MAIN TECHNICAL CONSIDERATIONS BY HIGH-SPEED RAIL SYSTEMS

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ABSTRACT

An increase in speed above a certain rate in the railway engineering creates a number of technical problems. However, The possibility of attaining high-speed rail (HSR) system opens up new prospects for the railway. It offers an efficient alternative to road and air transport over distance of 300-1000 km. It also embraces the fact that the railway can play a complementary role to other means of transport and thus help to create a homogeneous and economical transport system. This paper analyzes the basic technical problems arising out from the high-speed rail systems and introduces the respective solutions adopted.

Keywords: High speed Railway, Aerodynamic, Vibrations, Adhesion, Slab Track

INTRODUCTION

The railway offers certain advantages over the air and the road transport, such as:

- Greater capacity,
- Regular services,
- Negligible environmental Impact,
- Safety, and
- Lower energy consumption.

The strategy and aim of the railway should be to increase speeds to levels which will exploit these advantages to the utmost. A high-speed rail network may realize this aim and offers many direct and indirect advantages, such as:

- Creating a homogeneous and economical transportation system,
- Promoting regional development and decentralization,
- Improving the commercial economic relations between countries, and
- Helping the development of the new technologies.

A speed increase in the railway branch, beyond a certain rate, creates a number of problems, which may be resolved by special interventions on the rolling stock and the track. Some of these problems are:

- Aerodynamic problems (aerodynamic resistance, and noise),
- Vibrations problems,
- Adhesion Problems,
- Permanent way aspects,
- Rolling stock aspects,
- Braking distances aspects, and
- Signaling system aspects.

The objectives of this paper are to analyze the basic technical problems arising out from the high-speed rail systems and to introduce the respective solutions adopted.

AERODYNAMIC EFFECTS

High-speed railway means stronger aerodynamic and aero-acoustical phenomena, whose adverse effects grow as a function of the speed to the power 2 to 8 [1]. Therefore, aerodynamics becomes an essential element for the design of new high speed lines or to increase the speed on existing railways, particularly in the presence of tunnels.

AERODYNAMIC RESISTANCE

The reduction of the high aerodynamic resistance is a main aspect in a HSR system. This may require innovation concerning the shape of the power car, the trailer coaches, and the design of aerodynamically flush gangways between coaches.

To achieve such aim, it may be useful to analyze the train resistance in a HSR system. The total resistance R of a train moving on a straight horizontal plane at a steady velocity (V) is expressed by the model [2]:

$$R = A + BV + CV^2 \qquad (1)$$

where:
A, B, and C are coefficients whose values are expressed in terms of the characteristics of the rolling stock.

The first two terms represent the various mechanical resistances. The third expresses the aerodynamic resistance (turbulent flow). The second term increases in direct proportion to the velocity, the third increases in proportion to the velocity squared.

Researches indicated that an increase in speed from 200 to 300 km/hr. results in a 100% increase in the train aerodynamic resistance, though the mechanical resistance remain more or less unchanged [3].

AERODYNAMIC PHENOMENA IN PRESENCE OF TUNNELS

The aerodynamic phenomena observed when a train travels into a tunnel are significantly different, and greater in magnitude, from those observed in open air. The presence of a tunnel confines the air flow in a finite domain and constrains the air turbulence created by the vehicle movement to propagate along one direction only. Up till now, only a few existing tunnels of moderate length (less than 10 km), especially designed for HSR operation, are crossed at speeds higher than 250 km/hr. (by the Japanese Railways, SHINKANSEN lines, and by the German Railways, ICE lines, and by the French Railways, TGV routes).

The air flow generated by the vehicles movement in tunnels can be categorized into:

- A far-field flow (air flow far away from the train, characterized by the pressure waves propagation and the thermal exchange between air and rock), and
- A near-field flow (air flow in the vicinity of the vehicle with the unsteady wake).

