RACK RAILWAY – A WAY TO THE TOP

Tikhonova, Tatyana Yu., *Russian University of Transport (MIIT), Moscow, Russia.*

ABSTRACT

Today there are more than 160 rack railways around the world. Constantly (in winter and summer) about 60 of them operate. Half of all permanent roads are in Switzerland, where, as is known, more than 61 % of the territory is occupied by mountains. A rack railway is a special type of railway with a steep incline, which has toothed wheel gearings, usually located between track rails. The author tells in some detail about the history of their creation, construction and operation. Currently, they are used as a means of moving along tourist routes in mountainous terrain or as urban passenger transport (for example, in Budapest, Zurich or Stuttgart). At the same time, the Swiss rack railways are profitable. In the territory of Russia, there are no rack railways. This despite the fact that in Russia there are also many mountain territories (≈ 33 %). And, as the author rightly points out, rack railways could promote their development and organization of activities that contribute to the development of the local community and the country as a whole.

Keywords: mountain relief, tourism, rack railway, history, gear wheel, toothed wheel gearing, turn mechanism, spring shock absorber, Blenkinsop system, Abt system, Marsh system, Riggenbach system, Strub system, Morgan system, Locher system, Lamell system.

Background. *From the very beginning, a man explored actively the surface of the earth and its resources, used various forms of relief for safety and protection, inhabited mountains and plains. Plains were easier to be developed. But mountain relief forms provided a natural shelter for a man. On the low peaks of the mountains castles and fortresses, churches and monasteries began to be built. Such a situation solved strategic problems of protection from attacks of enemies, and for monasteries also provided privacy. Later, in these places, cities developed.*

In the course of historical development, many states found themselves in territories that have exceptionally mountainous terrain. Agricultural lands were created on mountain slopes. With the development of medicine and resort business in mountainous areas, hospitals and sanatoriums began to be located.

Over time, many objects lost their political and military importance and became museums. In addition, the emergence of paid vacations, technical and social progress, increased amount of free time, fashion for travel, the development of means of transport stimulated mass tourism. Natural and cultural attractions became objects of tourist interest spontaneously, or with the competent policy of local authorities. Many of these facilities were located in places with a difficult terrain, difficult to access for people, or in places with a special ecology, where special modes of transport were required.

The issue of the availability of special attractions was solved by railway transport, but also not ordinary, but special. Ordinary railway trains cannot overcome steep climbs. For this purpose, special types of railway transport have been created – rack railways and funiculars. They became also human helpers underground.

Objective. *The objective of the author is to consider history of development and construction of rack railways in different countries, using different systems.*

Methods. *The author uses general scientific method, historical-retrospective method, comparative analysis, evaluation approach.*

Results. *Trains of rack railway have special gear wheels. Rack railways are spread all over the world and today are not only means of delivery of tourists, but also a popular technical attraction. There are such railways in Austria, Brazil, Germany, Greece, Switzerland and other countries. The locomotive of rack railway is connected by its gear wheel to the gear of the third rail and only therefore does not roll back. Funicular works differently. Three distinctive features of the funicular are: presence of guides (in particular the track), cable traction and necessarily reversible cyclic movement. That is, the funicular is a railway of cyclic action with cable traction for moving passengers and cargoes along a steep rise (descent)[1]. The role of funiculars in tourism has been studied in more detail by the author earlier [1].*

Rack railway is a railway with a steep gradient, with toothed wheel gearings, usually located between track rails. For the movement of trains, one or more gear wheels, large or small, that engage in a rack railway, are used. This system allows trains to run on those railways, where the slope reaches an average of more than 7–10 %, which is the maximum for trains working on friction between wheels and rails. Most rack railways run in mountainous terrain, although there are several transit railways and tram lines designed to overcome steep gradients in an urban environment. Such roads turned into tram lines include the Pöstlingberg railway in Linz (Austria).

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[1] Tarkhov, S. A., Myasnikov, A. G. Our funiculars. Moscow, Zheleznodorozhnoe delo publ., 2008, p. 11.

