ASSESSMENT OF FACTORS OF ENERGY CONSUMPTION IN RAILWAYS WITH THE AHP METHOD

Yağmur ARIKAN[1], Ertuğrul ÇAM[2]
Electrical and Electronics Engineering Department, Kırıkkale University, Faculty of Engineering, TURKEY.

[1]yagmurarikan@kku.edu.tr, [2]cam@kku.edu.tr
Tel: 3183574242-1202

Abstract: Energy is one of the main issues that determine world politics. Energy efficiency has become compulsory in recent years. The energy consumed by transportation vehicles also has a great deal in world energy consumption. Therefore, today, we focus on energy saving and energy recovery in railway systems, which are frequently used in transportation. In this study, one of the multi-criteria decision making methods, AHP, was used to determine that which of the energy consumption factors in the railways is more important. For this purpose, some methods were chosen such as increased the power level, using of regenerative energy, using of energy storage systems, speed profile optimization and efficient driving methods. Also, energy consumption, emission reduction, travel time and system cost were chosen for AHP criteria. According to these criteria, the most important factor in energy reduction was obtained as the use of regenerative energy.

Keywords: Railway system, energy efficiency, regenerative energy, energy storage systems, AHP

Introduction

Today, rapid population growth, rapid urbanization rate and emission problem have increased the problems in energy sector. Transportation sector has a great share in total energy consumption and the energy which is used for transport constitutes approximately 33% of the total energy consumption and 86% use of fossil fuels. Therefore, railways systems are highly preferred because of high capacity and low energy consumption. Although, it is initially considered that the cost of these systems are more expensive than other transport systems, this cost is advantageous from others in terms of carrying capacity (Martinis V.D. & Gallo, 2013). Railway systems can be thought as modern and advanced tram and they are also reliable, economical, innovative and eco-friendly transport systems.

Rail systems are operated electrically and they rely on electrical supply from the national supply system in most countries. The most common ways of electrifying railways are by the 25 kV, 50 Hz AC single phase system or 750 VDC-1500 VDC system. Some railways use 15 kV AC single phase or 3000 VDC system but they are not common. In DC systems, the electric power is taken from the national grid as 33 kV or 11 kV voltage and the level voltage is reduced by the transformers along the way. Then, it is rectified and supplied to the conductor rails. In AC systems, the electric power is taken from the national grid as 132 kV or even higher and transmitted to transformer substation. This value is converted to the nominal value of 25 kV and this is given to line and transferred train by means of catenary system. This power is reduced to a lower voltage and is rectified by equipment on board the train (Bonnett, 2005).

Today, there are various energy efficiency and energy recovery studies in all energy consumption areas to ensure the sustainable energy. In the literature, several methods have been described to reduce energy consumption in railway systems. Gonzalez and the others, developed a method which includes energy optimization, effective driving methods and energy storage devices. The method provides about 25-35% gain the reduction in energy consumption (Gonzalez-Gil, Palacin, Batty, & Powell, 2014). Martinis and Gallo, tried to optimize the speed profiles of tracked vehicle systems and emphasized effective and efficient driving techniques (Martinis V.D. & Gallo, 2013). Açıkbaş and Söylemez, examined the effects of energy supply levels on energy consumption. For this purpose, they compared 750 VDC power system and 1500 VDC power system and observed that 1500 VDC power system gives approximately 10 % saving in traction of the system (Açıkbaş & Söylemez, 2004). Tian et all. pointed out that the best way to reduce the energy consumption is the effective use of regenerative energy for metro transit systems with frequently motoring and braking trains (Tian and others, 2017).

The methods which are used to reduce energy consumption in railway systems have various effects on system cost, emission and travel time. For example, the use of energy storage devices results in a significant increase in system cost or efficient driving techniques lead to an increase in travel time. Therefore, five different methods were evaluated in terms of four different criteria. These methods were increased the power level, using of regenerative energy, using of energy storage systems, speed profile optimization and efficient driving methods. The criteria were energy consumption, emission reduction, travel time and system cost. In this evaluation, Analytic Hierarchy Process (AHP) was used. This is one of multi-criteria decision making methods and to reach goal briefly or to choose among alternative for achieving a specific purpose is easily through these methods.

