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Development of High-Speed Rail in France from 2002 to 2022

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Abstract:

Purpose: *The aim of this publication is to present methods of studies on passenger transport and to evaluate the development of high-speed rail in France, and the impact of this technology on passenger transport volumes, environmental protection, and social and economic development.*
Design/Methodology/Approach: *The project was implemented using formalized methods, expert analyses, literature review, and the theoretical and practical experiences of the authors. The topic is presented comprehensively, as the development of transport is contextualized within the economy, using mathematical methods, examining, and discussing the interrelations between transport and the economy, highlighting the correct economic trends in this regard. The high-speed rail system – both the development of individual generations of trains and the infrastructure – was analysed considering technical, operational, economic progress, and financial security over the 20-year research period. Future development plans for high-speed rail in France are also presented.*
Findings: *The theoretical and practical value of the article is indisputable. France is the second-largest economic power in Europe and the seventh in the world, with a 48-year tradition in the development of high-speed rail. The first commercial journey on the high-speed line from Paris to Lyon took place on September 27, 1981. France's high-speed rail network is one of the most heavily utilized in the world, accounting for approximately 60% of all passenger transport. Therefore, a comprehensive presentation of the development of high-speed rail over a long research horizon may be beneficial for countries at a lower level of development in this area, especially since literature on high-speed rail with such a long research horizon and comprehensive approach is scarce. The widespread promotion of solutions related to the development of high-speed rail in France from a practical perspective seems highly purposeful and fully useful.*
Practical Implications: *The article presents studies on the most dynamically developing technology for passenger transport in France from 2002 to 2022 – high-speed rail. It presents the technical solutions of individual generations of trains and locomotives, as well as the linear infrastructure for French high-speed rail in a historical context. Additionally, it discusses financing methods and further development plans for high-speed rail.*
Originality value: *The publication analyses comprehensive material covering the research problem over a 20-year time horizon, systematizes it, and draws appropriate conclusions.*

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Paper type: *Research article.*

1. Introduction

The origins of high-speed rail development in France date back to the 1960s. Currently, France possesses the second-largest high-speed rail network in Europe (after Spain) and the fourth largest in the world (after China, Spain, and Japan). Research on the development of high-speed rail from 2002 to 2022 indicates the significant role of TGV in passenger transport. Concurrently, advancements in technical and operational development and increased efficiency for subsequent generations of trains contribute to environmental protection. The state policy aimed at increasing the share of rail transport enables the fight against climate change by reducing greenhouse gas emissions associated with transport.

The analysis of infrastructure, the state of progress in its development, and the technical parameters of the high-speed rail network also allow for the assessment of the state of expansion of direct connections both domestically and with the United Kingdom, Belgium, the Netherlands, and Germany. French LGVs were constructed primarily through public sector investments, as well as public-private partnerships (PPP). The financing of LGVs involves the government, local communities supported by taxes and bank loans, and the European Union.

Development plans that consider ecological aspects confirm the main thesis of the article, which posits the superiority of high-speed rail in passenger transport over traditional means of transport. Evidence supporting the research thesis includes travel time, safety, comfort, and the fact that in France, as much as 60% of total passenger transport is carried out by high-speed trains.

The conducted research extensively utilized bibliographic sources, mainly from French authors, as well as the authors' own experiences and reflections. An undeniable scientific merit of the article is the collection of such a broad (comprehensively covering the research problem) material over a 20-year time horizon, its systematization, and the drawing of appropriate conclusions.

2. Assessment of Transport in France

The road network in France is one of the densest in Europe, allowing for excellent connections within the country and with neighbouring countries and other Western

European nations. The highest density of expressways and highways is found in the northern and northeastern parts of the country, where the most important ports and industrial centres of France are located. The southern part of the country is also well-connected, with the major port in Marseille (Own elaboration based on: Mindur, ed., 2017). The total length of roads in 2021 was 1,105,094 km, including 11,664 km of highways (Table 1).

Table 1. *Transport Infrastructure in France in 2021 (in km).*

Type of Infrastructure	Length of Lines
Railways	27,057
Roads	1,105,094
Highways	11,664
National Roads	95,581
Regional Roads	378,906
Municipal Roads	704,942
Navigable Inland Waterways	5,216
Pipelines	6,400

Source: *Ministère de la Transition Ecologique et de la Cohesion des Territoires. https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-transports-2023/34-infrastructures-de-transport.*

Safe and fast rail connections are made possible by a well-developed and modern high-speed rail network, which competes with alternative means of transport. In terms of freight transport, it is commonly carried out through combined rail-road transport. France is connected to the network of waterways throughout Europe, with the length of navigable waterways in the country amounting to 5,216 km.

Analysis of freight transport work in France (Table 2) indicates the dominant role of road transport (in 2020, 286.5 billion ton-kilometres). The freight work carried out by rail transport was nearly nine times lower (31.6 billion ton-kilometres). The third place was occupied by the mass transported by pipelines (9.5 billion ton-kilometres), which has been on a downward trend since 2008. The freight work carried out by inland water transport amounted to 6.5 billion ton-kilometres in 2020.

