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A STUDY ON THE OPTIONS OF MEANS FOR RAILWAY PASSENGER TRANSPORTATION

Summary. A mathematical model to select the best rolling stocks of trains is introduced. The parameters of income and cost of the passenger transportation by railways depending on the technical characteristic of used vehicles are thoroughly evaluated. The options how to reduce the cost calculated by a model in one of the specific routes of Lithuanian Railways are given and practical decisions are argumentatively given.

ИССЛЕДОВАНИЕ ПОДБОРА ПОДВИЖНОГО СОСТАВА ДЛЯ ПЕРЕВОЗКИ ЖЕЛЕЗНОДОРОЖНЫХ ПАССАЖИРСКИХ ПЕРЕВОЗОК

Аннотация. Представлена математическая модель для лучшего подбора подвижного железнодорожного состава для пассажирских перевозок. В модели всесторонно оценены параметры доходов и расходов относителъно техническим параметрам подвижного состава при первозке пассажиров. С помощью модели расчитанны варианты уменшения расходов в одном из характерных маршрутов Литовских железных дорог а так же представлены аргументированы практические решения.

1. INTRODUCTION

The great demand of quality transport service is stimulated by the quick social economic development of the members of the European Union, technology development, the tendencies of the world trade globalization. The passenger transportation is an important branch of a country’s transport system, which ensures the functioning of cities, regions, of the whole country’s economy and international relations of inhabitants. The main normative acts of the European Union orient towards the forming of a modern, flexible and reliable transport system.

Nowadays, the existing system of a transport service based on the transportation by roads cannot satisfy the increasingly growing needs of consumers’ transportation [10]. The railway transport is safer, much more environment-friendly, more efficient than car transport; however, the railway transportation requires a lot of investments in the railway infrastructure. That is the reason why the railway transportation firstly gets financial support in Europe, gets credits on preferential terms, the cost on detrimental public activity is covered, because more attention is paid on the passenger transportation by railways and is more oriented towards the residents who have lower income. This activity is a non-profit one. These are problems in a lot of countries [1, 2, 9]. That is why rational ways how to increase income and reduce cost should be found by developing the technologies of passenger transportation – to use rational vehicles for transportation, improve the quality of provided services, investigate and to academically determine the most rational options of vehicle choice for specific passengers' routes and in this way to reduce experienced losses of this activity.

While looking for the rational passenger transportation methods, the worldwide scientific tendencies were reviewed. The paper [6] proposed an algorithm in which the rail network is examined in relation to passenger movement limitations. The results shows that the proposed access is an effective tool to optimize network usage issue. However, such an algorithm is not suitable for small country network, since the passenger movement is limited.

The paper [12] examine special passenger service route-setting conditions, long-distance passenger transportation methods and suitable route distances. The paper [13] analyse the structure of passenger transportation its peculiarities necessary to ensure integrated transportation system.

The above analysis prove that the main emphasis is on long-distance large passenger flows examination. However, scientific technical literature lacks complex – technical, technological organizational, economic problems of the passenger transportation by railways especially in such cases as in Lithuania's economy where passenger flows by many local railway routes are not big and transportation distances are not long (up to 400 km).

After evaluating the dynamics of passenger number in districts, distances, the main objective would be to select the most rational vehicles and their rolling stocks for every route; in this way cost would be minimized. In order to reach this goal, it is proposed:

1. to determine the income and cost components of passenger transportation by railways and to identify their dependency on technical vehicle parameters;
2. to form a selection model of rational vehicles of passenger transportation by railways;
3. to select vehicles for concrete routes referring to the example of passenger transportation by Lithuanian railways by applying the extreme search method of equation with a lot of variables and constraints to a model.

