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Evaluation of the efficiency of the duty cycle of refuse collection vehicle based on real-world data

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Abstract. In this paper a method of the efficiency evaluation of the duty cycle of Refuse Collection Vehicle is presented. Using real world data, two representative duty cycles were analysed. Total cycle efficiency was calculated, as well as the efficiency of particular cycle phases. Then, energy needed to collect and compact the waste and energy from fuel were compared. Measured and calculated values were shown on the diagrams illustrating hydraulic system parameters and the real load applied to the chassis combustion engine. Then, basic statistical analysis of 524 duty cycles was performed, which shown dependencies between measured parameters and efficiency. Results of the analysis show that presented method can be used to quantitatively assess performance of RCV's regarding efficiency of hydraulic power delivery

1. Introduction

Studies of the waste management in Europe indicate a constant increase of the amount of waste produced, regardless of their origin, season and standard of living. At the same time the bulk density of municipal solid waste decreases and collection points become more and more scattered across the collection areas [1,2]. This increases the requirements for the refuse collection vehicles (RCV's), especially regarding their carrying capacity and reliability. Also emissions reduction and increase of the collection efficiency have recently gained on importance. In case of RCV's with traditional drive train, consisting of an internal combustion engine and hydraulic pump driven through a power take-off (PTO), reduction of the fuel consumption can be achieved in two areas of operation: collection and transport. However, influence of the RCV's design on the fuel consumption is restricted to mass reduction (e.g. through FEA [3]) and disconnecting the pump from PTO. Efficiency of the collection process can be increased through modification of the control algorithm [4,5] and optimization of the drive train configuration [6,7,8,9,10]. This paper contains analysis of the work cycles of a RCV, focused on energy consumption and efficiency of energy conversion in the combustion engine – hydraulic pump coupling.

2. Refuse Collection Vehicle working principles

RCV's carry out three main tasks: emptying of the containers, compaction of waste and its transport. For the purpose of this paper, it is necessary to define the term "duty cycle" as operation of a RCV during standstill, starting after switching the hydraulic system on and finishing after switching it off before driving to the next stop. Throughout the study, each stop of the vehicle, during which



compactor or lifting device were used is considered to be a duty cycle (excluding emptying of the truck at landfill).

A duty cycle starts when the vehicle comes to standstill, engine is idling and the hydraulic pump is switched on. RCV is then ready to work: both lifting device and the compactor can be used by the operators. Use of the latter will increase the idle speed to a certain value (in most cases, approximately 1000 RPM) during its operation. It has to be noted that the lifting device can operate regardless of the engine speed. Parameters of a duty cycle depend, among others, on:

- operators habits
- type of the waste containers and their weight
- area of collection
- vehicle specification

This is why various duty cycles can significantly vary in number of bins emptied per one compactor cycle and cycle time.

Hydraulic system of a RCV is powered by a twin-flow, fixed displacement pump that supplies energy to two separate circuits: compactor circuit and lifter circuit. The former drives compaction mechanism, ejector plate and lifting of the tailgate and it requires flow rate of approximately 100 dm³/min to operate. The latter is used to operate the lifting mechanism and its required flow rate is around 40 dm³/min. Some RCV's use a variable displacement pump but they are not the scope of this article.

3. Examined vehicle

Tests were conducted on a RCV based on a Scania chassis, equipped with 19 m³ body, X4 type tailgate (figure 1) and SK350 lifting device (figure 2). Table 1 presents basic specification of this vehicle.

Operating pressure was measured using pressure sensors, installed at the outlet ports of both chambers of the pump, what allows to calculate hydraulic energy that was supplied to the hydraulic system. Fuel consumption and engine speed were collected from CAN bus according to the FMS standard [11]. All of the acquired data was sent to an internet platform run by Xtrack [12], what enabled to monitor the vehicle's operation in real time. Measurement apparatus used in this study is almost undetectable and does not disrupt operation of the vehicle.



