

Fifty Years of the Shinkansen 新幹線 50 年

Vaclav Smil

Japan of 2014 is clearly a troubled nation -- and I will remind the reader about only a few key components of its peculiar situation. The country is still rich by any global standard but its national debt is far higher than that in any other affluent country, and rising, and in 2014 its economy has been chronically close to, or actually in, a deflationary recession. Japan is still the world's third largest economy, but after decades of huge trade surpluses it is now running substantial trade deficits. The cause of these deficits goes beyond the post-Fukushima need for higher imports of oil and gas: offshoring of Japan's manufacturing has seen widespread loss of capacities and jobs, and many jobs have become part-time and temporary. Japan is still home to famous global brands (Toyota, Honda, Nikon) but performance of some of these companies has been tainted by poor quality products and corporate scandals (financial fraud by Olympus, massive recalls of Toyota cars, Takata's deficient airbags installed in millions of vehicles) and some firms that were previously pioneers of widely admired technical advances and the envy of corporate managers (Sony, Panasonic, Fujitsu) now face chronic difficulties, if they are not nearly bankrupt.

Japan's life expectancy retains its global primacy but concerns about the future delivery of affordable health care lead to bizarre attempts to robotize hospital tasks rather than open up the country to much needed immigration of skilled labor to provide medical and welfare support. Economic ties with its two most important Asian neighbors, China and South Korea, have deepened during the past generation -- but so have mutual recriminations and accusations and, for the first time in

decades, fears of actual armed confrontation in the case of China and Japan. And above it all hang the implications of the world's fastest-aging and now also inexorably declining population, a demographic destiny that will not be reversed by government appeals to marry early, have two children and move out of Tokyo.

Amidst this deepening *angst* one 2014 anniversary deserved much more attention, and considerably more praise, than it had received: on October 1, 1964 the first rapid train of Japan's new trunk line (*shinkansen*) left Tōkyō for Ōsaka -- and the first fifty years of its increasingly more frequent and faster service have been completed without a single fatal accident. Europeans, starting with the French and their TGV (*Train à Grande Vitesse*) and the Germans with their InterCity Express, eventually began to copy Japan's great example, and, most recently, rapidly modernizing China became the world's most extensive builder of rapid trains while North America's passenger trains remain embarrassingly old-fashioned, unreliable and slow. Why did Japan take the lead -- and has its commitment to rapid trains paid off, or is it yet another bottomless pit swallowing government subsidies?

Engineering (and other) challenges

As I explained in a book that traced the key technical advances of the 20th century¹, Japan's first high-speed train was a perfect example of a technical advance that did not require any new fundamental inventions but that resulted in a truly transformative outcome. Cars with steel wheels on steel rails represent a simple but reliable combination that results in firm

contact, steady guidance, minimized friction and ability to carry large loads with low energy costs. These were a key component of commercial railway transportation from its inception in the 1830s -- and the first *shinkansen* had the same ballasted track (sleepers resting on a bed of crushed stones) as all previous rail links. Rapid trains rely on electric motors, dependable and efficient prime movers that entered railway service before the end of the 19th century, and while *shinkansen* is powered by alternating current rather than by direct current used for the pioneering electric trains, that option has been commercially available since the late 1930s. Pantographs to tap electricity from the suspended wires, light car bodies, aerodynamic styling and regenerative brakes had to be redesigned, adapted and tested -- but none of them had to be invented.

That is why Shima Hideo, Japan's senior railway engineer who went to Washington in 1960 to secure a World Bank loan for the new rail link, stressed "that *shinkansen* techniques included no experimental factor but were an integration of proven advances achieved under the 'Safety First' principle". As such it was a perfect accomplishment of transformative engineering, a synergy of proven components that creates a new admirable outcome. Unfortunately, the World Bank bureaucrats saw it initially as an excessively risky experiment ineligible for funding.

