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High Speed Rail in Japan: A Review and Evaluation of the Shinkansen Train

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Mamoru Taniguchi

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I also extend my appreciation to those who provided me with useful information, especially Professor Kozo Amano and Lecturer Dai Nakagawa at the University of Kyoto.

PREFACE

This is one of a series of reports now being produced as the first output of our study of the potential for a high-speed passenger train service in California. Each report deals with a specific high-speed train technology; it attempts an evaluation, standardized as far as available data permit, of its technical and economic viability.

Specifically, each report assesses the particular high-speed technology against a number of criteria:

1. *Technical Performance:* configuration of roadbed in terms of gradients, curvature, and construction cost; power sources; capacity and speed; capacity to integrate with existing transportation facilities.

2. *Economic performance:* traffic levels; revenues; financial appraisal and overall cost-benefit analysis; level of public subsidy required, if any.

3. *Resource consumption and environmental performance:* type and amount of energy required; impact on non-renewable resources; environmental impact, including emissions, noise, visual intrusion and effect on local communities.

The present series includes five studies. Two companion studies, on British Rail's InterCity 125 and 225 services and on Tilting Trains (the Italian *Pendolino* and the Swedish X-2000 service), will follow shortly. Thereafter, a systematic comparative analysis will be published.

The CalSpeed study will continue with preliminary route alignments, also to be produced shortly, followed by market assessments, to be completed in Fall 1992. These will bring to a close the present phase of work, which will be the subject of an overall report also to be completed in Fall 1992.

We gratefully acknowledge the support provided by the U.S. Department of Transportation and the California State Department of Transportation (Caltrans) through the University of California Transportation Center. Of course, any errors of fact or interpretation should be assigned to us and not our sponsors.

PETER HALL
Principal Investigator

REVIEW AND EVALUATE EXISTING SYSTEMS: SHINKANSEN (JAPAN)

INTRODUCTION

This report aims to show the detail of the Shinkansen system, and to allow a comparison with other High Speed Rail systems for use in California. The Shinkansen system has operated since 1964, with maximum speed from 131 mph to 172 mph in Japan.

The following major subject areas are examined in this report:

1. Development History
2. Engineering: Train
3. Engineering: Track
4. Services
5. Economic Results
6. Environment
7. Future Extension
8. Summary

The following abbreviations are used in this report:

JNR	the Japanese National Railways
ATC	automatic train control
CTC	centralized train control
COMTRAC	computer-aided traffic control system

This report is part of the work of the California High Speed Rail Group at the Institute of Urban and Regional Development, University of California at Berkeley.

1. DEVELOPMENT HISTORY

Since Japanese conventional railway has been a narrow gauge system, it was necessary to construct a new standard gauge for more rapid service. In 1938, the first idea of a bullet train running at 125 mph between Tokyo and Shimonoseki was suggested. In 1940, construction began for the bullet train, but it stopped because of World War II. After 1958, "the business express Kodama," running at 57 mph average speed on a conventional line, connected Tokyo and Osaka in 6.5 hours, but service capacity was not enough for increasing travel demands.[1]

A committee of Shinkansen (New Trunk Line) research was organized in 1957, and the first Shinkansen Line opened in 1964 between Tokyo and Osaka. The maximum speed of the first service was 131 mph and it took four hours between the two cities. After that, new lines in Sanyo, Tohoku, and Joetsu have extended, as shown in Figure 1, and vehicles have also been improved. Now it takes less than three hours between Tokyo and Osaka, and the Joetsu Shinkansen operates at 172 mph maximum speed. Within several years, it will operate at more than 188 mph using new rolling stock.[2]

When the Tokaido Shinkansen opened its service in 1964, 60,000 passengers used Shinkansen on average per day. The number of passengers increased year by year, reaching 230 thousand passengers per day when EXPO '70 was held in Osaka in 1970.[3] Table 1 shows the rate of increase, and each line has carried the following number of passengers in 1989.

Tokaidou: 117 million

Sanyou: 62 million

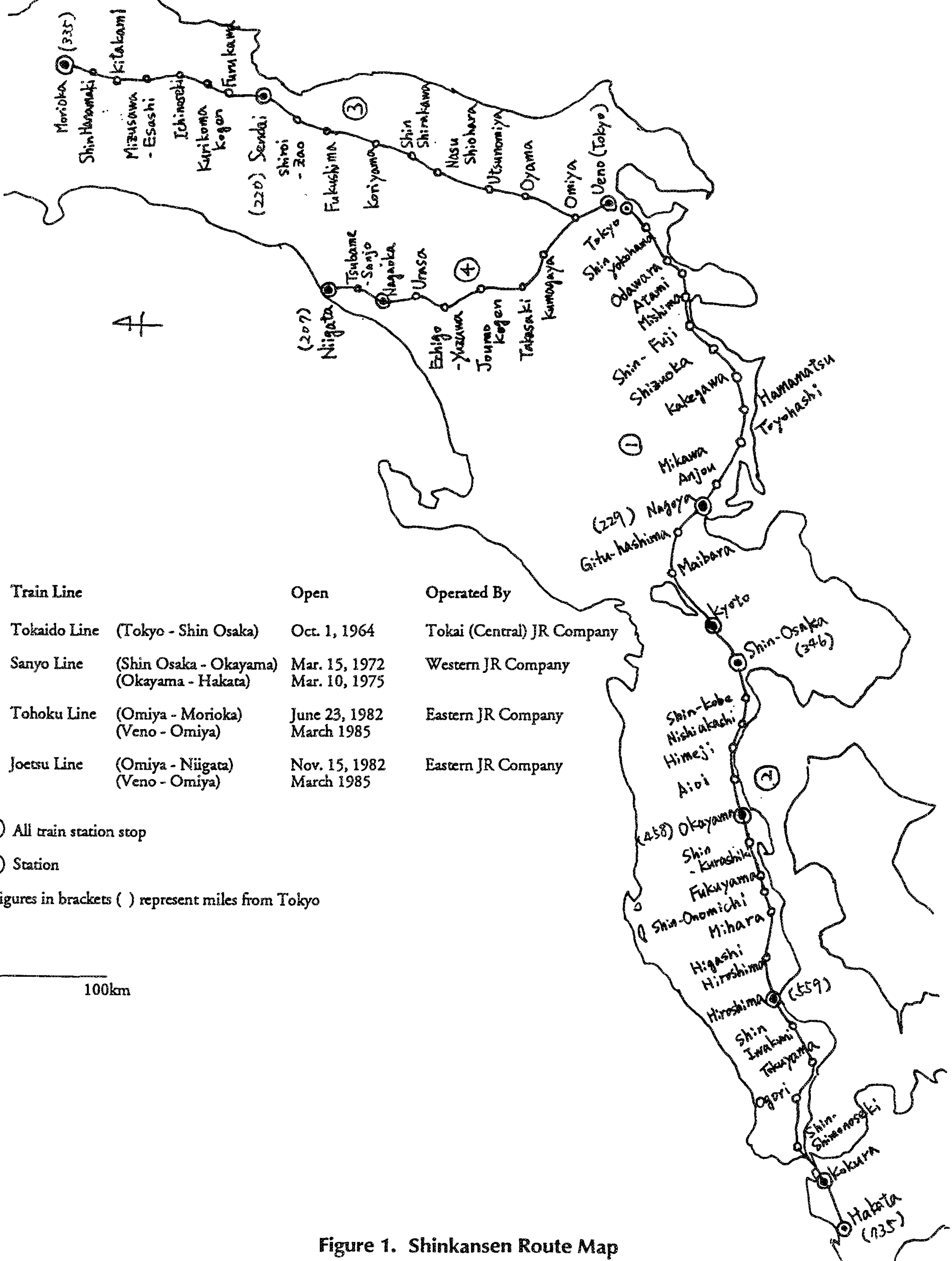
Tohoku: 51 million

Joetsu: 20 million[4]