Table 2. *Freight transport work in France from 2002 to 2014 (in billion ton-kilometres).*

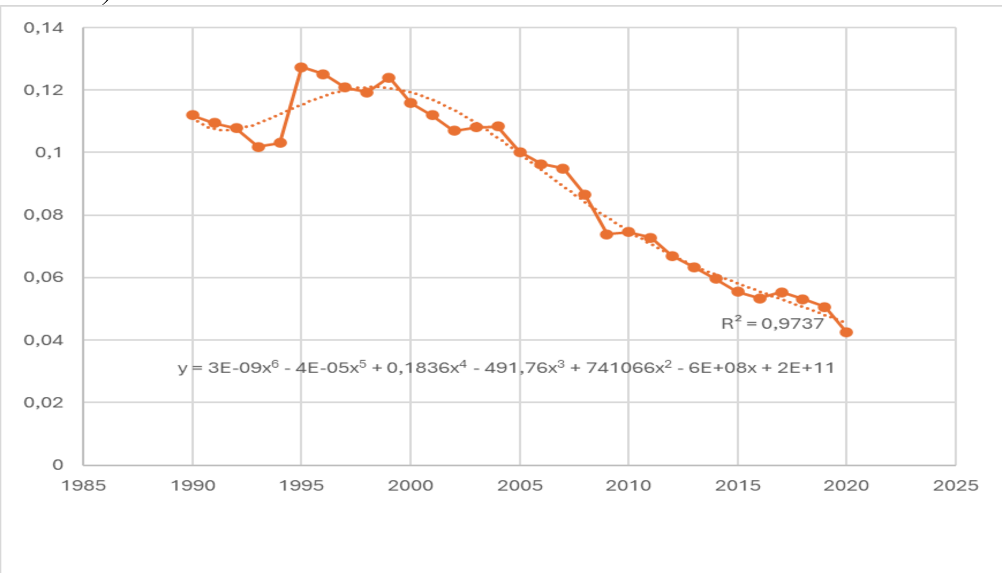
Year	Mode of transport			
	Road	Rail	Inland Waterway	Pipeline*
2002	204.4	50.0	8.0	21.0
2003	203.6	46.8	8.0	22.1
2004	212.3	45.1	8.4	20.6
2005	233.2	40.7	8.9	20.2
2006	241.8	41.2	9.0	22.2
2007	258.9	42.6	9.2	21.1
2008	243.0	40.5	8.9	20.9

2009	211.9	32.1	8.7	17.3
2010	300.5	30.0	8.0	17.7
2011	300.4	34.2	7.9	17.2
2012	283.5	32.6	7.8	15.2
2013	289.0	32.2	7.9	11.5
2014	286.1	32.6	7.7	11.4
2015	281.9	36.3	7.5	11.5
2016	289.0	34.8	6.8	11.3
2017	308.3	35.7	6.7	11.9
2018	317.3	34.1	6.7	12.4
2019	297.7	33.7	7.4	12.2
2020	286.5	31.6	6.5	9.5

Note: **Data refers to pipelines longer than 40 km.*
Source: *Eurostat. https://ec.europa.eu/eurostat/data/database*

The transport intensity of the French economy from 1990 to 2020, presented in the form of a curve developed using a sixth-degree polynomial and an exponential function, is shown in Figure 1.

Figure 1. *Transport Intensity of the Economy from 2002 to 2020 (Polynomial Function).*



Source: *Own elaboration based on OECD. https://data.oecd.org*

The analysis of the above curve indicates that the highest level of transport intensity in France was achieved in the years 1990–2000. Shaping irregularly during these years, from 2000 onwards, there was a radical decrease in transport intensity which continued until 2020. The reduction in transport intensity thus has a constant trend and has been ongoing for two decades.

The coefficient of determination is 0.9737, indicating a very high value and ensuring the full reliability of the conducted research. Such a radical and consistent reduction in the level of transport intensity over a long-time span is the result of ongoing changes in the French economy and its development based on the latest technologies. This impacts not only the competitiveness of the French economy globally but also environmental protection.

3. Stages of Development of High-Speed Rail in France

France possesses the second-largest high-speed rail network in Europe (after Spain) and the fourth largest in the world (after China, Spain, and Japan) (see International Union of Railways (UIC) & Fundación de los Ferrocariles Españoles, 2023). Services on the French high-speed trains TGV (Train à Grande Vitesse) are operated by the national railway operator SNCF (Société nationale des chemins de fer français).

The idea of launching high-speed rail in France emerged in the 1960s, following Japan's commencement of Shinkansen construction in 1959. At that time, the French government favoured recent technologies, exploring the production of hovercraft and Maglev trains, such as Aérotrain (Decomotiv, 2010). SNCF then began research on high-speed trains that would also operate on conventional tracks.

The TGV project was financed by the government in 1976, and construction of the first high-speed line, Sud-Est, between Paris and Lyon, designed for speeds of 300 km/h, commenced. The inaugural TGV journey took place in 1981 on the first of two sections of the Saint-Florentin–Sathonay-Camp line. The second section, Combs-la-Ville–Saint-Florentin, was completed in 1983. The total length of LGV Sud-Est is 425 km. Subsequent high-speed lines were opened in later years.

In 1990, the 292-kilometer LGV Atlantique was put into operation, running southwest from Paris Montparnasse, with intermediate stations at Massy-TGV and Vendome-TGV. The line has two branches in Courtalain: westward (towards Rennes and Le Mans) and south-westward (towards Tours).

The maximum speed achieved by trains on this line is 300 km/h. The LGV Rhône–Alpes (rail bypass of Lyon), measuring 122 km, was constructed between 1992 and 1994. This line extends southward from LGV Sud-Est, connecting with it near Lyon, bypassing the eastern built-up area of the city, and terminating in Valence. The maximum speed that trains can achieve on this line is 300 km/h.

Opened in 1994, the LGV Nord, measuring 346 km, connected Paris with the Belgian border and continental Europe with London via the Channel Tunnel. At that time, the Eurostar service began operating in TGV format, designed for use in the tunnel and in the UK. The branch towards the Belgian border and the Eurotunnel is located in Lille. Trains reach a maximum speed of 300 km/h on this line.

