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ENERGY EFFICIENCY OF RAILWAY LINES

ABSTRACT

Energy saving is necessary in accordance with the principles of sustainable development. Energy consumption is increasing, and the production capacities are limited. The three main railway segments such as: railway infrastructure, traffic management and dynamic train movement have an important impact on energy consumption for train haulage. The aim of the research presented in this paper is to determine energy consumption efficiency for train haulage, by choosing optimal construction parameters of railway lines, modern design of railway stations, optimal traffic management and energy efficient dynamic train movement. The paper gives a concrete presentation of energy consumption in all three segments of railway traffic and proposals for rationalization of energy consumption. The infrastructure managers and rail carriers should cooperate in the process of efficiency consumption of energy for train haulage. Saving of energy is a never-ending process.

KEY WORDS

line resistance, infrastructure, traffic management, dynamics, energy

1. INTRODUCTION

Consumption of energy in the World is increasing fast, and the production capacities are limited. For the transport of passengers and goods the railway consumes large amounts of energy, so the rationalization is also necessary in the railway traffic[1]. Directive 2006/32/EC[2] has declared improvement of energy efficiency and cost-effective energy savings in an economically efficient way.

Energy consumption for train haulage can be rationalized in different segments of the railway traffic [1]. This paper presents three most important railway segments from an aspect of energy consumption for train haulage. They are: railway infrastructure, traffic management and dynamic train movement.

Railway infrastructure has one of the main impacts on energy consumption for train haulage. Longitudinal gradient of a line represents the main resistance for the locomotive, driving uphill. Traffic management provides safe and orderly traffic for all trains, and depends on the existing railway infrastructure. The dynamic train movement is a discipline that deals with physical principles of train movement and it depends on different elements the most important of which are: technical characteristics of the locomotive, type of train and engine driver.

The past approach and considerations of the majority, regarding the analysis of energy consumption by all three rail segments, were unconnected. Energy consumption for train haulage is initially calibrated by using the statistical analysis of actual consumption for each locomotive in the existing rolling stock [2]. The impact of dynamic train movement on railway line represents the base mode for energy consumption analysis. Theoretically, the impacts between railway infrastructure and dynamic train movement were analyzed in the dissertation [5]. The railway line resistances such as longitudinal gradients, curvatures and tunnels, needed for energy consumption calculations are presented in papers [7, 9]. Some instructions about energy efficient driving were practically given to the engine drivers [2]. Energy efficient consumption can be expressed in the following way:

1. The existing railway infrastructure was built 150 years ago and does not allow major savings of energy. Modern railway infrastructure is the main condition for energy savings and undisturbed railway traffic. The design of each new railway line should be analyzed from an aspect of energy consumption for train haulage;
2. Traffic management should provide optimal energy consumption in technological processes of works on the existing railway infrastructure. Every braking and acceleration of the train, because of a wrong decision of the dispatcher, consumes energy;

3. The mass of train and type of locomotive also depend on the rail carrier. The carrier should educate engine drivers for the improvement in train driving from the aspect of energy consumption. About 10% of energy in the energy efficient dynamic train movement can be saved. The modern rolling stock is one of the main conditions for energy savings.

The infrastructure managers and rail carriers should reduce the energy consumption for train haulage in the railway traffic. The rail carriers should participate in energy-efficient driving and infrastructure managers with modern design of railway infrastructure. Compared to other branches of transport, energy rationalization in the railway traffic reduces the costs of transportation and increases the competitiveness of railway traffic.

2. ENERGY CONSUMPTION ON TECHNICAL AND TECHNOLOGICAL ELEMENTS OF RAILWAY LINE

The calculation of energy consumption for train haulage, during the train movement on railway line infrastructure was made by the simulation software tool VIST[3]. The software calculates the driving times, velocities, energy consumption and other useful data, on the basis of input data about the railway infrastructure and railway suprastructure[4]. The energy consumption for train haulage is measured in kilowatt hours (kWh).