In the case of HSR, the pressure waves which are generated during the train-tunnel entering or exit, are a far-field flow type. These waves are generated during the vehicle acceleration and deceleration, and characterized by slightly different amplitudes and very different gradients. As these waves propagate along the tunnel, their amplitude and gradient changes are influenced by the non-linear effects, friction, heat transfer, the tunnel characteristics (roughness, perimeter, length, presence of ballast, connections to the atmosphere or to another tunnel, changes of cross section). The presence of other vehicles and their associated pressure waves will also affect the unsteady pressure profile in the tunnel. These phenomena may diminish the comfort of the passengers and are responsible for the fatigue of the train structure and the tunnel equipment. When the pressure wave is partly reflected at the other end of the tunnel, micro-pressure waves are emitted outside the tunnel. This may lead to a sonic boom, considered as a new type of negative environmental impact. The amplitude of these phenomena depends highly on the train speed and the blockage ratio (blockage ratio is the train to tunnel cross-section ratio). The amplitude of the sonic boom is strongly influenced by the tunnel portals geometry and the vehicle nose shape. In the case of long tunnels, these pressure waves are significantly attenuated, but other physical phenomena like the thermodynamics, the ventilation and the aerodynamic drag become dominant.

The near-field flow is characterized by 3-dimensional (3D) effects. In the open air, the main aerodynamic problems are drag (at 300 km/hr., 80% of the total power consumption is used to overcome the aerodynamic drag) and noise (which grows with the power 6 to 8 of the speed), [1]. These effects are mainly influenced by the geometry of the leading and trailing vehicles, the current collector, the inter gap, the bogies and by the characteristics of the train surface. Unsteady aerodynamic effects can occur as the train passes another one (in which the distance between the two tracks plays an important role for a given speed and train geometry and characteristics). Recently, the interaction of the unsteady wake with the vehicle has been found to be significant at high speed.

For an HSR system, one of the most relevant issues is the choice of the tunnel cross-section which has in any case to be maintained small to ensure reasonable building costs, but sufficiently large to keep the aerodynamically impacts to a reasonable level.

Reduction of Aerodynamic Resistance in HSR

The third term (CV^2) in Equation 1 represents the aerodynamic resistance of the HSR. The constant C in this model can be represented by the following model:

$$C = C_1 * S + C_2 * L * P \qquad (2)$$

where:

C_1: Parameter which depends on the shape of the front and rear surfaces of the train,

S : Area of the affected surfaces,

L: Length of the train,

P: Metric perimeter of the rolling stock down to the rails,

C_2: Parameter which depends on the condition of the surface LP.

Reduction of the coefficient C_1 makes it possible to reduce coefficient C and consequently to reduce the aerodynamic resistance of an HSR system. The French National Railways (SNCF) could reduce the coefficient C_1 by 100% (from $20*10^{-4}$ to $9*10^{-4}$) in the TGV (Train Grand Vitesse) using the finite element method [4]. This method makes it possible to apply air flow forces at every point of the vehicle and thus establish the vehicle shape with minimum aerodynamic resistance and consequently with minimum energy consumption.

Reduction of the coefficient C_2 may be achieved by:

- fewer bogies per train,
- lower deck level,
- facilitated accomplishment of the compression-proofing of the trains.

In presence of tunnels, the aerodynamic resistance may be reduced by reducing the blockage ratio (BR), where:

$$BR = S / S_t \qquad (3)$$

where S is the cross-sectional area of the affected surface of the train, and S_t is the effective cross-sectional area of the tunnel. For a single track in tunnel, it is necessary that BR = 0.3-0.5, and for a double track in tunnel, BR = 0.14 [3]. Table 1 shows the required effective cross-sectional area of the tunnel related to the train speed for a double-track tunnel.

Table 1 Cross-sectional area of the tunnel related to the train speed for an HSR system.

Max. Speed (km/hr)	160	200	260
S_t (m^2)	40	55	71

Finally, the advances in material technologies and structural design allow for the construction of light and aerodynamically optimized passenger trains which meet the requirements for reduced traction energy, higher acceleration and increased maximum speed.