2. THE SELECTION OF RATIONAL PASSENGER ROLLING-STOCK

Any used technique both in railways and in an entire railway service will be used effectively only when it is maximally loaded. Considering passenger transportation by railways, it is equal to a bigger filling of carriages with passengers. For example, in Lithuanian railways, there are districts in which passenger loading depends on the day time, the date or the season. In different directions and in separate districts, the number of passengers varies a lot: it depends not only on the location of passenger attraction centers, but also on the day time or the season [4, 7]. Presently applied practice of a selection for the length of train unit and traction equipment is not always rational, since, concerning already introduced reasons, the seats filling in some trains sometimes makes up 10 percent or less. These parameters are usually changed for summer or winter periods. Railways network usually uses electric and thermal traction: diesel trains, carriages hauled by a separate diesel locomotive, and rail cars. Both ecologically and economically, it would be the best to use electric traction but only the main districts are usually electrified. Electrification of all districts requires huge investments, and, in order to service transit trains, it is necessary that the railway routes of neighboring countries be electrified, too. Therefore, it is necessary to select not only rational train units but also as cheap traction as possibilities allows. Having analyzed the latest six years' data [5] of rolling stock, exploited in different routes by Lithuanian railways, average expenditure, falling to one kilometer of one carriage and in different tractions, is calculated. Comparative costs according to tractions are shown in Table 1.

Table 1

Comparison between different traction of one carriage per kilometer costs and coefficient increase in expenses

Eil. Nr.	Type of traction	Expenditure, EUR	Coefficient
1	Electric traction	1,62	1
2	Railcar	1,72	1,06
3	Diesel traction	1,74	1,08
4	Separate locomotive	2,33	1,44

The table data shows that the cheapest traction of one carriage is the electric traction. Rail cars, diesel trains, passenger diesel locomotives (a separate locomotive) are attributed to thermal traction. Under all technical economical indicators and ecological parameters, the electric traction is the most appropriate. Considering the electric traction as a basis, i.e. as a unit, the usage of the other tractions might be expressed as a coefficient increase in expenses (Table 1). Provided data show the economical effectiveness of several of the used tractions. For example, using the thermal traction for passenger train units, expenditure increases 1,44 time if it is compared to the electric traction. According to the theory of electric and thermal engines, it is possible to state that 1kWh performs approximately 1,6 time more useful work using the electric traction rather than the thermal one. Therefore, the electric traction is always superior to the thermal traction both economically and ecologically. So, the content of Table 1 defines the traction sequence pursuant to an economical criterion.

Further, depending on the number of passengers and having chosen the most beneficial traction, we will try to determine the kilometer expenditure for one train when the length of train units is optimized.

Having investigated the dynamics of the passengers using local routes of Lithuanian railways [1], it is determined that in most cases the number does not overrun 80 passengers, i.e. not more than one carriage contains. From this aspect, a railcar is the most attractive vehicle.

Since not all of districts are electrified, presently there are no possibilities to select the least damaging (electric) traction for all routes; therefore, seeking to reduce losses in passenger transportation, it is purposeful, considering technical possibilities and streams of passengers, to analyze possible combinations of traction vehicles and the number of carriages in separate routes. In order to reach this aim, a mathematical model has to be formed by applying the extreme search method of equation with constraints to this model. This would allow optimizing the whole of cost components [8, 14] and selecting the most rational combination of traction vehicles and number of carriages for a concrete route (considering the year or the daytime).

Passenger Flows. Since the revenue for transportation of passengers is collected from the sale of tickets, so it is determined by the total number of railway transport passengers. Accordingly, the profit (loss) from activity is mainly determined by the small number of passengers. In addition, separate districts are loaded unequally and unevenly [3, 11]. Therefore, apparently there is a need to change the number of carriages in the same route. The research was performed on dynamics alteration of the number of passengers in routes [5] on purpose to know the current state of districts.

Mathematical Model. The model will calculate profit (loss) Δ for one train kilometer. A simplified formula for the model is the following:

$$\Delta = P - I \text{, where } P = \sum_{i=1}^{m} P_i \text{, } I = \sum_{j=1}^{n} I_j \qquad (1)$$

where:
Δ represents the difference between incomes and expenditures in EUR/train km); P – total incomes for EUR/train km; I – total expenditures, EUR/train km; P_i – i incomes received from passenger ticket sales, compensations for the discounts provided and subsidies for non-received incomes; I_j – j passenger transportation expenditures including the fees for the use of the public railway infrastructure, deprecation of the rolling-stock, staff salaries, costs of materials, fuel, repair, and other costs; m – the number of incomes (in our case m = 3); n – the number of expenditures (in our case n = 7).

