High-Speed Railways in Asia

The History and Future of High-Speed Railways in Japan

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Introduction

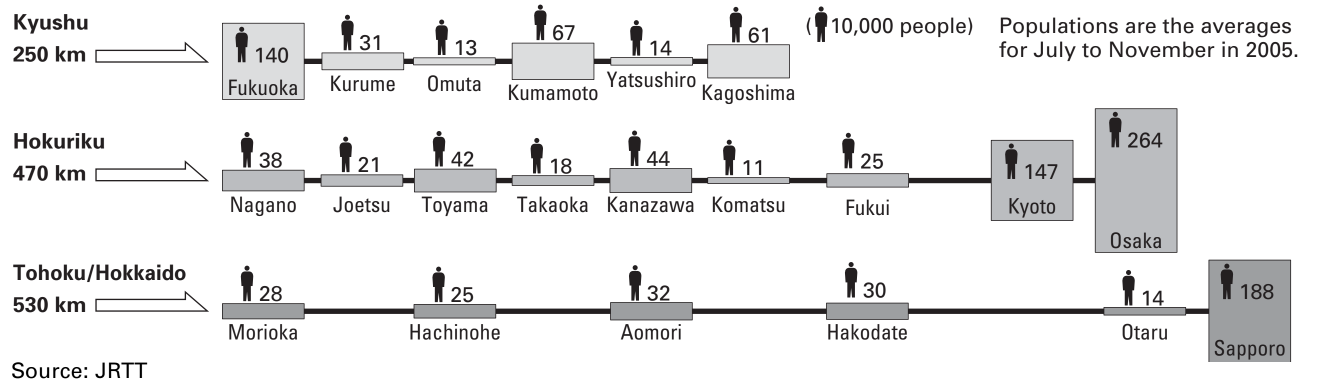
The Tokaido Shinkansen entered revenue service as the world's first full-scale high-speed railway system on 1 October 1964, just in time for the opening of the Tokyo 1964 XVIII Olympics. Since then, the shinkansen has played an important role in Japanese business and leisure travel, becoming the world benchmark for high-speed transport and carrying 2173 billion passenger-km in speed and safety. The shinkansen is also heralded for reversing the decline of railways in the face of increasing road and air travel and creating a new era of high-speed railway travel. Shinkansen technology has developed in line with Japan's social and economic changes and has seen rising speeds, cost savings, and safety, as well as falling environmental impact. Following the JNR privatization and division, a new shinkansen construction plan has seen the network expand while each regional operator in the JR group has developed new trains and improved infrastructure targeted at increased speeds and enhanced services based on regional transportation needs. Japan Railway Construction, Transport and Technology Agency (JRTT) is currently constructing about 590 km of new shinkansen lines on four routes and railways are attracting heightened recent interest due to their higher efficiency and lower environmental impact than air and road transport.
This article takes a look at the history of the shinkansen in Japan, the plan for building lines, lines currently under construction, development of shinkansen technology and the characteristics and impact of the shinkansen, as well as future systems.

Japan and High-Speed Railways

Geography

Japan is a long, thin archipelago at the edge of Eurasia on the Pacific Ocean. It is comprised of the four main islands of Honshu, Hokkaido, Kyushu and Shikoku, plus more than 3000 smaller islands. About 73% of the total land area is mountainous and the main centres of population for the 127 million Japanese are on the coastal plain or bordering rivers. As a result, the cities along the coastal plain have high population densities and are linked by railways. Sitting on the Pacific Rim of Fire, Japan is very volcanic with severe geological, geographic, and climatic conditions; volcanic eruptions, earthquakes, landslides, tsunamis, typhoons, and heavy snowfalls are all frequent. Running safe, on-time, high-speed services through this type of terrain requires many long tunnels and bridges designed to withstand earthquakes, as well as countermeasures to earthquakes, floods, and deep snow. Furthermore, since shinkansen tracks pass through densely populated cities, stringent noise and vibration environmental standards are required too.
Figure 1 shows the size of cities on shinkansen routes currently under construction and on planned routes.

Figure 1 Size of Cities on Shinkansen Routes



Source: JRTT

Intercity railway network and record

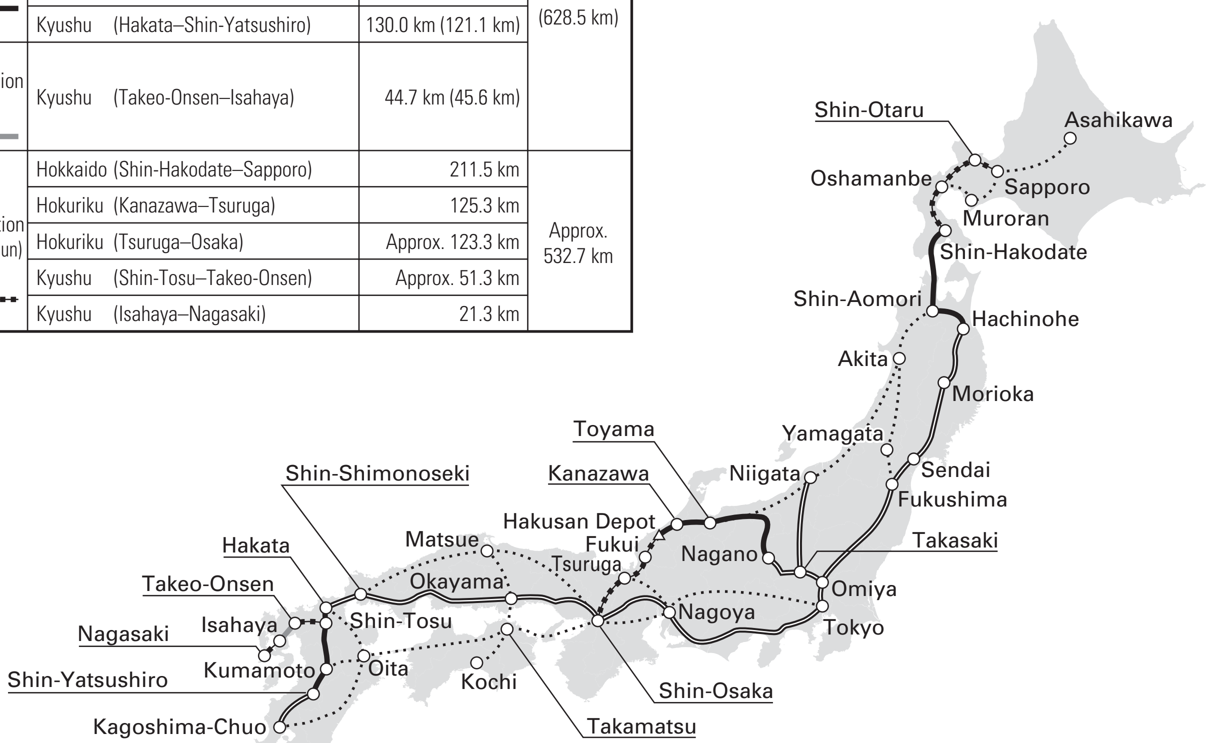
In FY2004, railways held a 24.8% share of transport in Japan, carrying an average of 60 million passengers every day. The average number of daily passenger-km for the same period was 1.06 billion (27.2% of all transportation modes), which is a greater proportion than in most other countries. On the other hand, only 3.9% of freight tonne-km went by rail with the vast majority carried by road and coastal shipping.

About 20,000 track-km of Japan's 27,300 track-km of passenger lines are owned by operators in the JR group of companies; there are about 153 railway operators in Japan, excluding monorails, new transit, and other light rail systems. The intercity network (excluding shinkansen, urban railways in major cities, and local lines) spans 10,596 km. In 1987, the newly formed operators in the JR group took over operation of the old Japanese National Railways (JNR) lines as a result of the privatization and division. All these conventional lines, except some directly linked to shinkansen, use the same narrow gauge (1067 mm). Another five shinkansen lines, using the standard gauge, have been built since the Tokaido Shinkansen—the San'yo, Joetsu, Tohoku, Hokuriku and Kyushu Shinkansen—for a current total of 2176 km in the network. Maximum speeds vary from 260 to 300 km/h. Another 590 km of shinkansen tracks are currently under construction on the Hokkaido, Tohoku, Hokuriku and Kyushu lines. A further 4100 km, including extensions to existing shinkansen lines, are in the planning stage (Fig. 2).

