Railways in the 21st Century (Tokaido Shinkansen)

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1. Introduction

The International High-Speed Railway Conference 2000 was held from November 29-30, 2000. Having the theme of "21st Century High-Speed Railways – Carving out the Future of Earth, Society, and Humankind," the conference was attended by delegates from 16 railway operators from Japan, Europe, the United States, and Asia. The sponsors were Central Japan Railway Co. (JR Tokai) and West Japan Railway Co. (JR West), and it was supported by the Ministry of Foreign Affairs, Ministry of Transport (now known as the Ministry of Land, Infrastructure and Transport) and the *Nihon Keizai Shimbun*. During the conference, the major issues facing the railway operators in each country were discussed. The socio-economic impact of railways was also reappraised and the conclusion arrived at was that policy efforts and endeavors by railway operators would both be necessary to ensure the further expansion and development of railways in view of their advantages in environmental preservation.

The history of the world's high-speed railways began with the start of the Tokaido Shinkansen line in 1964. Its impact on the 20th century was not just in terms of safety, reliability, large transporting capacity and high speeds, it also contributed greatly to local economies by spurring their development. As a high-speed railway, the design concept of the pioneering Tokaido Shinkansen line was truly remarkable for the time that it was constructed. In the 36 years since then, it has continuously transported passengers with high safety and reliability and the *shinkansen* system that was developed through the efforts of a great many people during this time was highly acclaimed all over the world. As a result, it received the tremendous honor of being simultaneously awarded the Milestone Award and Landmark Award by the IEEE (Institute of Electrical and Electronics Engineers) and ASME (American Society of Mechanical Engineers), which are given for outstanding achievements in the field of technology.

However, such an honor should not be dwelled upon. We now have to think of ways of further expanding shinkansen passenger use in the future and to this end will now look back on the technological advances that have been made since it was constructed.

2. Concept behind the construction of the Tokaido Shinkansen

The Tokaido Shinkansen started operation in 1964, the year of the Tokyo Olympic Games, as the world's first high-speed railway, linking Tokyo and Shin-Osaka stations. This 500km stretch of line covers the three megalopolises, Tokyo, Nagoya and Osaka, which together account for 40% of Japan's population and 50% of the nation's gross domestic products (GDP). In the last 36 years, it has served as a major artery between these megalopolises carrying a very large number of people between them each day.

During the 1960s, when the Tokaido Shinkansen was constructed, railways were considered by the majority of people to be in decline because motor vehicles and airplanes were being favored as a means of transporting people and freight. So, why was it that the "fathers" of the Tokaido Shinkansen, Sogo Shinji (head of the former Japanese National Railways [JNR]) and Shima Hideo (Vice-President-Engineering of the JNR) promoted the idea of constructing a high-speed railway like the Tokaido Shinkansen so enthusiastically?

One of the reasons was that passenger and freight capacity of the Tokaido mainline had become insufficient in the 1950s and an urgent need was seen to increase its capacity. The other was in consideration of the technological expertise gained through the operation of the existing line which it was thought would provide the basis for a safe high-speed railway.

3. Construction plan

Many ideas for enhancing transporting capacity were put forward. As regards track, plans for three systems were under consideration. These were to extend the existing track or build a separate line with a narrow gauge (1,067mm) used conventionally in the Tokaido Line, or build a separate line with a standard gauge (1,435mm). The two main ideas considered for the form of service were for passengers only or for both passengers and freight. For high-speed transportation, the standard gauge was necessary. To carry freight, as it would have been necessary to increase the axle load which would place limitations on the tracks, the policy decided on was to have a standard gauge line primarily for passenger traffic but also having the option of carrying freight. In order to solve the problem of insufficient transporting capacity, an efficient mass high-speed transportation system using a power-dispersed system (electric train) was adopted.

It was predicted that a passenger-only service using a separate standard gauge track would connect Tokyo and Osaka within three hours. Within only five years of the ground-breaking ceremony, the goal of covering the 500km between Tokyo and Osaka within three hours was achieved.

During the initial stage, Shima must

Photo : Central Japan Railway Co.

Series 300, 922 (Dr. Yellow), 0, 100, 300 and 700 shinkansen trains (from the left)

have expended much energy in drawing up technical standards for an integrated system in which there was compatibility between such aspects as tracks, overhead power lines, signals systems and train cars. At the time, there was no 200km/h railway anywhere in the world. In order to attain the highest level of safety, the system used was thus developed by focusing on tried and tested technologies and selecting the best from among them rather than developing completely new ones. The procedure for adopting individual technologies was as follows. Technologies were first tested and experimented on, principally by the Railway Technical Research Institute, in order to develop theories for their use and then development and design functions gave them form. Through the pooling of all these technologies, the shinkansen achieved prominence as a highly safe and comfortable form of transportation.

