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A Surface Model of Variation of Direct Operating Costs for Freight Trains – a Case from Bulgaria

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***Abstract*—A surface model of the variation in operating costs of freight block trains with constant number of wagons in the composition has been presented in the report. The results refer to the movement of freight trains with a constant composition between the initial train-forming and final for the train railway station. The study has been conducted for freight trains running on domestic rail lines in the Republic of Bulgaria. The model takes into account the costs for preparing and operating a freight train, related to: the charges for use of railway infrastructure; the costs of using electric locomotives; the costs of electricity for traction power; the costs of paying the labour of locomotive`s drivers and the costs related to the activities of preparing and check the train and load at the initial and final railway stations. The study has been carried out for freight block trains with a gross mass varying between 400 and 2,200 tons and for train route length varying between 100 and 500 km. The two parameters – the route length and gross mass – form the polygon of the graphical surface model. The results have been presented through the direct relative operating costs related to three widely used in railway transport parameters - the transportation work performed, travelled wagon-kilometres and number of wagons transported by train. The results of the study show, for the conditions it has been conducted, that the relative costs of the trains vary according to the different parameters respectively into intervals 10.31÷43.66 Euro per 1000 gross tkm, 0.61÷1.43 Euro per a wagon kilometre and 87.32÷518.52 Euro per a transported wagon by the train.**

***Keywords*—surface model, activity-based costing model, freight block-train, distance, gross mass, direct operating cost**

I. Introduction

Railway freight transport has a fundamental role in the functioning of modern logistics chains. Its participation as a stand-alone mode of transport or in combination with other modes of transport in the multimodal logistics chains requires to be seek opportunities to improve its operational performance. A key indicator of transportation, and in particular of freight railway transport, is their economic efficiency, which is directly related to the cost price of transportation. The cost price of rail transport reflects the costs that are directly related to the organization and performance of the relevant transport. The classification of these costs can be carried out according to various criteria. Depends on the way that the transport activity is related to costs, often used in railway transport classification of costs is into direct and indirect costs [1, 2]. The group of direct costs includes the operating costs that are directly related to transportation process. The direct operating costs in rail freight transport are the costs that arising from activities directly carried out to prepare the train and to perform transportation process with the train [3, 4]. The direct operating costs contribute to formation of the total cost of preparing and movement of the trains. Their assignation and research are significant for the subsequent tariff and shipping price formation. A way to determine costs in transport processes is to apply process-oriented approaches, including on determine the direct operating costs for the movement of freight trains [1, 5]. Based on this approach, an analytical model has been proposed in [4] where the operating costs associated with the preparation and movement of freight trains were determined according to the activities performed during the transport process. Through applying this model [4], a study of the operating costs of freight trains with a constant wagon composition has been conducted in the paper. The study has been carried out taking into account the main transportation parameters affecting the value of the operating costs for the preparation and movement of a freight train. The results obtained in the study are presented in an innovative graphical manner through a surface model reflecting the nature of change of costs in depends to the gross mass of trains and the length of the train route.

In systems analysis, surface modelling is a technique for mapping a system's functional behaviour based on parameter values and their variability. The surface model in the study is considered as a method of analysing system behaviour - the change in operating costs of conventional freight trains. In this case freight trains are considered as a part of the railway transport system that consists three main components – railway infrastructure, rolling stock and railway operations. Mathematical models for describe behaviour of the system have been used that focus on the logical and process relationships [4, 6, 7, 8].

II. Methodology of Research

The operating costs directly related to the railway transport of goods by a freight train include all costs for: preparation of the train for movement along the route; the transportation process between the initial train-forming railway station and the final-decomposing for the train railway station; carrying out the activities to complete of transportation and check the train and the load at the final railway station and the isolated movement of locomotives before and after servicing the train. For freight block trains running on with a constant wagon composition along the route between the initial and final railway station, without

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performing of local activities and shunting with the wagons, the value of direct operating costs for the train includes [4]:

- charges from the minimum access package for use of the National railway infrastructure of Bulgaria - infrastructure passing charge per gross ton kilometre, infrastructure passing charge per a train kilometre, infrastructure charge for use of the traction electrical equipment and price for distribution of traction electricity [9];
- the costs for use of the locomotives (per a kilometre) serving the train on the route;
- the costs for use of the locomotives (per an hour) serving the train on the route;
- the costs associated with isolated movement of the locomotives before and after servicing the train (per kilometre and an hour);
- the costs associated with consumption of traction energy from the electric locomotives in service the train and when they are moved as independent (isolate) locomotives;
- the costs for fuel for movement of diesel engine locomotives;
- the expenses for paying the labour of the locomotive drivers of the mainline locomotives service the train along its route and during their independent movement;
- the costs of activities carried out to prepare the train at the initial railway station, related to shunting and coupling locomotives to the wagons and performing a technical and commercial inspection and brake test of the train and
- the costs of activities performed at the final railway station - uncoupling the locomotives and performing a technical and commercial inspection of the wagons and cargo.

The total value of direct operating costs for the preparation of the train in the initial railway station, movement of the train along the route and perform activities in the final railway station for a freight single-group block train that is serviced by one or more electric locomotives, can be determined through [4]:

$$OC = IC + LC + EC + TDC + PT, \ EUR \qquad (1)$$

where: OC is the total value of the direct operating costs for the train, EUR; IC - the total value of the infrastructure charges for use and access to the National railway infrastructure of Republic of Bulgaria, EUR; LC - the total costs for use of locomotives per a passed kilometre and an hour, EUR; EC - the total costs of traction electricity to power of electric locomotives service the train, EUR; TDC - the total costs for service the train locomotives by locomotive drivers, EUR; PT - the total costs for preparing of train in the initial railway station and carrying out of final activities - technical and commercial inspection at the final railway station, EUR.

The total value of the infrastructure charges for use and access to the National railway infrastructure of Republic of Bulgaria [4, 9] from the minimum access package of the State Enterprise “National Railway Infrastructure Company” (IC, EUR) is calculated through:

$$IC = IC_{PC} + IC_{TEE} + IC_{DTE}.K_{DTE}, \ EUR \qquad (2)$$

where: IC_{PC} is the value of the railway infrastructure passing charge, EUR; IC_{TEE} - the value of the charge for use of the traction electrical equipment, EUR; IC_{DTE} - the value of the charge for distribution of traction electricity, EUR; K_{DTE} - the correction coefficient, coeff.

The value of the three components of IC is calculated respectively through:

$$\begin{aligned} &IC_{PC} = \\ &= \left[\left(Q_T + Q_L + Q_{AL} \right).C_{TKM} + C_{KM} \right].L_T + \\ &+ \left(Q_L.L_L + Q_{AL}.L_{AL} \right).C_{TKM} + \\ &+ \left(L_L + L_{AL} \right).C_{KM}, \ EUR \end{aligned} \qquad (3)$$

$$\begin{aligned} &IC_{TEE} = \\ &= \begin{bmatrix} \left(Q_T + Q_L + Q_{AL} \right).L_T.R_T + \\ +Q_L.L_L.R_L + \\ +Q_{AL}.L_{AL}.R_{AL} + \\ +\dfrac{T_{SL}.N_L.R_{SL}}{30} \end{bmatrix}.\frac{C_{TEE}}{1000}, \ EUR \end{aligned} \qquad (4)$$

$$\begin{aligned} &IC_{DTE} = \\ &= \begin{bmatrix} \left(Q_T + Q_L + Q_{AL} \right).L_T.R_T + \\ +Q_L.L_L.R_L + \\ +Q_{AL}.L_{AL}.R_{AL} + \\ +\dfrac{T_{SL}.N_L.R_{SL}}{30} \end{bmatrix}.\frac{C_{DTE}}{1000}, \ EUR \end{aligned} \qquad (5)$$