Having evaluated the costs of passenger transportation, the number of passengers and, based on the normative documentation, which defines the amounts of subsidies and compensations, the components of the model would be:

$$P = \{k_{kp} \times P_1 \times K(x) + k_{dot}(V \times L_{reis} \times I_m \times \left(1+\frac{r}{100}\right) - k_{kp} \times P_1 \times K(x) - I_k) + k_{komp} \times I_k\} \times \frac{1}{L_{reis}} \quad (2)$$

where:
k_{kp} is the proportionality coefficient of the passengers number (1; 1,05; 1,1; 1,15 ...); P_1 is the average ticket price in EUR, where $P_1 = \sum_{k=1}^{n_k} l_k b_{km}$ (with l_k – is the distance between stations, km; b_{km} – 1 travel cost per km, in EUR travel km cost); $K(x)$ – change of the number of passengers in the section based on the distance between stations, pcs.; k_{komp} – compensation coefficient; V – number of railway carriages in the train, in pcs.; L_{reis} – distance, km; I_m – actual costs for 1 railway carriage kilometer incurred when carrying out the obligations of public services, in EUR; r – profitability, %; I_k – compensation of expenditures for the train in relation to discounts offered to the passengers, Lt; k_{dot} – coefficient of subsidies.

The calculations of the model are provided for electricity traction, whereas for other tractions, such calculations are made applying the traction coefficient which is a ratio of electric traction and other selected traction. Having evaluated all above-mentioned components, the model for the components of expenditures would look like that:

$$I = \left[\left(\left(\frac{E_{kel}}{R_{kel}} + \frac{E_{kt}}{R}\right) \times \frac{R_1}{R_{kel}} + \left(\frac{I_{kel}}{A_{kel}} + \frac{I_{kt}}{A}\right) \times \frac{A_{kel}}{R_{kel}} + \frac{I_{kont}}{R_{kel}}\right) + \left(D_{už} + M + D_t + N + R_k + K_{iš}\right) \times f\left(Z_{vag}\right)\right] \times a \quad (3)$$

where:
E_{kel} – train traffic organization and management costs, incurred in relation to the services of railway companies carrying passengers and luggage, in EUR; E_{kt} – train traffic organization and management costs, incurred both in relation to the supervision of railway companies carrying passengers and luggage, as well as supervision of railway companies carrying freights; R_{kel} – mileage of the passenger trains (train/km); R – mileage of all trains (train/km); R_1 – reserved mileage of trains (train/km), I_{kel} – public expenditures for railway infrastructure, incurred in relation to the services of railway companies carrying passengers and luggage, in EUR; I_{kt} – public expenditures for railway infrastructure, incurred both due to the supervision of railway companies carrying passengers and luggage, as well as supervision of railway companies carrying freights, in EUR; A_{kel} – the operation scope of passenger trains, thou. km, gross; A – the operation range of all trains (thou. km gross); I_{kont} – expenditures for

contact net, in EUR; $D_{už}$ – salaries and wages, EUR/carr.km; M – expenditures for materials, in EUR/carr.km; D_t – expenditures for fuel, lubricants, in EUR/carr.km; N – deprecation of rolling-stock, in EUR/carr.km; R_k – repair expenditures, in EUR/carr.km; $K_{iš}$ – other expenditures, in EUR/carr.km; a – traction coefficient, where $a = \sqrt[T]{\prod_{t=1}^{T} \frac{a_{dt}}{a_{et}}}$ (and where a_{dt} – diesel/locomotive traction expenditures for t year, in EUR/train km; a_{et} – electric traction expenditures for t year, in EUR/train km; T – number of years; $f(Z_{vag})$ – relative number of carriages.