Figure 2 Japanese Shinkansen Network

Total			Line extension (Construction extension)	6,852 km
Lines in operation	Tokaido	(Tokyo–Shin-Osaka)	515.4 km	2,175.9 km New shinkansen lines 340.8 km
	San'yo	(Shin-Osaka–Hakata)	553.7 km	
	Tohoku	(Tokyo–Morioka)	496.5 km	
	Tohoku	(Morioka–Hachinohe)	96.6 km	
	Joetsu	(Omiya–Niigata)	269.5 km	
	Hokuriku	(Takasaki–Nagano)	117.4 km	
	Kyushu	(Shin-Yatsushiro–Kagoshima-Chuo)	126.8 km	
New lines planned (construction already begun)	Hokkaido	(Shin-Aomori–Shin-Hakodate)	148.8 km (148.7 km)	634.1 km (628.5 km)
	Tohoku	(Hachinohe–Shin-Aomori)	81.8 km (81.2 km)	
	Hokuriku	(Nagano–Kanazawa)	228.0 km (231.1 km)	
	Hokuriku	(Fukui Station)	0.8 km (0.8 km)	
	Kyushu	(Hakata–Shin-Yatsushiro)	130.0 km (121.1 km)	
(Construction planned)	Kyushu	(Takeo-Onsen–Isahaya)	44.7 km (45.6 km)	
(Construction not yet begun)	Hokkaido	(Shin-Hakodate–Sapporo)	211.5 km	Approx. 532.7 km
	Hokuriku	(Kanazawa–Tsuruga)	125.3 km	
	Hokuriku	(Tsuruga–Osaka)	Approx. 123.3 km	
	Kyushu	(Shin-Tosu–Takeo-Onsen)	Approx. 51.3 km	
	Kyushu	(Isahaya–Nagasaki)	21.3 km	

Lines in basic plan	Hokkaido	(Sapporo–Asahikawa)	Approx. 3,510 km
	Hokkaido south route	(Oshamanbe–Muroran–Sapporo)	
	Uetsu	(Toyama–Niigata–Akita–Aomori)	
	Ouu	(Fukushima–Yamagata–Akita)	
	Chuo	(Tokyo–Osaka)	
	Hokuriku/Chukyo	(Tsuruga–Nagoya)	
	San'in	(Osaka–Matsue–Shimonoseki)	
	Chugoku crossing	(Okayama–Matsue)	
	Shikoku	(Osaka–Takamatsu–Oita)	
	Shikoku crossing	(Okayama–Takamatsu–Kochi)	
	East Kyushu	(Fukuoka–Oita–Kagoshima)	
	Kyushu crossing	(Oita–Kumamoto)	

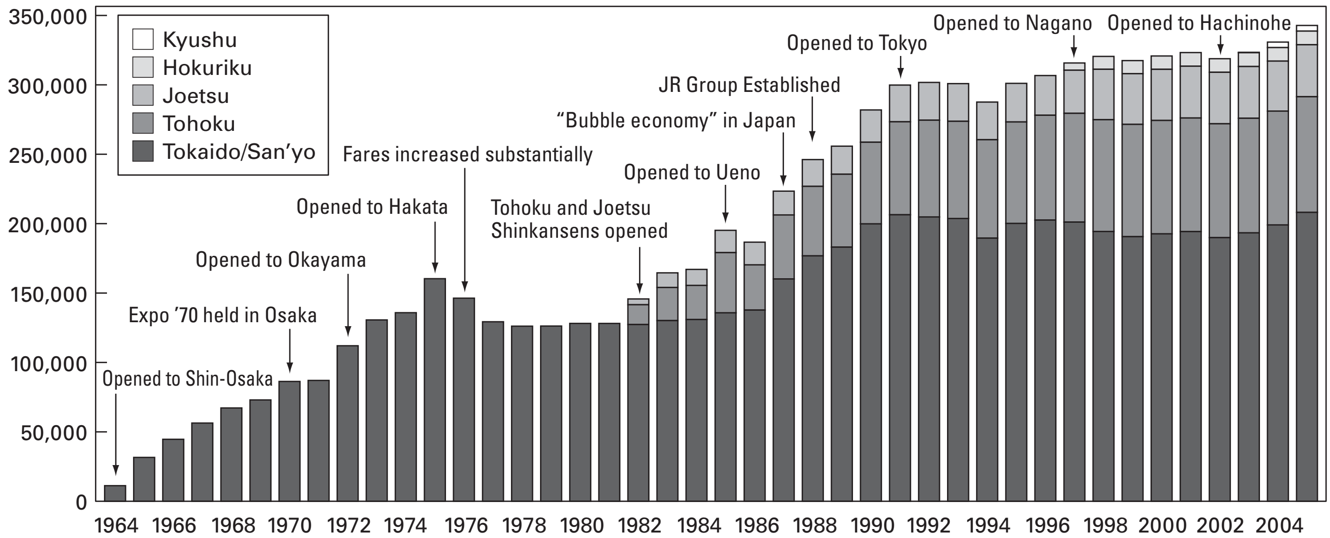


Source: JRTT

Figure 3 Annual Shinkansen Passengers

From FY1988, some passengers are counted more than once by different companies so there is no continuity from before that year.

(1,000 passengers per annum)



Source:
Railway Handbook (up to and including FY1985), Ministry of Land, Infrastructure and Transport Railway Bureau (from FY1988)
Railways in Numbers, 2006

The number of shinkansen passengers has risen annually in line with development of the system, although a short-term drop was seen during the economic recession and after the 1995 Great Hanshin-Awaji Earthquake in Kobe. By the end of FY2005, the shinkansen had carried a total of 8.2 billion passengers. In 2005, an average of 920,000 passengers used the shinkansen every day (approximately 213 million passenger-km per day) (Fig. 3). The number of passengers using a daily commuter pass to ride the shinkansen is also on the rise, reaching 47,000 in FY2004. The shinkansen accounts for 31% of total passenger-km travelled on all lines of operators in the JR group to date. Indeed, JR Central derived 85.9% of its revenue (non-consolidated basis) in FY2006 from the Tokaido Shinkansen. Shinkansen operations also account for a large proportion of JR East's revenue (24.6% in FY2006).

Postcard picture of 300 series shinkansen passing Mt Fuji

History of Shinkansen

Start of Tokaido Shinkansen

The first railway line in Japan opened between Shimbashi and Yokohama in 1872, using a narrow gauge of 1067 mm. All main lines built subsequently between major population centres in Japan prior to the shinkansen were to the narrow-gauge standard, and made a major contribution to Japan's economic, industrial, and social development. In 1906 and 1907, all existing 17 private lines were nationalized. Following the postwar reorganization of transport, JNR was established in 1949 as a public corporation.

Although the Tokaido Shinkansen—Japan's first high-speed railway—opened in 1964 with a line between Tokyo and Shin-Osaka, its construction had long been demanded because the carrying capacity of the old Tokaido main line serving the Tokaido coastal belt from Tokyo to Osaka had been reached. There had been various prior proposals about converting the narrow-gauge main line to standard gauge and expand capacity but it was finally decided to build a standard-gauge line completely separate from the existing narrow-gauge network. This is in contrast to many European and other networks where the entire network uses the same standard gauge. The 1964 opening of the Tokaido Shinkansen saw journey times for the 515.4 km between Tokyo and Osaka drop from 6 hours 30 minutes by limited express to 3 hours 10 minutes, making a 1-day round trip possible.

Opening of San'yo Shinkansen

Following the success of the Tokaido Shinkansen, JNR's third long-term business plan included plans to construct the San'yo Shinkansen parallel to the existing line between Shin-Osaka and Hakata. Construction of the 160.9-km section between Shin-Osaka and Okayama began in 1967 and opened for revenue service in March 1972. Work between Okayama and Hakata began in 1970 and the section opened in March 1975. About half the 553.7-km length of the San'yo Shinkansen is in tunnel and the 18.71-km Shin-Kammon Tunnel linking Honshu and Kyushu under the Kammon Strait was completed on schedule using the grouting and pipe roof methods.

Construction of the San'yo Shinkansen used new techniques, such as slab track along the entire track length, to cut life cycle and maintenance costs by eliminating ballast and conventional sleepers.

Shinkansen Railway Development Law and opening of Tohoku and Joetsu shinkansen

Development of the shinkansen network was a key part of the 1969 Second Comprehensive National Development Plan and led to the promulgation of the Nationwide Shinkansen Railway Development Law in May 1970. Originally, the shinkansen lines were seen as a way to solve the problem of insufficient capacity on JNR's conventional lines, but the passage of the Development Law meant that shinkansen lines had become part of the national strategy to achieve balanced development nationwide and to revitalize the regions.

