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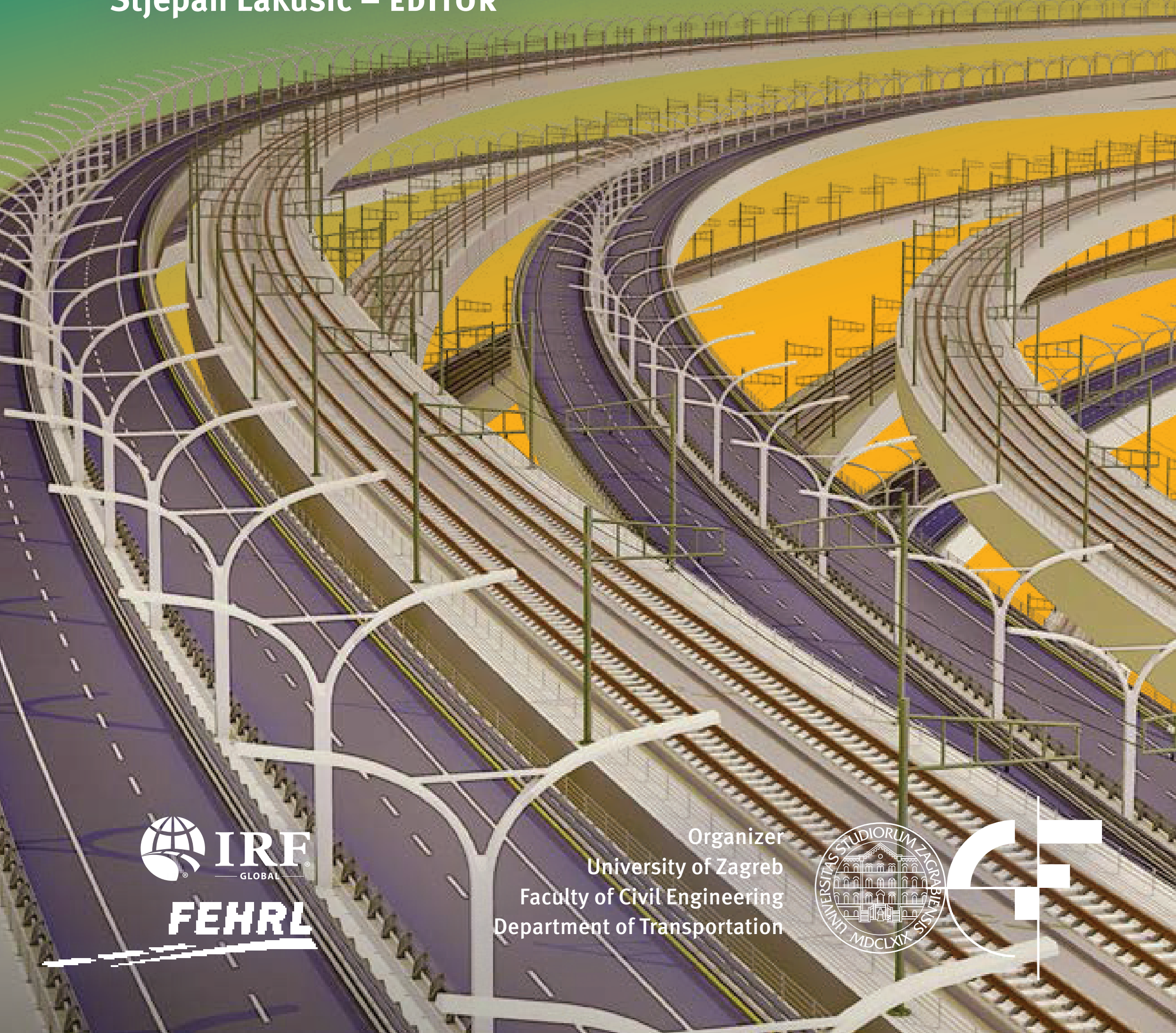

