High speed turnouts' geometry

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ABSTRACT

Turnouts are singular points of the railway track. A series of advances have been added to their design in the last 20 years, in the same way as the other elements that constitute the track structure. These developments have allowed the vehicles to increase their running speed over the turnouts, as well as to improve their reliability and security, reducing, in this way, maintenance costs.

This paper is focused in geometric improvements adopted in turnouts in order to get high speeds over direct (350 km/h) and diverging (160 – 220 km/h) tracks. These improvements are related to diverging track alignments introducing transition curves, switch rail design and mechanization in order to avoid the straight switch rail strike phenomenon, as well as to crossing modifications so as to avoid the existence of the gap.

1 INTRODUCTION

As it is known, a railroad turnout is a mechanical installation enabling trains to be guided from one track to another at a railway junction. These elements of the railroad track have always been singular points of great complexity, due to one of the main characteristics of railways: the automatic guidance of vehicles by means of the conicity and the use of interior flanges in the wheels, which link the vehicle path to the track layout. The existence of the flange leads to the need of leaving the appropriate space for the flange (flange path) to move forward without finding obstacles, which originates the particular components of the turnout that will be shown in the next section [1].

Since the first mine turnouts designed by John Curr (1976), these elements constitute singular points in the track, with expensive inspection and maintenance tasks. Indeed, Swiss Railways [2] estimate that between 20 and 40% of maintenance expenses are due to inspection, maintenance and renewal operations of turnouts and crossings. On the other hand, the maintenance cost of a turnout is equivalent to that of 300 to 500 m of conventional track.

So, it is not surprising that the design evolution of turnouts has been oriented to improve the safety and the speed of vehicles when running over them, reducing life cycle costs and extending their lifespan. These objectives are especially critical in turnouts for high speed lines. This is why this kind of turnouts uses the most modern technology and the most advanced solutions which make getting running speeds of up to 220 km/h over the diverging track possible and guarantying the safety and reliability of the system.

2 CRITICAL POINTS OF CONVENTIONAL TURNOUTS IN RELATION TO SPEED

Figure 1 shows the geometry of a simple right hand turnout for conventional tracks (not for high speed tracks) with its main elements.

Switch rails are the elements which guide the vehicle to run over the direct or the diverging track, according to the position of each switch rail in relation to its corresponding stock rail. In the case of the figure, due to the position of curved and straight switch rails, the turnout guides the vehicle over the diverging track. If these elements are in the opposite position, the turnout guides the vehicle towards the direct track.

On the other hand, the crossing is the turnout part which allows the two routes to cross each other avoiding that the vehicle' flanges find any obstacle in their movement. For this to happen, it is necessary to leave an empty space between the two rails that cross each other in the crossing, known as gap.

In order to guarantee the support of the wheel that is running over the crossing despite the existence of the gap, it is necessary to enlarge the connection rails to both sides of the frog. These parts of the crossing are known as wing rails.

Finally, due to the existence of the gap, the wheel running over the frog loses its guidance. For example, if the vehicle is running over the turnout of Figure 1 towards the diverging track, it will be guided by the contact of the left wheel flange with the curved switch rail, but when it reaches the gap, this wheel would lose its guidance because of this empty space, and as a result, it could strike the frog nose or even go towards the direction for which the turnout is not provided (in this case, towards the direct track). So as to prevent this from happening, check rails are disposed in the crossing, in such a way that when the left wheel is located over the gap, the right wheel can guide the vehicle by means of the contact between its interior face and the check rail. In this way, guidance over the crossing is guaranteed too.

In a conventional turnout with these characteristics, the critical points in relation to running speed are the following:

- A discontinuity in the course when the vehicles run towards diverging track, usually without the existence of a transition curve. This phenomenon leads to a discontinuity in the transversal acceleration or overacceleration due to the impossibility for establishing the appropriate superelevation for the curve.

- A discontinuity in the track stiffness, notably at the level of the crossing, both vertical and horizontal.
- Finally, and in particular, a discontinuity in the support of the wheels when passing through the crossing, when the wheel moves from the wing rail to the tip of the frog, or vice versa, crossing the gap [3].

In the following sections specific characteristics of high speed turnouts will be presented, which counteract the effect of the critical points presented previously, using as an example the Spanish high speed turnouts of Madrid-Seville and Madrid-Barcelona lines.

3 TURNOUT GEOMETRIC ALIGNMENT

As turnouts are railroad track elements, they must comply with specific operational requirements. So, Railway Administrations distinguish among turnouts suitable for using on a main track, provided with big radius of the diverging track and low values of the crossing angle tangent. On the other hand, turnouts with a smaller radius and a higher angle will be disposed in railroad yards or stations, leading to a better use of the land surface available. Therefore, the use of a turnout will be determined by its main parameters: diverging track radius (R) and crossing angle tangent (1:n).