The Japanese were building on considerable foundations of rapid train travel but they had to redefine, and they chose to recompose, some of its key ingredients. Fast trains have a long history, with a mile a minute (96 km/hour) run achieved on a scheduled English service already in 1847, less than 20 years after the beginning of railways.³ By 1900 speeds in excess of 100 km/hour were common on many straight sections in North America and Europe and new, powerful streamlined trains that entered service during the 1930s could average

nearly 150 km/h on straight runs and reach maxima of 180 or even 200 km/h.⁴

New post World War II developments in railway transportation were delayed until the mid-1950s, after Japan and many European countries regained their pre-war economic standing; Japan did so, in absolute terms in 1954, which means that in per capita terms it was still poorer in 1954 than in 1940. But just a few months after the first post-war Japanese expert delegation attended a major international railway conference in Lille, France four of Japan's leading companies (Hitachi, Toshiba, Fuji and Mitsubishi Electric) introduced electric motors suitable for rapid trains, and in May 1956 Japan National Railways (JNR) began to study the feasibility of a rapid train link between the capital and Ōsaka.

They had a bit of infrastructural foundation to build on. A pre-war project to operate a bullet train (*dangan ressha*) between Tōkyō and Ōsaka (and then further west) had resulted in land expropriation and a partial layout of the route and in the completion of a major tunnel before the work was abandoned in 1944, and the *shinkansen* took advantage of these fragmentary beginnings. But otherwise the setting was hardly encouraging. The late 1950s were not the most opportune time to think about new expensive railway links: inexpensive crude oil from the Middle East enabled Europe and Japan to follow North America and embrace automobiles and buses; railways were clearly on the way out in the US and stagnating in Europe, and long-term choice of rapid trains appeared to run against the emerging consensus that the just-introduced jet-powered flight (its commercial operations began in 1958) would be preferable for rapid travel.

But the decision was made to go ahead with the project and the construction of the *Tōkaidō shinkansen* began in April 1959: the first name was an obvious reference to the ancient land

route between Edo and Kyōto, the other one (new trunk line) was to distinguish the link, the country's first with standard gauge (1,435 mm) from the old narrow-gauge (1,067 mm) railways built in Japan since the first link between the capital and Yokohama in 1872.⁵ As with many other megaprojects, there were some questionable cost estimates, inadequate financing and (what we know now are almost inevitable) cost overruns. In 1958 JNR put the cost at an unrealistically low ¥ 194.8 billion (equal to \$ 541 billion in 1958 monies and to at least \$4.5 billion in 2014 \$) in order to secure the government's funding approval, and the World Bank's eventual loan of just \$ 80 million was only about 15% of that grossly underestimated budget. The actual cost reached ¥ 380 billion (just 5% short of doubling the original estimate) and even before the project was completed these large overruns led Sogo Shinji, the President of JNR, and Shima Hideo, the company's VP for engineering, to resign in 1963. But the project was finished on time on October 1, 1964, that is just in time for the Tōkyō Olympics, after five years and five months of construction.



Tōkaidō shinkansen launched at Tokyo Station, 1964 (Photo Sankei Archives/Getty Images)

Shinkansen since 1964

After *Tōkaidō* proved itself, the links were expanded both south- and north-ward. In 1972 the *Sanyō* line was extended from Ōsaka to Okayama and in 1975 to Hakata in northern Kyūshū. *Tōhoku* line to Morioka in northwestern Honshū, and *Jōetsu* line to Niigata on the Sea of Japan entered service in 1982 and in 1985 the lines were extended to Tōkyō's Ueno station. In 1987 deeply indebted JNR was privatized and divided into seven regional companies: *Tōkaidō shinkansen* now belongs to JR Central. In 1990 Japan's bubble economy began implode and although the 1990s became known as the lost decade there were no negative impacts on the *shinkansen*: new lines were opened, high standards of operation were maintained and technical progress continued.



