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Future trends in railway engineering

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Abstract: This article reviews the current state of railway engineering with a focus on the steady development of conventional technology that has led to the 575 km/h run of the French TGV train in 2007. Several key engineering areas are explored and predictions made for future technological developments in vehicle and track design including active suspension, improved aerodynamic performance, and novel track systems such as slab track. Non-conventional technologies such as magnetic levitation are discussed but the conclusion arrived at is that considerable improvements are still possible through optimization and incremental development of conventional engineering solutions and that, in the short to medium term, implementation of radically novel systems is less likely.

Keywords: railway development, railway engineering, vehicle design, track design

1 INTRODUCTION

In looking forward into the future of the railways it is relevant first to consider the current position and how we got here. From the early 'railway mania' in the middle of the 19th century when the network grew from one intercity line between Liverpool and Manchester to cover most of the industrialized world in little more than 30 years, the railways have seen long periods of stagnation and then decline in the face of competition from road and air transport. The technology that underlies the railway system is not, however, obsolete and steady improvements have meant that in many areas railways are currently experiencing considerable increases in performance.

On 3 April 2007 a TGV, running on the 'LGV Est' line achieved a new world record speed of 574.8 km/h (Fig. 1). This achievement not only demonstrated the potential of conventional railway technology to achieve significantly greater speeds but also provided a test bed and important measurements that will allow engineers and researchers to continue to make incremental improvements in many areas including those of vehicle dynamics, aerodynamics, acoustics, traction and braking, and catenary–pantograph interaction. George Stephenson, the founder of the institution with which this journal is associated, died 160 years ago, but had he witnessed the TGV speed record run he would have recognized much of the technology including the rails (still set at his gauge of four foot, eight and a half inches and supported on sleepers sitting on ballast), wheels, suspension, bogies, etc. Of course there have been changes but they have been incremental rather than revolutionary and this philosophy is deeply ingrained in the mentality of today's railways and the systems and standards that control them and in the engineers who work in this industry.

The headline speed record is important in demonstrating the capability of the technology, but there are many other measures of the success of the railways that are also steadily increasing. In the UK passenger traffic is growing rapidly with 19 000 services run every weekday, an increase of 11 per cent on 1995. Total passenger kilometres in the UK in 2007–08 were 49 billion, an increase of 6.0 per cent on 2006–07 [**1**]. Upgrades to the West Coast Main line and the introduction of tilting trains mean that the 182 miles from Manchester to London take under 2 h compared with 2 h 45 min 3 years ago and the latest timetable now has eight trains in 2 h in the morning peak to accommodate the increase in demand. The railway also provides an incredibly safe system of transport with the huge media reaction to rail accidents compared with the much more common road accidents being evidence of their comparative rarity.

Despite a slight downturn in recent times in line with the current economic depression, all predictions are for freight to continue to shift from road to rail and

Fig. 1 TGV record breaking run on 3 April 2007

the European Commission anticipates growth in rail's share of the freight market from 8 per cent (241·1 billion tonne-km) to 15 per cent (784 billion tonne-km) by 2020 [**2**].

This article reviews a number of developments in several key engineering areas and considers the effect of these on the shape of the railway in the future.

2 VEHICLE DESIGN

2.1 Construction

Early vehicles were constructed mainly from wood and techniques followed those of the stage coach constructor. Wood eventually gave way to steel, which is now the most common material for most bodies but where weight is critical, for example in high-speed vehicles, aluminium alloy has become popular. Techniques for extruding very large sections and for welding or even using adhesives to join these have resulted in strong light modular bodies with excellent strength and other properties. Composite materials are starting to be seen in railway vehicle bodies with many interior panels now being glass fibre, and composite sandwich structures have been used in experimental versions of the TGV and Shinkansen vehicles [**3**, **4**]. In Korea the new TTX high-speed tilting train has been designed with a hybrid body structure consisting of a stainless-steel underframe and body panels made up of aluminium honeycomb and carbon fibre skin. Panels are joined using rivets and adhesives [**5**].

