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High-speed trains in Japan in the years 2002–2020

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The article presents the development of high-speed rail in Japan, an island country located within the Ring of Fire of the Pacific. The analysis of the technical condition and the stages of the historical development of high-speed railways were preceded by an assessment of the economy and transport as well as a study of transport intensity. The summary of the article includes the effects and benefits of using high-speed rail, as well as methods of financing and plans for further development.

Key words: *Japanese economy, transport intensity, passenger transport, high-speed railways*

1. Introduction

High-speed trains are the most modern and advanced technology for moving passengers in land transport. Their main advantage is that they achieve high speeds, usually from over 200 to 300 km/h, which significantly shortens the travel time in relation to the time needed to cover the same distance by conventional trains. On the other hand, they are serious competition for high-speed air transport.

High-speed railways require special wagons and locomotives as well as appropriate infrastructure with much larger turning arcs, which are very durable and have a strong subgrade. Thus, as a rule, this type of infrastructure is built from scratch, and only in a few cases is the existing infrastructure adapted to the needs of high-speed rail. For the operation of high-speed rail, not only special trains and railway lines are needed, but stations and separate ticketing systems are also needed.

It should be emphasized that the implementation of investments to perform transport in this technology is very capital-intensive. Nevertheless, the required large expenditures for development are compensated by:
- high comfort and short travel time
- a huge impact on the economic development of regions and the country
- high level of safety and relatively low level of negative impact on the natural environment in relation to other transport branches
- high energy efficiency
- low external costs.

The above-mentioned basic premises resulted in the fact that in the rich countries of Western Europe and Asia, transport using this technology is developing dynamically.

The research period ended in 2020 in order to eliminate the negative impact on the economy of the effects of the global COVID-19 pandemic. The idea was for the research to be based on the main development trend and not be obscured by side causes.

2. General characteristics of the country

Japan is an island country located in the eastern part of Asia. The archipelago consists of four main islands: Hokkaido, Honshu, Shikoku and Kyushu, as well as about four thousand smaller ones. The country is located between the western Pacific Rim and the Sea of Japan, through which it borders with:
- China – from the south-west and west (Ryukyu Islands area) through the East China Sea
- the Republic of Korea – through the Korean Strait
- Russia – from the north through the Strait of La Pérouse (Hokkaido–Sakhalin region) connecting the Sea of Japan with the Sea of Okhotsk.

Fig. 1. Location of Japan [7]

The Japanese islands lie both within the seismically active orogenic zone and at the junction of three tectonic plates, within the so-called the Ring of Fire of the Pacific. Most of Japan is covered by mountains. According to the Japan Meteorological Agency, there were more than 110 active volcanoes in the country in 2018, including 10 submarines [14].

About 50 volcanoes erupted in the period 1900–2016 [37]. The largest population centres are therefore in the lowlands – between the cities of Nagoya and Osaka and Tokyo.

Japan's total population was 125.50 million inhabitants (16% of the world's population) in 2021 [34]. Japan is characterized by a high population density, in 2020 it reached the value of 338.2 people/km². Of the 47 prefectures of Japan, the largest population was in Tokyo Metropolis (14.05 million), followed by Kanagawa, Osaka, Aichi, Saitama, Chiba, Hyogo and Hokkaido prefectures – a total of 63.98 million inhabitants, which accounted for over 50% the entire population. The population density in the Tokyo metropolis was the highest among the prefectures of Japan and amounted to 6,402.6 people/km², i.e. almost 18.9 times more than the national average.

Japan is recognized around the world as one of the leaders of modern technologies. An excellent example of their use in practice is the development of high-speed rail since 1964, when the world's first Tōkaidō Shinkansen line was launched.

3. The level and assessment of the economic situation based on basic economic variables for the years 2002–2020

Japan's economy is one of the largest economies in the world, currently in third place behind the economies of the United States and China [6]. At the same time, Japan is the most indebted country in the world after the United States [41].