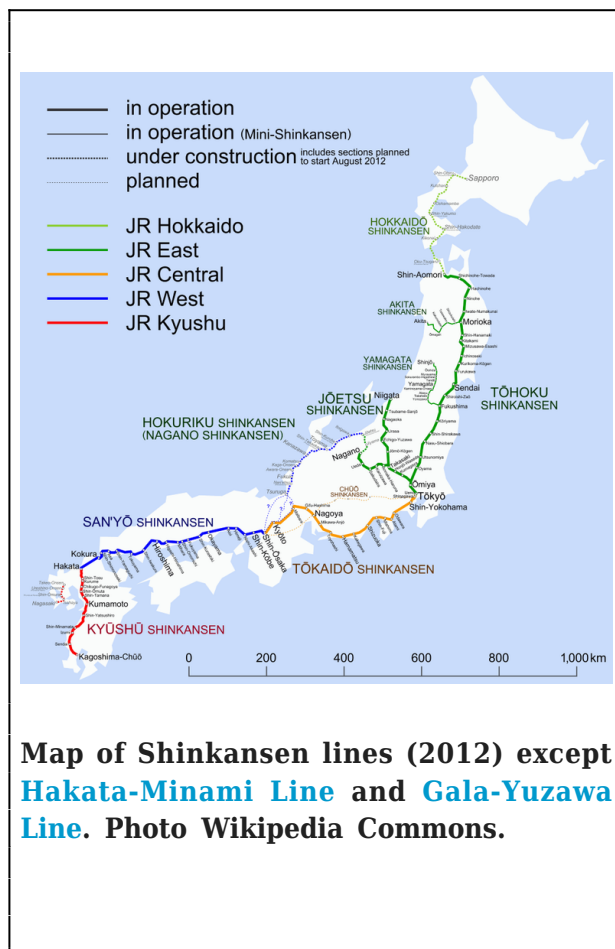
Mount Fuji with Shinkansen and cherry blossoms. Photo Wikipedia Commons.

In 1992 *Yamagata shinkansen* connected Fukushima with Yamagata and in the same year the new 300 series *Nozomi* trains (capable of 270 km/hour) went into service. In 1997 *Akita shinkansen* connected Morioka with Akita on the coast of the Sea of Japan, *Nagano shinkansen* was completed to bring athletes and visitors for the Winter Olympics of 1998,

and 500 series *Nozomi* (capable of 300 km/hour) went into service. In 1999 *Yamagata shinkansen* reached Shinjō, in 2002 the *Tōhoku* line was extended to Hachinohe and in 2004 *Kyūshū shinkansen* reached Kagoshima. The last two extensions took place in 2010 (*Tōhoku* line to Aomori) and 2011 (from Kagoshima to Fukuoka). Planned extension will bring *Hokuriku shinkansen* to Kanazawa in 2015 and *Hokkaidō shinkansen* should start running between Aomori and Hakodate in 2016. Clearly, Japanese planners have been both methodical and relentless in extending rapid trains even into the areas of (for Japan) relatively low population density.

motors) and then to curved wedge o 300 series introduced in 1992. Then came the short-lived (built only between 1995 and 1998) 500 series with very long, needle-like noses, and finally, since 1999, ones with flatter duck-bill noses but capable of the same speeds as the sleeker 500 series. As the country's population increased and as its economy expanded, ridership and daily frequency of trains on the busiest lines kept on increasing. *Tōkaidō shinkansen* now carries annually about 140 million people, slightly more than Japan's total population, and all *shinkansen* lines are boarded by nearly 300 million people a year. By comparison, French TGV system carries about more than 100 million people a year, and China's new rapid trains still serve less than 50 million passengers.

The frequency of trains on the *Tōkaidō* line went from just 60 per day in 1964 to 285 in the year 2000 and to more than 320 in 2014; the latest JR Central timetable shows 225 westbound trains a day with 145 trains leaving Tōkyō, as many as eleven per hour during peak periods, some at intervals of just three to four minutes. In recent years on-time performance has slipped somewhat but the numbers remain safely within the admirable range: the latest reported average delay, based on more than 150,000 trips made in a year, was 36 seconds in 2013⁷ -- despite all those frequent typhoon-generated strong winds and heavy rains, Tōhoku's snowfall and countrywide frequent earthquakes. And, most importantly, this operating precision under often inclement conditions has been achieved without a single fatality.