The infrastructure plans for the Tohoku (Tokyo–Morioka), Joetsu, and Narita shinkansen were approved in April 1971 and were closely followed by the October approval of the construction plans for the Tohoku Shinkansen between Tokyo and Morioka (496.5 km) and the Joetsu Shinkansen between Omiya and Niigata (269.5 km). Construction of the two lines began in the same year, with JNR overseeing the Tohoku Shinkansen, and Japan Railway Construction Public Corporation (JRCC) overseeing the Joetsu Shinkansen. (In October 2003, JRCC merged with the Corporation for Advanced Transport and Technology (CATT) to form the Japan Railway Construction, Transport and Technology Agency (JRTT).)

In 1973, the plans were approved for five shinkansen—the Tohoku (Morioka–Shin-Aomori), Hokkaido, Hokuriku, Kyushu (Kagoshima route), and Kyushu (Nagasaki route) lines—commonly called the 'projected shinkansen lines.'

The Tohoku Shinkansen opened between Omiya and Morioka in June 1982 and the Joetsu Shinkansen opened between Omiya and Niigata in November of the same year. The start of construction for the section from Tokyo to Omiya fell behind schedule due to opposition from people living along the planned route as a result of increased concerns about noise pollution but eventually opened in March 1985. Construction between Tokyo and Ueno was overseen by the Shinkansen Railway Holding Organization following the JNR privatization with the work commissioned to JR East; revenue service started in June 1991.

New shinkansen projects after 1987

In September 1982, the Cabinet decided to put the plans to build new shinkansen lines on hold based on the July 1982 recommendations of the Ad Hoc Commission on Administrative Reform due to JNR's worsening financial situation. Nevertheless, support for the shinkansen was so strong throughout Japan that the Cabinet decision was reversed in January 1987, immediately prior to the JNR division and privatization with JRCC selected to oversee construction of the lines. In Cabinet discussions, it was agreed to take note of the June 1986 recommendation by the Provisional Council on Administrative and Fiscal Reform to build the new shinkansen lines based on the results of the new operating companies following the JNR division and privatization and a review of income and expenditure.

The 1987 railway reforms transferred responsibility for operations of the Tohoku and Joetsu shinkansen lines to JR East, the Tokaido Shinkansen to JR Central, and the San'yo Shinkansen to JR West. The September 1987 Law on Transfer of Construction Projects for Shinkansen Lines Overseen by Passenger Railway Companies to JRCC transferred responsibility for constructing shinkansen lines to JRCC.

The Shinkansen Railway Holding Organization established as part of JNR privatization owned the four existing shinkansen lines (Tokaido, San'yo, Tohoku and Joetsu) and leased the infrastructure facilities to the operating companies. However, this arrangement was abandoned in 1991 when it was realized that the operators could not easily draw-up long-term business plans because they could not depreciate shinkansen assets and the Shinkansen Railway Holding Organization was disbanded in October 1991. Its role was taken over by the Railway Development Fund (RDF) with responsibility for transferring all shinkansen assets and liabilities to the railway operators in the JR group. Some profits from the sale were earmarked for development of urban and main lines. The RDF merged with a shipping-related organization in October 1997 to form CATT, which then merged with JRCC in October 2003 to form JRTT.

A government and ruling party working group established in January 1988 determined the priority for starting work on five sections on three lines (first: Takasaki–Nagano on Hokuriku and Takaoka–Kanazawa on Hokuriku; second: Morioka–Aomori on Tohoku; third: Kagoshima route on Kyushu; and fourth: Itoigawa–Uozu on Hokuriku), and procuring funding sources. Construction started in August 1989 but part of the funding changed in December 1996. Finally, the March 1988 opening of the Tsugaru-Kaikyo

Line through the 53.8-km Seikan Tunnel, linking Honshu and Hokkaido under the Tsugaru Strait, coupled with the April 1988 opening of the Seto Ohashi Bridges connecting Honshu and Shikoku made the long-awaited dream of linking all four Japanese main islands by rail a reality.

Through services to shinkansen

In 1988, the government proposed three shinkansen construction methods: full-scale standard-gauge shinkansen; narrow-gauge track for the foreseeable future but with infrastructure to accommodate future shinkansen (super express system); and conversion of conventional lines to standard gauge. Some narrow-gauge lines were widened to standard gauge so that through services using shinkansen trains could be operated but these were not covered by the Nationwide Shinkansen Railway Development Law. Gauge-change work was done between Fukushima and Yamagata (87.1 km) with this section opening in July 1992 and was extended 61.5 km (commonly called the Yamagata Shinkansen) to Shinjo in December 1999. A similar section between Morioka and Akita (127.3 km) opened in March 1997 and is commonly called the Akita Shinkansen.

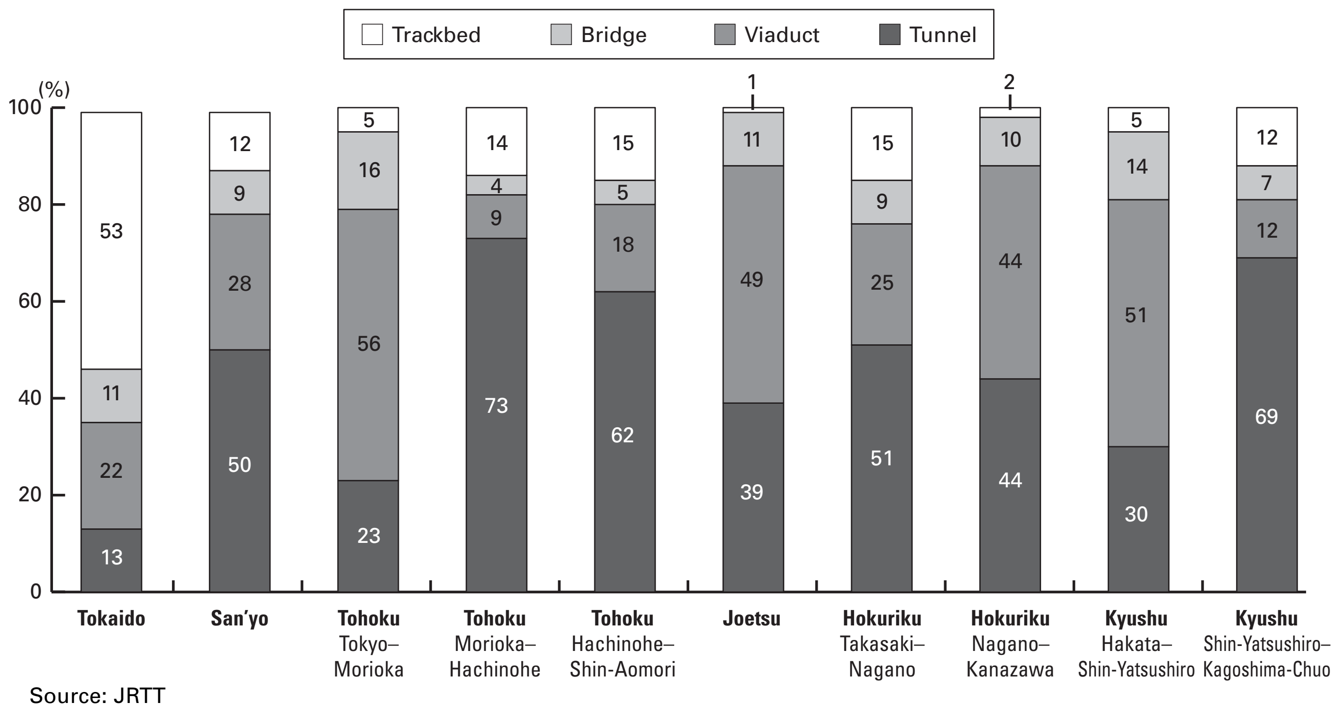
New shinkansen schemes

Following the formation of the JR group of railway operators, shinkansen operations have started over 340.8 km of new lines: the Hokuriku Shinkansen (117.4 km from Takasaki to Nagano), the Tohoku Shinkansen (96.6 km from Morioka to Hachinohe) and the Kyushu Shinkansen (126.8 km from Shin-Yatsushiro to Kagoshima-Chuo).

The Hokuriku Shinkansen is actually about 700-km long, extending from Tokyo to Osaka via Nagano, Toyama, and Kanazawa. Since it runs on the existing Joetsu Shinkansen from Tokyo to Takasaki, only the section between Takasaki and Osaka is new construction. Construction of the Takasaki–Karuizawa section was approved in June 1989 and work began in November. Construction of the Karuizawa–Nagano section was approved in October 1991 and the line opened in October 1997 in time for the Nagano 1998 XVIII Olympic Winter Games. It was difficult to hold down the Hokuriku Shinkansen construction costs and keep on schedule because overcoming the 660-m climb through the Usui Pass posed a considerable problem, requiring a steep grade of 30‰ (a first in shinkansen history) as well as development of new trains. Also ground-level stations, high-speed points, and simple overhead catenary were developed. Although slab track had previously only been used in tunnels and elevated viaducts, on this line it was also used for the trackbed on soil roadbed.

