work cycle (ship-stack-ship).

Measurements were taken for $N = 160$ truck work cycles at the terminal. After the measurement data were processed for all cycles, we discovered that the truck usually covered about 1.3 km of the road during its operating cycle. The

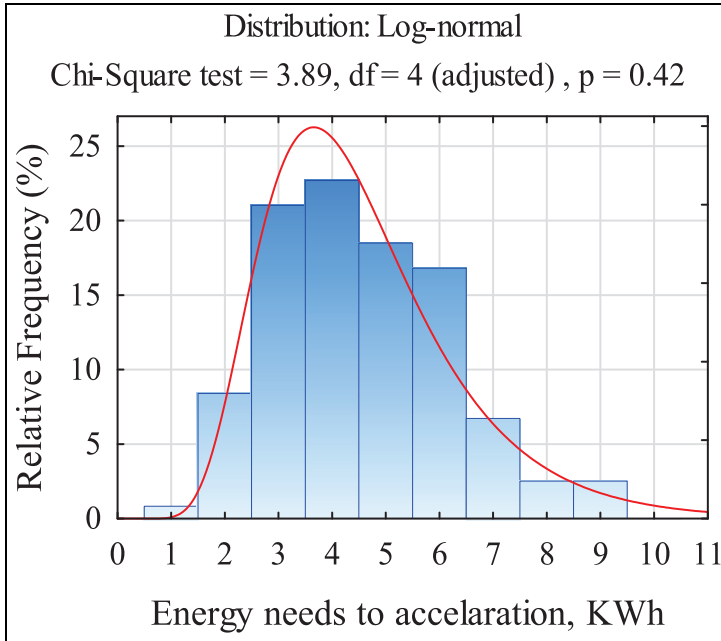


Figure 16. Histogram of the energy consumption of the truck.

distribution of the calculated energy consumption required to increase or maintain the velocity of the truck for each cycle is given in Figure 16.

We calculated that average amount of energy needed to accelerate the truck is at least 4.54 kWh for a 1.3 km cycle, that is, 3.49 kWh/km on average when the acceleration derivative is positive $da(t)/dt > 0$.

Figure 17 presents the loss of energy during the truck's braking cycle. The data best fits a lognormal distribution probability density (Chi-square test: $p = 0.48$). The observed mean is 1.99 kWh for 1.3 km, that is, 1.53 kWh/km on average. The energy loss during braking is about 43.8% of the total energy consumption of the truck. In this case, the truck executes braking by using the internal combustion engine in combination with brakes.

The diesel truck often queues or waits for the operation to start at the ship's crane or container crane during loading operations. Figure 18 shows the exact amounts of fuel consumed.

Lognormal distribution probability density can be applied to the data (Chi-square test: $p = 0.55$). These losses could be avoided by synchronizing cargo handling processes and integrating an electric drivetrain for the trucks. Calculations and experimental results show that during downtime, the trucks waste 0.131 of fuel on 22% of the loading cycles.

The coefficient of correlation r between the energy required for acceleration and the energy lost during braking is equal to 0.83 and shows a strong relationship.

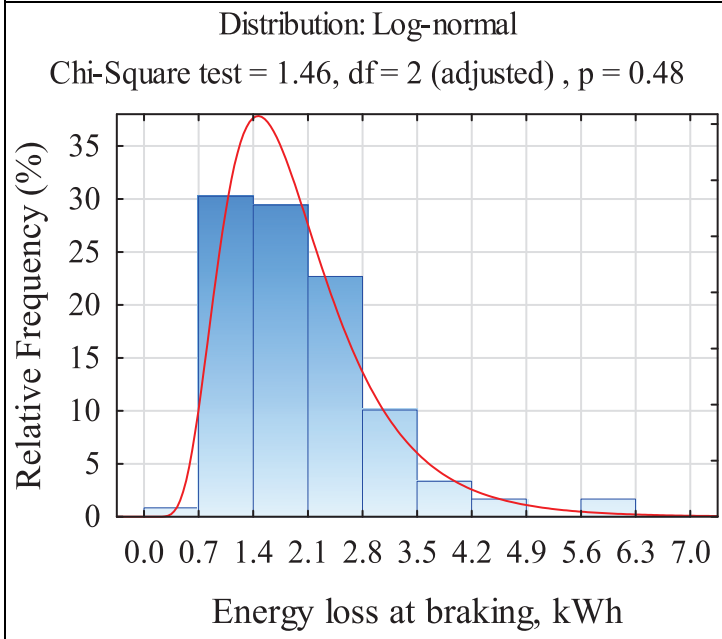


Figure 17. Histogram of truck energy loss during active braking.

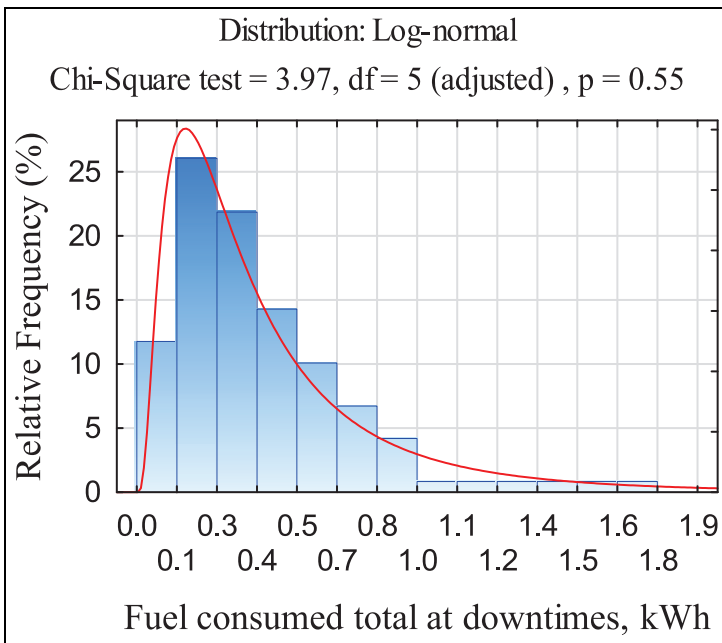


Figure 18. Histogram of truck fuel consumption during downtime.