Figure 1. Tested vehicle – Scania P320 equipped with X4 bodywork



Figure 2. Lifter SK350 – one of the most popular bins lifting system

Table 1. Vehicle specification

Chassis	Scania P320 6x2
Engine	320 HP, 9.3 liter disp.
Bodywork	X4+SK350
Body volume	19 m ³
Payload / GVM	11.5 t / 26 t
Waste fraction	Mixed

4. Working cycle efficiency analysis

Based on the collected data, oil flow was calculated using formula (1). Hydraulic power delivered to each of the circuits was calculated from (2) and (3). Energy was calculated as a product of power and time between measurements (0,05 s). Duty cycle efficiency was then calculated as a ratio of hydraulic energy to energy supplied in the fuel to the combustion engine throughout the cycle. It should be noted, that the hydraulic energy supplied by the pump, is not fully transformed into useful work. It contains energy loss due to friction in the mechanisms, pressure drop between the pump and actuators and energy used to operate the lifting device and compactor without load. At this stage it is not possible to univocally determine what part of the hydraulic energy was utilized to carry out useful work: lift the waste during lifter operation and compress it in the compactor. This would require a complex study, including measurement of the waste mass in each container, to determine: amount of energy required to collect 1kg of waste for given RCV configuration and amount of energy required to achieve 1m³ of waste compressed to a specified density. This is why the presented efficiency is only related to the conversion of energy from the fuel into hydraulic energy and is greater than zero even when the pump is only circulating the oil in the system when both lifer and compactor are not operating.

$$Q_{1,2} = \eta_p * q_{1,2} * n_{eng} * r_{PTO} \quad (1)$$

$$P_{1,2} = Q_{1,2} * p_{1,2} \quad (2)$$

$$P_{pal} = G_e * W_d \quad (3)$$

$$\eta = \frac{E_{hydr}}{E_{fuel}} = \frac{\sum(P_1 + P_2) * \Delta t}{\sum P_{fuel} * \Delta t} \quad (4)$$

$Q_{1,2}$ - flow rate

η_p - volumetric efficiency of the pump

$q_{1,2}$ - pump's displacement

n_{eng} - combustion engine rotational speed

r_{PTO} - transmission ratio of power take off

$P_{1,2}$ - hydraulic power

$p_{1,2}$ - pressure at pump's outlet

P_{fuel} - power delivered in fuel

G_e - fuel mass flow

W_d - specific energy of fuel

E_{hydr} - hydraulic energy

E_{fuel} - energy delivered in fuel

Δt - time between measurements

η - duty cycle efficiency

Presented analysis also allowed to determine the contribution of compactor and lifter circuits to total hydraulic energy consumption.

Efficiency analysis was conducted on 2 duty cycles that are presented in table 2:

Table 2. Test cycles

	Cycle 1	Cycle 2
Lifter movements	4	2
Compaction mechanism movements	2	1
Duration time	81 s	54 s

Figure 3 presents pressure end engine speed during cycle 1. During the first 27 seconds the engine is idling at $n=600$ RPM and the pressure only increases in the lifter's circuit (P2). After 27 seconds compactor is switched on, the engine speed rises to $n=1000$ RPM and pressure in the compactor's circuit (P1) increases. Emptying of the containers continues during the compactor operation, what is visible on the P2 curve. Characteristic fluctuations of the P2 pressure are caused by activation of the shaking function - repeating impacts of the bin against the bin catcher, ensuring that it will be fully emptied. After 73 seconds the compaction finishes, what ends this duty cycle. It is followed by departure of the vehicle, which is not shown on the graph. Figure 6 presents cycle 2 in similar manner.

Figures 4 and 6 show hydraulic power generated in each of the circuits (P1 and P2), total hydraulic power (P1 + P2) and the power delivered in fuel (G_e) for both analysed duty cycles. Based on the engine load 3 components of a duty cycle can be distinguished

- lifter operation (pump loaded, engine idling)
- compaction or compaction and lifter operation (pump loaded, engine speed increased)
- waiting (pump not loaded, engine idling)

Regardless of the operation of the hydraulic system, some energy is used to keep the engine running and drive auxiliaries such as climate control and alternator. Thus, the energy consumption can be separated into 2 components: energy used for idling and additional energy used to drive the hydraulic system:

$$E_{fuel} = E_{idle} + E_{PTO} \quad (5)$$

However, this approach has only limited practical application - operation of a conventional RCV's is only possible when the engine is running.