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ANALYSIS OF ENERGY EFFICIENCY OF SUBURBAN RAILWAY TRANSPORT NETWORK

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Abstract

Rising numbers of agglomeration residents cause increased need for people movement on daily basis. Because of congestion of local roads, air pollution and limited parking space, providing mass transit based on electric traction is reasonable. While the electric rail vehicles are considered highly efficient in themselves, they need to be analyzed as a part of a transport network, because energy consumption depends on operating conditions as well. Information about energy efficiency of whole system operating under realistic conditions could be helpful for modernization of traction power supply, timetable planning or while ordering new rolling stock. This paper presents approach to analysis of energy efficiency of a suburban rail network, using specialized software developed on Matlab/Simulink basis. For the sake of analysis, simple transport network consisting of three lines was considered. Vehicles, assumed as uniform electric multiple units, operate according to the set schedule, taking into account varying electric drive efficiency and mass dependent on passengers' number. Vehicles are supplied by four substations with nominal voltage of 3000 V DC, using overhead contact line. Developed model includes calculation of energy losses in power supply, therefore it is possible to determine efficiency of the whole network as a relation of mechanical energy of vehicles movement to electrical energy fed from public power system. Mean useful voltages for vehicles and substations are computed as well. Program structure allows for further expansion, e.g. with optimization algorithms.

Keywords: computer simulation, urban transport network, railway electric traction, energy efficiency, traction power supply

1 Introduction

Suburban transport networks are constantly changing in order to provide adequate service for passengers. Reliability, comfort and operation cost are the key factors forcing rolling stock and infrastructure modernization, as well as building new lines. Because such investments are expected to work efficiently in long-term perspective, precise planning is needed. This is especially important when entirely new infrastructure or vehicle is designed – because it is impossible to test object that does not exist yet. While basic parameters can be determined using empirical equations and averaged statistic data found in literature or norms, computer simulations could provide more accurate results. Moreover, a well-developed model should be capable of producing comprehensive data, allowing for precise determination of power supply and vehicle drive parameters, unveiling weak points (with highest voltage drop) or energy losses assessment.

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Numerical simulations of vehicle movement in transportation are widely used, mostly for timetabling and energy consumption calculations. Most of them, however use simplified models [1-3] – assuming one vehicle on route, constant values of line voltage and drive efficiency factors or idealized regenerative braking. While such simplifications will not noticeably affect basic results like travel time or movement dynamics, they have an impact on electrical parameters, especially values of current and line voltage [4, 5]. There is also need for calculation of voltage drop caused by power supply elements resistance, and mean useful voltage for vehicle and substations [6]. In order to achieve that, some applications compute these values assuming single vehicle run, then calculating parameters of whole system using superposition. The most complex models simulate multiple vehicles operating under realistic traffic conditions – which allow in-depth analysis of such system. However, complexity and stability of such programs are the major drawbacks that often narrow their usage to single line or section [7,8]. While it is possible to simulate substation load caused by vehicles on other sections (or branch lines) as additional current, analysing transportation system as a whole will be more accurate.
This paper presents a novel approach to suburban railway transport network simulation using model developed on the basis of Matlab/Simulink. Efficiency maps computed for both traction drives and substations (power transformer with rectifier) were used to approximate losses dependant on both mechanical and electrical load. For the sake of the analysis, theoretical simple railway network consisting of three lines was considered (Fig. 1).

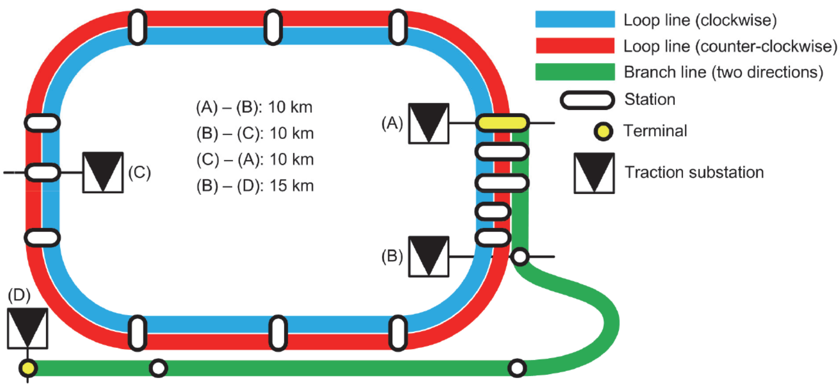


Figure 1 Map of analysed system

Vehicles operate according to set schedule, with 10 minutes tact on the loop line (in both directions) and 20 minutes tact on the double track branch line (similar to airport connections in some agglomerations). Simulation was conducted for timeframe of one hour of network operation, allowing assessment of energy consumption, losses and overall system efficiency under realistic circumstances.