2. ENGINEERING: TRAIN

***Vehicle and Engine**

The main features of the Shinkansen vehicles have improved, as shown in Table 2. Not only has the number of Shinkansen vehicles increased by about six times since its opening in 1964, but also many points in each vehicle have been improved. Type 961 vehicles have 2,200 kW power and operate at 172 mph maximum speed on the Joetsu line. The acceleration has now been improved to 1.0 (mi/h)s. Figure 2 shows the characteristic curve of engine that is used in Tohoku and Joetsu line. A typical train formation is shown in Figure 3.[5,6]



Train Line		Open	Operated By
1 Tokaido Line	(Tokyo - Shin Osaka)	Oct. 1, 1964	Tokai (Central) JR Company
2 Sanyo Line	(Shin Osaka - Okayama) (Okayama - Hakata)	Mar. 15, 1972 Mar. 10, 1975	Western JR Company
3 Tohoku Line	(Omiya - Morioka) (Veno - Omiya)	June 23, 1982 March 1985	Eastern JR Company
4 Joetsu Line	(Omiya - Niigata) (Veno - Omiya)	Nov. 15, 1982 March 1985	Eastern JR Company

◉ All train station stop

○ Station

Figures in brackets ( ) represent miles from Tokyo

0 100km

Figure 1. Shinkansen Route Map

Table 1. Number of Passengers Carried by Shinkansen[7]

	Passengers carried (1,000 persons)	Passengers-kilometers (million km)
FY1965	30,967	10,951
1968	65,902	21,027
1969	71,574	22,816
1970	84,628	27,890
1971	85,354	26,795
1972	109,854	33,835
1973	128,079	38,989
1974	133,195	40,671
1975	157,218	53,318
1976	143,464	48,147
1977	126,796	42,187
1978	123,689	41,074
1979	123,767	40,986
1980	125,636	41,790
1981	125,619	41,717
1982	142,907	46,105
1983	161,349	50,440
1984	163,790	50,826
1985	179,833	55,422
1986	183,012	55,943
1987	206,817	57,414
1988	227,000	64,361
1989	236,000	65,964

Table 2. Main Features of the Shinkansen Vehicle and Engine[8]

Items \ Cars	For Tokaido & Sanyo Series 0	For high speed test Type 951	Prototype for nationwide Shinkansen network Type 961
Power system	AC 25 kV, 60 Hz	AC 25 kV, 60 Hz	AC 25 kV, 50/60 Hz
Continuous rating output of 2-car unit	1,480 kW (185 kW x 8)	2,000 kW (250 kW x 8)	2,200 kW (275 kW x 8)
Maximum speed	210 km/h	250 km/h or more	260 km/h or more → now. 275 (km/h)
Axle load	less than 16 tons	less than 16 tons	less than 16 tons
Overall dimensions (L x W x H)	25 x 3.38 x 3.975 m	25 x 3.38 x 4.022 m	25 x 3.38 x 4 m
Trainset	16 cars, 400 m	2 cars, 50 m	6 cars, 150 m
Diameter of wheel	910 mm	1,000 mm	980 mm
Car body structure	Steel, welded structure	Aluminium, welded structure	Aluminium, welded structure
Power transmission system	Flexible coupling drive, gear ratio 1 : 2.17	Flexible coupling drive and others, gear ratio 1 : 2.07	Parallel cardan shaft drive, gear ratio 1 : 2.40
Main transformer	1,650 / 1,500 / 150 kVA	2,410 / 2,260 / 150 kVA	3,300 / 2,950 / 350 kVA
Main rectifier	Tap-changer and silicon rectifier, bridge connection, 1,650 kW	Thyristor-diode mixed bridge connection, 2,200 kW	Thyristor-diode mixed bridge connection, 2,400 kW
Traction motor	185 kW	250 kW	275 kW
Powering control	Tap changing of main transformer	Continuous phase control by thyristors	Continuous phase control by thyristors
Braking control	Dynamic brake and electro-magnetic straight air brake	Dynamic brake and eddy current rail brake	Dynamic brake and electric command air brake
Braking operation	ATC and manual	ATC and speed instruction system	ATC and ATO
Air conditioning	Heat pump units dispersed on roof	Centralized heat pump	Centralized cooler with heating coil
Power source for passenger accommodation	Tertiary winding of transformer 1 ϕ, 220 V	Tertiary winding of transformer 1 ϕ, 440 V	Motor-generator 3 ϕ, 440 V

Figure 2. Characteristic Curves[9]