Among the most developed industries in Japan are the automotive, electronics, machinery, pharmaceutical, steel and chemical industries. Industries crucial to the country's security also include petrochemicals, bio-industries, shipbuilding and aerospace. The products in which Japan is a technological leader include, among others, semiconductors, optical fibres and biochemistry [25]. At the same time, the domestic manufacturing industry increased its involvement in global production chains, moving production bases abroad in order to reduce manufacturing costs and avoid currency fluctuations [36].

The economic situation of Japan in 2002–2020 is presented in Table 1.

Analysing the data contained in Table 1, it should be stated that, similarly to other world economies, a clear deterioration of the economic situation occurred in 2008–2009 during the global economic crisis and in 2020 due to the outbreak of the COVID-19 pandemic, when economic activity fell as a result of sanitary restrictions, slowing down consumption and investment.

In the years 2002–2020, the inflation rate remained at a similar level, while unemployment after 2010 never exceeded 5%, reaching less than 3% in 2020.

In terms of international trade, Japan ranks fifth in the world. The most important trade and investment partner is the United States.

In 2019, the largest export partners were the United States (19%), China (18%), South Korea (6%), and Taiwan (6%), while in imports, China (23%), the United States (11%) and Australia (6%). The weak domestic demand of the Chinese economy and the stagnation of global demand (including in the United States and Europe), as well as the unprecedented economic slowdown caused by the global COVID-19 pandemic, resulted in, in the last two years, a weakening in some areas of exports and production. However, the upward trend in domestic demand was maintained, supported by factors such as improved employment and income situation and strong corporate profits.

In 2021, business activity in Japan was restricted periodically to prevent the spread of infection. Although the economy was recovering, the rate of growth was slow [36].

Figure 2 presents a study based on a sixth-degree polynomial showing the effects of socio-economic activity expressed in the value of Japan's gross domestic product in the years 2002–2020.

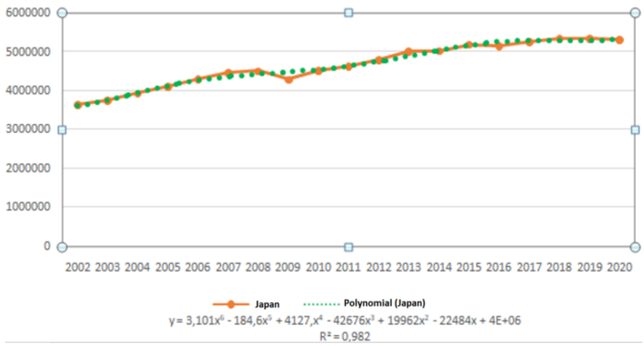

Fig. 2. Development of Japan's GDP in 2002–2020, in USD million [28]

Table 1. Basic macroeconomic indicators of the Japanese economy in 2002–2020 (annual changes in %) [37]

Details	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
GDP	0.3	1.7	2.4	1.3	1.7	2.2	–1.0	–5.5	4.7	–0.5
Private consumption	1.3	0.6	1.3	1.5	0.9	0.8	–1.1	–0.9	2.3	–0.5
Unemployment (rate in %)	5.4	5.3	4.7	4.4	4.1	3.9	4.0	5.0	5.0	4.6
Inflation (in %)	2.8	2.5	2.4	2.6	2.7	2.5	3.7	0.6	1.8	2.9
Current account balance (% of GDP)	2.6	3.1	3.7	3.5	3.8	4.7	2.8	2.7	3.8	2.1
Exports of goods and services (% of GDP)	7.9	9.6	14.4	7.1	10.3	8.7	1.6	–23.4	24.9	–0.1
Imports of goods and services (% of GDP)	0.8	3.4	8.5	5.9	4.7	2.3	0.7	–15.6	11.3	5.7

Details	2012	2013	2014	2015	2016	2017	2018	2019	2020
GDP	1.7	1.4	0.0	1.6	0.8	1.7	0.6	0.0	–4.5
Private consumption	2.0	2.6	–0.9	–0.2	–0.4	1.1	0.2	–0.5	–5.3
Unemployment (rate in %)	4.3	4.0	3.6	3.4	3.1	2.8	2.4	2.4	2.8
Inflation (in %)	2.2	1.6	1.7	0.7	1.2	2.3	2.6	2.1	1.4
Current account balance (% of GDP)	1.0	0.9	0.8	3.1	3.8	4.2	3.2	3.4	2.9
Exports of goods and services (% of GDP)	0.1	0.8	9.3	3.2	1.6	6.6	3.8	–1.5	–11.8
Imports of goods and services (% of GDP)	5.5	3.2	8.1	0.4	–1.2	3.3	3.8	1.0	–7.2