2.1 Railway infrastructure

The longitudinal gradients of railway lines, line curvatures and tunnels result in railway line resistance, which has to be overcome by the locomotive. The unit for railway line resistance is dekanewton per ton (daN/t), which represents the force of railway line resistance of 10N per each ton of the train [7].

For longitudinal gradient resistance calculations the data about length of the railway line section and the difference in altitude between the stations or points of section are needed. Longitudinal gradient resistance is equal to the size of railway line gradient [7]:

$$W_n = i \quad (1)$$

where:

W_n – longitudinal gradient resistance (daN/t),
i – longitudinal gradient (‰).

Software tools VIST was used to simulate freight train driving uphill in different longitudinal gradients. The input data for the simulations included: railway line length of 20km, electric locomotive Siemens ES 64 U4, and train weight 1,200 tons with maximum velocity of 90km/h.

The raising of the longitudinal gradients has main impact on energy consumption and velocity of the freight train. Energy consumption rises with higher line resistances. In the opposite direction, the velocity decreases. From 90 km/h at longitudinal gradient of 0‰ it declines progressively to only 25km/h at a gradient of 25‰. Energy consumption at 25‰ is almost three times higher than at 0‰.

The line curvature resistance belongs to resistance of the railway line, but it also depends on the type of rolling stock. The friction between wheel crown and track in the curvature causes curvature resistance. The resistance is experimentally determined as a function of curve radius. The influences of other factors are given as coefficients. The curvature resistance for radius larger[5] than 300m is determined according to the following formula [9]:

$$W_R = \frac{650}{R - 5} \quad (2)$$

where:

W_R – curvature resistance (dN/t),
650 and 55 – coefficients for railway line gauge 1,435mm,
R – curvature radius (m).

A similar simulation was taken for curvature resistance of railway lines at longitudinal gradient of 12‰. The simulation results are shown in *Figure 2*.