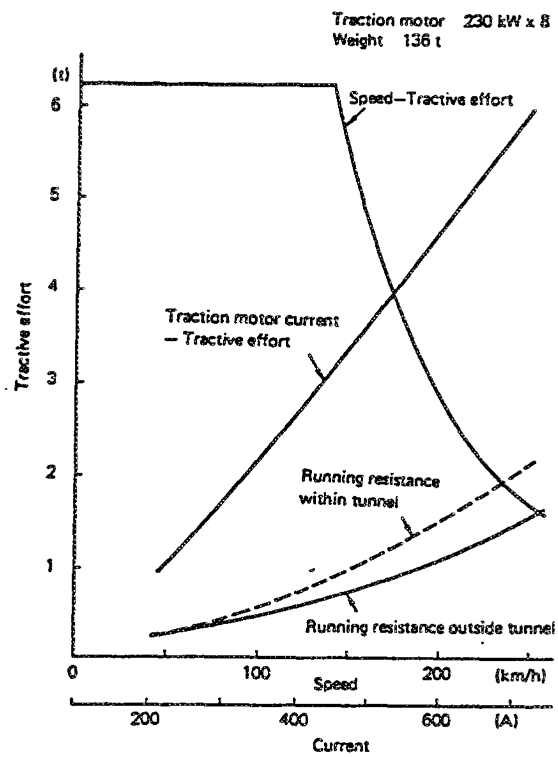
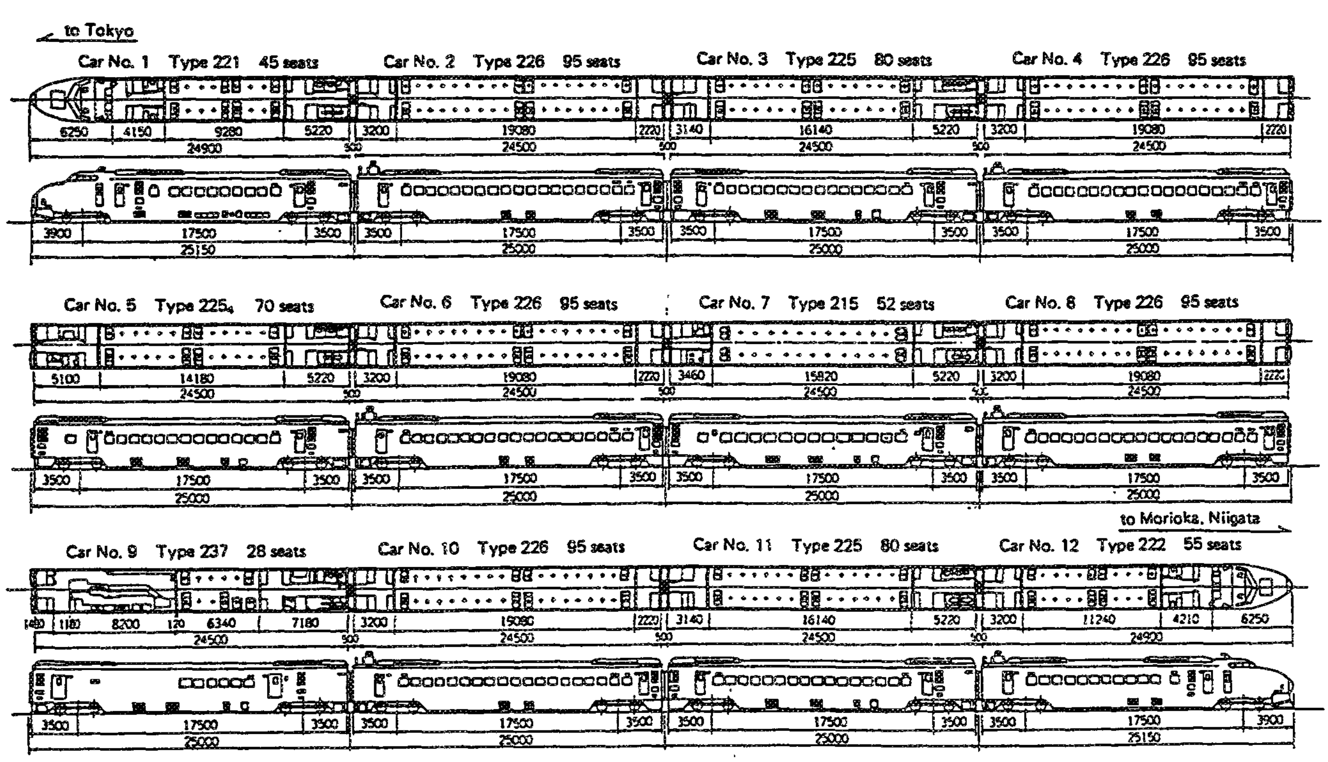


Figure 3. Train Formation of the Tohoku & Joetsu Shinkansen Lines[10]



***Intelligent Facilities in Train**

A new series of Tokaido Shinkansen MU vehicles is provided with various intelligent information systems.

1. The Monitoring System for drivers: The driver's cab in the front car is provided with a set consisting of a central control unit, a CRT (cathode-ray tube) display, and a recorder. Each car is provided with a terminal unit. These are connected by a fiber-glass optical transmission system. The display not only informs the driver about operating data, such as the present position of the train, but also indicates which device or equipment in which car is in trouble. In addition, the working condition of each device of each car can be displayed at any time.

2. Passenger Guidance Information System: The illuminated guidance device for passenger is located above the doorway at the end of each car. Figure 4 shows an example of this information. The distance to the next station and the running speed is displayed on real time, and tourist information about the region along the line is constantly scrolled.[11]

***Control System**

The Shinkansen train is usually operated by ATC system. Shinkansen trains that run at 125 mph require a 1.9 mile distance to stop. That is a major reason to use ATC system. In the case that the train speed rises over the speed showed by the cab signal, the brake acts automatically to keep it within the indicated speed. The track is divided into block sections which are the basic units to confirm the train's position. The center of operation of the Shinkansen exists in the general control center, located in Tokyo. This center executes comprehensive control by using CTC and COMTRAC systems.[12,13]

3. ENGINEERING: TRACK

***Track Standard**

There are a few differences in track standard between the original Tokaido and newer lines. Table 3 shows the main features and track standards of each line. Figures 5, 6, and 7 shows construction standards, as well as the general section and standard cross section of a tunnel on the Tohoku and Joetsu line. To operate trains safely under wind pressure, it is required to have enough space between tracks. According to several experiments (including a tunnel line), 0.8m width is enough to have a safe operation. To reduce noise from the track, a "resilient tie track"

Figure 4. Example of Passenger Guidance Information System[14]

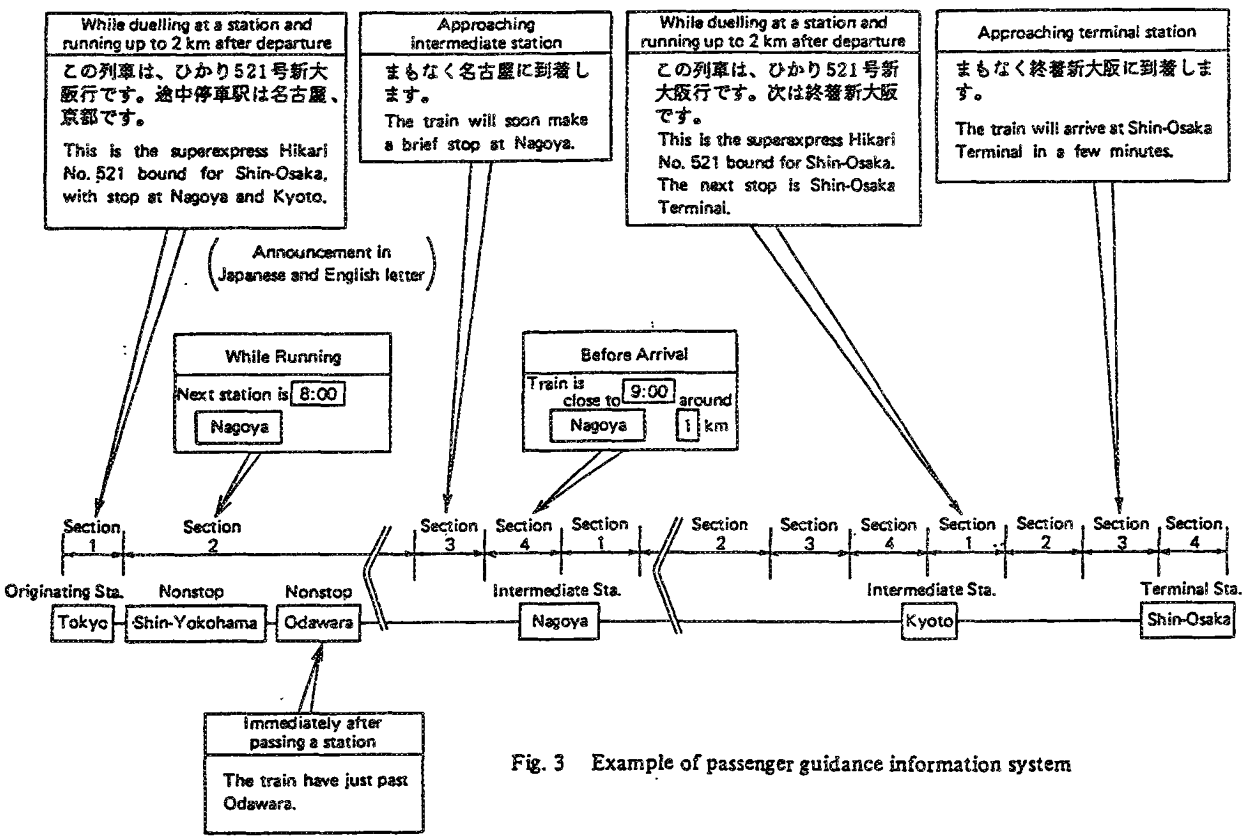


Fig. 3 Example of passenger guidance information system

Table 3. Comparison of Main Features of Each Shinkansen Line[15]