4. Start of Tokaido Shinkansen operations and its achievements

In the early days of operation, there were 60 trains a day carrying around 60,000 passengers. There are currently 285 trains a day carrying 360,000 passengers. This six fold increase has been achieved through having more trains and increasing the number of cars in a set from 12 to 16. Thus great efforts have been made in alleviating the shortage in transporting capacity between Tokyo, Nagoya and Osaka, from the beginning of operations to the present day.

If the economic effect of savings in time brought out by the Tokaido Shinkansen is calculated in terms of the number of persons carried, the amount of time saved and average salary, this is equivalent to ¥5.2 trillion when it started operation and increases in speed thereafter raised this by ¥2.2 trillion to ¥7.4 trillion. In addition to savings in time, the Tokaido Shinkansen has also contributed to the growth of the Japanese economy in such ways as spurring the development of areas along the line. This is very apparent if one compares the number of passengers carried by the shinkansen and GDP growth, which appear to be in proportion. And, its impact becomes even greater if we add the savings in social cost, for example through eliminating fatal accidents.

The Tokaido Shinkansen is not just a great technological achievement; its operation has also been very successful and as a result, the total length of lines in the Japanese shinkansen network has now reached 1,953km. Other countries have started operating high-speed railway systems since 1981, notably the French Train à Grande Vi tesse (TGV) trains and the German InterCityExpreß (ICE) trains. And, it has recently been decided to construct a high-speed railway in Taiwan using Japan's shinkansen system. Thus, many countries around the world have recently been reevaluating railways and inaugurating new routes.

5. Features of Japan's shinkansen

Japan's shinkansen has the four following features.

(1) Safe and reliable transportation

Safety is the shinkansen's greatest pride. In 36 years, there has not been a single death due to a train accident. As for reliability, the average delay is 0.4 minutes (average delay on arrival for all trains). Most of this delay is due to natural phenomena such as heavy rain, typhoons and snowfall.

(2) Large capacity transportation

Each train has a capacity of more than 1,300 passengers. As there are 285 trains a day, daily passenger volume is 360,000, making the shinkansen the high-speed railway with the largest transportation capacity in the world.

(3) High speed transportation

A limited express train used to take 6 hours 30 minutes from Tokyo to Osaka. With the start of the shinkansen, this was shortened to 3 hours 10 minutes. The speed was further increased in 1992 enabling the shinkansen to complete the 515km trip from Tokyo to Osaka in 2 hours 30 minutes.

(4) Environmentally friendly

The shinkansen is excellent in environmental terms as it produces relatively little noise and vibration and uses energy very efficiently. Traditionally, railways are an efficient mode of transportation which causes very little strain on the environment. In Japan, in carrying one person for one kilometer, the amount of carbon dioxide (CO_2) produced by railways is one-ninth of that produced by cars and one-sixth of that produced by airplanes. For example, an estimate was made of the amount of CO_2 produced for the case that the Tokaido Shinkansen did not exist and people used other modes of transportation. It was calculated that the shinkansen reduces the amount of CO_2 produced by all forms of transportation in Japan by one %.

The latest shinkansen trains, the Series 700, are even more friendly to the environment. The amount of CO_2 produced by them is one-seventeenth of that from a car and one-tenth of that from an airplane.

6. What has made the shinkansen so safe?

In order to ensure safety for railways it is necessary to create a total integrated system encompassing not just the hardware aspects of train cars, rails, electric power facilities and signal equipment but also such aspects as drivers, maintenance, operation and training. The management of such a system and improvements to it are also extremely important.

(1) Shinkansen track features

As railway trains use steel wheels which run on rails, they only have one degree of freedom in motion and cannot take any avoiding action to ensure their own safety. The majority of accidents occur at railway crossings over which the railway system has limited control. While the Tokaido Line had 600 crossings, the shinkansen has none, which was achieved by using elevated lines. In addition, access to the lines is restricted by law and entry permission is required even by railway personnel.

(2) Stopping system

The operation of railways should be based on a "fail-safe" system which errs on the side of safety when anything unusual happens. As railway trains only have one degree of freedom in motion, the safest situation for them is when they are stopped. Railways should thus incorporate a system which stops trains very quickly when something unusual happens.

