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# Determination of electrical energy recovery forklifts using supercapacitors battery

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**ABSTRACT**

The paper presents a model of energy consumption in transport and logistics system for the construction of a storage map of its power consumption (for trucks with electric drive). Based on the map of energy consumption determined amount of energy that can be recovered in the logistic system. To maximize the recoverable amount of energy the battery is designed supercapacitors, its size and weight - help formulate the technical capabilities of its building.

**KEYWORDS: optimization of logistics system, energy consumptions**

## 1. Introduction

The reduction of energy consumption in business processes has become a priority for the global economy. Savings are sought for as, on one hand, energy is costly and on the other, we are trying, using various methods, to reduce the global greenhouse effect, which for a number of reasons is undesirable. Attempts are made to reduce the amount of energy consumed by household appliances, lighting, manufacturing processes and by vehicles. Phasing out incandescent light bulbs yielded a drop in demand for electricity by 2400 MW, which corresponds to the capacity of a power plant the size of Turów. This drives the development of the economy, despite the fact that no new power plant of a similar capacity has been built [2], [4].

Energy efficiency has been analysed also in the case of logistic processes and logistic engineering. The continuous development of technology makes it possible to save energy where such savings have not been possible before. The processes include reloading, storage and works transport. Equipment used in these processes most often includes forklift trucks. The energy used to drive the truck holds a major share in operating costs. On the other hand, if one compares the mechanical work performed by a forklift truck to the energy consumed in the primary power source, the ratio does not exceed 30%. This applies both to internal combustion engine and electric trucks. The purpose of this study is to analyse the potential to save energy consumed by forklift trucks [3].

## 2. Essence of the problem

A forklift truck is equipped with two basic drive systems: the drive system and the working system [1]. The drive system powers the gearing system, i.e. drive wheels of the truck.

The working units drive system usually powers hydraulic pumps which in turn may lift the laden forks or power other auxiliary hydraulically powered mechanisms. The range of technical solutions in this area is still very wide.

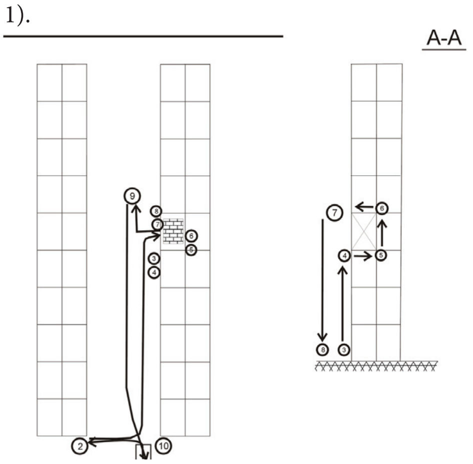
The classic drive unit solutions employed in forklift trucks include diesel engine which powers the truck's wheels through a mechanical gear box and a hydraulic pump which powers the lifting and lowering mechanisms and the turning system. In the case of the electric version, the electric motor drives the gearing system and the other engine powers the hydraulic pump which, similarly as in the previous case, drives trucks equipped with hydrostatic transmission. Then the motor drives the pump which powers the hydrostatic and other mechanisms. Through the analogy to other vehicles, in particular rail vehicles, drive units of fork lift trucks permit the recovery of energy while braking. The characteristic feature of any truck's work is the continuous accelerating and braking. During braking the energy is dispersed into the environment as heat. In working drive units (mainly the lifting and lowering system) one may consider the recovery of potential energy of forks lowered by gravitation.

Practically, during the braking process the same amount of energy could be recovered as is consumed during acceleration and load lifting. While lifting loads, energy equivalent to the lowering energy could be recovered. The share of drive at a steady speed is low compared to the energy consumed to accelerate the truck. It is worth estimating the values of energy fluxes and considering the opportunities to recover energy lost while slowing down the truck and lowered load.

# 3. Characteristics of forklift truck's work

Let us assume that a forklift truck handles the loading of vehicles with palletised load transported from a rack.

