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Analysis of power consumption for tramcar with pulse mode speed regulation

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Abstract

This article shows the equivalent schemes of tram car for traction and braking regimes. The operation principles of equivalent schemes are analyzed and the stages of movement which comprises the motion and braking regimes. There are showed the main basic principles of operation of mathematic model and assumptions that are needed for precise description of physical processes that are in nature. Article shows also results of mathematical modeling and later the results are analyzed. Article shows depiction of quantity of recuperation energy and graphics characterizing dependence of the quantity of energy consumption of tram car on braking distance. There are inspected the normalized quotations which were developed by results of analyze. There are inspected the regularities between the technical speed v_v of tram car and braking way.

Keywords

Electrical energy, tram car, recuperation, braking regimes, field, winding, excitation, armature, parameters.

Introduction

From year 1995 till 2000 there were done modernization of all tram cars - type T3A in Riga. In result there was installed new controller system with transistors for better speed regulation. This system provides automated stabilization of current for starting and braking regimes. This system also provides returning of recuperation energy within braking regime for other tramcars what are connected with the same network. The effectiveness of recuperation depends on number of connected loads and its total power what must be bigger that recuperation energy. Because at the present days traction substations are not equipped with bidirectional power flow controllers there are not possibilities to return recuperation energy. At the present days there are additional rheostats connected with controller system what is consuming energy of recuperation. The aim of this work is to make analyzes of recuperation energy and to get precise information about total energy amount what is consuming the tram car in different circumstances what also depends from many other physical factors. Actually this work should be done theoretically and making experiment, notwithstanding it is easier way to make computer modulation for motion of tram car on different specific factors. This task was started to solve in [1], but there were not paid attention to problems what concerned with recuperation energy.