Item \ Shinkansen / Section	Tokaido	Sanyo		Tohoku	Joetsu
	Tokyo – Shin Osaka	Shin Osaka – Okayama	Okayama – Hakata	Tokyo – Morioka	Omiya – Niigata
Route length	515 km	161 km	393 km	496 km	270 km
Tunnels	69 km (13 %)	58 km (36 %)	223 km (57 %)	115 km (23 %)	106 km (39 %)
Bridges	57 km (11 %)	20 km (12 %)	31 km (8 %)	78 km (16 %)	30 km (11 %)
Minimum curve radius	2,500 m	4,000 m			
Maximum grade	20/1,000	15/1,000			
Minimum longitudinal curve radius	10,000 m	15,000 m			
Construction gauge	Height: 7,700 mm Width: 4,400 mm				
Rolling stock gauge	Height: 5,450 mm Width: 3,400 mm				
Rail	60.8 kg/m, 1,500 m long-welded rails				
Track gauge	1,435 mm (4' 8 ½")				
Formation width	10.7 m	11.6 m	11.0 m	11.6 m	
Distance between track centers	4.2 m	4.3 m			
Power transmitting system	154 kV or 77 kV 2 lines	275 kV or 220 kV 2 lines		275 kV 2 lines	
Feeding system	A.C. 25 kV 60 Hz Single phase Booster-transformer	A.C. 25 kV 60 Hz Single phase Auto-transformer		A.C. 25 kV 50 Hz Single phase Auto-transformer	
Catenary system	Composite compound	Heavy compound			
Construction period	5 ½ years	5 years	5 years	10 ½ years (Omiya – Morioka)	11 years
Opening date	October 1, 1964	March 15, 1972	March 10, 1975	June 23, 1982 (Omiya – Morioka)	November 15, 1982
Stations (ave. km)	16 (32.2)	17 (32.6)		14 (35.4)	9 (30.0)

Figure 5. Construction Standards[16]

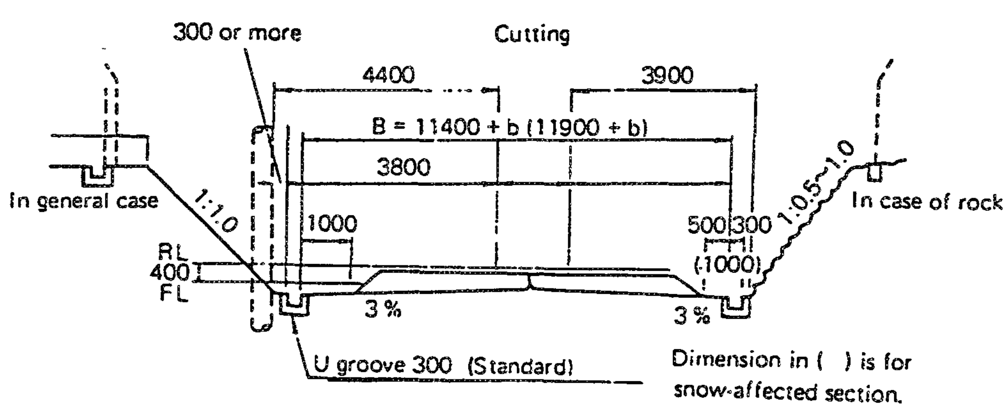


Figure 6. General Section[17]

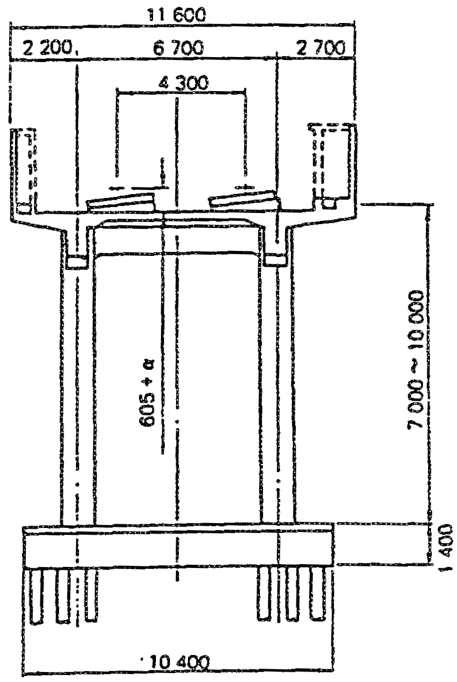
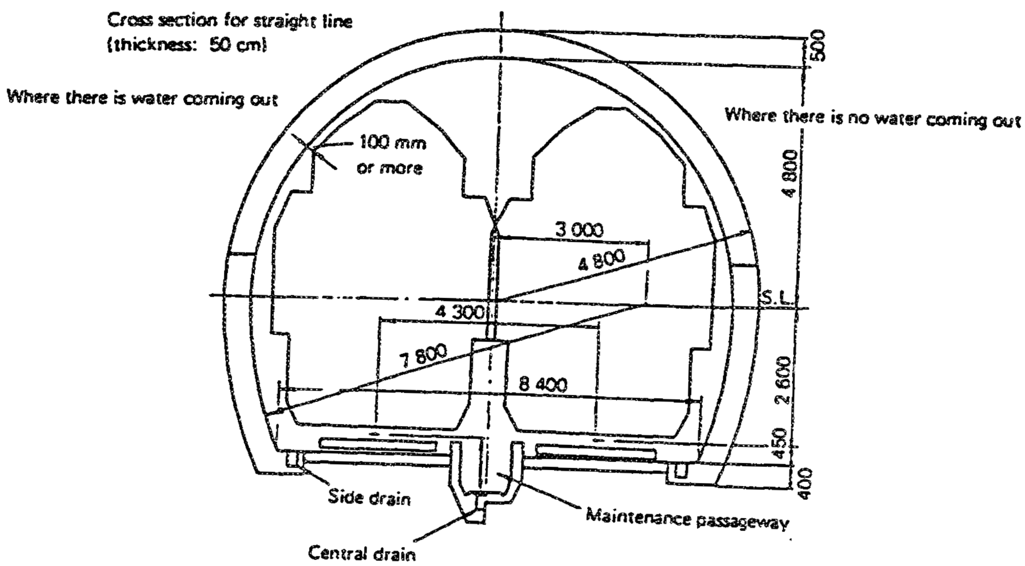