The Tohoku Shinkansen (Morioka–Hachinohe) opened in December 2002, following construction approval for the Numakunai–Hachinohe section in August 1991, and the Numakunai–Morioka section in April 1995. This was the first northward extension in 20 years since the Omiya–Morioka section opened in 1982. Although 73% of the Morioka–Hachinohe section is in tunnel, costs were cut by using large boring machines. Costs were also cut by building ground-level stations at Ninohe and Hachinohe.

Figure 4 Breakdown of Shinkansen by Percentage of Structures



Source: JRTT

The 257-km Kyushu Shinkansen (Kagoshima route) links Hakata Station on the San'yo Shinkansen Line with Kagoshima-Chuo Station. The section from Shin-Yatsushiro to Kagoshima-Chuo began revenue service in March 2004. It was the first new shinkansen in Kyushu since the San'yo Shinkansen opened 29 years earlier and is operated by JR Kyushu. *Tsubame* services make across-platform connections with *Relay Tsubame* expresses on the Kagoshima main line at Shin-Yatsushiro Station. About 70% of the Kyushu Shinkansen runs in tunnel and new boring technologies were developed for the weak ground in the Shirasu plateau to save construction costs. In addition, hybrid civil engineering and building structures were used to cut costs.

Kyushu Shinkansen *Tsubame* leaving Kagoshima-Chuo Station against backdrop of Sakurajima

Across-platform change at Shin-Yatsushiro Station

Table 1 Major Shinkansen Developments

Date	Development
Oct 1964	Tokaido Shinkansen (Tokyo–Shin-Osaka) opened
May 1970	Nationwide Shinkansen Railway Development Law enacted
Mar 1972	San'yo Shinkansen (Shin-Osaka–Okayama) opened
Mar 1975	San'yo Shinkansen (Okayama–Hakata) opened
Jun 1982	Tohoku Shinkansen (Omiya–Morioka) opened
Sep 1982	Plans to build new shinkansen lines put on hold as result of Cabinet decision
Nov 1982	Joetsu Shinkansen (Omiya–Niigata) opened
Mar 1985	Tohoku Shinkansen (Ueno–Omiya) opened
Jan 1987	Cabinet lifts freeze on building shinkansen lines
Apr 1987	JNR Division and privatization
Mar 1988	Tsugaru-Kaikyo Line (including Seikan Tunnel) opened
Jun 1991	Tohoku Shinkansen (Tokyo–Ueno) opened
Oct 1997	Hokuriku Shinkansen (Takasaki–Nagano) opened
Dec 2002	Tohoku Shinkansen (Morioka–Hachinohe) opened
Mar 2004	Kyushu Shinkansen (Shin-Yatsushiro–Kagoshima-Chuo) opened
Dec 2004	Decision to begin construction of Hokkaido Shinkansen (Shin-Aomori–Shin-Hakodate (provisional))
Apr 2005	Approval for construction of Hokkaido Shinkansen (Shin-Aomori–Shin-Hakodate (provisional))

Hybrid structure of Izumi Station on Kyushu Shinkansen

Future Shinkansen Construction

Development

Following the JNR division and privatization, part of the Nationwide Shinkansen Railway Development Law was amended to give JRTT responsibility for overseeing construction of all shinkansen lines. A two-tier system was established with infrastructure owned by JRTT and leased to the operators. To avoid a recurrence of the debts incurred by JNR, the cost and profitability of any new shinkansen line must be thoroughly examined before construction approval can be given. Other basic conditions include obtaining consent from local municipalities and concerned JR operators regarding the impact on and management of conventional lines running parallel to the new shinkansen.

Funding

In the JNR era, most funding for new shinkansen lines came from loans, raising public criticism about how JNR was responsible for its worsening finances. As an example, the Joetsu Shinkansen was almost exclusively financed by the Fiscal Loan Fund and other loans. Under the new leasing scheme, the operator pays track usage fees based on the operating profits accrued from the new shinkansen, but bears no other direct construction costs. The national government bears two-thirds of the direct construction costs (as public works costs and some profits from the sale from existing shinkansen) and local municipalities bear the other one-third.

Parallel conventional lines

Since the opening a new shinkansen inevitably reduces passenger numbers (and revenues) on conventional lines running parallel to the new line, in December 1996, the government decided to allow transfer of such lines from the operator to a third-sector company based on local circumstances.

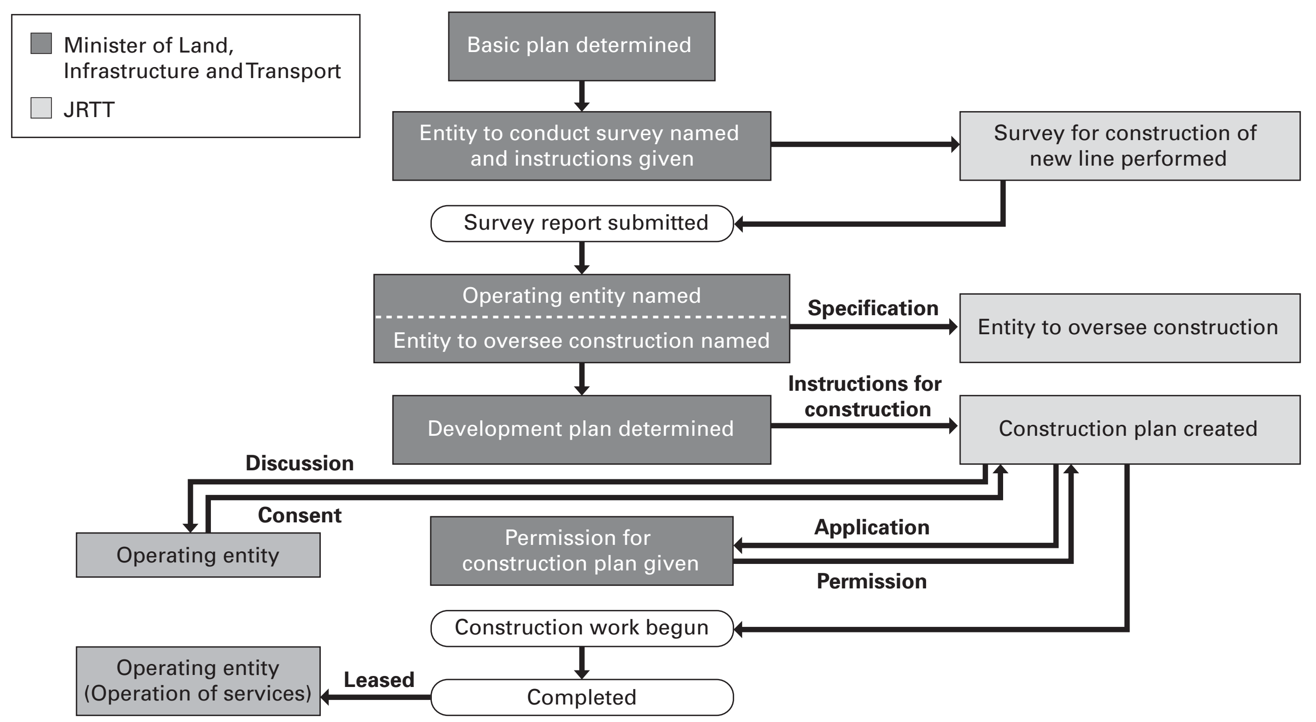
Environmental considerations

Before a new shinkansen line can be built, an environmental impact study on the effect of the proposed construction, infrastructure, and services (noise, vibration, etc.) on the landscape, scenery, animals, plants, residents, must be made in consultation with the local authorities based on the 1997 Environmental Impact Assessment Law.

Shinkansen Lines Now Under Construction

At April 2007, 590 km of new shinkansen lines are under construction on four routes—the Hokkaido Shinkansen (Shin-Aomori–Shin-Hakodate (provisional name)), Tohoku Shinkansen extension (Hachinohe–Shin-Aomori), Hokuriku Shinkansen (Nagano–Kanazawa and Fukui Station) and Kyushu Shinkansen (Hakata–Shin-Yatsushiro). A shinkansen corridor running almost the full length of Japan from Shin-Aomori Station at the northernmost tip of Honshu to Kagoshima-Chuo Station at the southernmost tip of Kyushu is scheduled to be complete by the end of FY2010.