The appearance of leading cars changed from bulbous noses of the original *Shinkansen* series to more pointed design of the 100 series produced between 1984 and 1991 (exceptionally, its leading cars had no electric



Shinkansen 0 series with Nozomi passing. Photo Wikipedia Commons.

Why it has been so safe

No *shinkansen*-related statistic is as impressive as the fact that by the end of 2014 the

entire system moved nearly six billion people (equivalent to more than 80% of the entire global population) without a single fatality, without a single collision, and with only two derailments caused not by human error or by mechanical or electronic failure but by natural disasters. The first derailment took place during an earthquake on October 23, 2004 as eight of ten cars of the *Jōetsu shinkansen* left the track near Nagaoka (with no injuries among passengers). The other one was on March 2, 2012 when *Akita shinkansen* derailed in a blizzard (again, with no injuries to passengers).

Safety starts with the track: completely dedicated, with no other trains using it, with no level crossings and with appropriate barriers and multipurpose inspection trains (they run between midnight and 6 AM when the *shinkansen* does not operate), with continuous checking of the state of the rails and the bed. Rails are continuously welded (they weigh 60 kg/m) and they are mounted on reinforced concrete slabs. Original specification allowed 2.5 km for the radius of curves and the

maximum gradient of 2%, but for new, faster trains the minimum curve radius is 4 km and the maximum slope is 1.67%. Electricity is supplied as 25 kV AC at 60 Hz and it is drawn from catenary wires made of copper or copper-clad steel. Unlike many other rapid trains, *shinkansen* trains do not have a locomotive (or locomotives).⁷



Shinkansen track. Photo Wikipedia Commons.

During the design stage in the late 1950s Shima Hideo argued that multiple electric motors placed in individual carriages are the best way to limit axle loads, reduce stress on tracks and allow the motors to be used for regenerative braking.⁸ This design has persisted, although some trains had one or two cars without any electric motors. The latest *Nozomi 700* series has 64 AC motors (four for every car) rated at 275 kW and able to deliver 13.2 MW of power, making it easier to perform sudden accelerations and decelerations and provide dynamic braking once the motors become generators driven by the wheels and exert drag on the train (pneumatic brakes are used at speeds of less than 30 km/h and as a backup).

Most importantly, the centralized traffic control (CTC), automatic train control (ATC), and Urgent Earthquake Detection and Alarm System ensure the highest degree of safety.

CTC oversees routes and train and crew scheduling, ATC maintains safe distances between fast-travelling trains and it is designed to engage train brakes automatically as soon as the speed exceeds the indicated limit. The earthquake detection system is perhaps most ingenious as it senses the very first seismic waves coming to the Earth's surface, instantly determines the risk levels and it can halt, or at least slow down, trains in the affected region before the main earthquake shock arrives.⁹

These safety measures have made it possible to raise routine operating speeds and to cut travel times. The first trains traveling from Tōkyō at no more than 210 km/h took four hour to reach Ōsaka; just a year later the trip was down to three hours and ten minutes, and in 1992 new *Nozomi* trains (travelling at the maximum of 270 km/h) reduced the travel time between the capital and Ōsaka to just two hours and 30 minutes; a further 5 minutes was shaved by the latest *Nozomi* version (N700). But these times do not reflect maximum possible speeds, because the fastest trains must reduce speed in many sections in order to minimize noise where the line transects inhabited areas.



**Nozomi 700 Series in November 2014.
Photo V. Smil.**

Although the aerodynamic design of trains (the 16-car assembly is 400 m long) reduces high-speed drag, noise and vibration are much more difficult to suppress. Because noise goes up in proportion to the 6th power of the speed it becomes excessive at high speeds: at 300 km/h the sound pressure level on the forward car is on the order of 100 dB.¹⁰ Because noise must be limited below 70-75 dB in residential and commercial areas --and these add up to 86% of the 513 km between Tōkyō and Ōsaka - *shinkansen* trains must travel well below their maximum capability on most of the *Tōkaidō* line. *Tōhoku shinkansen*, travelling through less populated areas, now reaches maxima of 320 km/h.