1 Equivalent schemes and motion stages

In equivalent schemes all electrical drives are

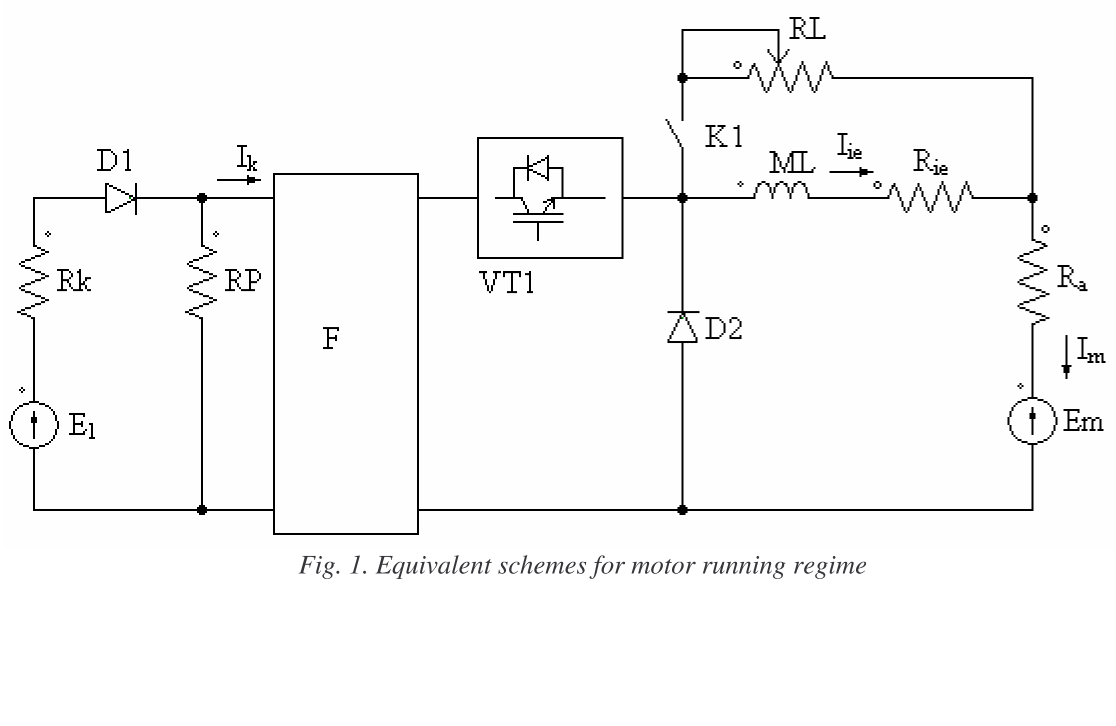

Fig. 1. Equivalent schemes for motor running regime

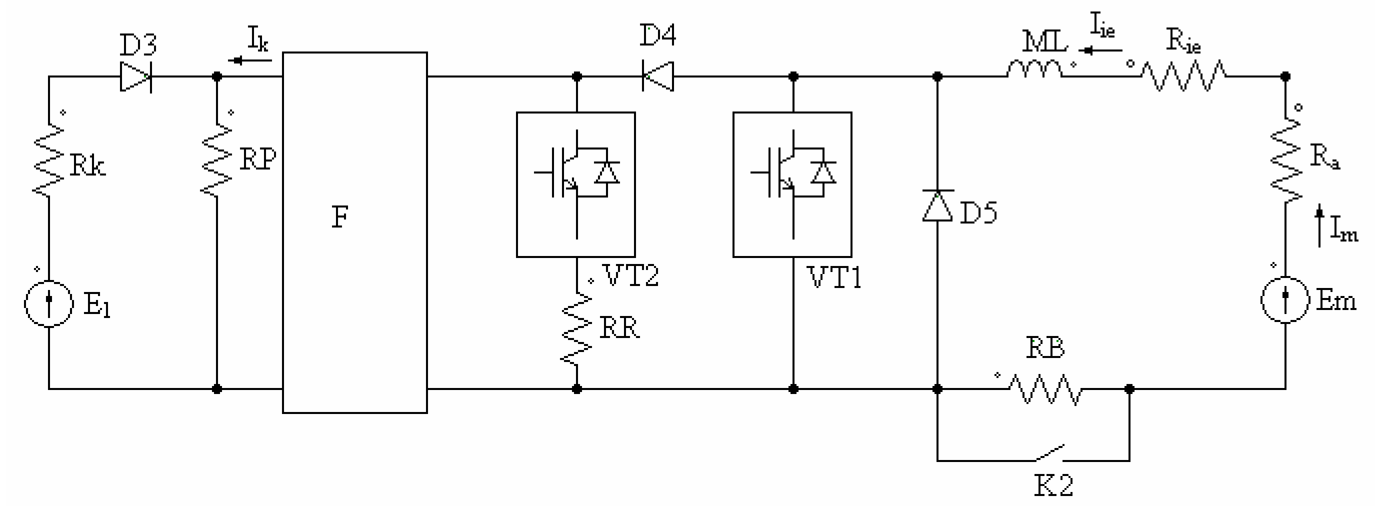

Fig. 2. Equivalent schemes for motor braking regimes

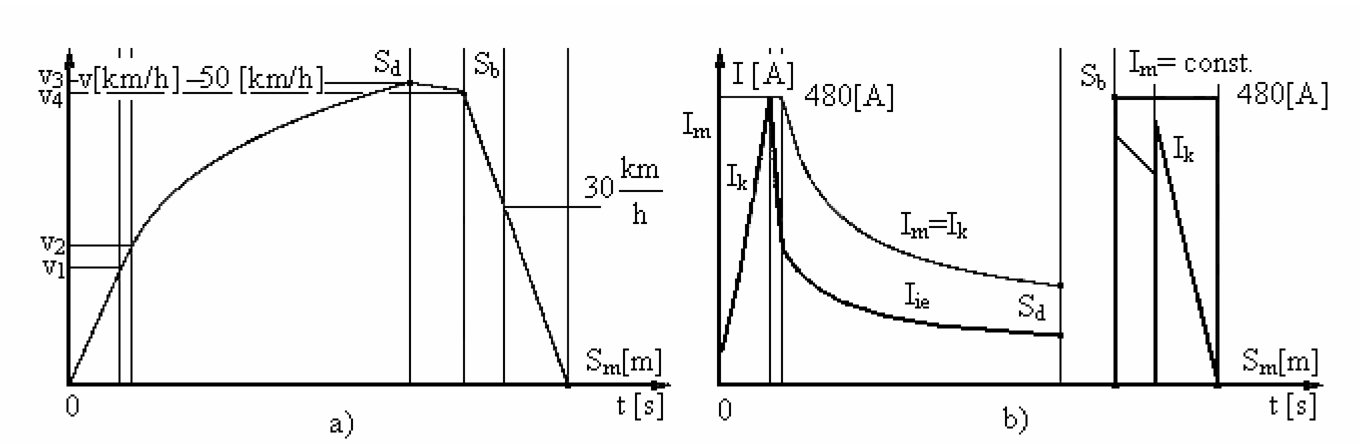

Fig. 3. Stages of tramcar between two stops

substituted in one voltage source E_m, where I_m – motor current, I_{ie}- exciting current, VT1 controller for motor current regulation. R_L – adjustable resistance for regulation of exciting current what can be connected with contactor K1. On the input of scheme there are filter F for the smoothing power grid current and traction substation is substitute by EDS E_1 and grid resistance R_k. In equivalent scheme the slacking resistance RR with transistor VT2 is connected parallel to power grid. Resistance RB is used when tram car has increased technical speed over 30 km/h , if speed slows down under 30 km/h then recuperation energy is neutralized by switching contactor K2. Other consumers on the line are presented in equivalent scheme like resistance RP outside of carriage scheme what is delimited by filter F. These schemes can provide motion in all six specific stages what makes three specific regimes: acceleration, rolling without current and back off regimes. In regime one controller is connected in series with motor. Then there are three specific stages (Fig. 3.).

1) Acceleration stage when technical speed is v_1 and I_m=I_{ie}=480 A;
2) Acceleration stage when technical speed is v_2 with weakened exciting and I_m=480 A
3) Acceleration stage when technical speed is v_3 with I_{ie}=0,5I_M and I_m <480 A.

When the speed reaches selected value usually driver disconnects the motor and begins the rolling regime without current. During this stage the speed decreases linearly till the concrete volume of speed nearly the stop when driver starts braking. If the moments are selected correctly then coming to stop will be very precise to stop. During the braking controller is connected parallel with circuits of drive. (Fig. 2.). It’s possible to see two other specific stages:

1) braking with high speed when RB is connected
2) braking when speed is lower than 30 km/h with disconnected resistance

2 Description of mathematical model

Following assumptions were done before mathematical model was developed:

- traction substation EDS is 630 V;
- resistance of grid changes between the least value 0.02 (normalized estimation factor - 1) up to R_k=0.3 Ω (+1);
- the current what have to be constant in all six stages excepting the 3rd and 4th stages;

- the distance between stops is within 100(-1) and 400 m (+1);
- the moment of resistance for empty carriage is M_{prt}=90.90+0.255*n, [Nm],what is calculated from experimental curves;