Figure 5 Procedures for Construction of New Shinkansen Line



Hokkaido Shinkansen

The Hokkaido Shinkansen will run from Shin-Aomori to Shin-Hakodate (provisional name) to extend the shinkansen from Shin-Aomori by 149 km. Including the section through the Seikan Tunnel, it will share 82 km with the Tsugaru-Kaikyo Line. Three new shinkansen stations are scheduled to be built on the route at Oku-Tsugaru (provisional), Kikonai, and Shin-Hakodate (provisional); the last two stations will have connections with services on conventional lines.

Bridges and viaducts total 29 km in Aomori Prefecture and 38 km in Hokkaido Prefecture. There are also 8 km of tunnels in Hokkaido. Infrastructure on the section shared with the Tsugaru-Kaikyo Line has been built to easily accommodate the shinkansen. For example, the conventional narrow-gauge track through the Seikan Tunnel has a third outer rail to run full-specification shinkansen services over the same section. The overhead shinkansen catenary is also in place too.

Boring Oshima-Tobetsu Tunnel on Hokkaido Shinkansen

Dual-gauge tracks in Seikan Tunnel

Tohoku Shinkansen extension

The Tohoku Shinkansen is being extended 82 km from Hachinohe to Shin-Aomori with a new intermediate station at Shichinohe (provisonal). Construction to full shinkansen specifications started after construction permission in March 1998. About 62% of the section between Hachinohe and Shin-Aomori is in tunnel as is most of the section between the Hachinohe and Shichinohe stations, which includes extensive diluvial upland and the northernmost tip of the Ou mountain range. In particular, the 26.5-km Hakkoda Tunnel under Mt Hakkoda is currently the world's longest double-track rail land tunnel.

Hokuriku Shinkansen extension

The Hokuriku Shinkansen is being extended by 228 km from the current Nagano terminus via Toyama to Kanazawa (Hakusan Depot (provisional). The section between Nishi-Isurugi Signal Box (provisional) and Kanazawa received approval for the super express system in August 1992, with the other sections approved later. Seven stations are scheduled to be built on this section at Iiyama, Joetsu (provisional), Itoigawa, Shin-Kurobe (provisional), Toyama, Shin-Takaoka (provisional) and Kanazawa.

About 44% of the extension is in tunnel, with some very long, including the 22.2-km Iiyama Tunnel crossing the border between Nagano and Niigata prefectures. There are also high bridges over motorways as well as other sections with long bridges.

The tracks at Fukui Station have been elevated over an 800-m section in conjunction with the Echizen Railway to save construction costs. The JR West Hokuriku main-line tracks have already been elevated and similar work is underway for the new shinkansen line.

Construction of elegant 7-span Himekawa Bridge on Hokuriku Shinkansen

Station for new shinkansen line under construction

Kyushu Shinkansen (Hakata–Shin-Yatsushiro)

The Kyushu Shinkansen is currently being extended by some 130 km from Shin-Yatsushiro to Hakata. Shinkansen facilities are being incorporated into two existing stations at Kurume and Kumamoto, while four new shinkansen stations will be built at Shin-Tosu (provisional), Funagoya, Shin-Omuta (provisional) and Shin-Tamana (provisional). Construction of the Hakata–Shin-Yatsushiro section is underway following approval of the plans (super express system) for the Funagoya–Shin-Yatsushiro section in March 1998 and for the Hakata–Funagoya section (full shinkansen) in April 2001.
The route has many viaducts and bridges but only about 30% is in tunnel, because the line crosses many relatively flat areas, such as the cities of Kurume and Kumamoto, as well as the Chikugo and Yatsushiro plains.

Development of Shinkansen Technology

Tokaido Shinkansen high-speed technologies

Prior to constructing the Tokaido Shinkansen, various technologies encompassing construction standards, civil engineering structures, track, rolling stock, electric power supply and automatic train control systems were researched to achieve the required speed, capacity and safety levels. Such technologies were verified using high-speed tests at the Kamonomiya test track. To achieve maximum operating speeds of 250 km/h, curves were specified with a larger radius than on conventional lines and the maximum grade was lowered. In addition, the entire line was designed with full grade separation to eliminate all level crossings.
Since shinkansen rolling stock uses an airtight structural design, the cross-section of (double track) tunnels was set to about 60 m^2. Optimization of track geometry was also investigated to solve problems of high lateral forces resulting from high train speeds.
Although many long-distance trains around the world are locomotive hauled, to achieve better performance (and faster turnaround) the shinkansen designers decided to use distributed traction with power units in each of the carriages, as well as electric service brakes. Technical problems caused by high speed, such as aerodynamic resistance, track adhesion, running stability, pantograph power collection, axle bearings, braking distance, and pressure waves when entering tunnels and passing at high speeds, were all the subject of extensive R&D. Since the

Relay Tsubame passing Chikugo Kumano Viaduct under construction on Kyushu Shinkansen

shinkansen draws much higher power than conventional electrical multiple units (EMUs), the overhead catenary is powered at the international standard of 25,000 V. The catenary wire and suspension all required new strengthened materials and designs with a high propagation velocity matching the high shinkansen speeds. Conventional trackside signalling systems were no longer of any use in securing safe operation at high speeds because shinkansen crews could not respond quickly enough to the signal aspects. To solve this problem, advanced in-cab signalling and automatic train control (ATC) systems were developed along with centralized traffic control (CTC). (See *JRTR* 21 for more details.) The technologies discussed above are essentially systems that skilfully combine already developed elements.

Increasing shinkansen speeds

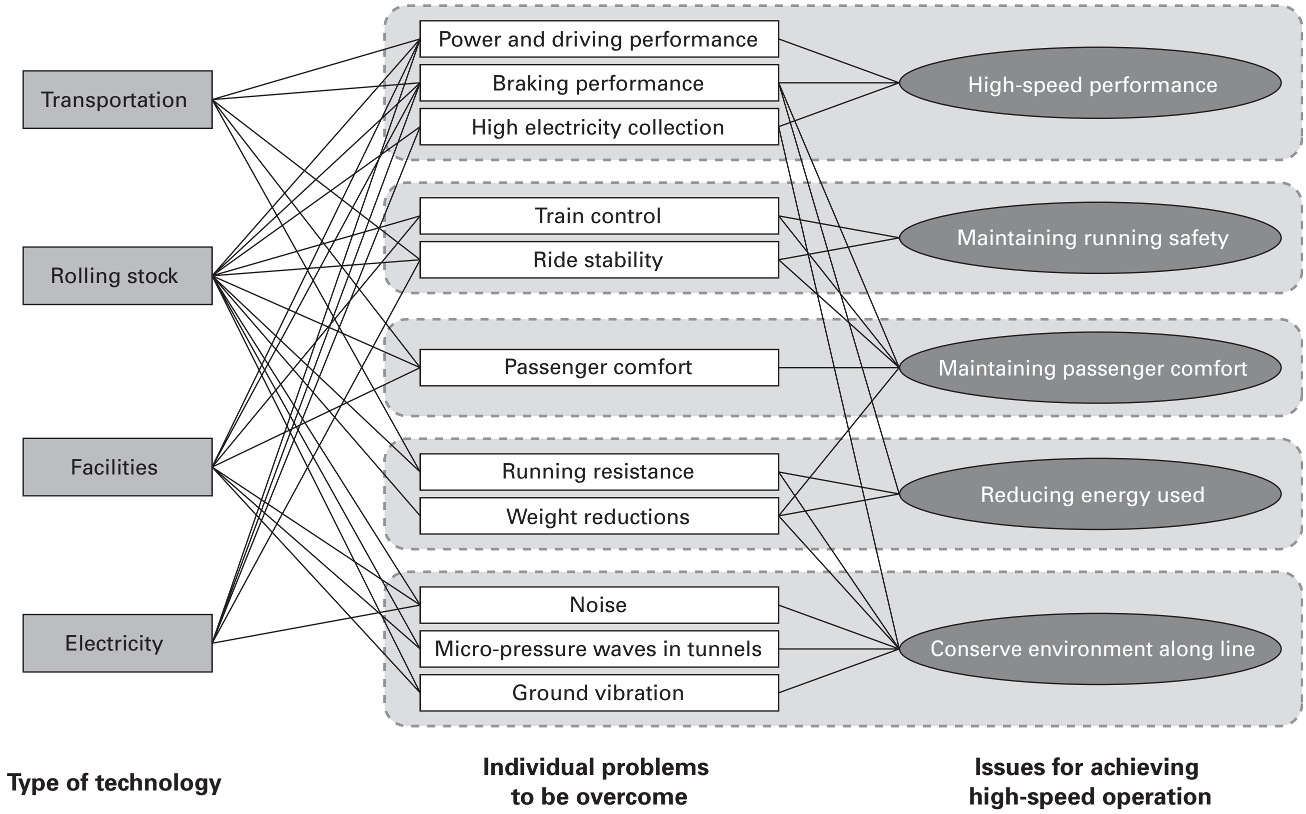
When the Tokaido Shinkansen started revenue operations, its maximum speed was 210 km/h. The experience gained from the Tokaido Shinkansen as well as new technical advances helped facilitate the opening of the San'yo Shinkansen. For example the minimum radius of curves was increased from 2500 m to 4000 m and the maximum grade was reduced from 20‰ to 15‰. Instead of the 50-kg rails used on the Tokaido Shinkansen, 60-kg rails were used along with more robust electrical facilities, including AT-feeding and heavy compound overhead catenary. Continuous ventilation provided a supply of external fresh air while maintaining the air pressure inside the train within a small range, irrespective of changes in external air pressure. Further improvements made during later construction of the Tohoku and Joetsu shinkansen and thereafter helped increase train speeds (Fig. 6). For example, the Tohoku Shinkansen reached a maximum speed of 240 km/h in 1985 just 3 years after opening in June 1982, while the maximum speed of the Tokaido Shinkansen was upgraded to 220 km/h after upgrading the ATC system to dual-frequencies in November 1986. Achieving even higher speeds meant overcoming a range of other problems, including maintaining running stability and passenger comfort, reducing energy consumption, and conserving the environment along lines. Operations, rolling stock, infrastructure, and power supply were all the subject of extensive R&D but the environmental considerations proved the hardest hurdle to overcome. Large weight savings were achieved by making full use of the EMU system (Fig. 7) and the 16-tonne maximum axle capacity of the first 0 series rolling stock has been reduced to 11.4 tons for the new N700 series, helping reduce track and infrastructure wear and tear, and cutting noise and vibration. Following the 1987 division and privatization, each operator in the JR group of companies began competing to develop technologies supporting higher shinkansen speeds. In 1992, JR Central's *Nozomi* 300 series reached a maximum speed of 270 km/h on the Tokaido Shinkansen. Not to be outdone, in March 1997, JR West increased the maximum speed of the *Nozomi* 500 series to 300 km/h on the San'yo Shinkansen. The corresponding maximum speed on the Tohoku and Joetsu shinkansen is currently 275 km/h.