For hundreds of years, the Pöstlingberg railway has been combining means of delivering tourists from all over the world to the Pöstlingberg mountain and a way to travel along the scenic path. The railway was laid along the old pilgrim route to the church, which stands on top of the mountain Pöstlingberg. After the reconstruction, the railway was easily integrated into the public transport network «Linz AG Linien» and now reaches the Main Square. The width of the track was reduced from 1000 to 900 mm. Within 20 minutes the train passes the whole route of the Pöstlingberg railway, which is 4,14 km long, and the level of ascent is 255 meters. The line uses new comfortable low-floor cars, and for fans of an authentic atmosphere, excursions are offered in the reconstructed old cars. The rack railway provides accessibility to the Wallfahrtskirche (Pilgrim Church), a viewing platform with a magnificent view of Linz, the city zoo, and the Grottenbahn railway with its fairy world and the realm of gnomes.

There are several different types of rack rails. Today the Abt system is used on most rack railways. This decision was preceded by a long way of creating and testing various designs. The history of construction and use of rack railway as a means of ensuring the availability of places of tourist interest is not separable from engineering developments of rack railway structures. Rack railway is in itself a phenomenon that provokes tourist interest. It combines the functions of a vehicle and a monument to the industrial heritage of mankind.

The pioneer of creation of rack railway in Europe was the Englishman John Blenkinsop. Despite the obviousness of today's relevance of the gear wheel when climbing to the heights, the first rack railway was created on the plain. The Middleton Railway, connecting the Middleton suburb with the city of Leeds in the west of Yorkshire (England), was the first rack railway. This railway operated on a system of toothed wheel gearings and gear wheels, developed and patented by John Blenkinsop in 1811.

J. Blenkinsop believed that the friction that occurs when steel wheels move along steel rails will not be enough. Therefore, in 1812, locomotives with twenty gear wheels (diameter 914 mm) on the left side were built for the Middleton Railway, on the left side, which engaged in rack rails (two teeth per 304 mm) located on the outside of the rail, cast-iron edge rails with their lateral teeth connected into one piece with a length of 914 mm. For the Bleckinsop rack railway, a locomotive of a special system was created, which A. Sinclair included in his list of Freaks and Curiosites in Locomotive Designs [2].

The first locomotive that used the patented design of J. Blenkinsop and the first commercially successful locomotive that passed along this railway was the Salamanca locomotive built in 1812 by Matthew Murray from Golbeck. The locomotive was named in honor of the victory of the Duke of Wellington at the Battle of Salamanca, held the same year. The steam locomotive of Salamanca appears in the watercolor of George Walker (1781–1856) «Miner» (1813). It is believed that this is the first image of a locomotive [3]. Four such locomotives were built for the railway. Six years after the launch, Salamanca was destroyed due to a boiler explosion. According to the famous George Stephenson, one of the «fathers of railways» testified in the parliamentary committee, the accident occurred because of the actions of the train driver, who intervened in the operation of the safety valve of the boiler [4].

The Blenkinsop system was used by the Middleton Railway for another 25 years, but it was almost never used, because the friction system was still considered more effective for railways running on level ground.

The world's first rack mountain railway in the New World was Mount Washington, built by Sylvester Marsh (USA). A native of Kempton, Marsh made his fortune in Chicago on a meat package. In 1857, Sylvester Marsh ascended to Mount Washington in New Hampshire, where he fell into a violent storm, which forced him to spend the night on the mountainside [4]. This almost fatal experience prompted him to invent a system by which the train could safely carry passengers to the top. The following year, he appealed to the Legislative Assembly of New

Hampshire for permission to build a steam railway on Mount Washington. He needed a state license to purchase a three-mile road to the mountain in an outstanding area. The plan of Marsh was considered insane, since he proposed to do the impossible. Tradition told us the story that the state legislature voted for permission on the basis of a common opinion that the damage caused by the construction, in case of failure will not be a problem, but in case of success the benefits will be guaranteed. Especially since Marsh invested his money, initially it was 5 000 dollars, but the amount could have increased. And all this was invested in the development of the local community, including the construction of the Fabyan House hotel at the nearby Fabyan station to accommodate the expected tourists. The project of Marsh was jokingly called the «Railway to the Moon» because one state legislator noticed during the trial that the Marsh should be given permission to build not only on Mount Washington, but also on the Moon. Marsh received permission to build the road on June 25, 1858, but because of the civil war, work had to be postponed until May 1866. He developed a prototype of the locomotive and a short demonstration part of the track, then he found investors and began construction. In 1861, S. Marsh was granted a patent of the United States of America on the creation of the idea of a rack railway, and in January 1867, the construction of a rack railway to Mount Washington [5].