The Electrification in Railway Systems

Railway systems are working with electricity and the basic components of electrification in rail systems are transformer centers, energy transmission lines and vehicles. The transformer central power demand depends on some factors such as train nominal power, frequency of train travel, the load, the number of rail etc. The voltage from the transformer substations is transmitted to vehicles by energy transmission system. Three different methods can be used as energy transmission line according to the level of DC voltage. These are catenary systems, 3rd rail systems and rigid catenary systems. Catenary system should be used for voltages above 1500 V and the vehicles are powered by the pantograph in this system. 3rd rail systems are generally used on subway lines and the vehicles are powered by equipment which is called as rail shoe. The rigid catenary system has been developed as an alternative to the others and can carry large currents. The energy that comes into the vehicles through energy transmission systems is consumed in proportion to the vehicle mass and speed of the vehicle according to Newton laws. Apart from these, the various comfort functions such as lighting, heating, cooling etc. in the system are another important part of the energy consumption. (Açıkbaş, 2008), (Sertsöz, 2012).

The railway system is the largest customer of electricity distribution companies according to energy consumption. In this respect, the energy optimization studies in railed systems will contribute to energy saving and positive environmental impact significantly (Baran, 2009). The Rail Energy project aims to reduce energy consumption by up to 6% in railway systems by 2020 in Europe (RailEnergy). According to the law which is published in 2008 by the Ministry of Transport in Turkey, it was emphasized to reduce electricity consumption in railway transportation to a minimum (Turkey Official Newspaper, 2008). There are some methods in the literature to reduce energy consumption in rail systems and five different methods were used in this article. These are described in below.

- **The increase of power supply level:** The energy losses occur in transformer center and transmission systems due to voltage drop. The first solution to reduce these losses is to increase of voltage level. In a study about this subject, 1500 VDC was preferred in the metro system that was opened in 2003 in Singapore (Gog, Chu, & Ng, 2004). In another study, a comparison of 750 VDC and 1500 VDC was made and when 1500 VDC was used, the voltage drop was reduced by half. While the distance between the transformers was 1.5 m when using 750 VDC, this value was 6 m when using 1500 VDC (Arlı, 2010).

- **The use of regenerative energy:** Since most of the transformer centers use one-way rectifier, they allow one way transmission. For this reason, the kinetic energy that is released during train braking, that is electrical energy, cannot be returned to the network. If this energy can be utilized in various forms, energy consumption can be significantly reduced. In a study, it was noted that energy losses during braking increase greatly due to red signal lamps (Lehmann & Hauser, 2002). In another study, several scenarios were been tested with the Belmann-Ford Algorithm including travel time and speed limits to increase the rate of use of regenerative energy in suburban trains and they found an increase of 17% (Lu, Weston, Hillmansen , Gooi, & Roberts, 2014).

- **The use of energy storage systems:** Nowadays, the energy that is released during braking can be stored with various systems such as batteries, ultra-capacitors and flywheel. These systems are used on the vehicle or along the line. Before using these systems, cost-efficiency studies are required. In an article which was done with ultra-capacitor, it was stated that the amount the load was increased. However, energy saving of between 23%-26% was been achieved according to type of ultra-capacitor and the number of passengers (Barrero, Mierlo, & Tackoen, 2008).

- **The speed profile optimization:** Some speed reductions provide energy saving but the time of travel should be within the limits according to speed. For example, over 10% during travel time can be equivalent to 25% energy saving (Dalyan, 2011).

- **The efficient driving methods:** The driving techniques have an important effect on energy consumption. The speed profile should be as follows: high initial acceleration, low coasting speed, long time with coasting, high braking acceleration, low standby time. Energy consumption can be reduced by 12% with efficient driving methods compared to normal driving (Açıkbaş, 2008).

The Multicriteria Decision Making

Decision making is simply to achieve the goal or choose from alternatives for achieving a specific goal. Multi-criteria decision making is a sub branch of decision making. Today, different techniques are used in evaluation of alternatives according to the criteria. There are three steps to use any decision making technique including numerical analysis of alternatives. These can be expressed as:
-Determine the relevant criteria and alternatives,
-Attach numerical measures to the relative importance of the criteria and to impacts of the alternatives on these criteria,
- Process the numerical values to determine a ranking of each alternative (Triantaphyllou, 2000).

Today, different techniques are used in the evaluation of alternatives according to some criteria. Analytic hierarchy process (AHP), Analytic network process (ANP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Elimination and Choice Translating Reality English (ELECTRE), The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), and Vise Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) are of some of these techniques. In this paper, AHP method was used for evaluation five different alternatives (increase of power supply level, the use of regenerative energy, the use of energy storage systems, the speed profile optimization and efficient driving methods) according to four different criteria (reduction of energy consumption, reduction of amount of emission, travel time and system cost). The numerical analysis of AHP is described below.

Analytical Hierarchy Process

This method was developed by Saaty in decision problems. The steps of the method are given below (Saaty, 1990).

