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Transition Zone between Ballastless and Ballasted Track: Influence of changing stiffness on acting forces

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Abstract

The track's ballasted superstructure is a multilayered construction consisting of several constitutive layers. In the slab track for High-Speed Lines, or the embedded track for terminal port stations, a concrete slab replaced the ballast. For the estimation of the increase of the mean value of the static vertical wheel load, a probabilistic approach should generally be adopted in order to cover the statistically desirable safety level. Four calculation methods are cited. An investigation of the change of track stiffness coefficient, both static and dynamic, in Ballasted Track, Transition Zone and Ballastless Track was performed and it is presented.

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Keywords: Railway Infrastructure; Fastenings; Stiffness; Forces, Actions; Stresses; Substructure.

1. INTRODUCTION

The track superstructure is a multilayered system that consists of the rails, which support and guide the train wheels and distribute the wheel loads, the sleepers with their fastenings which distribute the loads applied by the rails and maintain the rail gauge. In the case of the classic ballasted track the superstructure also includes the ballast (Figure 1 left), the equivalent of a flexible pavement, and the blanket layer (sub-ballast) consisting of compacted sand and gravel, which further distributes the loads and protects the substructure from the penetration of crashed ballast particles, mud ascent and pumping. In the case of the more recently developed Slab Track (Figure 1 right) the superstructure also includes the concrete slab or

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Continuously Reinforced Concrete Pavement (CRCP) which is the equivalent of a rigid pavement. The concrete slab seats on a series of successive bearing layers with a gradually decreasing modulus of elasticity: the Cement Treated Base (CTB), underlain by the Frost Protection Layer (FPL) and the foundation or prepared subgrade. The Slab Track is typically used in High Speed lines (V>200 km/h) of mixed passenger and freight traffic with maximum axle load of 22.5 t.

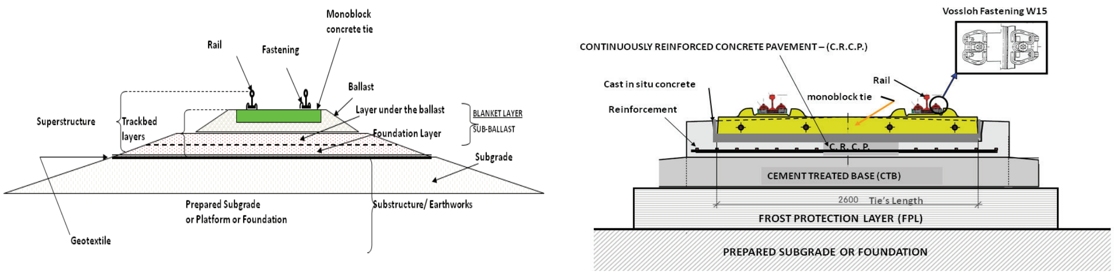

Fig.1. Greek network: (left) cross section of classic Ballasted Track with monoblock sleepers, terminology (UIC, code 719R, 1994) and (right) cross section of Rheda Sengeberg type Slab Track system as in Tempi tunnel (Tsoukantas et al., 2006).

Another type of Ballastless Track is the Embedded Track, which is similar to the Slab Track and is typically used in terminal port stations and maintenance facilities of railway vehicles to minimize the maintenance needs of the track. In these applications there is a need to replace the ballast-bed with a concrete floor for functional reasons (i.e. washing of vehicles and flowing out of the waste water and oils, maintenance pits between the two rails, circulation of road vehicles on the tracks, transshipment of cargo etc.). Its main difference from the Slab Track is the low speed of train circulation and, consequently, the small magnitude of dynamic loads. In both cases of Ballastless Track systems presented above the role of ballast-bed and blanket layer is undertaken by a concrete slab.

The application of Slab Track and Embedded Track technology in a railway network creates the need for Transition Zones, which serve as interfaces between the ballastless and ballasted track sections, where significant and abrupt change in stiffness occurs. The Transition Zones guarantee a smooth stiffness transition between slab track and ballast-bed, resulting in a smooth variation of the forces that act on the track (see Giannakos et al., 2010b).

