

50 Years of Progress in Railway Technology

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Introduction

In the 1960s, before he became President of SNCF (and subsequently President of UIC), Louis Armand said, 'The railway will be the mode of transport for the 21st century if it survives the 20th.' We have now turned the corner into the 21st century and rail transport in Europe is perhaps more alive than ever.

The railway's history over the last 50 years has been punctuated by major technological changes and this article reviews the highlights and shows how the changes were serious gambles in preparing for the 21st century.

The leap in the popularity of high-speed trains (250–300 km/h) played a key role in this evolution, which is both irreversible and fundamental to passenger transport in Europe. Much of this article is about high speed and there are two information boxes on the evolution of high speed in Germany, and on the development of Italy's famous *Pendolino* technology that has now conquered most of Europe.

Due to its major role in Europe's progress in rail transport, I will discuss changes in electrical power techniques, traction and signalling. Part of this article examines the design and construction of carriage bodies and some pages cover the impact

(which are still largely to come) of electronics and digital techniques on railway engineering. Finally, I will touch on rail freight, which has not yet taken advantage of the technological changes in Europe.

High Speed—from Diversity to a European Standard

Constant quest for higher speed

Since the early 1950s, it has been clear in Europe that increased train speed, particularly on passenger trains, is crucial to rail transport's competitiveness. The railways were forced to react as the automobile advanced in tandem with the growth of the motorway network to offer significant gains in time and comfort. In 1955, SNCF signalled its determination to develop faster trains when it set a speed record of 331 km/h with an Alsthom-built locomotive. However, at this time, there seemed to be two possible ways forward—using the current infrastructure or building new infrastructure.

Choosing between old and new lines or slow maturation of tilting trains

The first idea that enters a railway engineer's head when wanting to increase train speed is to introduce tilting or

pendulum techniques to permit faster speeds on curves.

SNCF was the first European rail operator to research this field when it ran a series of tests in the early 1960s on carriages using natural tilting (swing around centre of gravity) and controlled tilting. It came to the conclusion that the potential gain in speed on conventional lines was significant with controlled tilting but that 1960s technology could not provide sufficiently accurate and reliable control to deliver the required ride quality. As a result, SNCF decided to opt for high speed on new lines, requiring higher infrastructure investment but delivering much greater timesavings.

Italy was the second European country to attempt the tilting technique and produced a prototype that was well ahead of its time but was to remain restricted to two experimental trains in Italy and Spain. Paradoxically, the opening of the new Rome–Florence line in 1988 (almost 15 years after the prototype) saw Europe's first true tilting train based on Fiat's design, while Fiat in the meantime had become Alstom Ferroviaria.

However, we should not forget developments in England during the same period. In the late 1970s, British Rail produced the prototype Advanced Passenger Train (APT) with tilting action. Like the Italian *Pendolino*, it was designed to travel at speeds of up to 250 km/h on the East Coast main line. Unlike the *Pendolino*, the APT was articulated and required extremely bold technological solutions (like hollow axles to allow hydrokinetic braking by injecting ultra-pure oil into the axles).

The APT engineers were perhaps too far ahead of their time and the new technologies encountered many problems, so the APT never went beyond the prototype stage. The UK had to wait until the late 1990s for the delivery of Alstom and Fiat Ferroviaria tilting trains for Virgin West Coast Trains Ltd., operating



Artist's impression of high speed in Europe

(Alstom Transport)

out of London Euston on the West Coast main line.

Finally, the Spanish company Talgo-Transtech has perfected the *Talgo XXI* pendulum train featuring a natural tilting action, which although it does not allow as great a speed increase as controlled tilting, does offer simplicity.