The values of the gross domestic product of Japan in the analyzed years were characterized by an upward trend with a noticeable decrease during the global financial crisis, which peaked in 2007–2009. Emerging from the crisis, the Japanese economy continued the development from before 2007, which was characterized by a continuous increase in GDP in the following years.

The credibility of the above study was checked with the R^2 agreement coefficient, which reached the value of 0.982.

4. Transport in Japan

In Japan's general transport infrastructure, the road network is the best developed, with a length of 1 227 000 km. km. The second place is occupied by rail transport, with a total length of the network of 27.3 thousand km. km, with the vast majority of electrified railway lines (15.7 thousand km). The length of the pipelines is 4.7 thousand km. km, and inland waterways 1.8 thousand. km (Table 2).

Table 2. Transport infrastructure in Japan in 2020 (in km) [36]

Type of transport infrastructure	Length
Railway lines	27 311
Roads	1 227 000
Highways	9 100
National roads	56 000
Regional roads	130 000
Municipal roads	1 033 000
Inland waterways	1 770
Pipelines	4 734

Almost all freight transport is carried out by cars and cargo ships, while rail transport is the most important in passenger transport.

The road infrastructure includes 9.1 thousand km of motorways, 56 thousand km of national roads, 130 thousand km of regional roads, and 1 033 000 km of municipal roads. Roads are managed by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

The operator of Japanese railway lines with a total length of 27.3 thousand km. km is in the vast majority of Japan Railways Group [41]. Shinkansen high-speed rail lines run through the most important industrial, political, cultural and financial centers [11], with rail connections to the four largest islands of the archipelago (Fig. 3).

Inland waterway transport plays a marginal role in the movement of goods [41]. The main problem limiting the possibility of using inland waterways is their swift current and large seasonal fluctuations in the water level, which is mainly caused by the mountainous topography of Japan. Due to topographic features, inland waterway transport developed near coastal regions where wider channels and calmer river currents allowed it [35].

Fig. 3. The network of railway connections in Japan [30]

There is a total of 4,734 km of pipelines in Japan, mainly used to transport LNG [41]. Japan, like China, is almost entirely dependent on gas imports due to its small domestic production [15]. The existing and planned pipeline networks in Japan are shown in Fig. 4.

Fig. 4. Existing and planned pipeline networks in Japan [21]

Table 3 shows the transport performance performed in the years 2002–2020 by land transport.

The analysis of both the transport infrastructure and the volume of transport performance shows that in the years 2002–2020, road transport was of dominant importance in the transport of goods by land. A much lower level in relation to road transport was reached in the period under examination, measured by the volume of transport performance carried out by pipelines and rail transport. It should be noted, however, that road transport, measured by the volume of transport performance, decreased in 2010 and, for the following years, remained at a similar level. Issues in the field of cargo transport have been discussed in more detail in the book "Transport Technologies" [24].

Table 3. Transport performance in Japan in 2020 (in billion tkm) [36]

Mode of transport	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Road	312	322	328	334	346	355	345	333	243	233
Rail	22	23	23	23	23	23	22	21	20	20
Pipeline	60	62	63	63	62	61	58	58	59	58

Mode of transport	2012	2013	2014	2015	2016	2017	2018	2019	2020
Road	209	214	210	204	210	211	210	214	212
Rail	20	21	21	21	21	22	19	20	20
Pipeline	56	55	52	53	53	51	49	47	48

The transport intensity of Japan in the years 2002–2020 using the sixth-degree polynomial and the exponential function curve is shown in Fig. 5 and 6.