Aerodynamic Noise

For an HSR system, various aerodynamic noises are generated from the variances of surface configuration of the railway cars. They can be classified into:

- Aerodynamic noise from pantographs (for electric locomotives),
- Aerodynamic noise from the nose shape of the leading car,
- Aerodynamic noise from windows, doors, and gap of neighboring cars, and
- Aerodynamic noise from the equipment of air conditioner.

Generally, all aerodynamic noises are generated from the unsteady air flows induced by the various shaped parts, cavities and roughness of the train cars and equipment. They depend on:

- the aerodynamic shape of the body-work,
- the installation and the number of pantographs (for electric locomotives),
- The shape, the formation, and the length of the train.

Researches indicated that, at speeds up to 300-350 km/hr. the increase in noise is a function of the speed to the third power ($F(V^3)$), while at higher speeds the increase in acoustic disturbance is a function of the speed to sixth or seven power ($F(V^6-V^7)$), [5].

Reduction of Aerodynamic Noise in HSR

Aerodynamic noise may be reduced by certain technical interventions, such as:

- Aerodynamic design of the front surface of the train (reducing coefficient C_1, Equation 2),
- Reduction of the number of the pantographs,
- Protection of the pantographs with special aerodynamic covers,
- Smooth the lateral surfaces of the train (reducing coefficient C_2 Equation 2),
- Use of articulated trains of standard formation (fewer bogies, low floor level, fewer gaps between vehicles), and
- Using noise-absorbing material.

Vibrations Effects

There are two kinds of vibrations caused by HSR operation, namely vertical vibrations on superstructure and lateral train vibration on car body. Vertical vibrations on superstructure caused by HSR system at ground level are transmitted to the soil. The induced vibrations in the frequency range of around 8 to 25 cycles/s (Hz) mainly affect buildings nearby tunnels with timber ceilings or steel girder constructions. Excitation frequencies of railway-induced vibration between 40 and 80 Hz may cause significant acoustic phenomena, called structure-borne noise.

Vertical vibrations on superstructure in an HSR system are caused by discontinuities and irregularities of both the running wheel and the rail/track construction. The critical band extends up to about 80 to 120 Hz [6]. Vibrations cause elastic waves which are sent out into the surrounding soil that may force the foundations of buildings nearby the HSR, specially in tunnels.

Lateral train vibrations in an HSR system are caused mainly by aerodynamic force on car body when a train runs within tunnels or in open sections, especially when another train running from the opposite side. This continuous lateral vibration has a frequency of 2-3 Hz in tunnel and 1-1.5 Hz in open sections, and noticeable on the tail car, on the cars loading large pantograph cover, and also on the intermediate cars located at the rear part of the train [6]. The amplitude of the lateral train vibrations is affected by the induced aerodynamic force, which depends on the relative air flow velocity.

Vibrations Protection Measures by HSR

The most effective and economical measures for reducing ground transmitted vibrations for an HSR system are those performed on the track, such as:

Rail Surface

Grinding the rail is the main remediation technique to reduce vibrations in an HSR system, as short and long corrugations, and turnouts are the cause of high vibrations.

Highly elastic rail fastenings

Highly elastic fastening of the rail in HSR systems permits a large defection of the rail under the wheel, this reduces the mechanical impedance of the superstructure, which in turn reduces the excitation of vibrations.

Variation in thickness of ballast layer

Normally, the ballast layer thickness is about 30 cm, an increase of the thickness has no effect on vibrations reduction, while decreasing the thickness below 30 cm leads to a noticeable deterioration.

Sub-ballast mats

Sub-ballast mats in HSR in tunnels are elastic layers (with variation of products) placed under the ordinary ballast bed (see Figure 1). Researches indicated that high efficiency mats with thickness up to 80 mm lower the vibrations level leads in many cases to a reduction of the noise level down to 30 to 35 dB(A), [7].