The first public test of the Marsh's rack railway was conducted on August 29, 1866, when only 402 meters of track were laid. The gear wheels on the trains had deep teeth, which ensured that at least two teeth were always engaged with the railway; this safety measure helped to reduce the likelihood that the gear wheels will derail.

Despite the fact that the road had not yet been completed, the first paid customers began travelling on August 14, 1868. The construction reached the summit of the mountain in July 1869. In August 1869, President Ulysses S. Grant personally visited New England to escape the heat of Washington. During his tour, he climbed by the Marsh railway to the top of Mount Washington.

Today, the Mount Washington rack railway is the only rack railway of the east of the Rocky Mountains and the only transport that allows to climb to the top of Mount Washington – the highest point in New England. The railway is approximately 4,8 km in length and rises to the top of a mountain with a height of 1917 m. To transport tourists to the top of the mountain, retro-trains with locomotives or environmentally friendly trains with locomotives with biodiesel are used. The train rises to the mountain at a speed of 4,5 km/h and descends at a speed of 7,4 km/h. Depending on the power of the locomotive, it takes approximately 37–65 minutes to climb, and 40 minutes to descend [6].

For about an hour the tourists are at the top with a height of 1917 m, from where they have a breathtaking panoramic view of the mountains and valleys of New Hampshire, Maine and Vermont, extending to the north to Canada and to the east to the Atlantic Ocean. Here is the Sherman Adams Demonstration Center, the Mount Washington Observatory Weather Museum and the Tip Top House Hotel, built in 1853. In memory of the visit, you can send postage stamps from the top of Mount Washington and be photographed against the backdrop of the sign of the summit.

At the Marshfield station it is possible to get to know the history and the museum collection of the rack railway, one of the exhibits of which is the Old Peppersass locomotive, and it is possible also to study the peculiarities of the amazing weather and the ecosystem of the summit of Mount Washington [5].

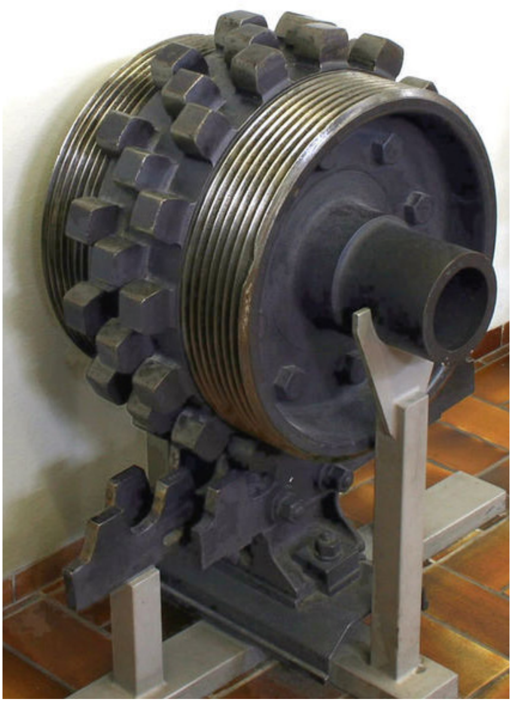
In Europe, the first mountain rack railway called «Vitznau-Rigi Bahn» was laid on the mountain Rigi in Switzerland in 1871 on the basis of the Riggenbach system. On two tracks, laid at that time, trains still run.

The system of the Riggenbach rack railway was created by Niklaus Riggenbach, who worked at the same time as Marsh. Riggenbach was granted a French patent in 1863 for a working model, which he used to interest potential Swiss investors. During this time, the Swiss consul in the United States of America visited the rack railway of Marsh and enthusiastically reported about it to the Swiss government. Intending to give impetus to the development of tourism in Switzerland, the government commissioned Riggenbach to build a rack railway on the mountain Rigi. In the quarry near Bern the prototype of the train and the test track were built. On May 21, 1870, on Riggenbach's birthday, locomotive No. 1, named Stadt Lucerne, passed the first test launch. Riggenbach personally took the first train to Rigi's upper end in Staffelhohe. The line from Vitznau to Rigi Staffelhohe was 5 km in length and climbed a

total of 1115 m to reach the top of 1550 m. Exactly one year later on May 22, 1871 the road was officially opened [7].