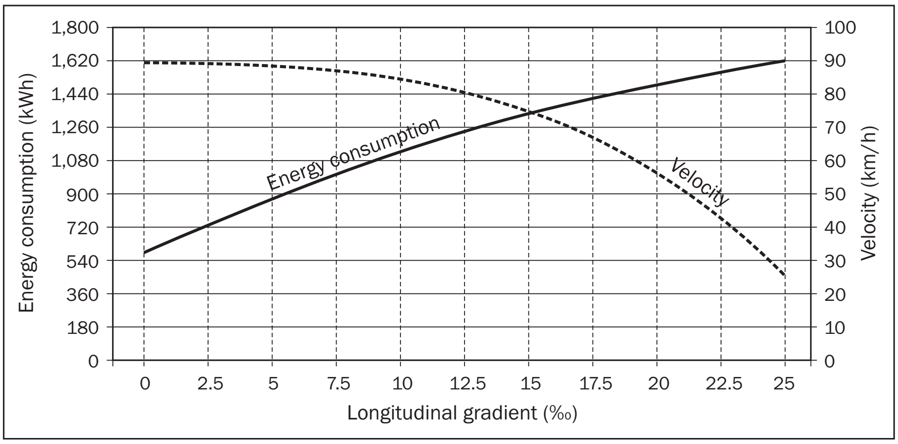

Figure 1 – Impact of longitudinal gradient on energy consumption and velocity

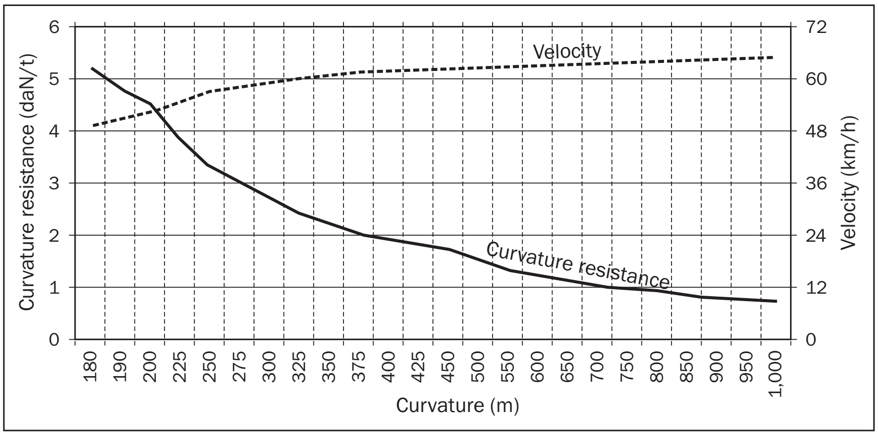

Figure 2 – Impact of curvature on resistance and velocity

The curvature resistance is higher at smaller radius and progressively falls at higher curvature radii. At radius of 1,000m the curvature resistance is less than 1 daN/t. The velocity of freight train is lower at small radii and slowly rises with higher radii. In case of longer freight train up to 700 meters and difficult terrain, the train is at the same time in two or even three curvatures. In that case the curvature resistance is even higher[6].

2.2 Traffic management

Traffic management integrates the rail carriers and railway infrastructure. The technological processes of operating procedures are adapted to the existing railway infrastructure. The following segments have important impact on the energy consumption for train haulage: the number of open line tracks, the design of the railway stations, the type of signal-safety devices, etc.

The railway station must ensure high safety level for passengers using the public transport. The passenger platform is the contact point between railway infrastructure and railway suprastructure. The platform must ensure safe passengers movement, when they board or get off the train. An important element of safety and energy consumption for train haulage are the access ways for passengers. Access ways connect the station house with the passenger platforms[7]. In case of level access for passengers, the traffic management must ensure passengers by signal-safety devices.

Level crossing access ways for passengers (*Figure 3*) do not allow the train driving on track 2, while the passengers walk on access ways, because of passenger multiple units, standing on track 3. The locomotive is allowed on track 2, while passengers safely leave the access ways. Braking and acceleration of locomotive in front of the station entry signal consume energy.

Acceleration of heavy freight train, when running on a railway line, consumes energy. A simulation of the current situation of train running through the station and restarting of a train in front of an entry station signal is presented in *Figure 4*. A freight train, weighing 1,200 tons consumes about 10% more energy because of stopping in front of the entry signal of the station. It should be noted that maintaining high velocity of train while driving uphill consumes more energy than when driving in the same conditions, but at lower velocity.

The traffic management of trains running on double track railway lines, compared to single track line is more energy efficient. On a double track line there are usually no intersections of trains and the trains run in sequences. To provide higher capacity of a line, the sections between stations are equipped with automatic block devices (ABD). The automatic block devices increase railway line capacity, on the base of more trains