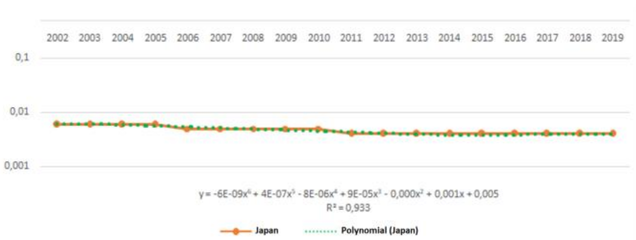

Fig. 5. Japan's transport intensity calculated using a sixth-degree polynomial

The analysis of the curve calculated on the basis of a sixth-degree polynomial allows us to conclude that the transport intensity of Japan in the analyzed period remained at a low, stable level. The coefficient of conformity R^2 was 0.933.

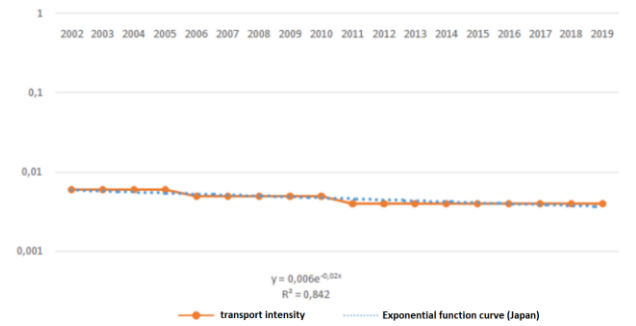

Fig. 6. Japan's transport intensity calculated using the exponential function curve

Figure 6 shows the curve of the exponential function illustrating the development of the transport intensity of the Japanese economy in the analyzed period. The R^2 coefficient is 0.842 [35].

Comparing the studies, it can be concluded that the study based on the sixth-degree polynomial, in this case, is characterized by more reliable results, as indicated by the higher result of the R^2 coefficient of agreement.

Transport intensity in the analyzed period remains at a low level with a downward trend. This means a stable cost of producing and moving individual goods, which in turn results in stable prices. On this basis, it can be concluded that Japan takes appropriate rationalizing and limiting measures to increase transport intensity and maintains it at a constant level [26].

5. Characteristics of the high-speed railway

Japan is considered the home of high-speed rail, as well as the first country to face the challenges of such an innovative technical and structural design. The implementation of the project began in 1958 with the approval by a special government commission of the plan to build the Tokyo–Osaka line [11]. The world's first high-speed line, the Tōkaidō Shinkansen, opened in October 1964 for the Tokyo Olympic Games. This line, 515 km long, runs from Tokyo to Osaka via Nagoya and Kyoto. Its initial maximum speed was 210 km/h [8]. Currently, in Japan there is a whole system of high-speed rail called Shinkansen, reaching speeds of up to 320 km/h.

The high debt of the Japanese State Railways related to the construction of high-speed lines, which – despite the growing number of passengers – was not compensated by the proceeds from ticket sales, forced the Japanese government to decide in 1987 to privatize the railway and introduce its shares to the stock exchange. Such a move made it possible to repay the loans taken out for the implementation of this investment [11]. At the same time, Japanese railways were privatized by dividing them into six passenger operators, forming the Japan Railways Group, and one freight operator:

- East Japan Railway Company
- Central Japan Railway Company
- West Japan Railway Company
- Hokkaido Japan Railway Company
- Shikoku Japan Railway Company
- Kyushu Japan Railway Company
- Japan Freight Railway Company.

Each of the above-mentioned passenger transport companies operates in a specific area of the country (Fig. 7), while the Japan Freight Railway Company provides freight services on the entire national network. The restructuring of the railroad has already yielded profits in the first year of operation under the new rules.

Fig. 7. Territorial range of passenger railway operators in Japan [19]

Initially, the state retained its shares in each of these companies, but in 2000, the process of complete privatization of JR Central, JR East, and JR West began, which was completed in 2003, 2002, and 2004, respectively [11].

6. Technical solutions in trains and locomotives – power supply methods

The decision to build a high-speed railway was a big challenge for its creators. In addition to designing the route itself, an important element was the appropriate rolling

stock. It was necessary to develop a completely new type of trains, for which the following assumptions were made:
- number of wagons – from 12 to 16
- axle load – approx. 16 tons
- train weight – approx. 800 tons [11].