Figure 7. Standard Cross-Section of Tunnel[18]



was developed, as shown in Figure 8. Conventional ballast tracks cause less noise and cost much more than conventional slab tracks. This new resilient tie track combined the noiseless ballast track and costless slab track. New Shinkansen lines, such as Tohoku and Joetsu, began to use this new track.[19,20]

***Devices for Reliable and Safety Operation Along Track**

Some regions suffer heavy snowfall (more than 200 cm) and -20C temperatures along the Joetsu line. The snow-strong system is indispensable for reliable operation in these areas. For the Tohoku line where snowfall is not so heavy, snow will generally be kept in the storage space provided under the rail of the slab-track section, as shown in Figure 10. The water-sprinkler snow-melting method has been adopted for a 47.5 mile section on the Joetsu line, and 1.8 miles on the Tohoku line. As shown in Figure 11, hot water is sprinkled over the snow as it falls on the track, and prevents it from accumulating. The snow-melting system works with an efficient water-heating and recirculating device in which the water sprinkled over the track is recollected, reheated, and sprinkled again.[21,22]

Since Japan is one of the most notable countries for earthquake risk, Shinkansen has a train-protection system from an earthquake, as shown in Figure 12. New equipment gives earlier notice about the occurrence of an earthquake in the Pacific earthquake zone. An immediate message is sent to reduce train speeds before the tremor reaches the Shinkansen lines. This message is conducted in a reliable double system through wires on the ground and the communication satellite.[23]

4. SERVICES

***Schedule and Capacity**

The number of trains that start from Tokyo Station in the Osaka direction are seven "Hikari: Super Express" and four "Kodama: Express" per hour. The maximum number of trains operated per day is approximately 290 on this line.[24]

Figure 13 is a sample Tokaido and Sanyo Shinkansen schedule. Trains are operated at four minutes' minimum head. "Kodama: Express" stops at every station, but "Hikari: Super Express" skips lots of stations to meet a different transportation demand. The Tohoku and Joetsu lines have the same kind of schedule system as the Tokaido and Sanyo line. On the Tohoku line, the

Figure 8. Resilient Tie Track[25]

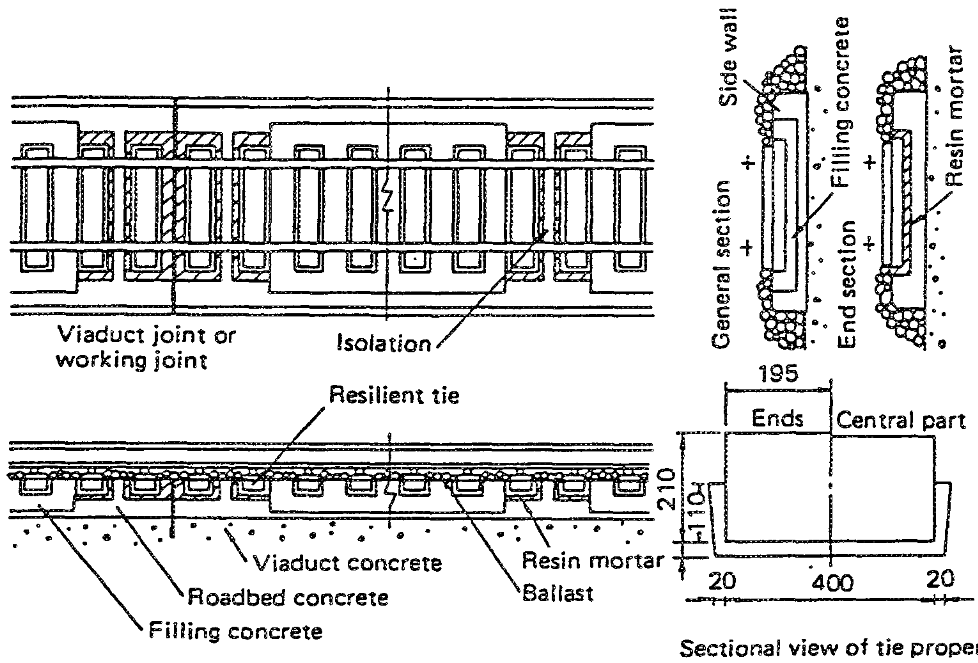


Figure 9. Switching Point[26]

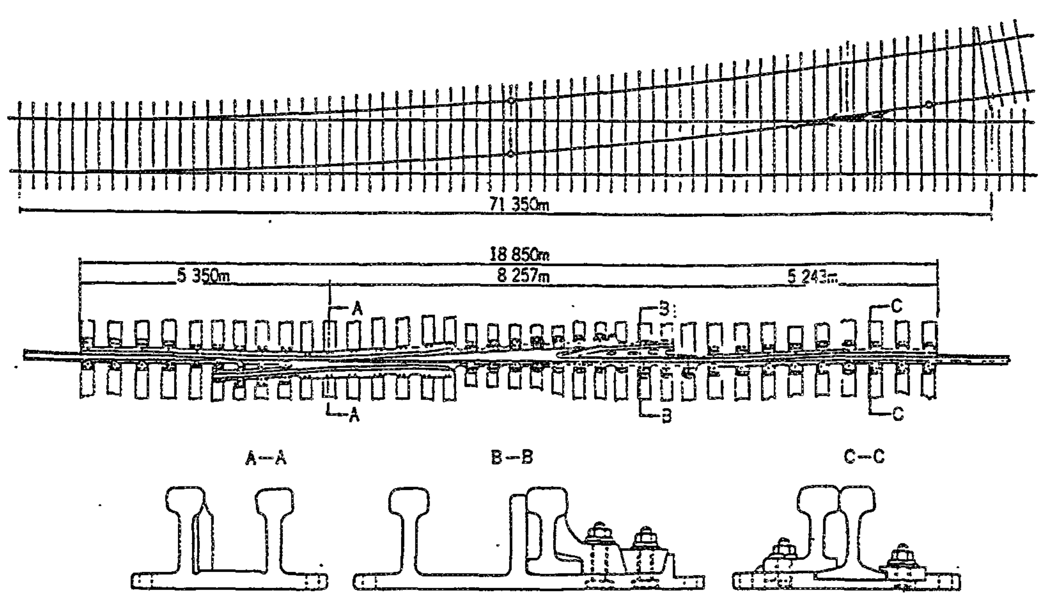


Figure 10. Sectional View of Snow-Storing Type Viaduct[27]

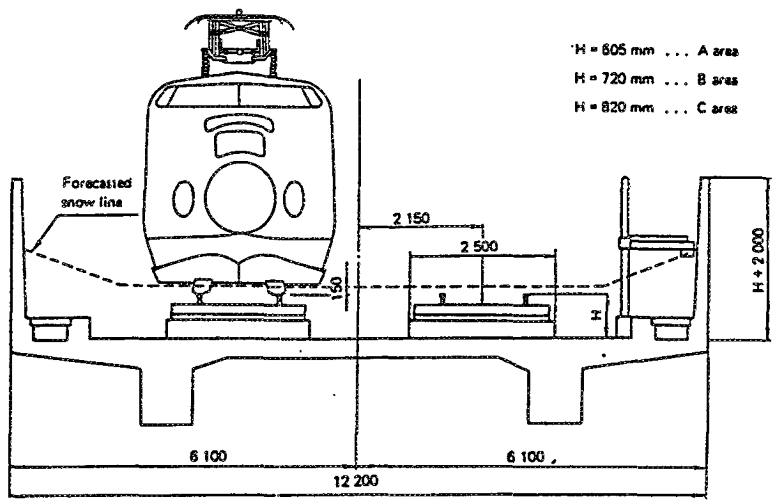


Figure 11. Outline of Water Sprinkler Snow-Melting System[28]