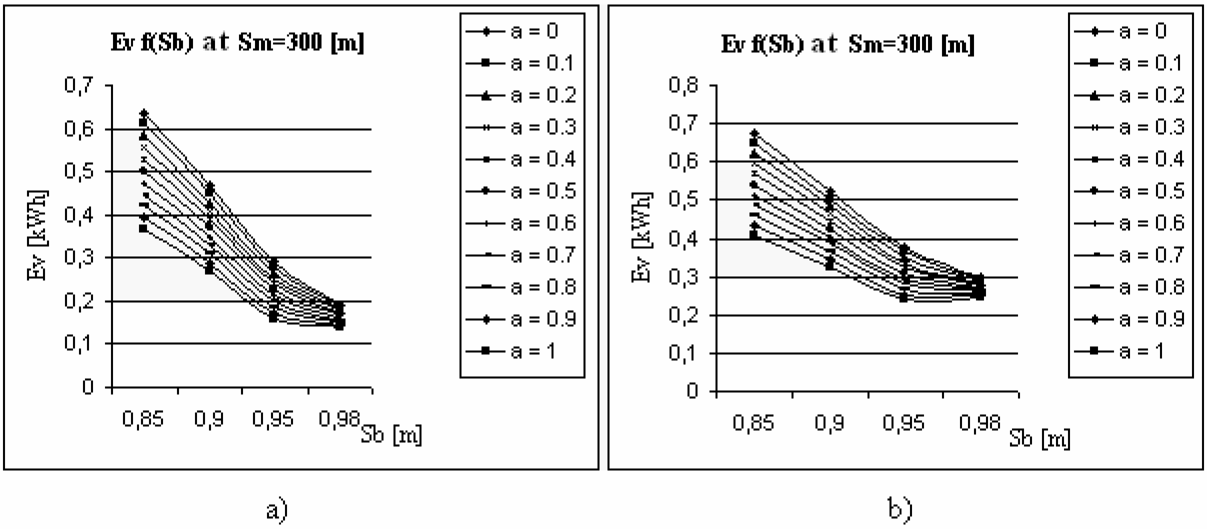

Fig. 4. Energy consumption characteristics of carriage at S_m=300m a) for full b) empty carriage at a=0-1

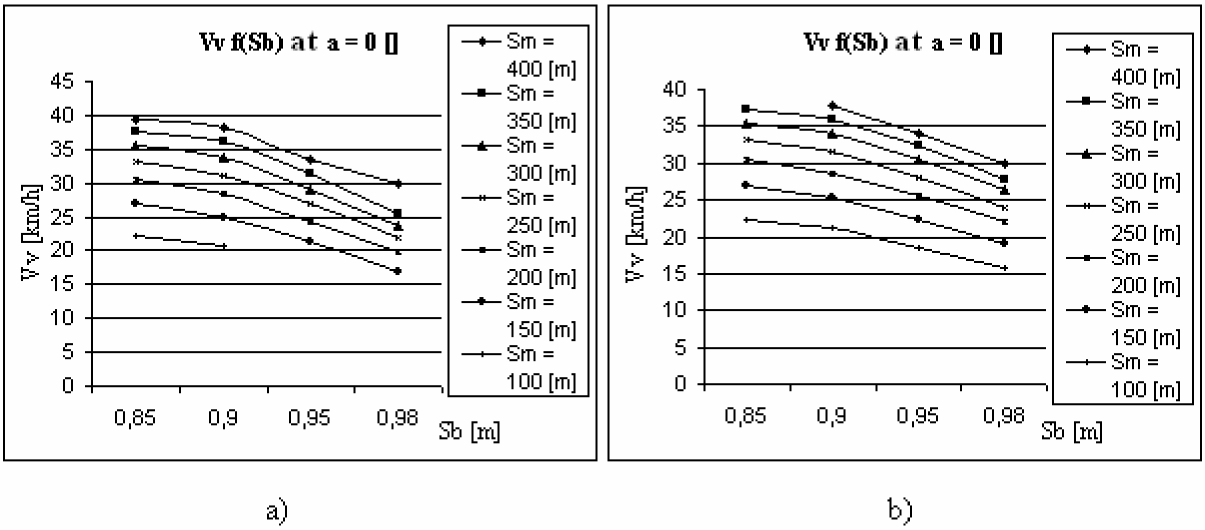

Fig. 5. Characteristics of average technical speed of carriage at a=0 a) for full b) empty carriage at S_m=100 m to S_m=400 m

- the moment of resistance for full carriage is M_{prp}=220.35+(-2,38)*n, [Nm], what is calculated from experimental curves, too;
- Moment of inertia J = 259.49 [Nm*sek^2] for empty carriage;
- Moment of inertia J = 408.06 [Nm*sek^2] for full carriage;
- Parameters for equivalent motor is calculated from technical specification of motor;
- Diameter of wheel is 0.655[m];
- Gear ratio is 7.4.