The truck transports the pallets from the middle of the warehouse to vehicles waiting at the ramp. This process is shown in figure 1, numbers in circles designate the typical milestones in truck's work. The description of the working cycle is presented in table (fig. 1).




| 1 | 2 | | 3 |
|---|---|---|---|
| | Operation number | | Name of operation |
| 1 | 1-2 | - | Withdrawing an empty forklift truck from inside the vehicle. |
| 2 | 2-3 | - | Travelling to the rack to pick the pallet. |
| 3 | 3-4 | - | Raising the fork to the middle level of the rack. |
| 4 | 4-5 | - | Inserting the forks under the pallet and moving the truck ahead. |
| 5 | 5-6 | - | Raising the pallet up by 2 cm. |
| 6 | 6-7 | - | Taking the pallet out of the rack. |
| 7 | 7-8 | - | Lowering the pallet. |
| 8 | 8-9 | - | Reversing the truck in the aisle. |
| 9 | 9-10 | - | Travelling ahead with the pallet. |
| 10 | 10-11 | - | Lowering the pallet onto the vehicle floor. |

**Fig. 1. Forklift truck working cycle while loading a vehicle [own work based on 4]**

The following of the above operations: {1-2}, {2-3}, {8-9}, {9-10} include the starting, driving and braking the truck. The duration of these operations depends on the distance and technical specifications of the truck (travelling speed).

Detailed calculations should precisely determine the speed profile, starting and braking time, force on the wheels and energy used for these operations.

The results of energy saving will be more visible if there are more stages of unsteady travel than those at steady speed. The question may be answered by a minimum time analysis of the truck along the set route. This travel is described in fig. 2.

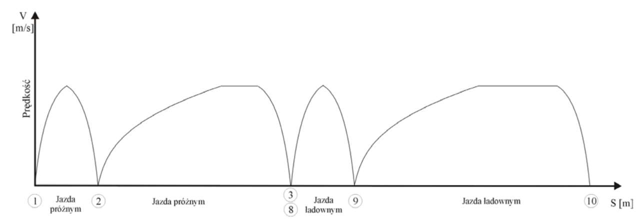



**Fig. 2. Model minimum time travel [own work]**

In addition, energy may be recovered during motion (7-8), i.e. lowering the pallet from the rack, if the truck structure permits energy recovery from the power system of the truck's auxiliary equipment.

# 4. Principles of calculating the minimum-time travel

The movement of the truck is described by an equation of motion which balances the forces exerted on the truck in time-variable conditions. In line with Newton's second law of motion:

$$\xi m \cdot \frac{dv}{dt} + W_c(v) = F_t(v) \qquad (1)$$

where: $m$ – weight of the truck; $\xi$ – coefficient of spinning masses; $W_c(v)$ – total truck driving resistance variable in the function of speed; $F_t(v)$ – tractive forces – in line with engine specifications, in the function of speed. The resistance to motion $W_c(V)$ may be defined as rolling resistance. Compared to the resistance to motion of a car, the frictional resistance in the suspension is not taken into consideration. Apart from the operator's seat, the forklift truck has no spring elements. The wheel tracking resistance and aerodynamic drag are negligible. We assume that the motion of the truck is not obstructed by other, unmentioned resistances. Then:

$$W_c(v) = Q \cdot f_t \tag{2}$$

basically, resistance $f_t$ is independent from speed. The coefficient of spinning masses in road vehicles used in the formula is within the range from 1.05 to 1.5. This coefficient takes on a similar value for rail vehicles. The spinning elements in a forklift truck include: drive wheels and in some cases spinning elements of engines. In the case of a forklift truck, the coefficient of spinning masses has been estimated at $\xi = 1.02$.

The tractive characteristics of the truck need some clarification. Taking into account the truck speed adjustment, the so-called external characteristics may be similar to that presented in [6].