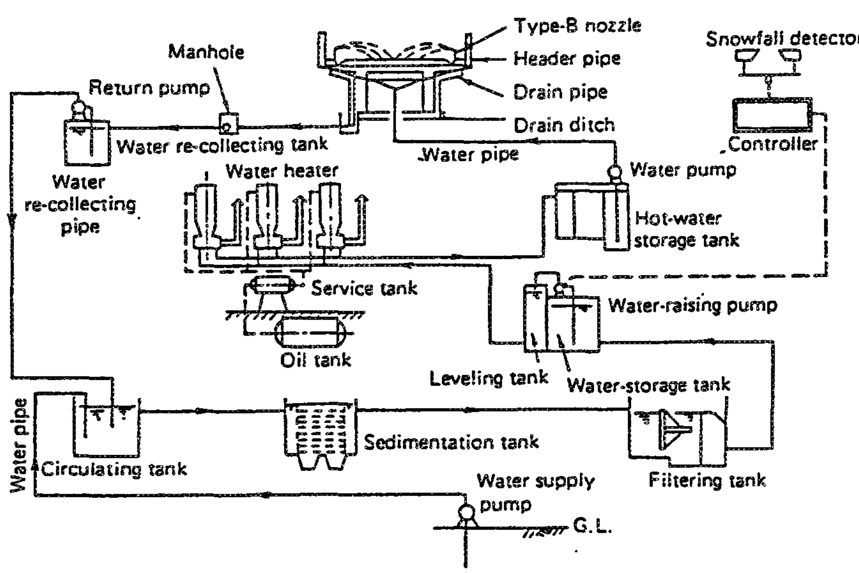


Figure 12. Earthquake Detection Along the Coast[29]

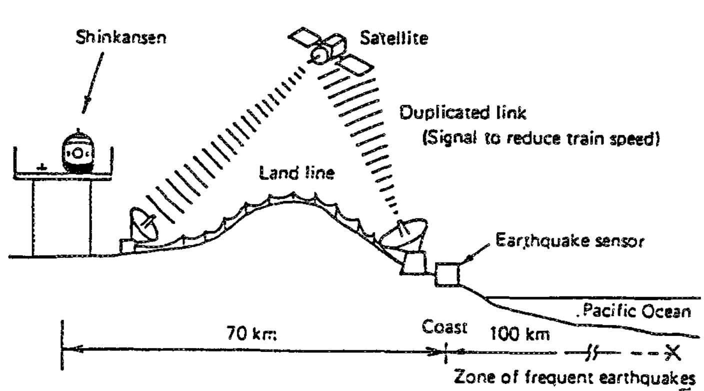
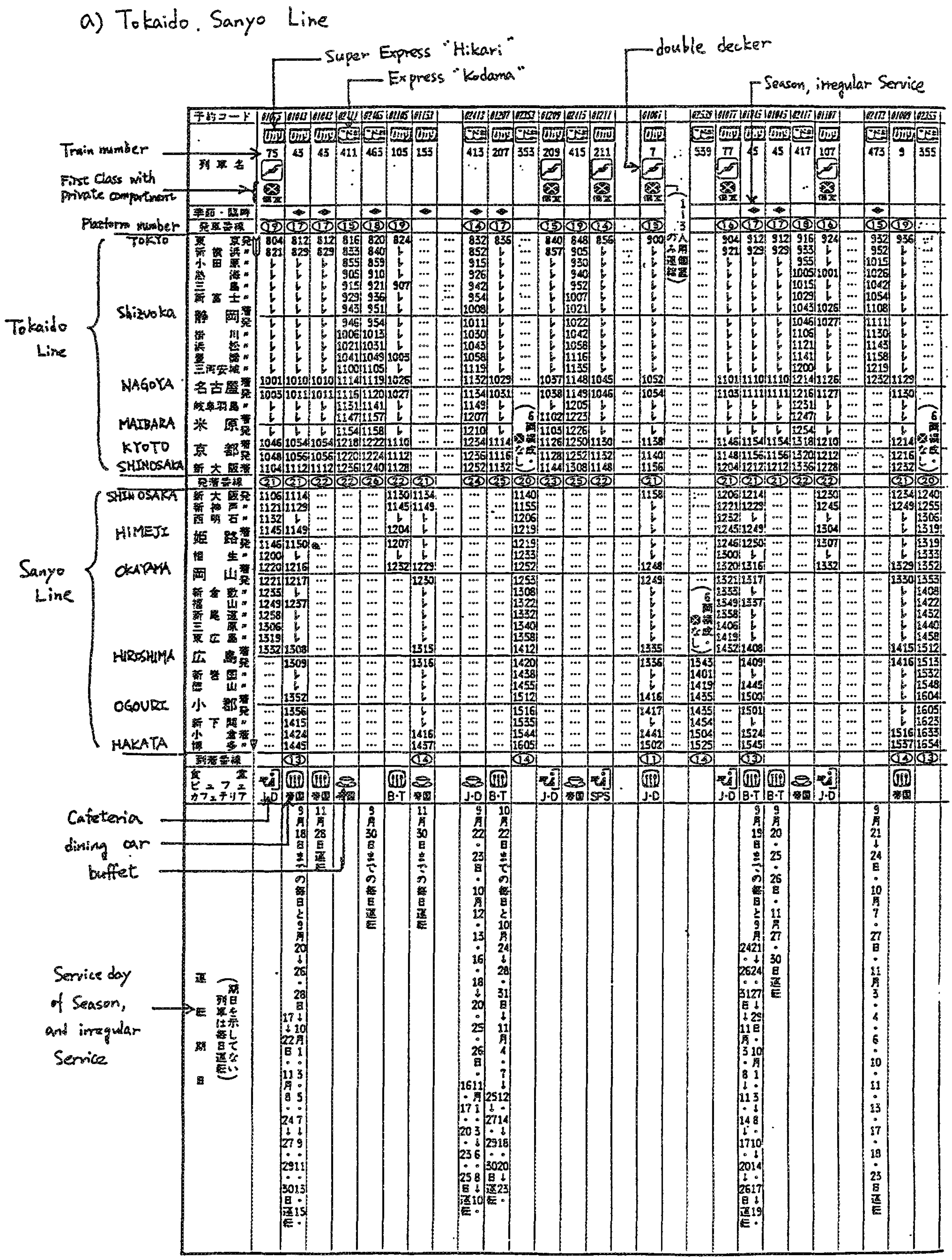


Figure 13. Shinkansen Time Table[30]



super express train is called Yamabiko and the express is called Aoba. On the Joetsu line, the super express train is called Asahi and the express is called Toki.[31]