The LGV Interconnexion Est IDF, opened in 1994 and 1996, measures 105 km and runs through the suburbs of Paris, connecting LGV Nord, LGV Est, LGV Sud-Est, and LGV Atlantique. It has three branches starting in Coubert: westward (towards Paris and western France via LGV Atlantique), northward (to LGV Nord), and southward (LGV Sud-Est). The southern and western branches are also shared with the Sud-Est line. The maximum speed of trains is 300 km/h.

In 2001, the LGV Méditerranée connected Valencia with Marseille via a 259-kilometer route. The opening of this railway line made train travel competitive with air transport, as it allows travel from Paris to Marseille (over 750 km) in three hours. Currently, the railway handles two-thirds of all trips on this route.

The maximum speed that trains can achieve on this line is 300 km/h. In 2007, the first phase of LGV Est Europe was completed, connecting Vaires-sur-Marne near Paris with Baudrecourt (between Metz and Nancy). This is the first high-speed railway in France (maximum speed 320 km/h) that does not pass through Paris. The line provides mixed traffic connections with Basel in Switzerland, southwestern Germany, and northwestern Switzerland.

The second phase of the aforementioned LGV Est Europe was completed in 2016. The 122 km section connected Baudrecourt and Vendenheim near Strasbourg, providing, along with the first phase, fast connections from Paris to major cities in eastern France, as well as to Luxembourg and Germany. The maximum speed achieved by trains on this line is 320 km/h.

In 2017, the western branch of LGV Atlantique was extended by 219 km to Rennes (LGV Bretagne-Pays de la Loire project), while the southern branch to Bordeaux was extended by 340 km (LGV Sud Europe Atlantique project). The maximum speed of trains on these sections is 320 km/h. It should be noted that TGV trains also operate in mixed traffic on standard tracks, at speeds ranging from 160 to 220 km/h. Only about 25% of the total length of tracks covered by TGV services is on dedicated high-speed lines (see Figure 2).

TGV trains carry over 110 million passengers annually, making the French network one of the most heavily utilized high-speed rail systems in the world. Passenger traffic on high-speed trains (TGV) accounts for approximately 60% of total rail passenger transport (Ministères Aménagement du Territoire Transition Ecologique, 2022). The freight work performed by passenger rail transport overall and TGV from 2005 to 2021 is presented in Table 3.

The freight work performed by TGV systematically increased until 2019, reaching 61.9 billion passenger-kilometres. The sudden drop to 35.7 billion passenger-kilometres in 2020 was caused by restrictions related to the COVID-19 pandemic, which significantly limited rail traffic and long-distance travel opportunities.

Figure 2. *High-Speed Rail Network in France.*

Source: *International Union of Railways (UIC) & Fundación de los Ferrocariles Españoles (2023). Atlas High-Speed Rail 2023. Data updated as of December 2022. https://uic.org/IMG/pdf/atlas_uic_2023.pdf*

Table 3. *Freight work performed by passenger rail transport overall and TGV in France from 2005 to 2021 (in billion passenger-kilometres). Including international trains, excluding vehicles operating in the Eurotunnel.*

Year	Total Passenger Transport	TGV Transport
2005	76.9	43.4
2010	ND	53.9
2011	91.3	55.2
2012	91.2	55.2
2013	90.5	54.9
2014	89.5	54.9
2015	91.4	55.2
2016	91.8	54.8
2017	95.0	59.6
2018	91.8	58.6
2019	96.5	61.9
2020	56.6	35.7
2021	75.9	48.6

Source: *Statista. https://fr.statista.com/statistiques/507555/transport-ferroviaire-passager-voyageurs-kilometres-tgv-france/*

With TGV performing 37.5 billion passenger-kilometres in 2020, rail passenger transport (excluding shuttle vehicles in the Eurotunnel) decreased by 42.3% compared to 2019. The following year saw an increase in transport to 48.6 billion passenger-kilometres. TGV trains can reach over 200 cities across France and Europe. SNCF Voyageurs provides passenger services in France and Europe under two TGV brands (Société nationale des chemins de fer français (SNCF), n.d.):

- OUIGO – a cheaper travel option. Services are operated by double-decker trains, which have one class equivalent to second class, with tickets available exclusively online. There are two types of tickets: OUIGO ESSENTIEL, a basic fare where for an additional fee, one can choose a seat with a power outlet, Wi-Fi, or extra luggage, and OUIGO PLUS, which includes all OUIGO services;
- INOUI – offering a higher level of comfort: free onboard Wi-Fi connection, power outlets, reclining ergonomic seats, and more space, especially in first class, as well as a restaurant car.

France is connected to Switzerland by high-speed trains under the TGV Lyria brand, owned by Lyria SAS, which is 74% owned by SNCF and 24% by the Swiss national carrier CFF. TGV Lyria operates daily trains to Geneva, Lausanne, Zurich, and Basel, departing from Paris or Dijon. During the summer, TGV Lyria also serves Switzerland from Lyon Part-Dieu, Avignon TGV, Aix-en-Provence TGV, and Marseille (TGV Lyria Company).

Through international Eurostar services, France has direct connections with the United Kingdom, Belgium, the Netherlands, and Germany. Initially, Eurostar operated as a collaboration of three separate corporate entities from France, the United Kingdom, and Belgium. Since 2010, the company has been registered as a single legal entity under the name Eurostar International Limited, in which SNCF held a 55% stake. In 2022, the European Commission formally approved the merger of Eurostar International and the Belgian Thalys Group. The new entity, named “Green Speed,” will provide high-speed rail travel from the United Kingdom to Germany.