The formation of train costs depend on the number of carriages. In our case, it is very important because the model will choose the minimum number of carriages for a particular section of passenger service. It is therefore necessary to determine how costs change depending on the number of carriages selected. Such dependence describes the relative number of carriages whose value is determined by the function shown in Figure 1.

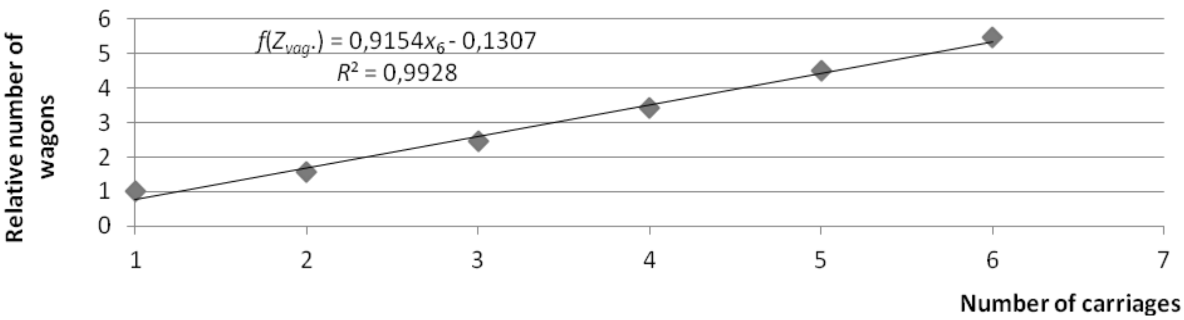

Fig. 1. Relative number of carriages
Рис. 1. Относительное количество вагонов

This correlation, indicating an increase in cost depending on the number of carriages in the set, is suitable for all traction. It increases according to a linear dependence.

Search for optimal solutions of the model will be applied in a mathematical optimization method. As the target function that is introduced in the paper the purpose thereof is to minimize the values of the variables (costs), this method shall be applied to the search of solutions. The subroutine “fmincon” of the MATLAB (*Matrix Laboratory*) matrix designed for the search of the lowest values when solving nonlinear equations with a number of variables and limitations (appendix) was chosen for this purpose.

Practical Application of Mathematical Model. In practice, we will check the effectiveness of the model after examining one of the typical Lithuanian railways’ routes, i.e. Vilnius - Klaipeda - Vilnius. As already mentioned, in this route it is also an uneven number of passengers depending on the day or season. Therefore, as an example we will take the route Klaipeda - Vilnius with the average intensity of passenger flow, for which by the prepared model, the most rational combination of rolling-stock will be chosen.

The Trip Klaipėda-Vilnius. The study of the alteration dynamics of this trip has shown that at the beginning of this trip the number of passengers is slightly over 100, and from midway (Radviliškis) it decreases almost in half. The graphical interpretation of passenger alteration according to stations is shown in Figure 2.

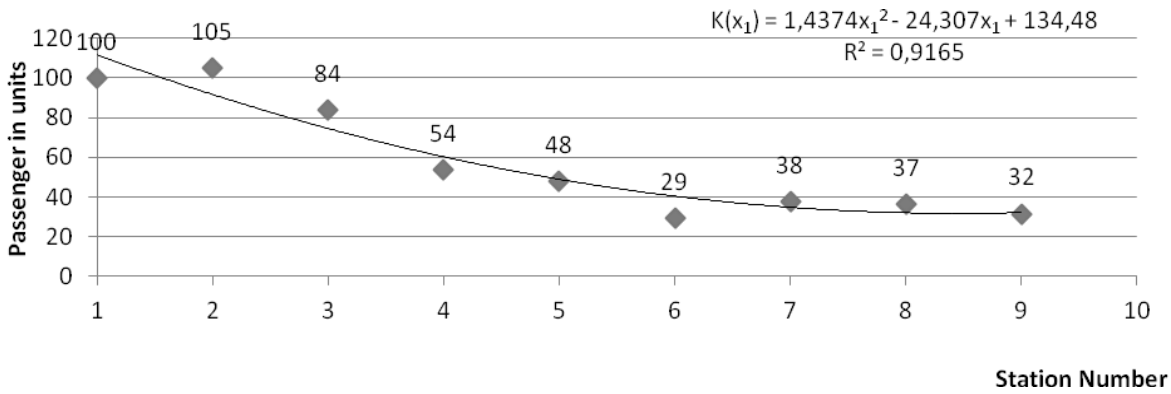

Fig. 2. Passenger alteration at the route Klaipėda–Vilnius
Рис. 2. Изменение количества пассажиров маршруте Клайпеда - Вильнюс

