Railway Speed-up: A Review of Its History, Technical Developments and Future Prospects*

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This short paper briefly summarizes some key events in the history of the speed-up of railways. Some of the factors inhibiting speed-up of the railway as a system are reviewed: safety, passenger comfort, economies and environmental performance. Finally, some speculations are made on the future of railway speed-up.

Key Words: Railways, Speed, Speed records, Shinkansen, Economics, Environment, Prospects

1. Introduction

“That any general system of conveying passengers would... go at a velocity exceeding ten miles an hour, or thereabouts, is extremely improbable.”

Thomas Tredgold, Practical Treatise on Railroads and Carriages, 1835.

“Rail travel at high speed is not possible because passengers, unable to breathe, would die of asphyxia” Dr Dionysus Lardner, (1793 - 1859) Professor of Natural Philosophy and Astronomy at University College, London.

Despite pessimistic predictions, of which the above are typical, railways achieved remarkable speeds very soon after their introduction. In 1830, after the Member of Parliament for Liverpool, William Huskisson, was run over by the locomotive Rocket at the opening of the Liverpool and Manchester Railway, he was driven by George Stephenson to Manchester at the then world record speed of 35 miles per hour (56 kph), in a vain attempt to save his life[3]. Although railways were initially designed to carry freight, usually heavy goods for which speed was relatively unimportant, very soon time-dependent goods like fresh fish, newspapers and mail, required higher speeds. Passengers, naturally, wished to complete their journeys as quickly as safely possible, and appreciated the ability to travel reliably whatever the weather. It was rapidly realized that speed demanded not just improvements to motive power, but to the whole supporting apparatus which made the railway a system.

Lardner[3] was one of the first to recognize that it was a mistake to regard railways as a means of transportation similar to the established canals and turnpike roads, which were used by individual vehicle owners upon the payment of a toll:

“It was expected that the public should be admitted to exercise the business of carriers upon them (the rails), subject to certain specified regulations and by-laws. It soon became apparent, however, that this new means of transport was attended by qualities which must exclude every indiscriminate exercise of carrying business. A railway, like a vast machine, the wheels of which are connected with each other, and whose movement requires a certain harmony, can not be worked by a number of independent agents. Such a system would speedily be attended by self destruction. The organization of a railway requires unity of direction and harmony of movement, which can only be attained by the combination of the entire carrying business with the general administration of the road.”

As speeds became greater and traffic density increased, this observation became even more important. It is strange that in recent times, it has been thought possible to separate the infrastructure from the operation of various railway administrations in

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misguided efforts to improve the financial performance of railways. This paper, after briefly reviewing the history of railway speed-up, will concentrate on the aspects of system performance which have to be improved to allow operations at faster speeds.

2. Brief History of Railway Speed-up

Some details of significant speed events are shown in Table 1. In the table WSR refers to a World Speed Record, which is, of course, a very different matter than timetabled everyday running. Much could be said of all these events, but particular mention might be made of the German streamlined Schienenzeppelin which in 1931, pushed by an aircraft engine, attained 230 kph, a WSR which was unbeaten for more than 20 years. Figure 1 clearly shows the fusion of aeronautical and railway technology in a shape which was to become familiar with the Series 0 Shinkansen in 1964. Many aspects of these speed records are discussed in a book by Hughes[39]. We are all intrigued by significance of round numbers. For example, running at a mile a minute was a key target for express trains in everyday service in the years up to 1940 and 50’s. By chance, in metric units, 60 mph is just about 100 kph giving it extra significance. Although electric and diesel traction were introduced well before this era (see, for example, the record of the German Flying Hamburger in the 1930’s), it was in the post-war era that the higher speeds of which these types of trains were capable translated into common service. In recent decades, starting with the introduction of the Tokaido Shinkansen in Japan in 1964, much higher speeds were achieved on dedicated high-speed track, initiating a new era for rail travel.

Although operations in Japan started at 210 kph, the Tokaido is now operating at 270 kph, the Sanyo extension to Kyushu at 300 kph, whilst the latest high-speed line in Spain is designed for 350 kph running. Major considerations are needed about the economics of increasing speeds, the maintenance of the track, the generation of noise and the power consumption: this latter item brought into focus in recent years because of real concerns about global warming. Although the greatest speeds of operation have been made possible by building new segregated track with generous radii curves, considerable efforts have been made to speed-up operations on existing conventional track. Although economic constraints lay behind, for example, the efforts in the UK to build a tilting Advanced Passenger Train, more recently environmental and societal pressures make the building of new track more difficult. Even the up-grading of existing routes has met with opposition. A classic case is described by Bololm[40], concerning the efforts to renovate the