Since it is very difficult for a train driver to be completely aware of all signals along the track when traveling at over 200km/h, a system which displays signals inside the driver's cabin was developed for the shinkansen. The automatic train control (ATC) system enhances safety by preventing trains from colliding with each other. The system sends signals to trains informing them of the permissible speed which will enable them to stop in the distance between them and the train in front. If a train is going too fast, the brakes operate automatically.

(3) Safety in severe weather conditions and earthquakes

Rain gauges and anemometers are installed along the shinkansen track. If measurements exceed certain standard values, the shinkansen's speed is reduced or it is brought to a complete stop. As measures against snow accumulating underneath cars and then falling off stones to fly up, the underside of cars has been made smooth, and speed reduction is enforced. For earthquakes, the shinkansen has an urgent earthquake detection and alarm system (UREDAS) which issues commands to operate brakes of cars within stipulated areas when the initial small shocks (primitive waves) of an earthquake are detected. There are also earthquake sensors in the substations for the shinkansen, which make trains come to an emergency stop by stopping the power supply to the overhead cables when a Gal measurement over a predetermined level is detected.

(4) Shinkansen maintenance system

To ensure the safety of the shinkansen it is very important both to build up the structures and systems and to have a maintenance system that can keep their functions. At night after train operation has finished, fine adjustments are made to rail positions. Also, rails and overhead catenary showing signs of wear and deteriorated ballast are replaced. During operation, a multiple inspection train (called Doctor Yellow) is run once every 10 days to make a precision check of the condition of the tracks, overhead power catenary, signals and communications. Maintenance is conducted on the basis of the findings. The maintenance of cars consists of daily inspections focusing mainly on the replacement of worn parts, regular inspections which mainly check functions, dismantling inspections for bogies and a general overhaul which includes the inspection of the car body. These inspections are conducted

Table 1 **Major Specifications of Shinkansen Series**

	Series 0	Series 100	Series 300	Series 700
Configuration	16 M	12 M 4 T	10 M 6 T	12 M 4T
Seating capacity	Economy class 1,208 First class 132 Total 1,340	Economy class 1,153 First class 168 Total 1,321	Economy class 1,123 First class 200 Total 1,323	Economy class 1,123 First class 200 Total 1,323
Weight	970 ton/train set	925 ton/train set	711 ton/train set	708 ton/train set
Maximum speed	220 km/h	220 km/h	270 km/h	270 km/h (Tokaido line) 285 km/h (Sanyo line)
Power running control system	Low-voltage tap changer	Thyristor continuous phase control	Variable voltage variable frequency control (Gate Turn Off thyristor)	Variable voltage variable frequency control (Insulated Gate Bipolar Transistor)
Brake control system	Rheostatic brake system and electromagnetic straight air brake system	Rheostatic brake system and electrically-controlled air brake system	AC regenerative brake system and electrically-controlled air brake system	AC regenerative brake system and electrically-controlled air brake system
Body construction	Steel body	Steel body	Large-sized extrusions of aluminum alloy	Large-sized hollow extrusions of aluminum alloy
Bogie	Wheel diameter 0.91 m	Wheel diameter 0.91 m	Wheel diameter 0.86 m	Wheel diameter 0.86 m
Traction motor	DC traction motor	DC traction motor	AC 3-phase cage asynchronous motor	AC 3-phase cage asynchronous motor
Pantograph	Diamond-shaped pantograph	Diamond-shaped pantograph	Diamond-shaped pantograph	Single-arm pantograph
Number of train sets (January 1, 2001)	Retired in September,1999	40 train set	61 train set	20 train set

on the basis of kilometers traveled or at set time intervals.

Thus, through the combined inspection of track facilities and train cars, deterioration in shinkansen hardware is constantly monitored to ensure that safety is always maintained at a high standard.

7. What is supporting the stability of the Tokaido Shinkansen?

The primary factor in securing consistent transportation is to eliminate accidents and problems by, for example, increasing the weight of rails and overhead catenary, improving the noise immunity of ATC signals, and using reliable parts and systems. It is also important that every system being used can easily recover from problems that may occur. For this purpose, car-monitoring equipment has been introduced to enable the driver to quickly identify faulty devices and mechanisms and remotely control them from the driver's seat. Also, the instruction transmission line to each transformer substation has been made into a loop to multiplex the transmission path. The service control performed when a problem occurs and after recovery from the problem can greatly affect the consistency of transportation. To ensure good service control, a centralized control center having the computer-aided traffic control (COMTRAC) and centralized traffic control (CTC) systems performs integrated control of information and enables control and recovery actions to be taken as soon as possible. To prevent accidents from recurring, maintenance divisions are taking various measures such as reviewing inspection methods, measurement items, and allowable limits; reflecting problem data in redesigns for improvement; executing scheduled repairs; and raising employees' skills and awareness.

