ANALISIS ESTRUCTURAL DE LA SEPARACION DE TRAVIESAS EN VIAS DE FERROCARRIL*

*Structural Analysis of the Separation between Sleepers in Railway Tracks***

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RESUMEN
El objetivo del proyecto ODSTRACK es establecer la distancia optima entre traviesas para disminuir los costes de construcción de vía sin poner en peligro la integridad estructural de sus componentes. Estudios dinámicos preliminares empleando elementos finitos muestran que la distancia se puede incrementar y, por lo tanto, es posible reducir los costes de construcción de la superestructura ferroviaria. Se propone inicialmente un modelo para el estudio de esta separación. Esto ayudará a establecer los efectos de la separación y las consecuencias sobre los componentes de la superestructura de vía.

ABSTRACT
The objective of ODSTRACK Project is to establish an optimal distance between sleepers in order to decrease the track construction costs without jeopardizing the structural integrity of the track components. Preliminary finite elements dynamic analyses have shown that the distance between sleepers can be increased and, therefore, it is possible to reduce the construction costs of the railway superstructure. Initially, a modelling approach for the separation between sleepers in the track is proposed. This will help to assess the effects of different separations and the consequences in the track superstructure.

PALABRAS CLAVE: hormigón, distancia entre traviesas, ferrocarril, variables estructurales, análisis dinámico.
KEYWORDS: concrete, sleepers' distance, railways, structural variables, dynamic analysis.

1. Introduction

1.1 The problem

The biggest cost driver for the development of new railway routes and for the operation of the existing ones is the construction and maintenance of the track structure. Sleepers and fastenings are the most numerous elements on the track and railway. A fixed separation between them is generally used worldwide by administrators. Therefore, the cost per km of these elements is directly proportional to their number along the track. For this reason, one of the simplest ways to reduce track construction costs is to decrease the number of these elements. There are no studies in the literature about the effects of reducing or increasing the sleepers' distance, Besides, the values used in the track design are based on experience, with limited scientific support [1].

The motivation of this project (ODSTRACK) was double, first to analyse and study the influence of the distance between sleepers on the track performance and second, the importance of a potential reduction of the construction cost if this distance can be increased (See figure 1). Thus, the derived objective of this study is to establish an optimal distance between sleepers in order to decrease the track construction costs without jeopardizing the structural integrity of the track components. Preliminary finite elements dynamic analyses have shown that the distance between sleepers can be increased and, therefore, it is possible to reduce the construction costs of the railway superstructure. Not only this study will present the optimal distance and cost reduction but also the effects on the track due to these changes will be analysed. Initially, a modelling approach for the separation between sleepers in the track is proposed. This will help to assess the effects of different separations and the consequences in the track superstructure. For this purpose, static and dynamic analyses, using a finite element methodology, of a track section will be studied.

The numerical studies and modelling approaches will be calibrated and supported by laboratory experiments (static, dynamic and fatigue tests).
The research-based values for the optimal distance between sleepers proposed in this study can be used not only in the construction of new rail routes, but also in the renewal/maintenance phase of existing ones. For this purpose, a feasibility study to put in practice this solution will be provided in order to see the technical and economic advantages of increasing the sleepers distance. Therefore, it is expected that this work will support the development of solutions with technological relevance contributing to improve the competitiveness of the railway transport. It is expected to give answer to the industry most recent needs to reduce the price of the track construction and the life-cycle-costs of the rail structure. It will contribute to improve the competitiveness of the railway transport.

Figure 1. Usual distance between sleepers in Europe 0.6 m in High Speed and conventional ballast track.

1.2 Importance of the study

Spain is a leading country in the construction of high-speed railways. The evolution of construction techniques makes the process faster and cheaper than before. A previous careful study and analysis showed that this process can potentially be made even cheaper, without altering the resistant characteristics of the infrastructure. The contribution of this proposed study will be expected to result in significant savings in the construction and maintenance of the railway infrastructure.