2.2 Suspension

The suspension is a critical part of any ground vehicle, its role being to isolate the passengers or payload from any irregularities in the supporting surface (track or road) and also to spread the load applied to this surface evenly. Almost all current railway vehicles have suspensions that are entirely mechanical using the elasticity of steel or rubber and energy dissipation through viscous damping or friction. Some of these are relatively sophisticated, especially in freight vehicles, where the huge difference between tare and laden mass results in an additional challenge, but other solutions are now possible. Active suspensions have been known about by engineers for many years and the techniques for designing and applying these solutions are starting to be used in the automotive industry. In railways, the adoption of active solutions has been much slower with the only widespread example being the tilting mechanism now being used in passenger trains on some routes.

Active suspension has the potential to provide a step change in suspension capability with the improvement being taken as an increase in vehicle speed or passenger comfort or a reduction in required track and vehicle maintenance costs due to reduced forces [**6**]. Active elements could be included in the secondary suspension where they could improve behaviour in the lower frequency range and significantly benefit passenger comfort. An example of this is the Japanese E2 and E3 Shinkansen vehicles introduced in 2002 [**7**]. A pneumatic actuator is installed in parallel with a secondary suspension damper (Fig. 2) and reductions in accelerations of up to 9 dB were measured in the passenger compartment.

Active elements in the primary suspension are more challenging due to the higher characteristic frequencies but improvements are possible and reduction in forces at these higher frequencies may bring substantial reductions in damage to wheels and rails and consequent lower maintenance costs. Another possible use of active control is to steer the wheelset or wheels to optimize the interaction with the rail and the distribution of the guiding forces and also to improve the stability of the wheelset, which in a mechanical system can become unstable and 'hunt' above a critical

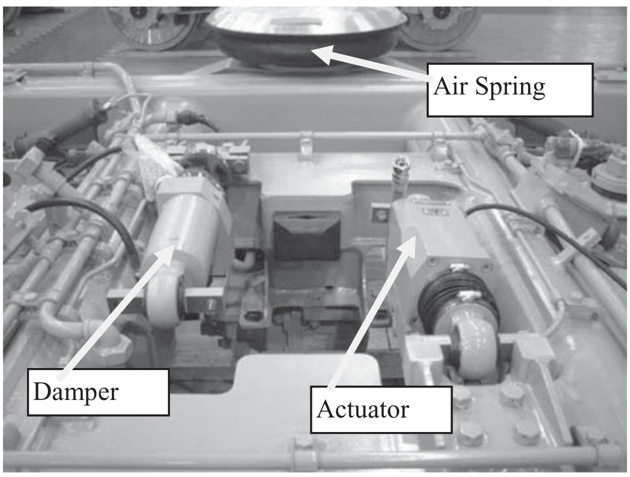

Fig. 2 Active secondary suspension system in Shinkansen vehicle (from reference [**7**])

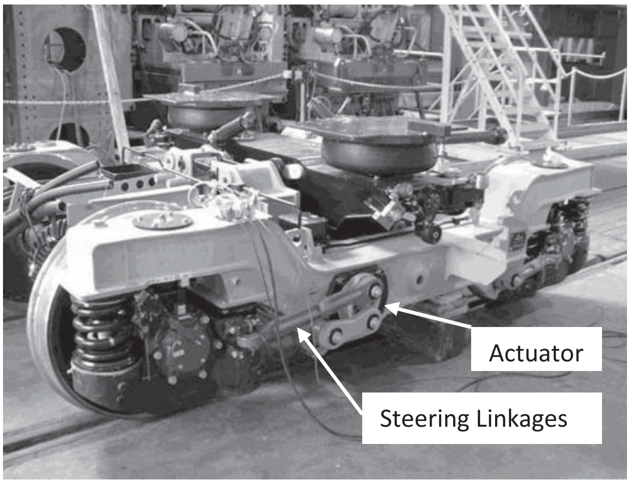

Fig. 3 Actively controlled bogie (from reference [**7**])

speed. Goodall and Mei [**7**] report on an experimental modified bogie that uses two electrically driven actuators, which act to yaw the wheelsets and demonstrate effective control at speeds in excess of 300 km/h (Fig. 3).