Efficiency (4) of selected components of the duty cycle (figures 5 and 7) is presented in table 3. It varies from 10,6% when the pump is not loaded to 35,6%, when compactor and lifter operate simultaneously. Consequently, under the assumption that the power losses in mechanisms and the hydraulic system do not significantly change with the load, operation of a RCV under highest possible load is beneficial for the efficiency.

Contribution of each of the hydraulic circuits to overall energy consumption is presented in table 6. For both investigated cycles the proportions are similar (figure 7): During cycle 1 17,7% of energy was consumed by the P1 circuit, while P2 circuit consumed 11,6%. This results in overall cycle efficiency of 29,3%. Accordingly, for cycle 2 these values are equal to 17,2%, 10,5% and 27,7%.

Table 3. Energy used in cycle 1 and 2.

	Cycle 1		Cycle 2	
E_{fuel}	3009 kJ	100%	1694 kJ	100%
$E_{compaction}$	531 kJ	17.7%	291 kJ	17.2%
$E_{lifting}$	350 kJ	11.6%	178 kJ	10.5%
$E_{compaction+lifting}$	881 kJ	29.3%	469 kJ	27.7%

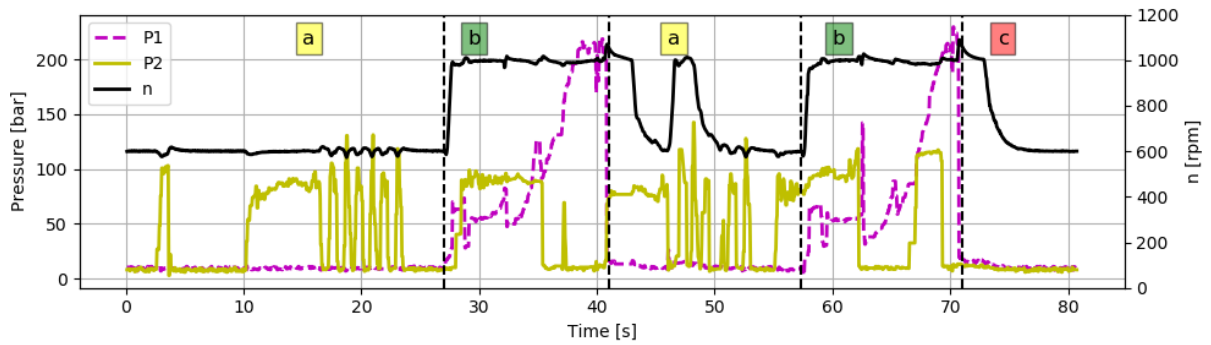


Figure 3. Pressure and engine rotational speed during cycle 1

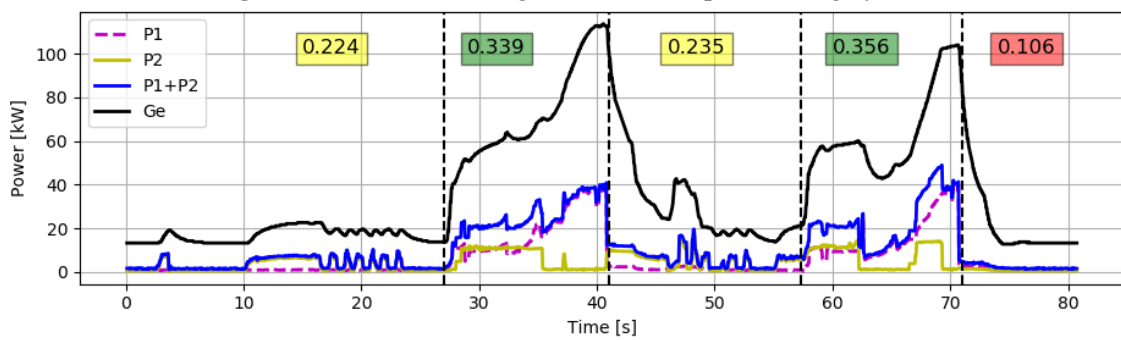


Figure 4. Fuel and hydraulic power during cycle 1. Efficiency of each phase (separated by dashed lines) shown in boxes