The determining subject to establish the diverging track radius for a high speed turnout is the maximum running speed over that track. The relation between radius and speed is given by three fundamental parameters which are enforced by each Railroad Administration considering its experiences and criteria. These parameters are:

- Unbalanced centrifugal acceleration when running over diverging track.
- Over-acceleration.
- Jerk.

3.1 Centrifugal acceleration

The centrifugal acceleration experienced by a body which travels over a circular curve of radius R (m) at a speed of v (m/s) is:

$$a_c = \frac{v^2}{R} \tag{1}$$

In a circular curve without superelevation (the case of the diverging track in a turnout provided in a straight direct track), the value of the unbalanced centrifugal acceleration (a_{cub}) is the same as the centrifugal acceleration ($a_c=a_{cub}$). So, equation (1) can be used to determine a_{cub}.

It is very common to transform equation (1) to introduce speed in km/h, obtaining:

$$\left.\begin{aligned} a_{cub} &= \frac{v^2}{R} \\ v_{(m/s)} &= \frac{V_{(km/h)}}{3.6} \end{aligned}\right\} \rightarrow a_{cub} = \frac{V^2}{12.96 \cdot R} \tag{2}$$

With equation (2) the maximum speed allowed over the diverging track (V, in km/h) can be determined, imposing that the vehicle does not overpass the maximum value of unbalanced centrifugal acceleration. In this way, if the limit value of a_{cub} is 0.65 m/s^2 (a very common limit), the relation between maximum speed V (in km/h) and circular radius of the diverging track (R, in m) will be:

$$V_{max} = 2.9 \cdot \sqrt{R} \tag{3}$$

In turnouts with a curved direct track, the value of superelevation should be considered. In any case, this value will be the same for the diverging and direct track, due to construction requirements, and normally it will be adapted to the needs of running over the direct track.

3.2 Overacceleration

As it is known, the geometry of railroad tracks must allow a progressive transition between different alignments with different transversal acceleration, to avoid sudden changes of its values. So, it is necessary to provide a transition alignment between straight track and circular curves.

The variation of transversal acceleration with time (its derivative), is known as over-acceleration (ψ) or instantaneous quality. This parameter is one of the criteria used to guarantee passenger comfort. Its mathematical expression when there is not superelevation is as follows:

$$\Psi = \frac{da_{cub}}{dt} = \frac{d\left(\frac{V^2}{12.96 \cdot \rho}\right)}{dt} \qquad (4)$$

In a circular curve, the value of a_{cub} is constant, as so it is ρ (with value R). Therefore, over-acceleration will be nil. Nevertheless, in a transition curve the radius (ρ) changes. So, in the case that the transition is, for example, a clothoid (Euler spiral), the over-acceleration value will be constant and not nil through the transition curve.

Over-acceleration is limited, mainly, because of its influence in comfort. But it is important to highlight that over-acceleration is related to the appearance of supplementary transversal forces between the vehicle and the track, as is shown by the studies carried out around 1970 by the Track Equipment and Maintenance Institute's Laboratory of former USSR [4].

3.3 Jerk

When a vehicle, considered as a mass concentrated on one point, passes directly from a straight alignment to a circular curve, the unbalanced transversal acceleration value changes suddenly from zero to a_{cub}. This fact would imply an infinite theoretical over-acceleration.

In real life the vehicle is not a mass concentrated on one point, as it has certain length. So, unbalanced transversal acceleration will not act with its whole value, in the vehicle's centre of mass, until the whole length of the vehicle is in the circular curve, that is, until its last truck or wheelset is located in the curve's origin (Figure 2). At this moment, the vehicle will have moved the distance between its wheelsets or trucks (wheel-base or bogie-base of the vehicle) forward.

In this case, the concept of over-acceleration as derivative of unbalanced transversal acceleration with time loses its sense. The parameter of interest is now the average value of unbalanced transversal acceleration in the time used to get from the first to the second position in Figure 2 [5].

This value ψ* is known as jerk in English, *ruck* (German), *choc* (French) and *empellón* (Spanish, proposed by Prof. García Díaz-de-Villegas in [6]). It is formulated in the following equation, where E is the distance shown in Figure 2, and v is the vehicle's velocity.

$$\Psi^* = \frac{\Delta a_{cub}}{\Delta t} = \frac{\Delta a_{cub}}{\frac{E}{v}} \qquad (5)$$

The influence of jerk in comfort, track geometry' degradation and other subjects is not well know yet. In fact, this is an open question for researching. In this sense, some interesting contributions are the following:

- Theoretical works by Prof. J. Megiery, in which he makes a thorough vectorial treatment of railroad alignment, suggesting layouts with continuous function and derivative [7].
- Contributions by J. Nasarre, M. Cuadrado, P. González and E. Romo [8] with a new interpretation of jerk.

