# POTROŠNJA ENERGIJE ELEKTRIČNE ŽELJEZNICE
# ELECTRIC RAILWAY POWER CONSUMPTION

Milivoj Mandić – Ivo Uglešić – Viktor Milardić, Zagreb, Hrvatska

Električne željeznice predstavljaju specifičnog potrošača elektroenergetskog sustava. Radi racionalnog korištenja električne energije i odgovarajućih ušteda nastoji se optimirati potrošnja energije električnih vlakova i ostalih postrojenja električne željeznice. U radu je prikazan algoritam za simulaciju kretanja vlakova kojim se određuje najprije mehanička, a potom i električna snaga potrebna za vuču. Dionice elektrificirane pruge se napajaju iz elektrovučne podstanice (EVP), a za potrebe elektrovučnog proračuna formira se električna mreža. Na osnovi maksimalnog voznog reda za određeni vremenski period provodi se proračun električnih prilika; struja, napona, električnih snaga, kao i ukupno utrošene energije. Za određivanje potrošnje energije vučnog vozila treba izračunati otpore kretanja pojedinog vlaka na svakoj dionici. Ulazni podaci nužni za takav proračun su parametri profila pruge, planirane brzine kretanja na pojedinim dionicama, te karakteristike vlaka i lokomotive. Uz model za simulaciju kretanja vlaka u članku je prikazana analiza utjecajnih faktora na potrošnju električne energije za elektromotorni vlak, koji prometuje na hrvatskim prigradskim željeznicama. Rezultati su dobiveni algoritmom za simulaciju kretanja vlaka pomoću kojeg se izračunavaju položaji vlakova, kao i njihove mehaničke i električne snage potrebne za vuču. Na konkretnom primjeru napajanja postojećeg EVP-a su uspoređeni rezultati dobiveni elektrovučnim proračunom i mjerenjem. Dani su neki od rezultata elektrovučnog proračuna za EVP Zaprešić pri napajanju prigradske pruge Podsused Tv. – Samobor – Bregana, koja se planira izgraditi.

The electric railways is a specific consumer of the electric power system. For the purpose of using electric energy rationally and making adequate savings, efforts are made to optimize electric energy consumption of electric trains and other electric railway facilities. The work shows the train movement simulation algorithm which serves to determine primarily the mechanical and then also the electric power required for traction. The sections of the electrified tracks are supplied from the electric traction substation (TS) and, for the requirements of the electric traction calculation, an electric network is formed. Based on the maximum time table for a certain time period, calculation is done of the electric circumstances; electricity, voltage, electric power, as well as the total consumed electric energy. For the determination of the electric energy supply of the traction unit, movement resistances of the certain train on each section need to be calculated. Input data necessary for such a calculation are the tracks profile parameters, planned movement speeds on certain sections, and the properties of the train and the locomotive. Besides the train movement simulation model, the article also shows the analysis of impact factors on the electric energy consumption for the electromotor train which travels the Croatian suburban rails. The results are obtained by the train movement simulation algorithm, by virtue of which the locations of trains are calculated, as well as their mechanical and electric powers necessary for traction. The particular example of the supply of the existing SS serves for comparing the results obtained by electric traction calculation and measurement. Some of the results are given of the electric traction simulation for the Zaprešić SS at the supply of the suburban Podsused factory – Samobor – Bregana which is planned for construction

Ključne riječi: elektromotorni vlak; EVP; elektrovučni proračun; koeficijent adhezije; potrošnja električne energije; rekuperacija; simulator kretanja vlaka
Key words: adhesion coefficient; electric energy consumption; electric traction calculation; electromotor train; TS; recuperation; train movement simulator

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# 1 UVOD

Optimalnom potrošnjom energije električnih vlakova nastoje se ostvariti uštede i racionalizacija sveukupnog poslovanja uz uvjet efikasnog i pravovremenog prometa vlakova. Radi kontinuiranog trenda rasta cijene električne energije, problemi ekonomičnog i pouzdanog korištenja električne vuče postaju sve veći izazov za korisnike i proizvođače električnih željeznica.

Glavni pristup uštede energije u željezničkom prometu ovisi o energetski efikasnoj konstrukciji lokomotiva, efikasnom reduciranju otpora pri kretanju vlaka, kao i o odgovarajućem održavanju voznog parka i tračnica [1].

Zbog porasta cijene energije i sve većeg razvoja prigradskog željezničkog prometa, sve više se pozornosti posvećuje racionalnoj potrošnji električne energije prigradskih vlakova. Parametri koji utječu na potrošnju električne energije elektromotornog vlaka su:

- vučne karakteristike elektromotornog vlaka (vučni pasoš),
- kočione karakteristike elektromotornog vlaka,
- faktor snage,
- masa vlaka,
- snaga pomoćnih pogona (rasvjeta, hlađenje motora, grijanje vagona i sl.),
- profil pruge (radijus krivine i nagib),
- maksimalno dozvoljena brzina na određenoj dionici,
- rekuperacija (predviđeno vraćanje snage u kontaktnu mrežu pri kočenju),
- grafikon voznog reda.

Računske simulacije kretanja vlakova predstavljaju efikasno i ekonomično sredstvo kojim se može odrediti potrošnja energije vlaka, uz određene ulazne parametre. Između ostalog je u nastavku dan matematički model simulacije kretanja vlaka i parametarska analiza utjecajnih faktora na potrošnju energije za elektromotorni vlak koji prometuje prigradskim prugama.

# 2 MATEMATIČKI MODEL SIMULACIJE KRETANJA VLAKA

Pri kretanju vozila prugom pojavljuju se različiti otpori vožnje koji se protive tom kretanju. Da bi otpori bili svladani, vučno vozilo mora na obodu pogonskih kotača ostvariti vučnu silu jednaku zbroju svih otpora. Otpori vožnje mogu biti stalni i promjenjivi.

# 1 INTRODUCTION

Electric trains' optimum power consumption is used to achieve savings and rationalization of the total business operation under the condition of efficient and timely railway traffic. For the purpose of a continued trend of rising electric energy prices, the issues of economical and reliable use of electric traction are becoming more and more of a challenge for the users and producers of electric tracks.

The main approach of energy savings in railway traffic depends on the energy-efficient locomotive construction, efficient resistance reduction at train movement as well as on the adequate maintenance of the rolling stock and the tracks [1].

Because of the rise in energy prices and the increasing development of the suburban railway traffic, an increasing amount of attention is given to the suburban trains' electric energy consumption. The parameters which impact electromotor train electric energy consumption are:

- electromotor train traction properties (rolling resistance),
- braking characteristics of the electromotor train,
- power factor,
- train weight,
- auxiliary drive power (lighting, motor cooling, wagon heating, etc.),
- tracks profile (bend radius and slant),
- maximum allowed speed on the certain section,
- recuperation (planned return of power into the contact network at braking),
- time table graph.

Computational train movement simulations represent an efficient and economical means by which the consumption of train's electric energy can be determined with certain input parameters. Inter alia, a mathematical model of train movement simulation is given below, as well as the parameter analysis of impact factors on the electromotor train electric energy consumption which travels the suburban tracks.

# 2 MATHEMATICAL TRAIN MOVEMENT SIMULATION MODEL

When the vehicles move along the tracks, various drive resistances appear which oppose that movement. In order for the resistances to be handled, the traction vehicle must realize a traction force equal to the sum of all resistances at the edge of the driving wheels. Drive resistances can be constant or variable.

Stalni otpori se pojavljuju uvijek pri kretanju vlaka i za njihovo izračunavanje se koriste iskustveni izrazi koje se mogu razlikovati u različitim zemljama. U modelu koji je predložen u nastavku usvojen je izraz za specifični otpor po Strahl-u [2]. Specifični otpor se dobije svođenjem otpora na jedinicu mase.

Specifični otpori se posebno računaju za vučno vozilo, a posebno za vlak.

Povremeni otpori su otpori koji se pojavljuju ovisno o profilu pruge, a tu spadaju:

— otpori uspona,
— otpori krivine.

U proračunu otpora krivine koriste se eksperimentalne formule u kojima uglavnom egzistira polumjer zavoja kao najutjecajnija veličina pa se za izračunavanje specifičnog otpora krivine u simulaciji kretanja vlaka korišten izraz (1):

Constant resistances always appear when the train moves and their calculation requires empiric expressions which might differ from country to country. The model which is suggested below contains the expression for the specific resistance according to Strahl [2]. The specific resistance is obtained by reducing the resistance to the weight unit.

Specific resistances are calculated separately for the traction vehicle and separately for the train.

Occasional resistances are resistances which appear depending on the tracks profile and these include:

— climb resistances,
— bend resistances.

In the calculation of bend resistances experimental formulas are used in which the turn radius mostly exists as the most influential dimension so that the following expression is used for the calculation of the specific bend resistance in the train movement simulation (1):

$$f_z = \frac{8\ 000}{R} \cdot 10^{-3} \tag{1}$$

gdje je:

$f_Z$ – specifični otpor u zavoju, N/kg,
R – radijus krivine, m.

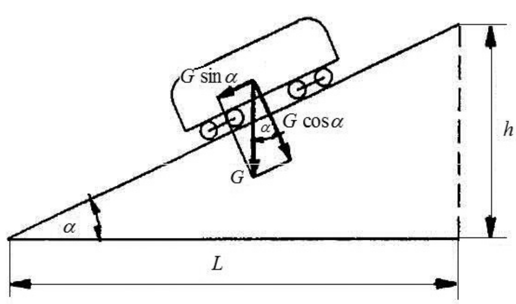
Otpor na usponu, čiji je nagib pod kutom $\alpha$, se određuje pomoću sile $F_i$ koja je paralelna tračnicama (slika 1), a iznosi:

where it is as follows:

$f_Z$ – specific resistance in the turn, N/kg,
R – bend radius, m.

The resistance at the climb, the slant of which is at the angle $\alpha$ and which is determined by virtue of the force $F_i$ parallel with the tracks (Figure 1) and which amounts to:

$$F_i = \pm G \cdot \sin\alpha, \ \ \mathrm{N} \ . \tag{1a}$$




**Slika 1** — Prikaz sila na usponu
Figure 1 — Overview of the forces at the climb

Taj otpor mora biti svladan da bi se vozilo moglo kretati uz uspon. U slučaju kretanja niz uspon ovaj otpor ima negativan predznak i djeluje kao vučna sila.

