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ENERGY- SAVING CONTROL OF TRAMS WITH DC SERIES MOTORS ALLOWING FOR LIGHT SIGNALLING

Novelty of this paper consists in simultaneous analysis of the traffic of some tram vehicles taking into consideration the criterion of the electric energy consumption minimum. Problems of traffic disturbances have been also included. First of all the influence of the light signalling at the crossing has been analysed to reduce the energy use caused by long stops forcing necessity of quicker subsequent ride to liquidate delay in relation to the time-table. Within the elaborated methodology, the tram route is divided into parts in keeping with different motion resistances for individual route fragments. Such simulation is more real and precise for tram ride conditions in the city. The paper deals with modernized trams driven by DC series motors supplied from modern choppers. For the stage of the vehicle running with the constant speed, the best choice of the value of the field-weakening coefficient can increase the motor efficiency.

KEYWORDS: tram vehicles, energy-saving control, DC series motors, light signalling

1. INTRODUCTION

Application of choppers to supplying DC series traction motors is one of methods of tram vehicle modernization. Choppers make possible increase of efficiency of the electric driving system. Energy savings can be obtained also by improvement of the tram traffic control. Novelty of this paper consists in synchronous analysis of the coordinated ride of some trams taking into account the minimization of electric energy use. Within the tram ride in the city, different traffic disturbances can appear: unexpected stops, unplanned speed limitations.

For the most part, the influence of the light signalling at the crossing has been analysed to reduce the electric energy consumption caused by long stops. At large traffic delay the quicker subsequent running is necessary to restore the ride in accordance with the time-table.

Within the elaborated methodology, the tram route is divided into parts in keeping with different motion resistances for individual route fragments. Such simulation is more real and precise for tram ride conditions in the city.

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For the modernized trams with DC motors supplied from choppers, at the stage of the vehicle running with the constant speed the best choice of the value of the field-weakening coefficient can increase the motor efficiency.

Within the framework of practical employment, calculations problems connected with the energy-saving control of some trams require computer of large power. Here cooperation with modern central supercomputer in the same city can be very useful.

2. SIMULATION MODEL OF TRAM RIDE

The mathematical simulation of the tram ride refers to equations of electrical circuits of driving motors, mechanical parameters of the vehicle and properties of the route of the running tram.

The dynamical vehicle state can be described as follows:

$$k_m m \frac{dv}{dt} = F_p - W(v) \quad (1)$$

where m is the tram vehicle mass, k_m - the rotating masses factor, v - the tram speed, F_p - the tractive force, $W(v)$ - the motion resistances. If the electrical machines are in the motoring type of operation the connection between the tractive force F_p and the useful motor torque T_U is given by the formula:

$$F_p = \frac{n_S T_U z \eta_p}{r} \quad (2)$$

where z is the transmission ratio, η_p - the gear efficiency, r - the driving wheel radius, n_S - the number of motors. For calculation of the motion resistances $W(v)$ the Cooper formula [4] is used.

Voltage equations of the DC series motor are given in [7]. In this paper for the stage of the vehicle run with the constant speed, the original method of the determining the maximum efficiency is given for the DC series motor supplied from the chopper. The field weakening factor k_w can be controlled. The factor k_w is the ratio of the field current I_f and the armature current I_a . The saturation degree in the DC series motor can change very much and the nonlinear magnetization characteristic $\Phi = f(I_f)$ is here taken into account (Φ is the magnetic flux). The electromagnetic torque T of the DC motor is the following:

$$T = k \cdot \Phi \cdot I_a = k \cdot f(I_f) \cdot \frac{I_f}{k_w} \quad (3)$$

The electromagnetic torque T is the sum of the useful torque T_U , the torque T_m connected with the mechanical losses and the torque T_{Fe} relating to the iron loss ΔP_{Fe} (the sum of the hysteresis loss ΔP_{Feh} and the eddy current loss ΔP_{Few}):

$$T = T_u + T_m + \frac{\Delta P_{Feh}}{\omega_m} + \frac{\Delta P_{Few}}{\omega_m} \quad (4)$$

$$\Delta P_{Feh} = \Delta P_{FehN} \cdot \frac{\omega_m}{\omega_{mN}} \cdot \left(\frac{\Phi}{\Phi_N} \right)^2 \quad (5)$$