3.4 Parameters' quantification

Railroad Administrations quantify the value of dynamic parameters which determine track geometry. Some Administrations distinguish between recommended values for broad tracks and for turnouts, although most of them do not establish less strict recommendations for turnouts as they are a part of the whole track bearing in mind the total continuity criterion.

For Spanish high speed turnouts, values of Table 1 have been set.

3.5 Turnouts' geometry evolution to comply with high speed requirements

Bearing in mind what has been previously presented, it is easily deduced that as running speed over the diverging track of the turnout increases, simple circular curve layouts have to be abandoned, and other kinds of alignments must be used which allow to reduce over-acceleration and jerk values. This is why layouts based on two circular curves, which were first used in German turnouts in the eighties, have been rejected since the nineties, giving way to layouts with clothoids or cubic parabolas.

French Railroads (SNCF) introduced, in Paris Sud-Est High Speed line, turnouts with a diverging track consisting of a transition curve (cubic parabola) tangent to the straight alignment with an initial radius of 3000 or 6720 m (due to the fact that it is physically impossible to provide a parabolic transition starting from infinite radius on a switch rail). This parabola ends with an infinite radius at the frog nose [9].

Swiss Railroads (SBB) was the first administration to introduce turnouts with a diverging track consisting of two clothoid arcs. This solution, known as “tip clothoid”, allows a reduction in the switch’s deviation angle with respect to French geometry. This is the geometry proposed nowadays by most German manufacturers, with a configuration known as asymmetrical clothoids, consisting of two clothoids with different parameters linked between each other.

The tip clothoid solution has, nevertheless, the inconvenience of high values of transversal acceleration generated when running over the turnout at high speeds. For this reason, the working group which was constituted to develop the design for High Speed Turnouts for the Madrid-Seville line in Spain (with experts from Renfe, TIFSA and Cantabria University), set out a new kind of layout known as “plateau clothoid”. This solution is based on the use of two clothoid arcs connected by a circular curve [6]. Greater performance turnouts with this geometry provided in Spanish High Speed lines from Madrid to Seville and to Barcelona are presented schematically in Figure 3.

4 SWITCH GEOMETRY IMPROVEMENT

In order to get design improvements which lead to the reduction of interaction forces between the vehicle and the turnout, it is necessary to analyze the movement of railroad vehicles through switch and crossing, considering every situation which can affect vehicle running (mechanical characteristics of the vehicle, weight, speed, initial conditions when entering the switch, etc.) as well as turnout characteristics (geometry, kind of rails, worn profile, switch position, etc.). This study is approached, in the first stages of design, by simulating the vehicle’s behavior over the turnout by means of a mathematical model which represents, with acceptable accuracy, the actual physical phenomena.

4.1 Straight switch rail strike phenomenon

As it is known, the conical shape of railroad wheels, together with the inherent wheelset property of making the wheels rotate at the same speed without differential turns between them, have been a traditional way of guiding in railroads. This design, which has been used since the beginning of the XIX century, and is still used nowadays even in High Speed trains, is the origin of a disturbing movement known as hunting. By means of this movement, the wheelset reacts to a specific disturbance which moves it away from its equilibrium position (centered in the track and with its rotational axis perpendicular to it), trying and locating its center of mass over the track center again by means of a series of oscillations around it.

One of the specific situations in which hunting movement appears is when a change of track gauge occurs. This phenomenon appears, in fact, when the vehicle wheelsets run over a turnout switch advancing through the direct track. Indeed, while the straight switch is not wide enough to withstand the supporting contact with the corresponding wheel, this wheel will have to roll over the curved stock rail. Therefore, while the wheelset is penetrating into the switch, the points of the rails over which both of its wheels are supported (that is, the curved and the straight stock rails contact points) are progressively farther from each other (see Figure 4), so the distance between rolling points gets higher. This fact makes the wheelset move trying to locate its axis over the effective track axis. Due to this phenomenon, the flange of one of the wheels can even contact with the straight switch rail, which will lead the vehicle to move along the direct track [10]. This strike movement lasts until the wheel is supported by the straight switch. At that time, the track gauge returns to its normal value, and the wheelset will try to center its axis in relation to the new track axis. See this whole movement in Figure 4.

This strike movement of wheelsets against the straight switch rail leads to:

- Impacts and consequent wear in turnout elements, specifically in the straight switch rail, as well as in the vehicles’ wheelsets and trucks.
- Higher maintenance costs, mainly in switch elements.
- Noise.
- Discomfort.

Nowadays, there are two systems which avoid impacts against the straight switch rail, which will be presented in the next sections.

4.1.1 Fakop system

The Fakop system (acronym for *Fahrkanteoptimierung*, rail edge optimization), has been developed by the German company *Butzbacher Weichenbau GmbH* (BWG). It is the only solution that, until now, has been used in actual turnouts, being the Spanish High Speed lines the first ones in the whole world to use this system in their turnouts.