4. Technical Solutions in Selected Trains and Locomotives

TGV 001 – The first prototype was the five-car articulated TGV 001 produced by Alstom in 1969 (Figure 3). The vehicle had two gas turbines in each car powering generators that supplied electricity to two motors located in each of the six bogies. The cars were connected by Jacobs bogies (Graff, 2012). The total power of the train was 3760 kW. During tests, the train reached a maximum speed of 318 km/h. Achieving such a high speed was due to the power-to-weight ratio of the design. The train was designed to accommodate 34 first-class and 56 second-class passengers, as well as a restaurant. The concept of building turbine-powered trains was abandoned due to the oil crisis in 1973 in favour of electric-powered vehicles.

TGV PSE – The successor to TGV 001 was the serially produced TGV PSE (orange TGV Sud-Est trains), which is electric-powered (see Figure 4). It was built by

Alstom and Francorail-MTE. The train consisted of two motor cars and eight passenger cars, utilizing Jacobs bogies. The total length of the train was 200.19 m, and the units could be coupled. The total weight was 385 tons. During tests, the train set a new world speed record of 380 km/h on the line from Paris to Lyon.

The technically permitted maximum speed was from 1981, 260 km/h, raised to 270 km/h in 1983, and subsequently, like most of the fleet, to 300 km/h. TGV PSE trains were produced in a dual-voltage version: 25 kV 50 Hz (for high-speed lines) and 15 kV 16.7 Hz (to ensure access to cities in Switzerland), and several units were also adapted for 1.5 kV DC power (to operate on conventional SNCF lines).

Figure 3. *Prototype TGV 001.*

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The train's power was 6450 kW. In 1984, two TGV PSE trains underwent a second-stage suspension retrofit, replacing springs with air cushions, significantly improving ride comfort. As a result, from 1986 to 1990, all TGV PSE trains underwent such retrofitting. In 1994, all TGV PSE trains were equipped with the classic KVB safety system, and some of the operated TGV PSE trains were equipped with the TVM 430 or TVM 300 systems (Graff, 2012, pp. 16–21).

From 1978 to 1988, a total of 111 TGV PSE traction sets were built. Initially, TGV Sud-Est sets were used on connections between Paris, Lyon, Marseille, and other cities in southeastern France. In 2013, 55 sets were still used on connections to southeastern France and on international routes. The remaining sets were replaced by TGV POS in 2019. The maximum speed was 300 km/h. The train, which had 350 seats, was fully equipped with air conditioning and closed-loop toilets.

TGV Atlantique – This is the next generation of trains after TGV Sud-Est, built by Alstom from 1988 to 1992, with a total of 105 units for servicing LGV Atlantique.

The train was designed as a dual-voltage unit – 25 kV 50 Hz for high-speed lines and 1.5 kV DC for conventional lines.

TGV Atlantique consists of two motor cars located at the ends of the train and ten middle cars. The total length of the train is 237.5 m. The most meaningful change compared to TGV PSE trains was the use of eight brushless synchronous traction motors instead of 12 DC motors, increasing the power of a single train to 8800 kW (Graff, 2012).

Figure 4. *Preserved TGV-PSE Motor Car 23121, built by Alsthom and Francorail-MTE, on display at Cité du Train – Patrimoine SNCF – Musée – Mulhouse – Alsace.*

Source: *https://creativecommons.org/licenses/by-sa/2.0/deed.en*

Additionally, the vehicle's sealing and acoustic insulation were improved. The maximum speed of the train is 300 km/h. The sets were equipped with KVB and TVM 430 safety systems. TGV Atlantique featured metallic blue-grey colours (see Figure 9). Starting in 2015, many of these units were scrapped, and by 2022, only 28 remained in service for passenger transport. Some of the fleet that has been refurbished operates slower lines between Paris and Bordeaux, running only on parts of LGV Atlantique and LGV Sud Europe Atlantique.

The trains were numbered from 301 to 405. In 1990, the modified unit 325 set a new world speed record on the newly opened LGV Courtalain–Tours route, reaching 515 km/h. To improve the power-to-weight ratio, the set – with improved aerodynamics, larger wheels, and enhanced braking – was reduced from a weight of 250 tons to two motor cars and three middle cars. This record was surpassed by TGV POS on April 3, 2007, on LGV Est, as discussed below.

The train was designed to carry 485 passengers: 116 in first class and 369 in second (after refurbishment, the number of seats increased to 459). The cars have facilities for disabled passengers, bicycle storage, and air conditioning. In both first and second class, passengers can use power outlets available at each seat, free Wi-Fi, and purchase food and beverages (G2RailG2Rail-Global and Guided Rail, 2020).

TGV Réseau – The TGV Réseau sets, built by Alstom from 1992 to 1996, entered service in 1993. A total of 80 sets were ordered, of which 50 were in a dual-voltage version, intended for domestic traffic (25 kV 50 Hz, 1.5 kV DC) and 30 in a tri-voltage version (additionally adapted to operate under 3 kV DC), to ensure operation on the railway network of Belgium and Italy (on the Paris–Lyon–Turin–Milan route). The last ten tri-voltage units are Thalys PBA sets (Paris–Brussels–Amsterdam route), built for Thalys, but after the merger in 2022 with Eurostar, they will bear the new logo (SNCF Groupe, 2023).

Figure 5. *TGV Atlantique Train at Montparnasse Railway Station in Paris.*

Source: *https://creativecommons.org/licenses/by-sa/2.5/deed.en*

The mechanical design of TGV Réseau does not differ from that used in TGV Atlantique. However, regarding the electrical part, a higher power transformer and traction motors with higher permissible operating temperatures were introduced.