The cost per length of track directly depends on the number of sleepers employed (see (1)). Thus, cost in a track per length depends directly on the distance between sleepers.

$$n_{Sleepers/U.length} = \frac{L_{track}}{d} \quad \textbf{(1)}$$

$$\mathrm{CTL}=(\mathrm{n}_{Sleepers/U.length})\cdot C_{Sleeper} \quad \textbf{(2)}$$

$$CTL = \frac{Longitud}{d} \cdot C_{Sleeper} \quad \textbf{(3)}$$

Where n is the number of sleepers in a determined rail length L, d is the distance between sleepers' axles. CTL is he total cost of sleepers per length, which can be put as formula (3). Other way to quantify the number of sleepers is with sleeper's density.

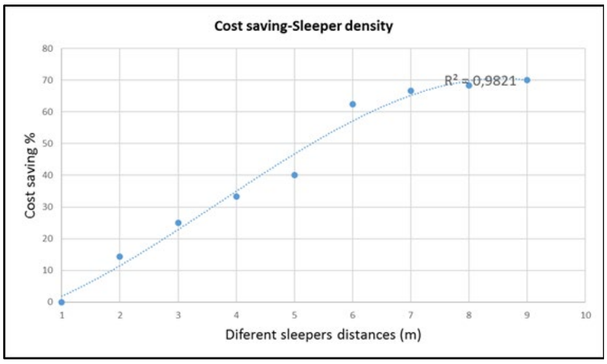

Figure 2. Cost savings vs sleeper's density. X values correspond to sleepers' distance (1=0.6 m, 2=0.7 m, 3=0.8 m, 4=0.9 m, 5=1.0 m, 6=1.6 m, 7=1.8 m, 8=1.9 m and 9=2 m).

Stablishing a reference cost for the most common sleeper distance equal to 0.6m, Figure 2 shows the saving when increasing sleeper distance. Cost can be reduced around 25% if a distance between sleepers equal to 0.8 m can be achieved. Cost savings increase rapidly when the distance between sleepers is increased until point 5. From there the rate of saving decreases until it reaches a maximum around a distance of 1.9m.

Motivation of this project, ODSTRACK has been made clear and this paper presents their aims and stages and preliminary results in the following.

2. State of the art

Dimensions of the track elements employed nowadays are product of a long development throughout history mainly based on experience and trial error approximation.

Evolution of the railway, and the development of high-speed lines [2] during the last years have led to new, better and more resistant elements of the railway structure. Models and solutions have been developed to improve the track performance. Track elements are well defined and well known [3, 4]. However, influence on track behaviour caused by the position of the supports has not been deeply studied. E.g. Although there are a lot of studies about the quality of the infrastructure [5] there is a lack of analysis of track stresses and displacements generated when different distance between sleepers are used.

A distance of 0.6 m between sleepers' axels is the most commonly used value in European countries. United States recommendations for railways construction depend on the ballast section and sleeper materials, separation between sleepers can vary between 0.546 m and 0.711 m. A distance of 0.546 m is recommended for wood sleepers in a 0.152 m ballast section. A distance of 0.61 m is suggested in cases of steel sleepers in a 0.203 m ballast section. Finally, 0.711 m between sleepers is recommended when concrete sleepers are used in a 0.203 m ballast section, where continuous welded rail is recommended [6]. Indian railways use different sleepers' distances depending of several factor: Type of track, fish-plated track (depending on sleeper's material, wood or metal) or welded track (Long welded rails LWR, Short welded rails SWR) [7]. The distance of LWR can be 0.65 on the other hand when rail track is SWR this distance increases up to 0.78 m.

Sleepers distance not only have influence and affect to several superstructure elements (sleepers, fastenings, rail welds, ballast integrity, etc.) but also moving material and railway users. This distance can involve changes in vibrational frequency which could cause accelerated wear in ballast and settlements of sleepers [1].

Reference studies about track stiffness can be found in [8] where an increase in the size of sleeper is evaluated. In this sense the ODSTRACK Project will evaluate the distance between sleepers and a possible change in the size of the sleepers. Track stiffness must be analysed just because high stiffness values produce accelerated wear, fatigue and cracking problems [9]. There are some studies about rail corrugation and sleepers' distance [10]. The study involves support separation in slab track. The conclusion was that when decrease slab separation (from 1 m to 0.5 m) short pitch corrugation tend to cease. Nothing is done when referring to sleepers in ballast track. Effect of sleeper distance in rail corrugation over ballast has to be analysed.