where: Q_T is the gross mass of the freight train according to the list of wagons, t; Q_L - the service gross mass of the main locomotive service the train along the route, t; Q_{AL} - the service gross mass of the auxiliary locomotive service the train along the route, t; L_T - the length of the train route, km; L_L - the distance travelled of the main train locomotive as an isolate locomotive, km; L_{AL} - the distance travelled of the auxiliary locomotive as an isolate locomotive, km; R_T - the average consumption rate for traction electricity of electric locomotives service the train, MWh/1,000 gross tkm; R_L - the average consumption rate for traction electricity of the main train locomotive during its isolated movement, MWh/1,000 tkm; R_{AL} - the average consumption rate for traction electricity of the auxiliary locomotive during its isolated movement, MWh/1,000 tkm; C_{TKM} – the infrastructure passing charge per gross ton kilometre, EUR/gross tkm; C_{KM} – the infrastructure passing charge per a train-kilometre, EUR/train km; C_{TEE} – the infrastructure charge for use of the traction electrical equipment, EUR/MWh; C_{DTE} – the charge for distribution of traction electricity, EUR/MWh; T_{SL} - the average period for shunting activity for coupling or uncoupling a locomotive to the train, min; R_{SL} - the average consumption rate for the traction electricity of an electric locomotive for shunting activities per an hour, kWh/h; N_L - the number of locomotives service the train along the route, number.

The value of the correction coefficient (K_{DTE}, coeff.) takes into account the increase in the cost of the charge for distribution of traction electricity from fees to Electricity

System Operator and reactive power when a train is running with electric traction.

The value of the cost for use of locomotives per a kilometre and per an hour (LC, EUR) is determined through:

$$LC = T_L.C_{LH} + T_{AL}.C_{ALH} + \\ +(L_T + L_L).C_{LKM} + L_{TAL}.C_{ALKM}, EUR \quad (6)$$

where: T_L is the period for service the train along its route by the train locomotive and for its isolate movement before and after service the train, h; T_{AL} - the period for service the train along its route by the auxiliary locomotive and for its isolate movement before and after service the train, h; C_{LH} - the hourly cost rate for use of a main locomotive, EUR/h; C_{ALH} - the hourly cost rate for use of an auxiliary locomotive, EUR/h; C_{LKM} - the kilometric cost rate for use a main train locomotive, EUR/km; C_{ALKM} - the kilometric cost rate for use an auxiliary locomotive, EUR/km; L_{TAL} - the total distance travelled by the auxiliary locomotive during its isolated movement and when service the train, km.

When the train is serviced by a main and an auxiliary locomotive, the value of L_{TAL} is determined through:

$$L_{TAL} = L_T + L_{AL}, km \qquad (for\ N_L = 2) \quad (7)$$

The total cost of traction electricity to power of electric locomotives serviced the train (EC, EUR) is determined through:

$$EC = \\ = \begin{bmatrix} (Q_T + Q_L + Q_{AL}).L_T.R_T + \\ +Q_L.L_L.R_L + \\ +Q_{AL}.L_{AL}.R_{AL} + \\ +\dfrac{T_{SL}.N_L.R_{SL}}{30} \end{bmatrix} . \frac{P_E}{1000}, EUR \quad (8)$$

where: P_E is the price of electricity used for traction needs, EUR/MWh; T_{SL} - the average period for a shunting to couple or uncouple a locomotive from the train, min.

The total cost for service the train locomotives by locomotive drivers (TDC, EUR) is determined through:

$$TDC = T_{TDL}.C_{TDH} + T_{ATDL}.C_{ATDH} + \\ +(L_T + L_L).C_{TDKM} + \\ +L_{TAL}.C_{ATDKM}, EUR \quad (9)$$

where: T_{TDL} is the duration of service of the main locomotive by the locomotive drivers, including during its isolate movement, h; C_{TDH} - the hourly cost rate for paying the labour of the locomotive drivers service the main locomotive, EUR/h; T_{ATDL} - the duration of service of the auxiliary locomotive by the locomotive drivers, including during its isolate movement, h; C_{ATDH} - the hourly cost rate for paying the labour of the locomotive drivers service the auxiliary locomotive, EUR/h; C_{TDKM} - the kilometric cost rate for paying the labour of the locomotive drivers service the main locomotive, EUR/km; C_{ATDKM} - the kilometric cost rate for paying the labour of the locomotive drivers service the auxiliary locomotive, EUR/km.