Figure 6 Shinkansen Construction Specifications

	Tokaido	San'yo	Tohoku/Joetsu	Hokuriku Takasaki–Nagano	Tohoku Morioka–Hachinohe	Kyushu Yatsushiro–Kagoshima-Chuo
Minimum radius of curvature (m)	2,500	4,000	4,000	4,000	4,000	4,000
Maximum grade (‰)	20	15	15	30	20	35
Basic track structure	Ballast	Ballast, Slab	Slab	Slab	Slab	Slab
Rail weight (kg/m)	53 → 60	60	60	60	60	60
Overhead catenary voltage (V)	25,000	25,000	25,000	25,000	25,000	25,000
Frequency (Hz)	60	60	50	50/60	50	60
Feeding system	BT → AT	AT	AT	AT	AT	AT
Overhead catenary system	Composite element ↓ Heavy compound	Heavy compound	Heavy compound	High-speed simple overhead catenary	High-speed simple overhead catenary	High-speed simple overhead catenary
ATC System	Single-frequency →Dual-frequency →Digital	Single-frequency →Dual-frequency	Dual-frequency	Dual-frequency	Digital	Digital
Train radio system	Radio waves→LCX	Radio waves, LCX	LCX	LCX	LCX	LCX
Core transmission line	Multiple small-diameter coaxial cables	Multiple small-diameter coaxial cables	Multiple small-diameter coaxial cables→ Optical fibre cable	Optical fibre cable	Optical fibre cable	Optical fibre cable

Notes: 1. Standard specifications have been given. The specifications on some sections of track may differ.
2. The arrow sign shows the initial specification and subsequent improvements made.

Figure 7 Diagram of Speed-related Technologies



Source: A History of Technologies Developed for Higher Speeds for the Tokaido Shinkansen

Environmental conservation

Noise and other environmental problems resulting from the high shinkansen speeds were a significant problem for trackside residents and the Environment Agency issued a recommendation in December 1972 about urgent measures to reduce shinkansen noise. Environmental standards for noise levels on shinkansen lines under construction were set in July 1975 and vibration guidelines were issued in March 1976. As a result, work began on developing various technologies to reduce noise, vibration and other environmental effects of shinkansen in an attempt to meet the targets. Most R&D was carried out at the Oyama Test Line on the Tohoku Shinkansen with improvements to both ground facilities and rolling stock. New ground facilities included vibration-absorbing slabs and similar track structures, noise barriers, and baffles at tunnel portals to mitigate micro-pressure waves causing tunnel boom. For rolling stock, the shape of the lead car nose was redesigned for lower drag, train weight was reduced, pantographs were redesigned to generate less aerodynamic noise, and the number of pantographs was cut.

Safety measures

When the Tokaido Shinkansen entered service, the ATC was using only single frequency. Dual-frequency ATC started in 1982 with the opening of the Tohoku and Joetsu shinkansen. More recently, new ATC systems using digital technologies based on train position data have been developed to perform smooth stepless braking control. Further, successive improvements have been made to CTC systems, and other systems have been developed, notably COMTRAC in 1972, and COSMOS in 1995.

The Joetsu Shinkansen passes through Japan's snow country where overnight falls can exceed 1 m. Safe and punctual winter operations on this shinkansen are assured by using track sprinklers to melt snow and ice. The Tohoku Shinkansen also runs through snowy regions so the line is elevated and the concrete slab trackbed is deeper than normal.

Since the coastal part of the Tohoku region near the Pacific Ocean is very earthquake prone, the Tohoku and Joetsu shinkansen infrastructure is designed with high seismic resistance and is backed up by the Urgent Earthquake Detection and Alarm Systems (UrEDAS) using a network of detectors that instantly stop all trains in the nearby regions when the first earthquake P-waves are detected (see *JRTR* 43).

Cost reduction

Another problem with shinkansen construction is how to hold down costs and construction time. Construction costs tend to rise in line with inflation, delays in buying residential land, the need for environment conservation measures, aseismic design requirements, etc. These can be partly mitigated by various initiatives in the planning stage, such as restricting the height of structures, using more powerful trains to climb steeper grades, downsizing station facilities, and using existing facilities when possible. Further cost savings can be achieved by using standard designs and developing new civil, electrical, and mechanical engineering technologies.
Legal attempts have also been made to obtain required land more easily by using the Land Expropriation Law.

Kyushu Shinkansen running on ladder track

Service improvements

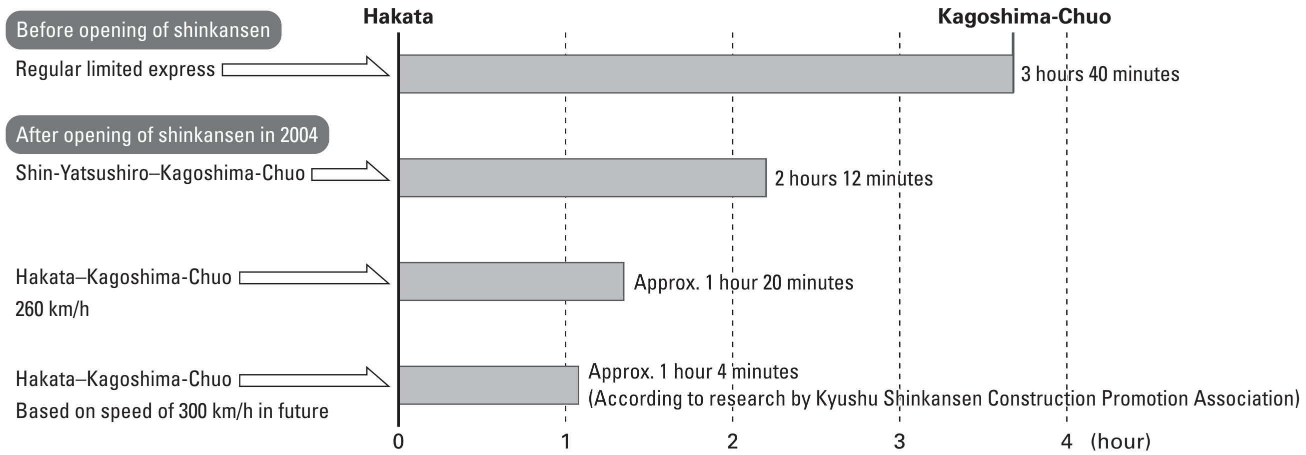
Following JNR division and privatization, the six successor operators in the JR group of companies have worked hard to tailor their services to the regional and customer needs. For example, the various shinkansen series now in operation include 16-car train sets, mini-shinkansen operating through services on both shinkansen and conventional lines, double-decker commuter carriages, etc. Other recent initiatives include Internet seat reservations and e-tickets using mobile phones.