By its design, the Riggenbach system is similar to the Marsh system. It uses a step tooth rack made of steel sheets and connected by circular or square bars laid on the same interval. The disadvantage of the Riggenbach system is complexity and high cost of making its tooth gear in comparison with other systems.

Keeping in mind the success of Vitznau-Rigi Bahn railway, Riggenbach founded Maschinenfabrik der Internationalen Gesellschaft f r Bergbahnen (IGB), which produced the locomotives of the rack railway according to its drawings.



The Riggenbach road became the basis for the creation of a whole transport system, which formed the basis for the social and economic development of the region. Today Rigi Bahnen is a group of railways on the mountain of Rigi, located between the two channels of Lake Lucerne. It includes two rack railways Vitznau-Rigi Bahn and Arth-Rigi Bahn, as well as one large and six small cable railways. The Vitznau-Rigi Bahn is the highest standard gauge track in Europe, also known as the first mountain railway in Europe and the second in the world, after the Mount Washington railway.

The highest Swiss rack railway became Jungfraubahn. It was built on the basis of the cog system of Strub. There were many plans to build this road, but all of them failed, until in 1896 fate brought Emil Strub and Adolf Guyer-Zeller. In 1891, E. Strub was appointed inspector of the Bern railway. In 1894 the entrepreneur Adolf Gaier-Zeller took a concession for the construction of a rack railway, which began from the Klein-Scheidegg station in Wengernalpbane, with a long tunnel across the Eiger and Mönch to the Jungfrau summit.

In February 1896 Adolf Gaier-Zeller, through a scientific committee appointed to prepare the Jungfraubahn railway project, allocated 30 000 francs for awards for the best solutions to a number of issues on the construction and operation of this railway. Strub won the first prize of 5 000 francs for his proposed system, which turned out to be brilliant and went down in history as the Strub system [8].

It uses a rolled flat-bottom rail with teeth of the railway mounted in the railhead at a distance of about 100 mm from each other. Safety braces mounted on the train interact with the bottom of the head to prevent the train from slipping off the track and also serve as a brake. The American patent of Strub, granted in 1898, also included details of how the rack rail interacts with the turn mechanism.

From 1896 to 1898, E. Strub was the director of the railway Jungfraubahn. Construction began in 1896 and went, as they would say in Soviet times, at a rapid pace. In 1898 Jungfraubahn was opened to the railway station Eigerglecher, at the foot of the Eiger. Unfortunately, the construction of the road was not *without tragedy. Part of the railway line was to be in the tunnel. In 1899, explosive work began and six workers were killed during these works. This provoked a four-month strike. On April 3 in Zurich from a heart attack Adolf Gayer-Zeller dies. But his business continues and on August 2, a section of the road opens from the station Eigergletscher to the station Rotstock.*

This was the beginning of a glorious history. The Jungfraubahn railway, like its predecessor, the Vitznau-Rigi Bahn, has become an axial frame that has made it possible to develop a hard-to-reach area. Today Jungfraubahn-Gruppe is the largest mining railway company and the leading travel company in Switzerland. It offers its customers an amazing adventure in the mountains and on the train. The main offer is a trip to Jungfraujoch to an altitude of 3471 m. The Jungfrau railway group also operates its own hydroelectric power station and sells complete travel packages on its website in cooperation with partner companies. Until the end of 2019, it is also planned to gradually integrate a number of catering enterprises into the group in order to fully provide customers with services at their own enterprises.

E. K. Morgan from Chicago continued the development of mechanisms for rack railways. In 1900, he received a patent for a railway system that resembled the Riggenbach system, but the rake was also used to power the locomotive with electric transmission. E. K. Morgan was working on the development of heavier locomotives and, together with J. H. Morgan, developed a turning mechanism. In 1904 he patented a simplified, but complex, rack rail on which the teeth of the wheels of the train came into contact with square holes made in a central rail constructed in the form of a bar. J. H. Morgan proposed several alternative rotation mechanisms for this system. It is noteworthy that J. H. Morgan proposed to displace the rack rail so that pedestrians and animals could pass along the tracks. Several photographs of the early stage of the construction of the Morgan road prove it. The rack railway could be used on tracks with a slope of up to 16 degrees.