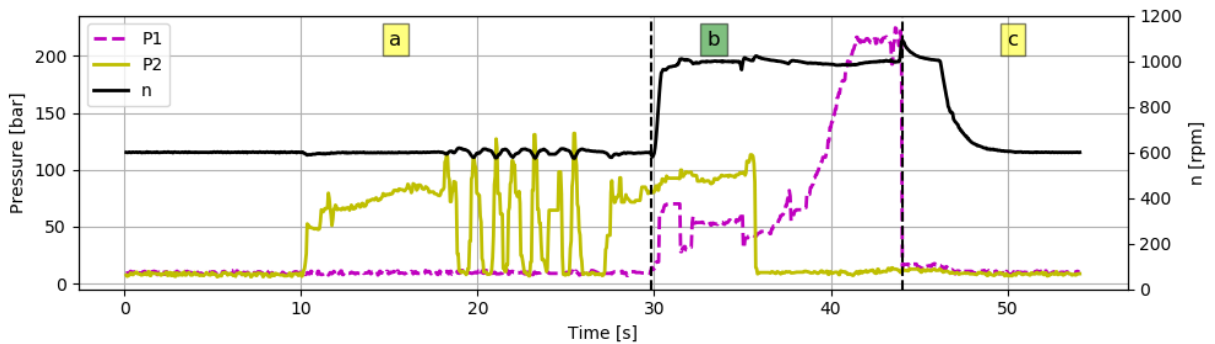


Figure 5. Pressure and engine rotational speed during cycle 2

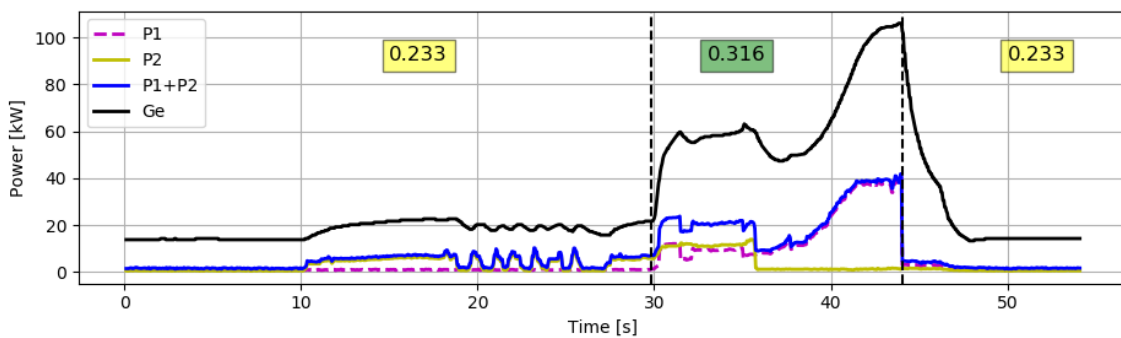


Figure 6. Fuel and hydraulic power during cycle 2. Efficiency of each phase (separated by dashed lines) shown in boxes