Due to the weight of the train, it was impossible to use a traditional locomotive, and the decision was taken to use the so-called traction unit. It consisted in installing electric motors along the entire length of the train. Each motor was a DC motor with relatively low power (185 kW).

Series 0 Shinkansen

The first generation of trains designed to transport passengers on high-speed lines were Shinkansen series 0 trains. The weight of each car was 64 t, and the axle load, as assumed, was 16 t. A pantograph, transformer, rectifier and other electrical equipment were mounted on every second car. The trains were powered by 25 kV at 50 Hz, with all wagon axles powered by 185 kW (248 hp) traction motors, giving a maximum operating speed of 220 km/h (137 mph). Originally, the trains consisted of 12 sets. However, some were extended to 16 sets. To ensure sufficient sound insulation, the windows of the carriages were equipped with triple glazing.

The train could take 1,208 passengers in second class, and 132 passengers in the first class, while the seating arrangement was as follows:
- 2+3 in class 2
- 2+2 in class 1.

At the head of the train, under a cover in the shape of a hemisphere, there was a coupler, after disassembly of which the train could be towed (Fig. 8).

Fig. 8. A series 0 Shinkansen train at the Kyoto Railway Museum [3]

The 0-series trains were in operation between 1964 and 2008, with a total of approximately 3,216 sets produced, which ran on the Tokaido and Sanyo routes. The last 6-car sets were used by JR West on the service between Shin-Osaka and Hakata and on the Hakata-Minami line.

Series 100 Shinkansen

The series 0 had many successors, one of them was the series 100 Shinkansen, operated from 1986 to 2012. The nose profile of the train in series 100 was more pointed than in series 0. Light alloy body sheathing was replaced with steel. In the 16-set trains, not all members were powered; the sections at each end were unpowered, as were the two two-level middle sections.

Fig. 9. Shinkansen 100 series train [20]

The power of the traction motors was 230 kW (in series 0–180 kW), while the power of the entire train was 11,040 kW (in series 0–11,840 kW). A new solution has been introduced where the brakes use eddy currents. The train reached a maximum speed of 220 km/h.

Double-deck cars were used in the train for the first time – on the upper deck, there was a restaurant section with kitchen facilities, and on the lower deck, there was a small buffet. The number of seats in the second class (standard) was 1,153, while the first class (green) was 168. Series 100 trains ran on the Tokaido and Sanyo route [11].

Series 300 Shinkansen

Another high-speed train in Japan was the Shinkansen series 300. It was introduced into production and operation in the 1990s, and was withdrawn in 2012. Compared to the older type of trains, a number of changes and improvements have been made to the structure. A more aerodynamic shape was introduced, which allowed for a significant (by about 20%) reduction in air resistance. Light steel alloys were used for the production of the train, thanks to which the weight of the 16-car set was reduced to about 710 tons (in the 0 series, the weight was 925 tons). The modernization of the structure also resulted in a reduction of the axle load to approx. 11.3 t.

Fig. 10. Series 300 Shinkansen train [38]

The maximum speed of the train was 270 km/h. The train could take 1,323 passengers (200 in the green class and 1,123 in the standard class). The train ran on the Tokaido and Sanyo routes.

The biggest change for the 300 series was the replacement of DC motors with AC motors (three-phase asynchronous motors) and the use of kick starting. These motors were much lighter than DC motors, more powerful, and took up much less space. This made it possible to reduce the number of powered cars to 10. The introduction of a new type of engine also required the development of new electronic equipment and a computer controlling the entire system.

In the 300 series, bogies of a different design were also used, omitting the bolster beam, which was present in older generations. The box rested on air cushions.

Thanks to weight reduction, new engines, and a number of other improvements and innovations, it was possible to shorten the travel time between individual stations. For example, the average travel time from Tokyo Central Station to Shin-Osaka Station in 1992-1993 was 2 hours 54 minutes, the maximum speed was 220 km/h, while the average was 177 km/h. This increased the attractiveness of this type of transport for passengers [11].