High speed on new lines

While not forgetting JNR and the opening of the Tokaido Shinkansen in 1964, SNCF was the originator of the modern high-speed rail system in Europe. Although SNCF had put tilting techniques on hold, unlike Germany and Japan who were both looking at development of magnetic levitation systems, SNCF still believed that the speed potential of adhesion-based wheel and rail systems above 300 km/h was largely unexploited. In the mid-1960s, it started the C03 research programme to establish the basic parameters of a new high-speed railway system with highly optimized catenary, signalling, operations, rolling stock, etc., as outlined below:

- Specialist high gradient line (35%)
- On-board signalling with attendant disappearance of trackside signalling
- Articulated multiple units with adhesion focused on motor units at the front and back and lightweight, highly stable bogies

This was in sharp contrast to other countries like Germany and Italy, which were introducing new lines based on more traditional concepts, particularly low-gradient mixed-traffic lines.

French TGV

The French TGV has enjoyed exceptional growth in France over the last 20 years and its engineering success is largely due to an exceptional partnership between SNCF and rolling stock manufacturers, especially Alstom.

Since the whole story extends far beyond



Third-generation TGV Duplex

(Alstom Transport)

the scope of this article, I will just mention the main milestones:

- 1972—TGV001 prototype exceeds 300 km/h in first year of testing
- February 1981—First-generation full-production trainset sets world rail speed record of 380 km/h
- September 1981—First-generation TGV SudEst enters commercial service at 260 km/h rising to 270 km/h in 1982
- 1989—Second-generation TGV Atlantique enters commercial service at 300 km/h with three-phase traction using synchronous motors, pneumatic suspension, high-power disk brakes, and on-board computer train command and control systems
- 1990—TGV Atlantique sets world rail speed record of 515.3 km/h on 18 May 1990
- 1994—*Eurostar* links London, Brussels and *Thalys* links Paris, Brussels, Cologne and Amsterdam
- 1997—Third-generation TGV Duplex with high seating capacity enters service as culmination of speed, comfort and economy

Although advances in the technologies of traction, computer systems, structural alloys, etc., have brought constant

improvements in speed, comfort, capacity and economy, the basic design of the three TGV generations (articulation, concentrated traction, lightweight and stable bogies, on-body traction motors) has remained remarkably unchanged.

Future of high speed in Europe

High-speed rail transport is now reaching maturity in Europe and it is the technology that has been chosen for Europe's high-speed transport network—no practical application has been found for magnetic levitation. Far from competing, the technologies of high speed on new dedicated lines and tilt trains on conventional lines have been combined to produce high-speed tilting trains like the tilting TGV tested in France in 1999 and 2000 and now in use on the Paris–Toulouse and Paris–Brittany services. (Italian Railways (FS) has similar projects.) Although the concept of high-speed dedicated lines has gained currency in Europe wherever passenger traffic justifies its use, the mixed passenger/freight line concept still finds applications on the Lyons–Turin transalpine line and the Perpignan–Barcelona line across the Pyrenees.

Europe's entire high-speed rail system is now being standardized following a

decision by the European Community and the technical specifications for interoperability (TSI) cover all system components, including infrastructure, signalling, rolling stock, operations, etc. Clearly, a lot of ground has been covered in 30 years!

Changes in Power Supply Technologies

Europe's railways inherited electrification systems designed at the beginning of the last century when two major trends dominated the choice of technology:

- Simplicity and economy while permitting use of commutator motor
The choice was for high voltage (15 kV) with alternating current (for easy stepping down through a transformer) but at a very low frequency (16 2/3 Hz) so as not to overburden the motor commutator. Germany, Switzerland, Austria and Sweden chose this route.
- Simple power conversion on-board the locomotive
The choice was for low voltage (1.5 or 3 kV) direct current, which had the disadvantage of complex and heavy

line equipment. Most other countries in Europe chose this route.

In the late 1950s, the limitations of DC electrification prompted SNCF to explore a completely new but considerable technological gamble—high voltages (25 kV) at the same frequency (50 Hz) as the national electricity grid. Engineers like Armand and Fernand Nouvion realized that such a system would have the great advantage of needing fewer substations and produce savings in catenary equipment. But this was offset by the increased complexity of the locomotives requiring on-board power transformation. Various schemes were tested including power-conversion generators powering either commutator motors or induction motors, and mercury-arc rectifiers for commutator motors.