$$\Delta P_{Few} = \Delta P_{FewN} \cdot \left(\frac{\omega_m}{\omega_{mN}} \right)^2 \cdot \left(\frac{\Phi}{\Phi_N} \right)^2 \quad (6)$$

where ω_m is the mechanical angular rotor speed. The magnetic flux Φ is here approximated with the help of the function depending on the field current I_f . For the known vehicle speed, the quantities: angular speed ω_m , torques: T_u , T_m have the constant values. The flux Φ is replaced by the function $f(I_f)$. We compare the right sides of equations (3, 4). For the given weakening factor k_w , the nonlinear equation with one unknown I_f ought to be solved. The maximum motor efficiency η will be determined for such factor k_w when the sum of iron loss – formulae (5, 6) – and copper loss ΔP_{Cu} will be minimum; the loss ΔP_{Cu} is:

$$\Delta P_{Cu} = R \cdot I_a^2 + R_f \cdot I_f^2 + 2\Delta U_p \cdot I_a \quad (7)$$

where R_f is the resistance of the field winding, R – the sum of resistances of all remaining windings connected in series, $2\Delta U_p$ – the voltage drop of brushes.

The electric energy En used by the motors can be obtained by the integration:

$$En = n_S \int_{t1}^{t2} u i dt \quad (8)$$

The optimization procedure enables determination of the tram traffic algorithm with the minimum electric energy use. For the particular trams (the total vehicles number is N), there are the following numbers: 1, 2, ..., m , ..., N . Within problems of the minimum energy use, the author of this paper has elaborated generalization of the optimization procedure by taking any number K of different parts of the ride segment into account. Individual parts between tram stops have numbers: 1, 2, ..., j , ..., K . For the part with the number j , by $ns(j)$ there is denoted the number of startings, the number of runnings with the constant speed has the notation $ncs(j)$, $nc(j)$ is the number of coasting phases, $nb(j)$ – the number of braking stages. $T(j)$ is the ride time in the part j (without time connected with unexpected internal stop), $L(j)$ – the length of this part. For the tram of the number m , the following relations are fulfilled:

$$\sum_{i=1}^{ns(m,1)} Ts_{m,i} + \sum_{i=1}^{ncs(m,1)} Tcs_{m,i} + \sum_{i=1}^{nc(m,1)} Tc_{m,i} + \sum_{i=1}^{nb(m,1)} Tb_{m,i} = T(m,1) \quad (9)$$

$$\sum_{i=1}^{ns(m,1)} Ls_{m,i} + \sum_{i=1}^{ncs(m,1)} Lcs_{m,i} + \sum_{i=1}^{nc(m,1)} Lc_{m,i} + \sum_{i=1}^{nb(m,1)} Lb_{m,i} = L(m,1) \quad (10)$$

$$\sum_{i=1}^{ns(m,2)} Ts_{m,i} + \sum_{i=1}^{ncs(m,2)} Tcs_{m,i} + \sum_{i=1}^{nc(m,2)} Tc_{m,i} + \sum_{i=1}^{nb(m,2)} Tb_{m,i} = T(m,2) \quad (11)$$

$$\sum_{i=1}^{ns(m,2)} Ls_{m,i} + \sum_{i=1}^{ncs(m,2)} Lcs_{m,i} + \sum_{i=1}^{nc(m,2)} Lc_{m,i} + \sum_{i=1}^{nb(m,2)} Lb_{m,i} = L(m,2) \quad (12)$$

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$$\sum_{i=1}^{ns(m,j)} Ts_{m,i} + \sum_{i=1}^{ncs(m,j)} Tcs_{m,i} + \sum_{i=1}^{nc(m,j)} Tc_{m,i} + \sum_{i=1}^{nb(m,j)} Tb_{m,i} = T(m, j) \quad (13)$$

$$\sum_{i=1}^{ns(m,j)} Ls_{m,i} + \sum_{i=1}^{ncs(m,j)} Lcs_{m,i} + \sum_{i=1}^{nc(m,j)} Lc_{m,i} + \sum_{i=1}^{nb(m,j)} Lb_{m,i} = L(m, j) \quad (14)$$