Additionally, the braking power on each motor block was increased from 1200 to 1600 kW. Compared to TGV Atlantique, more energy-efficient air conditioning units were used. The train also received new software (hardware and software) and a modified TVM 430 cab signalling system. In the electrical part, filters, chokes, and slightly pantographs were changed (Graff, 2012, pp. 17–20).

Each set, 200 m long, consists of two motor cars (8800 kW under 25 kV – the same as TGV Atlantique) and eight middle cars. The maximum speed achieved by the train is 320 km/h.

Many TGV Réseau trains operate on northern routes, where the most tunnels are located. The discomfort experienced by passengers due to pressure changes when entering tunnels at high speed led to the cars being appropriately sealed, maintaining constant pressure inside. Initially, the train had 377 seats (120 in first class and 257 in second). Refurbished sets have 110 seats in first class and 254 in second.

TGV POS – In 2006, for the operation of LGV-Est from Paris towards the east, including Strasbourg and Luxembourg, Alstom delivered 19 TGV POS sets, consisting of two motor cars and eight refurbished TGV Réseau passenger cars. The project allowed for the introduction of new tri-voltage driving cars onto the French high-speed network, needed before the opening of LGV-Est, without slowing down the production of Duplex sets (discussed below).

Figure 6. *TGV Réseau Train at Stade-de-France Saint-Denis Railway Station.*

Source: *https://creativecommons.org/licenses/by-sa/2.0/deed.en*

Asynchronous motors provided 100 kW more power compared to synchronous motors (Charlier, 2006). The tri-voltage function used in the motor cars was essential for continuing the journey from the German border, where electrification switches to the 15 kV 16.7 Hz AC system, as well as on lines in western, southwestern, and southeastern France, where 1.5 kV DC voltage is used. The maximum speed that the train achieves in each system is 320 km/h, with an output power of 9.6 MW under 25 kV 50 Hz AC and 6.8 MW below 15 kV 16.7 Hz AC. From 2013 to 2019, all TGV POS sets were moved from LGV Est to operate under the TGV Lyria brand, and since 2019, they have exclusively served domestic lines.

The safety systems used in the sets include the French RS (so-called crocodile), KVB, and TVM (so-called bi-standard), German Indusi/PZB and LZB, Swiss Signum/Integra and ZUB, with the bi-standard TVM system being a combination of TVM-430 and ERTMS 2 (Graff, 2012, p. 26).

In April 2007, TGV POS V150, consisting of two motor cars and three double-decker cars, set a new world speed record on LGV Est between Meuse and TGV Champagne–Ardenne stations, reaching 574.8 km/h. The train set was equipped with larger wheels, and the voltage in the overhead lines was increased from the standard 25 kV to 31 kV ("French set new rail speed record," 2007).

TGV Duplex – The decision to build the double-decker TGV Duplex train was influenced by the very high number of passengers using the southeastern LGV Sud-Est line. The goal was to increase the capacity of TGV without extending the train or introducing more rolling stock. The project was entrusted to Alstom, which began work on it in 1987. The first batch of 30 units was delivered for operation between 1995 and 1998, with further deliveries occurring after 2000. Currently, the Duplex fleet consists of 160 units that operate on all major high-traffic routes in France.

Figure 7. *TGV POS Train Set No. 4415 in Strasbourg.*

Source: *https://creativecommons.org/licenses/by-sa/3.0/deed.en*

TGV Duplex consists of two motor cars and eight passenger cars, with a length of 200 m. The weight of the powered train with eight three-phase motors with a total power of 8800 kW is 380 tons. Thanks to the extensive use of aluminium in the construction of the boxes, stairs connecting both levels in the passenger cars, and the construction of passenger seats, the axle load is maintained at 17 tons.

The aerodynamic front of the driving units and the distance between the trailers ensure that the train's resistance at a speed of 300 km/h is only 4% greater than that of a single-level TGV (Trains d'Europe, n.d.). The vehicle incorporates innovative solutions by introducing crumple zones in the extreme cars, which absorb energy in the event of a collision.

Additionally, single-stage, microprocessor-controlled Faiveley Cx pantographs with adjustable pressure on the overhead line are installed. The adjustment of the stiffness of the upper part of the pantograph optimizes the contact of the collector with the network when changing speed, voltage, type of overhead line, and when the train operates in single or double traction: 25 kV 50 Hz or 1.5 kV DC (Graff, 2012, p. 21). The maximum speed of the train is 320 km/h.

Passengers using TGV Duplex have access to three first-class cars (with 182 seats), four second-class cars (with 328 seats), and one car with a café-bar. Power outlets are installed at all seats, and free Wi-Fi is available. Both the upper and lower levels have luggage racks and toilets.

Figure 8. *TGV Duplex at the Station in Toulon.*

Source:*https://creativecommons.org/licenses/by-sa/3.0/deed.en*

In 2006, 38 Réseau motor cars were slightly modified and combined with new Duplex cars, creating 19 TGV Réseau Duplex units, which are now part of the TGV Duplex fleet (Trains d’Europe, 2019). The second generation of TGV Duplex consists of Duplex Dasye (Duplex-Asynchrone-ERTMS) trains, built by Alstom from 2008 to 2011. These vehicles are equipped with asynchronous traction motors and ERTMS systems (Railway Technology, 2024), making them suitable for operations on LGV-Est and Perpignan–Figueras lines, as well as BPL and SEA on the Atlantic coast (Kemmeter, 2023).