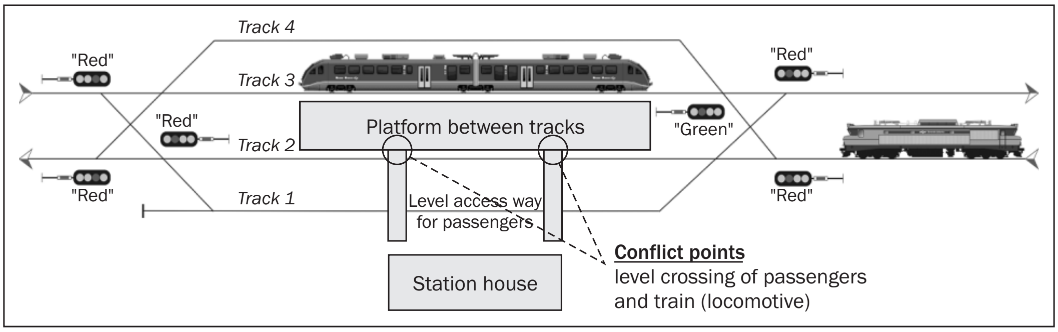

Figure 3 – Passengers protection at level access ways

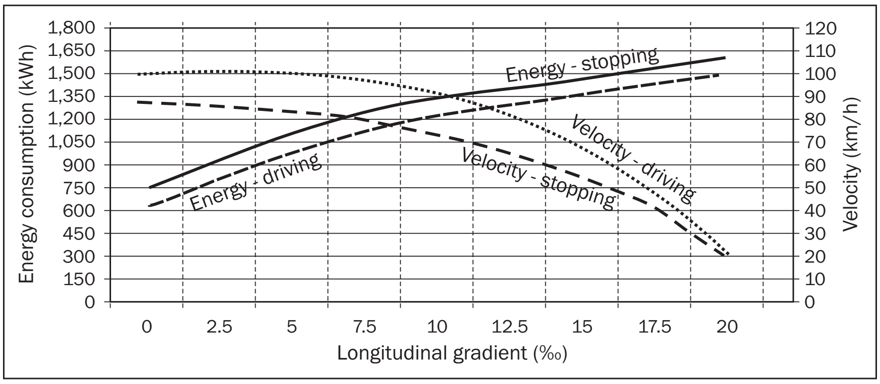

Figure 4 – Energy consumption and velocity at instance of driving and stopping of train

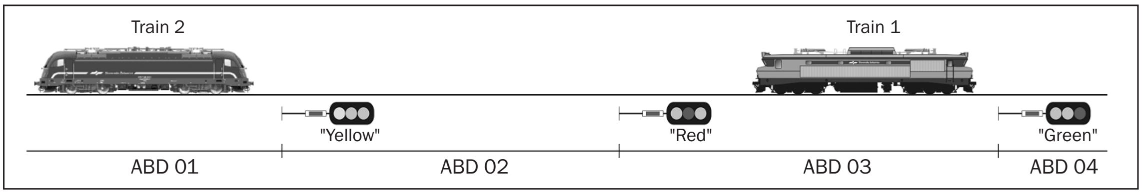

Figure 5 – Train driving in ABD

on the section between two stations. The minimum length of one ABD is the same as the braking distance for safe stopping in front of the next red signal.

The ABDs allow »driving into yellow lamp«, which means only one free ABD section between two trains on the same part of the railway line section (*Figure 5*). Train 2 is entering ABD 02 section and the entry signal of this section shows »cautiously, expect stop« (one yellow lamp). Train 2 must brake to stop in front of the next signal with red lamp. Braking and stopping of the train is followed by acceleration and this means more energy consumption for train haulage.

2.3 Dynamic train movement

Dynamic train movement is a discipline that deals with physical principles of train movement and depends on different parameters, the main ones being: velocity, weight, acceleration and engine driver. The dynamic train movement is in compliance with railway infrastructure and railway suprastructure.

The load of locomotive, based on infrastructure elements of railway lines, defines the weight of the train for each type of locomotive hauled on a defined railway line. The loads of locomotives are different and depend on technical characteristics of each locomotive. The load of locomotive defines the weight of the train, which can be hauled on a defined railway line in case of medium good adherence conditions.

The locomotive loading conditions are [5]:

- train velocity,
- line resistance,
- permissible load of draw hooks,
- useful length of the main station tracks,
- maximum length of train in accordance with the Braking instructions.