The new AC electrification technique owes its success to the very rapid arrival of power rectifiers (diodes and then thyristors) enabling use of increasingly simple electrical on-board systems.

The 25 kV, 50 Hz AC system soon spread rapidly throughout Europe to become the standard for modern electrical traction.

The appearance of the first French TGV Nord line caused an interesting development known as 2 x 25 kV. This development uses a dual power supply via a positive-phase 25 kV overhead catenary and a negative-phase 25 kV feeder with auto-transformers at regular intervals along the line to earth the rail potential. This saves on substations and reduces Joule losses. It also cuts electromagnetic interference in the environment because the opposite-phase catenary and feeder largely cancel out each other.

Thanks to the development of power electronics, this system won the day in Europe and has become the standard for Europe's high-speed railway network. The original 15 kV 16 2/3 Hz system now only remains on old conventional lines that would be too expensive to convert.

The Electronic Revolution

With few exceptions, electric traction began in most countries by using the commutator motor. In Europe, this motor was powered either by variable DC voltage using an electromechanical device, or in Germany with variable (15 kV, 16 2/3 Hz) AC voltage.

In all configurations, the power conversion system (electromechanical converter and commutator motor) was limited by the motor commutation capacity (especially at 16 2/3 Hz) and by the complexity and vulnerability of the power converters.

This led railway engineers to improve the traction systems by two methods:

- Replacing electromechanical converters with solid-state converters
- Replacing commutator motor with three-phase motor

The first method bore fruit in the early 1970s with the appearance of diodes and power thyristors. Locomotives and EMUs



Astride asynchronous drive electric locomotive

(Alstom Transport)

were soon running with mixed (diode/thyristor) rectifier bridges for AC voltage, and DC-voltage thyristor current choppers for DC voltage. These techniques also simplified design of multi-voltage locomotives to run on different European networks with different power supply systems. This first electronic revolution enabled production of traction equipment that was more powerful, more reliable and above all cheaper to maintain than previous generations. Typical examples of these locomotives are the Alstom-built BB15000, BB7200 and BB22200, which are more powerful (4400 instead of 3200 kW), twice as reliable and less costly to maintain than their predecessors, and the first-generation TGV SudEst.

The second method of replacing the commutator motor with a three-phase motor was the second electronic revolution based on the arrival of gate turn-off (GTO) thyristors and today's insulated gate bipolar transistors (IGBTs). These developments were undertaken in the early 1980s with two competing technical solutions:

- In France, the commutator motor was replaced by the simple self-exciting synchronous three-phase motor, retaining the simple thyristor current inverter. The 'universal' BB26000 locomotives were built on these design principles (high power for passenger trains, and high start-up torque for freight trains). Most importantly, the second-generation dual-voltage TGVs used this principle to provide 4400 kW in a mass of only 68 tonnes. (The four-voltage *Thalys* uses the same design too.)
- Other European countries chose the asynchronous motor powered by a voltage inverter with conventional thyristors. Notable examples are Germany's Class E120 locomotives and the early ICE 1. Although the asynchronous motor is very simple, the converter used natural turn-off

thyristors and was complex, large, expensive and not very reliable. Happily—perhaps miraculously—the appearance of GTO thyristors simplified the converter and Germany changed the design of its ICE 1 motor units to this voltage inverter. SNCF adopted the new technology in its BB36000 *Astride* locomotives.

In conclusion, we must not forget the arrival of the IGBT, which is more reliable and has a simpler chopping function than the GTO thyristor. It has brought compact, simple and reliable power converters.

The advent of voltage-inverter-based asynchronous traction has reduced the equipment mass to such an extent that we can now build trains—particularly EMUs—that were completely unimaginable just a few years ago.