It is also worth mentioning the commissioning in 2011 of the most modern TGV sets – Avelia Euroduplex (TGV 2N2), which are considered the third generation of TGV Duplex. This series is intended for connections between France and Germany and Switzerland (tri-voltage trains) and for handling increased traffic due to the opening of LGV Ren–Rhone (dual-voltage) and connections with Spain (trains serving passengers under the Ouigo brand, also dual-voltage). These trains are equipped with the ERTMS 2 system.

The French railway industry has implemented its technology, skills, and experience in high-speed rail in 25 countries worldwide. Trains derived from TGV currently operate passenger transport in Spain, Morocco, South Korea, Taiwan, Italy, and the United States (Jones, 2023).

5. Linear Infrastructure for High-Speed Trains

The planning and construction of the French railway system is managed by the Société nationale des chemins de fer française (SNCF). The infrastructure manager of the national railway network is SNCF Réseau. The railway lines, including LGV, are concentrated around Paris and radiate outward in all directions. TGV trains operate on 2737 km of dedicated lines (International Union of Railways (UIC) & Fundación de los Ferrocariles Españoles, 2023) and in mixed traffic (on standard tracks, they reach speeds of 160 to 220 km/h).

Currently, the high-speed rail network mainly focuses on passenger transport. Freight railways transport only 9% of French cargo, which is about half the European average (Boudet & Steinmann, 2020).

French high-speed railway lines are characterized by the following basic technical parameters:

- Maximum axle load: 17 tons,
- Maximum speed: 320 km/h,
- Minimum horizontal curve radius: 4000/4456/7000 m,
- Maximum cant: 25–35‰,
- Track bed width: 13/13.6/13.9 m,
- Distance between track axes: 4.2/4.5 m,
- Cross-section in tunnels: 71.0/2×46, 100 m²,
- Track gauge: 1435 mm,
- Power supply: 25 kV 50 Hz AC, 3 kV DC, 1.5 kV DC (Graff, 2011).

On the latest high-speed lines, trains can achieve speeds of 320 km/h in normal operation. Like most high-speed trains in Europe, TGV on conventional tracks (French: lignes classiques) operate at the normal maximum speed applicable on those lines, which is up to 220 km/h. All LGV junctions are grade-separated. Thanks to the construction of viaducts or tunnels on the lines, the tracks do not intersect.

Monitoring of the French railway network is based on modern technologies that enable real-time data tracking, allowing for increasingly widespread use of predictive maintenance (SNCF Réseau).

For rapid safety checks on French high-speed lines, TGV IRIS 320D is used. This train checks the condition of LGV infrastructure 2–3 times a week, moving at a maximum speed of 320 km/h. The onboard computers, sensors, cameras, detectors, and antennas allow for real-time control of infrastructure in various areas (track, signalling, overhead networks, and telecommunications). This train is equipped with over 75 sensors and 17 measuring systems. All measurements from the sensors are collected and recorded in a computer system consisting of acquisition chains, servers, and operator stations.

In case of detected irregularities, operators send graphs to the monitoring centre, enabling maintenance personnel to adopt necessary corrective measures. The computer software allows expert teams to quickly verify the accuracy of measurements, send alerts, and export these measurements to the national platform (Eurailtest, 2021).

Work is underway to equip high-speed lines with ETCS, which will replace the existing TVM cab signalling system by 2025 and allow for increased train capacity. To test ETCS, NCF Réseau and SNCF Mobilités launched a specially equipped train X72633/634, which replaced one of the existing SNCF test trains. The vehicle is equipped with 27 sensors and antennas installed on the chassis, 23 antennas mounted on the roof, and 5 sensors installed to monitor bogies, axles, and wheels (Railway Pro, 2018).

The ETCS Level 1 system has already been built on the Nîmes–Montpellier bypass, with commissioning planned for 2020–2022, on the Longuyon–Basel branch in the North Sea–Mediterranean corridor. The ETCS Level 2 system is used on the LGV Est (connecting Vaires-sur-Marne near Paris and Vendenheim near Strasbourg), on the HSL Southern Europe Atlantic (between Tours and Bordeaux), and HSL Brittany–Pays de la Loire.

By 2025, it will also operate on the LGV Marseille–Ventimiglia and Paris–Lyon routes. On this last, busiest route, where an average of 240 trains operate daily, SNCF Réseau launched the "LGV+" project in 2020, which, in addition to ERTMS, includes the implementation of Central Network Control (CCR) and the digital traffic control tool GOC 2.0 (SNCF Groupe, 2020).

Since December 2020, the French railway market has been open to competition. However, new carriers face many challenges in entering the high-speed rail market. A study conducted by the Transport Regulatory Authority (ART) identified numerous obstacles, including difficulties in acquiring and integrating onboard safety systems necessary for operating on the French network. High prices for access to railway infrastructure were also noted (Barnier, 2022).

Nevertheless, in 2021, Trenitalia launched a connection from Milan to Paris, operated by Frecciarossa trains. Additionally, the Spanish operator Renfe, interested in servicing LGV Rhône–Alpes, Méditerranée, and Perpignan–Barcelona, began operations on these lines with AVE trains in 2023 (Geerts, 2022).

6. Funding Methods for High-Speed Rail

The program for constructing high-speed lines not only in France but also in Europe is part of government and regional socio-economic development strategies. French LGVs have been built both through investments made solely by the public sector and through public-private partnerships (PPP). Financing for LGVs involves the government, local communities supported by taxes and bank loans (e.g. EIB), and the European Union.

Examples of investments realized by the public sector include LGV Sud-Est, LGV Rhône–Alpes, and LGV Est, while the construction of LGV Atlantique on the Tours–Bordeaux section (running westward) and the LGV Bretagne–Pays de la Loire extension towards Rennes and Nantes in the south was financed through PPP.