Looking back

A half-century after the first *shinkansen* run Japan's pioneering achievement remains notable for the boldness of the idea and for its near-flawless execution. Costs have been high but a true account, as with any complex system, could be established only when taking other factors into consideration, and when considering the cost of alternatives. The *shinkansen's* speed, safety and reliability have combined to make a major, and lasting, positive economic contributions to Japan's modern development but, undoubtedly, capital and operating costs of rapid trains are high and they require government subsidies in all countries that have built them.



Modest 50th anniversary: small stickers in *shinkansen* cars in 2014. Photo V. Smil.

We take for granted that governments should be involved in taking care of security and improving the conditions for economic development. Both of these goals require adequate investment in basic infrastructures that will provide decades-long benefits: in North America there is little argument that highways belong to this category: just consider the continuing economic, social and security benefits of the U.S. interstate system launched under Eisenhower and built with federal financing. This does not mean that there should be an indiscriminate preference for rapid trains. After all, it must be acknowledged that Japan has the uncommon advantage of concentrated population (with daily passenger density per km of rail route almost six times higher than it is in France, and in the region served by *Tōkaidō shinkansen* about five times the Japanese national mean) that makes it

much easier to justify high capital cost of rapid train links.

But every major economy would benefit by using rapid trains to link large cities that are 300-900 km apart, distances that can be covered between one (or one and one half) and four hours and where rapid trains have a clear time-saving advantage compared to air travel. In North America rapid trains will never make sense as links between Toronto and Vancouver or between Minneapolis and Seattle: distances are too long, population densities are too low. But they are the superior solution for moving people between any pair of large cities that are now connected by frequent shuttle flights that last 60-90 minutes: the four obvious North American choices include the northeastern megalopolis (Boston-New York-Philadelphia-Washington), Houston-Dallas, San Francisco-Los Angeles, and Toronto-Ottawa-Montreal.

Convenience is an obvious advantage: writing as both a frequent flyer and a frequent rider of rapid trains, I cannot imagine how anybody could argue that getting to distant airports, being subject to pre-boarding security gauntlets, waiting for luggage on arrival and getting somehow to downtown to connect with other transportation links (a sequence that can easily add up to three hour for an hour-long flight) is preferable to comfortable downtown-to-downtown rides in rapid trains. But there are also unmatched energy and environmental advantages that are often ignored by those who look strictly at the financial cost of auto, air and high speed train.

No other form of land transport consumes less energy per passenger and hence has a lower environmental impact than do high-speed trains. *Tōkaidō shinkansen* requires 80% less energy per passenger-kilometer than driving between the country's two largest cities, and that is assuming actual driving time, not the time now habitually spent idling on Japan's congested highways. And in the age concerned

about carbon emissions and global climate no comparison is more persuasive than the fact that carbon dioxide emissions per seat average just 4.2 kg on the Tōkyō-Ōsaka trip, compared to about 50 kg when flying the same distance in a commercial jetliner by JAL or ANA from Haneda to Itami.

Shinkansen as a model

Half a century after the first *Tōkaidō* ride, rapid trains connect the Japanese capital with even the most distant regions on the main island, Honshū, and also go to Kyūshū, Japan's southernmost island. Europe, the birthplace of trains, hesitated for a while but it eventually became an enthusiastic builder of rapid trains, most notably France, whose *TGV* began operating on the Paris-Lyon route in September 1981, *TGV Atlantique* to Brittany came in 1989 and to Bordeaux in 1990 (this was the world's first line to see scheduled speeds of up to 300 km/h), *TGV Nord* to Calais was added in 1993 and to the Channel Tunnel a year later, and the link to Belgium (*Thalys*) started in 1997.