That resistance must be overcome in order for the vehicle to be able to move upward. In case of moving downward, this resistance has a negative prefix and acts as a traction force.

Izraz za specifični otpor uspona koji je korišten u algoritmu je dan izrazom (2):

The expression for the specific climb resistance used in the algorithm is given by the expression (2):

$$f_i = \pm \frac{i}{100} \quad , \tag{2}$$

gdje je:

$f_i$ – specifični otpor na usponu, N/kg,
$i$ – uspon pruge, ‰.

it is as follows:

$f_i$ – specific resistance at the climb, N/kg,
$i$ – tracks climb, ‰.

Otpor ubrzavanja se pojavljuje pri svakoj promjeni brzine, a izraz za specifični otpor ubrzanja koji je korišten u algoritmu je dan izrazom (3):

The acceleration resistance appears at any change of speed, and the expression for the specific acceleration resistance used in the algorithm is given by the expression (3):

$$f_a = (1 + \varepsilon) \cdot a \tag{3}$$

gdje je:

$f_a$ – specifični otpor ubrzanja, N/kg,
$\varepsilon$ – koeficijent rotirajućih masa (0,06–0,08),
$\alpha$ – ubrzanje vlaka izraženo, m/s$^2$.

where it is as follows:

$f_a$ – specific resistance at acceleration, N/kg,
$\varepsilon$ – rotating masses coefficient (0,06–0,08),
$\alpha$ – train acceleration expressed, m/s$^2$.

Nakon određivanja otpora koji se pojavljuju prilikom kretanja pojedinog vlaka potrebno je utvrditi posjeduje li elektrovučno vozilo dovoljnu vučnu silu za svladavanje otpora. Radi toga se provjerava tzv. vučni pasoš električnog vozila, koji po svojoj konturi predstavlja granične mogućnosti vučnog vozila. Grafički se prikazuje kao ovisnost vučne sile o brzini. Vučni pasoš daje osnovno obilježje vučnih mogućnosti i popratni je tehnički dokument svakog vučnog vozila. Pri malim brzinama vučna sila može doseći veoma velike vrijednosti i premašiti silu adhezije te će nastupiti proklizavanje. Da ne bi došlo do proklizavanja pogonskih kotača po tračnicama mora biti ispunjen sljedeći uvjet [3]:

After the determination of the resistances which appear at the movement of a certain train, it is necessary to assess whether the traction vehicle has sufficient traction force for overcoming the resistance. That is why the rolling resistances of the electric vehicle are verified, as its contour represents the borderline possibilities of the traction vehicle. It is graphically depicted as the dependency of the traction force on the speed. The rolling resistance properties provide the basic criterion of traction possibilities and these represent the supporting technical document of each traction vehicle. At small speeds, the traction force may reach very high values and exceed the adhesion force, and then sliding will take place. In order to prevent the driving wheels from sliding on the tracks, the following condition must be met [3]:

$$F_{\mathrm{v}} \le \xi \cdot G_{\mathrm{ad}} = F_{\mathrm{ad}} \tag{4}$$

gdje je:

$F_{\mathrm{v}}$ – vučna sila, N,

where it is as follows:

$F_{\mathrm{v}}$ – traction force, N,

$F_{a\,d}$ – sila adhezije, N,
$G_{ad}$ – adheziona težina (težina vučnog vozila), N,
ξ – koeficijent adhezije [4].

Iz izraza (4) se može zaključiti da vučna sila mora biti manja ili jednaka sili adhezije $F_{a\,d}$.
Koeficijent adhezije, osim o stanju tračnica, ovisi i o stanju kotača. Ako je kotač oštećen, osovinski pritisak varira pa se ξ smanjuje. Također postoji njegova ovisnost o brzini prikazana u izrazu (5).

$F_{a\,d}$ – adhesion force, N,
$G_{ad}$ – adhesion weight (traction vehicle weight), N,
ξ – adhesion coefficient [4].

From the expression (4), it can be concluded that the traction force must be lower or equal to the adhesion force $F_{a\,d}$.

Besides the condition of the tracks, the adhesion coefficient also depends on the condition of the wheels. If the wheel is damaged, the axis pressure varies and ξ decreases. There also exists its dependency on the speed shown in expression (5).

$$\xi = \frac{\xi_0}{1 + 0{,}015 \cdot v} \tag{5}$$

gdje je:

$v$ – brzina vozila, km/h,
$\xi_0$ – statički koeficijent adhezije za koji se uzima:
$\xi_0 = 0{,}38$ – za suhe tračnice,
$\xi_0 = 0{,}25$ – za mokre tračnice,
$\xi_0 = 0{,}18$ – za masne tračnice.

Izraz (5) pokazuje da se povećanjem brzine smanjuje koeficijent adhezije. Ograničeni koeficijent adhezije ograničava maksimalnu snagu, maksimalno ubrzanje i maksimalni uspon (odnosno pad) koji se može svladati pa je maksimalna vučna snaga u zavisnosti od brzine $v$ dana izrazom (6):

where it is as follows:

$v$ – vehicle speed, km/h,
$\xi_0$ – static adhesion coefficient for which it is taken:
$\xi_0 = 0{,}38$ – for dry tracks,
$\xi_0 = 0{,}25$ – for wet tracks,
$\xi_0 = 0{,}18$ – for greasy tracks.

The expression (5) shows that with the increase of the speed, the adhesion coefficient decreases. The limited adhesion coefficient limits the maximum power, maximum acceleration and maximum climb (that is, decline) which can be overcome, so the maximum traction power is dependant on the speed $v$ given by expression (6):

$$P_{v\,max} = F_v \cdot v = \xi \cdot G_{a\,d} \cdot v = \frac{\xi_0}{1 + 0{,}015 \cdot v} \cdot G_{ad} \cdot v \quad , \tag{6}$$

Na osnovi izraza (6) se može zaključiti da je $P_{v\,max}$ ograničena zbog adhezije. Ovo znači da u laganu lokomotivu nema smisla ugrađivati motore velike instalirane snage. Zbog male adhezije pri velikim brzinama se ne može iskoristiti sva instalirana snaga vučnog motora.

Vrijednost za maksimalno ubrzanje vlaka dana je izrazom (7) iz [5]:

Based on the expression (6) it can be concluded that $P_{v\,max}$ is limited due to adhesion. This means that it doesn't make sense to install locomotives of great installed power. Due to small adhesion at great speeds, not all the installed power of the traction vehicle can be used.

The value for maximum train acceleration is given by the expression (7) from [5]:

$$a_{max} = \frac{1\,000 \cdot \xi \cdot G_{ad}}{102 \cdot (1+\varepsilon) \cdot (G_{ad} + G_t)} \quad , \tag{7}$$

gdje je:

$G_t$ – težina tereta, N,
$G_a + G_t$ – ukupna težina elektromotornog vlaka, N.

where it is as follows:

$G_t$ – cargo weight, N,
$G_a + G_t$ – total train electromotor weight, N.

Izraz (7) pokazuje da je maksimalno ubrzanje vlaka proporcionalno težini vučnog vozila, a obrnuto proporcionalno ukupnoj težini vlaka.

Ako uzmemo da ukupna težina elektromotornog vlaka ($G_{ad} + G_t$) iznosi 1 800 N, a težina vučnog vozila ($G_{ad}$) 670 N dobije se da maksimalno ubrzanje za elektromotorni vlak iznosi oko 1,14 $m/s^2$.

Isto tako se dobije da maksimalno ubrzanje teretnih vlakova tipično iznosi oko 0,5 $m/s^2$. Maksimalno ubrzanje je također ograničeno zbog udobnosti putnika, u simulacijama kretanja vlakova se može koristiti ubrzanje od 0,5 $m/s^2$.

Znajući potrebnu vučnu silu za ostvarenje kretanja vlaka, moguće je izračunati mehaničku snagu na obodu kotača prema izrazu (8):

Expression (7) shows that the maximum train acceleration is proportional to the weight of the traction vehicle and inversely proportional to the train's weight.

If it is taken that the total weight of the electromotor train ($G_{ad} + G_t$) amounts to 1 800 N and that the weight of the traction vehicle ($G_{ad}$) is 670 N, the result is that the maximum acceleration for the electromotor train amounts to about 1,14 $m/s^2$.

The result that the acceleration of cargo trains typically amounts to about 0,5 $m/s^2$ is obtained in the same way. Maximum acceleration is also limited for the purpose of the passengers' comfort; in the simulations of train movement maximum acceleration of 0,5 $m/s^2$ can be used.

If the traction force necessary for the realization of train movement is known, it is possible to calculate the mechanical force on the wheels' edges according to the expression (8):

$$P_m = F_v \cdot v \tag{8}$$

gdje je:

$P_m$ – mehanička snaga, W,
$F_v$ – vučna sila, N,
$v$ – brzina, m/s.

Za izračunavanje djelatne snage koju vlak uzima iz mreže potrebno je poznavati faktor korisnosti ($\eta$) vučnog vozila koji ovisi o brzini kretanja vlaka i naponu mreže. U slučaju da nije poznata krivulja promjene faktora $\eta$ može se pretpostaviti neka konstantna vrijednost, npr. 0,8 ili slična. Potrebno je još poznavati snagu pomoćnih pogona vlaka (hlađenje motora, grijanje vagona i sl.). Ta snaga se mijenja po mjesecima [6], a u simulacijama se može uzeti neka konstantna vrijednost snage pomoćnih pogona, npr. 250 kW.

Električna djelatna snaga koju vlak uzima iz mreže može se odrediti prema izrazu (9):

where it is as follows:

$P_m$ – mechanical power, W,
$F_v$ – traction force, N,
$v$ – speed, m/s.

For the calculation of the active power which the train takes from the network, it is necessary to know the efficacy ($\eta$) of the traction vehicle which depends on the train movement speed and the network voltage. In case the $\eta$ factor alteration curve is not known, a certain constant value can be assumed, e.g. 0,8 or similar. It is also necessary to know the power of auxiliary train drives (motor cooling, wagon heating, etc.). That power changes according to month [6] and a certain constant value of the auxiliary drives power can be taken in the simulations, such as 250 kW.