<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>Speed Record</th>
<th>Distance</th>
<th>Notes</th>
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<tbody>
<tr>
<td>1840</td>
<td>GWR, UK</td>
<td>54.6 mph</td>
<td>88 kph</td>
<td>London to Didcot</td>
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<tr>
<td>1903</td>
<td>Germany</td>
<td>WSR electric traction, AEG railcar</td>
<td>210 kph</td>
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<tr>
<td>1904</td>
<td>GWR, UK</td>
<td>City of Truro</td>
<td>100 mph, (161kph)</td>
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<td>1923</td>
<td>GWR, UK</td>
<td>Cheltenham Flyer, untimed Bristol to London, 70 mph (113 kph)</td>
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<tr>
<td>1931</td>
<td>Germany</td>
<td>Schienenzeppelin, WSR 230kph</td>
<td></td>
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<tr>
<td>1933</td>
<td>Germany</td>
<td>Flying Hamburger, 150 kph, Berlin/Hamburg, 125 kph average</td>
<td></td>
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<tr>
<td>1938</td>
<td>UK</td>
<td>Mallard, WSR steam, 126 mph (203 kph)</td>
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<tr>
<td>1955</td>
<td>France</td>
<td>WSR, diesel 331 kph</td>
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<tr>
<td>1964</td>
<td>Japan</td>
<td>Tokaido Shinkansen, 210 kph</td>
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<tr>
<td>1981</td>
<td>France</td>
<td>TGV, Paris/Lyon 260 kph</td>
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<tr>
<td>1987</td>
<td>UK</td>
<td>WSR HST diesel 148.5 mph (239 kph)</td>
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<td>1988</td>
<td>France</td>
<td>WSR, electric 408 kph</td>
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<tr>
<td>1990</td>
<td>France</td>
<td>WSR, electric 515 kph</td>
<td></td>
<td></td>
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<tr>
<td>2003</td>
<td>Japan</td>
<td>WSR, maglev 581 kph</td>
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Fig. 1 Kruchenburg's Schienenzeppelin, with aluminium sheets covering a steel tube frame, attained 230 kph in 1931.

West Coast line in Sweden from Göteborg to Malmö.

It is worth considering why we want to travel faster. The obvious answer is to save time and a key component of saving time is what we can achieve in a day. The very word journey stems from the thirteenth century Old French journee, a day, a day’s travelling, itself from the Latin, diurnum, day’s portion. By making a return journey out from home and back again possible within a day, we open up all sorts of possibilities about where people choose to work and live. We bring people from distant parts of the country to the capital or the centers of commerce and government and we lubricate the economy make making possible the social intercourse on which it depends. The concept of a day is useful in considering what might be reasonable targets of time and distance for trains in their efforts to win custom from the airlines. We must not forget, however, that the over-
all door-to-door journey time is what is critical for the passenger in determining what he or she can achieve in a day. Speed-up of one of the stages of the journey may be fruitless if the passenger is slowed down by congestion in the cities at either end. So speed-up of the less glamorous urban trains and subways and, therefore, peoples travel to main stations, can be just as important as the as the inter-city journey in the overall travel experience.

The core concept of saving time can also be approached from the usefulness of the time available in the comfort of a modern high-speed train. Time available to work on papers and reports, read a book, have a nap or a meal (but hopefully also to escape from the modern tyranny of the mobile telephone!), can be valuable time to use and a strong selling point in favour of trains over the more discontinuous and uncomfortable time spent on a relatively short air journey.

We may summarize speed-up desires as being constrained by safety, passenger comfort, economics and environmental performance. Each of these factors, cited above in no particular order of precedence, interacts with the design of the train, the infrastructure and the control system of the whole railways. We will therefore examine each in turn.

3. Factors Inhibiting Speed-up

3.1 Safety

Although it is often said that speed kills, closer thought indicates that speed in itself is not dangerous, but sudden changes, such as a result of a collision or derailment, can be very unhealthy. The key contributions to the relative safety of high-speed rail systems, stem from running on segregated track, with no conflicting movements, traffic moving at the same speed, and the elimination of level (grade) crossings. There is a parallel here with high-speed roads, which, despite fears to the contrary, are often the safest in terms of accidents per passenger km. Of course, not all these options are possible for running at higher speeds on ordinary (sometimes called conventional or classic track) with mixed traffic. Capacity is also hampered by running higher speed trains mixed into slower traffic, partly because of the need to have a block control system capable of dealing with the longer stopping distances needed by higher speed traffic.