Series E5 Shinkansen

The research program for the E5 series was initiated in 2002 to design a train that could reach speeds of 360 km/h. The rolling stock is produced by a consortium of Hitachi and Kawasaki companies [5]. The train consists of two units, each consisting of four driving cars and a steering car without a drive. In the case of this model, the hull sheathing was made of reinforced aluminium sections. As a result of air flow tests, the characteristic shape of the head car was extended to 15 m.

Fig. 11. Series E5 Shinkansen train [22]

The construction uses three TM212 transformers with a unit power of 3130 kVA, the voltage of which is converted into 32 three-phase MT207 traction motors with a unit power of 300 kW. Two pantographs type PS208, located on the roofs of carriages No. 3 and 7, are used to collect electricity. The trains are powered with a voltage of 25 kV 50 Hz. The weight of each of the 10 powered cars is 47 t (42.7 t without the drive), and the total weight is 453.5 t. The trains are equipped with the DS-ATC traffic safety system. The maximum speed they reach is 320 km/h [13].

The trains can carry 731 passengers at a time, including 658 in the standard class, 55 in the green class and 18 in the luxury gran class, which was introduced for the first time in the trains of this series.

The E5 series is operated by the East Japan Railway Company. The trains were introduced to Tohoku routes in March 2011 and Hokkaido routes in March 2016.

Series E7/W7 Shinkansen

One of the newer high-speed trains running on Japanese railway lines is the Shinkansen of the E7/W7 series, built in 2013. The production of the kits was jointly developed by Kawasaki Heavy Industries, Hitachi Kasado and other Japanese companies.

The external appearance of both the E7 and W7 series (in terms of painting and overall shape) is virtually identical. The difference is that the E7 sets are operated by the East Japan Railway Company and have a number starting with the letter F, while the E7 sets are operated by the West Japan Railway Company and have a number starting with the letter W.

Fig. 12. Series E7 Shinkansen train [22]

The sets consist of 12 cars, of which 10 are powered cars. The hull sheathing of the train is made of aluminium, the front of the train is designed in an aerodynamic shape. Thanks to the use of four airbags, the car body could be placed on the bogie. A distributed drive was used to move the train; each driving car had 4 three-phase motors, each with a power of 300 kW. Two PS208A pantographs located on the roofs of the cars No. 3 and 7 were used to collect the current.

The trains are powered by 25 kV 50/60 Hz. The total weight of the train is 543 t. The trains are equipped with the DS-ATC and RS-ATC traffic safety systems. The maximum speed they achieve is 260 km/h [27].

Each train has 934 seats, including 853 in standard class, 63 in green class and 18 in gran class (apart from the Tsurugi configuration, which does not have gran class [20]). Economical LEDs were used to illuminate the compartments. The seats can be adjusted individually using an electric adjustment system. The train also has a compartment for a mother with a child and a compartment for a person requiring special care.

Trains operate on the following routes: Tokyo–Nagano (E7 from 2014 and W7 from 2015), Tokyo–Kanazawa and Toyama–Kanazawa (from 2015), as well as Tokyo–Niigata and Tokyo–Echigo–Yuzawa (from 2019). The route to Kanazawa with a length of 454 km is covered in 2 hours and 30 minutes. The maximum speed of the train is reached in the Takasaki–Kanazawa section.

7. Line infrastructure for high-speed trains

Currently, Shinkansen trains can run at a maximum speed of 320 km/h. Due to the high speed they reach and the aerodynamic shape of their beaks, they are called "bullet trains".

Each Shinkansen line includes fast, semi-fast and local trains. Train traffic is mainly on conventional steel rails mounted on concrete sleepers, with the fastest ones using dedicated tracks to avoid collisions with slower trains and only stopping at major stations [34]. In order for the trains to run at their maximum speed (up to 320 km/h), the Shinkansen tracks do not have sharp curves and, moreover, do not cross other railway lines at the same level.

Existing high-speed rail lines allow trains to move at speeds above 200 km/h, and the most modern solutions even allow for speeds exceeding 300 km/h. Such performance would be impossible if not for the appropriate linear infrastructure. Among the basic design parameters for the Shinkansen line, the following are distinguished:

- track gauge 1067 mm and 1435 mm
- cant 290/330 mm
- radius of the horizontal curve (2500 m for the speed of 270 km/h, 4000 m for the speed of 320 km/h)
- longitudinal inclination 25/35‰
- vertical curve radius 10,000 m (5,000 m on sections where the maximum speed is 250 km/h)
- width of the intertrack 1.435 m.