The total cost for preparing the train in the initial railway station and carrying out of technical and commercial inspection of the wagons and cargo at the final railway station (PT, EUR) is determined through:

$$PT = \\ = \left(T_{TR}.C_{TR} + T_{CR}.C_{CR} + \frac{T_{BR}.C_{BR}}{2} \right) . \frac{N_W}{30} + \\ + \frac{T_{SL}.N_L.C_{TR}}{30}, EUR \quad (10)$$

where: T_{TR} is the average normative duration of the period for carrying out a technical inspection per one wagon at the initial and final railway stations, min; T_{CR} - the average normative duration of the period for carrying out a commercial inspection per one wagon at the initial and final railway stations, min; T_{BR} - the average normative duration of the period for carrying out a brake check per a wagon for the train composition at the initial railway station, min; N_W - the number of wagons in the train composition, number; C_{TR} - the hourly cost rate for paying the labour of employees performing technical inspection of train composition, EUR/h; C_{CR} - the hourly cost rate for paying the labour of employees performing commercial inspection of train composition, EUR/h; C_{BR} - the hourly cost rate for paying the labour of employees performing brake test of train composition, EUR/h.

To be developed a surface model, the relative values of operating costs to specific parameters will be determined. Similar parameters, specific for railway transport, are: the transportation work performed by the train; travelled wagon kilometres and number of wagons in the train composition. The values of these relative parameters have been determined through equations (11÷13) respectively.

The relative value of operating costs according to the transportation work performed by the train (OC_{TKM}, EUR/gross tkm) is determined through:

$$OC_{TKM} = \frac{OC}{L_T.Q_T}, \frac{EUR}{gross\ tkm}. \quad (11)$$

The relative value of operating costs according to the travelled distance from the train (OC_{WKM}, EUR/wagon km) is determined through:

$$OC_{WKM} = \frac{OC}{L_T.N_W}, \frac{EUR}{wagon\ km}. \quad (12)$$

The relative value of operating costs according to the number of wagons transported by the train (OC_W, EUR/wagon) is determined through:

$$OC_W = \frac{OC}{N_W}, \frac{EUR}{wagon}. \quad (13)$$

The values of L_T and Q_T is varied at the intervals:

$$L_T = L_{MIN} \div L_{MAX}, km, \quad (14)$$

$$Q_T = Q_{MIN} \div Q_{MAX}, t. \tag{15}$$

where: L_{MIN} and L_{MAX} are respectively the lower and upper limits of the studied interval for length of the train route, km; Q_{MIN} and Q_{MAX} - respectively the lower and upper limits of the interval for change the gross train mass studied in the paper, t.

III. Results and discussion

A study of the variation of value of direct operating costs for freight block trains that transport customer wagons no additional shunting and local work with wagons has been conducted in the paper. The wagons are submitted into a group on the tracks in the initial and final railway station and no additional local or shunting work is performed with them. One or more locomotives are attached to the group of wagons to be formed the train composition in the initial railway station. Locomotives are uncoupled from the wagons at the final railway station or when is performed a change of locomotives at intermediate railway stations along the train's route. In the study is assumed that the trains on the route are serviced by one or more electric locomotives with a service gross mass of 126 t (for example: locomotives class 46, Manufacturer: Electroputere - Craiova, Romania).

Conventional freight block trains with gross mass varying in the interval between Q_{MIN}=400 t and Q_{MAX}=2,200 t have been studied through conducted numerical experiment in the paper. The length of train route is varied between L_{MIN}=100 km and L_{MAX}=500 km in the study. It is accepted in the study the trains with a constant number of wagons in the composition have been moving along the route between the initial and final railway station with an average section speed equal of 53 km/h. In the study has been assumed that trains with a gross mass over 1,600 tons are served through two electric locomotives along the route. At the initial railway station, shunting activities are carried out to attach one or more locomotives and prepare the train for departure - commercial and technical inspection and brake test. A commercial and technical inspection of the train and shunting activities for uncoupling the locomotives have carried out at the final railway station. The average period for performing a technical or commercial inspection per one wagon is assumed to be 3.5 minutes in the study. The average period for performing a full brake test per a train composition is assumed to be 3.5 min per each wagon. The total period for inspection is varied in depends of the number of wagons in the train composition. The average duration of the period for coupling or uncoupling of a locomotive into the group of wagons is assumed to be 20 min for each activity. The train compositions in the study consist of up to 20 freight wagons for trains with a gross mass of up to 1,600 t, up to 24 wagons for trains with a gross mass between 1,600 and 2,000 t and up to 26 wagons for trains with a gross mass between 2,000 and 2,200 t.