2 Model design

Model presented in this work was developed aiming for maximum versatility, allowing for easy parameter editing and expansion for future analyses. Because of that, Matlab/Simulink was chosen as a basis for program design – Simulink block diagram synergizes well with modular/layered structure concept (Fig. 2), while it is still possible to run additional operations using coded functions and scripts, improving computation performance.

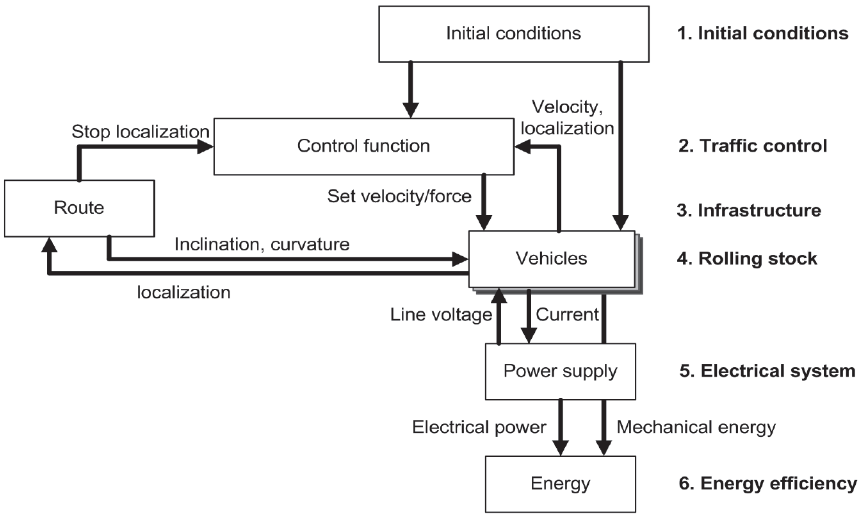


Figure 2 Simplified block diagram of the developed program

It is worth noting, that every module contains standalone model, which can be copied and executed as a part of different program as long as sufficient parameters are provided. Also, it is possible to modify input parameters to simulate various types of rolling stock, different catenary or number of working power transformers in substations.

2.1 Vehicle movement

Vehicles were assumed as uniform, six-section electric multiple units (EMUs), similar to vehicles used by suburban rail operators worldwide (e.g. Newag Impuls, Siemens Desiro, Urban-Liner Next etc.). Each EMU is powered by eight induction motors with total power of 3 MW, allowing for top speed of 44,5 m/s (160 km/h). Detailed vehicle data are shown in Table 1.

Table 1 Parameters of analysed vehicles

Parameter	Value	Unit	Comment
Axle layout	-	-	Bo'Bo'+2'2'+2'2'+2'2'+2'2'+Bo'Bo'
Max. tractive effort	250	kN	Acceleration/braking
Vehicle mass	195/220	Mg	Empty/full load
Rotating mass coeff.	1,15	-	
Passenger places	300	-	Assumed 75 kg per passenger
Auxiliary power	320	kW	Assumed constant

Vehicle movement dynamics are computed using basic physical equations. Acceleration is calculated by division of motive force by vehicle mass and rotating mass coefficient. Velocity is computed by integrating acceleration, while distance is the result of velocity integration.
The motive force is dependent on drive parameters and values set by control function, to ensure execution of velocity profile. Braking is performed according to braking curves, with constant deceleration value of 0,9 m/s^2. Adequate brake force is achievable at all speeds because combined brake system is implemented (electrodynamic and friction brakes) [9]. Because value of motive force generated by motors is needed for correct regenerative brak-