Turnouts are an important structure of high-speed lines. On the Shinkansen lines, the solution is to locate the turnouts very close to the ends of the platforms. High-speed turnouts are not used, and trains move at a relatively low speed on the existing turnouts. The inner radius of the largest turnouts used on the Shinkansen is 1,106 m [39].

The above-mentioned parameters, combined with appropriate service, as well as care for travel comfort and safety, have a real impact on the number of passengers who decide to use train services in Japan. The Shinkansen lines are in a phase of continuous development. Currently, several investments are planned to provide for the creation of new connections, which will be discussed later in the article. Despite the great benefits resulting from traveling by high-speed rail, Shinkansen lines account for only a few percent of all trips made by rail.

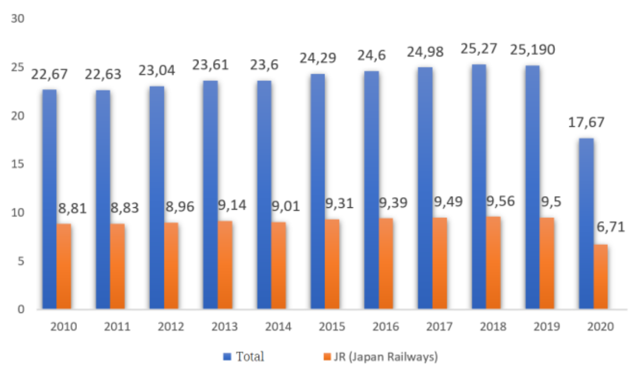

Fig. 13. Total rail passenger transport, including the Japan Railways Group, in 2010–2020, in billions [35]

Figure 13 presents the number of passengers using railway services in general and Japan Railways Group in 2010–2020. In the analyzed period, the number of passengers using the services of the Japan Railways Group accounted for almost 40% of all rail transport passengers and was systematically increasing every year, with the exception of slight decreases in 2014 and 2019. A clear slowdown occurred in 2020, i.e. in the first year of the COVID-19 pandemic.

8. Ways of financing

The current structure of Japanese railways is the result of the privatization of the national railway, which was completed in 2004, forced by a financial deficit, which was caused by high expenses incurred for the construction and launch of the Shinkansen. Three out of seven privatized companies (Central JR, East JR, West JR) are profitable and do not receive state subsidies. They are listed on the Tokyo Stock Exchange. In addition, rail operators are profitable in real estate around their rail stations, and they also make profits from servicing shopping centers, restaurants and hotels. At the same time, profitable Shinkansen lines and express trains subsidize the smaller, non-profit lines they operate [3]. Other companies (especially JR Hokkaido operating in the north of the country), unprofitable due to the small number of transports on smaller islands, receive subsidies from public funds and all remain state property. Most of the funding for the development of new Shinkansen lines is contributed by central and local governments.

In accordance with the existing cost-sharing rules, members of the former state-owned Japan Railways group lease high-speed train infrastructure from the Japan Railway Construction, Transport and Technology Agency (JRTT) – an independent government agency established in 2003 under a parliamentary act that deals with the construction of new Shinkansen lines and providing state-of-the-art technology for railway expansion projects (including tunnels and bridges) and other transportation projects throughout Japan [2].

In 2019, lease payments were calculated on the basis of estimated revenues from railway operations over 30 years. On the other hand, costs other than lease payments were shared between the central government and local governments 2:1 [29].

Since 2014, Japanese railways have been promoting their own technology of high-speed rail lines on the international arena (e.g. in the United States or India), which in the future may undoubtedly help find new customers willing to purchase their systems [19].