The Fakop system is based on inducing an opposite movement to the one that makes the wheelset strike the straight stock rail. This opposite movement is achieved by enlarging the distance between both stock rails (straight and curved), in an adequate way and in a localized area. This fact is achieved by locally curving the straight stock rail, adopting the shape shown in Figure 5 (the scales have been deformed in such a way that the stock rail modification can be observed). With this straight stock rail geometry, at the same time that the wheel over the curved stock rail is experiencing a movement of its contact point towards the exterior, the wheel over the straight stock rail will be supported by a contact point which is separated more and more from the curved stock rail. In this way, the track axis of the direct track remains straight, and so, the movement against the straight switch rail to center the wheelset axis over the track axis disappears, while the wheelset and the track already have the same axis [11].

Both the length and the geometry of the straight stock rail to be curved are obtained by trial and error, analyzing the results of the vehicle's behavior simulation when running over the modified switch of the turnout. Therefore, the optimum solution is not achieved, but one which is almost optimum is.

The main drawbacks of this solution are related to the manufacturing process. In fact, giving the modified geometry to the straight stock rail leads to a more complex mechanization of the curved switch rail which has to fit it. In addition, it is necessary to calculate position variation of drill holes for fastenings in the turnout sleepers, bearing in mind concrete retraction. All these facts lead to a more difficult production, and increase noticeably the costs of both design and construction.

Additionally, this solution requires the adoption of specific techniques in order to make tamping, aligning and leveling operations in the switch zone, to maintain the accurate modified geometry in the straight stock rail.

On the other hand, the main advantage of this solution consists of the improvement of the vehicle's behavior when running both through the direct and the diverging track.

KGO (Kinematics Gauge Optimisation) is a system based on FAKOP solution [12].

4.1.2 CATFERSAN system

The CATFERSAN solution [8, 13] is based on the re-profiling of the straight stock rail's head in a specific zone with a precise geometry, in such a way that contact between the wheel and stock rail is avoided in this area (but keeping the guidance by the flange), as can be seen in Figure 6.

In the same way as the Fakop solution, the length and geometry of the mechanized area are determined by a trial and error strategy, simulating the behavior of the most aggressive vehicle running over the switch zone by means of a railroad's dynamics software.

The mechanization of the stock rail head is effective for solving the strike phenomenon against the straight switch rail, getting, with reasonable costs, the following benefits:

- Lower lateral forces over the straight switch, which lead to lower lateral wear in it.
- Softer lateral movements of railway vehicles, which lead to lower actions over the rest of elements of the turnout, lowering maintenance costs in this way.
- Improved passenger comfort.

The CATFERSAN solution does not require the design modification of turnout sleepers. Specific maintenance procedures for the turnout switch zone are not needed either.

Figures 7 shows the wheelset lateral displacement obtained by simulation of the vehicle's behavior over the High Speed Turnout prototype developed by the Spanish firm *Felguera Melt S.A.*, which can be used for speeds up to 220 km/h over a diverging track, with the Fakop and the CATFERSAN solutions. The first part of the figure shows lateral displacement of first wheelset of an AVE (Spanish High Speed Train) when running over the turnout from the switch to the frog. The second part shows the same displacement when running in the opposite direction.

5 CROSSING'S IMPROVEMENT

In order to get a higher speed circulation over the diverging track, it is necessary to increase the value of the diverging track radius, in such a way that limit values for centrifugal acceleration, over-acceleration and jerk are observed (see section 3). This increase of the radius value leads to a reduction of the crossing angle and, as a consequence, to a longer gap in the crossing zone so as to get the appropriate flange path for the flange to pass both towards the diverging and direct track. If this gap enlargement is excessive, it could prevent the safe running of vehicles over the crossing. In this case, the gap must be removed.

On the other hand, the existence of the gap generates a vertical and lateral discontinuity which causes high impact forces, jerks, discomfort and excessive wear, which are greater the higher the speed is. So, due to this fact, it is also recommended to remove the gap for speeds over 160 km/h.

In order to remove the gap, movable elements are provided to keep the adequate distance between the frog and the wing rails (flange path) in the appropriate position related to the switch rails state (that is, for the turnout given for the circulation over the direct or the diverging track). In this way, check rails become unnecessary, although some Railroad Administrations keep them as an additional safety measure.

Although until ten years ago movable wing rails were used to remove the gap, nowadays all the Railroad Administrations with High Speed lines have selected the solution of the movable frog nose. In this case, the frog nose is not static, but able to move in order to be put together with the corresponding wing rail. In this way, the gap and one of the flange paths are removed, keeping the other path empty to allow the flange to pass through it.

There are two ways of getting the mobility of the frog nose, which are the German and the French design, which will be presented in the following sections.