The need for effective signaling and control systems for traffic on railways has had a long history. We have come a long way since trains were flagged from section to section by guards relying on line of sight. The idea of a safe time interval between trains, was superceded by the idea of signaling through a cleared block, when the technology of the electric telegraph became available around the 1850’s. It is remarkable that the addition of a speed indicator in the cab of a train is a relatively recent addition. A report of 1952, after a serious accident caused by a train failing to observe a temporary speed restriction, recommended that speed indicators should in the future from part of the equipment of new locomotives. Contrast this with the situation on many high-speed trains today, which are completely computer controlled, without recourse to line-side signals, the speed, rather than distance from the train ahead being the controlled parameter.

The implementation of automatic train control has a long history. Although the signalman has largely been protected from the danger of making a mistake, in many high-speed operations on conventional lines, the driver’s vigilance and attention to signals, is still the fundamental defense against disaster. The elimination of human error in controlling a train is technically relatively straightforward. The absence of such protection has been recently tragically and graphically illustrated by high-speed collisions at Southall (90 mph, 145 kph) and Ladbrooke Grove (130 mph, 210 kph) in the UK. The huge benefits of such systems were seen to advantage when the driver of a JR West Shinkansen was reported to have fallen asleep in his cab whilst the train was travelling at 270 kph, but the train automatically and safely stopped at the next station.

The response to the accidents in the UK has been a programme of fitment of the Train Protection and Warning System (TPWS), which, whilst not infallible, is a huge step forward. Future developments throughout the European Community include the fitting of ETRMS.

3.2 Passenger comfort

Increases in speeds increase the dynamic forces acting between the wheel and rail. This simple fact, discussed in more detail later, has profound consequences for the design of both vehicle and infrastructure. The need to reduce mass in order to reduce these dynamic forces is obvious. Whilst the un-sprung mass is key, the need to reduce mass overall (and hence axle loads) is a challenge to designers. The passenger, whilst unaware of the reasons for this mass reductions, is very aware that the coach in which he is travelling is becoming more like an aircraft cabin, the space he has available is reduced, noise levels are higher and so on. The authors personal opinion of the Grand Hikari Green cars of the Series 100 Shinkansen in Japan leads him to believe they represented a standard of passenger comfort which has not been attained by subsequent designs. The double-deck concept has had to be dropped in order to have a lower
profile to reduce aerodynamic drag: speciousness has been sacrificed to improve the capacity of the new cars. A further comparison is the comfort of the Mark 3 coaches of British Rail designed, over 30 years ago, for 125 mph (200 kph) travel. Visitors from overseas regard the tables, comfortable and generous seats together with the ambience of the spaciousness as high-lights of their travel experience. As engineers we should bear in mind that speed alone is not the only criterion which makes train travel attractive to passengers. Its is also worth recalling that on-board services play an important role. Air conditioning, toilets, catering facilities and the like add to the problems of the designer in reducing mass. Information, entertainment systems and power points are increasing needed and the technologies for these are rapidly improving. Because of the long life of railway vehicles it is important that these facilities are built-in on first build, as retro-fitting can be difficult and expensive.

3.2.1 Dynamic loads The importance of dynamic loads cannot be overemphasized. The very reason why the steel wheel on steel rail is such an energy efficient form of transportation, is also a difficulty which inhibits speed-up and leads to great construction and maintenance costs of the permanent way. The difficulty arises from the very stiff nature of the wheel rail contact, the small area at the interface for carrying weight, traction, braking and steering forces. The passenger "feels" this problem through ride comfort levels, acceleration changes, jerks affecting for example his ability to read, drink from a cup, use a portable computer etc.

The following example illustrate the system nature of this problem.

Relatively simple models of the kind shown on Fig. 2, if combined with accurate information of the spring and damper values of the vehicle and track, give good predictions of the dynamic loads generated by discontinuities in the track (such as joints, dips, corrugations) or the wheel (flats and our-of-roundness). We used illustrative vehicle parameters to produce the results shown in Fig. 3, for two designs of Shinkansen trains operating at different speeds across a rail dip of 5 mm. The key features of the 300 Series are the reduced wheel loads (half axle loads) and reduced un-sprung mass. The so-called P1 and P2 forces are both reduced in the Series 300 train even at the higher operating speed of 230 kph. This reduction, obviously of benefit to the passenger, has profound effects on track deterioration and therefore maintenance costs as shown in Fig. 3.

This example serves to further emphasize the need for vehicle and track engineers to work hand-in-hand to achieve optimum performance, a point extending beyond the previously quoted thoughts of Larnder who was only thinking of operational problems.