***Reliability**

The number of train accidents and obstructions in transportation is 3-4 per one million kilometers of Shinkansen-running. The mean delay time per train is about two minutes, and 80 percent of the trains arrived at terminal stations on scheduled time. The main reason for delay is snow on the Tokaido Shinkansen in winter. Though the Tohoku and Joetsu lines were constructed through a heavy snow area, trains are rarely more delayed than on the Tokaido line. New counter-measures against snow damage work very well on these new lines.[32]

***Competition with Airline Service**

Highways in Japan are subject to toll and have insufficient capacity. In addition, fuel costs are about three times as expensive as in the U.S.A. Because of this, people in Japan don't use cars for inter-regional transportation. Though air service competes with Shinkansen service, the Shinkansen shows a large share under 438 miles distance. Table 4 shows most people choose Shinkansen between Osaka and Tokyo (346mi). The reasons are as follows:

1. More operation services than air
2. Cheaper transportation fare air
3. Shinkansen stations are located in the downtown of each city
4. Reliability of schedule
5. Safety operation

5. ECONOMIC RESULTS

***Construction Cost**

The construction cost of the Shinkansen is not the same among the different Shinkansen lines. Generally speaking, older lines are cheaper and newer lines are more expensive.[33]

Table 4. Comparison of Passenger Number: Shinkansen and Airplane (from Tokyo)

	Mode	Time	Freq.[1]	Price[2]	Share
Nagoya (229 mi.)	Shinkansen	1 hr. 48 min.	100[3]	10,380	Nearly 100%
	Airplane	1 hr.[4]	1[5]	11,600	Nearly 0%
Osaka (346 mi.)	Shinkansen	2 hr. 44 min.	100[3]	13,480	80-90%
	Airplane	1 hr.[4]	15	14,600	20-10%
Hakata (735 mi.)	Shinkansen	5 hr. 57 min.	23[3]	21,300	30%
	Airplane	1 hr. 40 min.	24	25,350	70%

(1)Per one day.
(2)Full price including seat reservation fare (yen).
(3)Only super express "Hikari," excluding express "Kodama."
(4)It takes a longer time than Shinkansen if you include access time to the airport and waiting time at the airport.
(5)Tokyo has two airports. One is the domestic "Haneda" airport, the other is the international "Narita" airport. This one service for "Nagoya" is not from "Haneda" but from "Narita." Air service between "Haneda" and "Nagoya" was abandoned after the opening of the Shinkansen.

Total Construction Cost (billion $)

Tokaido (346 miles):	0.92 (1964 price: $1=¥360)
Sanyo (389 miles):	2.95 (1975 price: $1=¥308)
Tohoku (335 miles):	11.02 (1985 price: $1=¥254)
Joetsu (209 miles):	6.69 (1985 price: $1=¥254)

There are two reasons why the Shinkansen system is more expensive compared with other high-speed rail systems. First, the Japanese land price is the highest in the world. Second, the Japanese topography requires many kinds of expensive infrastructure such as tunnels and bridges for straight railway. Details of expense and of the infrastructure proportion in the case of the Sanyo Shinkansen between Shinosaka and Okayama (103mi) are as follows:[34]

Proportion of each expense by total cost

Infrastructure:	58.3%
Land Price:	25.8%
Electric Equipment:	10.9%
Track & Rail:	5.1%

Proportion of each infrastructure by total line length

Cut:	2%
Bank:	5%
Viaduct:	49%
Bridge:	9%
Tunnel:	35%
Total length:	100% (103mi)

In the case of the U.S., the average land price is about 1/50 of Japan, and the simple topography such as that found in the Central Valley is suitable for a most inexpensive ground-type track construction. On this point, construction of a Shinkansen system in the California corridor would cost less than 1/3 of the cost in Japan.

***Expenditure & Revenue**

The Tokaido and Sanyo Shinkansen have shown a large profit, as demonstrated in Table 5. Though the Tohoku and Joetsu lines are in deficit finance, they are currently improving due to an increase of passengers.[35]

6. ENVIRONMENT

***Noise Problem**

The construction of the Tokaido Shinkansen was decided in 1959 and the line had to be completed by 1964 (the year of the Tokyo Olympics). It was a very short period to estimate the environmental impact. After the opening of the Tokaido Shinkansen, a noise problem in the Nagoya area was pointed out. In 1975, environmental criteria were decided as follows:

- Under 70 hon: Residential area, outside house
- Under 75 hon: Commercial area, outside house

The Nagoya noise problem provided a good lesson for the Tohoku and Joetsu lines. These new lines were improved as follows:

- 20m wide environmental zone (both sides of right-of-way)
- Noise barrier
- Improvement of track ground
- Improvement of track basement
- Speed decreased through densely inhabited districts[36]

***Energy Consumption**

Shinkansen consumes 30Wh electricity per kilometer per passenger. Compared to other transportation facilities, Shinkansen is three times as efficient as the Maglev, and six times as efficient as air service.[37]

7. FUTURE EXTENSION

The success of the Tokaido Shinkansen encouraged the establishment of a "Shinkansen Reorganization Law." Based on this law, a plan to construct five lines was decided in 1973, as shown in Figure 14. But these plans were not executed. Not only was the total estimated

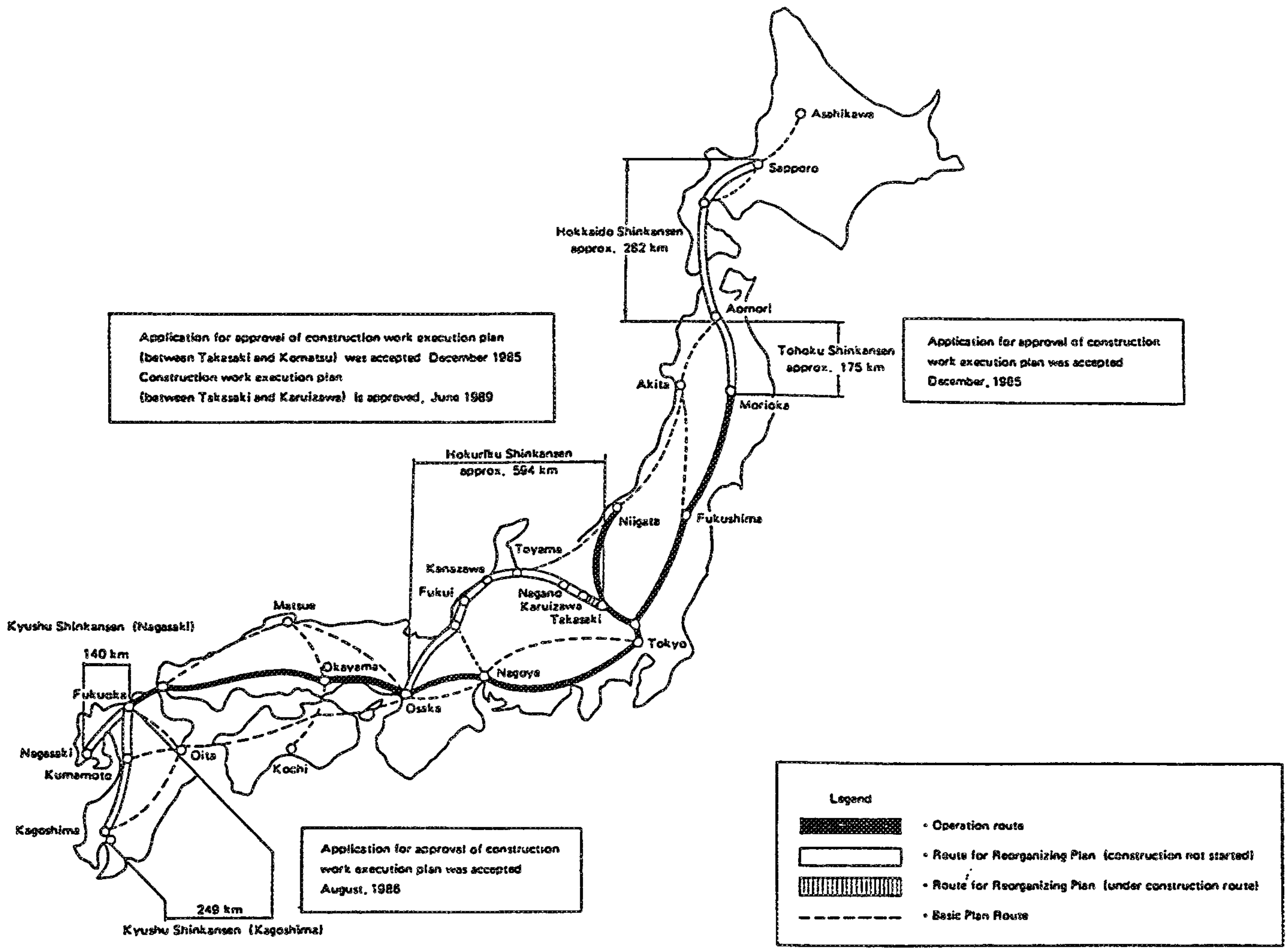
Table 5. Expenditure and Revenue of Shinkansen (billion yen, 1985)[38]