Shinkansen Features and Effects

High speed and reduced travel time

The speed of shinkansen services has reduced travel times and increased the appeal of rail compared to other transport modes. For example, the opening of the Hokuriku Shinkansen from Takasaki to Nagano cut the time required to travel from Tokyo to Nagano by more than 50% from 2 hours 56 minutes to just 1 hour 23 minutes. As a result, the number of passengers increased by more than 40%. Similarly, extension of the Tohoku Shinkansen from Morioka to Hachinohe reduced the time taken to travel from Tokyo to Hachinohe on the fastest train by 37 minutes to 2 hours 56 minutes. The result was a better than 60% increase in passenger numbers. The opening of the Kyushu Shinkansen from Shin-Yatsushiro to Kagoshima-Chuo cut the time to travel from Hakata to Kagoshima-Chuo from 3 hours 40 minutes to 2 hours 12 minutes and passenger numbers rose sharply by 240% (Fig. 8).
A survey of Kyushu Shinkansen passengers on their transport mode before the shinkansen showed 20.9% had travelled by car, 16.2% by plane, and 6.9% by express

Figure 8 Comparison of Travel Times Before and After Kyushu Shinkansen Opening



Source: JR Kyushu

bus, indicating a clear shift from other transport modes to the shinkansen. Furthermore, 16% said that they would have travelled somewhere else or not made the trip at all if the shinkansen was not operating, showing that the new shinkansen line has created new travel demand.

Figure 9 shows the percentage share of various transport modes for travel from Tokyo to various cities on the shinkansen route to Hakata. The shinkansen commands a 50% to 80% share for journeys between 200 and 800 km. However, rail's share is 20% to 40% less for cities the same distance apart but not linked by shinkansen. It seems that speed helps shinkansen to compete with cars, planes, and other transport modes. Although air enjoys a large market share for distances over 800 km, this is because Fukuoka Airport is close to the city centre so airport access times are short. Travel by shinkansen is convenient because stations are usually in the city centre, provide quick inter-modal transfers, and train services are frequent. Motorways have a larger share than shinkansen for distances of less than 200 km, although this mode has safety and congestion problems.

Capacity and frequency

Although a shinkansen's passenger capacity depends on the train series and configuration, as two examples, 16-car Tokaido Shinkansen 700 series trains accommodate 1323 passengers, while 16-car Tohoku Shinkansen E4 series trains configured with all double-decker cars carry 1634 passengers. These figures are two or three times the capacity of a Boeing 747.

The Tokaido Shinkansen entered service with 60 runs a day, increasing to 235 after 1987 and again to 301 in FY2006. In fact, shinkansen run about as frequently as subways in major cities or urban railways. During the morning rush hour, the shinkansen minimum headway is just 3 minutes with an average of 15 runs per hour, including trains forwarded to the depot. The Tokaido Shinkansen alone carried an average of 390,000 passengers each day in FY2006.

Safety and punctuality

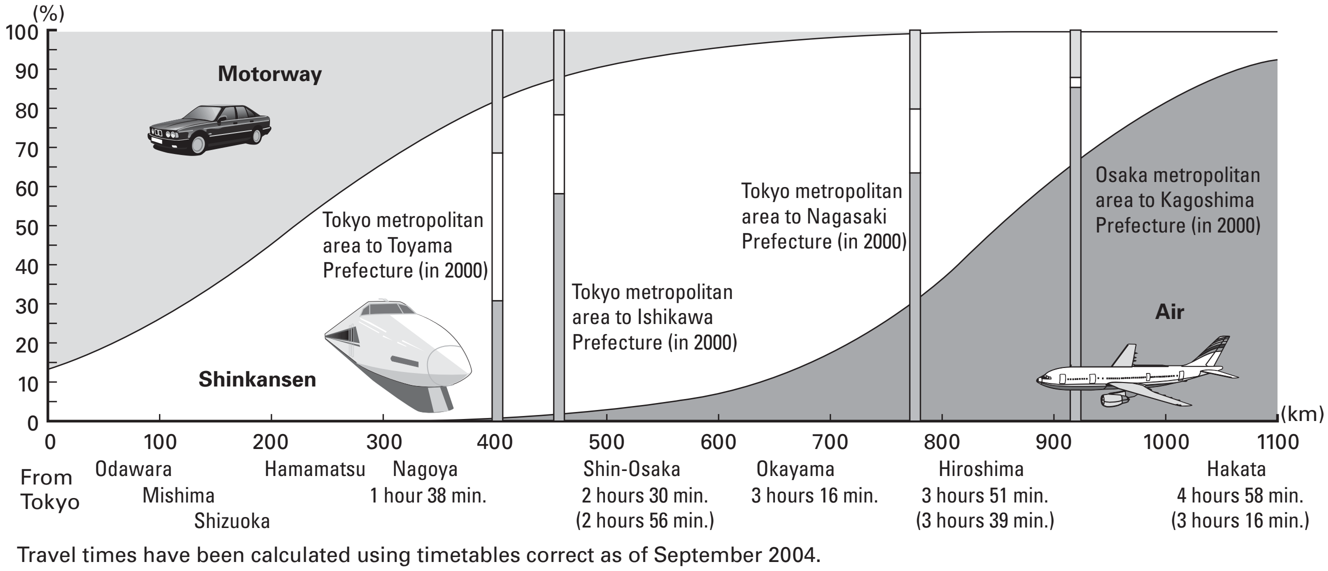
Not a single fatal passenger accident has occurred since the shinkansen began operation in 1964, thanks mainly to the grade separation and ATC safety systems. This compares with 6625 deaths in car accidents in FY2005 (285 on expressways). Clearly the shinkansen is much safer than travelling by car.

As an example of the shinkansen's excellent punctuality record, the Tokaido Shinkansen maintained an average delay per service of only 36 s in FY2005. In winter, services on the Tohoku and Joetsu shinkansen passing through areas with heavy snowfall are almost unaffected thanks to the snow countermeasures, while airports are often closed and motorways are subject to speed restrictions.

Energy reduction and other environmental considerations

Global warming, energy consumption and depletion of oil reserves are now serious environmental problems in which expanded use of rail for travel can play an

Figure 9 Share of Transport Modes with Distance Travelled



Travel times have been calculated using timetables correct as of September 2004.
The lower figures in parentheses include transfer times to and from airports.
Shares have been calculated from results of the third Net Movement of Passengers on Trunk Routes throughout Japan Survey (2000) (areas along shinkansen lines).
Figures for the Tokyo metropolitan area are calculated by summing the results for Saitama, Chiba, Tokyo, and Kanagawa prefectures.
Figures for the Osaka metropolitan area are calculated by summing the results for Kyoto, Osaka, and Hyogo prefectures.

important role because rail is more environmentally friendly than other transport modes because full trains use less energy per passenger and produce fewer CO_2 emissions. For example, the amount of CO_2 per rail passenger-km is about 16% of the figure for air and about 11% of the figure for a car.

Although the latest *Nozomi* series on the Tokaido Shinkansen runs 60 km/h faster (270 km/h) than the first 0 series (210 km/h), it consumes 32% less energy due to the lighter weight, regenerative braking, etc.

Ripple effects of new shinkansen

Construction of new shinkansen lines brings a range of benefits to passengers and the railway operator. As well as shorter travel times, which allow passengers to travel further and stay longer at their destination, the shinkansen also offers enhanced safety, comfort and reliability. There are also several considerable knock-on benefits for areas along the line, such as enhancing the location of companies, promoting tourism and social interactions.

In particular, the expansion of the high-speed transportation system from large-scale investment in shinkansen lines, motorways, airports, harbours and other transportation infrastructure that began in the 1960s supported Japan's subsequent rapid economic growth. By allowing some manufacturers to locate their plants throughout the country, the development of Japan's nationwide high-speed transport network has also played a role in helping solve the over-centralization of people and resources in major cities, which causes regional disparities in employment opportunities and income.

As an example, what has been the impact of the March 2004 opening of the Kyushu Shinkansen between Shin-Yatsushiro and Kagoshima-Chuo?