This characteristics (the dependence of the total force on drive wheels from $F_t(v)$ in the speed function $v$) is limited, the first limitation results from the limited value of tractive adhesion to the floor the truck travels on. The maximum force on wheels will amount to:

$$F_{\max.} = Q_N \cdot \mu_1 \tag{3}$$

where:
$Q_N$ – driven weight, means the vertical load which presses the drive wheels to the floor; The $Q_N$ value depends on the distribution of truck weights, both unladen and laden. With double axle drive this will cover the entire truck weight; $Q_N = m_C \cdot q$,
$\mu_1$ – coefficient of tractive adhesion of truck wheels to the floor.

The other limitation of the characteristics is the maximum travel speed of the truck which results from the balance of forces exerted on the truck: driving force $F_t(v)$ and resistance to motion $W_C(v)$. With limited speed of forklift trucks (incomparably small against the speed for a car, for instance), the resistance to motion may be constant and independent from speed. The largest impact on the resistance to motion is made by additional resistance: grade resistance $W_i$ and truck rotational resistance. While grade resistance is simple to estimate and amounts to:

$$W_i = Q \cdot \sin\alpha \tag{4}$$

where: Q – weight of unladen or laden truck; $\alpha$ – grade of floor, with small grades $\sin\alpha = tg\,\alpha = \alpha[rad]$, and with higher; $\alpha -$ the trigonometric variable of $\sin\alpha$ should be taken into consideration.

The turning resistance depends on the turning radius, travel speed and changes in speed along the bends, resulting from braking and/or accelerating, location of the centre of gravity and the type of tyres. The analytical description of this phenomenon is complex. Having the safety of the load in mind, we assume that the motion along the bend is steady and that the truck travels with speed at which the centrifugal acceleration influencing the load and the entire truck does not exceed $a_0 = 0{,}25$g.

The tractive calculations are based on the equation of truck motion:

$$\xi \cdot m \frac{dv}{dt} + W_c = F_t(v) \tag{5}$$

considering that $m = \frac{Q}{g}$ and having put the equation in order we end up with:

$$\frac{\xi}{g} \cdot \frac{dv}{dt} = \frac{F_t(v) - W_c(v)}{Q} \tag{6}$$

which may further be noted as

$$k_i \cdot \frac{dv}{dt} = p(v) \tag{7}$$

in this equation $k_i$ - for diesel engine is constant. The value $p(v)$ means the accelerating force per unit as the relation between the surplus of driving force to the weight of the truck. From the mathematical point of view, this is an ordinary, non-linear differential equation. An analytical solution to this equation is possible in certain cases. In the entire range of the truck's work, the approximation method of equation solving must be employed. Taking into account that $dt = \frac{dS}{v}$ and substituting the differential growths with difference growth, the following equations:

$$p(v) = k_i \cdot \frac{dv}{dS} \cdot \bar{v} \tag{8}$$

from where:

$$\Delta s = k_i \cdot \frac{\Delta v}{p(v)} \cdot \bar{v} \tag{9}$$

where: $\Delta s$ - path length increment; $\Delta v$ - assumed speed growth; $p(v)$ - accelerating force per unit; $\bar{v}$ - average truck speed along $\Delta s$. Based on the above, time increment may be calculated for each section of path length $\Delta s$.

$$\Delta t = \frac{\Delta S}{\bar{v}} \tag{10}$$

For each section of path length $\Delta s$, the average value of driving force $F_k(v)$ may be read from the truck's tractive characteristics, and hence the work performed by the truck may be determined

$$\Delta W = \overline{F_k(v)} \cdot \Delta S \tag{11}$$

Based on the work performed by the drive system, one can calculate the conventional amount of fuel consumed by the truck.

$$\Delta W = \Delta B^* \cdot W_{op} \cdot \eta_c \tag{12}$$

from where

$$\Delta B^* = \frac{\Delta W}{W_{op} \cdot \eta_c} \tag{13}$$

where: $\Delta B^*$ - consumption of conventional fuel on section $\Delta S[g]$ $\Delta W$ -elementary work of the drive system; $W_\varphi$ -conventional calorific value of fuel, often $W_{op} = 41860\left[{}^{kJ}\!/_{kg}\right]$ is assumed; $\eta_c$ - total efficiency of the drive system, including engine efficiency. For the purpose of comparison with diesel engine trucks, in the case of battery-powered trucks all energy efficiencies should be taken into account – fuel combustion in the power plant, current transformation and transmission, battery charging efficiency and, finally, the efficiency of the truck drive. The efficiency understood as shown above is in both cases at 30%, $\eta = 0.3$.