Mass-spring-system

The most efficient, but expensive, solution to hinder vibrations by HSR in tunnels is a mass-spring-system (floating-slab-system). The basic concept is to prevent vibrations from penetrating into the soil by inserting a linear harmonic oscillator with a very low natural frequency. The spring usually consists of elastomeric elements (bearings) or foamed polyurethane mats. They should have good linearity over the whole loading range, and need to have their fundamental frequency in the right range. Figure 2 shows a mass-spring system constructed in a station as a vibration protection method for an HSR system.

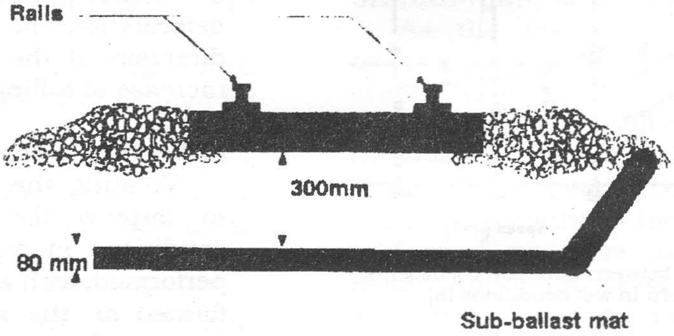

Figure 1 Sub-ballast mat as a vibration protection method in an HSR system

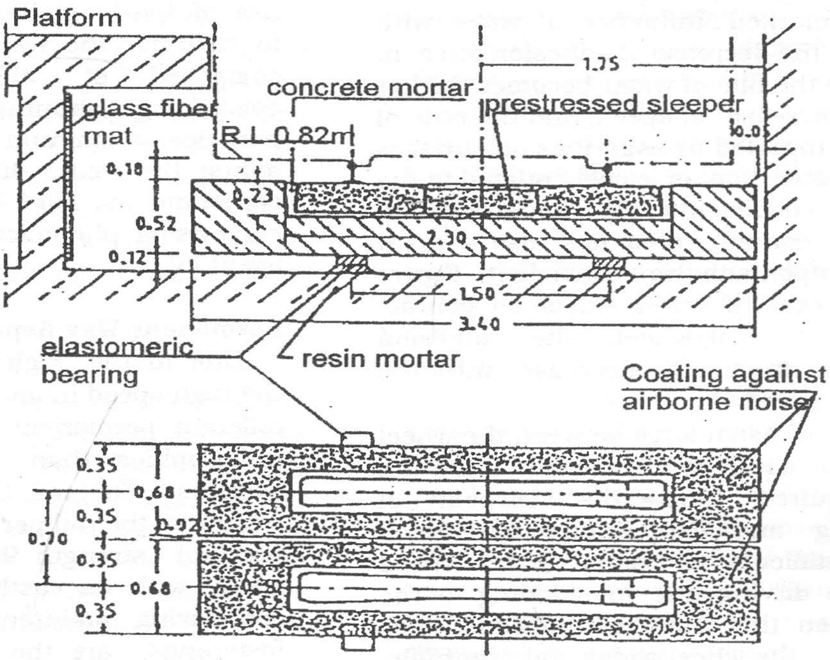

Figure 2 Mass-spring-system as a vibration protection method for an HSR system

The most effective and economical measures for reducing lateral train vibrations on car body are those performed on the train surfaces. Removing car gaps, which are the main factors to stimulate the growth of aerodynamic pressure fluctuation, is a main measure to reduce this type of vibration.

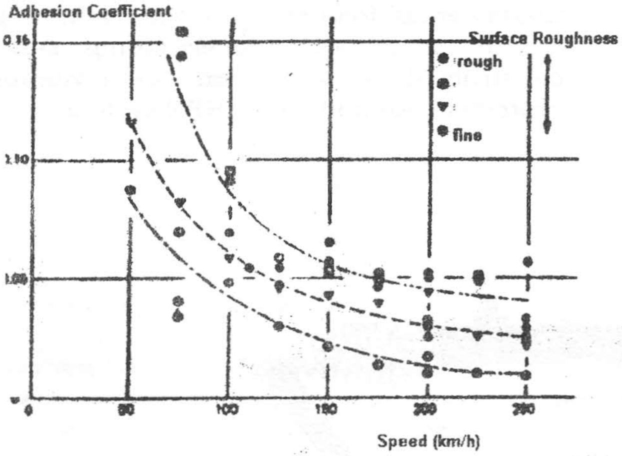

Figure 3 Relationship between adhesion coefficients and train speed in wet conditions [8]