Here on the axle of abscissa, the localization space in trip are suspended from 1 to 9 that would be more convenient to use them in mathematical model, determining the current number of passengers on the train (Figure 2, Table 2). These regression equations [5] of all local routes of Lithuanian Railways are concluded on the basis of statistics of the last six years. Equations, concluded to predict the number of passengers has a long-term value in the sense that if no significant changes in the routes occur, for example, no new centers of attraction, factories, cities and so on, the number of passengers will increase or decrease everywhere more or less evenly. To that end, coefficient k_p of the passenger alteration (proportionality) is predicted in the model.

It is noticeable from the provided documents that at the beginning of the route, the train unit must consist of not less than two carriages, and in the middle of the route it is considered appropriate to uncouple two carriages. In the Table 2, the total profit (loss) in the side tracks is provided, and it has been calculated by recently created model.

The examination of the data in Table 2 shows how it is possible to reduce the loss, selecting the traction and number of carriages. This route is particular by the fact that under the present situation it can be used thermal and electric tractions - from Klaipėda to Kaišiadorys - thermal, and from Kaišiadorys to Vilnius - electric, since only this district of this trip is electrified. The model shows these opportunities. The data show that the most useful would be to begin a trip with two rail cars to Šiauliai, to continue the trip with one railcar to Kaišiadorys, and from here to use the electric traction, i.e. to seat passengers to electric train Vilnius-Kaunas. In this case, the final loss of the trip would consist of only 52 EUR, using one railcar from Šiauliai to Vilnius, the losses would be similar using two rail cars throughout the district, the losses would increase up to 467 EUR, and from Šiauliai seated to a diesel train with one carriage, the losses would reach up to 126 EUR, a passenger carriage pulled by separate locomotive would cost 283 EUR. All other choices are much detrimental. For currently existing infrastructure and passenger fleet would be appropriate to use a combination of two rail cars, uncoupling one from Šiauliai station. In most cases (depending on the season), in this trip train units of three carriages run with separate locomotive and diesel traction. Losses arising from the exploitation of such trains are shown in Figure 3.

Table 2

Mid-station profit (loss), calculated on the basis of the drafted model, in EUR

Serial Nr.	Station	Electric traction, 1 carr.	Railcar	2 railcars	Diesel, 1 carr.	Diesel, 2 carr.	Locomotive, 1 carr.	Locomotive, 2 carr.	Diesel 3 carr.	Locomotive, 3 carr.
1	Klaipėda			0		0		0	0	0
2	Kretinga			1,02		-6,56		-22,68	-85,25	-120,93
3	Plungė			-17,91		-40,31		-87,82	-272,56	-377,98
4	Telšiai			-41,75		-73,80		-141,74	-406,12	-556,95
5	Šiauliai		-125,03	-125,03	-181,55	-181,55	-301,31	-301,31	-767,20	-1033,19
6	Radviliškis		-114,32	-153,53	-172,46	-217,00	-295,75	-351,30	-874,13	-1172,56
7	Kėdainiai		-90,03	-254,55	-153,55	-336,74	-288,15	-521,09	-1225,57	-1627,79
8	Jonava		-80,79	-306,00	-146,91	-398,87	-286,89	-605,84	-1398,49	-1850,99
9	Kaišiadorys	-72,10	-72,10	-356,04	-140,74	-459,26	-285,94	-688,12	-1566,09	-2067,25
10	Vilnius	-51,53	-51,72	-466,84	-125,99	-593,15	-282,83	-870,72	-1939,05	-2548,87