Step 1: Definition of Decision Making Problem

The decision points and the factors must be determined to define the problem. The number of decision points is symbolized by m, and the number of factors affecting decision points is symbolized by n.

Step 2: Creating Factor-to-Factor Comparison Matrix

The comparison matrix of the factors is a dimensional square matrix. The components of this matrix on the diagonal take the value 1. The comparison matrix is shown in Equation 1.

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & a_{m3} & \cdots & a_{m4} \end{bmatrix} \tag{1}$$

The comparison of the factors is done in one to one and reciprocal manner according to their importance values. The importance scale in Table 1 is used in the comparison of the factors.

Table 1. Importance scale used in AHP

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	More important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over the other.
9	Absolutely more important	The evidence favouring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed.

Step 3: Determine of the Factor's Percentage Distribution

The comparison matrix shows the significance levels of the factors according to each other within a certain semantic. The column vectors of the comparison matrix are used in order to determine the weights of these factors in all or the percentage distribution of factors. A and B column vector is formed with n-component and the components of the column vector B are calculated as shown in Equation 2. According to Equation 2, B column vector is shown in Equation 3.

$$\mathrm{b_{mn}} = \frac{\mathrm{a_{mn}}}{\sum_{\mathrm{m=1}}^{\mathrm{k}} \mathrm{a_{mn}}} \tag{2}$$

$$\mathrm{B_i} = \begin{bmatrix} \mathrm{b_{11}} \\ \mathrm{b_{21}} \\ \vdots \\ \mathrm{b_{n1}} \end{bmatrix} \tag{3}$$

When B columns vectors are combined in a matrix format, the matrix-C is formed and this is shown in Equation 4.

$$\mathrm{C} = \begin{bmatrix} \mathrm{c_{11}} & \mathrm{c_{12}} & \cdots & \mathrm{c_{1n}} \\ \mathrm{c_{21}} & \mathrm{c_{22}} & \cdots & \mathrm{c_{2n}} \\ \vdots & \vdots & \vdots & \vdots \\ \mathrm{c_{n1}} & \mathrm{c_{n2}} & \cdots & \mathrm{c_{nn}} \end{bmatrix} \tag{4}$$

The percentage significance distributions that show the important values with respect to each other can be obtained with using C matrix. As shown in Equation 5, the weighting vector-W is formed by taking the arithmetic mean of the row components of C matrix.

$$w_m = \frac{\sum_{n=1}^{k} c_{mn}}{k} \tag{5}$$

$$\mathrm{W} = \begin{bmatrix} \mathrm{w_1} \\ \mathrm{w_2} \\ \vdots \\ \mathrm{w_n} \end{bmatrix} \tag{6}$$

Step 4: Determine of Consistency of Factor Comparison

In this step, consistency of factor comparison is measured. The consistency rate (CR) indicates whether comparisons made are true or false. D, column factor is found by multiplying comparison matrix A with weighting vector W. The evaluation factor (Ei) is obtained by dividing column vector D to the corresponding elements of column vector W as shown in Equation 8. The evaluation factor related to the comparison (λ) is obtained by taking the mean of Ei elements as shown in Equation 9. Then, consistency index (CI) and the consistency rate (CR) are calculated as shown in Equations (10) and (11)

$$D = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} x \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{7}$$

$$E_i = \frac{D_i}{W_i} \; i = 1,2,..n \tag{8}$$

$$\lambda = \frac{\sum_{i=1}^{n} E_i}{n} \tag{9}$$

$$CI = \frac{\lambda - \mathrm{n}}{n-1} \tag{10}$$

$$CR = \frac{CI}{RI} \tag{11}$$

where RI is called random indicator and it has different values according to the number of criteria (n). The values of RI according to n, is given in Table 2. If the consistency rate (CR) is smaller than 0.10, comparison matrix is consistent [20].

Table 2. The values of RI

k	**RI**	**k**	**RI**
1	0	6	1.24
2	0	7	1.32
3	0.58	8	1.41
4	0.90	9	1.45
5	1.12	10	1.49

Step 5: Found The Percentage Distribution of the Decision Point for Each Factor

In this step, the percent significance distributions of the decision points are determined for each factor. Individual comparisons and matrix operations are repeated as many times as the number of factors (n times). The size of the comparison matrix that will be used as the decision points of each factor will be mxm. After each comparison operation, column vectors S that show percentage distribution and have a size of mx1 are obtained. It is given in Equation 12.

$$S_m = \begin{bmatrix} s_{11} \\ s_{21} \\ \vdots \\ s_{m1} \end{bmatrix} \tag{12}$$