In order to adopt the Slab Track technology, the Greek Railways performed an extensive investigation program that studied Slab Track systems laid in High-Speed tracks (V_{max} > 200 km/h) under operation, mainly in Germany. Two types of Slab Track systems were considered: Rheda Classic (Sengeberg), which was the first application of Slab Track that took place in 1972, and Rheda2000, which is the most up-to-date, modern and most technologically advanced type of the Rheda Slab Track "family". Based on the findings of the research program these two types of Slab Track were selected.

The actions on track panel and the implied stress on the substructure play key roles in the design and maintenance of High Speed railway tracks and their magnitude mainly depend on the track stiffness coefficient (Giannakos, 2011a). However, there is a lack of data in the international literature correlating the magnitude of stress on the track substructure and the track stiffness coefficient of High Speed lines under operation. The research performed for the Greek Railway network (Giannakos, 2008, Tsoukantas, 1999) addressed this issue. These results, highlighting the interaction between superstructure and substructure of a railway track, are presented in this paper. A method for the calculation of loads and stresses on a railway track was developed as a result of this research (Giannakos, 2004). This method together with three methods found in the international literature are used to calculate the stresses on the track substructure and the results are compared and discussed.

2. METHODS FOR ESTIMATION OF REACTIONS/ ACTIONS ON EACH SLEEPER/ TIE

General

All methods model the railway track as a continuous beam on elastic foundation and use different assumptions in their approximation of the random nature of load application on a railway track. In all methods the total static stiffness coefficient of the railway track, $\rho_{total,}$ plays a key role in the load distribution. This coefficient, is given by (Giannakos & Tsoukantas, 2009a) :

$$\frac{1}{\rho_{total}} = \sum_{i=1}^{v} \frac{1}{\rho_i} \qquad (1)$$

where i is each individual layer of the multilayered structure constituting the track (Figure 2).

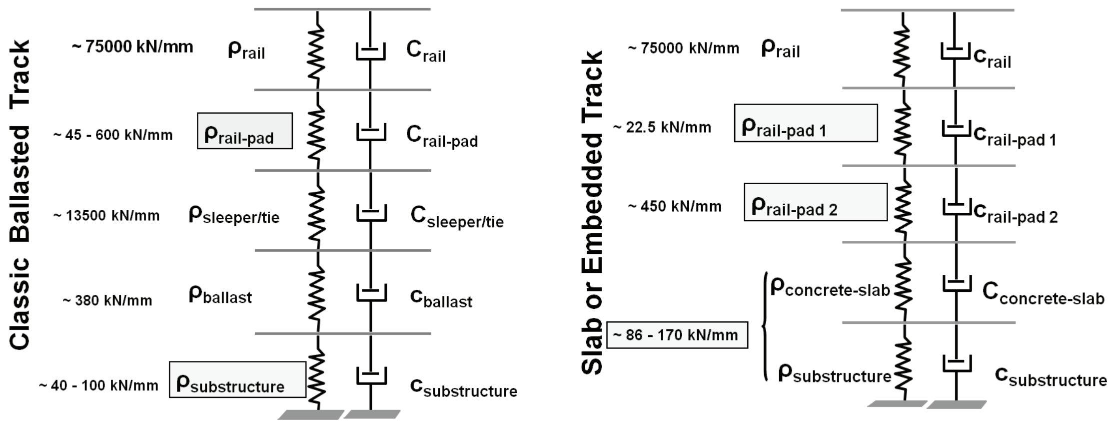

Fig. 2. The track structure as an ensemble of springs and dampers (left) classic ballasted track (right) Slab Track, with characteristic values of ρ_i in kN/mm.

French Literature Method

The action on the sleeper is calculated (Alias, 1984, Prud'homme et al., 1976):

$$R_{total} = \left(Q_{wheel} + Q_\alpha + 2 \cdot \sqrt{\left[\sigma^2\left(\Delta Q_{NSM}\right)\right] + \left[\sigma^2\left(\Delta Q_{SM}\right)\right]} \right) \cdot \bar{A}_{stat} \cdot 1.35 \qquad (2)$$

where: R_{total} = the total action on the sleeper after the distribution of the acting load, Q_{wheel} = the static load of the wheel (half the axle load), Q_α = load due to cant deficiency (or superelevation), $\sigma(\Delta Q_{NSM})$ = standard deviation of the Non-Suspended (or unsprung) Masses of vehicle, $\sigma(\Delta Q_{SM})$ = standard deviation of the Suspended (or sprung) Masses of the vehicle. The factor of 2 in the equation above covers a 95.5 % probability of occurrence.