Electric active power the train takes from the network can be determined according to the expression (9):

$$P_{el} = \frac{P_m}{\eta} + P_{pom} \ , \tag{9}$$

gdje je:

$P_{el}$ – električna djelatna snaga, W,
$P_{pom}$ – snaga pomoćnih pogona, W,
$\eta$ – faktor korisnosti vučnog vozila.

U slučaju izmjeničnog napajanja pored djelatne snage vlak uzima i jalovu snagu iz mreže. Jalova snaga se računa prema izrazu (10):

where it is as follows:

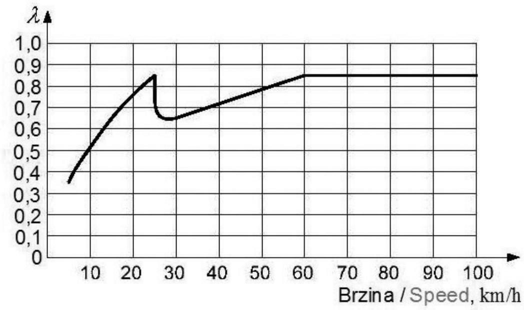
$P_{el}$ – electric active power, W,
$P_{pom}$ – auxiliary drives power, W,
$\eta$ – traction vehicle efficiency factor.

In case of alternate supply, besides the active power, the train also takes reactive power from the network. Reactive power is calculated according to the expression (10):

$$Q_{el} = P_{el} \cdot \tan[\arccos(\cos\lambda)] \quad (10)$$

Faktor snage $\lambda$ je ovisan o brzini kretanja vozila, a izgled te krivulje za elektromotorni vlak je prikazan na slici 2. $\cos(\varphi)$ predstavlja faktor snage koji se odnosi samo na osnovni harmonik, dok faktor $\lambda$ uključuje udjele viših harmonika koji su prisutni u struji vuče.

The power factor is dependant on vehicle movement and the appearance of that curve for the electromotor train is shown in Figure 2. $\cos(\varphi)$ represents the power factor which refers only to the basic harmonic, while factor $\lambda$ also includes the shares of higher harmonics present in the traction current.




**Slika 2** — Krivulja faktora snage $\lambda$ elektromotornoga vlaka
**Figure 2** — Electromotor train power factor curve $\lambda$

Poznavanje faktora $\lambda$ je naročito važno u prometu s čestim pokretanjem i zaustavljanjem jer je pri malim brzinama faktor snage manji.

Moderne lokomotive sadrže u sebi PWM (pulsno širinska modulacija) pretvarače koji stvaraju više harmonike, a oni se zatim šire kontaktnom i prijenosnom mrežom [7].

Na moderna vučna vozila u sustavima električne vuče 25 kV, 50 Hz postavljaju se zahtjevi na smanjenu potrošnju jalove energije i smanjen sadržaj viših harmonika u struji vuče. Potrošnja električne energije vlaka u vremenskom intervalu t se računa prema izrazu (11):

Knowing the $\lambda$ factor is especially important in traffic with frequent starts and stops because the power factor is lower at smaller speeds.

Contemporary locomotives contain within themselves the pulse-width modulation (PWM) converters which create higher harmonics which then spread through the contact and transmission network [7].

Contemporary traction vehicles in the 25 kV, 50 Hz electric traction systems are subjected to requirements regarding reduced consumption of reactive power and reduced contents of higher harmonics in the traction current. The train's electric energy consumption in the time interval t is calculated according to the expression (11):

$$E = \sum_{i=1}^{n} P \cdot \Delta t \quad (11)$$

gdje je:

- $\Delta t$ – korak proračuna, s,
- $P$ – djelatna snaga za svaki korak proračuna, MW,
- $n$ – broj iteracija proračuna, $t/\Delta t$.

where it is as follows:

- $\Delta t$ – calculation step, s,
- $P$ – active power for each calculation step, MW,
- $n$ – number of calculation iterations, $t/\Delta t$.

Iz izraza (10) se vidi da se energija računa numerički za svaki korak proračuna $\Delta t$ i na kraju se sumira da bi se dobila ukupna potrošnja energije elektromotornog vlaka.

U simulaciji kretanja vlaka je također omogućeno uzimanje u obzir povrat snage u mrežu, tj. rekuperacija prilikom kočenja vlaka. Krivulja elektrodinamičke kočnice elektromotornog vlaka serije HŽ 6111 i formule za izračun snage koja se vraća u mrežu se nalazi u [3]. Faktor korisnosti električne kočnice ($\eta_k$) kreće se od 0,66 do 0,85 ovisno o konstrukciji kočnice. U algoritmu je pretpostavljena vrijednost $\eta_k = 0{,}85$. Snagu je moguće vratiti u mrežu u slučaju da vlak pri kretanju koči električnom kočnicom (na većim strminama) ili prilikom zaustavljanja jer u tim slučajevima je $P_m < 0$. Snaga kočnice se računa prema sljedećem izrazu (12):

The expression (10) reveals that the power is numerically calculated for each calculation step $\Delta t$ and it is summed up in the end in order to obtain the electromotor train's total power consumption.

The return of the power into the network, that is, recuperation at train's braking, can also be taken into consideration at train movement simulation. The curve of the electromotor train electrodynamic brake of the HŽ 6111 series and of the formula for the calculation of the power which returns into the network can be found in [3]. The electric brake efficiency factor ($\eta_k$) fluctuates from 0,66 to 0,85 depending on the brake structure. The value of $\eta_k = 0{,}85$ is assumed in the algorithm. The power can be returned to the network in case the train, while moving, brakes with the electric brake (on greater precipices) or when stopping because in such cases $P_m < 0$. The brake's power is calculated according to the following expression (12):

$$P_{ek} = F_k \cdot v \quad . \tag{12}$$

gdje je:

$P_{ek}$ – snaga kočnice, W,
$F_k$ – sila električne kočnice, N,
$v$ – brzina, m/s.

where it is as follows:

$P_{ek}$ – brake's power, W,
$F_k$ – electric brake force, N,
$v$ – speed, m/s.

Budući da prilikom kočenja mehanička snaga na obodu kotača ima negativni predznak, u mrežu je moguće vratiti snagu ovisno o tome da li je apsolutna vrijednost mehaničke snage veća ili manja od snage kočnice pa imamo dva slučaja:

Because the mechanical power on the wheel's edge has a negative prefix upon braking, the power can be returned into the network regardless of whether the absolute value of the mechanical power is greater or lower than the brake's power, so, two cases arise:

Ako je $P_m > P_{ek}$ u mrežu je moguće vratiti snagu:

If $P_m > P_{ek}$ power can be returned into the network:

$$P_e = P_{ek} \cdot \eta_k - P_{pom} \quad , \quad \mathrm{W} \, , \tag{13}$$

Ako je $P_m < P_{ek}$ u mrežu je moguće vratiti snagu:

If $P_m < P_{ek}$ power can be returned into the network:

$$P_e = |P_m| \cdot \eta_k - P_{pom} \quad , \quad \mathrm{W} \, . \tag{13}$$

## 3 SIMULACIJA ELEKTRIČNE VUČE

Napajanje kontaktne mreže 25 kV, 50 Hz iz elektrovučnih podstanica može biti jednostrano (radijalno) ili dvostrano, Na hrvatskim prugama 25 kV, 50 Hz najčešće se koristi jednostrano napajanje.

Ovdje će se prikazati odgovarajući algoritam za elektrovučni proračun, koji je primijenjen za slu-

## 3 ELECTRIC TRACTION SIMULATION

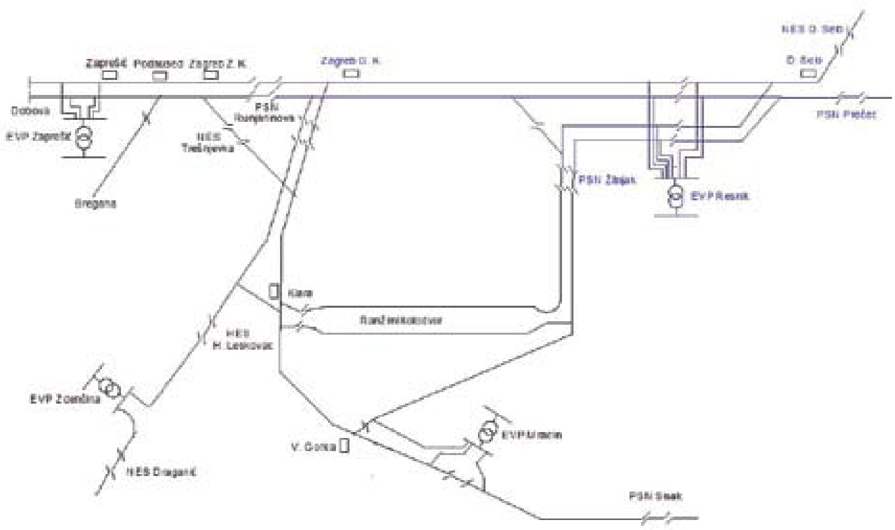
Supplying the 25 kV, 50 Hz-contact network from electric traction substations can be unilateral (radial) or bilateral. On the Croatian 25 kV, 50 Hz-railway tracks, unilateral supply is most often used.

The adequate algorithm for the electric traction calculation, applied in the unilateral supply case, will be čaj jednostranog napajanja. Rezultati dobiveni proračunom usporedit će se s rezultatima mjerenja, koja su provedena u elektrovučnoj podstanici Resnik.

Shema napajanja željezničkog čvora Zagreb prikazana je slikom 3. Vidljivo je područje redovitog napajanja EVP Resnik (plava linija) kao i područja napajanja susjednih EVP-a.

shown here. The results obtained by calculation will be compared with the results of the measurements undertaken at the Resnik electric traction substation.

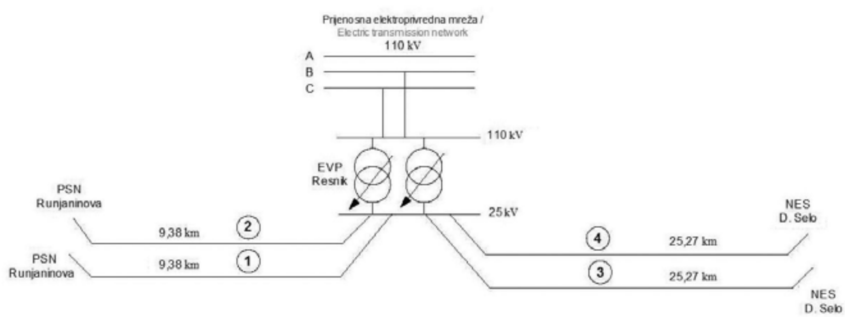
The Zagreb railway knot supply scheme is shown in Figure 3. The area of regular supply of the Resnik electric traction substation (SS) (blue line) is visible, as well of the neighbouring TSs.