The last component in electrical traction that still constrains railway engineers is the bulky and heavy 15 kV, 16 2/3 Hz transformer. It is a good bet that the third revolution in electrical traction will involve this component.

ERTMS in Europe

Right from the first days of railways, Europe's signalling systems developed completely independently. The result is a real kaleidoscope of systems, making cross-border operations very difficult.

Some major trends are emerging from this great diversity of systems:

- More complex systems to transmit data on location and speed to moving trains
- Shift from ground to on-board processing of information on location and speed
- Disappearance of analog systems, such as first-generation German LZB and French TVM on high-speed lines, in favour of less-costly but more complex digital techniques providing more

information with less risk of interference. To integrate Europe's diverse signalling systems, the EC is financing development of the European Rail Transport Management System (ERTMS), a unified command and control system for rail traffic. The fully digital secure system transfers data from the ground to on-board by using GSM radio. The train calculates its location and safe headway and sends this information back to the ground.

Three trials are in progress in Germany, Italy and France to test the compatibility of products developed by the national manufacturers and rail operators.

Carriage Structures

Although early locomotives were built of steel, the rolling stock was largely a metal chassis with wooden superstructure. A number of serious fatal accidents in the early 20th century convinced everyone of the need to use metal for all rolling stock. High-grade special steels are now widespread in Europe and progress in coatings means that today's locomotives and carriages are much more resistant to fatigue cracking and corrosion, etc., than 30 years ago. We have now moved from a general overhaul at every 6 to 8 years to overhauling at every 15 to 18 years, or halfway through the design life.

However, unlike North America and Japan, stainless-steel construction is still not widespread in European passenger carriages. Where it is used, improvements in welding techniques such as seam welding instead of spot welding have greatly improved mechanical strength.

Introduction of welding robots has promoted more use of aluminium alloys in carriages, especially carriages of high-speed trains (ICE, TGV Duplex), where light weight and good corrosion resistance are particularly important.

However, aluminium alloys have vastly inferior plastic-deformation and energy-



First-generation ICE train

(U. Bitterberg)

High Speed in Germany

Starting in 1972, the wheel-on-rail research programme of the German Federal Ministry of Research and Technology was devoted initially to an in-depth study of the fundamentals of railway engineering and adopted a unique, systematic approach. All areas of railway technology were investigated in an attempt to understand the development potential for a high-speed rail (HSR) system and to determine its technical and economic limits. Rolling stock was a focal point of this programme. In addition to creation of design tools, research centred on development of carriage components and systems. Finally, in the early 1980s, preparatory steps were taken towards putting a high-speed test and demonstration train on the tracks—the ICE/V—that integrated the best development results. This first ICE/V was operational by late 1985 and completed a programme of comprehensive tests and demonstrations in the following 3 years. Then, in May 1988, an unmodified ICE/V set a railway speed record of 406.9 km/h. Subsequently, the ICE/V provided the basis for the 1988 decision to build a production series of ICEs for operation on Deutsche Bahn's (DB AG) new high-speed lines.

High-speed ICE 1 trains entered revenue service on 2 June 1991 and immediately took the lead from other transport modes. ICE trains are not only DB AG's fastest trains, they are also the most popular because of their speed, punctuality and comfort. The commissioning

of the first high-speed lines and 60 ICE 1 trainsets marked the completion of the first stage of Germany's high-speed rail system.

The 60 first-generation ICE 1s were based on the following design concepts:

- Maximum design speed of 280 km/h
- Block train formation with up to 14 trailer carriages
- More comfortable than IC system
- Approved for operation on Austrian (ÖBB) and Swiss (CFF/SBB/FFS) lines
- Platform heights of 76 cm and 55 cm

Since German reunification, the high-speed line linking Hannover and Berlin (264 km) is being rebuilt over some 170 km to permit operation of 250 km/h ICEs. A further 60 km is being upgraded for 200 km/h. Regular service started in May 1998 with 44 ICE 2s on the routes between Berlin and Cologne and Berlin and Frankfurt. Traffic studies in the expanded high-speed railway network showed that short trainsets improve loading factors on some routes while reducing the required number of vehicles. As a consequence, the ICE 2 development specifications were as follows:

- Half-train configuration with coupling of 1 power car + 6 trailer cars + 1 driving trailer, and extended train configuration with coupling of 1 power car + up to 14 trailer cars + 1 power car.
- Automatic coupler at each end of train for coupling two half trains
- Uniform carbody shell with identical window spacing and defined fastening

points for interior fittings, air-spring bogies to improve ride quality and decouple structure-borne noise

- Updated maintenance concept
- Weight reduction of at least 5 tonnes per trailer car compared to ICE 1

The new high-speed line between Cologne and Rhine/Main is the most important project in the DB AG network at this time, shortening the distance between Cologne and Frankfurt from 222 km through the Rhine Valley to 177 km. About 130 km of the route will be covered at speeds of 300 km/h, reducing the present 2 hour and 15 minute journey to less than 1 hour. The line is scheduled to enter revenue service in 2002. International high-speed trains on the route will be joined by ICE 3 multiple-unit trains, representing another new development. Ongoing development of ICE trains is based on design requirements stemming from expansion of German high-speed routes and the European high-speed network. The demands with the greatest impact on ICE design are greater tractive power for a maximum running speed of 330 km/h, a maximum grade of 40‰, and a maximum static axle load of 17 tonnes. These demands and continued progress in lightweight carriage construction focused attention on the EMU concept with the result that the new ICE 3 is a true EMU configuration. The first scheduled ICE 3 service started with EXPO 2000 in Hannover and will total over 200 units when in full service.



Italian Railway's ETR460, basis for tilting trains in Europe

(Alstom Transport)

Tilting Trains in Italy

The tilting principle enables the carriage body to lean in on curves, achieving the same effect as traditional canting. With a tilting train, it is possible to travel in complete safety with a non-compensated lateral acceleration at bogie level of 2 m/s^2 . Combined with the track cant angle, the body can be inclined up to 8° reducing the non-compensated lateral acceleration at passenger level to just 0.65 m/s^2 , well within the comfort zone of 0.8 to 1.2 m/s^2 . This allows a 35% increase in speed on curves compared to conventional trains in full safety

and comfort with no need to change the track geometry and layout.

The initial tests on tilting-body technology were carried out by Fiat Ferroviaria (now Alstom Ferroviaria) in the late 1960s in collaboration with FS. The results using a tilting seat installed on an ALn 668 railcar were so encouraging that it was decided to build the first YO16 tilting railcar, which soon became nicknamed the *Pendolino*.

In 1974, after extensive testing, FS ordered the first prototype tilting EMU consisting of four carriages. The resultant ETR 401 entered service in 1976. A similar prototype was

delivered to Spanish National Railways (RENFE). Thanks to the positive experience gained from these trains, in 1985, FS ordered fifteen ETR 450 tilting trains consisting of 9 carriages each, with electric traction and a hydraulic tilting system. The ETR 450 entered commercial revenue service in 1988 on the Milan–Rome line immediately revealing its advantages in terms of comfort and a huge drop of some 22% in travel times. The distributed power configuration keeps the axle load low (about 13 tonnes) thus reducing the force of the wheel on the rail despite the speed increase.

Thanks to its success in Italy, the *Pendolino* soon came to the attention of several other European railways and in 1990, DB AG starting operating a fleet of 20 tilting VT 610 railcars to handle fast regional traffic on non-electrified lines in the Nuremberg area. These trains consisted of two carriages with the *Pendolino* tilting technology and had a maximum speed of 160 km/h. They covered a total of 30 million km up to November 2000. The time reduction on the Nuremberg–Hof line amounted to 23%.

Italian Railways' ETR 460 was the first third-generation *Pendolino* with all the tilting equipment mounted under the carriage floor. The electrical traction features 9 MW of distributed power in 9 carriages and includes a GTO-chopper-inverter unit and asynchronous motors. Ten trainsets started revenue service in May 1995 and have covered more than 11 million km by November 2000.