5.1 Movable frog nose by German design

The movable frog nose provided in the Madrid-Seville Spanish High Speed lines are the heavy standard type from German Railroads (DB), as the one shown in Figure 8. The central part of the elastic frog nose consists of only one piece, forged homogenously, and manufactured from a standard steel section.

To allow the movement of the frog nose to fit the corresponding wing rail, a device is provided in the rail which avoids the constitution of a not deformable triangle.

The movable frog nose is protected rounding it and sheltering it 3 mm under the wing rail (in a similar way as the switch rail protection under the stock rail), in such a way that the wheel can only touch it tangentially. Connection UIC-60 rails are welded to the mechanized nose by means of flash welding.

Longitudinal forces of continuously welded rails are transmitted from wing rails to movable nose backs by means of 2 or 3 pads, screwed down by high resistance screws and auto-blocking nuts. In its turn, other pads are provided between the two rails on the back of the movable nose, screwed down in the same way, to equalize the forces of the two rails (see figure 8).

5.2 Movable frog nose by French design

In movable frog nose turnouts provided in French High Speed lines, the two main elements of the frog are (Figure 9):

- The berth, which plays, in relation to the movable frog nose, the same part as the stock rail regarding the switch rail.
- The elastic movable point.

The movable frog nose is obtained by mechanized rails with UIC 61 A profile (see figure 9). It is composed by the point itself and the check-point, which are linked by studs. This configuration of point – check-point allows the movement of the frog nose by avoiding the formation of a not deformable triangle. This configuration is the one used in the High Speed Turnouts of Madrid-Barcelona line in Spain.

In the last conceptions of this kind of crossings with the movable frog nose, the berth design has been simplified, in such a way that it is casted in only one manganese steel piece, to which standard steel rails are welded by means of a patented method. This welded joint guarantees the continuously welded rail’s forces transmission between the berth and the rails on the back of the frog nose, both in traction as in compression.

6 CONCLUSIONS

In this paper, the modifications needed in turnouts to allow running at high speed over them have been presented, both in relation to geometric improvements in the turnout layout, the geometric improvement in the switch rail design to avoid the straight switch rail strike phenomenon, as well as the crossing design modifications necessary to prevent the existence of the gap. In addition, turnouts used in Spanish High Speed lines have been shown as examples of the modifications explained.

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TABLE INDEX

FIGURE INDEX

TABLE 1 Limit values of acub, overacceleration and jerk in Spanish High Speed Turnouts

TURNOUT	a_{cub} **(m/s^2)**	ψ **(m/s^3)**	ψ^* **(m/s^3)**
DSIH-60-10000/4000-0.026-CM-D (Madrid-Seville High Speed Line)	Normal: 0.51 Maximum: 0.65	Maximum: 0.40	Normal: 0.40 Maximum: 0.85 Exceptional: 1.20
DSIH-60-17000/7300-0.02-CM-D (Madrid-Barcelona High Speed Line)	0.50	0.60	1.10

FIGURE 1 Geometry of a simple right hand turnout for conventional tracks.

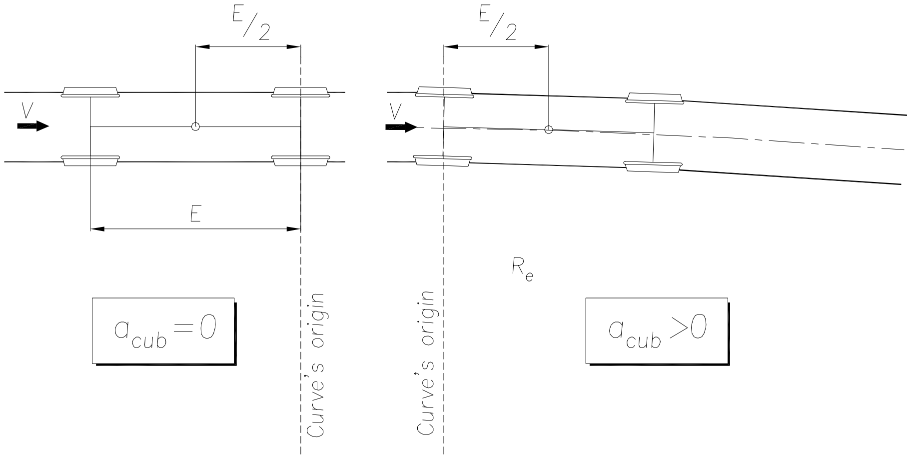


FIGURE 2 Interval between 0 and maximum values of a_{cub}.

FIGURE 3 Turnouts DSIH-60-10000/4000-0.026-CM-D (Vmax over diverging track: 160 km/h) and DSIH-60-17000/7300-0.02-CM-D (Vmax over diverging track: 220 km/h).