Simulation program is calculating motion equitation

$$\pm M_m - M_{pr} = J\frac{dn}{dt} \qquad (1)$$

Where M_m is moment of motor and M_{pr} is moment of resistance. The speed of rotation is measured in following units [1/s]. Distance between stops is assumed as S_m and divided in three stages: $S_m = S_d+(S_b-S_d)+(S_m-S_b)$, where in stage S_d is calculated acceleration regime in stage (S_b-S_d) is calculated rolling stage without current. In stage (S_m-S_b) is calculated regime of recuperation. In acceleration regime the current of the grid $I_k=g*I_m$ and voltage on motor is $U_m=(E_1-I_kR_k)*g$. In braking regime the current of grid is $I_k= (1-g)*a*I_m$, and voltage of the motor $U_m=(E_1+I_kR_k)(1-g)+I_m*R_b$. Parameter g is duty ratio for pulse chopper. $(E-I_kR_k)$ and $(E_1+I_kR_k)$ are voltages of grid respectively in acceleration and braking regimes where R_b=1 Ω when speed is high and R_b=0 Ω when speed is low. a -is factor of probability within 0 (-1) and 1(+1).

The consumed energy amount of carriage with discretization steps Δt – are calculated as following:

$$E_{v\Delta t} = (E_1 - I_k.R_k).I_k.\Delta t \quad (2)$$

Within the step Δt the energy amount what are consumed in traction substations is calculated as following:

$$E_{a\Delta t} = E_1.I_1.\Delta t \quad (3)$$

During the simulation for the given distance S_m between sops, were assumed the distance what the carriage had gone before braking – and was searched the distance S_d what tram car had gone within the acceleration regime

3 The results of modulations

As result of simulation the following characteristics were obtained, E_v=f (S_b) on different S_m and a for full and empty carriage. The characteristic of such function is showed in (Fig. 4.) on S_m=300 m. If S_b increases then energy consumption is decreasing. If the distances are longer then E_v becomes higher. If the number of factor of probability increases then consumption of electrical energy becomes lower.
Very important characteristics were obtained where is possible to see the technical speed which it dependence on S_b at different distances between stops. In (Fig. 5.) is showed that if S_b increases then technical speed decreases for full and empty carriages and if distance is changing within 100 and 400 m then average speed increases at non-variable S_b. The great data massive was obtained using mathematical model, what allows to make detailed analyze about existing situation. Data massive describes concrete range Ω. Limit of range Ω determines normalizing factors (-1) and (-1). Making characteristics there were assumed normalization parameters see (Tab. 1.), what were used in mathematical statistic method.

Table 1. Normalized parameters and factors

Normalized parameters	Normalizing factor (-1)	Normalizing factor (+1)
S^*_m	150 [m]	400[m]
S^*_b	S_m-(85 % of S_m)	S_m-(98% of S_m)
a^*	0	1
v^*	16.77 [km/h]	39.2564 [km/h]

For easer way to make out conclusions using linear statistic method of mathematics there were provided synthesis of normalized equitation, from what was made analyzes of system. From obtained characteristics there was made synthesis of normalized equitation's for calculations of consumption of electrical energy what was consumed between two sops depending on normalized parameters a^*, $S_m{}^*$, $S_b{}^*$, where $S_b{}^*$, is assumed within range 0.85 (-1) to 0.98 (+1) according tab.1. In result of synthesis there was obtained normalized equitation's with normalized factors.