Then, an mxm dimensional K decision matrix which is consisted from n dimension column vector, S is formed. It is given in Equation 13.

$$K = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ s_{m1} & s_{m2} & \cdots & s_{mn} \end{bmatrix} \tag{13}$$

Finally, when the decision matrix and weighting factor are multiplied, the column vector, L-column vector is obtained. L vector gives the percentage distribution of decision points.

$$L = \begin{bmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ s_{m1} & s_{m2} & \cdots & s_{mn} \end{bmatrix} x \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} l_{11} \\ l_{21} \\ \vdots \\ l_{m1} \end{bmatrix} \tag{14}$$

Results

In this paper, Analytic Hierarchy Process (AHP) method was used for evaluation of the methods used to reduce energy consumption in railway system. Various papers in the literature was been utilized to determine the methods and the criteria. The five different methods which used in the paper can be listed as follows: increase of power supply level, the use of regenerative energy, the use of energy storage systems, the speed profile optimization and efficient driving methods. The four criteria which used in the paper can be listed as follows: reduction of energy consumption, reduction of amount of emission, travel time and system cost. The solution steps of AHP were carried out one by one.

Firstly, the comparison matrix, A for the 4 criteria was formed as Table 3. EC is symbolized for reduction of energy consumption, LE is symbolized for low emission, TT is symbolized for travel time and SC is symbolized for system cost. While the values in Table 3 were being prepared, Table 1 was taken as reference. In the paper, the reduction in energy consumption was chosen as the most important criterion in the study. Then, the order of importance was determined as low cost, low emission and travel time respectively.

Table 3. Comparison matrix for four criteria.

	EC	LE	TT	SC
EC	1	5	7	3
LE	0,2	1	3	0,333
TT	0,143	0,333	1	0,2
SC	0,333	3	5	1

Then, weighting vector, W was found using B and C matrix. These operations were carried out with using Equations 2-5. The consistency rate (CI) was found using the Equations 7-11 to find the consistency of the criterion comparison matrix. According to Table 2, the random indicator (RI) was taken as 0.90 due to four criteria in calculations. A CR value must be less than 0.10 for consistent matrix. We found this value to be 0.0555, so the comparison matrix is consistency. These values are shown in Table 4.

Table 4. Weighting vector of criteria, the results of consistency

Wec	0.557	**λ**	4.149
Wle	0.122	**CI**	0.050
Wtt	0.056	**RI**	0.90
Wsc	0.263	**CR**	0.055

Later, the values of alternatives were created according to criteria. The order of the alternatives in terms of energy consumption is determined as follows.

Regenerative Energy (RE)> Energy Storage Systems (ESS)> Increase of Power Supply Level (PSL)> Efficient Driving (ED)>Speed Profile Optimization (SPO)

The order of the alternatives in terms of low emission is determined as follows.

Regenerative Energy (RE)> Energy Storage Systems (ESS)> Speed Profile Optimization (SPO)>Increase of Power Supply Level (PSL)> Efficient Driving (ED)

The order of the alternatives in terms of travel time is determined as follows.

Increase of Power Supply Level (PSL)> Energy Storage Systems (ESS)> Regenerative Energy (RE)> Efficient Driving (ED)≥ Speed Profile Optimization (SPO)

The order of the alternatives in terms of low system cost is determined as follows.

Speed Profile Optimization (SPO)> Efficient Driving (ED)> Regenerative Energy (RE)> Energy Storage Systems (ESS)> Increase of Power Supply Level (PSL)

Table 5.a, 5.b, 5.c, 5.d were formed according to Table 1 and these sequences. The values of alternatives are shown in Table 5.a according to energy consumption. The values of alternatives are shown in Table 5.b according to low emission. The values of alternatives are shown in Table 5.c according to travel time. The values of alternatives are shown in Table 5.d according to system cost. The consistency rate was found for all matrices which have shown in Table 5.a, 5.b, 5.c, 5.d. These values are 0.0541, 0.0608, 0.0468, and 0.0711. Therefore, all matrices are consistent.