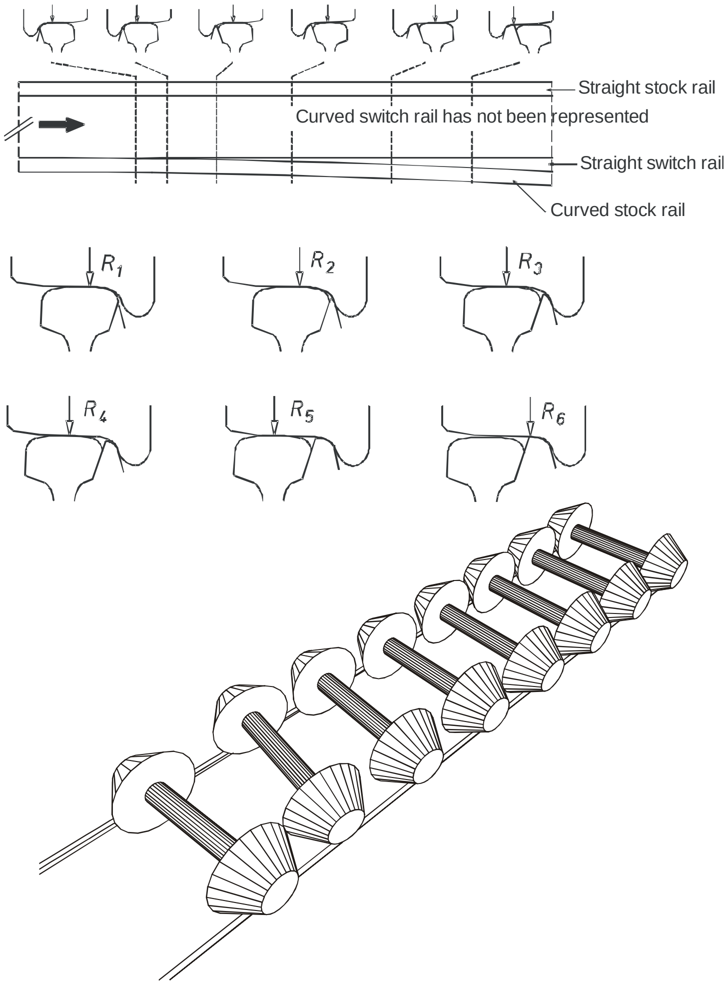


FIGURE 4 Gauge increase when running through direct track and induced straight switch rail strike phenomenon.