Consumed electrical energy for full carriage

$$E_V = 0.301975 + 0.185675 \cdot S^*_m - 0.14535 \cdot S^*_b - 0.08275 \cdot a^*$$

$$\sigma_V = 0.032396 \text{ (kWh)}, E_v>=0 \quad (4)$$

Consumed electrical energy in traction substation

$$E_a = 0.37515 + 0.2173 \cdot S^*_m - 0.1758 \cdot S^*_b - 0.07323 \cdot a^*$$

$$\sigma_a = 0.031447 \text{ (kWh)}, E_a>=0 \quad (5)$$

The recuperated energy of carriage

$$E_{rek} = 0.082738 + 0.034763 \cdot S^*_m - 0.05076 \cdot S^*_b + 0.082738 \cdot a^*$$

$$\sigma_{rek} = 0.022737 \text{ (kWh)}, E_{rek}>=0 \quad (6)$$

Respectively for full carriage normalized equitation's are:

$$E_V = 0.28049 + 0.19456 \cdot S^*_m - 0.0998 \cdot S^*_b - 0.0642 \cdot a^*$$

$$\sigma_V = 0.02976 \text{ (kWh)}, E_v>=0, \quad (7)$$

$$E_a = 0.34816 + 0.22766 \cdot S^*_m - 0.1242 \cdot S^*_b - 0.0571 \cdot a^*$$

$$\sigma_a = 0.02966 \text{ (kWh)}, E_a>=0, \quad (8)$$

$$E_{rek} = 0.0642 + 0.0285 \cdot S^*_m - 0.0473 \cdot S^*_b + 0.0642 \cdot a^*$$

$$\sigma_{rek} = 0.0214 \text{ (kWh)}, E_{rek}>=0 \quad (9)$$

σ -average quadratic inaccuracy. From calculations we can se that inaccuracy of calculations is small within range (0.02 to 0.03 kWh). According obtained normalized equitation's with normalized parameters is possible to evaluate physical processes what are happening in range Ω (Fig. 6.).

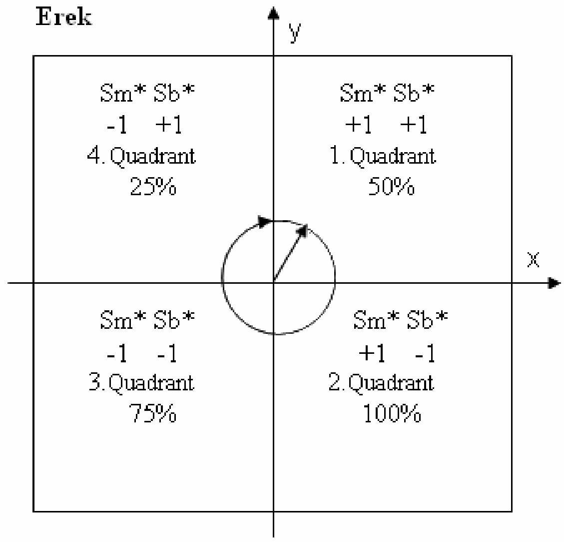

Fig. 6. Diagram of evaluation in range Ω.

From data massive is possible to get equitation's with normalized parameters including average technical speed V_v for empty carriage.

$$V_{vt}=28.1559-4.8829S_b{}^*+6.3569S_m{}^* \text{, km/h.} \quad (10)$$

This expression (10) can be inserted in expression what calculates amount of electrical energy and also can be inserted in expression of recuperation energy equitation.

E_{vt}=-0.5203+0.0292 V_{vt} - 0.0027 S_b^*-0.08275a^* kWh E_v>=0; (11)

E_{rekt}=-0.0712+0.00546V_{vt}–0.024S_b^*+0.08273a^*kWh E_{rek}>=0. (12)

Similarly expressions can be obtained also for full carriage.