It is assumed in the study the trains are serviced by electric locomotives with a traction electricity consumption rate determined according to data described in [5] for hilly terrain, varying at the interval R_T=0.0144÷0.0338 MWh/1,000 tkm in depends of the gross mass of train. The lower values of R_T are applied to heavier trains, and higher values to trains with lower gross mass. During the isolated movement of locomotives, before and after service the trains, is assumed an average consumption rate for traction electricity R_L=0.040 MWh/1,000 tkm.

It is assumed the price of electricity for traction needs in the calculations 147.00 EUR/MWh. The value of the charges for use the railway infrastructure of State Enterprise "National Railway Infrastructure Company" [9] have been used in the study is indicated in Table I. The value of the charges described in [9] is indicated in Bulgarian Nacional currency (BGN). The value of the charges has been determined at a rate 1 EUR = 1.95583 BGN.

TABLE I
Infrastructure Charges

Symbol	Dimension	Value
C_{TKM}	EUR/gross tkm	0.00104
C_{KM}	EUR/train km	0.30974
C_{TEE}	EUR/MWh	26.31
C_{DTE}	EUR/MWh	76.43

Source: [9]

The calculations have been performed through use of average cost rates for labour and use of locomotives. The values of rates are varied within intervals specified in Tables II and III. The data is according to a market survey conducted among licensed railway undertakings carrying out freight transport by rail in the Republic of Bulgaria. In table II are shown intervals of variation the labour rates for personnel directly involved in the transportation. In table III are shown intervals of rates for use of electrical locomotives.

TABLE II
Labor Rates

Symbol	Dimension	Value between
C_{TDH}	EUR/h	65.00 ÷ 85.00
C_{ATDH}	EUR/h	55.00 ÷ 85.00
C_{TDKM}	EUR/km	0.35 ÷ 0.65
C_{ATDKM}	EUR/km	0.35 ÷ 0.65
C_{TR}	EUR/h	20.00 ÷ 30.00
C_{CR}	EUR/h	18.00 ÷ 26.00
C_{BR}	EUR/h	20.00 ÷ 30.00

Source: Own research of the author

TABLE III
Rates for use of a Locomotive

Symbol	Dimension	Value between
C_{LH}	EUR/h	20.00 ÷ 42.00
C_{ALH}	EUR/h	20.00 ÷ 42.00
C_{LKM}	EUR/km	1.50 ÷ 4.50
C_{ALKM}	EUR/km	1.50 ÷ 4.50

Source: Own research of the author

The calculations in the study have been performed with the values of parameters as follows: K_{DTE}=1.14, coeff.; C_{LH}=30.00 EUR/h; C_{ALH}=30.00 EUR/h; C_{LKM}=3.00 EUR/km; C_{ALKM}=3.00 EUR/km; C_{TDH}=75.00 EUR/h; C_{ATDH}=75.00 EUR/h; C_{TDKM}=0.50 EUR/km; C_{ATDKM}=0.50

EUR/km; C_{TR}=25.00 EUR/h; C_{CR}=22.00 EUR/h; C_{BR}=25.00 EUR/h; L_L=20.00 km; L_{AL}=20.00 km.

The value of variation of direct operating costs has been presented on a surface graphic model through use three measures - the gross transport work performed during train movement, the wagon kilometres travelled by one train and the number of wagons included in the train. The results for the various measures are determined for freight trains with gross mass varying in the interval $Q_{MIN}÷Q_{MAX}$ and for a train route length between $L_{MIN}÷L_{MAX}$. The minimum and maximum values of the train`s route length and its gross mass define the polygon of the surface model. The results for variation of the value of OC_{TKM}, OC_{WKM} and OC_W according to the route length and the gross train mass are presented in 3-dimensional view (3-D) graphically in Fig. 1, 3 and 5. The same results are presented in 2-dimensional (2-D) view in Fig. 2, 4 and 6.