Moreover, $\bar{A}_{stat}$ is the static reaction coefficient of the sleeper which is equal to:

$$\bar{A}_{stat} = \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\rho_{total} \cdot \ell^3}{E \cdot J}} \qquad (3)$$

ρ_{total} = coefficient of total static stiffness of track in kN/mm, ℓ = distance among the sleepers in mm, E, J = modulus of elasticity and moment of inertia of the rail

German Literature Method

The action on the sleeper is estimated (Fastenrath, 1981, Eisenmann, 2004):

$$R = S = \frac{Q_{total} \cdot \ell}{2 \cdot L} \Rightarrow R = \frac{Q_{total}}{2} \cdot \sqrt[4]{\frac{\rho_{total} \cdot \ell^4}{4 \cdot E \cdot J \cdot \ell}} = Q_{total} \cdot \frac{1}{2\sqrt{2}} \cdot \sqrt[4]{\frac{\rho_{total} \cdot \ell^3}{E \cdot J}} = \overline{A}_{stat} \cdot Q_{total} \quad (4)$$

where L the elastic length of the track given by:

$$L = \sqrt[4]{\frac{4 \cdot E \cdot J \cdot \ell}{\rho_{total}}} \quad (5)$$

and $\overline{A}_{stat}$ is calculated through equation (3). Additionally:

$$Q_{total} = Q_{wheel} \cdot (1 + t \cdot \overline{s}) \quad (6)$$

where $\overline{s}$ ranges between 0.1φ and 0.3φ depending on the condition of the track according to the following: $\overline{s} = 0.1 \cdot \varphi$ for excellent, $\overline{s} = 0.2 \cdot \varphi$ for good and $\overline{s} = 0.3 \cdot \varphi$ for poor track condition and φ is a function of the speed: φ = 1 for V < 60 km/h since for 60 < V < 200 km/h it is given by:

$$\varphi = 1 + \frac{\mathrm{V} - 60}{140} \quad (7)$$

where V the maximum speed on a section of track and t a coefficient that depends on the probability of occurrence (t=1 for P=68.3%, t=2 for P=95.5% and t=3 for P=99.7%).

Prof. Eisenmann in 1993 for speeds above 200 km/h proposed a dynamic amplification coefficient given by:

$$\varphi_{V > 200 km/h} = 1 + \frac{\mathrm{V} - 60}{380} \quad (7a)$$

it is obvious that this equation results in even smaller values of actions on track, but we include these values also in the following figure 5. This equation leads to even greater under-estimation of the acting loads on track with possible consequences to the dimensioning of track elements -like e.g. sleepers- as the literature describe (see Giannakos & Loizos, 2009c, Giannakos, 2010b etc)

American Literature Method

This method is described in AREMA (2005, p.16-10-26/32 and Chapter 30) and in Hay (1982, p.247/273). The total load (static and dynamic) acting on the track depends on an impact factor θ (AREMA, 2005, p.16-10-9, Hay, 1982, p.256):

$$\theta = \frac{D_{33} \cdot V}{D_{wheel} \cdot 100} \quad (8)$$

where D_{33} is the diameter of a 33-inch wheel, D_{wheel} the wheel diameter of the vehicle examined in inches, and V the speed in miles/hour and the total load is:

$$Q_{total} = Q_{wheel} \cdot (1 + \theta) \quad (9)$$

Note that this method does not account for the probability of occurrence and U in psi is the rail support modulus derived by the relation p=U·y, U=ρ/ℓ, and

$$\beta=\sqrt[4]{\frac{U}{4\cdot E\cdot J}}=\sqrt[4]{\frac{\rho}{4\cdot E\cdot J\cdot \ell}}=\frac{1}{L} \tag{10}$$