8. Acceleration of Tokaido Shinkansen trains

The Series 0 train, which made its debut when the Tokaido Shinkansen line was opened, had a maximum speed of 210km/h and was retired last year. The Series 100 train was introduced in 1986 as a "double decker train." The Series 0 train had a motor on all of its

16 cars; while the Series 100 train includes four trail cars without motors. It was with the introduction of the Series 100 train that the increase of the maximum speed to 220km/h was finally made possible. The biggest reasons for the difficulty of increasing maximum speed were the environmental restrictions regarding ground vibrations and noise along with the line are very strict – which are said to be the strictest in the world.

(1) Series 300 train

In 1986, the JNR was divided and placed under private management and the Tokaido Shinkansen came under the management of the JR Tokai. The company planned to reduce the time required for transportation between Tokyo and Shin-Osaka on the Tokaido Shinkansen as an effective way to enhance competitiveness and transportation capacity. Then, we set the goal of 2 hours 30 minutes for that route and began pursuing it. To attain the goal, it was necessary to develop a new train that could run safely at 270km/h while keeping vibration and noise at conventional levels along the line. Therefore, the weight of the train had to be reduced.

The body of the Series 300 car was therefore made about 40% lighter than the conventional steel car body. This was achieved using a large-sized extrusions of aluminum alloy for the new car. The new material was light, sufficiently strong, and easy to process.

An AC asynchronous motor drive system was introduced as the train's electric power system (the conventional shinkansen trains used DC motors). Also, an electric power regenerative braking system using power conversion technology was developed. These developments were made possible by advancements in power electronics technology, including gate-turn-off (GTO) thyristors. Power conversion technology greatly reduced the weight of electric devices and equipment. The bogie had a lightweight structure and no bolstering, and it was about 30% lighter than the conventional type when the weight reduction due to the use of AC motors was included.

As with the bogie, the equipment and parts that were closely related to safety were carefully designed from various aspects. It was difficult to develop all these items so they could be put to practical use in a short term. They were finally completed after ten years of research and development based on the technical experience and knowledge accumulated in the days of the JNR.

As the result of these efforts, the weight of a train of 16 cars with the maximum number of passengers on board could be reduced from 925 tons (Series 100 train) to 710 tons (Series 300 train). The Series 300 is the true second-generation shinkansen train, which became the prototype of subsequent shinkansen models. In line with the development of the Series 300 train, the company raised the track maintenance standards to assure the passengers' comfort and reinforced the electric facilities.

(2) Series 700 train

The Series 700 is the newest train and was introduced in 1999. It was developed jointly by the JR Tokai and the JR West, reflecting the field data on train operations at high-speed that was collected from operating the Series 300 train, technical knowledge accumulated through development of the 300X-series test models and the Series 500 train, and other new technologies. The Series 700 train was developed under four concepts: (1) provision of a comfortable passenger cabin, (2) consideration of harmony with the environment, (3) improvement of rolling-stock performance, and (4) reduction of total cost. To provide a comfortable cabin, the passengers' comfort was improved and the noise inside the car was reduced. To improve the passengers' comfort, nonlinear type air springs, longitudinal dampers, and a semi-active vibration control system were incorporated. The noise inside the car was greatly reduced by filling the double-skin, hollow extrusions of aluminum alloy with sound-insulating material, and the noise produced from electric equipment was reduced by the use of insulated gate bi-polar transistor (IGBT) devices.

To address environmental concerns, low-noise single-arm pantographs and insulator covers were used for the pantograph facilities, which are the biggest noise source. Also, the surfaces of the car-linking sections and the structures under the floor were smoothed.

Air movement in tunnels is a problem that appears as the maximum speed of trains is increased. When a train runs into a tunnel, the air inside the tunnel is compressed, a pressure wave is produced and propagated, and the air near the exit of the tunnel is hit by the pressure wave. This pressure wave is called the "micro-pressure wave." Conventional studies indicated that a gradual and consistent change in the cross-sectional area of the front of the train can eliminate this problem. With this in mind, further computer simulation and testing with variously shaped models were conducted. Based on the conventional studies and the results of the simulation and tests, the length of the front of the Series 700 train was set to 9.2 meters, which is 3.2 meters longer than that of the Series 300 train.