Meanwhile the first German *ICE* (*Intercity Express*) started in 1991, as did the first Spanish AVE (*Alta Velocidad Española*), from Madrid to Seville. Later came links to Barcelona (2008) and Valencia (2010), and Italy's ETR 500 (*Elettro Treno Rapido 500*) came in 1993, followed by *Frecciarossa* (Red Arrow). In Asia, South Korea began its KTX (Korea Train eXpress) in 2004, Taiwan's rapid trains came in 2007 as did China's first link between Qinhuangdao and Shenyang (China now has the world's longest network of rapid trains, about 11,000 km, or twice the distance across the United States, which also includes the longest, nearly 2,300 km, direct link between Beijing and Guangzhou). In contrast, the United States and Canada are notable for their lack of rapid trains. Acela's pitiful performance between Boston and Washington DC does not make it a real rapid train: although it can go up to 240 km/h, its average speed

(including stops) is just 116 km/h, less than half the normal operating speed of true rapid trains.

The conclusion is obvious: all major affluent economies outside of North America, as well as China and soon, with China's help, Russia, count rapid trains among essential modern infrastructures that deserve government support and continuing improvement. Most of the technical solutions developed by the designers of the *shinkansen* have not been simply copied by other countries that built their rapid trains (for a variety of reasons ranging from the preference for supporting domestic industries to China's chronic Japanophobia) -- but the importance of the path-breaking example of Japan's bold experiment and its long-term operational success cannot be denied.

The best engineering designs are those where the users can form spontaneous positive impressions and bestow well-deserved admiration. That is why I can offer no better ending than the summary of my impressions written a decade ago when I was marking *shinkansen's* 40th anniversary:¹¹

I have traveled in the comfort of the first class Green cars as well as standing in packed compartments at the end of *obon* holidays, catching the first train from the capital as well as arriving just before the services end by midnight. All of these trips have one thing in common: this is travel as an event because even when the rapidly receding scenery is hidden, even when standing in a nonreserved crowded carriage, you know that on the same track and just three minutes and 45 seconds behind you is another sleek assembly of 16 cars with 64 asynchronous motors moving in the same direction at 300 km/h --

and that when you arrive after a journey of hundreds of kilometers the most likely delay will be 24 seconds!

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This paper draws on the following three publications by the author:

Smil, V. 2004. *Omedeto gozaimasu! (Congratulations!)*. *Tech Central Station*, October 1, 2004.

Smil, V. 2006. *Transforming the Twentieth Century: Technical Innovations and Their Consequences*. Oxford University Press, New York, x + 358 pp.

Smil, V. 2014. *Do the locomotive*. *The American*, October 4, 2014.

For a typical Japanese anniversary write-up see: Nippon.com. 2014. *The Shinkansen turns 50: The history and future of Japan's high-Speed train*.

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Notes

1 Smil, V. 2006. *Transforming the Twentieth Century: Technical Innovations and Their Consequences*. New York: Oxford University Press, New York.

2 Shima, H. 1994. Birth of the Shinkansen - A memoir. *Japan Railway & Transport Review* 3:45-48.

3 O'Brien, P., ed. 1983. *Railways and Economic Development of Western Europe, 1830-1914*. New York: St. Martin's Press.

4 Ellis, C.H. 1983. *The Lore of the Train*. New York: Crescent Books.

5 Aoki, E. et al. 2000. *A History of Japanese Railways, 1872-1999*. Tokyo: East Japan Railway Culture Foundation.

6 JR Central. 2014. 0.6 minutes/train annual average delay.

7 In contrast, French TGV has two power cars (locomotives) in every trainset, each with the mass of 68 t and power rating of 4.4 MW.

8 Shima, op. cit.

9 Noguchi, T. and T. Fujii. 2000. Minimizing the effect of natural disasters. *Japan Railway & Transport Review* 9:52-59.

10 Mellet, C. et al. 2006. High speed train noise emission: Latest investigation of the aerodynamic/rolling noise contribution. *Journal of Sound and Vibration* 293: 535-546.

11 Smil, V. 2004. *Omedeto gozaimasu! (Congratulations!)*. *Tech Central Station*, October 1, 2004.