and the maximum rail seat load R_{max} on an individual sleeper, is given by the following equation:

$$R_{max}=p_{max}\cdot\ell=U\cdot y_{max}\cdot\ell=U\cdot y_{max}\cdot\ell=U\cdot\frac{\beta\cdot Q_{total}}{2\cdot U}\cdot\ell=\sqrt[4]{\frac{\rho_{total}}{4EJ\ell}}\cdot\frac{Q_{total}\cdot\ell}{2}=\frac{1}{2\sqrt{2}}\cdot\sqrt[4]{\frac{\rho_{total}\cdot\ell^3}{E\cdot J}}\cdot Q_{total}=\bar{A}_{stat}\cdot Q_{total} \tag{11}$$

Giannakos (2004) Method

The actions on the track panel are calculated through the following equation (Giannakos et al., 2009d):

$$R'_{max}=\left(Q_{wh}+Q_{\alpha}\right)\cdot\bar{A}_{dyn}+\mu\cdot\sqrt{\sigma\left(\Delta R_{NSM}\right)^2+\sigma\left(\Delta R_{SM}\right)^2} \tag{12}$$

where Q_{wh} = the static wheel load, Q_{α} = the load due to cant deficiency, $\bar{A}_{dyn}$ = dynamic coefficient of the sleeper reaction, μ = coefficient of dynamic load (3 for a probability 99.7 % and 5 for 99.9 %), $\sigma(\Delta R_{NSM})$ = the standard deviation of the dynamic load due to non suspended masses, $\sigma(\Delta R_{SM})$ = the standard deviation of the dynamic load due to suspended masses and (Giannakos, 2004) :

$$\bar{A}_{dynam}=\frac{1}{2\sqrt{2}}\cdot\sqrt[4]{\frac{\ell^3\cdot h_{TR}}{E\cdot J}} \tag{13}$$

where h_{TR} the total dynamic stiffness of the track given by (Giannakos et al., 2009d):

$$h_{TR}=\frac{1}{2\cdot\sqrt{2}}\cdot\sqrt[4]{E\cdot J\cdot\frac{\rho_{total}}{\ell}} \tag{14}$$

This method uses: (i) the dynamic coefficient $\bar{A}_{dynam}$ for the distribution of the static and semi-static components of the load, and (ii) the dynamic component of the load is not distributed to the adjacent.

Comparison of theoretical calculation of sleeper loading with track observations

In Greece between 1972 and 1999, twin-block concrete sleepers of French technology were exclusively used, namely Vagneux U2, U3 with RN fastenings, for tracks designed for V_{max} = 200 km/h and temporary operational speed V_{oper} = 120-140 km/h. Extended cracking was observed at a percentage of more than 60 % of the U2/U3 sleepers laid on track. The methods cited in the international literature at that time (French, German, American) did not provide any satisfactory justification for the appearance of the cracks, resulting in much lower values of actions on sleepers than the cracking threshold, thus predicting no cracking at all. After an extensive research that included collaboration among various universities and railway organizations in Europe, the Giannakos (2004) method was developed whose results successfully predicted the extended cracking of the U2/U3 sleepers (Giannakos, 2004, 2010b, 2011a; Giannakos & Loizos, 2009d), calculating actions over the cracking threshold and in some cases over the failure threshold. This method was derived from theoretical analyses, measurements from laboratory tests performed in Greece, Austria, France, and Belgium and observations from real on-track experience. The method was also calibrated for the calculation of loads on ballastless track systems and the results were verified against measurements on Slab Track. Moreover, International Federation of Concrete (fib) has adopted this method for precast concrete railway track systems (fib, 2006).