Sleepers distance varies depending of the track structure beneath them. When sleepers are placed over a singular structure such as bridge or viaduct, distance between axles can decrease. This usually happen in singular rail track structures. Normal values outside the structures are 0.6 m and in structures, they can be up to 0.57 m [11, 12]. An example of this distance change is found in track transitions, steel bridges, and other singular structures over the railway track.

Other authors talk about sleepers' density. It proposed as M+X [7], where M is the length of rail in metres and x is a number that varies according to diverse factors such as: 1) axle load and speed, 2)type and section of rails, **3**) type and strength of sleepers, **4**) type of ballast and depth of ballast cushion, and **5**) type of formation. The spacing of sleepers is fixed depending upon the sleeper density. Spacing **is** not kept uniform throughout the rail length. It is closer near the joints for structural integrity reasons. There is also a limitation in the close spacing of sleepers due to tamping reasons (there is a minimum length to allowed to tamp). Recent studies in relation to sleeper distance can be found in [1 **and** 13], here the problem of distance between sleepers and supports are analysed. This study shows different study cases but mostly **the ones** focused on the limit between ballasted track and slab track in a track transition. The study showed that a separation less than 0.45 m from the las sleepers to the concrete of slab track was problematic. Larger distance was study as well until values of 1 m between supports.

National guidelines [14, 15] or even American Standards [16] does not recommend or specify any distance regarding sleeper's separation.

Existing literature about this topic is not broad, and there is a lack of technical and fundamentals involved as it is mainly based on experience. Therefore, two questions arise; Why Railways administrators use this distance? Why this distance usually goes to 0.6 m? This study tries to clarify and give scientific support to this fact.

3.Proposed study the ODSTRACK project

The final purpose of the ODSTRACK project is to find an optimal geometry without cost increasing which allows incrementing sleepers distance without jeopardizing stability and security. With the aim of clarifying the two questions presented and do it with scientific support the project has been structured and divided in different steps.

1. To summarize the main ideas of the state of the art. To identify influencing factors and find cases employed.

2. Initial attempt to limit the sleepers' distance that should be studied. To stablish their minimum and maximum limits. To propose different ways to increase spacing by modifying sleeper's geometry and materials. Several examples as: to increase the base area of the sleeper, change the materials or geometry will be considered.

3. To propose and design study cases varying the sleepers' distance. Numerical analysis of the track performance. Finite elements 2D dynamic analyses and 3D cases.

4. To perform laboratory tests of supports separation. Static analysis, dynamic analysis and fatigue and vibrations tests over ballast. (Vibrational study of the track).

5. To see in influence of sleeper spacing on the rail dynamic deflection and the railway-induced vibrations. In addition, monitoring track elements, such as rail, fastenings, sleepers, ballast, will be perform to check track performance.

6. To find correlation between numerical models and laboratory tests. Analysis of the results. Establishment of correlation models.

7. To perform an analysis of the economic benefit based on the increase in displacement between supports. Correlations according to the distance between sleepers. Optimal separation distance without compromising functionality.

8. To analyze the feasibility and implementation of the solution. This objective tries to see if the solution is feasible in terms of using it in existing tracks during renewal conditions or in new construction tracks. Following this, a technical guideline will be proposed.

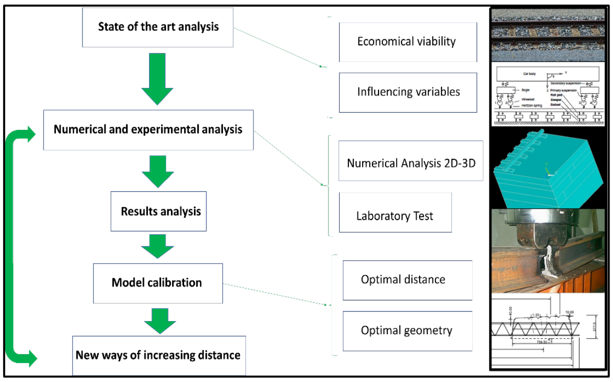

Figure 3. Proposed Methodology

Figure 3 summarizes the steps in a flow chart. There is an iterative part that should be repeated for the different options and will help to find the optimize solution.

