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COMPREHENSIVE MODELLING OF THE COST EFFECTIVNESS OF RAILWAY LINE ELECTRIFICATION

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Abstract: Subject of this paper is the mathematical model estimating the Economical threshold between usage of combustion engine traction and electrical traction for new and modernized railway passenger communication lines. Currently available models do not coincide with the whole complexity of the problem. The proposed model was implemented into Matlab and then validated on "Pomorska Kolej Metropolitalna" investment time-frame and its cost of infrastructure, type of Diesel Multiple Units (DMU) and track geometry. The vehicles maintenance levels are taken into consideration as well. Usage of the Energy Storage Systems is considered. The final result of this analysis is threshold of economic efficiency in analyzed period of 30 years for traffic flow expressed in value of passenger per hour in rush hours.

Keywords: railway traction, economical threshold, life cycle cost, modeling train dynamics.

1. INTRODUCTION

Since joining European Union in 2004 Poland has gained opportunities to realize many infrastructural projects supported by European funds. One of the biggest beneficiaries is the Polish Railways. Dozens of railway lines have been built, modernized and electrified. However, a great number of lines still has not been adapted to electrical traction vehicles, which are found more energy-efficient, cleaner, easier to control and able to reach higher speed compare to combustion one.

Nevertheless not always there is the economic base to electrify a railway line if the costs of the investment will not exceed profits in predefined life cycle. Therefore, in order to distribute European funds wisely all planning investments should be preceded by a precise economical threshold evaluation.

The economical threshold should determine when it is reasonable to use an electrical traction over diesel engine traction in predefined or predicted traffic flow given in number of the passengers per year as it is illustrated in figure 1. Cost of construction of the diesel traction line is much smaller however with increase of traffic flow one reaches a point where electric traction is equalled expensive. Above the traffic flow at this point the cost of used energy becomes significantly higher and it is reasonable to use electric traction. To specify economical threshold, a number of factors regarding constant and variable costs have to be taken into account.

Topography and curvature of the analyzed line have to be known as well as distribution of the stops. To analyze energy consumption the theoretical run has to be simulated. Costs of both, line construction or modernization and traction vehicle must be known or estimated. The long-term maintenance costs have to be taken into consideration as well. Therefore, in order to speed up the investment and decision-making process a comprehensive model for economical threshold estimation has been created. In addition the approach has been extended of the Life Cycle Cost (LCC) analysis and simulation of the energy storage system (ESS) in Electrical Multiple Unit (EMU).

The model and its implementation in Matlab Simulink environment were tested and validated on the "Pomorska Kolej Metropolitalna" (PKM) investment. A PKM railway line was constructed with no electric traction however in investment plan it is assumed that economical threshold will be achieved by 2023. The results obtained with model show that estimated economical threshold is convergent with the used case study.

Objective of this study is to propose, implement and validate one comprehensive model for economical threshold estimation with consideration of the factor not included in currently used methodology, such as long-term maintenance of the traction unit and usage of the energy storage system (installed in the car or in the track substations).

2. SURVEY OF RELATED WORKS

Nowadays in the western countries, almost all new constructed railways are electrical traction lines. This is due to the fact that commonly high speed train lines are planned. Such vehicles have to be driven by the electric motors in order to reach a required speed. Moreover, electrification of railway has been done mostly in the previous century. Therefore an issue of economical threshold is not commonly discussed. Analysis of benefits of switching to electrical traction can be found for example in [1, 2].

However, in Polish conditions not all new lines are high speed investments. In order to gain European funds investor should prove the purposefulness of electric traction construction over combustion traction. Therefore an economical threshold is taken into account during investment planning.

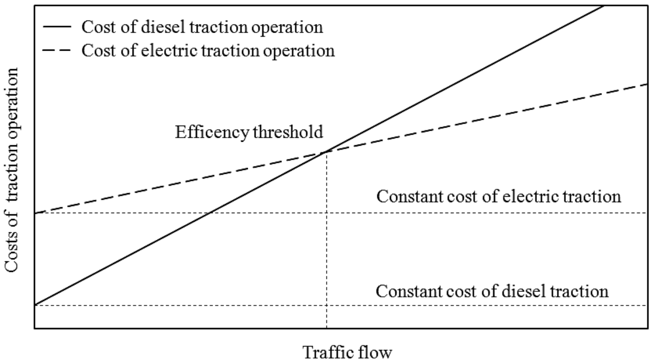

Fig. 1. Threshold of economic efficiency between usage of diesel and electric traction in function of traffic flow

One of the most important parts in the threshold estimation is the proper model of train dynamics. Relevant work can be found in [3]. Life cycle cost analysis (LCC) is often performed in a case of estimate all costs of railway vehicles. Effectiveness of different means of transport based on a LCC is studied e.g. in [4].