Adhesion Effects

In HSR system, it has been found that there is marked influence of water with regard to the decrease of adhesion force, in which case the film of water becomes thicker with the increase of speed, and the ratio of the load supported by asperities on surfaces through water film is closely related to the adhesion coefficients [8]. Roughness of rail/wheel contact area has also a great influence upon adhesion coefficient. Figure 3 shows that if water exists on contact surfaces of rail/wheel, the adhesion coefficients drastically decrease with the increase of speed.

If the adhesion force between the wheel and rail in a railway system falls below the value required from the viewpoint of accelerating and decelerating speeds, it becomes difficult to increase the speed during the driving due to skidding of the wheel. When the brake is applied in these conditions, the wheel slides and eventually locks in, thus causing a flat on the wheel-treated and further extending to shelling. The wheel damages in these conditions may cause noise and vibrations, and may lead to various problems such as deteriorating of riding comfort and shortening the life of bearings, car axles, or rails by applying excess impact load. Furthermore, macro slip or sliding generates local heat on the wheel tread, and cooling of this locally heated portion results in formation of a metallographically transformed layer. Micro cracks which generated in this transformed portion led to abnormal shelling [9].

Finally, macro slip or sliding between wheel and rail poses various problems even it does not lead to locking of the wheel. One of these problems is a plastic surface deformation of the wheel tread in the direction of the circumference, resulting in increase of rolling noise while running.

Adhesion Protection Measures by HSR

Treating the wheel surfaces is a process to improve the adhesion force under wet conditions in an HSR system. This may be performed with a number of micro asperities formed on the surface of wheel by rubbing the wheel tread with light pressing force of some 490 N during braking and by effective use of hard metallic particles produced due to wear for the train cars. This material is composed of abrasive grains mainly comprising aluminum oxide, ferro-alloy particles, aluminum and copper powder to adjust the wear, diatom earth and calcium carbonate as filler, binding material mainly comprising phenolics resin and reinforcing agent [8].

Permanent Way Aspects

Due to the high stresses produced from the high speed in an HSR system, it requires different permanent way constructions and philosophies than the traditional railway systems. The rail UIC 60 (increasing the weight of the rail per meter and its strength, nominal strength 900 N/mm^2), the slab track, with its costly construction but its cost-saving maintenance, and the elastic fastenings, are the main elements of the permanent way in this system. Based on the varied operating programs and experiences of the HSR countries (Japan, Germany, France, Italy, and Great Britain), the slab track has proved a high efficiency because:

- It has a high resistance to lateral and longitudinal displacement,
- Lateral buckling and rail distortion are ruled out,
- It poses a high operational availability,
- Full track maintenance is unnecessary, and
- It increases the service life of the track.

Figure 4 illustrates the slab track Rhede-type used in the German HSR system in a curve.

With respect to track alignment, minimum curve radius should be defined for an HSR system. For example, for the TGV system with a speed of 300 km/h, a minimum curve radius was fixed at 4000 m. For the German Railway DB (Deutsche Bahn) the minimum curve radius was defined to be 7000 m for the HSR system.

To ensure smooth transition of grade in an HSR system, a minimum radius of vertical curve should be defined. For the Japanese Railway line SHINKANSEN (SANYO, TOHOKO and JOETSU with speed 260km/h) this value is set at 15,000 m [10]. To maintain the level of riding comfort in an HSR system the value of permissible cant (elevation) should be higher than 150 mm. By the SHINKANSEN system, this value is set at 180 to 220 mm for a speed 300 km/h, while by the German Railway, this value is set at 160 mm.