3.3 Economics

We must be prepared to recognize that the construction costs of new high-speed lines are extremely
high. Table 2 attempts to illustrate indicative costs on a per km basis in current monetary values for achieved and current projects. The approximate nature of the figures arises from many sources—unreliability of published data, conversion of currencies and inflation values to bring historic costs to present day values. The nature of each project also needs to be born in mind: some have relatively easy geographies, some need heavy earthworks, some need expensive tunneling.

Even the costs of upgrading existing lines is high. The West Coast project in the UK is a spectacular example. Current estimates are running at about €22 m/km, which does not include a allowance for the severe disruption to traffic on the existing line and when finished will only allow relatively modest increases in speed from 170 to 200 kph and a saving of 40 minutes in the journey time between London and Glasgow.

Inevitably, given such high costs, the question is asked: will a project pay? It is now becoming clear that construction costs are difficult, if not impossible to recover from fares. The Shinkansen system in Japan was a major factor in the incredible debt accumulated by Japan National Railways. In France, where the railway has recently been (partially) separated into an infrastructure company, French Rail Network (RFF) and an operations division, French National Railways (SNCF), an inherited debt, linked mainly to the construction of the TGV network, of some €22 billion has been taken over by RFF and €7.1 billion retained by SNCF. The President of SNCF has expressed the view that, “If there had been competition in the 1970’s, there would not be a TGV network today... SNCF would not have taken such a big risk with the development of the high-speed network”[110].

Perhaps a better question is: is a project worthwhile in its totality and in the long-run? Many of the benefits which arise are not collected by the operators, but accrue to society in general. Supporter of the railway argue that an efficient transport system is essential to the economy. Present estimates of the economic loss caused by congestion in the UK are in the order of €14 billion per year. Although railways provide only 6% of passenger-km in the UK, delays caused by the infrastructure operator lead to an estimated €0.75 billion per year. If the economy is to continue to expand, demand for transport will also expand. It is clear that road building cannot keep pace with demand, the only land based transportation system which has the capacity to match rising demand for inter-city journeys over, say the next 50 years, is the dedicated high-speed railway.

Many commentators argue that if fair cost comparisons are to be made, a “level playing field” must be established, taking into account taxation polices and external costs. The issue of external costs and the environment is one that presents the railway with opportunities that will be discussed in the following section.

### 3.4 Environmental performance

#### 3.4.1 General environmental impacts

Many reviews have been written on the general environmental impacts of railway operations, see for example the book by Carpenter[111], and a paper looking specifically at high-speed rail travel by Pyrgidis[112]. Much research has concentrated on reduction of noise generation and on the attenuation of the increased dynamic loads, and hence transmitted vibrations, caused by higher-speeds. The same principles apply, to a lesser extent, to rail’s other niche market, the operation of commuter trains into large cities.

It is worth noting here rail’s dramatic advantage in terms of capacity of infrastructure; cars can move some 200 persons per hour per meter width of road, buses can move 1,500 and a train about 9,000. This advantage is however bought at the relatively much higher infrastructure cost of rail track, perhaps about 16 times higher/unit length than road. True light rail systems are about 3.5 times more costly than road, and therefore offer economic as well as environmental advantages.

#### 3.4.2 Economics of environmental impacts

In a recent report by the International Union of Railways[113] an attempt was made to compare the external costs of various modes of transport. At 1991 prices,
the total external costs of cars in the EU, was estimated at some € 50/1000 passenger-km and those of rail to be € 10/1000 passenger-km. The most significant costs in this study was shown to be that of accidents. In general, trains are safer than car, and high-speed trains have an outstanding safety record.

But, we would do well to note that, in general, road accidents and their consequences are decreasing sharply, certainly at a steeper gradient with time than rail accidents. At first sight, it seems strange to include these figures in a comparison of environmental effects. However, the argument as to where the system boundary is drawn is extremely important, and it is undoubtedly true that treating the victims of accidents consumes many economically scarce resources. A dramatic example has come from Japan[14]. If the passengers using the Tokaido Shinkansen between Tokyo and Osaka were to switch their journeys to cars, some 1 800 extra deaths and 10 000 serious injuries would result every year. The same argument can be used in reverse: if railways can attract people from their cars, the potential for saving lives, avoiding injuries and saving health care resources is enormous. The argument cannot, however, be carried over to switches from air transport to trains because statistically, air travel is safer than train travel on a passenger-km comparison. The environmental advantage of a switch from air to rail travel comes from energy, emission and CO₂ saving, a topic to which we now turn.