In the proposed model one can simulate energy stored system for breaking energy recovery. Both, ESS installed in the electrical multiple units and in the traction substations are considered. Energy recovery and storage in the traction application are widely discussed in the literature. In [8] authors present a method for optimal sizing of supercapacitor (SC) energy storage system on the case of one traction substation of Riga tram network. In [9] the possibility of improving the energy recovered during the braking and reduction of power peaks during accelerating of railway vehicles with onboard ESS are discussed. Design and control of a supercapacitor storage system for traction applications are discussed in [10]. In presented model supercapacitor calculation are based on [11].

3. SOLUTION

The estimation is performed over given time period related to design life cycle. In figure 2, the estimating procedure used in our model is presented. Procedure consists of the following steps:

Firstly, we define the initial conditions that are costs related to infrastructure construction, such as costs of the centenary lines, the substations and the power lines. Cost of the vehicles and ESS are also taken into account. We base on project infrastructural expenses and cost of given multiple units or, if unknown we can compare costs with similar railway investment.

Secondly, in order to estimate variable costs theoretical run simulation on an analyzed line in dynamics sub-model is performed. Variable cost include the amount of consumed and recovered electrical energy in case of an electrical multiple unit and the fuel consumption in case of a DMU. Estimated variable cost is related to the current market energy prices. In dynamics sub-model factors such as the track topography and parameters of the vehicle motors are taken into consideration.

Thirdly, from the results obtained by dynamics simulation the LCC analysis can be performed. The analysis defines constant cost of car maintenance, which varies with train operator timetables.

Summing up all the costs resulting from the described steps and linking them with traffic flow analysis we estimate economical threshold of railway line electrification, which is

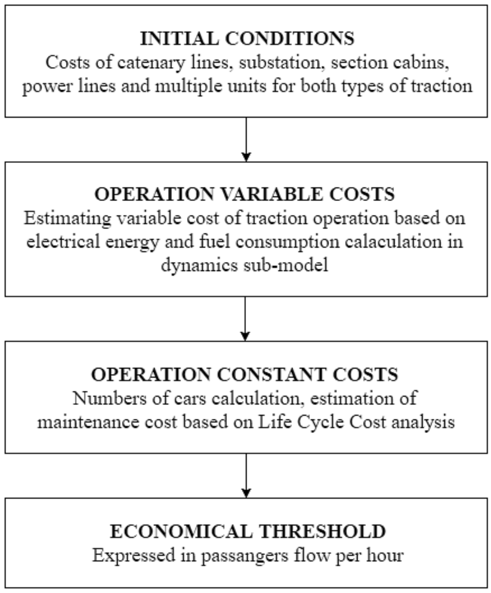

Fig. 2. Procedure of estimating the economical threshold of railway line electrification

the time that the electrification would be cost-effective. The economical threshold estimation can be defined in the traffic flow of passengers or cargo as well.

3.1. Train dynamics model for the variable costs estimation

The mathematical model accurate enough for EMU dynamics described by the traction force $F(v)$, train resistance force $W(v)$ and train resistance depending on track geometry $G(s)$ and given in N

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \frac{F(v) - (W(v) + G(s))}{m \cdot k} \ (\mathrm{m/s^2}) \qquad v(t=0) = 0 \ (\mathrm{m/s}) \tag{1}$$

where: m – mass of the loaded multiply unit (kg),
k – accelerating mass coefficient.

Dynamics of vehicle breaking are defined by

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \frac{-F(v) - (W(v) + G(s))}{m \cdot k} \qquad v(t=t_b) = v_b \tag{2}$$

where: t_b – initial time of breaking (s),
v_b – initial velocity of breaking (m/s).

The train resistance force W can be described by the polynomial (3) commonly used in the Polish conditions and defined by "The Railway Institute". It describes multiply unit resistance force dependency on velocity.

$$W(v) = (K + 0.53 \cdot v) \cdot m_t + 147 \cdot M + f \cdot (2.7 + n) \cdot v^2 \ (\mathrm{N}) \tag{3}$$

where: K – coefficient depending on the bearings type ($K \approx 6.4$), m_t – mass of the loaded multiply unit (t), f – coefficient related to a type of the section in the unit ($f \approx 1.27$), M – is a number of the axis in the unit, n – number of the sections in the unit.

Resistance force resulting from the geometry of the track is

$$G(s) = \frac{m \cdot g \cdot i(s)}{1000} \quad (4)$$

where: g – constant of gravity (9.81 m/s^2),
i – railway gradient including gradients from the track curves (in ‰).