**Slika 3** — Mreža elektrificiranih pruga na području Zagreba
Figure 3 — The network of electrified tracks in the Zagreb area

Duljine krakova napajanja EVP Resnik u normalnom pogonu su prikazane na slici 4. Napojni vod 1 priključen je na dio kontaktne mreže koja napaja vlakove koji prometuju prema Zagrebu, a napojni vod 2 vlakove prema Sesvetama.

The lengths of supply arms of SS Resnik under normal operation are shown in Figure 4. Feeder current 1 is connected onto the part of the contact network which connects trains travelling towards Zagreb and feeder current 2 onto the part which supplies the trains towards Sesvete.

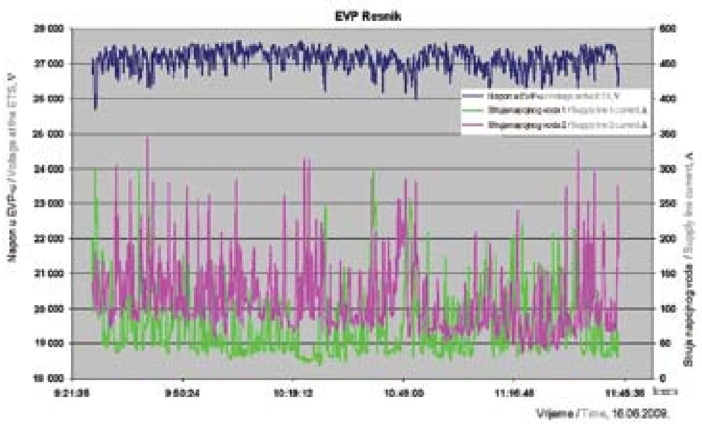



**Slika 4** — Duljine krakova napajanja EVP Resnik
Figure 4 — The network of electrified tracks in the Zagreb area

Mjerenja struja i napona na 25 kV strani EVP 25/100 kV Resnik provela su se na sekundarnoj strani, pri čemu su mjerni instrumenti bili priključeni na zaštitnu jezgru strujnog i naponskog transformatora

Measurements of currents and voltages on the 25 kV-side of the 25/100 kV SS Resnik were undertaken on the secondary side, whereat the measurement instruments were connected onto the safety u 25 kV dijelu postrojenja. Rezultati mjerenja su prikazani na slici 5.

core of the current and voltage transformer in the 25 kV-part of the facility. Measurement results are shown in Figure 5.




**Slika 5** — Napon i struje u EVP Resnik na 25 kV strani

**Figure 5** — Voltage and currents at the Resnik ETS on the 25 kV side

Mjerenja su obavljena 16. lipnja 2009. u vremenskom intervalu od 9:30 do 11:30.
Plava linija prikazuje iznos napona u EVP-u u tom vremenskom periodu, dok crvena i zelena linija prikazuju struje napojnih vodova 1 i 2.

U tablici 1 se nalazi popis vlakova koji su prometovali u tom vremenskom periodu na dionici Zagreb G.K. – D. Selo.

Measurements were undertaken on 16 June 2009 in the time interval from 9:30 to 11:30.
The blue line shows the amount of voltage at the SS in that time period while the red and the green lines show the currents of the feeder currents 1 and 2.

Table 1 shows the list of trains which travelled during that time on the Zagreb G.K. (Main Railway Station) – Dugo Selo section.

Tablica 1- Popis vlakova na dionici Zagreb GK – D. Selo (16.06.2009. od 9:30 do 11:30)

Table 1 – List of trains on the Zagreb GK – D. Selo section (16 June 2009 from 9:30 - 11.30)

| Šifra vlaka / Train code | Težina vlaka / Train weight t | Vrijeme polaska / Time of departure h:m | Vrijeme dolaska / Time of arrival h:m | Mjesto polaska / Place of departure | Mjesto dolaska / Place of arrival | Vrsta lokomotive / Locomotive type |
|---|---|---|---|---|---|---|
| 8029 | 176 | 9:09 | 9:33 | Zagreb GK | D. Selo | 6111-023 |
| 741 | 273 | 9:15 | 9:35 | Zagreb GK | D. Selo | 1142-012 |
| 8030 | 176 | 9:55 | 10:21 | D. Selo | Zagreb GK | 6111-023 |
| 8031 | 176 | 9:25 | 9:50 | Zagreb GK | D. Selo | 6111-008 |
| 8032 | 176 | 10:22 | 10:47 | D. Selo | Zagreb GK | 6111-008 |
| 2013 | 134 | 9:46 | 10:10 | Zagreb GK | D. Selo | 1141-306 |
| 1751 | 198 | 10:03 | 10:20 | Zagreb GK | D. Selo | 1142-004 |
| 703 | 203 | 10:09 | 10:28 | Zagreb GK | D. Selo | 1141-004 |
| 744 | 210 | 10:40 | 10:59 | D. Selo | Zagreb GK | 1141-230 |
| 2012 | 135 | 11:00 | 11:24 | D. Selo | Zagreb GK | 1141-015 |
| 8034 | 176 | 11:08 | 11:34 | D. Selo | Zagreb GK | 6111-007 |
| 8035 | 176 | 10:13 | 10:39 | Zagreb GK | D. Selo | 6111-007 |
| 38025 | 82 | 9:38 | 9:57 | Zagreb GK | D. Selo | 462-002 |
| 47981 | 759 | 11:15 | 11:39 | D. Selo | Zagreb GK | 1141-007 |
| 45902 | 1245 | 10:45 | 11:08 | Zagreb GK | D. Selo | 1141-106 |
| 415 | 289 | 11:04 | 11:21 | Zagreb GK | D. Selo | 1142-015 |
| 2173 | 176 | 10:38 | 11:04 | Zagreb GK | D. Selo | 6111-024 |

U zadnjem stupcu tablice 1 je navedena vrsta lokomotive koja pokreće pojedini vlak. Mogu se uočiti 4 vrste lokomotiva i to:

— 6111 – elektromotorni vlak,
— 1141 – četiriosovinska diodna lokomotiva,
— 1142 – četiriosovinska tiristorska lokomotiva,
— 462 – šestosovinksa diodna lokomotiva.

Vučne karakteristike lokomotiva predstavljaju podatak potreban za proračun, a navedene su u [3].

U nastavku će se prikazati rezultati dobiveni simulacijama za navedeni vozni red. U elektrovučni proračun su uzeti i vlakovi koji prometuju na dionici od Zagreb G.K. – PSN Runjaninova u danom vremenskom intervalu, kako bi se dobilo stvarno stanje reda vožnje.

U prvoj fazi proračuna simulira se kretanje vlaka, a kao rezltat simulacije se dobije za svaki vlak lokacija vlaka (udaljenost od EVP-a), brzina, zatim djelatna i jalova snaga potrebna za napajanje vlaka iz kontaktne mreže. Ovi se podaci privremeno pohranjuju u bazu i kasnije se koriste za druge proračune, pa se tako može na primjer dobiti podatak o vlakovima, koji se istodobno nalaze na pojedinom kraku napajanja EVP-a.

Nakon simulacije kretanja svakog pojedinog vlaka slijedi formiranje električne mreže, koje je specifično iz razloga što se shema napajanja stalno mijenja (neki vlakovi ulaze, a neki izlaze iz područja napajanja).

Nakon formiranja električne mreže slijedi proračun tokova snaga i to se ponavlja za svaki korak proračuna (najčešće 2 sekunde) u promatranom vremenskom periodu simulacije elektrovučnog proračuna.

Rezultati proračuna uspoređeni su s mjerenim rezultatima u kraćim vremenskim peridoima.

Za napojni vod 1 je promatran vremenski interval od 10:40 do 10:45. Prikaz rezultata dobivenih proračunom i mjerenjem za taj vremenski period se nalazi na slici 6.

The last column of Table 1 determines the type of locomotive which drives the certain train. 4 locomotive types are evident, namely:

— 6111 – electromotor train,
— 1141 – four-axis diode locomotive,
— 1142 – four-axis thyristor locomotive,
— 462 – six-axis diode locomotive.

Locomotives' traction properties represent information necessary for the calculation and these are stated in [3].

The results obtained by simulations for the said time schedule will be presented below. The electric traction calculation also included the trains travelling the Zagreb GK – PSN Runjaninova section in the given time interval, so as to obtain the real condition of the time schedule.

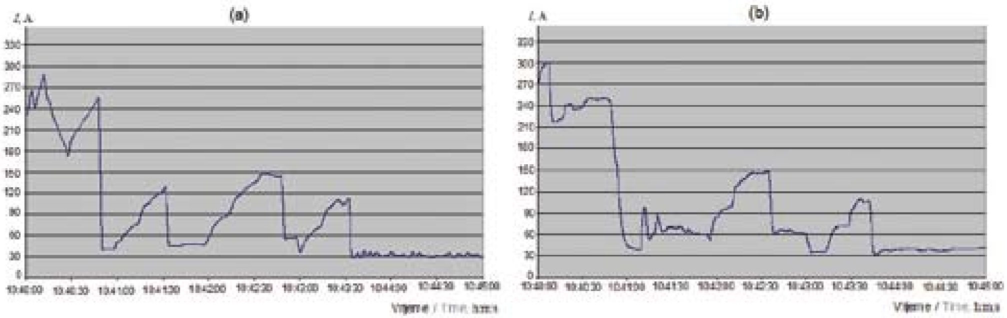
In the first calculation phase, train movement was simulated and as a result of the simulation, train location was obtained for each train (distance from the SS), its speed, active and reactive powers necessary for supplying the train from the contact network. These data are temporarily stored in the database and then used later for other calculations, so that, for example, data can be obtained on trains which are located on a certain SS supply arm at the same time.

After the simulation of the movement of each particular train, the forming of the electric network follows which is specific because the supply scheme changes constantly (some trains enter and some exit the supply area).