The data in Table 2 and Figure 3 suggests that if the rail car traction were used and one rail car was uncoupled in Šiauliai, the losses for the often-used diesel traction could be reduced up to 37 times and up to 49 times for thermal traction. If two rail cars were run without uncoupling in Šiauliai, the losses would be reduced by 4.2 and 5.5 times respectively. This example clearly illustrates the flexibility of using vehicles for passenger transportation, achieved through variation of train unit composition and traction when the number of vacant seats is reduced to minimum and the organizational possibilities (i.e. coupling and uncoupling of carriages in side tracks, passengers changing vehicles, use of standing-rooms, etc.) are taken by marking up adequate reasonable train units (by changing their composition and traction) inside the route.

Figure 3 presents graphical interpretation of all possible train units in Klaipeda-Vilnius trip according to the data in Table 3. It shows that all possible combinations of units and tractions are less detrimental than the ones that are currently exploited. Using this model, the selection of a combination of units and tractions, similar results were obtained in other routes and some of them received a positive result (profit instead of loss) [5].

The advantages of the model described in detail are the possibility to change the components of income and expenses, foreground the weakest points (i.e. what causes the most losses and how to reduce them), quickly and purposefully predict technical, organizational and economic parameters of the passenger fleet as well as to consistently apply the essential measures such as purchase of new technology, places of passenger carriage coupling and uncoupling, respective technical maintenance points, compatibility of timetables, etc. The data presented in Table 3 shows how the losses of the trip Klaipeda-Vilnius may be reduced by changing separate parameters, but without modifying the present situation, i.e. three train units driven by diesel traction.

The analysis of possible income increase when three carriages are driven by diesel traction under current conditions of the route has demonstrated that without increasing the number of passengers in a single trip (the main source of income) and changing the number of carriages, other components should vary in order to avoid losses in such trip ($\Delta = 0$), as it is shown in Table 3. For this purpose, it is necessary to increase the km per passenger rate by 28%, the compensations received by 70% and to reduce the charges for using the public infrastructure by 30%. Figure 4 presents the data where only the number of passengers and at the same time the amount of tickets sold are increased, whereas other data on expenses remains the same.