Rolling Stock Aspects

In order to overcome aerodynamic and other resistances, an HSR system requires more traction power than the traditional one. The high nominal engine power required for HSR system, combined with the need to provide the network with high momentary traction power, makes an electrified network a prerequisite for high speed-travel.

Running stability is the very basis of the HSR system. The main elements in this issue are the bogies. HSR system requires light-weight bolsterless bogies that improve the running stability on a straight line and allow better negotiating ability over curves at the same time. Furthermore, the wheel base may be extended from 2.5 m to 3.0 m to prevent bogies from yawing [11].

Weight reduction of rolling stock and unsprung mass is very effective in an HSR system to decrease the load on tracks and to reduce also ground vibrations, structural noise, and energy consumption. An adoption of. aluminum alloy coach-body has been performed by the Japanese system, the SHINKANSEN, to achieve this goal.

As the train speed rises, its riding comfort grows worse. Furthermore, in curved section, the centrifugal force grows higher. These problems may be solved through improvement of track accuracy, cants and transition curves. For an HSR system, another innovations may be performed to solve such problems. The height above rail level of air spring of bogie supporting car-body can be raised from 1.0 m to 1.7 m, and the height of coach-body gravity center my be lowered close to the floor level of coach (approx. 1.2 m above the rail level) aiming at damping down the vibrations. Furthermore, the adjacent coaches of the HSR trains can be coupled together with oil dampers, and thus vibration of the coaches is suppressed by each other.

In addition to the above, to make the car body roll gently and smoothly in curved sections in an HSR system, car body tilting system should be required to damp down centrifugal forces. Figure 5 shows car body tilting systems. This figure indicates two systems of tilting, the left one depends on a tilting mechanism which is installed under the floor of the coach, and the right one depends on adjustable wheel sets which reduce the spread of the dynamic forces on wheels and axles, and thus allowing a higher curve speed without exceeding the permitted lateral track forces.