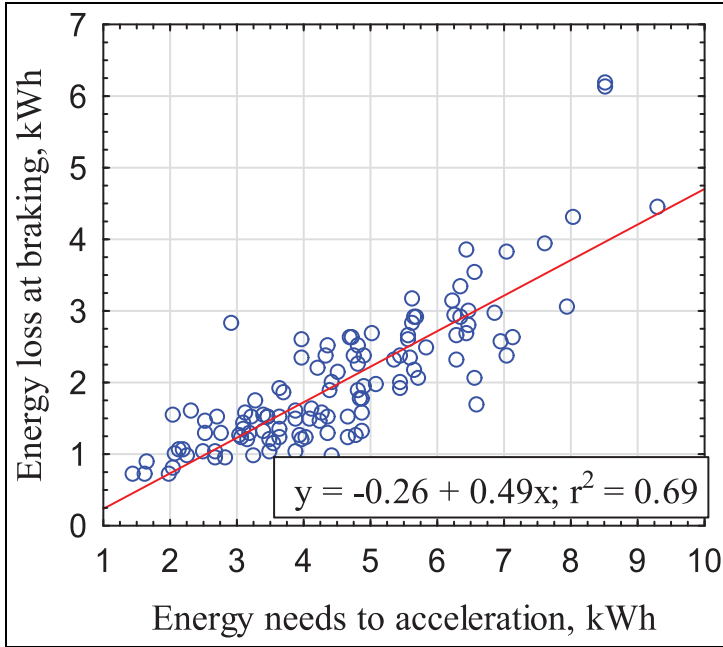


Figure 19. Relationship between energy required for acceleration and energy lost during braking.

Figure 19 presents a linear regression relationship $y = 0.497x - 0.26$ between the energy required for acceleration (x) and the energy lost (y) during braking.

The analysis shows that this energy could be recovered during the truck's operations via recuperation using an electric motor-generator and a smart battery storage system. Current transportation management is applied through non-optimal scheduling methods; cranes and trucks both experience frequent downtimes while they wait for container loading and unloading. Excess fuel is consumed as a result of these downtimes and raises the CO_2 emissions and other air pollution at the port. The pollution problem is serious, especially when a port, such as Klaipėda, is located in an urban area.

Notes and discussion

All the statistical data were acquired from the observation of 160 full work cycles of container trucks at the terminal. The effects of weather (wind speed, humidity, etc.) on the accuracy of the measurements was not considered in the model, nor was this information used to estimate the accuracy of the statistical data acquired. According to the on-site operators, the weather conditions do not significantly affect traction on the diesel truck tyres during summer and autumn. These conditions were therefore ignored, but they should be considered in future research.

According to the operators, visibility decreases during harsh weather conditions (heavy rain and wind) and they must be more cautious at these times. Crane operators are also more cautious under these conditions since they affect the speed of container placement on diesel trucks or AGVs. During winter, ice-covered roads may affect overall tyre traction by increasing the distance required to brake while transporting heavy cargo.

Downtime occurs frequently, and sometimes, either because of error or other scheduling reasons, the destination of the container changes several times per cycle. When the deck of the ship is fully unloaded, the lids which cover the ship's hull must be removed. This creates long waiting times (downtimes), the removal procedure taking up to 30 min to complete.

Fuel consumption is currently measured by acquiring the readings from sensors installed in the diesel truck's fuel tank. The observed measurements varied greatly in each work cycle. In future experiments, a different fuel consumption measurement method should be used. All these observations are critical and should be considered in future research and for the development of new synchronization tools and methods for port operations.

Conclusion

Each new solution and method must include concrete factors, that is, the travel speed of the trucks (with all acceleration points for each driver), and the quay crane and stack crane operational capabilities (for each operator). Consideration of these factors will certainly not only aid in increasing the efficiency of overall operations in the transport chain globally but will also help decrease harmful emissions.

The experimental measurements and the described methods show that the total energy losses reached 3.49 kWh/km during the transportation of a container, and the energy loss for braking reached 1.53 kWh/km on average. For each new cycle, the energy loss during braking reached 43.8% on average of the truck's total energy consumption.

The proposed fuel consumption model proved to be 91% accurate (it is very sensitive to real fuel consumption measurements and the statistical data of previous measurements with slight approximations). The coefficients of the proposed model were calculated from the two measurements taken during the on-site experimental study. The model was applied to calculate the theoretical fuel consumption for the third measurement. The results were compared to real fuel consumption, and only a 9% deviation was observed.

To ensure the model's long-term accuracy and possible adaptation in port operations, it is vital to measure the fuel consumption as accurately as possible. A slight change or deviation from the real value (up to 0.11) can have a critical effect on the final results (the accuracy of the proposed model). The methods, which we verified with an experimental study, can determine the fuel consumption of any port container truck (with or without a load), calculate the energy due to momentum, and determine the most rational control parameters for optimal fuel consumption

at any given moment based on real-time acceleration data. The truck, if operated effectively, would move with an even velocity to maximize fuel economy and solve the problem of fuel wasted as a result of downtime.

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