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$$\sum_{i=1}^{ns(m,K)} Ts_{m,i} + \sum_{i=1}^{ncs(m,K)} Tcs_{m,i} + \sum_{i=1}^{nc(m,K)} Tc_{m,i} + \sum_{i=1}^{nb(m,K)} Tb_{m,i} = T(m, K) \quad (15)$$

$$\sum_{i=1}^{ns(m,K)} Ls_{m,i} + \sum_{i=1}^{ncs(m,K)} Lcs_{m,i} + \sum_{i=1}^{nc(m,K)} Lc_{m,i} + \sum_{i=1}^{nb(m,K)} Lb_{m,i} = L(m, K) \quad (16)$$

$$Ts_{m,i} \geq 0 \quad Ls_{m,i} \geq 0 \quad Tcs_{m,i} \geq 0 \quad Lcs_{m,i} \geq 0 \quad (17)$$

$$Tc_{m,i} \geq 0 \quad Lc_{m,i} \geq 0 \quad Tb_{m,i} \geq 0 \quad Lb_{m,i} \geq 0 \quad (18)$$

$$T(m,1) + T(m,2) + \dots + T(m, j) + \dots + T(m, K) = T(m) \quad (19)$$

$$L(m,1) + L(m,2) + \dots + L(m, j) + \dots + L(m, K) = L(m) \quad (20)$$

where $T(m)$ is the total ride time of the tram with the number m in the segment consisting of K component parts (without time connected with unplanned internal stops), $L(m)$ is the total segment length.

3. DISCUSSION OF CALCULATION RESULTS

Computations were realized for four the same trams 105N. Modernization of the tram 105N has been made by using choppers supplying DC series motors. The nominal power and the number of driving motors were identical. Mechanical parameters of the tram vehicle were unvarying.

Every tram has four identical driving motors of the total power 160 kW. The nominal data of the tram are the following: the voltage of the traction network:

600 V (DC), total length: 13,5 m, tare mass: 16500 kg, nominal load: 8750 kg, rolling diameter of the wheel: 0,654 m, transmission ratio: 7,16, the maximum speed: 72km/h.

The rated data of the driving DC series motor are: the power: 40 kW, the voltage: 300 V, the current: 150 A, the rotational speed: 1890 rev/min, the efficiency: 88%, field-weakening coefficient: $1 - 0,63$.

Only part of calculation results is here presented; the results are relating to the example when the tram mass $m = 22000$ kg; it means the passengers number is equal 80 (in percentage form it is 64% in relation to the nominal tram vehicle load).

For the traffic without disturbances (green light at the crossing, Figs. 1 - 4) the planned ride parameters for the individual trams are the following:

- the tram 1 in the ride segment A: the distance 1200m, ride time 105 s,
- the tram 2 in the ride segment B: the distance 500m, ride time 50 s,
- the tram 3 in the ride segment C: the distance 900m, ride time 90 s,
- the tram 4 in the ride segment D: the distance 1000m, ride time 100 s.

The factor kr presents what part of the energy is recuperated during the tram braking. For $kr = 0$, the energy recuperation doesn't occur. Figs. 1 – 10 present the values of boundary speeds – diagram points – for consecutive stages of the tram vehicle traffic.

For the tram 1 (long distance between tram stops: 1200 m), Fig. 1 presents the ride without disturbances (green light of the signalling at the crossing). The energy use is here minimum owing to using the optimization procedure and determining the most advantageous duration for the starting stage, the phase of the running with the constant speed, the coasting and the braking.

It is interesting that at the DC series motors (in opposition to trams with three-phase induction motors) the algorithm of the energy-saving ride (with minimum energy consumption) doesn't depend on the value of the recuperation factor kr . For trams with DC motors it is also typical that the energy-saving ride possesses the longest coasting and lack of the phase of the running with the constant speed. At DC motors, the energy-consuming traffic (maximum energy use) occurs when the coasting doesn't exist and the stage of the running with the constant speed is the longest.

In Fig. 1, for the factor $kr = 1$ the minimum energy $En_{min} = 1,244$ kWh however for $kr = 0$ this minimum energy is equal: $En_{min} = 1,460$ kWh (by 17,4% more because of the lack of the energy recuperation during the braking phase). The modern devices of power electronics enable the electric energy recuperation and this possibility considerably improves the general energy balance.