After the formation of the electric network, the calculation of current flows follows, and this is repeated for each step of the calculation (most often 2 seconds) in the observed time period of the simulation of the electric traction calculation.

Calculation results are compared with the results of the measurement in shorter periods of time.

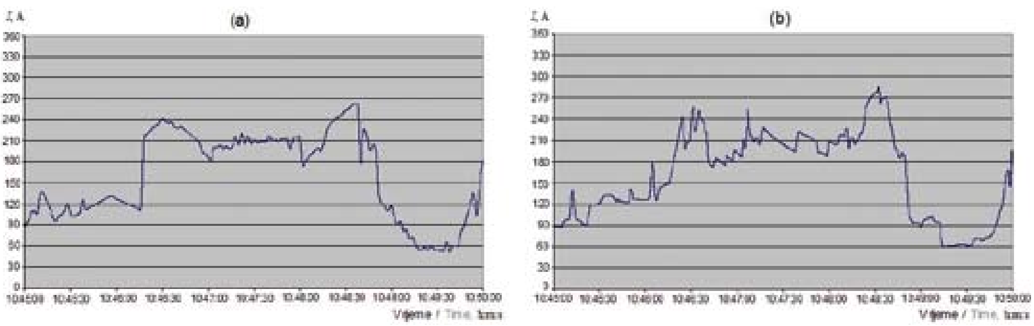
For feeder current 1, the time interval from 10:40 to 10:45 is observed. The overview of the results obtained by the calculation and measurement for that time period can be found in Figure 6.




**Slika 6** — Struja napojnog voda 1: a) proračun b) mjerenje
**Figure 6** — Supply line 1 current: a) calculation b) measurement

Za napojni krak 2 je promatran vremenski interval od 10:45 do 10:50, kada je prometovao teretni vlak mase 1 245 t i 6 elektromotornih vlakova. Prikaz rezultata dobivenih proračunom i mjerenjem za taj vremenski period se nalazi na slici 7.

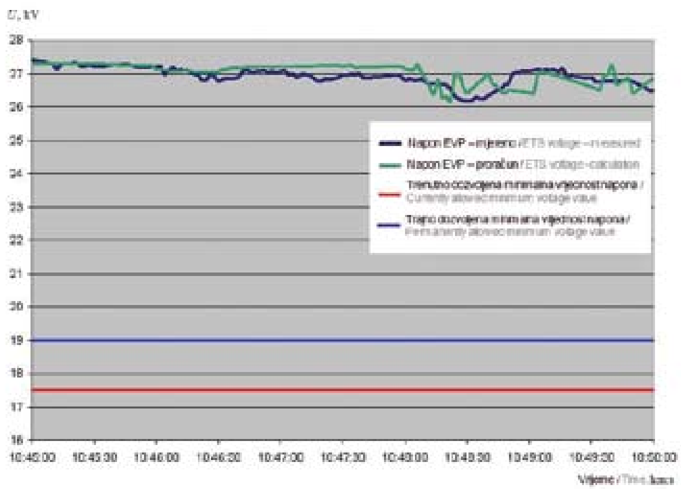
For the feeder current 2, the time interval from 10:45 to 10:50, when the 1 245 t cargo train and 6 electromotor trains travelled, is observed. The overview of the results obtained by calculation and measurement for that time period can be found in Figure 7.




**Slika 7** — Struja napojnog voda 2: a) proračun b) mjerenje
**Figure 7** — Supply line 2 current: a) calculation b) measurement

U proračunima je potrebno poznavati veliki broj ulaznih parametara, a neki od njih su promjenjivi u vrlo širokim granicama, pa se tako za proračune uzimaju pretpostavljene srednje vrijednosti (kao npr. ubrzavanje). Stvarno izmjerene struje zavise i o načinu upravljanja vučnim vozilom, što se u proračunima isto tako pretpostavlja. Na osnovi navedenih grafičkih prikaza može se zaključiti da se dobiveni rezultati elektrovučnim proračunom relativno dobro slažu s mjerenim rezultatima struje napojnih vodova 1 i 2. Slična podudarnost rezultata dobiva se i kod napona u EVP-u (slika 8).

When performing the calculation, it is necessary to know a large number of input parameters and some of these are variable within very wide limits so that the assumed mean value (such as, for example, acceleration) is taken for the calculations. The actually measured currents also depend on the manner of handling the traction vehicle, and this is also assumed in the calculations. Based on the said graphic presentations, it can be concluded that the results obtained by electric traction calculation agree relatively well with the measurement results of the current of feeder currents 1 and 2. Similar conformance of results is also obtained with the voltage at the SS (Figure 8).




**Slika 8** — Napon u EVP Resnik
Figure 8 — Voltage at the Resnik ETS

## 4 ANALIZA UTJECAJNIH FAKTORA NA POTROŠNJU ELEKTRIČNE ENERGIJE ELEKTROMOTORNOG VLAKA

U ovom poglavlju će se prikazati parametarska analiza nekih utjecajnih faktora na potrošnju električne energije elektromotornog vlaka. Parametri tog vlaka su navedeni u [3], a rezultati su dobiveni algoritmom za simulaciju kretanja vlaka pomoću kojeg se izračunavaju položaji vlakova, kao i njihove mehaničke i električne snage potrebne za vuču [2].

### 4.1 Radijus krivine

Ulazni podaci potrebni za simulator kretanja vlaka se nalaze u tablici 2.

## 4 ANALYSIS OF IMPACT FACTORS ON THE ELECTROMOTOR TRAIN ELECTRIC ENERGY CONSUMPTION

In this chapter, the parametric analysis of certain impact factors on the electromotor train electric energy consumption will be presented. That train's parameters are stated in [3], and the results are obtained by the train movement simulation algorithm by virtue of which train locations are calculated, as well as their mechanical and electric powers necessary for traction [2].

### 4.1 Bend radius

Input data necessary for the train movement simulator can be found in Table 2.

Tablica 2 – Ulazni podaci simulatora kretanja vlaka za parametarsku analizu radijusa krivine
Table 2 – Input data of the train movement simulator for the parametric analysis of the bend radius

| Redni broj dionice / Section number | Duljina dionice / Section length, m | Radijus krivine / Bend radius, m | Uspon pruge / Tracks climb, ‰ | Planirana brzina / Planned speed, km/h |
|---|---|---|---|---|
| 1. | 500 | 300 | 0 | 100 |
| 2. | 500 | 500 | 0 | 100 |
| 3. | 500 | 800 | 0 | 100 |
| 4. | 500 | 1 500 | 0 | 100 |
| 5. | 500 | 3 000 | 0 | 100 |
| 6. | 500 | 5 000 | 0 | 100 |
| 7. | 500 | 10 000 | 0 | 100 |
| 8. | 500 | ∞ | 0 | 100 |

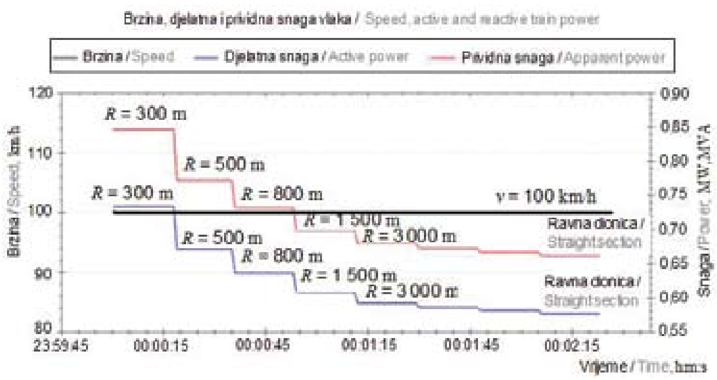
Proračun je proveden za prosječne brzine elektromotornog vlaka (70 km/h do 100 km/h) uz pretpo-

The calculation was undertaken for electromotor train average speeds (70 km/h to 100 km/h) under stavku da elektromotorni vlak cijelo vrijeme vozi planiranom brzinom.

Na slici 9 su prikazani rezultati ovisnosti djelatne i prividne snage o radijusu krivine za ulazne podatke (tablica 2) dobiven pomoću algoritma za simulaciju kretanja vlaka. Vidljivo je da je ta ovisnost zanemariva za velike radijuse krivine.

the assumption that the electromotor train is travelling at the planned speed the entire time.

Figure 9 shows the results of the dependency of the active and apparent power on the bend radius for input data (Table 2) obtained by virtue of the train simulation algorithm. That dependency is evidently insignificant for extensive bend radiuses.




**Slika 9** — Ovisnost djelatne i prividne snage o radijusu krivine pri konstantnoj brzini
**Figure 9** — Dependency of the active and reactive power on the bend radius at constant speed

Slična ovisnost bi se dobila i za ostale brzine kretanja elektromotornog vlaka. Rezultati simulacije kretanja vlaka (potrošnja električne energije i djelatna električna snaga) za navedene planirane brzine se nalaze u tablici 3. U zadnjem stupcu su dobivene vrijednosti za ravnu dionicu pruge.

Na osnovi dobivenih rezultata se može zaključiti kako nema značajnije promjene u potrošnji energije elektromotornog vlaka za radijuse krivine iznad 5 000 m.

Proračuni pokazuju da razlika u potrošnji energije elektromotornog vlaka, za slučaj kada dionica ima radijus krivine od 300 m u odnosu na slučaj kada je dionica potpuno ravna, za sve brzine iznosi oko 27 %.

Similar dependency would also be obtained for other electromotor train movement speeds. Train movement simulation results (electric energy consumption and active electric power) for the said planned speeds can be found in Table 3. The values obtained for the straight tracks sections can be found in the last column.

Based on the obtained results, it can be concluded that no significant change in the electromotor train consumption occurs for bend radiuses over 5 000 m.

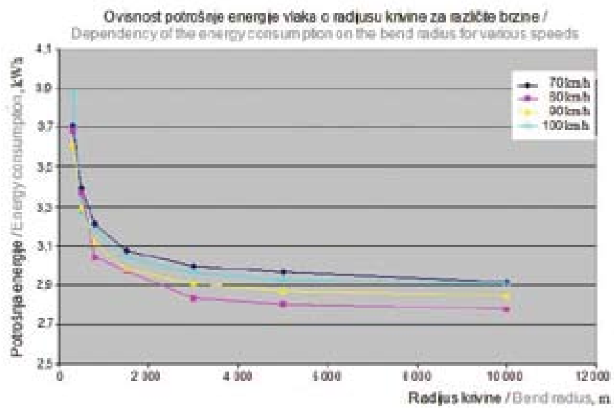
The calculations show that the difference in the electromotor train energy consumption, for the case when the section has a bend radius of 300 in relation to the case when the section is completely straight, amounts to about 27 % for all speeds.