The results in Fig. 1÷6 are presented in zones classified through intervals with a step of 5.00 EUR/1,000 gross tkm, 0.20 EUR/wagon km and 100.00 EUR/wagon respectively for the different metrics.

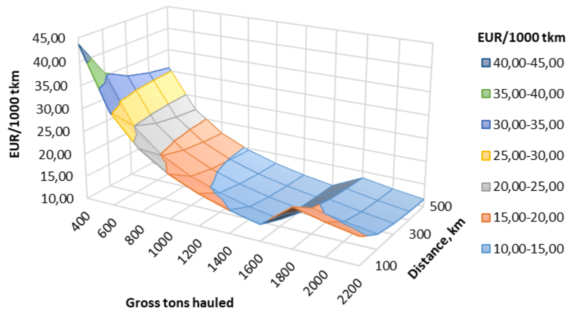

Fig. 1. 3-D view of variation of the operating costs per 1,000 gross tkm.

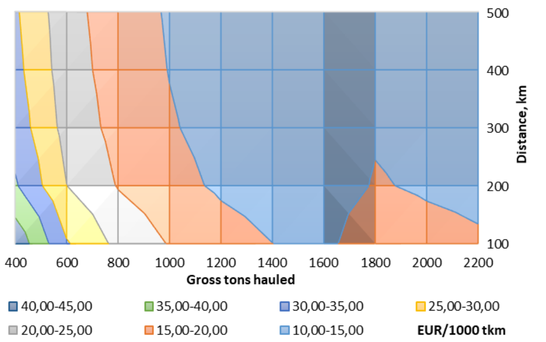

Fig. 2. Zones of variation of the operating costs per 1,000 gross tkm.

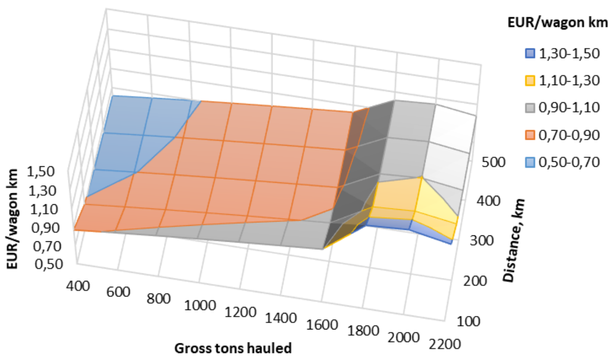

Fig. 3. 3-D view of variation of the operating costs per wagon km.

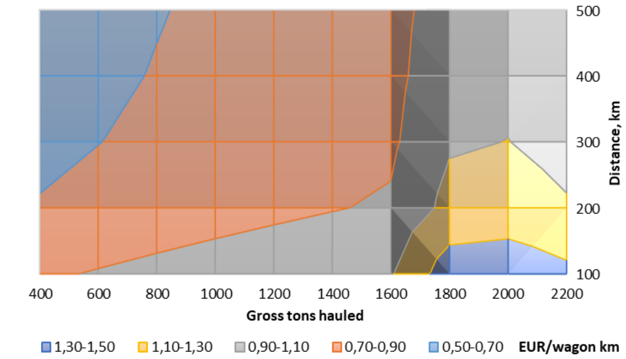

Fig. 4. Zones of variation of the operating costs per wagon km.

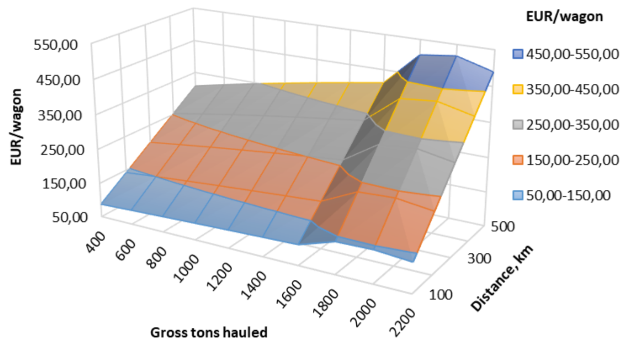

Fig. 5. 3-D view of variation of the operating costs per transported wagon.