4. Preliminary analysis and results

The project started in October 2019. First, a preliminary study was carried out to determine the limit of the maximum distance between sleepers, based on two criteria, the technical and the economical. As presented before in figure 3 distances over 1.9 m are not interesting for the economical point of view. Therefore, technical criteria such as vertical transient displacements, vertical transient stresses and rail bending moments between supports should be checked to stablish this maximum distance.

To this purpose a track model were simulated numerically using 2D Finite element. Track elements of 0.1 m, rail, pads, sleepers and ballast were initially modelled. Parametric studies of train velocity were performed. The distances between sleeper analyzed were 0.6 m, 0.7 m, 0.8 m, 0.9 m, 1.00 m. The reference case was the one with a moving train at 200 Km/h. In order to see the effect of a speed increase two more velocities were analyzed for each variable, 250 Km/h and 300 Km/h.

Authors considered that an initial transient analysis will serve to give a quick answer and to establish the limits of sleeper's separation.

Three main variables were studied. Vertical displacements under sleepers, vertical stresses under sleepers and rail bending moments in the middle between supports. These variables seem to be the most important to see the initial track behavior and to establish a limit of separation based on technical issues and not only based on economic issues.

Results from these simulations are presented in terms of vertical displacements under the sleepers, stresses under sleepers and rail bending moments in figures (5-10).

4.1 Preliminary results

The focus of the preliminary results was to find the limit of the distance between sleepers based on two criteria, the technical and the economical. As presented before in figure 2.

As it was expected, figure 4 shows how increasing sleeper distance produce an increase in sleeper vertical displacements. When de distance is 0.6m vertical displacements are 0,42 mm they increase up to 0,65 mm when the distance between sleepers is 1 m. The difference between them is less than 0.5 mm which can be considered invariable when train speed is constant. It is important to say that this analysis is a transient analysis so these results could vary. Initial values when talking about vertical displacements are negligible.

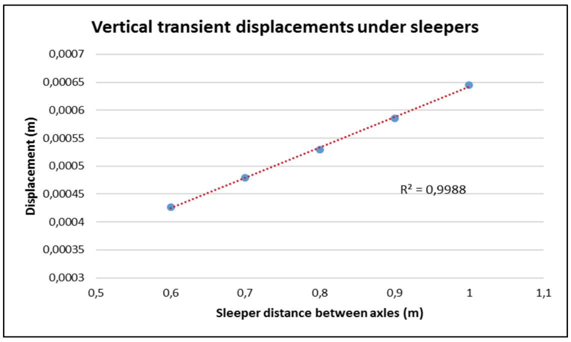

Figure 4. Vertical transient displacements. Train speed 200 Km/h.

Regarding train speed variation, results in terms of maximum vertical displacements are presented in figure 6. They show that speed influence in the range of 200km/h to 300 km/h has not an important effect as variations are lower than 0.2 mm.

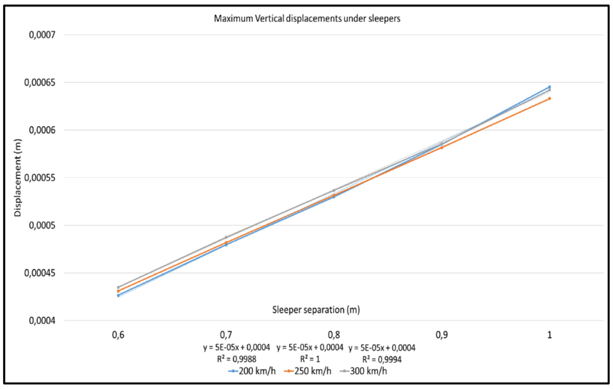

Figure 5. Effect of train speed over vertical transient displacements. Analysed speeds (200, 250, 300 Km/h)

However, looking at figure 5 it is relevant to say that there is a change in the relationships between displacements produced when the velocity is 200 km/h and when it is 300km/h. When the sleeper separation is lower than around 0.85m, movements are higher for the highest velocity. However, when the distances are higher than that values it changes and they are lower the ones of higher velocity. This give us an idea of a limit of distance between 0.8 and 0.9 m.