The company also decided to monitor the running condition of the Series 700 train by a monitoring system and conduct automatic inspection of equipment and facilities at periodic train inspections to achieve efficient and accurate maintenance.

On the assumption of running from Tokyo to Shin-Osaka at 220km/h, the electric power consumption of the Series 700 train is 34% lower than that of the Series 0 train. Thus, the Series 700 has achieved a big reduction in power consumption. Although the total power consumption of the Tokaido Shinkansen is naturally proportional to the number of trains and the total running distance, the total power consumed in fiscal 1999 was about 15% lower than that consumed in fiscal 1990.

9. Future issues

Thirty-six years of safe and consistent transportation by the Tokaido

Shinkansen is a great achievement and is a large factor in the company's business success. Efforts should be made to continue to offer safe and consistent transportation. Safety-related devices and equipment may become obsolete and continuous improvement efforts from various experiences including efforts to deal with troubles and to make them more efficient will be necessary. Procedures to implement improvements should be planned carefully and accurately. The safety-first principle will never be changed, but measures to cope with the increase in the amount of information and information transmission speed will have to be taken.

It is impossible to specifically describe the basic and additional functions and the quality that will be required of the railway in the 21st century. The following explains only the urgent issues.

(1) Functions

The primary concerns of customers when they select a means of transportation will remain the same: the time required for door-to-door transportation and the frequency of service. Therefore, we must consider the time required for transportation between stations on the Tokaido Shinkansen line together with the service schedule and the other transportation facilities around each station. The time required for transportation between stations is not expected to change much because the current linear form of service will be maintained. The service schedule will be improved after the planned 2003 opening of the Shinagawa Station. It will also be improved by the new ATC system being developed (train intervals will be reducible because of a shorter braking time).

Additional factors include the passengers' comfort in a broad sense and the information services. These factors should correspond to the level of private and social lives of passengers. However, it is very difficult to change the railway system so that it can fully adapt to the information technology (IT) revolution and the radical changes in information-processing equipment, including mobile phones. We must rearrange our information infrastructure, that is, the information transmission network for the railway system, so we can make our service conform to the information-oriented age and meet our customers' needs. We can decide how to apply the transmission network after considering the installation of necessary peripherals in view of cost-effectiveness.

(2) Quality

The basic requirement of a railway is consistent transportation. Delay in service is an important criterion of quality evaluation. High standards must be maintained; therefore, daily maintenance of trains and facilities must be conducted carefully and accurately. The persons who maintain the railway system will change (their personal standards and number will change) as time goes by, and the maintenance system and organization will have to follow those changes. In other words, the automation of inspection and mechanization of repair will have to be further promoted.

The environment along the lines will inevitably be the source of even stricter restrictions. We must continue technical development activities to solve environmental issues. We should not have the illusion that the railway has an advantage over other transportation facilities concerning global environmental pollution. The organizations pertaining to other means of transportation are carrying out the necessary technical development with the belief that environmental issues threaten their existence. We have to think therefore that our advantageous position can easily be taken away from us by our competitors.

10. Conclusion

The safety of the shinkansen was not established in a day: it has been formed on the basis of our predecessors' wisdom, the preservation of maintenance skills, and ideas regarding system modifications. Especially, the basis of the safety system was created from superior technical knowledge and wisdom when the Tokaido Shinkansen line was constructed. Following our predecessors' fundamental ideas, we railway engineers should continue our efforts to further improve the railway system so that it is even more a safe, convenient, comfortable, and energy-saving efficient means of transportation. One of our predecessors said "Partial optimization is an evil to the whole." We should always remember that the railway is a total integrated system and it is important to keep all of its parts well balanced. This concept will result in a safe, consistent, and comfortable transportation service.

The declaration adopted in the International High-Speed Railway Conference 2000 presented how we, high-speed railway operators, should fulfill our social and economic duties continuously in the 21st century. Finally, I conclude this document with a quotation from the declaration:

Environmental issues are the world's common and significant themes for the 21st century, for which the transportation sector also has great responsibilities.

In order for the railway sector to carry out this responsibility, it will be necessary to have both policy efforts so that each mode of transportation is used in accordance to its most favorable characteristics and efforts from railway operators such that railways, which are superior in regard to the environment-friendly qualities will be chosen by even more passengers.

We, high-speed railway operators will make every effort to improve so that passengers will more than ever choose high-speed railways. JJTI

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