Another possibility is to move away from the conventional wheelset consisting of two wheels rigidly linked by an axle. This provides steering due to the conicity (see below) but also introduces potential instability above a certain 'critical' speed. Independent wheels have been used for some time on trams where having a low floor throughout the vehicle is important and in some designs these wheels are also driven individually. There is therefore potential to control the torque at each wheel independently and thus to achieve the optimum torque at each wheel [**8**].

2.3 Freight

Despite their low cost and huge numbers, freight bogies have surprisingly sophisticated suspensions. Bogies such as the 'Y25' – the most common freight bogie in Europe and the 'Three-piece bogie' – ubiquitous everywhere else in the world, have complex mechanisms based on links or wedges that provide progressive friction damping, which increases with the vehicle load. These innovations have been driven by the need to control vehicle behaviour in both tare and laden states with vastly different vehicle weights.

The Leila freight bogie (Leicht und LaermArm – a German acronym for 'light and low-noise') aims to improve the bogie used in freight vehicles by innovative lightweight design (Fig. 4). The bogie has an internal frame which cuts about 1.5 tonne off the weight of a wagon. The wheelsets are cross braced to allow steering, therefore reducing wheel and rail wear. Damping is provided by hydraulic dampers mounted in the vertical direction and a secondary rubber spring, placed beneath the centre pivot, provides some elasticity in the horizontal plane. The use of disc brakes contributes to a reduction in noise by 18 dB [**9**].

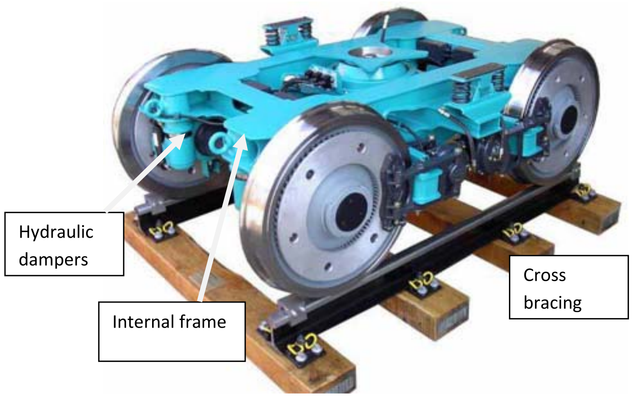

Fig. 4 The Leila bogie (from reference [**9**])

2.4 Wheel profiles

Wheel profiles have only seen small changes in 150 years but these have recently become very significant. The original wheel profiles were probably cylindrical but quickly changed to conical with a flange to prevent derailment (the flange was originally on the rails but its migration to the wheels would have allowed a considerable reduction in rail cost). The cone angle was no doubt decided by trial and error in the early days and was probably largely determined by manufacturing criteria. In the 1960s various railway organizations started to adopt a more complex 'worn' profile, which consisted of a series of curves that mimicked the shape to which wheels tended to wear in the hope of avoiding the initial rapid phase of wheel wear [**10**].

These worn profiles (for example the P8 profile used in the UK or the S1002 profile widely used in Europe) have worked well for 20 years but as speeds and loads have steadily increased problems have started to emerge. The wheel–rail interface is very highly loaded as all the forces that support, accelerate, brake, and guide the vehicle have to be transmitted through this small contact patch (typically the size of a thumbnail). The steel of both wheel and rail comes into contact, compress elastically at first and then plastically, transmitting high loads in the normal and tangential directions and then separate within a few milliseconds or even less. This loading cycle is repeated millions of times and it is a considerable engineering challenge to control the deterioration that this causes [**11**]. The main mechanisms of deterioration are wear (including flow as well as loss of material) and fatigue (usually called rolling contact fatigue or RCF in this context) [**12**].