Tablica 3 – Utjecaj različitog radijusa krivine pruge na potrošnju energije elektromotornog vlaka
Table 3 – Impact of different tracks bend radiuses on the electromotor train energy consumption

| Brzina vlaka / Train speed, km/h | Radijus krivine / Bend radius, m | 300 | 500 | 800 | 1 500 | 3 000 | 5 000 | 10 000 | ∞ |
|---|---|---|---|---|---|---|---|---|---|
| 70 | $E$, kWh | 3,712 | 3,394 | 3,213 | 3,077 | 2,997 | 2,968 | 2,939 | 2,918 |
| | $P$, kWh | 0,514 | 0,470 | 0,445 | 0,426 | 0,415 | 0,411 | 0,407 | 0,404 |
| 80 | $E$, kWh | 3,686 | 3,367 | 3,043 | 2,975 | 2,836 | 2,805 | 2,781 | 2,756 |
| | $P$, kWh | 0,577 | 0,527 | 0,498 | 0,476 | 0,464 | 0,459 | 0,455 | 0,451 |
| 90 | $E$, kWh | 3,611 | 3,294 | 3,117 | 2,983 | 2,910 | 2,872 | 2,850 | 2,828 |
| | $P$, kWh | 0,650 | 0,593 | 0,561 | 0,537 | 0,523 | 0,517 | 0,513 | 0,509 |
| 100 | $E$, kWh | 3,873 | 3,262 | 3,180 | 3,040 | 2,965 | 2,930 | 2,910 | 2,724 |
| | $P$, kWh | 0,734 | 0,671 | 0,636 | 0,608 | 0,593 | 0,586 | 0,582 | 0,577 |

Prikaz ukupnih rezultata (tablica 3) se nalazi na slici 10 i može se zaključiti da potrošnja energije za pojedini radijus krivine nije proporcionalna brzini (iako je potrebna djelatna snaga proporcionalna brzini, tablica 3). To pokazuje da je optimizacija potrošnje energije vlaka omogućena optimiranjem brzine pojedine dionice [8].

The overview of the overall results (Table 3) can be found in Figure 10 and the conclusion can be drawn that the energy consumption for particular bend radiuses is not proportional to speed (although the necessary active power is proportional to speed, Table 3). That shows that the optimization of the train's energy consumption is enabled by optimizing the speed of the particular section [8].




**Slika 10** — Krivulja ovisnosti potrošnje energije elektromotornog vlaka o radijusu krivine
**Figure 10** — Curve of the electromotor train energy consumption dependency on the bend radius

## 4.2 Uspon pruge

U nastavku će se promatrati ovisnost potrošnje energije elektromotornog vlaka o usponu pruge. Ulazni podaci potrebni za simulator kretanja vlaka se nalaze u tablici 4. Budući da se vrijednost maksimalnog uspona za željeznicu kreće do 30 ‰ (proporcionalna adhezionoj težini vozila, a obrnuto proporcionalna ukupnoj težini vozila) za simulaciju su uzete vrijednosti nagiba pruge navedene u četvrtom stupcu tablice 4.

Proračun je proveden, kao u prethodnom slučaju, za prosječne brzine elektromotornog vlaka (70 km/h do 100 km/h), uz pretpostavku da elektromotorni vlak cijelo vrijeme vozi planiranom brzinom.

## 4.2 Tracks climb

The dependency of the electromotor train energy consumption on the tracks climb will be observed below. The input data necessary for the train movement simulator can be found in Table 4. Because the value of the maximum climb for the railway fluctuates up to 30 ‰ (proportional to the vehicle's adhesion weight and inversely proportionate to the vehicle's total weight), values of the tracks slant stated in the fourth column of Table 4 are taken for the simulation.

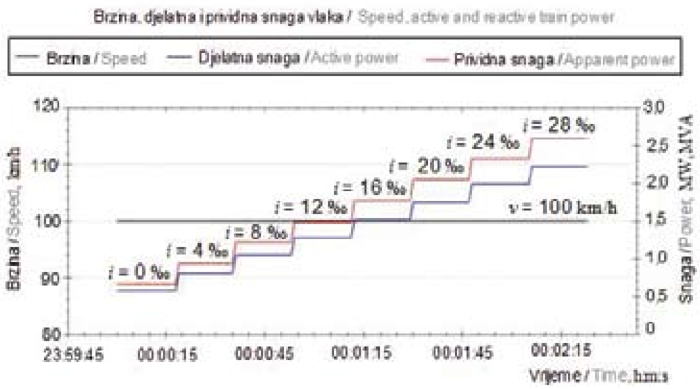
The calculation was undertaken, as in the former case, for electromotor train average speeds (70 km/h to 100 km/h) under the assumption that the electromotor train is travelling at the planned speed the entire time.

Tablica 4 – Podaci za parametarsku analizu nagiba pruge
Table 4 – Data for the parametric analysis of the tracks slant

| Redni broj dionice / Section number | Duljina dionice / Section length, m | Radijus krivine / Bend radius, m | Uspon pruge / Tracks climb, ‰ | Planirana brzina / Planned speed, km/h |
|---|---|---|---|---|
| 1. | 500 | ∞ | 0 | 100 |
| 2. | 500 | ∞ | 4 | 100 |
| 3. | 500 | ∞ | 8 | 100 |
| 4. | 500 | ∞ | 12 | 100 |
| 5. | 500 | ∞ | 16 | 100 |
| 6. | 500 | ∞ | 20 | 100 |
| 7. | 500 | ∞ | 24 | 100 |
| 8. | 500 | ∞ | 28 | 100 |

Na slici 11 su prikazani rezultati ovisnosti djelatne i prividne snage o radijusu krivine za podatke dane u tablici 4 iz koje je vidljiva linearna ovisnost.

Figure 11 shows the results of the dependency of the active and apparent power on the bend radius for the data given in Table 4, which reveals the linear dependency.




**Slika 11** — Ovisnost djelatne i prividne snage o usponu pruge pri konstantnoj brzini

**Figure 11** — Dependency of the active and apparent power on the bend radius at constant speed

Slična ovisnost bi se dobila i za ostale brzine kretanja elektromotornog vlaka. Rezultati proračuna potrošnje električne energije i djelatne električne snage za navedene planirane brzine su prikazani u tablici 5.

Similar dependency would also be obtained for other electromotor train movement speeds. Results of the electric energy and active electric power calculation for the stated planned speeds are shown in Table 5.

Tablica 5 – Utjecaj različitog uspona pruge na potrošnju energije elektromotornog vlaka

Table 5 – Impact of different tracks climbs on the electromotor train energy consumption

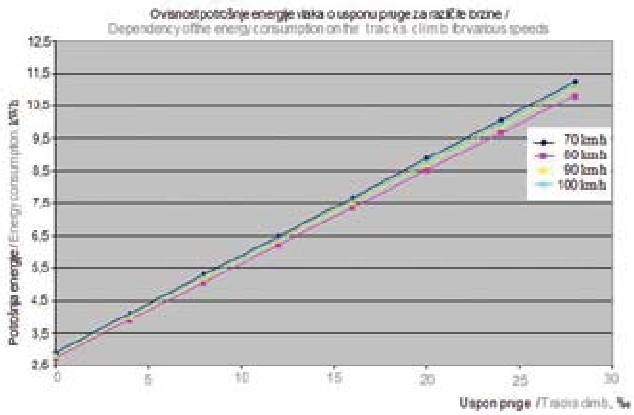
| Brzina vlaka / Train speed, km/h | Uspon pruge / Tracks climb, ‰ | 0 | 4 | 8 | 12 | 16 | 20 | 24 | 28 |
|---|---|---|---|---|---|---|---|---|---|
| 70 | $E$, kWh | 2,918 | 4,109 | 5,301 | 6,486 | 7,677 | 8,869 | 10,053 | 11,245 |
| | $P$, kWh | 0,404 | 0,569 | 0,734 | 0,898 | 1,063 | 1,228 | 1,392 | 1,557 |
| 80 | $E$, kWh | 2,756 | 3,911 | 5,060 | 6,209 | 7,358 | 8,513 | 9,662 | 10,811 |
| | $P$, kWh | 0,451 | 0.640 | 0,828 | 1,016 | 1,204 | 1,393 | 1,581 | 1,769 |
| 90 | $E$, kWh | 2,828 | 4,000 | 5,178 | 6,356 | 7,533 | 8,706 | 9,883 | 11,061 |
| | $P$, kWh | 0,509 | 0,720 | 0,932 | 1,144 | 1,356 | 1,567 | 1,779 | 1,991 |
| 100 | $E$, kWh | 2,885 | 4,060 | 5,240 | 6,415 | 7,590 | 8,770 | 9,945 | 11,120 |
| | $P$, kWh | 0,577 | 0,812 | 1,048 | 1,283 | 1,518 | 1,754 | 1,989 | 2,224 |

Prikaz ukupnih rezultata je dan na slici 12 s koje je vidljivo da potrošnja energije elektromotornog vlaka linearno raste s porastom uspona promatrane dionice pruge.

Sa slike 12 je vidljivo da postoji manja ovisnost potrošnje energije za određeni iznos uspona pruge o trenutačnoj brzini vlaka nego u prethodnom poglavlju (krivulje su gušće raspoređene).

The presentation of the overall results is given in Figure 12 which reveals that electromotor train energy consumption increases linearly with the increase of the climb of the observed tracks section.

Figure 12 reveals that there is less dependency of energy consumption for the certain tracks climb value on the train's momentary speed than in the previous chapter (the curves are more densely arranged).