For the tram 2 (short distance between tram stops: 500 m), Fig. 2 illustrates the ride without disturbances (green light) within the framework of the optimization and determining the best solution according to the criterion of the

minimum energy use. In this case (Fig. 2), for the factor $kr = 1$ the minimum energy $En_{min} = 0,664$ kWh and for $kr = 0$ this minimum energy is: $En_{min} = 1,069$ kWh (by 61,0% more). The relative difference (61,0%) is here much bigger than in Fig. 1. For short distances, energy savings - connected with the energy recuperation at the vehicle braking – are much larger in comparison with the ride case at long distances.

Fig. 3 is connected with the ride of the tram 3 – distance of 900m. Here there also are no traffic perturbations (green light). For the factor $kr = 1$ the minimum energy $En_{min} = 0,875$ kWh and for $kr = 0$ this minimum energy is: $En_{min} = 1,045$ kWh (by 19,4% more).

Fig. 4 illustrates the ride of the tram 4 – distance of 1000 m and the green light at the crossing. For the factor $kr = 1$ the minimum energy $En_{min} = 0,949$ kWh and for $kr = 0$ this minimum energy is: $En_{min} = 1,094$ kWh (by 15,3% more).

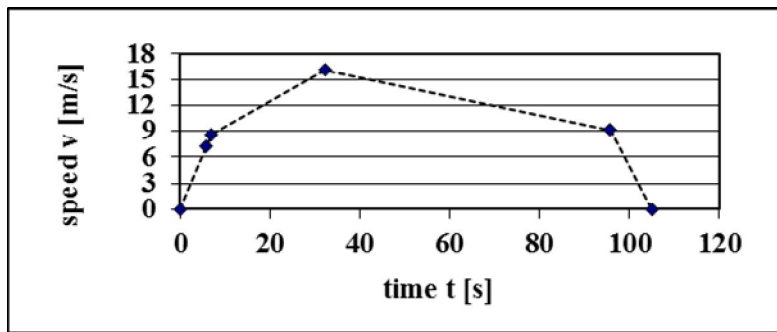


Fig. 1. Tram 1; the long distance between tram stops; length: 1200 m, time: 105 s; ride without disturbances (green light of the signalling at the crossing) at the minimum electric energy use equal: $En = 1,460$ kWh for the factor $kr = 0$ and $En = 1,244$ kWh for the factor $kr = 1$

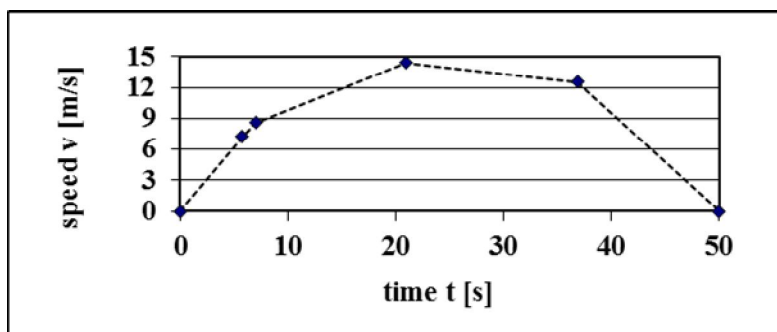


Fig. 2. Tram 2; the short distance between tram stops; length: 500 m, time: 50 s; ride without disturbances (green light of the signalling at the crossing) at the minimum electric energy use equal: $En = 1,069$ kWh for the factor $kr = 0$ and $En = 0,644$ kWh for the factor $kr = 1$

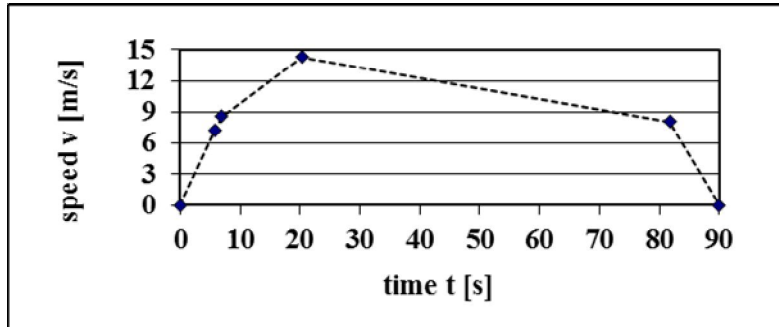


Fig. 3. Tram 3; the distance between tram stops: 900 m, time: 90 s; ride without disturbances (green light of the signalling at the crossing) at the minimum electric energy use equal: $E_n = 1,045$ kWh for the factor $kr = 0$ and $E_n = 0,875$ kWh for the factor $kr = 1$