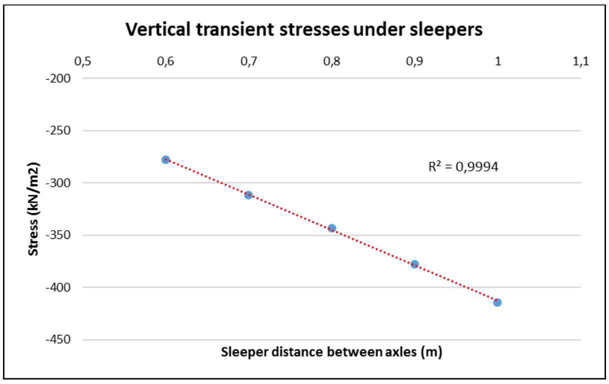

Figure 6. Vertical transient stresses under sleepers. Train speed 200 Km/h.

Other analysed variable was the stress under sleepers which is considered relevant as it is directly related with the damage over ballast bed. A negative effect of increasing the distance between sleepers on the stresses under them is clearly seen in figure 6. Compressive stresses go from -270 kPa for a distance of 0.6m to -410 kPa when they are 1m apart from each other. Compressive stress varies more than 150 KN/m^2 when sleepers distance goes from 0.6 m to 1.0 m.

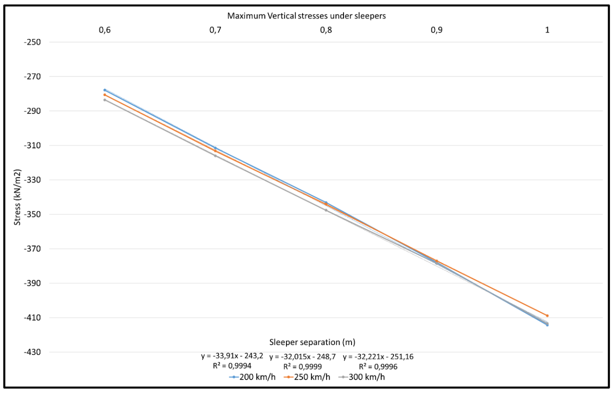

Figure 7. Effect of train speed over vertical transient stresses under sleepers. Analysed speeds (200, 250, 300 Km/h).

Stresses under the sleeper considering train velocity are presented in figure 7. It shows that there is a change in the trend when the distance between sleepers goes form 0.8 m to 0.9 m. Distances and trends are slightly different for the different speeds. This figure shows an intersection between graphics at different speed between 0.8 m and 0.9 m of sleeper's distance.

The last variable analysed in this preliminary study were the rail bending moments. Figure 8 shows rail bending moments (between supports) when modified sleepers' distance at the same speed of 200 Km/h. Values go up from less than 14 KN·m to 16.5 KN·m so the increment is just around 2.75 KN·m. These values are within the range of acceptable values.

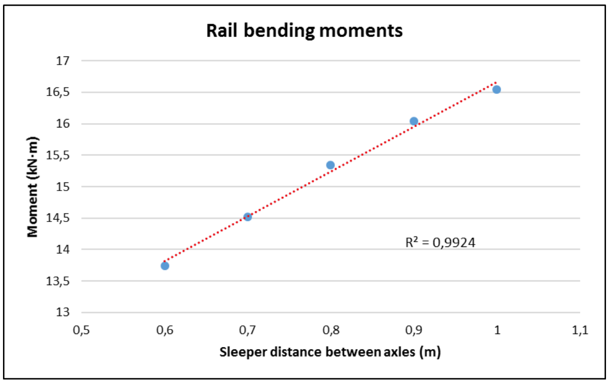

Figure 8. Rail vending moments. Train speed 299 Km/h

The influence in the bending moments is not relevant for the studied range. When looking at the train velocity parametric study presented in figure 9. The influence of train velocity is not prominent