Table 5.a. The value of alternatives according to energy consumption

Energy Consumption	PSL	RE	ESS	SPO	ED
PSL	1	0,2	0,333	5	3
RE	5	1	3	9	7
ESS	3	0,333	1	7	5
SPO	0,2	0,111	0,143	1	0,333
ED	0,33	0,143	0,2	3	1

Table 5.b. The value of alternatives according to low emission

Low emission	PSL	RE	ESS	SPO	ED
PSL	1	0,143	0,2	0,333	3
RE	7	1	3	5	9
ESS	5	0,333	1	3	7
SPO	3	0,2	0,333	1	5
ED	0,333	0,111	0,143	0,2	1

Table 5.c. The value of alternatives according to travel time

Travel time	PSL	RE	ESS	SPO	ED
PSL	1	5	3	8	7
RE	0,2	1	0,333	4	3
ESS	0,333	3	1	6	5
SPO	0,125	0,25	0,166	1	0,5
ED	0,143	0,333	0,2	2	1

Table 5.d. The value of alternatives according to system cost

System Cost	PSL	RE	ESS	HPO	ED
PSL	1	0,2	0,333	0,111	0,143
RE	5	1	3	0,2	0,333
ESS	3	0,333	1	0,143	0,2
SPO	9	5	7	1	3
ED	7	3	5	0,333	1

Finally, according to AHP method, the selection matrix of alternatives was found as in Table 6.

Table 6. Evaluation of alternatives

PSL	0,112
RE	0,385
ESS	0,209
SPO	0,170
ED	0,114

Conclusions

The energy efficiency has become more important because of the constant increase in energy demand. Various methods have also been developed for railway system which are the most important energy consumption units. In this paper, the methods were evaluated for different criteria. The AHP method was used in this evaluation process. Because we can evaluate alternatives in terms of criteria with this method. Five different methods for reducing energy in railways were selected as increase of power supply level, the use of regenerative energy, the use of energy storage systems, the speed profile optimization and efficient driving methods. Also, for the AHP, four different criteria were selected as reduction of energy consumption, reduction of amount of emission, travel time and system cost. As a result of the study, it can be seen that the use of regenerative energy is the most effecting factor in energy consumption with 38%. The other factors are the use of energy storage systems with 21%, speed profile optimization with 17%, efficient driving methods with 11.4%, increase of power supply level with 11.2%.

References

Açıkbaş, S. (2008). Energy Efficient Driving Control in Multi Trains Multi Lines Rail Systems. In *İstanbul Technical University* (pp. 1-15). İstanbul.

Arlı, V. (2010). Kent İçi Raylı Sistemler. *Teknik,* 15-18.

Baran, S. (2009). *The usage and analysis of regenerative braking energy in the urban rail system operation.* Istanbul Technical University: Master Thesis.

Barrero, R., Mierlo, J., & Tackoen, X. (2008). Supercapacitors On-Board Light Rail Vehicles:Enhanced Energy Storage Systems For İmproved Vehicle Efficieny. *IEE7/ASME Joint Rail Conference.*

Bonnett, C. F. (2005). *Practical Railway Engineering.* Imperial College PRESS.

Dalyan, M. (2011). *Energy Optimization Oriented Studies ın Railway Systems.* Yıldız Techinical University, MSc Thesis .

Gog, E., Chu, K., & Ng, N. (2004). 1500 V DC traction system for the North East Line. *Int'1 Conf. on Power System Techology* . Singapore-POWERCON.

Gonzalez-Gil, A., Palacin, R., Batty, P., & Powell, J. (2014). A Systems Approach to Reduce Urban Rail Energy Consumption. *Energy Conversion and Management*(80), 509-524.

Lehmann, H., & Hauser, A. (2002). *Mehrverbrauch im Eisenbahnbetrieb-Ursachen und Ermittlung.* ZEVrail Glasers Annalen.

Lu, S., Weston, P., Hillmansen , S., Gooi, H., & Roberts, C. (2014). Increasing the Regenerative Braking Energy for Railway Vehicles. *IEEE Transactions on Intelligent Transportation Systems, 15(6),* pp. 2506-2515.

Martinis V.D., & Gallo, M. (2013). Models and Methods to Optimise Train Speed Profiles with and without Energ Recovery Systems: A Suburban Test Case. *Procedia-Social and Behavioral Sciences*(87), 222-233.

RailEnergy. (n.d.). *"Innovative Integrated Energy Effficiency for Railway Rolling Stock,rail infrustructure and train operation".*

Saaty, T. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research, 48(1),* (pp. 9-26).

Sertsöz, M. (2012). Energy Efficiency of Rail Sytems. Kocaeli University.

Tian, Z., Weston, P., Zhao, N., Hillmansen, S., Roberts, C., & Chen, L. (2017). System Energy Optimization Strategies for Metros with Regeneration. *Transportation Research Part C, 75,* 120-135.

Triantaphyllou, E. (2000). Multi-Criteria Decision Making Methods.

Turkey Official Newspaper. (2008). Retrieved from http://www.resmigazete.gov.tr/eskiler/2008/06/20080609-3.htm