The recent development of computer tools to simulate wear and RCF has allowed further optimization of the wheel profile and has recently resulted in an 'anti-RCF' profile now known as the P12 profile, which is currently on trial in the UK. If successful this profile will improve the resistance of wheels to fatigue cracking and the techniques developed during this process will allow further optimization and, where possible, specific profiles to be designed for specific applications such as heavy freight or high-speed passenger or highly curved metro. Such an anti-RCF wheel profile (now given the designation P12) was developed by the Centre for Surface Transportation Technology at the National Research Council of Canada to provide optimum RCF performance on UK railways while still providing reasonable levels of curving behaviour and wear rates [**13**].

Computer simulation techniques have been developed to predict the wear of the profiles running on three typical UK routes. The wear prediction methodology was adapted from the methods successfully implemented and validated in Sweden by KTH [**14**]. These methods are based on the Archard wear model and utilize vehicle dynamics simulations with real track data to provide the wheel–rail contact responses for input into the wear calculation.

Validation of the methodology for predicting the wear of wheel profiles on the UK railway infrastructure has been undertaken by comparing the predicted wheel profile shape, wear distribution, and profile measurements, including flange height and thickness, with those obtained from profiles measured from each of the simulated routes [**15**]. Figure 5 shows an example comparison of the wheel profile and wear distribution for a modern UK multiple unit.

2.5 Aerodynamics

Several of the biggest current problems, as vehicle speeds increase, are related to aerodynamics.

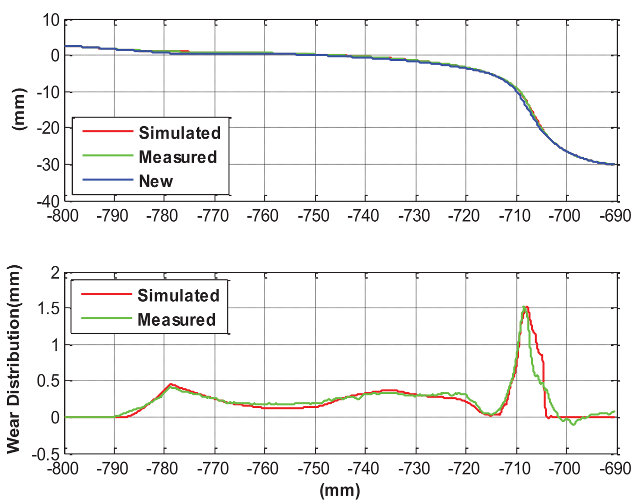

Fig. 5 Comparison of predicted and measured wheel profile shape and wear distribution after 54 000 km [**15**]

Cross winds can have a number of effects on trains, the most obvious of which is to cause the train to overturn in conditions of high cross winds and there have been a number of such incidents in recent years [**16**]. There are also, however, a number of other potential effects – for example turbulent cross winds can, in principle, result in a loss in ride quality if specific vibration modes are excited; the lateral displacement of trains in cross winds can cause the kinematic envelope to be infringed, and can also cause potential dewirement problems with large-scale pantograph displacements [**17**]. A proper consideration of all of these problems requires the integration of the unsteady aerodynamic forces and moments caused by unsteady cross winds with the suspension system of the vehicle and its interaction with the track [**18**].

Aeroacoustics is also important due to the requirement to reduce noise. Aerodynamic noise increases much faster with train speed than rolling noise and therefore is being studied intensively. Pressure pulses can also cause problems as speed increases and critical areas are where high-speed trains pass each other or enter tunnels. When a high-speed train enters a tunnel, a compression wave is generated and travels through the tunnel at sonic speeds. When the wave reaches the exit, the compression wave is radiated as an impulsive wave causing noise and vibration problems. One solution adopted by some Shinkansen trains is to increase the leading vehicle nose length to increase the time over which the pulse occurs [**19**].

2.6 Propulsion systems

Although railways are a relatively efficient transport mode, the environmental advantages over other modes are most evident when load factors are high and when power is generated from non-fossil fuels. Smith [**20**] states that 'the case for increasing electrification ratios is therefore very strong on environmental grounds'. He also points out that 'the short-term economic case is often used to prevent this investment for the future'.

The cost of energy consumption makes up a large proportion of the operating cost of a freight railway and energy conservation measures are being actively considered as a means of improving the efficiency of transit operations. Liu and Golovitcher [**21**], for example, describe a novel method for calculation of energy optimal control for a vehicle moving along a known route, which can be used in automated train operation systems.