The first project implemented in France, LGV Sud-Est, had a total estimated cost of €2.9 billion, with €236 million co-financed by Alsace communities, including €95 million from the Alsace region (Toute l'Europe. Comprendre l'Europe, 2011).

LGV Atlantique, on the Tours–Bordeaux section, was built based on a signed 50-year concession agreement in 2011, the largest to date (Railway Technology, 2017), concluded between LISEA and RFF (now SNCF Réseau). LISEA is a company owned by VINCI Concessions (33.4%), Caisse des Dépôts (25.4%), MERIDIAM (24.4%), and Ardian (16.8%), with its concession agreement expiring in 2061 (LISEA).

Under this agreement, LISEA was responsible for the realization, financing, and currently maintaining the infrastructure line from Tours to Bordeaux. The total value of the contract was €7.8 billion. LISEA's contribution amounted to €3.802 billion, including €773 million in equity and €3.029 billion in bank loans. Eiffage receives remuneration based on availability fees for the line.

Also in 2011, a 25-year contract was signed between RFF and Eiffage Rail Express (ERE), a subsidiary of the Eiffage group, covering the design, construction, financing, and maintenance of LGV Bretagne–Pays de la Loire (Rennes–Le Mans). The total value of the contract was €3.3 billion, including contributions from local authorities and RFF of €1.851 billion, funds obtained from loans from financial institutions (12 commercial banks, Caisse des Dépôts et de Consignation, and EIB) of €1.029 billion, equity contributions of €129 million, and European grants of €11 million.

The contract was divided into two phases: construction and maintenance. In return for the investment, the state committed to paying ERE rent for part of the investment pre-financed by RFF and rent for the maintenance and renewal of the line during the operational phase until 2036 (Eiffage Infra-Bau SE).

Currently, work is underway on the 409-kilometer high-speed line LGV Sud-Est between Paris and Lyon to implement ETCS, which replaced the existing TVM cab signalling system by 2025. The project value is €700 million, of which €125 million comes from EU funds. Equipping high-speed lines with the ETCS system will increase capacity from 13 to 16 trains per hour (Smith, 2020).

Despite ongoing modernization of the railway network, including the implementation of Central Network Control (CCR) and ERTMS, France remains far behind other European countries, such as Germany or Switzerland, in this regard (La Galaxie Sénat, 2022).

The main reason for this delay is the lack of sufficient public funding for the modernization of existing lines. In a report submitted to the French Senate in December 2022, it was stated that the project to update the agreement between SNCF Réseau and the government does not foresee any changes in the pool of funds allocated for the revitalization of the railway network, which will remain at a constant level of around €2.85 billion until 2030.

In comparison, under the 2030 Climate Action Program, Germany has planned €62 billion for the modernization of its railway network by 2030. According to the authors of the report, France lacks a funding model and a precise assessment of the full cost of projects that could activate plans for implementing ERTMS and CCR, as well as stimulate compliance with environmental commitments and modal shift.

Discussing the funding of LGV in France, it is worth mentioning the Great South-West Rail Project (GPSO), which involves the construction of two high-speed lines branching from Bordeaux towards Spain: Bordeaux–Toulouse and Bordeaux–Dax, along with a complete reconstruction of stations on these routes. The project owners are SNCF Réseau and SNCF Gares & Connexions (the company managing railway stations).

The total investment cost is estimated at €14 billion (before the Covid-19 pandemic), of which 40% is to come from the state budget, 40% from municipal revenues (administrative regions of Occitanie and New Aquitaine), and 20% from EU funds (Peychieras, 2022). The participation of municipalities in the investment will be based on a new tax on special equipment (TSE), introduced by the financial law for 2023 (LOI n° 2022-1726). The tax applies to landowners – legal entities and individuals based in municipalities located less than 60 minutes by car from a station served by the future high-speed line (this concerns 2,340 municipalities) (Arcuset, 2023).

It should be noted that high-speed rail transport in France is not subsidized, as its economic efficiency remains appropriately high. The passenger rail market is subsidized with public funds, with the share of subsidized transport amounting to 38% (Raczyński and Pomykała, 2019).

7. Plans and Directions for Further Development

The SNCF Group, along with other European railway companies, with the support of the EU and national governments, has joined the campaign to combat climate change by increasing the share of rail transport. Achieving this goal is expected to enable the fight against climate change by reducing greenhouse gas emissions associated with transport by 26% by 2030 (SNCF Groupe).

Efforts to reduce the environmental impact of rail transport are being conducted on many fronts, including reducing the carbon footprint of lines, reusing materials removed during track modernization, managing a recycling facility for railway materials, and limiting waste.

Actions have also been taken to recover ballast, the extraction of which causes enormous losses in biodiversity and water resources. By 2025, SNCF Réseau aims to use 25% of recycled aggregate annually on the railway network. Currently, used ballast is collected, screened in factory trains, washed, and processed, and then divided into various categories and reused in the railway system for stabilizing high-speed lines or the French network of small rural lines, or sold to the construction industry.

On railway-owned land, over 1,000 hectares have been designated where SNCF plans to install photovoltaic panels capable of generating peak energy of about 1,000 megawatts (MWp), which in the first phase of the project will cover 15–20% of the current electricity demand of the railway. Panels will be installed as ground-mounted devices, as well as on building roofs and canopies over parking lots.

Energy from photovoltaic installations will help power trains, of which 80% are electrically powered, and will also be used to power electrical devices at railway stations, in industrial and residential buildings, and in electric vehicle charging points in stop parking lots.