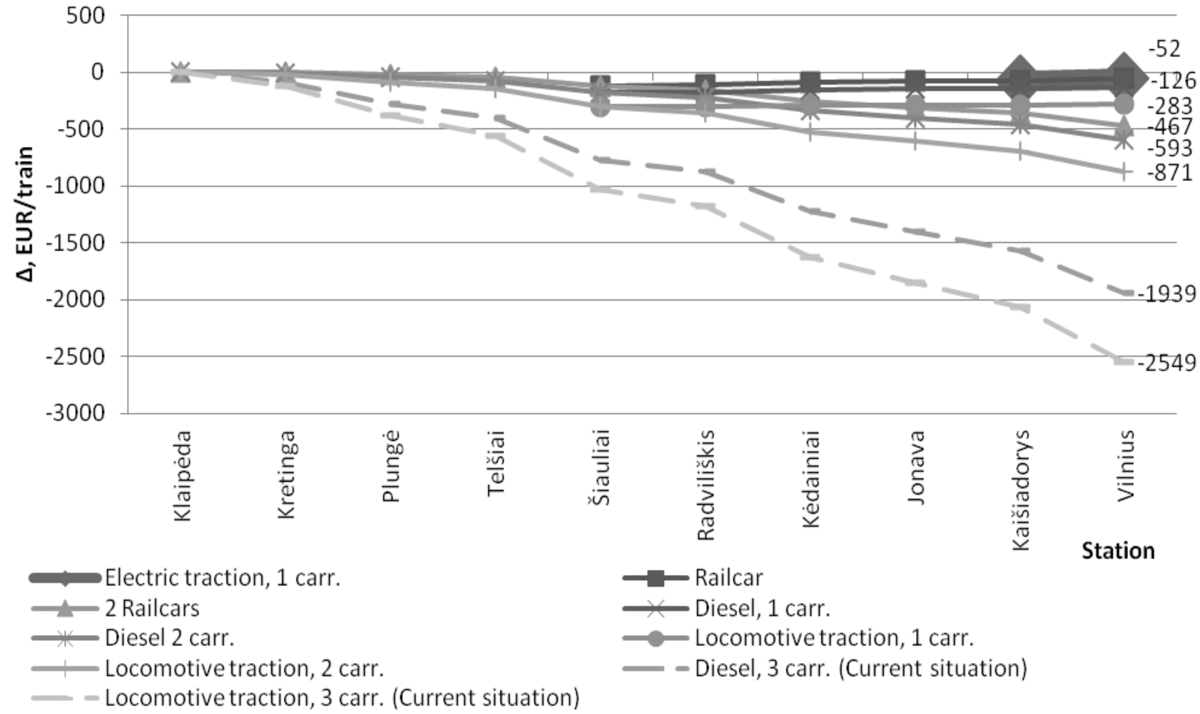

Fig. 3. Possible combinations and calculation of income (loss) for the route Klaipėda–Vilnius, EUR/train
Рис. 3. Возможные комбинации и расчет прибыли (потерь) для маршрута Клайпеда-Вильнюс, EUR / поезд

Table 3

Income increase (loss reduction) options analysis using 3 carriages combination with diesel traction at the route Klaipėda–Vilnius

Income figures	Change in percent
1 passenger km cost	+28
Subsidy, compensation	+70
The fee for the use of public railway infrastructure	–30
Δ	0

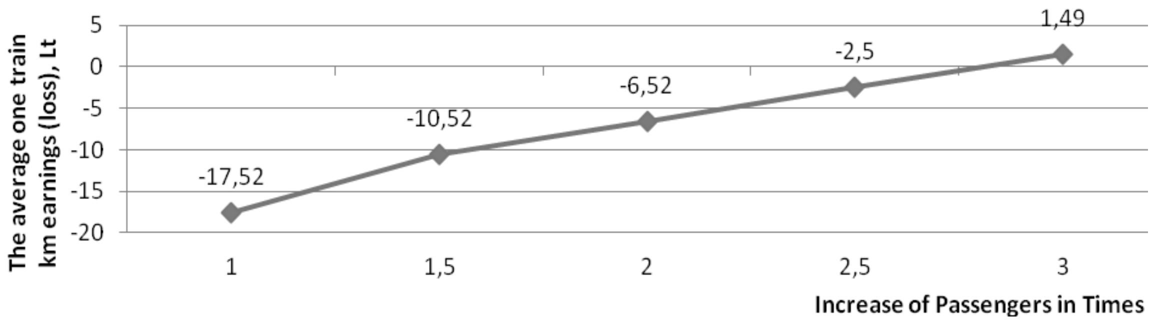

Fig. 4. Earnings (loss) per 1 train/km on the basis of passengers number at the route Klaipėda–Vilnius
Рис. 4. Прибыль (убыток) на 1 поезд / км на основе подсчета количества пассажиров на маршруте Клайпеда-Вильнюс

The figure clearly shows that the loss limits of the route Klaipeda-Vilnius would be exceeded only if the amount of tickets, or their price correspondingly, was trebled. In this way, such mathematical model allows for optimal variants in any trip by changing different income and expenses criteria and taking into consideration the present condition of the railway network.

3. CONCLUSIONS

1. An important reason, determining the loss emerging from the passenger transportation by railway, is that in most cases the passenger rolling-stock fleet is not optimally accommodated for passenger transportation by local routes when a flexible transformation of vehicles for passenger transportation is applied regarding the type of traction and variable number of passengers.
2. A mathematical model of income and expenses, which assesses all possible factors regarding income and expenses, was developed. On the basis of this model, a methodology for the selection of most appropriate train units for every route was prepared.
3. The marking-up of train units following the presented methodology enables reducing the losses significantly and even achieving a positive result in some cases.
4. For the renovation of the railway fleet under the conditions of Lithuania or separate EU countries (where the number of passengers is small and the distances are short), it is reasonable to purchase quickly and easily transformable vehicles for passenger transportation, for example modular trains.

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