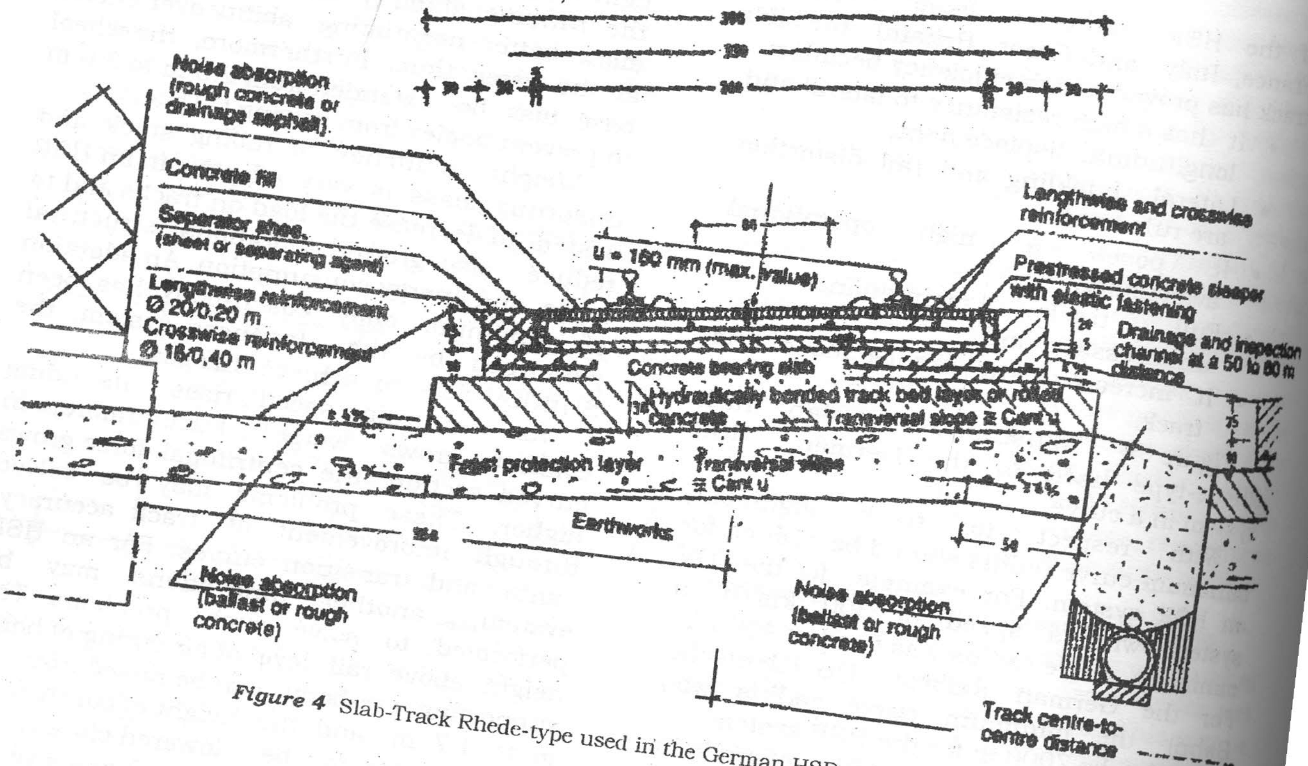

Figure 4 Slab-Track Rhede-type used in the German HSR system in a curve

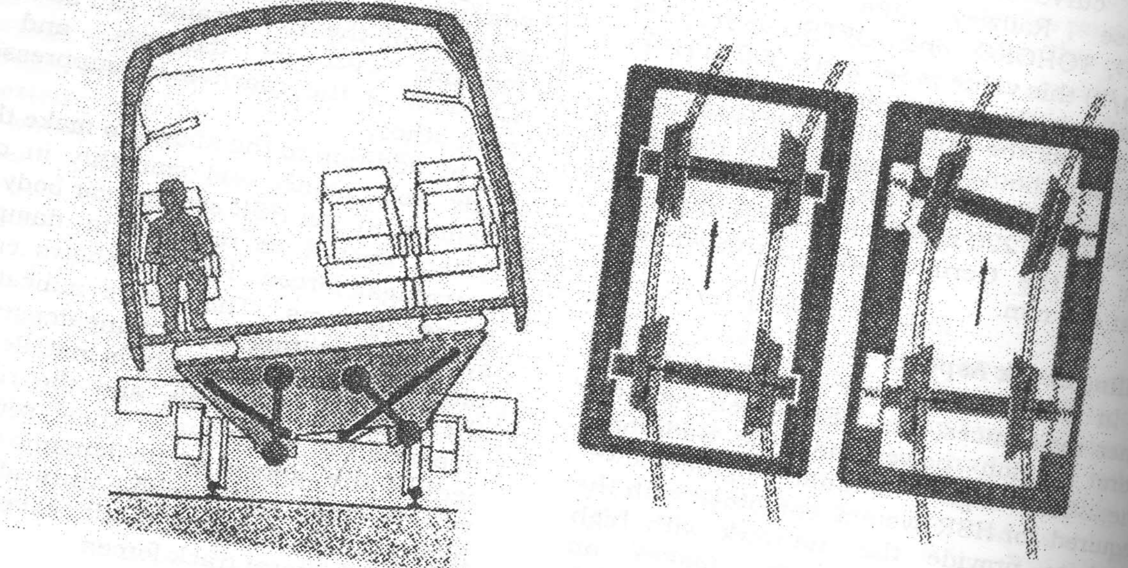

Figure 5 Car body tilting system for an HSR system

The HSR system requires also an efficient braking system. The German HSR system, namely ICE (Inter-City Express) is equipped with a combination of disc brake (made of specially processed steel), electric brake, and linear eddy current brake. The harmonized interaction between these brakes is ensured by an electronic braking control system and an optical-fiber data bus used for the transmission of braking commands and error massages.

Braking Distances Aspects

The train braking distance increases approximately in proportion to the speed squared. This factor, combined with reduced wheel adhesion at high speeds, also increases the power consumed in the process of braking. Table 2 illustrates the braking distance required for HSR systems for a sudden and gradual braking.