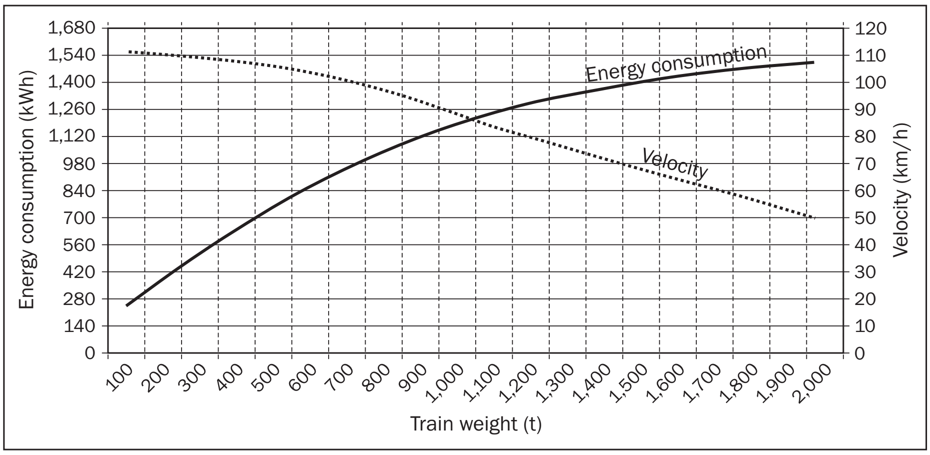

Figure 6 – Impact of train weight on energy consumption and velocity

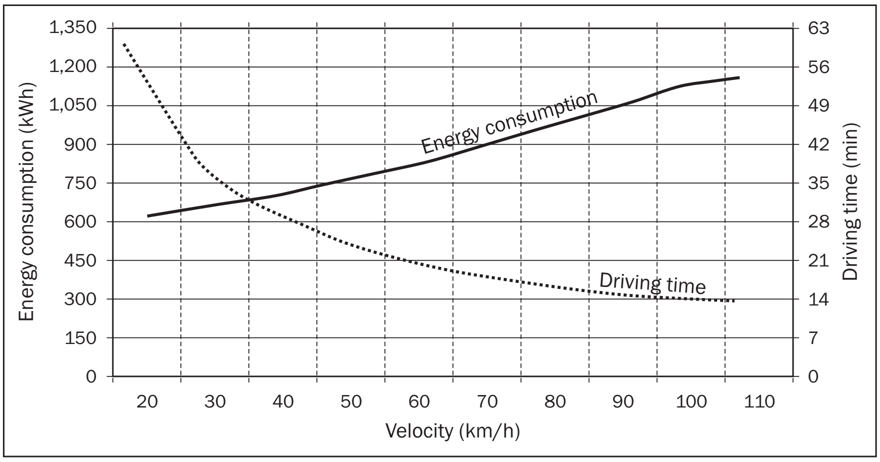

Figure 7 – Energy consumption impact on velocity

To find out the impact of the train weight on energy consumption and train velocity a simulation on a railway section in the length of 20km and longitudinal gradient of 8‰ was performed. The hauling electric locomotive Siemens ES 64 U4 was in each simulation progressively loaded by 100 tons. A graph of energy consumption for train haulage and train velocity is presented in *Figure 6*.

The weight of the freight train has main impact on energy consumption in the dynamic train movement. Energy consumption rises constantly with higher locomotive loading. In the opposite direction, the velocity decreases. The intersection of curves is at 85km/h and 1,100 tons.

Another simulation shows the impact of velocity on energy consumption. The same locomotive as in the previous simulations, with freight train and weight of 1,000 tons on a 20km railway line section with longitudinal gradient of 8‰. In progressive simulations the upper locomotive velocity limit $V_{\max}$ was for each simulation higher by 10km/h. Because of weight and resistance the train reaches maximum velocity of 110km/h.

Energy consumption at 110km/h is almost two times higher than at only 20km/h. While energy consumption for train haulage rises with higher velocities, the running time decreases. The train velocity is in coherence with train load and longitudinal gradients of the railway line.

3. ENERGY CONSUMPTION COSTS

As mentioned above, the energy consumption is measured in kWh. An average price of one kWh of electric energy for train haulage at the Slovenian railways is €0.10. The energy costs for train haulage depend on the railway line characteristics, train management and dynamic train movement. In some cases, energy costs are several times higher than costs for using rail infrastructure[8].