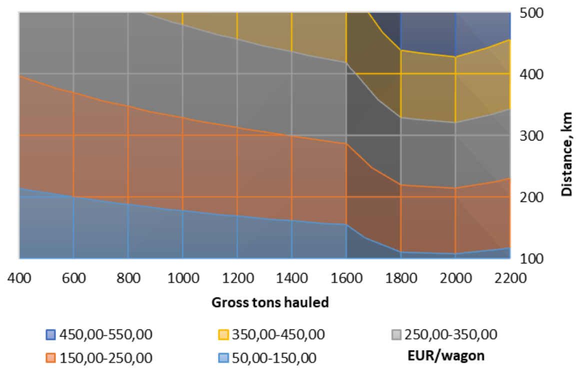

Fig. 6. Zones of variation of the operating costs per transported wagon.

The results have been presented graphically through use two basic for the organization of railway transport parameters – the length of the route and the gross mass of the freight trains. Of the graphic surface models could be seen the values of operating cost are grouped into separate zones. The nature of the change and distribution of the zones in the studied area varies in depends on type of used measure - transportation work, wagon kilometres or number of wagons. The results show that for the conditions of the study the operating costs are:

- between 10.31 EUR/1,000 gross tkm and 43.66 EUR/1,000 gross tkm for transport work performed (Fig. 1 and 2). The minimum value is observed for a train with a gross mass Q_T=1,600 t when it is transported over a distance L_T=500 km. The maximum value is for a train with a gross mass Q_T=400 t that is transported over a distance L_T=100 km;
- between 0.61 EUR/wagon km and 1.43 EUR/wagon km for metric performed as a wagon-kilometre (Fig. 3 and 4). The minimum value is observed for a train with a gross mass

Q_T=400 t when it is transported over a distance L_T=500 km. The maximum value is for a train with a gross mass Q_T=2,000 t that is transported over a distance L_T=100 km;

- between 87.32 EUR/wagon and 518.52 EUR/wagon for the number transported wagons by train (Fig. 5 and 6). The minimum value is observed for a train with a gross mass Q_T=400 t when it is transported over a distance L_T=100 km. The maximum value is for a train with a gross mass Q_T=2,000 t that is transported over a distance L_T=500 km.

The results obtained in the study show that in depends on the applied metric, the relative operational costs and the nature of its variation are different. An increase in the value of the relative costs has been observed in all three metrics for trains that are served by more than one locomotive.

IV. CONCLUSION

A surface model illustrating the variation of operating costs for freight block trains moving with a constant number of wagons in composition between an initial and a final railway station has been proposed in the paper. The model presents results for the variation in the value of relative operating costs for freight trains through an innovative graphical surface manner. The costs are determined through applying a process-based approach that allows to be determine the value of all technological activities performed in the transport process and the value for use of the technical elements and equipment (locomotives, railway infrastructure, etc.). In determine the value of operating costs, the following factors have been taken into account: infrastructure charges; costs for kilometric and hourly use of locomotives; costs for consumption of traction energy of locomotives; costs for payment of labour for locomotive drivers and costs for preparatory and final activities with the train and wagons – technical and commercial inspection, etc.

The results obtained in the study and the graphical surface model of variation of operational costs can find potential applications in the field of: tariff formation and pricing strategies for railway undertakings; cost-benefit analysis of rail projects and evaluating the economic viability of investments; pricing strategies for rail infrastructure access and determining appropriate charges for use of railway infrastructure; optimizing train operations and identifying the most efficient train configurations and operating practices; assessing the impact of policy changes and the effects of regulations on freight transportation costs and modal choices, etc. The surface model and results obtained in the study can provide valuable insights into the complex dynamics of freight train operating costs and support informed decision-making in the railway industry.

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