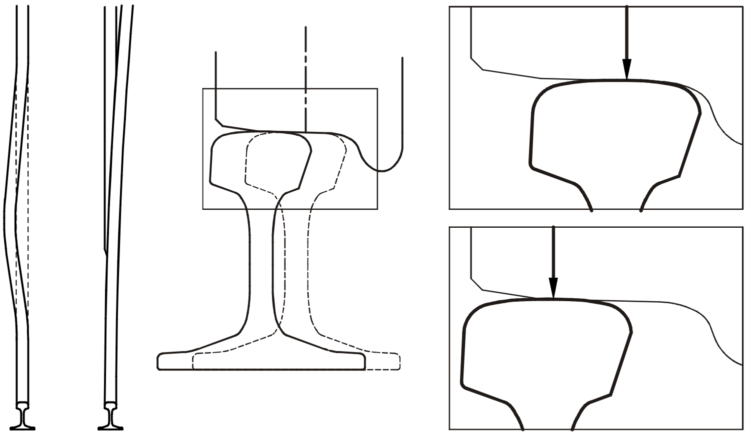


FIGURE 5 ***Fakop*** **system.**

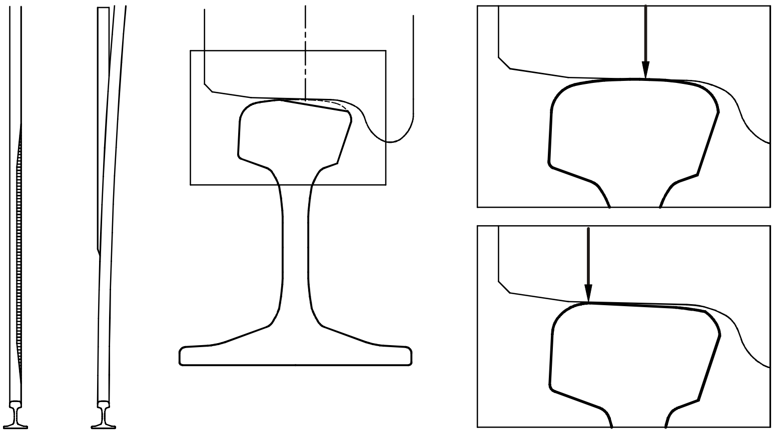
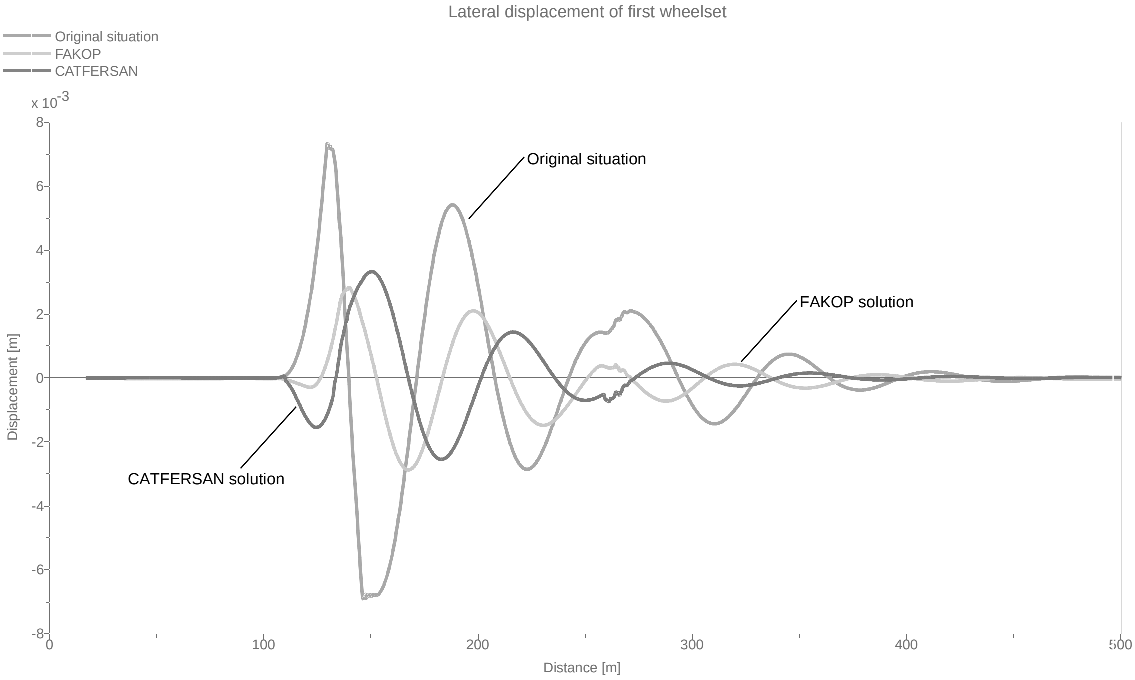
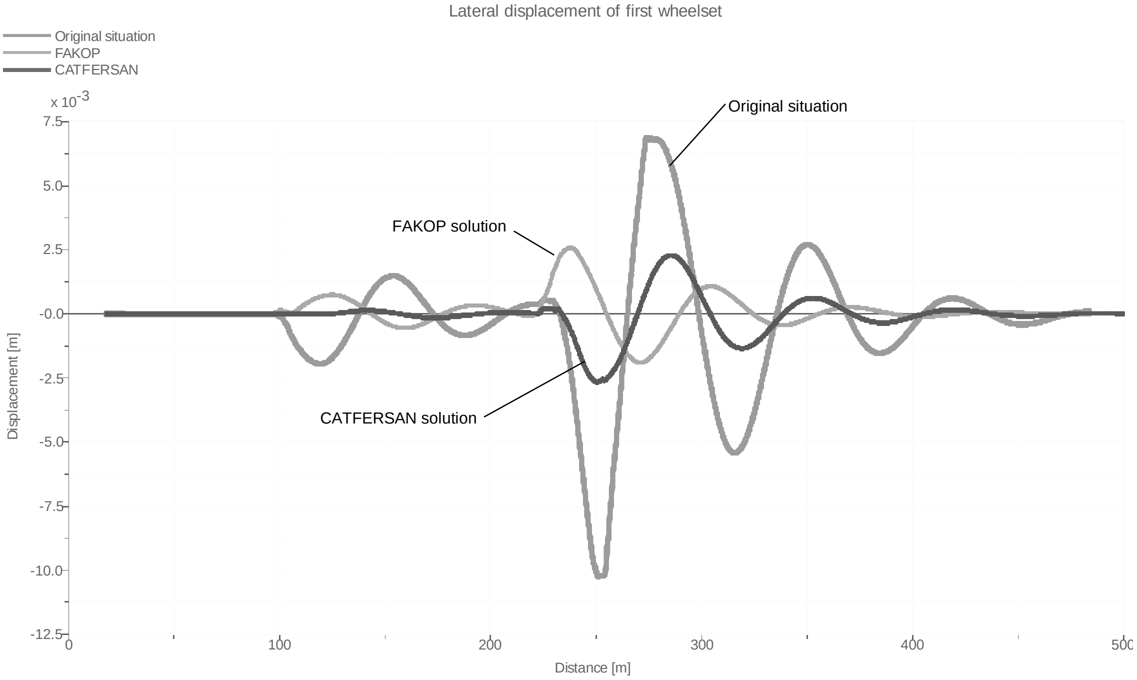


FIGURE 6 ***CATFERSAN*** **system.**



Speed: 300 km/h
Initial lateral displacement of wheelsets, trucks and carbody nil. Initial wheelsets attack angle nil.