The Goodman Equipment Company began selling the Morgan system to mining companies, and it was in high demand, especially where the steep incline was found underground. By 1907 Goodman established offices in Cardiff (Wales) to enter the UK market. McKell Coal & Coke Company (from 1903 to 1909) in Rayleigh County, West Virginia used in its mines a network of railways of the Morgan system with a length of 10700 m. Between 1905 and 1906, for the company Mammoth Vein Coal Company, 2500 m of the railway track of the Morgan system were laid in two mines in Everest, Iowa, where the maximum slope reached 16 %. Donohoe Coke Co. in Greenwald, Pennsylvania, in 1906 had a 3050 meter rail network. The Morgan system was operated on a single common railway carrier in the United States, Chichago Tunnek Company, a narrow-gauge freight carrier that had one steep section to a distribution station that was the coastal strip of Lake Chicago.

The roads of the Morgan system, unlike their predecessors, were mostly laid underground. They have found their application in the coal mining industry and cargo transportation.

The Abt system was developed by Roman Abt, a Swiss steam locomotive engineer. At one time Mr. Abt worked for Riggenbach in Olten and then at his company «IGB», which produced the locomotives of rack railways. In 1885, he decided to establish his construction company.

At the same time, Roman Abt worked on the development of an improved system of rack railway, which could correct the shortcomings of the Riggenbach system. The construction and maintenance of the Riggenbach rack railway was too expensive. Still there was a complex system of switch turnouts. In 1882, R. Abt developed a new rack railway using massive slats with vertical teeth embedded in them. Two or three slats were installed in the middle between the rails with angled teeth. The use of several identical slats with built-in teeth at an angle ensured that the teeth of the wheels of the train were constantly engaged with the rails. The construction of the railway of the Abt system was cheaper, since it required less

weight of the rails on the given track. Nevertheless, the wear resistance of the Riggenbach system was much higher than that of the Abt system.

R. Abt developed also a system of smooth transition from friction to adhesion, using a section of a rack rail with a spring shock absorber so that the teeth of the wheels gradually engage with the rail.

The first time the Abt system was used on the Harzbahn railway in Germany, which was opened in 1885.

One of the features of the Abt system is that the gear wheels can be mounted on the same axis as the rail wheels or installed separately. The locomotives of the Tasmanian mining company Mount Lyell Mining and Railway Company had separate cylinders that propelled the gears, as did the locomotives of 10^{th} class of Nilgiri Mountain Railway in India, which is now in conjunction with the Darjeeling Himalayan Railway a World Heritage Site (UNESCO list)).

One of the most famous and popular railways today using the Abt system is Cremallera de Montserrat, a mountain railway line in the north of Barcelona in Catalonia (Spain). This line runs from the municipality of Monistrol de Montserrat to the monastery of Montserrat, which is on the same mountain.

The length of the railway is 5 km, and the track width is 1000 mm. On the first kilometer of the road, between Monistrol and the only intermediate station Monistrol Vila, the usual system of adhesion is used. The remaining part of the route is a rack railway of the Abt system, which allows to overcome this path, whose height reaches 550 m with a maximum gradient of 15,6 degrees. Electricity supply of the railway passes through a contact network 1500 volts direct current. This road is served by the railway operator FGC (Ferrocarrils de la Generalitat de Catalunya).

The route of the railway opened in 1892. In 1930, a cable car was built. In addition, it was possible to get to the monastery in the old way – along a narrow pedestrian road. The railway by that time was distinguished by low financial indicators and a large number of incidents. Therefore, on May 12, 1957, it was decided to close it.

Nevertheless, after a while it turned out that the cable railway and pedestrian route could not serve the whole stream of those wishing to enter the monastery. After many years of discussion and planning in 2001, the program for rebuilding the rack railway was developed, and already on June 6, 2003 the railway was presented to the passengers in a modern way. For the first 12 months, Montserrat has served 462964 passengers.

The peak occurred in August 2003, when 63692 passengers took advantage of this route, the lowest load was shown in February 2004, which had 22996 passengers.

The most significant work along the way was the construction of the Pont del Centenari bridge across the Llobregat River. The bridge is 480 m in length and 5 m in width. The bridge is divided into nine sections, the length of which varies from 35 to 55 m. Everything is constructed of steel pipe grids to give a light design and minimize visual impact on the landscape. The bridge is supported by eight pillars, the maximum height of which is 37 m.