	Expenditure	Revenue
Tokaidou	286	676
Sanyo	207	284
Tohoku	367	208
Joetsu	159	82

Table 6. Priority for Starting Construction Works[39]

1)	i) Hokuriku Shinkansen	Line section between Takasaki and Karuizawa in the Plan of the Ministry of Transport. As to the section between Karuizawa and Nagano, a decision will be made within three years considering the issues such as the site of the Winter Olympics in 1992.
	ii) Hokuriku Shinkansen	Line section between Kanazawa and Takaoka in the Ministry of Transport Plan.
2)	Tohoku Shinkansen	Plan of the Ministry of Transport.
3)	Kyushu Shinkansen	Plan of the Ministry of Transport.
4)	Hokuriku Shinkansen	Line section between Uozu and Itoigawa in the plan of Ministry of Transport.

Figure 14. Shinkansen Reorganizing Plan[40]



expenditure so large (more than 5 trillion yen), but also the oil shock stopped these projects. After JNR privatized and divided into several groups, the frozen project was revised, as shown in Figure 15. To reduce construction cost, the following changes will be required on new lines[41]

1. Standard Gauge New Line
2. Through Service Line with Shinkansen
3. New Line to Shinkansen Standard

8. SUMMARY

The Shinkansen system is one of the most successful projects in Japan. Though this paper explains many details about Shinkansen, the important reasons for the success are the following two points:

1. Shinkansen is a very punctual system.

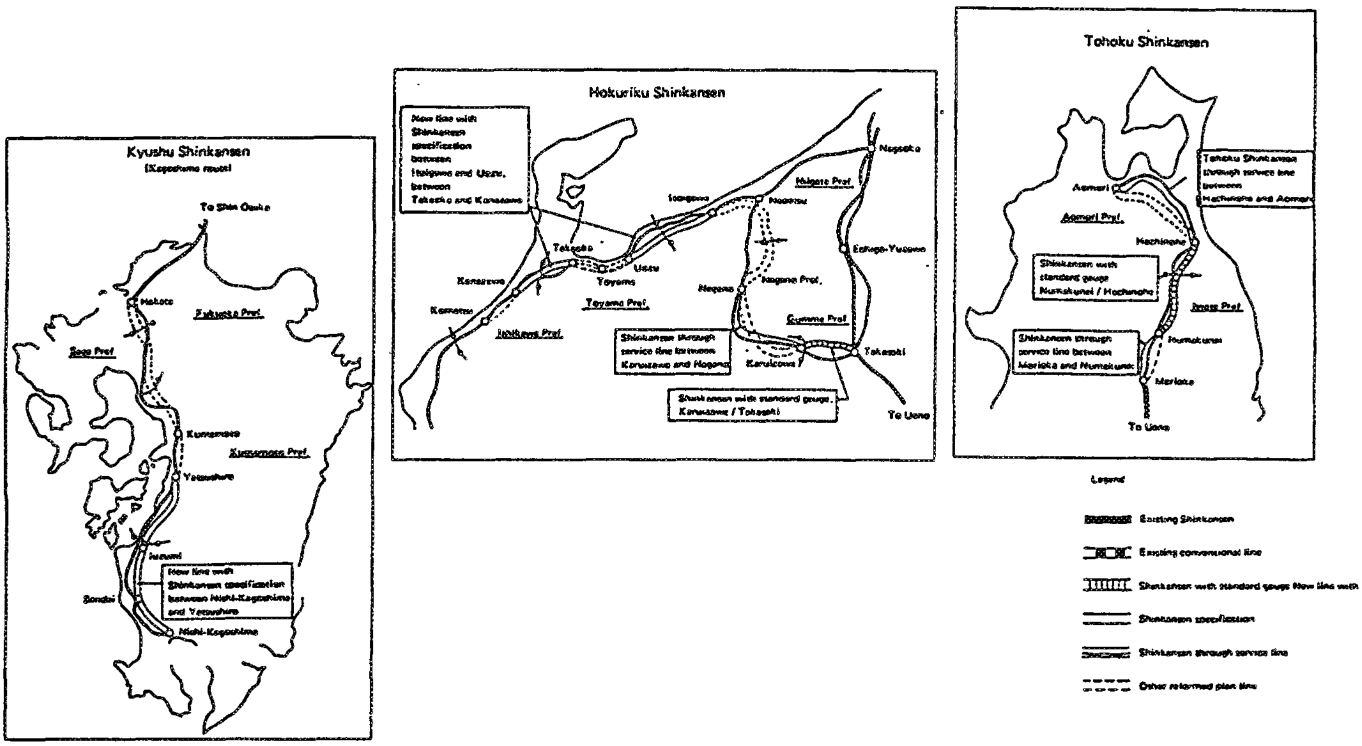
   People, especially business persons, make much of punctuality. They choose a 156 mph train which is operated on time instead of an unpunctual 250 mph train. The Shinkansen system has a greater punctuality record than either airplanes or autos, and can get a very large share of business trips.

2. Shinkansen service is very frequent.

   Whenever you go to the stations, you can take a Shinkansen train without waiting. You need not reserve a seat beforehand. In addition, you can choose Super Express for long trips, and express for short trips, and you can easily combine them.

Shinkansen is a dedicated system, and that enables these two features. The construction cost of Shinkansen is not so low, but it proves to be a most effective system under large travel demands.

Figure 15. Diagrams of the Plan of the Ministry of Transport[42]



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