The last parameter necessary to perform the simulation of the train dynamics is a traction force $F(v)$. To obtain value of the force one needs to estimate a traction effort curve that presents the effort force in function of the vehicle velocity.

3.2. LCC analysis

The LCC analysis includes cost of buying the vehicle but also maintenance costs of and even scrapping costs [4]. To perform the constant cost estimation with a use of LCC analysis the service documentation divided into 5 levels of vehicle maintenance must be known. Each level describes the maintenance objectives in given millage or time of operating. In figure 4 the example of maintenance schedule for an electrical multiple units Newag 14WE is presented.

The maintenance levels P1, P2 and P3 describe actions that are carried out to make the unit operational. P4 level assumes disassembling the most important parts of trains such as inverters, auxiliary inverters and engines, in order to replace them by new ones. The P5 level determines the full modification of the unit, for example by renewing the propeller system with use of the new boogies, inverters and engines, or by changing all the train comfort systems.

To perform this analysis in our model we define the millage between different types of maintenance levels for both types of traction units. Costs of each maintenance level are determined as well.

The next step is to define the number of vehicles operating in the line. This number can be obtained from a flow traffic study. The number L of train cars needed to operate the line is

$$L = \frac{P}{2 \cdot C \cdot \frac{3600}{t}} \quad (5)$$

where: P – number of the passengers per hour,
t – time of running through all the line (in s),
C – vehicle passengers capacity.

4. "PKM" CASE STUDY

We implemented the proposed model in Matlab Simulink environment. To validate a model and its implementation the case study of "Pomorska Kolej Metropolitalna" railway line investment was used. We divided implementation into two parts. First one, related to the train dynamics was made in Simulink with use of the graphical language. Second, with all the costs initialization, calculation and result presentation was made in *m*-file script.

In order to simulate train dynamics the real gradients of the track geometry were applied to dynamics sub-model. In addition, calculated traction effort for the rated power of 764 kW DMU was included. Chosen DMU is similar to the PESA 219M DMU which is mainly operating in PKM line.

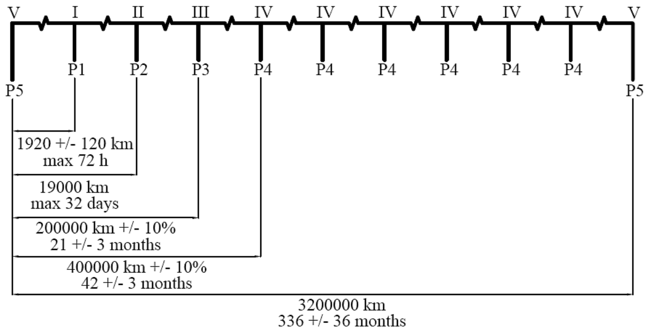

Fig. 4. Cycle of servicing the Newag 14WE

To validate the economical threshold estimation model the constant cost of infrastructure construction from modernization of the E65 Warsaw – Gdańsk railway line were taken as initial values. Unit prices of fuel and electrical energy were taken from the auctions of railway operators in Poland. Purchase, service costs of multiple units and their life time were taken from the Life Cycle Cost analysis performed in paper [5] and public available documentation of the train cars. EMU used in validation was PESA 21WE. Variable costs were obtained in dynamics sub-model. Traffic flow data were taken from feasibility study for PKM line, assuming as the initial variant the most conservative one [6]. Estimation was performed over the 30 years long time period (life time cycle of EMU) and has shown that the cost of diesel traction operation exceeds electric traction