Simulations in this paper were implemented on an electrified railway line section in the length of 20km. The usage of railway infrastructure is charged separately for freight trains of up to 1,500 gross tons and for trains over 1,500 tons [8]. The charges on 20km long main railway line section for freight trains of up to 1,500 tons are €22.3, and €44.6 for trains over 1,500 tons.

The simulation cost analysis shows the difference in costs for energy consumption. The highest costs to move one ton over a distance of 20km are made with lighter freight trains. The cost for 800 ton train at 2‰ is two times lower than at 16‰.

4. PROPOSALS TO IMPROVE ENERGY CONSUMPTION EFFICIENCY

Planning and design of new railway lines should consider the energy aspect. One of the most important conditions in railway line construction is the land-

Table 1 – Average energy costs for movement of one ton of freight train with different mass on a railway line in the length of 20km and with different longitudinal gradients

mass (t)	100	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
costs (€) at 2‰	0.14	0.11	0.09	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.06
costs (€) at 8‰	0.25	0.18	0.15	0.14	0.13	0.12	0.11	0.10	0.09	0.08	0.08
costs (€) at 16‰	0.30	0.22	0.19	0.17	0.16	0.14	0.13	0.11	*	*	*

**two Siemens ES 64 U4 locomotives needed* scape relief, which defines the technical infrastructure characteristics of railway lines. New locomotives are designed for railway line gradients of up to 17‰. The railway line gradients over that limit are energy wasteful and uneconomical[9]. The construction of railway tunnels reduces energy consumption; the train velocities are higher and running times lower, which means competitive railway traffic, compared to other branches of transport.

The railway stations should be designed for rational and easier traffic management. The technological work processes in the traffic management should provide undisturbed train control in the spirit of rational energy consumption. The passenger access ways to platforms should be designed as subways. The subways will increase the passenger safety as well as the station and railway line capacity.

The crossing of two trains on a single track line is usually determined by timetables, but in real situations, it is determined by the dispatcher. The dispatcher should consider the traffic conditions on the railway line, that heavy freight train running up the hill has no stops at the stations. The dispatching process should foresee the situation in which the downhill running opposite trains already wait at the stations.

According to the simulations in different conditions of train running uphill along the railway line, an optimal freight train velocity from the aspect of energy consumption for train haulage shall be up to 90km/h. In any case, the velocity depends on railway line resistances. A load of train is defined by the railway line resistances and technological processes of works (number of hauling locomotives in train). On the average, railway line resistances (around 10-12 daN/t) freight trains shall be loaded with 1,000–1,400 gross tons, and it also depends on the type of locomotive. In locomotive loading the adherence conditions between tracks and locomotive driving wheels should be taken into consideration.

New modern electric locomotives like Siemens ES 64 U4, with electrodynamics braking of the train downhill generate electrical energy and return it to the electricity grid of the railway line (recuperation of electrical energy and it is produced from renewable energy sources). New locomotives operate as producers of electrical energy. For efficient consumption of "green energy" one should assure some conditions in catenary-type overhead contact line and conditions of traffic management like two trains in the same section on the double track line.

The dynamic energy efficient running also depends on the engine driver. The three main points of energy savings through dynamic train movement [2] exploit kinetic energy, as much as possible. Constant velocity brings savings; the engine driver should avoid peaks of velocity. It is necessary to exploit the configuration of the terrain. The engine driver should find the right moment to switch off the traction. The engine drivers should learn energy efficient dynamic driving by train simulators.

5. CONCLUSIONS

One of the main factors in the future will be the reduction of energy consumption in the transport sector; in accordance with the principles of sustainable development. It should be realized, that the railway sector must be involved in energy saving processes. The rationalization of energy consumption is necessary in all railway traffic segments: infrastructure, traffic management and dynamic train movement. These segments are the main course to achieve greater effects of lower energy consumption for train haulage.