Unlike shinkansen links to Tokyo, the Kyushu Shinkansen trackside population is relatively low. As a result, the local regions undertook a number of initiatives in the run-up to the opening. For example, JR Kyushu helped redevelop the area around the Kagoshima-Chuo Station terminus building with entertainment facilities, shops, restaurants, and cinemas. The areas around other shinkansen stations were also made more appealing. Station plazas have been developed for better inter-modal connections with other transport modes, such as buses and taxis, and an active south Kyushu tourism promotion campaign was also conducted by local authorities and private companies.

According to a survey by the Kagoshima Regional Economic Research Institute, 53% of Kyushu Shinkansen passengers in the year immediately after it opened came from outside Kagoshima Prefecture. The Institute estimates that the increased consumption in Kagoshima Prefecture as a result of the extra visitors totalled ¥9.6 billion and that the total knock-on effect was worth ¥16.6 billion. The Kagoshima success story is thought to be attributable to the strategic initiatives taken to maximize the effect of the shinkansen through cooperation between local government and private companies and provides a shining example for new shinkansen lines in the future.

Development of station buildings and plaza at Kagoshima-Chuo Station for opening of Kyushu Shinkansen

Future Outlook

National Spatial Strategies and high-speed railway network

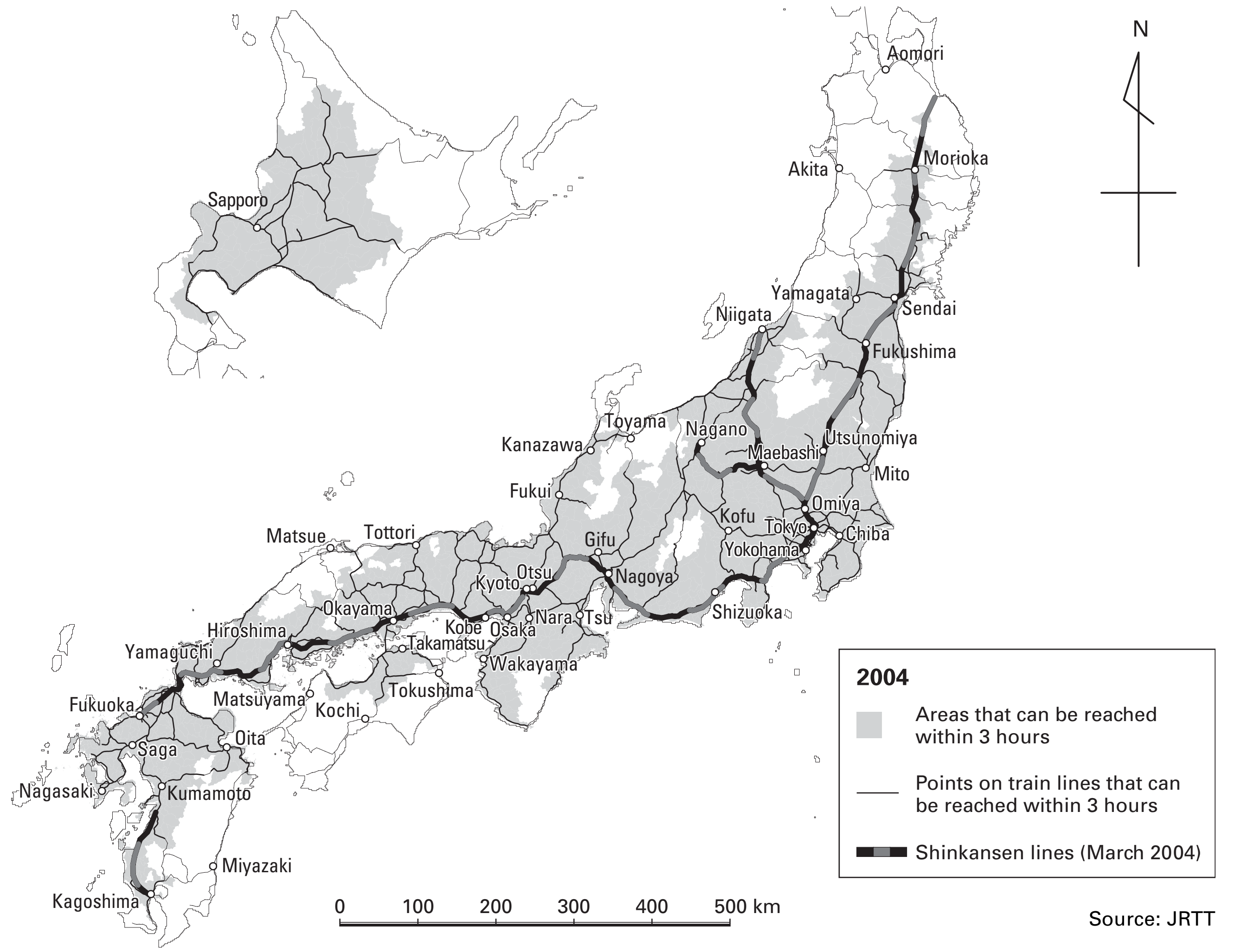
With rising income and more leisure time, Japanese consumption patterns are set to change and diversify. Population and industry are also likely to be more decentralized and the industrial structure will probably shift towards high-added-value, knowledge-intensive businesses and service industries. Meanwhile tighter energy supplies, environmental restrictions, IT developments, internationalization and the aging Japanese population will all significantly impact social changes. The National Spatial Strategies currently being formulated by the government aims to enhance the international competitiveness of Japan's regions by dividing the country into large-scale economic blocs. As part of the policy focus, shinkansen are seen as revitalizing regions outside the Pacific coastal belt by promoting tourism and social interaction within and between the large-scale blocs.

One-day Travel Initiative

In August 2000, the Council for Transport Policy proposed a One-day Travel Initiative making all major regional cities accessible within 3 hours from Tokyo, Osaka, Nagoya, Sapporo, and Fukuoka. To achieve this aim, the plan advocated both continued expansion of shinkansen lines and creation of extended rail networks linking both shinkansen and conventional lines to achieve increases in speed and convenience.

Construction of new shinkansen lines requires securing of appropriate funding, cutting construction costs, and reaching agreement between related parties. Achieving extended rail networks linking shinkansen and conventional lines requires faster speeds on main lines and convenient transfers between shinkansen and other trains. To achieve through operations on both shinkansen and conventional lines with different gauges, a Gauge Change Train (GCT) is being developed so the axle length can adjust automatically to either standard gauge (1435 mm) or narrow gauge (1067 mm). Testing of the second GCT prototype is currently scheduled for summer 2007.

Figure 10 Map of Locations within 3 Hours of Five Main Japanese Cities (2004)



Increase in shinkansen speed and performance

JR Central and JR West have developed the next-generation N700 series shinkansen for the Tokaido and San'yo Shinkansen. It features an air-spring tilting system to permit travel through tighter curves (2500-m radius) at 270 km/h; other key features are full covers between cars, low noise, more comfortable and wider seats, and reduced power consumption. JR Central has announced that revenue service will start on 1 July 2007.

In a bid to operate shinkansen at 360 km/h, JR East is testing its FASTECH360 train at speeds up to 400 km/h to evaluate reliability, environmental compliance, and passenger comfort. In addition, JR East completed the E954 series test train for use on shinkansen lines in 2005, and the E955 series test train for through operation on shinkansen and conventional lines in March 2006. The E955 is undergoing running tests on the Tohoku Shinkansen and a section of the Akita Shinkansen. Tests are also being made on running the E954 and E955 on adjacent tracks in opposite directions at high speed, and on coupling the two trains.

Maglev development

Maglev R&D began in 1962 when it was realized that the practical limit of steel wheels on rails is somewhere around 350 km/h. A record speed of 517 km/h was achieved on the Miyazaki Test Track in 1977 and tests continued on the 18.4-km Yamanashi Test Line from 1997. The world speed record of 581 km/h was achieved in December 2003, proving that the fundamental technology was ready for commercialization. The test line is scheduled to be extended to 42.8 km by FY2013 and various tests on longer Maglev trains will be conducted to verify the technology for commercialization by the end of FY2016. Plans to build a new Chuo Shinkansen are also underway because the Tokaido Shinkansen is approaching its capacity limit and JR Central has announced its intention to use Maglev technology for the Chuo Shinkansen, linking Tokyo and Osaka in just 1 hour.

Conclusion

The shinkansen has brought considerable cultural and economic benefits to people in Japan, and shinkansen technology has also been used by the Taiwan High Speed Rail Corporation for the Taipei to Kaohsiung 700T. Japan has provided technical assistance for high-speed rail projects in many countries, including China, Spain and the USA.

Since rail is more environmentally friendly than other transport modes, it is increasingly seen as the main transport mode of the future, but meeting the needs of the time will require continuing technical innovation and diversification of services.

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