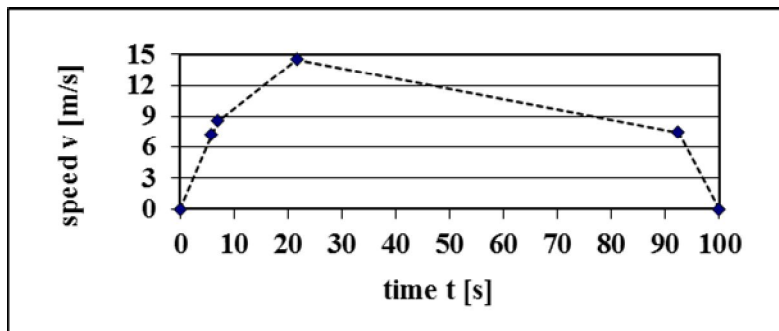


Fig. 4. Tram 4; the distance between tram stops: 1000 m, time: 100 s; ride without disturbances (green light of the signalling at the crossing) at the minimum electric energy use equal: $E_n = 1,094$ kWh for the factor $kr = 0$ and $E_n = 0,949$ kWh for the factor $kr = 1$

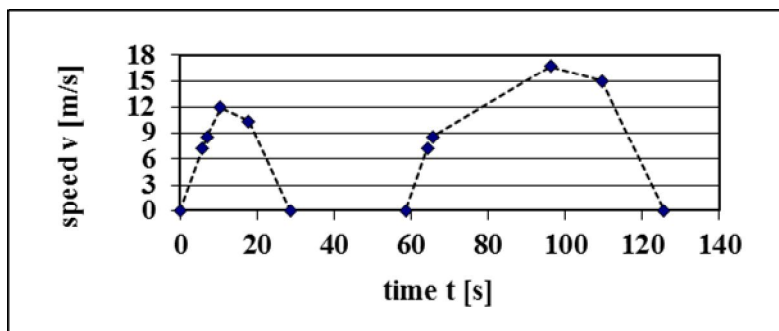


Fig. 5. Tram 4, 1000 m; ride with traffic disturbance caused by the red light of the signalling and the unplanned long tram stop of 30 s after the distance 200 m; the minimum electric energy use equal: $E_n = 2,333$ kWh for the factor $kr = 0$ and $E_n = 1,677$ kWh for the factor $kr = 1$

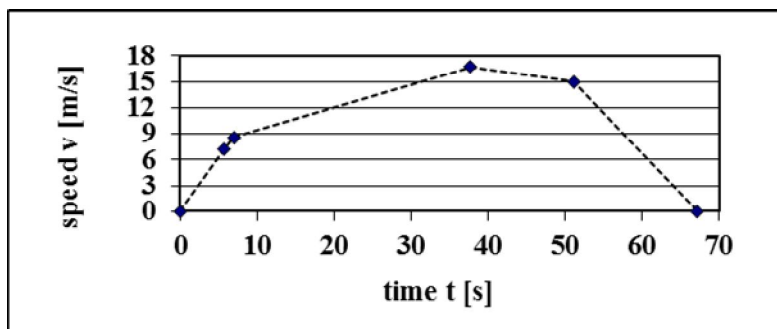


Fig. 6. Tram 4; ride in the same 2 segments: E and F (800 m) at liquidation of the large traffic delay caused by the unplanned long tram stop of 30 s in the segment D; the minimum electric energy use equal: $En = 1,641$ kWh for the factor $kr = 0$ and $En = 1,080$ kWh for the factor $kr = 1$

Within the second traffic variant shown in Figs. 5–8, it was not possible to ensure the green light for the tram 4 and the route D (1000 m) at the crossing (for the segments A-C and the trams 1-3 there is the ride without perturbations - the green light). The traffic disturbance (red light of the signalling) has appeared and the tram 4 first reduced the speed and then stopped a long time (30 s). With full particulars: after time 10,49 s the driver has noticed light change of the signalling and he realized first the tram coasting and then the vehicle braking. The tram has stopped after 200 m from the starting point (it is here the section I). After 58,5 s (counting from the route beginning place) the tram began the ride within the section II of the length 800 m. Owing to the large traffic delay, the time lag must be liquidated during the quicker ride in some next segments; these are the segments E and F in Fig. 6 or the segments E, F and G in Fig. 8 (slower delay elimination including longer time). The segments E, F and G are identical: the distance 800 m, initially planned ride time 80 s. Within the section II in Figs. 5 and 7, the ride is also quicker because at the beginning of the section II the procedure of delay liquidation is also starting.