The following item presents sample tractive calculations for the truck in a set working cycle.

# 5. Calculation example

We are considering the work of the truck in the following cycle - reflecting the typical possible actual cycle. The travel along distance $s_1$ =10$m$, acceleration and braking, then travelling $s_2$ = 50$m$ - braking, lifting empty forks at 3m, lowering forks with a pallet to 2.8 m, travel $s_3$ =8$m$, braking, travel $s_4$ =60$m$ and braking. Let us assume that a pallet weighs 600 kg. For the sake of the analysis a Jungheinrich truck has been assumed, with the following technical specifications [6]:

With larger delays in breaking, the inertial force of the load on the forks would exceed the value of friction force and the load would slip from the forks.

Based on the above model the calculations regarding the truck's motion were made. The results of calculations are presented in figure 8. For the purpose of calculation step

$0.5\frac{m}{S} = \Delta V, i = 0^{\circ}, Q_{EP} = 600[kg]$ was assumed.

The calculations were made for truck's working cycle as presented in fig. 1, assuming that section {1}-{2}=10m, {2}-{3}=50m, {8}9-{9}=60m.

The work of the truck in each stage of travel comprises: acceleration phase, braking phase or travel at steady speed.

Due to uniform working conditions, the complex working cycle may be made of the following phases Fig. 3: travelling unladen, travelling laden, braking laden, braking unladen, and travelling at steady speed.

Figure 3 presents the results of calculations of speed in the function of path length – for highlighted fragments of the working cycle:

- Time to cover the distance
- Energy consumed for whole working cycles of the truck.

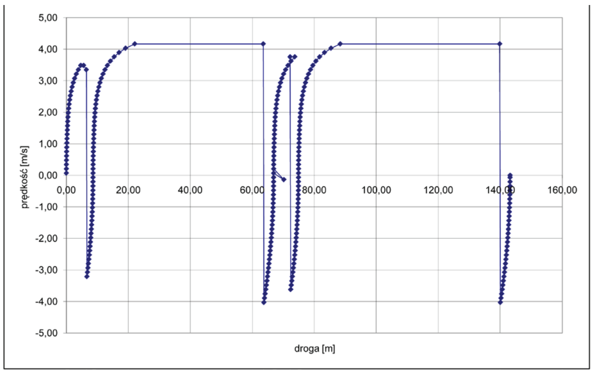



**Fig. 3. Illustration of calculation results**

# 6. Conclusion

The results of the simulation help assess the amount of energy that can potentially be recovered in the logistic warehouse systems equipped with electric forklift trucks.

In the analysed example the following amount is can be recovered:

$$E_k = \frac{m_C v^2}{2} = \frac{5000 \cdot (3,5)^2}{2} = 30625{,}0 \ [J] \tag{14}$$

It accounts for 30% of energy required to accelerate and travel at a steady speed.

These calculations pertain solely to truck travelling and braking. From the point of view of energy consumption, load lifting and lowering operations are also important. These processes are related to the work performed by the lifting and lowering system. In the discussed case the energy amounts to:

$$\underline{E}_p = mgh = 600kg \cdot 9.81 \cdot \frac{m}{s^2} \cdot 3{,}3 \cdot m \cong 20000[Nm] = 20000[J] \tag{15}$$

where: m – weight of the load (including the weight of carriage); h – average pallet lift height from the 4$^{th}$ row of racks, h = 3.3 [m].

The entire discussed energy balance will be different for releasing loads from the warehouse or for filling a warehouse (storage of goods).

To sum up, the presented method permits a precise analysis of the motion of the truck, helps define the working parameters and calculate the tractive calculations for the truck in a detailed and relatively precise manner. Based on this method one can carry out detailed analyses, optimise the workload, estimate fluxes of energy dispersed in some process which could be reused, e.g. by accumulation in gel supercapacitor.

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