**Slika 12** — Ovisnost potrošnje energije elektromotornog vlaka o usponu pruge
**Figure 12** — Dependency of electromotor train energy consumption on the tracks climb

## 4.3 Rekuperacija

Ako je vučno vozilo predviđeno za rekuperaciju, tada je moguće vratiti dio snage električne kočnice u mrežu. Rekuperacija, odnosno povrat snage u mrežu, može značajno utjecati na uštedu potrošnje energije u prigradskom prometu [9]. Poboljšanom izvedbom kočionih diskova se može uštedjeti značajan iznos električne energije [10]. Iskustva pokazuju da prilikom takvog kočenja prigradska elektrovučna vozila mogu davati u mrežu i do 40 % ukupno preuzete energije. Elektromotorni vlakovi imaju bolje rekuperativne kočione karakteristike od vlakova vučenih lokomotivama, jer je kod njih uključeno više osovina prilikom kočenja. Što je veća snaga elektromotora, te uz veći broj osovina uključenih u kočenje, više energije može biti vraćeno u kontaktnu mrežu. U algoritmu je također modelirana rekuperacija prilikom kočenja vlaka i u nastavku će se na konkretnom primjeru simulacije vlaka razmotriti ušteda energije, ako je rekuperacija omogućena. Ulazni podaci trase za koju je proveden proračun se nalaze u tablici 6. Ukupna duljina trase je 13,5 km.

## 4.3 Recuperation

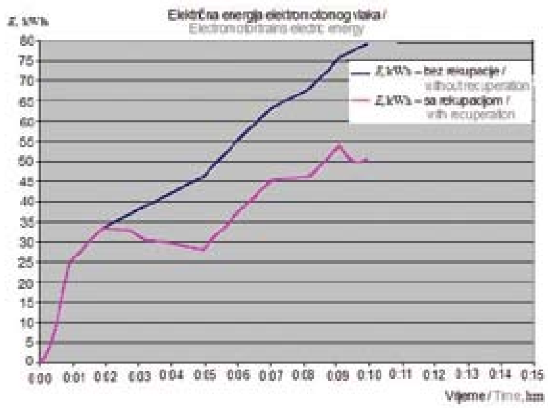
If the traction vehicle is planned for recuperation, then it is possible to return a part of the electric brake's power to the network. Recuperation, that is, return of power into the network, can significantly affect the savings in energy consumption in suburban traffic [9]. Improved performance of brake disks can provide for savings of significant amounts of electric energy [10]. Experience shows that upon such braking, suburban electric traction vehicles can bring even up to 40 % of the total overtaken energy into the network. Electromotor trains have better recuperative brake properties than the trains pulled by locomotives because these include more axes upon braking. The greater the electromotor power, and the greater the number of axes participating in braking, the more energy can be returned into the contact network. The recuperation upon the train braking is also modelled in the algorithm, and energy savings will be analysed on a particular train movement simulation example in the text below, if recuperation is enabled. Input data for the route for which the calculation was undertaken can be found in Table 6. The total route length is 13,5 km.

Tablica 6 – Podaci za proračun kretanja vlaka uz rekuperaciju
Table 6 – Data for the calculation of the train movement with recuperation

| Redni broj dionice / Section number | Duljina dionice / Section length, m | Radijus krivine / Bend radius, m | Uspon pruge / Tracks climb, ‰ | Planirana brzina / Planned speed, km/h |
|---|---|---|---|---|
| | 1 298 | ∞ | 0 | 90 |
| | 955 | ∞ | 0 | 90 |
| | 1 180 | 40 000 | –12,5 | 90 |
| | 750 | 38 000 | –19,4 | 90 |
| | 850 | 38 000 | –12,5 | 90 |
| | 1 750 | 40 000 | –14 | 90 |
| | 1 995 | 40 000 | 0 | 90 |
| | 1 150 | 40 000 | –1 | 90 |
| | 1 750 | 40 000 | –10 | 90 |
| | 1 995 | 40 000 | 0 | 90 |

Treba napomenuti da se elektromotorni vlak kreće trasom na kojoj nema nijednog uspona i da je na većem dijelu trase nizbrdica, na kojoj rekuperativno svojstvo vlaka dolazi do izražaja. Usporedba potrošnje energije elektromotornog vlaka sa i bez mogućnosti rekuperacije je prikazana na slici 13 s koje je vidljivo da ušteda utrošene energije zbog rekuperacije iznosi do 40 %. Naravno, ušteda energije zavisi o profilu pruge, smjeru kretanja i učestalosti potrebe za kočenjem elektromotornog vlaka. Rekuperacijom je omogućena ušteda energije i na postojećim trasama pruge, pa se mogućnost rekuperacije može uzeti u obzir prilikom projektiranja vučnog vozila i elektrovučnih podstanica.

It should be said that the electromotor train moves along the route on which no climbs exist and that the largest part of the route is downhill where the train's recuperative property is manifested. The comparison of electromotor train energy consumption with and without the possibility of recuperation is shown in Figure 13, which reveals that the savings in energy due to recuperation amount up to 40 %. Of course, energy savings depend on the tracks profile, movement direction and the frequency of the electromotor train's need for braking. The recuperation provides for energy savings even on the existing railway routes so the possibility of recuperation can be taken into consideration upon engineering the traction vehicle and the electric traction substations.




Slika 13 — Potrošnja energije elektromotornog vlaka za slučajeve sa i bez rekuperacije

Figure 13 — Electromotor train energy consumption for the cases with and without recuperation

## 4.4 Brzina

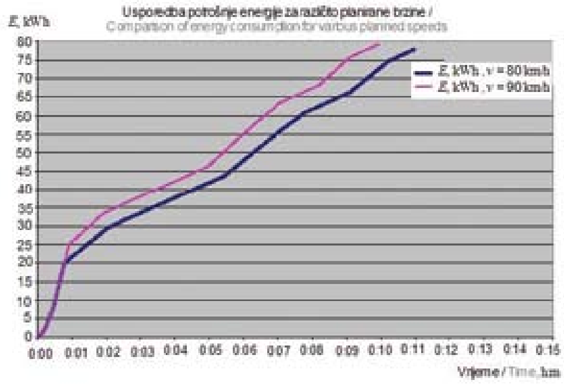
Ako planiranu brzinu iz prethodnog slučaja smanjimo sa 90 km/h na 80 km/h (vrijeme trajanja puta se povećalo za oko 10 %) ušteda energije je oko 2 %. Usporedba dobivenih rezultata je prikazana na slici 14, iz koje je vidljivo da nije došlo do značajnije uštede energije pri proporcionalnom smanjenju brzine na svim dionicama za gore navedeni profil pruge. Prema [11], ako se vrijeme trajanja puta vlaka produži za 5 %, ili smanjenjem maksimalno dozvoljene brzine vlaka ušteda energije može iznosit i do 20 %.

Proračuni simulacije kretanja vlaka pokazuju da iznos uštede energije, pri proporcionalnom smanjenju planirane brzine dionica, ne ovisi značajno o profilu pruge već o masi vlaka. Budući da ukupna masa elektromotornih vlakova nije velika, ta ušteda neće biti znatna.

## 4.4 Speed

If the planned speed from the previous case is reduced from 90 km/h to 80 km/h (travelling duration time increased by about 10 %), energy savings are about 2 %. The comparison of obtained results is shown in Figure 14, which reveals that significant energy savings did not occur upon proportional reduction of speed on all sections for the above stated tracks profile. According to [11], if the train travelling time is reduced by 5 %, or if the maximum train speed is reduced, energy savings can amount up to 20 %.

Train movement simulations show that the amount of energy savings, at proportional reduction of the planned section speed, do not depend significantly on the tracks profile but on the train weight. Since the total electromotor train weight is not great, these savings will not be significant.




**Slika 14** — Usporedba potrošnje energije za različite planirane brzine
Figure 14 — Comparison of energy consumption for various planned speeds

## 5 POTROŠNJA ELEKTROVUČNE PODSTANICE

Kontaktna mreža električne željeznice napaja se preko elektrovučnih podstanica, priključenih na elektroprivrednu mrežu . Na primjeru EVP-a Zaprešić pokazat će se način proračuna potrošnje električne energije.

Za proračun utrošene energije koristi se prikazani algoritam simulacije kretanja vlaka iz kojeg se dobivaju podaci o vremenu, udaljenosti od EVP-a, kao i potrebnoj djelatnoj i jalovoj snazi za kretanje vlaka, Iz podataka o svim vlakovima koji se kreću promatranom prugom može se formirati električna mreža. Podaci o transformatorima u EVP-ima, te duljinama krakovima napajanja nužni su za proračun . Formiranje električne mreže u elektrovučnom sustavu je na određeni način specifično, jer se shema napajanja mijenja u svakom trenutku. Pojedini vlakovi ulaze i izlaze iz područja napajanja, dok se drugi vlakovi zaustavljaju, pa na taj način nestaju kao potrošačko čvorište. Nakon formiranja električne mreže slijedi elektrovučni proračun napajanja za pojedini EVP. Proračun se provodi s vremenskim korakom za željeni vremenski interval.

### 5.1 Elektrovučni proračun napajanja EVP Zaprešić

Prikazat će se rezultati elektrovučnog proračuna za novoizgrađeni EVP Zaprešić, koji napaja planiranu prigradsku prugu kol. Podsused Tv. – Samobor – Bregana duljine 15,5 km namijenjenu isključivo za putnički prijevoz. Pojednostavljeni uzdužni profil i vršni dvosatni maksimalni grafikon voznog reda navedene pruge s ucrtanom lokacijom EVP Zaprešić prikazani su na slici 15.

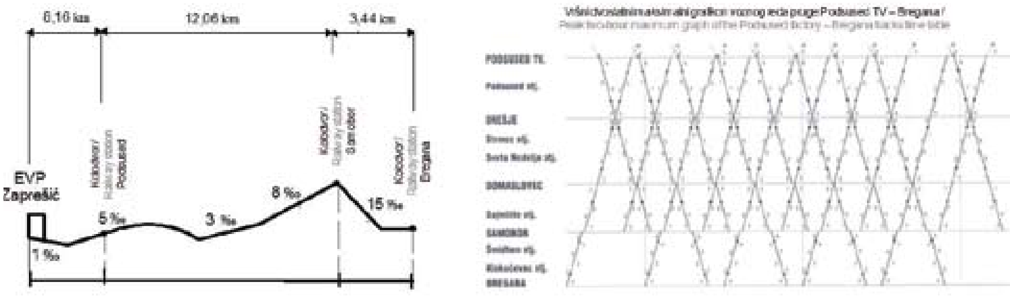
## 5 THE CONSUMPTION OF THE ELECTRIC TRACTION SUBSTATION

The electric railway contact network is supplied through electric traction substations connected onto the electric network. The example of the SS Zaprešić will show the manner of calculating the electric energy consumption.