Local authorities that participate in financing the investment will be able to use part or all the energy to power local equipment and buildings, providing communities with a new way to diversify their energy basket and accelerate ecological awareness. In 2021, the French parliament adopted a decree banning domestic flights on short distances that can be reached by train within 2.5 hours (L'administration française, 2023), thus the necessity to limit greenhouse gas emissions creates opportunities for the expansion of high-speed lines, which was restricted in 2017.

Currently, work is underway on the construction of the Lyon–Turin high-speed line, which is part of the Mediterranean TEN-T corridor, with completion planned for 2032. The connection requires the boring of two base tunnels crossing the Alps, measuring 57.5 km in length, including 45 km in France. It is estimated that thanks to the future line, passenger train travel from Paris to Milan will take five hours, reducing the journey by two hours (Virano, 2021). Additionally, the French government in 2021 considered the construction of the new routes discussed below (Kemmeter, 2021).

The LGV Montpellier–Perpignan will connect the French and Spanish high-speed networks with a 150-kilometer section. Currently, the LGV ends at the Montpellier station, while in Perpignan, another international high-speed line begins, leading to Barcelona in Spain and also constituting part of the Mediterranean TEN-T corridor.

The new line will accommodate mixed traffic. The construction consists of two phases: the first between Montpellier and Béziers (about 53 km) and the second between Béziers and Perpignan (98 km). The first phase is expected to be completed by 2034, and the second by 2040 ("Funding agreement advances high speed link to Perpignan," 2022). The aforementioned Great South-West Rail Project (GPSO) includes the LGV Bordeaux–Toulouse, measuring 222 km, intended for passenger traffic, with commissioning planned for 2030. The extension of the Bordeaux–Dax line is planned in the second phase of GPSO ("Le financement du projet de la ligne à grande vitesse Bordeaux-Toulouse officiellement bouclé," 2022), with both lines having a common section of 55 km connecting southern Bordeaux and southern Gironde.

It is estimated that the implementation of GPSO, due to the modal shift from air and road transport to rail, will have a positive CO_2 emission balance after 10 years (Dailey, 2023). In the years 2038–2042, work is also planned on the concept of building a connection from Dax to Spain, which will serve as a link in the Atlantic TEN-T corridor. The commencement of work on this line is planned for after 2043 (CADE, 2023).

The reconstruction of LGV Massy–Valenton ("Barreau de Massy"), located about 30 km from Paris and constituting the southern bypass of the capital, will ensure good connectivity of the high-speed network in the southwest and southeast of the country. Currently, about 100 trains of the Paris suburban railway (RER C), TGV, and freight trains operate on this line, with one track for TGV traffic between Massy and Antony, as well as crossing zones for TGV and RER C.

Ongoing development work on the western sector of LGV Massy–Valenton will eliminate conflicting crossings and create a second route dedicated solely to TGV. The construction of a new station at Pont-de-Rungis will also enable convenient connections to Orly Airport. The completion of the project is scheduled for 2025 (SNCF Réseau, 2023).

In addition to planned investments in the expansion of high-speed lines, work continues on the application of modern technologies in high-speed trains. In 2016, SNCF and Alstom signed a contract to design and build a new generation of trains that will reduce acquisition and operating costs, decrease energy consumption, and improve travel comfort (Barrow, 2016).

As a result of this process, the fourth-generation TGV project, named Avelia Horizon (TGV M), was completed in 2018. In the same year, SNCF ordered 100 such trains, with deliveries expected to begin in 2024 ("SNCF confirms TGV of the Future order," 2018). Energy recovery, eco-driving, and a more aerodynamic shape of the vehicle allow for a reduction in energy consumption by one-fifth. TGV M will be equipped with two innovative, shorter driving heads (cars) that combine high efficiency and compactness.

The double-decker passenger cars are based on Jacobs bogies. The modular design is intended to allow for the assembly of the number of units (7, 8, or 9), depending on needs, and even reconfiguration of space, e.g., first class to second or seating to luggage or bicycle storage. In maximum configuration, it will be able to accommodate up to 740 passengers (20% more than currently).

Figure 9. *TGV M tested on the Paris–Brest line.*

Source: *https://creativecommons.org/licenses/by-sa/4.0/deed.en*

The carbon footprint of the TGV M being built is the lowest on the market, and 97% of the train's components are recyclable. TGV M is fully compliant with SNCF Group's environmental protection commitments, as CO_2 emissions are reduced compared to current generations by 32%. SNCF estimates that maintenance costs will be 30% lower.

The maximum speed of the fourth-generation TGV will be the same as that of the current fleet, which is 320 km/h (Coste, 2021). The train has been operating on the French network since 2024, both in INOUI and OUIGO TGV services (Schindler, 2022).

8. Conclusions

The following conclusions can be drawn from the studies presented in the article. France is the seventh-largest economy in the world and the second in Europe. The French economy is characterized by a very modern structure. Transport and its infrastructure in France are also modern and well-developed. Both the economy and transport in France are based on the latest technologies. The dynamic development of high-speed rail has increased the mobility of the French society, which undoubtedly contributes to economic and social development.

Currently, high-speed rail accounts for over half of total passenger transport. This makes the French network one of the most heavily utilized high-speed rail systems in the world. The technical solutions in the sequentially introduced generations of trains and locomotives are increasingly modern and efficient. Thanks to them, higher vehicle speeds, greater safety, and comfort of travel are achieved. An important criterion for the changes made is the planned replacement of traditionally sourced energy for propulsion with renewable energy.

However, experts argue that a certain drawback in the development of high-speed rail infrastructure in France is the lack of a funding model and a precise assessment of the full scope of the project. Eliminating this drawback could contribute to activating implementation plans.

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