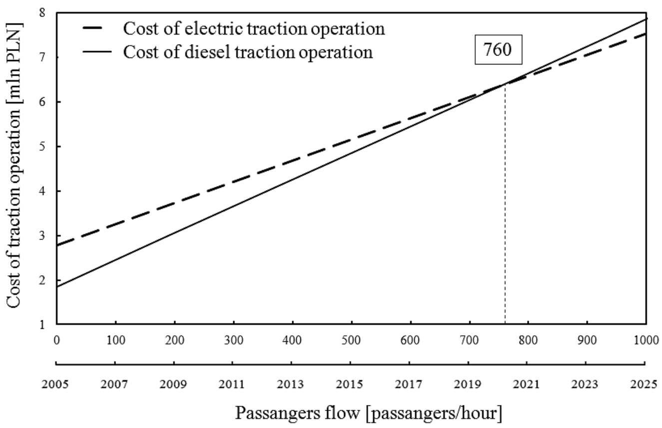

Fig. 5. Calculated economical threshold for PKM line

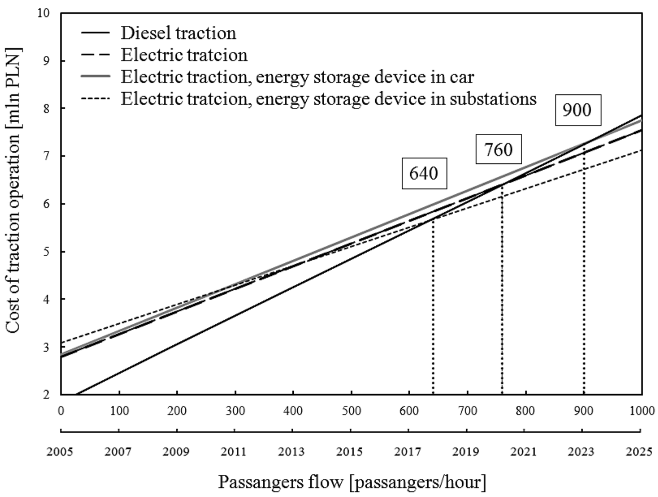

Fig. 6. Economical thresholds for PKM line with consideration of different energy storage systems

Table 1. Result of the supercapacitor storage system calculation

Case	I	II (SubA)	II (SubB)
Effective supercapacitor energy [kWh]	3.28	9.84	6.56
Total supercapacitor energy [kWh]	4.38	13.13	8.75
Recovered energy [kWh]	40.00	120.72	94.21
Cost [mln PLN]	0.64	1.92	1.28
Life time [years]	7.14	6.30	6.09
Economical gain [thousand PLN/year]	84.13	158.70	123.84

operational cost at the passengers flow level of 760 passengers per hour. According to feasibility study that level of traffic flow will be achieved about 2020. In figure 5 the analyze results are shown.

The results of the estimation with consideration of the energy storage systems are presented in the figure 6. The most effective is to install ESS in track substations. In that case, economical threshold will be achieved at the passengers flow level of 640 passengers per hour. Supercapacitor storage device installed in the cars is the least effective. Cost of operation will even diesel traction operational cost at the level of 900 passengers per hour.

ESS parameters used in this study are presented in the table 1. Results of the recovered energy calculation in case of different ESS location are presented as well. Case "I" regards ESS located in all the electrical vehicles operating on PKM line, in case "II (SubA)" and "II (SubB)" ESS is located in substations "Gdańsk Wrzeszcz" (existing) and "Gdańsk Osowa" (planned) respectively.

5. CONCLUSION

Calculating economical threshold is complex and multidisciplinary task. All the factors regarding constant and variable cost have to be considered, such as a dynamics of the train or energy prices. Estimation allows predicting when it is cost-effective to switch from the diesel to the electric traction. In this paper authors proposed complex model for this purpose, even extend of LCC analysis and ESS simulation. Model and its implementation in Matlab were validated on "Pomorska Kolej Metropolitalna" investment. Results from dynamics sub-model are almost equal to real timetable. PKM board is planning to electrify line by year 2023 [7]. A threshold calculated in model indicates that is profitable about 2020 with traffic flow at level of the 760 passengers per hour. Costs of operation are average costs over the analyzed 30 years long time period. Regarding limited amount of information the proposed model is very good estimator of economical threshold.

6. REFERENCES

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MODELOWANIE PROGU EFEKTYWNOŚCI EKONOMICZNEJ ELEKTRYFIKACJI LINII KOLEJOWEJ

W artykule zaproponowano model matematyczny służący do estymowania wartości progu efektywności ekonomicznej pomiędzy użyciem trakcji spalinowej a trakcji elektrycznej na modernizowanych lub nowo budowanych pasażerskich liniach kolejowych. Obecnie używane modele nie uwzględniają całej złożoności problemu. Przedstawione rozwiązanie zostało zaimplementowane w środowisku Matlab, a następnie zweryfikowane w odniesieniu do inwestycji w budowę pt. "Pomorska Kolej Metropolitalna". W modelu uwzględniono czas realizacji i istnienia projektu, koszty proponowanej infrastruktury, rodzaj pojazdów spalinowych i elektrycznych oraz kształt i topografię linii kolejowej. Koszty związane z utrzymaniem pojazdów (analiza LCC) oraz możliwe zastosowanie superkondensatorowych zasobników energii w pojeździe lub w podstacjach trakcyjnych są również uwzględnione w modelu. Końcowym wynikiem przeprowadzonej analizy jest estymacja progu efektywności dla założonego czasu istnienia inwestycji wyrażona w potokach pasażerów w godzinach szczytu.

Słowa kluczowe: trakcja kolejowa, próg efektywności ekonomicznej, koszt cyklu trwałości (LCC), modelowanie dynamiki ruchu pojazdu.