On the Montserrat railway, five low-floor electric motor cars of the Stadler GTW type, built by Stadler Rail in Switzerland, run. The cars are numbered, like AM1-AM5 and named after local peaks. These cars can move at the same time due to the friction of rails and wheels, as well as by engaging in the gear part of the railway. Each car accommodates 200 passengers. There are air-conditioners in the cars, and panoramic windows open a wonderful view of the environment. Trains move at a speed of 30 km/h on the toothed section of the road and at a speed of 45 km/h on the standard part of the road. In addition, this railway uses an E4 electric locomotive of 1930, transported from the Vall de Nuria rack railway for construction and installation works.

The rack railway is connected to the Liobregat-Anoia railway, which starts from Barcelona Pla a d'Espanya station and reaches the municipality of Manresa. The rack railway connects Monistrol de Montserrat, also known as Monistrol Central. Connecting the track to Monistrol allows the rack railway cars to run from the depot near the Martorell municipality and return there overnight.

Every hour, trains run between Monistrol-Enlla and the top of the mountain, connecting the FGC trains, which run from Barcelona to the municipality of Manresa and back. Additional trains run between Monistrol Vila, where there is a parking for cars, designed for 1000 seats, and the top of the mountain.

There are also two funiculars of the railway operator FGC. The funicular De Sant Joan raises the passengers to the top of the mountain, and De Santa Cova descends them from the top down to the monastery [9].

In the 1880s, a truly «axial epoch»[2] for rack railway systems, the Swiss engineer Eduard Locher invented his system, in which the teeth were on the sides of the rail, and not on its top and were driven by gearing with two cogwheels of the train. Unlike other systems,

[2] Term introduced by the philosopher K. Jaspers.

where the teeth can jump out of the rack rail, this system allows to lay roads in areas with a steep slope.

E. Locher worked on the creation of a rack railway system, which could be used in a locality where the slope reaches 50 %. The Abt system is the most commonly used system in Switzerland, it can work with slopes up to 25 %. E. Locher showed that in the territory with a steep slope the Abt system is predisposed to twisting the cogwheels, which can lead to the derailment of the train, as R. Abt himself predicted. To solve this problem and to lay the road in the steep neighborhoods of Pilatus (Switzerland), E. Locher developed a rack railway where the tooth rack is a flat metal rod with symmetrical horizontal teeth. The horizontal gear wheels engaged in the metal rod in the middle, which set the train in motion and prevented it from deviating from the center of the road [10].

This system provides an extra-stable binding of the train to the railway, besides it protects the car from overturning due to strong transverse winds. Such devices also make it possible to drive a car, so even flanges on wheels are not necessary. The biggest drawback of this system is that standard railway switches do not fit it and transverse devices or other complex devices need to be used where it is necessary to go to another branch of the track. After the completion of the tests in 1889, according to the Locher system, the steepest rack railway Pilatus Railway was built. No other public railway uses Locher's system, although some European coal mines use a similar system on routes with a steep incline under the ground [11].

The Lamell system (also known as the Von Roll system) was developed by Von Roll company after the all-rolled steel rails used in the Strub system became inaccessible. It consists of one metal strip cut in a similar way, as in the Abt system, but, as a rule, it is wider than Abt's rack. Trains designed for the Riggenbach or Strub systems can be traversed by the Lamell rack railway system because the safety braces, which were part of the original Strub system, are not used. Some railways use racks of different systems, for example, the St. Gallen Gais Appenzell Railway in Switzerland has sections of Riggenbach, Strub and Lamell racks. This is due to the fact that in the course of the historical development of the economy, this road has gradually integrated several small railways built not far from each other, including four rack railways [12]. Most of the rack railways of the late 20th century are built according to the Lamell system.

Conclusions. *Cog rack-wheel systems are a unique achievement of the human engineering idea. Thanks to this invention, hard-to-reach areas on the ground and underground were developed. High peaks were able to be conquered not only by people with special skills, but also by ordinary travelers. Countries where the mountains occupy a large territory, such as Switzerland (the area of mountains is more than 61 %), could make them accessible and develop economic use. In Russia, there are also many mountainous areas (≈ 33 %) and rack railways could promote their development and organization of activities that contribute to the development of the local community and the country as a whole.*

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Information about the author:
Tikhonova, Tatyana Yu. – Ph.D. (Philosophy), associate professor of the department of Service and Tourism of Russian University of Transport (MIIT), Moscow, Russia, umago@mail.ru.

Article received 20.07.2017, accepted 24.10.2017.