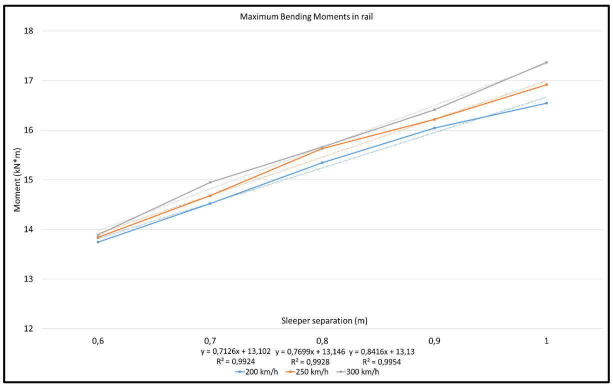

Figure 9. Effect of train speed over rail bending moments. Analysed speeds (200, 250, 300 Km/h).

Variables such as sleepers' vertical displacements and vertical stresses under sleepers have different effect when speed and distance between sleepers' changes. This does not happen with rail bending moments, here the trend is clear, and these rail bending moments increase with train speed and sleeper distance.

Only rail bending moments are in the same line when increasing the train velocity, which means that an increase in train speed means an increase in rail bending moments. This effect was not observed when talking about vertical transient displacements and vertical transient stresses under sleepers.

Thank to these preliminary analyses, authors can stablish initial limits to sleepers' distance between axles is to see the maximum allowed values for each variable. This will give us a first restriction for a possible increase in the sleepers' distance. The initial maximum limit seems to be 1.9 m.

All analysed variables show a good correlation with the sleeper's distance. This fact must be further studied with more analysis and experimental tests. These next steps are planned in the project and they will be done during next years.

5. Conclusions

This article outlines the motivation, aims and procedure to achieve them of the ODSTRACK project. It has started in October 2019 and has a timeline of 3 years. The main objective is to establish the limits for the optimal distance between sleepers in a railway track. Although the project is in its starting point, up until now there are several preliminary results and several initial conclusions, which were obtained and can be summed up.

This paper presents a preliminary study to find the initial maximum limits to sleepers' distance mainly based on two approaches, economic and technical.

Economic approach gives a great span to increase the distance between sleepers. This goes up until 1.9 m distances. This is not possible when technical details are considered.

From a technical point of view the most important variables were, vertical displacements under sleepers, vertical stresses under sleepers and rail bending moments.

Vertical displacements show small variation when increasing sleepers' distance and train speed. Train speed and sleeper distance have also negative influence in rail bending moments.
Stresses under sleepers seems to be the most restrictive variable when looking at technical issues. Values taken from technical analysis gives a limitation of distance between sleepers in the range of 0.8 – 0.9 m.

Despite the fact that the project has already started, this is a preliminary study which tries to introduce and narrow down the problem. This preliminary analysis was a transient analysis. In order to give more reliable results, the introduction of more variables to the study are necessary together with performing medium and a long-term analysis. These are the next steps to follow.

All track superstructure and infrastructure elements will be also analysed. Besides, the influence of this sleeper's separation on the track infrastructure and the terrain underneath will be also studied. Track stiffness characterization must be done in order to see what happen with total track stiffness and support stiffness when varying sleepers' distance.

Laboratory test and vibrational analysis will be carried out in order to compare numerical results with theoretical analysis.

ODSTRACK project will serve to industry and railway administrators to save costs under construction and during maintenance.
Other variables such as tamping must be analysed. How tamping affect to an increase in sleepers' distance. Tamping operations can be harmful for the integrity of track components.
Guidelines regarding maximum vertical displacements and maximum stress and rail bending moments need to be checked. Up until now this analysis shows that a percentage between 20 and 30 % of cost can be saved.

This project will also try to analysis distance between supports in conventional a slab track as an initial analysis of this phenomena in slab track systems.

This preliminary study has allowed authors to establish initial limits to sleepers' distance in a ballast track and set the basis to continue numerical analysis and laboratory tests to have a better knowledge of the track performance when increasing sleepers' distance.

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