V_{vp}=25.8146 – 4.0286 S_b^* + 6.7335 S_m^* km/h; (13)

E_{vp}=-0.4654+0.0289V_{vp}+0.0166S_b^*-0.0642a^* (14)

E_{rekp}=-0.045+0.0042V_{vp}–0.03S_b^*+0.0642a^* (15)

As we can see from expressions amount of consumed energy is very dependent on technical speed and parameter of possibility of recuperation. If technical speed is higher then consumed energy amount is smaller. If possibility of probability is higher then consumption of energy is smaller. When

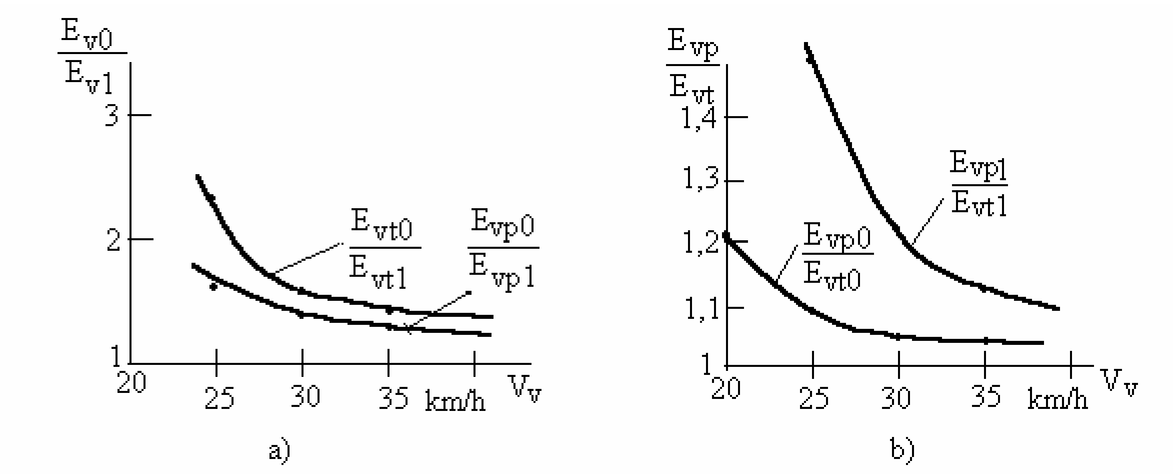

Fig. 7. Attribution of consumed energy E_{vo} of tramcar carriage without recuperation against consumption E_{v1} with full recuperation a) relation of consumption b) for full and empty carriage depending on average technical speed

technical speed of empty carriage is 27.5 km/h then amount of electrical energy without recuperation relate to consumption at full recuperation is 1.8 times higher, what shows as big influence of probability of recuperation. In (Fig. 7.) we can see consumed energy of carriage without recuperation relation against consumed energy of carriage with recuperation when a=1. For full carriage at the same average technical speed attribution of energy consumptions without recuperation against full consumption is 1.48 what designates that effectiveness of full carriage is lower than for empty carriage. The same affirmation is able to get with calculations according expressions of recuperation energy, when at this speed for empty carriage is possible to recuperate 0.162 kWh and for full carriage 0.135 kWh. From expressions of energy we can see that very important is the moment when the braking is started. For full carriage recuperation amount of energy can be increased and all energy for carriage can be decreases if parameter S_b is decreased. (If the braking is started little bit earlier). Comparing consumption of energy for full carriage with empty carriage (Fig. 7.) we can see, that relation without recuperation is smaller than with recuperation. Its proves again the big significance of recuperation for saving energy.

Conclusions

1. The effectiveness of recuperation depends on factor of probability and average technical speed and moment of starting of braking in walk.
2. All mentioned factors can be normalized and using computer modulation program of motion of tramcar is able to get normalized equitations.
3. If the average technical speed is higher then effect of recuperation decreases. This effect for empty carriage is higher than for full carriage.
4. Energy consumption of full carriage with recuperation related to energy consumption of empty carriage is higher that without recuperation.
5. It is very significant to make experimental measurements to get precise factor of probability of possibility.

Reference

1 Rankis I., Brazis V. Simulation of tramcar's energy balance// The second International conference „Simulation, Gaming, Training and Business Process Reengineering in operations". Riga, 2000.