An increasing focus on energy utilization driven by environmental considerations as well as rising fuel costs is resulting in several radical energy conversion and storage solutions. Fuel cells, super capacitors, and even flywheels are being evaluated for possible future use in railway vehicles. The PLATHEE research programme (Platform for Energy-Efficient and Environmentally Friendly Hybrid Trains) initiated by SNCF is studying and testing a range of solutions for future railway systems and have set up a test bed using a hybrid diesel locomotive [**22**]. The PLATHEE vehicle has a conventional diesel generator and hydrogen fuel cells to produce the average power required but also has batteries to provide low power over a long period and ultra capacitors to provide the peak power demand. The switching between these various modes is complex and suitable control systems are being evaluated.

One of the challenges in the use of fuel cells is storage of the hydrogen. A North American consortium has developed a prototype 'zero-emission' hydrogen-fuelled fuel cell–battery hybrid switch (shunt) locomotive for urban and military-base rail applications [**23**]. Continuous power of 250 kW is provided by a proton exchange membrane fuel cell. Carbon fibre composite hydrogen storage tanks operating at 350 bar are located on the roofline.

3 TRACK

The track structure has not changed significantly since the early days of the railways with steel rails supported on sleepers in turn supported on ballast. There have of course been improvements in materials with concrete sleepers replacing timber and much of the maintenance is now automated. There are, however, some significant developments in the pipeline, which are becoming more widespread and may change the nature of the track system.

3.1 Slab track

In recent years there has been a move away from conventional ballasted track in some countries with the introduction of concrete slab track [**24**]. This aims to provide a consistent support for traffic and therefore lower peak forces and its higher installation cost is outweighed by a lower maintenance cost. One of the early installations of slab track was at Rheda station on the route from Dortmund to Hanover. In 30 years of fairly intensive operation this section of track has required no significant maintenance other than rail grinding and slab track is now installed at over 60 locations in Germany.

3.2 Vanguard

In most track systems the rail foot sits on a pad and is held in place with clips. In the novel vanguard system the rail is supported under the head and in the web with large rubber wedges, leaving the foot of the rail suspended. The rubber wedges are carried in cast iron side brackets, which are in turn fastened either to a shoulder cast into a concrete sleeper or to a baseplate. The assembly allows relatively large vertical movement of the rail but close control of lateral movement. Typically this provides effective isolation down to about 20 Hz, as opposed to resiliently mounted baseplates, which can only isolate vibration down to 40–50 Hz.

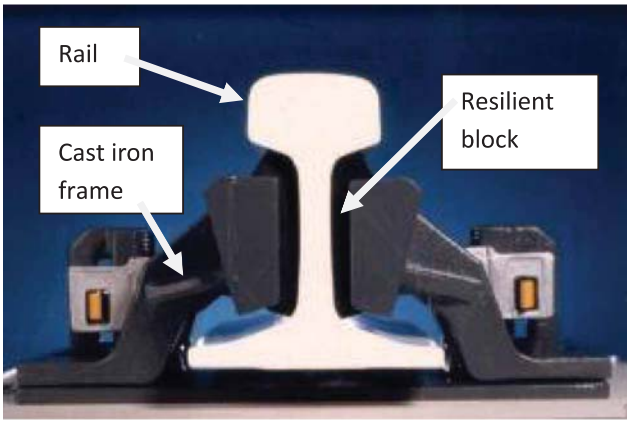

Fig. 6 The Vanguard system

Vanguard (Fig. 6) has been installed in several locations, mainly where transmissions of vibration need to be kept to a minimum. For example, the vibration at street level above a trial site on London Underground was reduced by about 7 dB (linear 10–200 Hz), while the sound level directly under a steel bridge structure on Thameslink was reduced by 10 dBA [**25**]. The nature of the support also means that as the impact of the passing wheel load is spread over a longer time the peak forces are reduced.