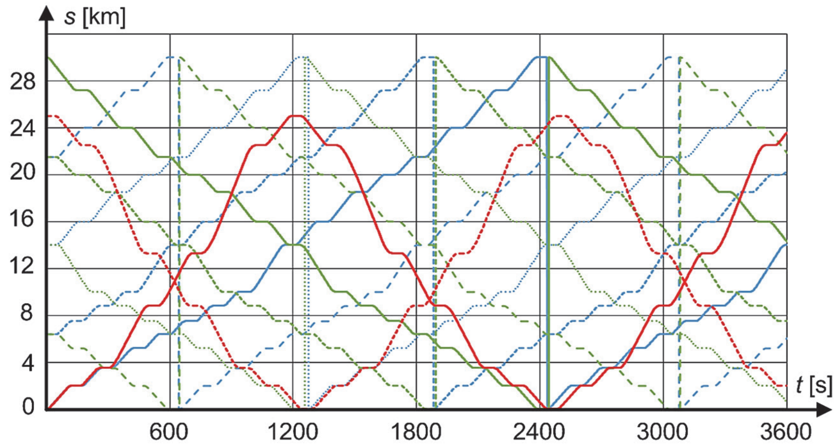
ing analysis, friction braking force is excluded from energy calculations. Motion resistance depends on route geometry and vehicle construction.
Control function is responsible for determining values of set velocity (or motive force), braking curves calculation and station stops. While in this situation network simplicity allows for open-loop movement regulation (every vehicle is running according only to pre-set schedule and velocity profile), control function is designed to cooperate with global regulator allowing for simulation of signalization or realistic traffic scenarios in future iterations.

2.2 Electrical system

Electrical system of developed program contains models of traction substations, catenary and vehicles' drives. Whole transportation network in 3 kV DC system can be depicted using equivalent electrical circuit, with substations modelled as real voltage sources, vehicles as controlled current sources and other elements (overhead contact line, rails, power cable) as resistances [6-8]. Layout of this circuit, however, is constantly changing due to vehicles movement, so parametrization of such system might be challenging [1]. Because of problematic modelling of train running through multiple sections using basic Simulink libraries like Power Systems or Simscape, dedicated functions were developed. Those were designed to allow for simultaneous simulation of the whole network, where vehicle nodes are not confined to single sector.
Electrical power of vehicle is calculated by adding mechanical power divided (multiplied if vehicle is braking) by variable drive efficiency factor and power of auxiliary needs (lighting, air conditioning, passenger information etc.). Energy consumed by vehicle is computed by integrating electrical power in time domain. Vehicle current is a result of division of electrical power and line voltage. Initial line voltage value is set as 3600 V, which in analysed system equals no-load voltage.
Model structure enables detailed analysis of energy losses in every element of the traction power supply. Insight in such data allows to identify when and where the most energy is lost. Losses in substations (power transformers and rectifiers) are calculated using efficiency map. Values of resistance of contact line, rails and power cable, parameters of substations and number of active power transformers are set independently for each section/element. Layout of power supply system depends solely on connections between each model, and sequence of sections which each of vehicles travel through is set by the control function.

3 Energy efficiency of analysed network

In this analysis, one hour of transport network operation was considered. Trains operated according to set schedule (Fig. 3) – delays and varying station dwelling time were disregarded. Round trip for every line takes about 40 minutes.



3.1 Energy and power losses

Analysis shown, that most energy is lost in vehicles' traction drive (Fig. 4). For a single train, momentary losses may reach up to 600 kW. Losses in substations are slightly higher than losses in catenary mostly because situations of multiple trains accelerating with full power happen in proximity of the substation. Losses in power cables are negligible – because of relatively short length of the cable.

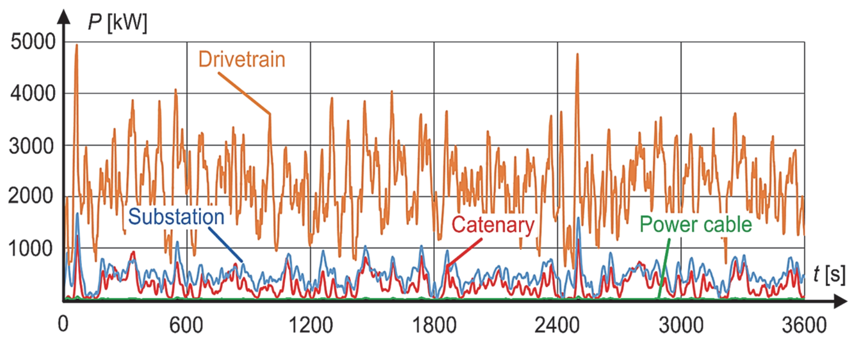


Figure 4 Waveforms of losses' power

Sometimes, losses in contact line get close or even exceed losses in substations – it is possible, when energy of regenerative braking is transmitted through catenary to other vehicles over longer distances.

3.2 Voltage assessment

Values of voltages on substations' output (Fig. 5), line voltage on vehicles' pantograph and mean useful voltages for substations and vehicles were computed.