Speed: 300 km/h
Initial lateral displacement of wheelsets, trucks and carbody nil. Initial wheelsets attack angle nil.

FIGURE 7 First wheelset' lateral displacement when running from switch to frog and from frog to switch.

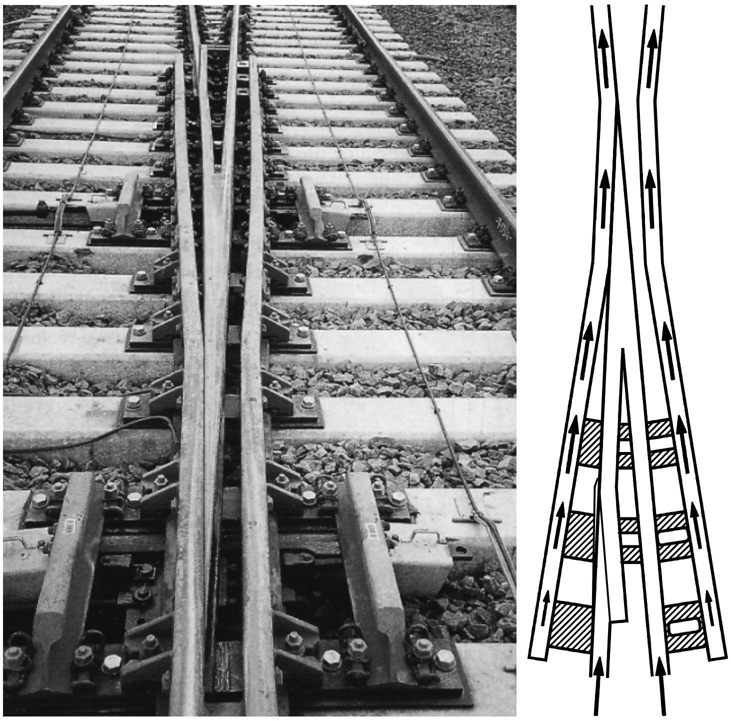


FIGURE 8 Movable frog nose by German design.

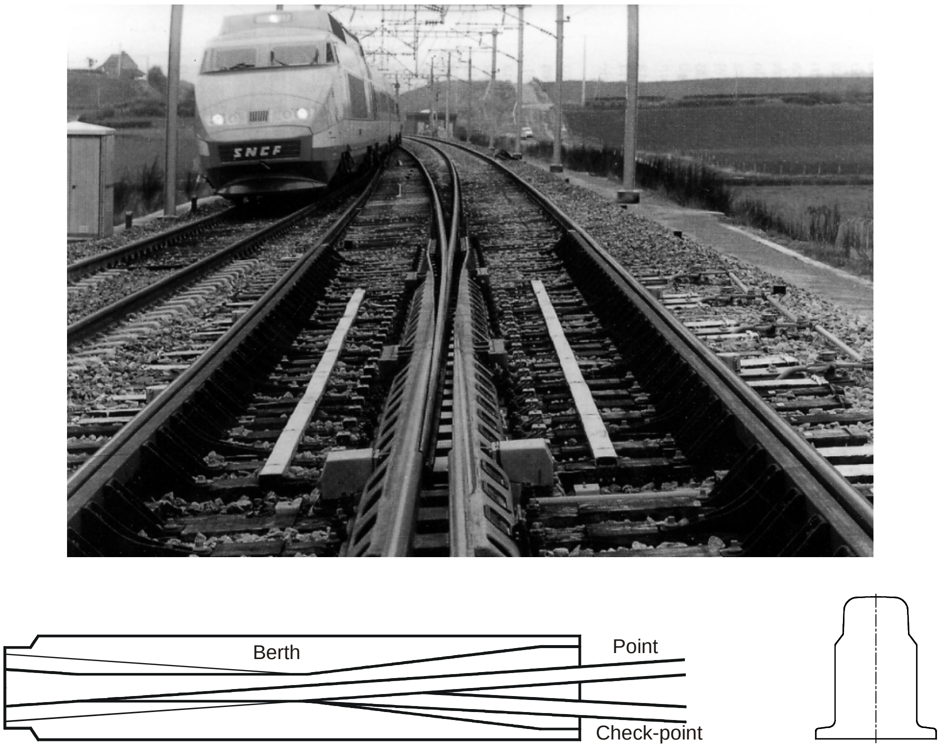


FIGURE 9 Movable frog nose by French design.