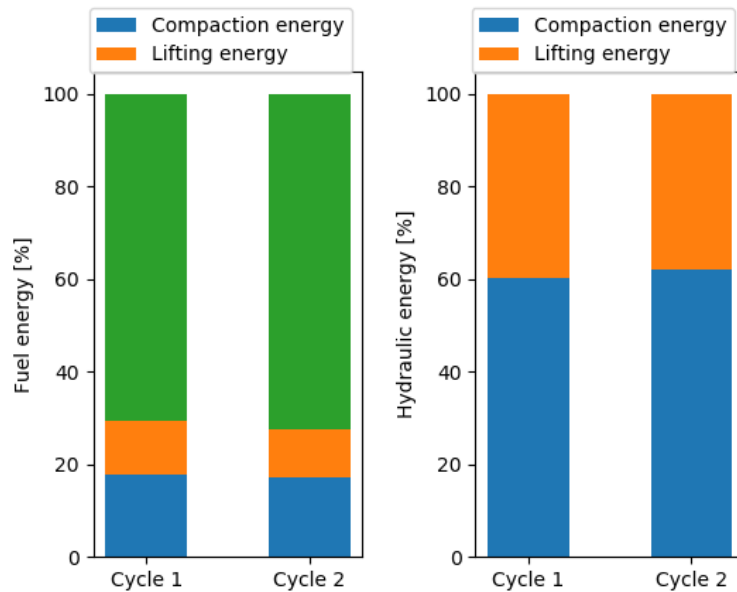


Figure 7. Waste collecting and compaction energy as percentage of fuel energy and of hydraulic energy

5. Working cycles statistical comparison

So far, two working cycles were described, with estimation of total cycle efficiency and its particular phases. But while examining particular working cycles, there is a question how representative these cycles are, referring to the whole day of work. Based on exploitation data from 8 days of regular RCV operation a basic statistical analysis was performed.

Considering the total of 524 cycles, median value of hydraulic energy in cycle was 316 kJ, and during 50 % of cycles 250÷430 kJ of hydraulic energy was used per cycle. In case of fuel energy, median value was 1030 kJ, and 50% of cycles required 920÷1420 kJ. These values are shown on a boxplots (Figure 8) as well as cycle efficiency. Its median value was 30,2%, and in more than a half of cycles 25%÷33% fuel energy was used to power the hydraulic system.

In each considered day the number of cycles was different, what is shown as a bar chart in Figure 9. Total number of analysed cycles was 524. Other statistical plots were shown as boxplots to unveil distribution of measured data. The duration time in Figure 10 suggest that in some days the working cycles are quick and repeatable, and in others may significantly vary. In day 4,6 and 7 predominant number of cycles are no longer than 20 s, whereas in days 1,2,3 and 8 the distribution is wider and majority of cycles lasted from 17 to 34 s.

Figures 11 and 12 represent boxplots of hydraulic energy in cycle and fuel energy in cycle respectively. Obvious similarity in boxplots shape is apparent comparing to duration time boxplot, because the longer the cycle is, the more fuel and hydraulic energy are used. However, there is no similarity in shape of efficiency boxplot shown in Figure 13.

To find correlation between variables mention above, three plots of cycle efficiency in different domain are shown in Figure 14. It is clear that duration time as well as hydraulic energy do not correspond to efficiency. However, introducing new variable, which is hydraulic energy divided by cycle time, a correlation is apparent. The more energy hydraulic system used per second, the higher efficiency was obtained. It is in compliance with initial assumptions, that the best way to work with high efficiency is to receive high power from combustion engine.

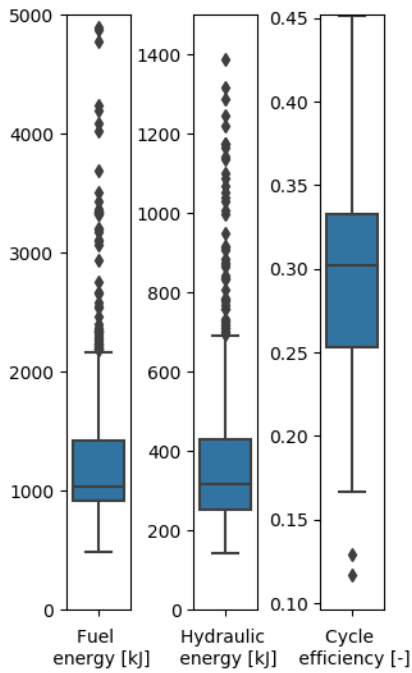


Figure 8. Boxplots of fuel energy, hydraulic energy and efficiency for 524 cycles