In Fig. 6, the ride algorithm was found with the help of optimization calculations taking into account the criterion of the minimum energy use. The common traffic time: 67,17 s (instead of 80 s) has been determined for identical segments E and F. For each segment E, F, the quicker ride with the speed 11,91 m/s (for the traffic without disturbances it was planned 10 m/s) makes possible diminution of the delay by 12,83 s. In Fig. 6 the minimized energy consumption is equal $En_{min} = 1,080$ kWh for the recuperation factor $kr = 1$ and $En_{min} = 1,641$ kWh for $kr = 0$ (the energy recuperation doesn't exist). In comparison with the ride without disturbances (green light), the energy increase in percentage form is in each segment: 34,0% for $kr = 1$ and 63,1% for $kr = 0$.

Of course in Fig. 8 (the same segments: E, F, G), the ride time: 70,38 s is longer than in Fig. 6. In every segment, the quicker run with the speed 11,37 m/s (instead of

10m/s) enables delay decrease by 9,62 s. After energy minimization in Fig. 8, the energy use is equal $En_{min} = 0,965$ kWh for recuperation factor $kr = 1$ and $En_{min} = 1,350$ kWh for $kr = 0$ (lack of energy recuperation). In comparison with the ride without disturbances – green light, the energy increase in every segment is: 19,7% for $kr = 1$ and 34,2% for $kr = 0$. It is the rule that for greater number of segments including liquidation of the traffic delay, the energy use is smaller. The number of these segments must be compromising owing to social costs because regularity and punctuality of tram vehicles are important for passengers.

The third traffic variant (Figs. 9, 10) doesn't have the priority of green light for the tram 3 and route C (900 m) at the crossing (for the segments A, B, D and the trams 1, 2, 4 there is ride with green light). Because of red light, the tram 3 first diminished the speed (Fig. 9) and then stopped a short time (5 s). After 33,5 s (counting from the beginning of the route C) the tram began ride within the section II (length 700 m). Traffic delay is here liquidated by quicker ride in some next segments; this is only one segment H (700 m) in Fig. 10 and additionally (in other case of calculations) two identical segments: H, I (each of 700 m).

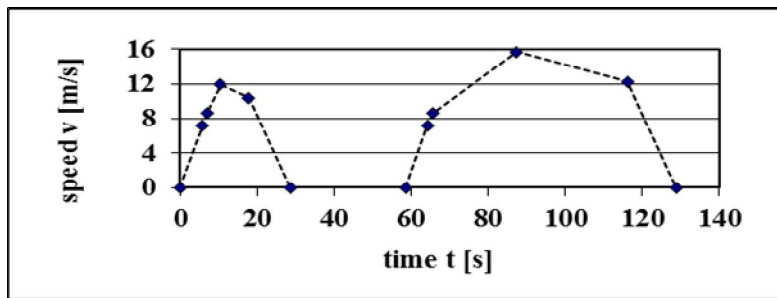


Fig. 7. Tram 4, 1000 m; ride with traffic disturbance caused by the red light of the signalling and the unplanned long tram stop of 30 s after the distance 200 m; the minimum electric energy use equal: $En = 2,042$ kWh for the factor $kr = 0$ and $En = 1,562$ kWh for the factor $kr = 1$

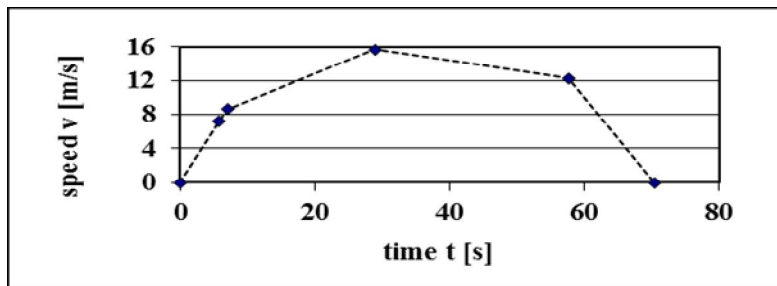


Fig. 8. Tram 4; ride in the same 3 segments: E, F and G (800 m) at liquidation of the large traffic delay caused by the unplanned long tram stop of 30 s in the segment D; the minimum electric energy use equal: $En = 1,350$ kWh for the factor $kr = 0$ and $En = 0,965$ kWh for the factor $kr = 1$