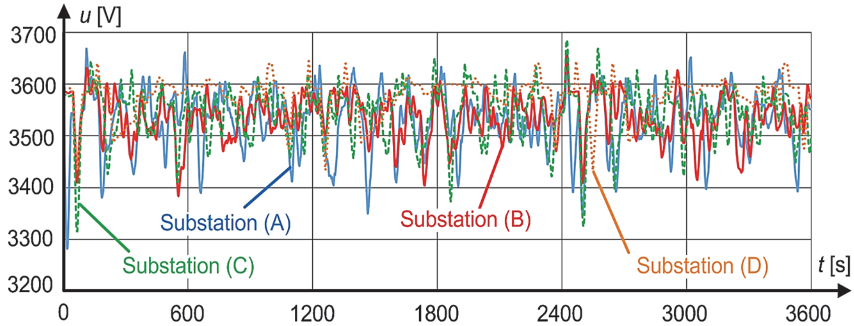


Figure 5 Waveforms of substation output voltages

It can be concluded, that analysed system met the requirements of EN 50163 norm [10]. Most of the time, voltages fluctuated between 3400 V and 3600 V with occasional peaks of about 3700 V and drops below 3300 V. Mean useful voltage values also complied with the norm, being at the level of about 3500 V for the substations and 3300 V – 3400 V for the vehicles.

3.3 Global system efficiency

One of the aspects of transportation network energy efficiency analysis is how much of energy fed from public power system is actually used to move the trains. Conducted simulation allows to compare values of both mechanical power of vehicles movement and electrical power of the substations (Fig. 6).

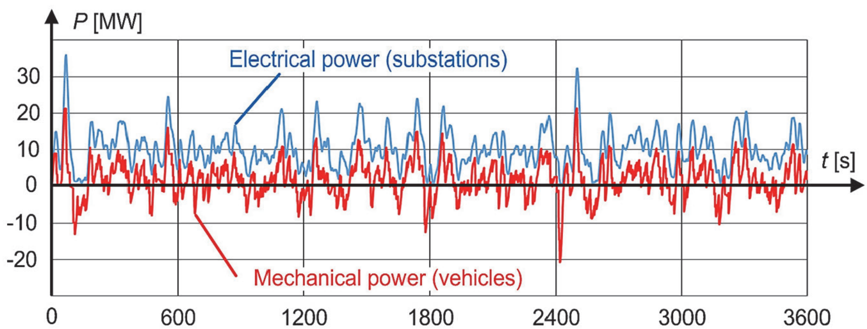


Figure 6 Comparison of mechanical and electrical power (fed to substations from public power system)

Mechanical power, constitutes for slightly less than half of total electrical power fed to the substations from public power network. It can, however, achieve negative values during braking phase, sending energy back to the drive. Situation, when multiple vehicles accelerate or brake translates to peak in losses' power and waste of regenerative braking energy. About 50 % of energy fed from public power system is used for trains' movement (Table 2).

Table 2 Energy consumption summary (values in MJ)

Parameter	Value	Efficiency
Total energy fed by power system	37240	-
Energy consumed - movement	18550	49,8 % (of fed energy)
Auxiliary needs	11520	80,7 % (with movement)
Drivetrain losses	7952	-
Substation losses	1718	-
Catenary losses	976	-
Power cable losses	26	-
Total consumed	40742	-
Regenerative braking	11790	-
Regenerated energy	3502	29,7 %

Large amount of consumed energy is used for powering auxiliary needs, including systems responsible for passenger comfort. If those would be considered as a part of transport system, then about 81 % of energy is used for passengers' sake. Efficiency of regenerative braking is slightly lower than 30 % – it could be improved by using optimized schedule, reversible substations or energy storages [9, 11].

4 Conclusions

Conducted analysis show, that significant part of energy consumed by transport network is dissipated in form of heat losses, and only about half is used to move vehicles. However, it is possible to determine, which element of system causes highest energy losses, and under what circumstances it happens. Developed model also provides insight in line voltage values, allowing for localization of points of highest voltage drops and reliability of power supply, measured by mean useful voltage. Such information can be helpful while planning modernization of power supply, timetabling or considering order of new rolling stock. Program structure allow further modifications, e.g. implementation of optimization algorithms or energy storage analysis.

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