3.4.3 Railways' energy environmental advantage

At first sight, trains can offer substantial energy efficiencies over competing modes, if a comparison is made in terms of passenger-kilometres, Smith[15]. Furthermore, in terms of their overall contribution to the transport market, trains consume a much lower proportion of the energy budget than their proportional share of the market. As examples, in Sweden, trains use only 1.8% of the total transport energy to carry 7% of the passenger kilometres and 38% of the freight tonnes-km; in Japan, with a very high 30% share of the passenger market, trains consume only 7% of the total transport energy. The Tokaido Shinkansen, in Japan, which has a generally very high load factor, and regenerative breaking, claims a very high figure for energy efficiency in the order of 3 pass-km MJ⁻¹, twice the usual figure quoted for a generic urban trains.

A major environmental advantage of the train is its ability to run on clean forms of electricity, thus reducing emissions whilst also conserving hydrocarbon fuels. In Switzerland all trains are electric with 97% of their power coming from renewable hydropower. In France, 77% of the railway passenger kilometres are on electric trains, the vast majority of the energy for which comes from nuclear power. The case for increasing electrification ratios is therefore very strong on environmental grounds, particularly if the power is generated from non-fossil fuels; however the short-term economic case often is used to prevent this investment for the future.

3.4.4 Noise and vibration

As speeds have increased, so have the levels of noise and vibration generated by moving trains. This problem has been attacked in many ways. Container noise by enclosing running gear as far as possible has proved to be very effective. Smoothing the profile of the train and connections between coaches, both reduces drag and noise generation, efforts have been made to smooth the airflow around current collectors which become significant generators of noise as speeds increase. Aerodynamic effects become extremely important: the reduction of drag by reducing train cross sections had already been mentioned. Tunnels have been fitted with hoods to reduce the effect of mini-sonic booms created when high speed trains exit tunnels. In urban location sound baffles have been fitted to the sides of track in order to meet the increasing stringent legal constraints on noise. Some efforts have not been so successful. The worst high-speed rail accident in history to the German ICE at Eschede in June 1998, had its roots in an attempt to reduce noise transmission to the inside of the vehicle by the use of resilient wheels.

4. Future Prospects & Conclusions

It is interesting to note that as long ago as 1881, Osborne Reynolds, famous for his eponymous dimensionless number in Fluid Dynamics, wrote a series of articles[16], in which he discussed the various limits to speed of land transportation. One limiting factor he considered was the inherent strength of materials. He supposed that a railway wheel’s speed was ultimately limited by rotational stresses. It is easy to show that the peripheral speed of a rotating ring (the tyre of a wheel), is limited by the square root of the tensile strength divided by the density. By using a value for the tensile strength of iron of 104 MPa, he went on to show that the maximum speed a wheel could withstand was approximately 400 km/h i.e. a much greater speed than any then attained, but less than has been attained by the use of modern materials. Much more recently, the great Japanese railway engineer, Matsudaira, wrote a perceptive and authoritative review[17] in 1966. He wrote, “for realizing a super-high-speed operation of trains, there are much more practical, mechanical and electrical problems to be studied, such as strength and endurance of (the) wheel (and) axle,
wear prevention of the wheel tread, strength and lubrication of (the) axle bearing and driving system, anti-wear materials for the pantograph and overhead wire, and so on. Though each of these problems had to be tackled, they do not seem to be decisive and unmanageable obstacles for speed-up. For the conventional form of railway such as the new Tokaido Line, a practical speed limit should be considered as from 250 to 280 kph for service. Then, if (the) implication of a traction system free from adhesion, such as the linear motor, is combined with a very wide track gauge, the orthodox wheel-on-rail railway system will probably attain a speed of about 350 kph. In the still higher range of speed, there will be no other way but to make the vehicle float.”

Although these predictions have been exceeded on special track, the 350 kph limit seems sensible in terms of economics. Speed-up on ordinary lines will be limited by the speed differentials of other traffic. The selling point of dedicated high-speed lines in the future is more likely to be based on capacity, rather than absolute speed. The costs are such that they are unlikely to be returned from operational revenues.

On 29 December 2003, the world’s first fare-paying high-speed maglev opened between Shanghai airport and Pudong in China. Travelling at 430 kph, it covers the 31 km route in just 7.5 minutes. Despite this noteworthy landmark in transport, a decision has been made to build a new Beijing-Shanghai line based on steel-wheel technology. Amongst the reasons cited are the costs of maglev infrastructure, incompatibility with the existing network and capacity constraints.

The concept of whole journey time makes the speed-up of local and conventional lines attractive, particularly if the speed-up can be achieved at reasonable cost.

Enough has been said to demonstrate the importance of the operation of the railway as a system. Current experiments to divide responsibilities at the wheel/rail interface have ranged from poor to mixed. The most successful railways will continue to be vertically integrated.

References


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