3.3 Embedded rail

Another novel track supporting structure has been developed by Balfour Beatty Rail Projects and consists of a fully embedded rail that does not rely on being supported by either sleepers or base plates. Known as BBEST (Balfour Beatty Embedded Slab Track) there have been operating trials at Medina del Campo in Spain and at Crewe on the line between Kidsgrove and Stoke-on-Trent in the UK. BBEST (Fig. 7) consists of a low-profile fibre-reinforced concrete slab in which rails of almost rectangular section with a mass of 74 kg/m are embedded. The rail is supported continuously by an elastomeric pad and a fibre-reinforced plastic shell and the surface profile on which the wheels run matches the profile of a standard rail head [**26**].

This type of embedded track potentially offers several advantages over other types of slab track. As the rail is supported continuously rather than at regular intervals, the peak loads are reduced. Rail support stiffness is independent in the lateral and vertical directions and this means that rail rotation can also be closely controlled.

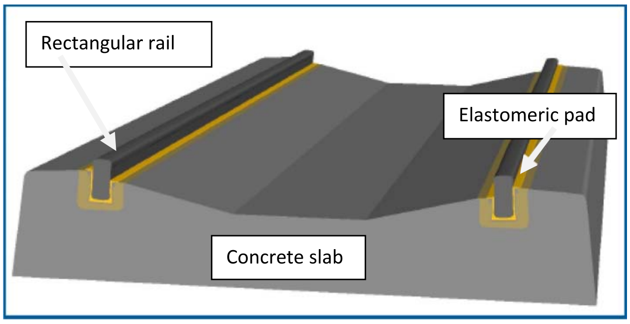

Fig. 7 The BBEST embedded track system

It is likely that these types of support systems will grow in popularity over the coming decades as the better control and lower maintenance cost outweigh the higher initial costs.

4 CONDITION MONITORING

Computers have affected most areas of railway engineering, and condition monitoring is a good example of this. The shrinking size of much instrumentation has also contributed and a modern railway vehicle is packed with monitoring equipment. Modern trains can alert their maintenance depot to any problems when in normal service and the appropriate replacement components, tools, and staff can be ready at the correct location when the train reaches its service point.

Switches can now be instrumented and signals sent to a central monitoring station. Any unexpected changes can then be used to trigger inspection or maintenance visits and failures prevented [**27**].

5 NOVEL SYSTEMS

The Meccano Magazine in August 1930 reported on the 'George Bennie Railplane system of Transport' (Fig. 8), which made use of cars suspended from an overhead structure 16 feet above the ground and using airscrews as the means of propulsion. Cars weighed 10–12 ton and were to run at 120 miles per hour. A test track was set up near Glasgow but the system did not enter commercial service [**28**]. This is one example of many novel railway systems that were developed but failed to provide significant benefit over conventional arrangements. More successful was the Micheline Railcar developed in France in the 1930s [**29**] and also briefly operated in the US and UK. This had pneumatic tyres running on conventional rails but the lower maximum axle load possible with this arrangement proved to be a serious limitation despite the low noise and vibration and better acceleration and braking capability. Pneumatic rubber tyres are still used on some metro systems but usually running on concrete surfaces rather than rails, and solid rubber tyres are used on some mining locomotives where high traction on track with large irregularities is essential.