Several tilting trains designs have evolved from the ETR 460 and 65% of the active tilting trainsets in operation or under construction in Europe today have tilting devices designed and manufactured by Alstom Ferroviaria.

absorption characteristics compared to steel for dimensionally equivalent structures. This weakness of light alloys has led SNCF, in partnership with Alstom, to begin R&D into passive and controlled deformation so that the decision to use light alloys for the TGV Duplex does not result in reduced passenger safety. Interestingly, these developments have spread beyond the TGV Duplex and application of modern structural design in major deformations (crashworthiness) has spread throughout Europe as the

subject of a European standard. This unexpected result is a positive effect of the decision to move to light alloys for third generation TGVs!

Against this panorama of widespread metal construction, what should we think about new materials like composites? These materials are commonly used in other industries, but they are still rare in air, sea or land vehicles despite their many interesting qualities. R&D is continuing in Europe but application in a complete rail vehicle is only foreseeable in the medium term.

Digital Technologies and Railways

The digital revolution is having a profound impact on all areas of rail technology. Design has moved from mainly experimental techniques to more modelling and prediction through simulation. Paradoxically, simulation shows its limits in the capacity of engineers to use good judgement both in formulating the model and interpreting the results—how many errors have almost

been committed through overhasty use of a computer model?

In Europe, this means that instead of dispensing with experimental tests, modelling is used to improve test preparation and understanding. Consequently, we are witnessing a dovetailing of modelling and testing, which is indispensable but extremely costly.

Electronics and information technology will play an increasing part in real-time train monitoring and operations control. The early imperfect on-board electronics in the TGV Atlantique and ICE 1 have matured to form the 'nervous system' of increasingly 'intelligent' trains. As part of this development, extraordinary progress has been made in using digital techniques to manage adhesion (the Achilles heel of railways compared to other transport methods) during braking, etc.

Rail Freight—The Poor Relation

No article on the progress of rail technology in Europe would be complete without mentioning the fact that although rail freight has benefited from considerable progress in traction, it has not experienced the depth of change seen in high-speed and tilting trains.

The great opportunity for automatic coupling and traction that all European railways were committed to in the mid-1970s and which had been in preparation for many years was missed because of an inadequate return on investment.

The European rail network—which does not offer the same capabilities as the North American freight networks in terms of axle load, clearance profile, and length of sidings or turnouts—has barely changed at all despite the impact of fierce competition from road transport. This has led the railways to cost cutting and insufficient margins for freight investment. As a result, European railways have

suffered significant losses of freight market share over many years, but they are still alive. However, new concerns over the environmental and health burdens of heavy truck traffic are forcing Europeans to realize the importance of railways in freight traffic. At the same time, the transfer of passenger traffic to dedicated high-speed networks is freeing up capacity on conventional lines for freight.

Developments are under way, both directly at the European level and through partnerships between networks like SNCF and DB AG to produce a new on-board braking system for freight trains—UIC brake technology is 150 years old—that will greatly enhance the performance of rail freight transport. The objective is to achieve a performance leap equivalent to that already made for passengers and create a true European rail freight network offering much more productivity.

Conclusion

The last 50 years, and especially the last 20 years, have seen railway technologies move much further than other transport modes. The progress in high-speed technologies is such that the European high-speed rail network is increasing its impact on Europe every year, but the network is still hobbled by diverse electrical power and signalling systems. Standardization and unification have begun at last but the fruits will be some time in coming.

The rail freight sector faces relentless competition from road transport and has

not progressed as much as the passenger sector.

Many European politicians and the general public now realize that rail's speed, convenience and intrinsic environmental friendliness make it the preferred transport mode for this new century. But to achieve their full potential, Europe's railways need the backing of determined politicians and creative dedicated railway engineers and managers. ■



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