The reduction and optimization of energy consumption measures in a shorter time period are feasible in dynamic train movement segment. The measures in this segment are also the cheapest cost of investment. Over a longer time period and higher costs of investment, the measures taken in the railway infrastructure such as the construction of new railway lines with more favourable characteristics, reconstruction of stations, curves, etc. Financially and regarding time, the measures for rational energy consumption in traffic management are ranked between dynamic train movement and railway infrastructure. Investments in railway traffic segments are presented in *Figure 8*.

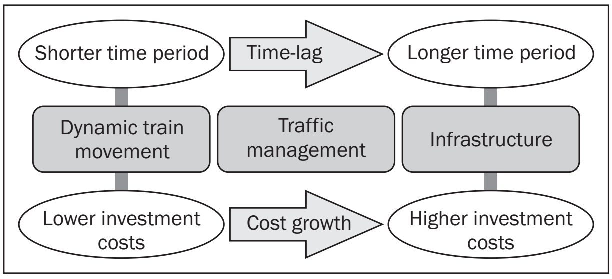

Figure 8 – Investments in railway traffic segments

Costs for energy, needed for train haulage are in cases of steep railway lines (more than 17‰) several times higher, compared to the infrastructure charging costs. The infrastructure managers and the rail carriers should jointly participate in measures that will lead to the reduction of energy consumption for train haulage. By new design of railway lines, modern traffic management and more energy-efficient driving will raise the level of quality of transport services by rail. That will mean more competitive railway traffic, compared to other branches of transport.

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the consumption of an average Slovenian household during an entire year. The train must manage the railway line over a length of 46km and an altitude of 534 meters.

2. Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC.
3. VIST (*abb.*) – Train, Infrastructure, Simulation, and Technology is a software tool, developed for the calculation of train driving times for the Slovenian railways.
4. The railway suprastructure is structured by railway vehicles: locomotives, coaches, wagons, multiple-units, etc.
5. Röckl resistance formula for radius, smaller than 300 m is
$$W_R = \frac{500}{R-30}$$
6. When the train is at the same time in more curvatures:
$$W_R = \frac{12.2\sum\alpha}{l},$$
where α – central angle of curve and l – train length.
7. Railway Transport Safety Act declares conditions for grade-separated passenger's access ways (like subways), at stations with annual average daily traffic of 500 passengers and 70 trains.
8. Energy costs for freight trains of 1,700 tons in Koper – Divača direction are around €410, and costs for using the rail infrastructure are €103.
9. Maximum railway line gradient for new construction of main railway lines is 12.5‰, with exception at difficult topographic areas being 17.5‰.

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SAŽETAK

ENERGETSKA EFIKASNOST ŽELJEZNIČKIH PRUGA

Energiju je potrebno štedjeti u skladu s načelima održivog razvoja. Potrošnja energije je sve viša, a proizvodne kapacitete su ograničene. Tri glavna željeznička segmenata kao što su: željeznička infrastruktura, upravljanje prometa i dinamička vožnja vlaka imaju veliki utjecaj na potrošnju energije za vuču vlakova. Cilj istraživanja prezentiranog u ovom radu je utvrđivanje efikasnosti energetske potrošnje za vuču vlakova sa izborom pogodnih građevinskih parametara željezničkih pruga, suvremenim dizajnom kolodvora, optimalnom upravljanjem prometa i energetsku štedljivu dinamičku vožnju vlaka. U radu je dat konkretan prikaz potrošnje energije za sva tri segmenta željezničkog prometa i prijedlozi racionalne potrošnje energije. Upravljač željezničke infrastrukture i željeznički špediter moraju raditi zajedno u procesu efikasne potrošnje energije za vuču vlakova. Proces štednje energije nikada nije završen.

KLJUČNE RIJEČI

otpor pruge, infrastruktura, upravljanje prometom, dinamika, energija

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