Table 2 The braking distance required for HSR systems [12]

Case	Speed (km/h)	Braking Distance (m)
Sudden Braking	300 220 160	3200 1600 800
Gradual Braking	260 200 160	6000-8000 2500-3000 1300-1400

Signaling System Aspects

For HSR systems, provision should be made for signals and information about the speed limits to be received inside the drivers cab. The signals are transmitted on special frequencies along the rails and on to special screens inside the cab. The Digital Automatic Train Control (DATC) is an example for a navigation system used for an HSR. The DATC system is a high-density safety system which transmits much information such as the absolute position of the train, and the relative position of the preceding train. On board, various kinds of information such as memorized data on curves, turnouts are compared with the corresponding track data being transmitted from wayside, and the maximum allowable speed at a specific position is calculated, and braking action is started if necessary. In this case uniform braking is applied depending on the distance to a preceding train or track information.

Figure 6 illustrates the DATC system configuration.

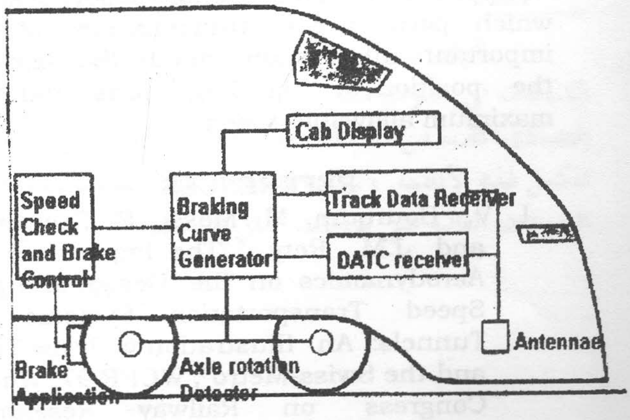

Figure 6 Essential elements on board for the DATC system

CONCLUSIONS

In order to attain an HSR system, a number of technical problems must be solved by special interventions on both the rolling stock and the track. Aerodynamic is an essential element for the design of new high-speed line or to increase the speed on existing line. Reduction of aerodynamic resistance and noise can be achieved by various techniques such as establishing a vehicle shape with minimum aerodynamic resistance, minimizing the bogie number per train, lowering the deck level of the train, smooth the lateral surface of the train, reduction of gaps between vehicles, and using noise-absorbing material.

Vertical vibrations on superstructure and lateral train vibrations on car body are other factors which must be considered in the design of a new HSR line. This problem can be solved by grinding the rail, using elastic rail fastening, and using the appropriate sub-ballast mat.

Wet conditions of the rail may affect the adhesion force in an HSR system. This can be treated by rubbing the wheel tread with light pressing force during braking.

UIC 60, slab track are the main aspects concerning the permanent way in an HSR system. Weight reduction of the rolling stock and the unsprung mass, and using the car-body tilting system are the main considerations in an HSR system concerning the rolling stock.

Finally, an HSR system must be equipped with a high-density safety system which permits the transmission of the important information about the signals, the position of preceding trains, and the maximum allowable speed.

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الإعتبارات التكنيكية الرئيسية لأنظمة السرعات العالية بالسكك الحديدية

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ملخص البحث

بالرغم من أهمية تكوين شبكات نقل ذات سرعات عالية على السكك الحديدية، فقد تؤدى زيادة السرعات على هذا الشبكات الى حدوث مشاكل تكنيكية متعددة. وقد يرجع أهمية السرعات العالية على السكك الحديدية الى تكوين نظام نقل إقتصادى كفء من شأنه أن ينافس أنظمة النقل الأخرى مثل النقل على الطرق والنقل الجوى. وقد تلعب هذه الشبكات الدور المكمل لهذه الأنظمة. ولذلك فإن هذا البحث يهدف بصورة أساسية الى تحليل المشاكل التكنيكية الناتجة عن إنشاء أنظمة السرعات العالية على شبكات النقل بالسكك الحديدية، وتقديم الحلول المناسبة لها.