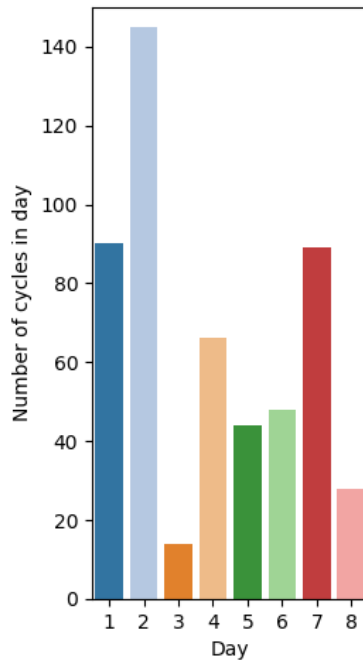


Figure 9. Bar plot of cycles in day

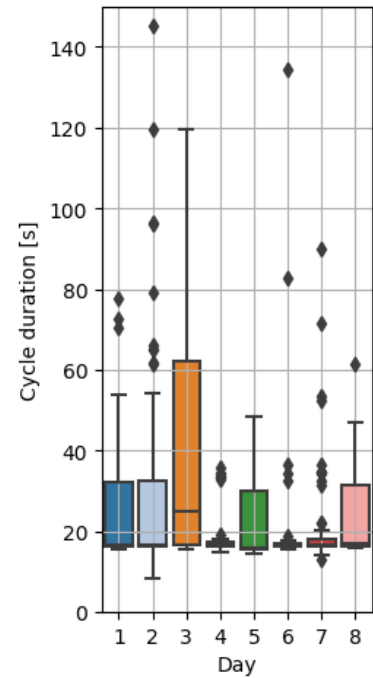


Figure 10. Boxplot of cycle duration time in day

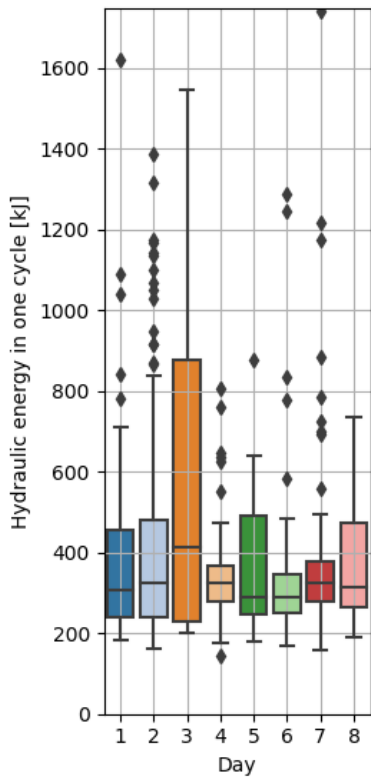


Figure 11. Boxplot of hydraulic energy per cycle in day

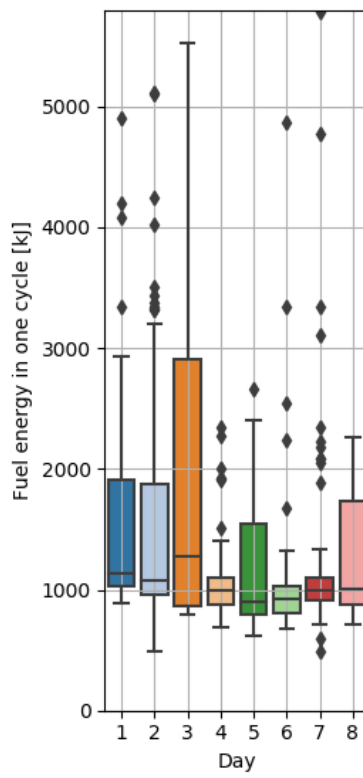


Figure 12. Boxplot of fuel energy per cycle in day

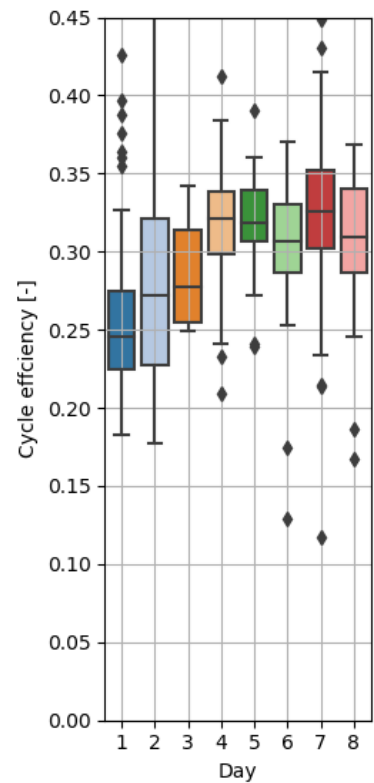


Figure 13. Boxplot of cycle efficiency per cycle in day

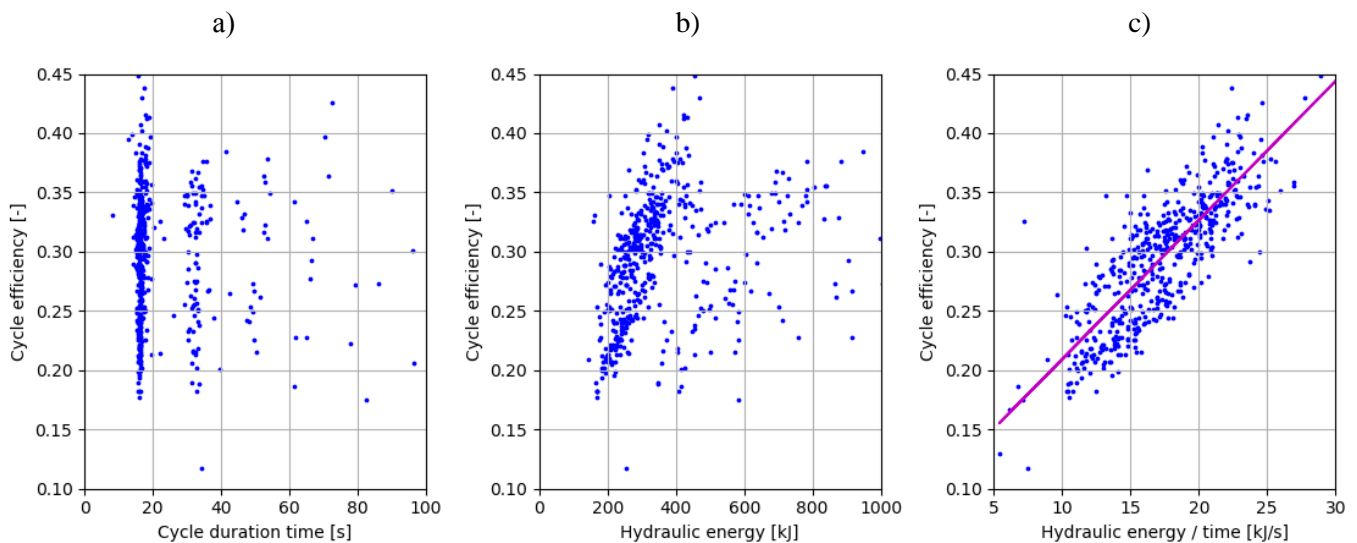


Figure 14. Cycle efficiency in domain: a) Duration time b) Hydraulic energy c) Hydraulic energy / time with correlation line

Summary

Results of the analysis show that presented method of evaluation of efficiency of a duty cycle can be used to quantitatively assess performance of RCV's regarding efficiency of hydraulic power delivery. Calculations based on measurement data show that the average cycle efficiency is close to 30% (27,7 and 29,3%) and depending on the load and operation mode (lifting, compaction, standstill) can vary by as much as 25 percentage points. Obtained efficiency figures are relatively high but it has to be emphasized that they relate only to energy conversion between combustion engine and hydraulic system. Overall efficiency of a RCV is expected to be significantly lower. Calculating its value requires considering efficiency of the hydraulic system, compactor and lifting device.

Presented evaluation method could be incorporated into a comprehensive energetic model of a RCV that would enable to quantitatively assess performance of various technical solutions. This model would also enable to indicate the most promising directions of development. Analysis of the statistical data describing the duty cycle characteristics also shows a potential for application in optimization of the configuration of a RCV for a specified collection area.

Future studies should focus on creation of an energetic model of compactor and lifting device to develop a comprehensive model of the system and evaluate its overall performance. Applicability of statistical analysis for the purpose of RCV configuration optimized for its collection area could also be further investigated.

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