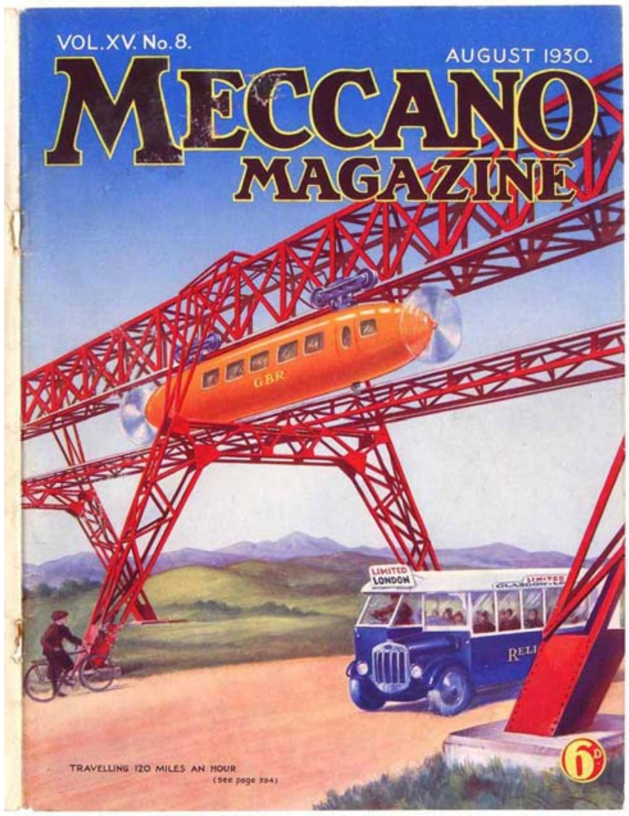

Fig. 8 The George Bennie railplane system

In more modern times magnetic levitation (MAGLEV) systems have been strongly promoted as possible alternatives to the conventional steel wheel on steel rail solution and offer potentially very high speeds [**30**]. A demonstrator system was set up in Hamburg in 1979 for a transport exhibition and a short system entered commercial service at Birmingham airport in 1984 but the technology has not been extensively used so far. This is probably partly due to the inherently conservative nature of railway engineers but also must indicate that the commercial benefits over conventional systems are not overwhelming. In a detailed comparison between MAGLEV and conventional high-speed rail systems, Vuchic and Casello [**31**] conclude the following.

1. Maglev, despite higher top speeds and greater acceleration, has little travel time advantage in real-world applications.
2. High-speed rail has an extremely significant advantage in its compatibility with other transportation systems and with built-up areas.
3. High-speed rail is less expensive to construct, has a known operating cost level, and has an advantage in energy consumption.

In recent years, Japan and Germany have been promoting MAGLEV solutions and a 30 km section of the TRANSRAPID system running from Shanghai airport to the city is now running in regular service with a top speed of 431 km/h.

6 CONCLUSIONS

Where will the developments mentioned here lead the railway industry over the next 30 years?

It can be seen that the industry is inherently conservative and it is therefore unlikely that any radical changes will overtake the railways. Developments are more likely to continue to be incremental and to be driven by the need to improve performance and reduce life cycle costs. Even without the radical changes that have been adopted in some other fields, impressive levels of performance have been achieved through conventional steel wheels running on steel rails. The conventional railway vehicle is inherently energy efficient and has been proved to work at up to 550 km/h with safety levels higher than any other transport mode. Radical solutions such as MAGLEV have been available for over 30 years but clearly do not offer a great enough advantage over the conventional system compared with the additional costs involved or they would have been adopted by now. Developments in computer and mechatronic technology have started to be adopted, for example the tilting trains mentioned in the introduction. Further incremental improvements are inevitable and will be driven by economic considerations.

Small changes to wheel and rail profiles, for example, have already been shown to have significant effects on the interaction between the vehicle and the track and recent improvements have led to reduced wear and fatigue damage. Computer tools now allow detailed prediction of this behaviour and further development is likely. It is possible that specific profiles will be developed for different types of vehicles or track but this would also rely on sophisticated tools to manage the maintenance of these. Freight vehicles will see continued improvements in bogie design, leading to increased efficiency and reduction in noise levels even at higher axle loads.

The more dramatic improvements that could be achieved by using mechatronic solutions such as active suspensions are also likely progressively to appear in railway vehicles. Their introduction has so far been fairly slow with only tilting in widespread use, but as reliability and confidence improves the significant benefits will surely mean that they will increasingly be adopted by passenger and freight vehicle designers.

Track is certainly also likely to see significant development with several innovative systems already in service or under trial. As with vehicles these innovations will need to demonstrate significantly improved life cycle costs if the increased initial cost and the changes to conventional systems are to be outweighed.

Overall, the railways look well placed to increase their market share and this will drive further investment in the technical developments described in this article. The peaks of performance now seen in some passenger and freight vehicles will gradually spread to all parts of the system and will produce a more reliable and controlled railway system fit for the needs of users well into the 21st century.

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