9. Plans and directions of further development

Huge sums, counted in billions of dollars, invested in the expansion and development of Shinkansen did not stop Japan from working on new technology – a super-fast maglev train moving without contact between the vehicle and the track, thanks to electromagnetic lift obtained by repulsion or attraction of permanent magnets or a system of electromagnets laid in the track and placed in the vehicle. The maglev, starting its journey, initially moves on rubber wheels, thanks to which the magnets under the train interact with the magnets of the runner. When the train reaches 150 km/h, the magnetic force lifts it to a height of 100 mm. At the same time, friction is eliminated so that ever higher speeds can be achieved. The same magnetic forces that lift the train also move it forward and keep it centered in the track.

During the experimental tests of the L0 using Superconducting Maglev (SCMAGLEV) technology, a maximum speed of 603 km/h was recorded, which was a world record in this range [16].

Fig. 14. Test run of the Maglev L0-950 train [31]

Japan's first magnetic rail line (SCMAGLEV) will be the Chuo Shinkansen connecting Tokyo to Osaka. It is performed by JR Central, the operator of the Tokaido Shinkansen. The planned speed of trains on this route would be up to 505 km/h, which would reduce the travel time from 2 hours and 22 minutes to only 67 minutes. Construction of the Chuo Shinkansen began in 2014 with an estimated cost of at least $90 billion. The planned date for launching the connection to Nagoya is 2027 and to Osaka, 2045. Chuo Shinkansen will be an alternative to the 57-year-old Tokaido Shinkansen – the oldest, most crowded and operated high-speed line in Japan [13].

The nationwide Shinkansen high-speed railway is in a phase of continuous development.

In the fall of 2022, a new section of the Nishi Kyushu Shinkansen line connecting Nagasaki with Takeo–Onsen was commissioned. Of the five stations on this route, two were built from scratch, especially for the needs of this line. It is the shortest Shinkansen high-speed rail line in Japan in terms of length (its total length is 66 km). Ultimately, the entire line is to connect Hakata with Nagasaki [40].

Fig. 15. Map of the existing Shinkansen network and new lines [33]

Currently, the Hokuriku Shinkansen line is being extended with another connection between the cities of Kanazawa and Tsuruga. It is estimated that the opening will take place in 2024, and the connection will be about 125 km long. Of the six stations, five will be added to the existing stations, and Echizen–Takefu Station will be built from scratch. Construction of the last section of this Osaka–Kyoto line is scheduled to start in 2030, with its exploitation scheduled for 2045 [17]. The Hokkaido Shinkansen line will be extended by 2031 with a section connecting Shin–Hakodate–Hokuto and Sapporo. The total length of the newly constructed section will be 212 km. The route will include 17 tunnels (80% of the new route) with a total length of 168.9 km, viaducts (30.3 km), and bridges (5.3 km) [17].

The existing Shinkansen lines and the location of the planned new connections are shown in Fig. 15.

10. Summary – benefits and effects of high-speed rail transport

Investing in high-speed railways brings a number of benefits, such as shortening the travel time between the largest agglomerations or greater convenience for passengers. In addition, it is a beneficial solution for the natural environment, which can be confirmed by the success of such lines in, among others, Japan or Western European countries, e.g. in the Federal Republic of Germany [23].

Although high-speed rail travel times may seem longer than air transport, there are a number of factors that make it more attractive, including:

– faster and easier access to the station, which in the case of high-speed rail is usually located in the city center
– connections from the center to the center of large agglomerations
– price
– frequency of connections
– more freedom to work with a computer
– no requirements as to the weight and dimensions of hand luggage [9].

High-speed railways also have many significant advantages in terms of environmental impact. These include:

– relatively low level of land occupation, especially in comparison with road transport (on average 3.2 ha/km of line, with 9.3 ha/km of motorway)
– high energy efficiency both compared to car transport (about 3.4 times higher) and air transport (about 8.5 times higher)
– low level of CO_2 emissions
– low external costs (about 9 times lower than those generated by passenger cars and 5 times lower than in air transport) [4].

A fundamental element of a developed high-speed railway system is a high level of safety, which is guaranteed by advanced technical systems. Very often, a high-speed railway line is an attraction in itself, which attracts tourists to the places where it is located and additionally causes economic growth in such regions. In addition to the advantages in terms of time, convenience and environment, high-speed rail also has a huge impact on the development of the regions and countries in which it operates, as it is an important element of an efficient transport system [4].

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