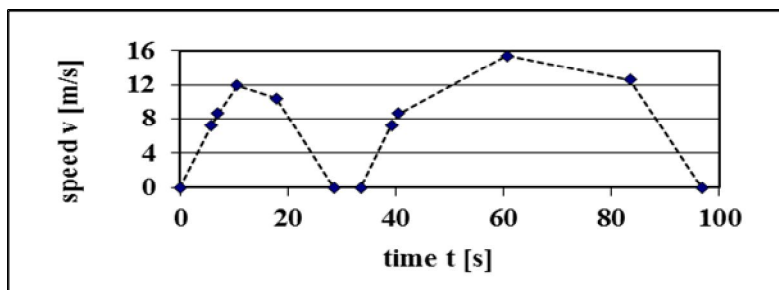


Fig. 9. Tram 3, 900 m; ride with traffic disturbance caused by the red light of the signalling and the unplanned short tram stop of 5 s after the distance 200 m; the minimum electric energy use equal: $En = 1,981$ kWh for the factor $kr = 0$ and $En = 1,473$ kWh for the factor $kr = 1$

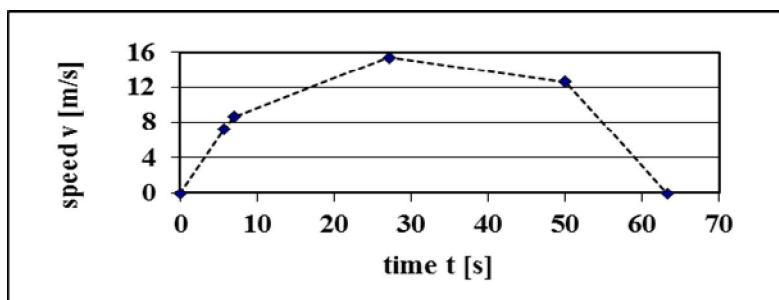


Fig. 10. Tram 3; ride in the segment H (700 m) at liquidation of the traffic delay caused by the unplanned short tram stop of 5 s in the segment C; the minimum electric energy use equal: $En = 1,289$ kWh for the factor $kr = 0$ and $En = 0,876$ kWh for the factor $kr = 1$

In Fig. 10, the ride algorithm was determined at minimum energy use. The traffic time: 63,25 s (instead of 70 s) requires the larger speed 11,07 m/s (instead of 10 m/s). In Fig. 10 the minimized energy use is equal $En_{min} = 0,876$ kWh for the recuperation factor $kr = 1$ and $En_{min} = 1,289$ kWh for $kr = 0$. In comparison with the ride without disturbances (green light), the energy increase in percentage form is in the segment H: 17,9% for $kr = 1$ and 31,4% for $kr = 0$.

If delay liquidation is within 2 segments: H, I, energy use is smaller: $En_{min} = 0,820$ kWh for $kr = 1$ and $En_{min} = 1,153$ kWh for $kr = 0$ (suitably by 10,4% and 17,5% more in comparison with the ride at the tram priority and green light).

4. CONCLUSIONS

Reduction of the tram energy use ought to be obtained by cooperation of many different methods. Among others, using modern materials, aerodynamical shape of the vehicle, application of choppers to supplying DC series traction motors, the suitable ride control (proper choice of duration of the ride phases).

Light signalling at the crossing within coordinated energy-saving traffic of trams ought to be taken into account. Synchronous analysis of ride of some trams allowing for minimization of energy use requires large computation power of the computer because the decisions must be realized within the online system.

Light signalling can cause disturbances: additional short or long tram stops. At large time lags of the traffic, the delay must be liquidated during the quicker run in succeeding ride segments. For greater number of such segments, energy use is smaller. The segments number must be compromising owing to social costs because regularity and punctuality of trams are important for passengers.

Within the elaborated methodology, the tram route is divided into parts in keeping with different motion resistances for individual route fragments.

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