For the calculation of used energy, the shown algorithm of train movement simulation is used, and data on the time, distance from the SS, as well as on the necessary active and reactive power for train movement and obtained from it. The electric network can be formed based on the data on all the trains which travel along the observed tracks. Data on the transformers in the SSs and the lengths of the supply arms are necessary for the calculation. Forming the electric network in the electric traction system is specific to a certain extent because the supply scheme changes every moment. Certain trains enter and exit the supply areas while other trains stop, and so they disappear as a consumption knot. After the formation of the electric network, electric traction supply calculation for the particular SS follows. The calculation is undertaken with a time step for the desired time interval.

### 5.1 Electric traction calculation of the SS Zaprešić supply

The results of the electric traction calculation will be shown for the newly built SS Zaprešić, which supplies the planned suburban 15,5 km-long tracks Podsused factory – Samobor – Bregana intended exclusively for passenger traffic. A simplified longitudinal profile and peak two-hour maximum graph of the said tracks' time-table with a mapped-in location of the SS Zaprešić are shown in Figure 15.




**Slika 15** — Pojednostavljeni uzdužni profil i vršni dvosatni maksimalni grafikon voznog reda pruge Podsused Tv. – Samobor – Bregana
**Slika 15** — Simplified longitudinal profile and peak two-hour maximum graph of the Podsused factory – Samobor – Bregana tracks time table.

Promatrano je vrijeme najgušćeg prometa maksimalnog prometa za vršni dvosatni maksimalni grafikon reda vožnje (od 6:00 do 8:00 h).

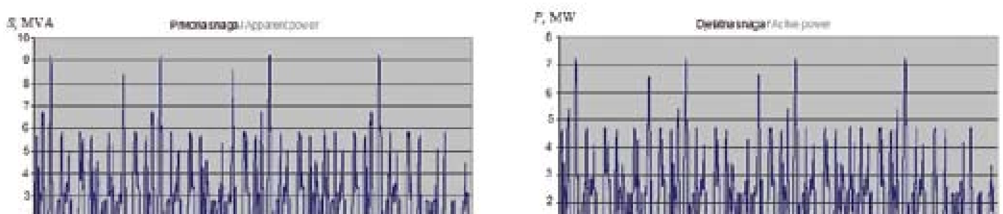
Napajanje ove pruge se odvija voznim vodom (kontaktni vodič 100 mm² i nosivo uže 75 mm² BZ II) . Ukupna impedancija voznog voda iznosi: $0{,}181 + j \cdot 0{,}447\ \Omega/\mathrm{km}$.

Duljina kraka napajanja EVP Zaprešić za ovu varijantu iznosi 2,38 km (8,3 km + 15,5 km). U proračunu je pretpostavljeno da EVP Zaprešić napaja 1 transformator nazivne snage $S_n$ = 15 MVA i napona kratkog spoja $u_k$ = 10 %. Prikaz nekih od rezultata dobivenih elektrovučnim proračunom za ovu prugu se nalazi na sljedećim slikama.

The period of the heaviest traffic of the maximum traffic for the peak two-hour maximum time-table graph (from 6:00 to 8:00) was observed.

The supply of these tracks takes place through the railway electric lines (contact conductor 100 mm² and bearing rope 75 mm² BZ II). The total impedance of the railway electric lines amounts to: $0{,}181 + j \cdot 0{,}447\ \Omega/\mathrm{km}$.

The length of the SS Zaprešić supply arm amounts to 2,38 km (8,3 km + 15,5 km) for this version. The calculation assumes that SS Zaprešić supplies 1 transformer with $S_n$ = 15 MVA nominal power and $u_k$ = 10 % short-circuit voltage. The presentation of some of the results obtained by electric traction calculation for these tracks can be found in the following Figures.

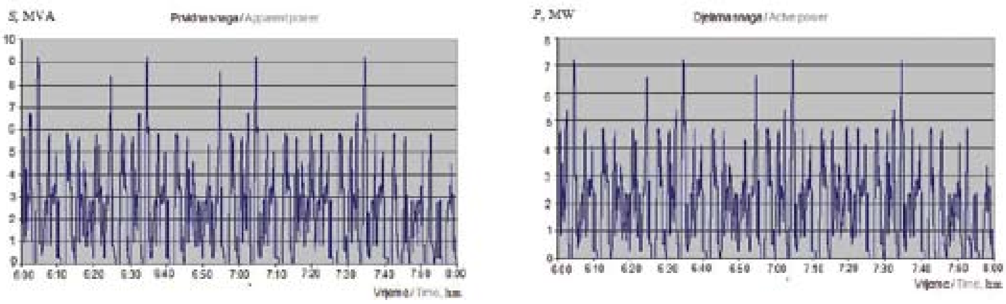



**Slika 16** — Opterećenje EVP Zaprešić prividnom i djelatnom snagom pri napajanju pruge Podsused Tv. – Samobor – Bregana
**Figure 16** — Loading of the ETS Zaprešić with apparent and active power upon the supply of the Podsused factory – Samobor – Bregana tracks

Sa slike 16 se može zaključiti da postoji očita razlika između prividne i djelatne električne snage, a time i potreba za kompenzacijom jalove snage pri napajanju električne vuče. Potrošnja električne energije EVP Zaprešić pri napajanju promatrane pruge za dvosatni period prikazana je na slici 17. U proračunima nije uzeta u obzir mogućnost rekupe-

Based on Figure 16 it can be concluded that there is obvious difference between the apparent and the active electric power and therefore the need for compensation of reactive power at the supply of the electric traction. Electric energy consumption of the SS Zaprešić at the supply of the observed tracks for the two-hour period is shown in Figure racije. Uz pomoć elektrovučnog proračuna moguće je razmatrati utjecaj raznih faktora na potrošnju električne energije, poput brzine vlakova i načina njihova kretanja, gustoće prometa, rekuperacije, kompenzacije jalove energije i drugo.

17. The calculations did not take into consideration the possibility of recuperation. With the help of the electric traction calculation, it is possible to analyse the impact of various factors on the electric energy consumption, such as train speed and manner of their movement, traffic density, recuperation, reactive power compensation, etc.




**Slika 17** — Potrošnja električne energije EVP Zaprešić pri napajanju pruge Podsused Tv. – Samobor – Bregana

**Figure 17** — Electric energy consumption of the ETS Zaprešić at the supply of the Podsused factory – Samobor – Bregana tracks

## 6 ZAKLJUČAK

U članku je prikazan matematički model simulacije kretanja vlaka kakav se koristi za proračune električne vuče, a uz čiju se pomoć može izračunati utrošena energija. Nakon usporedbe rezultata proračuna i mjerenja provedena je parametarska analiza utjecajnih faktora na potrošnju električne energije za elektromotorni vlak, koji prometuje na hrvatskim prigradskim željeznicama.
Rezultati dobiveni algoritmom za simulaciju kretanja vlaka i elektrovučnim proračunom uspoređeni su s izmjerenim, pa je pokazano da se izračunate struje i naponi relativno dobro podudaraju s mjerenim strujama napojnih vodova i napona na 25 kV strani EVP-a .

Na osnovi algoritma kretanja vlaka provedena je parametarska analiza utjecajnih faktora na potrošnju energije elektromotornog vlaka. Iz rezultata se može zaključiti kako nema značajnije promjene u potrošnji energije elektromotornog vlaka za radijuse krivine iznad 5 000 m, kao i to da potrošnja energije linearno raste s porastom uspona promatrane dionice pruge. Također je pokazano kako se uz mogućnost rekuperativnog kočenja, tj. povrata električne energije u mrežu može znatno smanjiti potrošnja energije elektromotornog vlaka, u nekim slučajevima i do 30 %, što naravno zavisi o profilu pruge.

Na kraju je prikazan izračun potrošnje električne energije za period dvosatnog vršnog maksimalnog prometa za EVP Zaprešić pri napajanju planirane

## 6 CONCLUSION

The article shows the mathematical train movement simulation model such as is used for the electric traction calculations by virtue of which the consumed energy can be calculated. After the comparison of the calculation and measurement results, the parametric analysis was undertaken of the impact factors on the electric energy consumption for the electromotor train which travels the Croatian suburban railways.

The results obtained by the algorithm for train movement simulation and by the electric traction calculation are compared with the measured results so it was revealed that the calculated currents and voltages coincide relatively well with the measured currents of the feeder currents and the voltages on the 25 kV side of the SS.

Based on the train movement algorithm, parametric analysis of the impact factors on the electromotor train electric energy consumption was undertaken. The results give rise to the conclusion that no significant change in the electromotor train energy consumption occurs for bend radiuses over 5 000 m, as well as that the energy consumption rises linearly with the increase of the climb of the observed tracks section. It has also been shown that, with the possibility of recuperative braking, that is, return of electric energy into the network, electromotor train energy consumption can be significantly reduced, in some cases even up to 30 %, which of course, depends on the tracks profile.

prigradske pruge Podsused Tv. - Samobor -Bregana. Prikazani elektrovučni proračun može poslužiti za razmatranje raznih faktora koji utječu na potrošnju električne energije s ciljem optimalne potrošnje.

Finally, the calculation of electric energy consumption was shown for the two-hour period of the maximum traffic for the SS Zaprešić at the supply of the planned Podsused factory – Samobor – Bregana suburban tracks.

The shown electric traction calculation can be used for analysing various factors which affect the electric energy consumption for the purpose of optimum consumption.

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**Adrese autora:**

Mr. sc. **Milivoj Mandić**
milivoj.mandic@fer.hr
Prof. dr. sc. **Ivo Uglešić**
Ivo.uglesic@fer.hr
Doc. dr. sc. **Viktor Milardić**
Viktor.milardic@fer.hr
Sveučilište u Zagrebu
Fakultet elektrotehnike i računarstva,
Unska 3
10000 Zagreb
Hrvatska

**Authors' Adresses:**

**Milivoj Mandić**, MSc
milivoj.mandic@fer.hr
Prof. **Ivo Uglešić**, PhD
Ivo.uglesic@fer.hr
Assistant prof. **Viktor Milardić**, PhD
Viktor.milardic@fer.hr
University of Zagreb
Faculty of Electrical Engineering and Computing,
Unska 3
10000 Zagreb
Croatia



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