3. TOTAL TRACK STIFFNESS: THEORETICAL CALCULATION VS MEASUREMENTS

The load, applied on the track, is dependent on the total track stiffness ρ_{total}. A range of ballasted track total stiffness values $\rho_{total,}$ is used for different combinations of railway track layers/elements, and their corresponding parameters derived from measurements' data of the German Railways (Alias, 1984, Giannakos, 2004) as: ρ_{rail} ranging from 50.000 to 100.000 kN/mm with an average of 75.000 kN/mm, $\rho_{sleeper}$ ranging from 500 to 800 kN/mm for oak wooden sleeper and 12.000 to 15.000 kN/mm with an average of 13.500 kN/mm for a concrete sleeper, $\rho_{ballast}$ in the order of 380 kN/mm for "polluted" ballast 2 years after laying, $\rho_{substructure}$ ranging from: (i) 20 to 60 kN/mm for pebbly subgrade with an average of 40 kN/mm, (ii) 80 to 100 kN/mm in the case of frozen ballast and ground, and (iii) on the order of 250 kN/mm for the case of a ballast-bed of small thickness laid on the concrete base of a tunnel or a bridge deck. The pad stiffness, ρ_{pad}, plays a key role in the loading of the sleeper, and its value is typically estimated from the load-deflection curve that is provided by the manufacturer using a trial-and-error method (Giannakos, 2004).

Table 1. Relation between ballast coefficient C and stiffness coefficient ρ in a line equipped with rails UIC60 and monoblock sleepers of prestressed concrete B70 and concrete slab

	Bearing Capacity of Substructure					
	Ballasted Track			Ballastless Track		
	poor	good	very good	Concrete slab		
C [N/mm³]	0.05	0.10	0.15	0.30	0.35	0.40
$\rho_{substructure}$ [kN/mm]	14	29	43	86	100	114

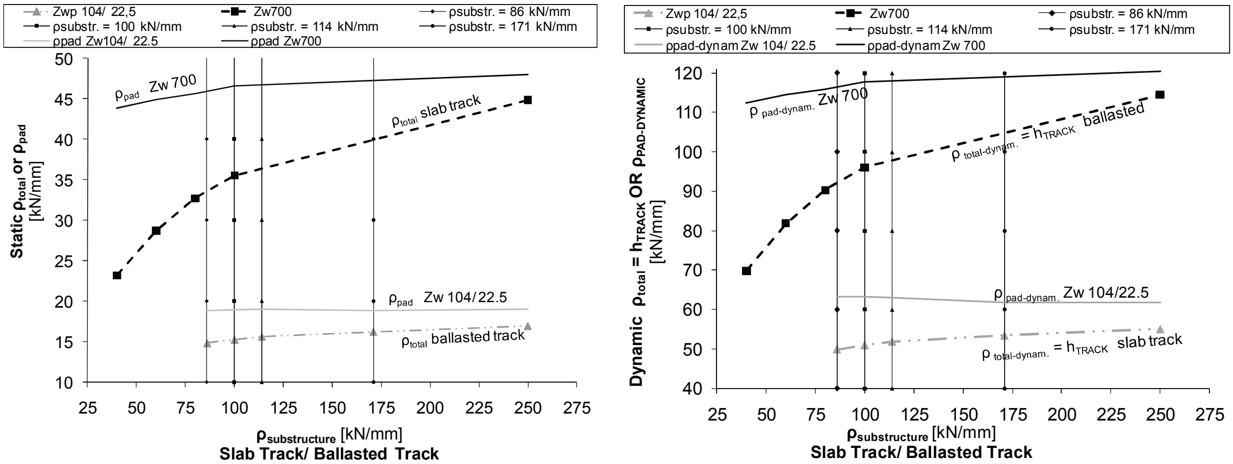

Fig. 3. Relation between (a) total static stiffness coefficient ρ_{total} (left illustration) or total dynamic stiffness coefficient h_{TRACK} (right illustration) and (b) static stiffness coefficient of substructure $\rho_{substruct}$ for resilient fastening (W14) in the ballasted track and W15 fastening in the slab track. The relevant pad stiffness in both cases and its influence in the modulation of ρ_{total} are depicted.

For the Slab Track, Table 1 can be used to determine the stiffness of the subgrade $\rho_{substructure}$ (Giannakos et al., 2011b). On the same table substructure's stiffness values are also provided for the ballasted track for different ballast conditions. For the ballastless case the classic Rheda type slab track was used (Figure 1 – right). The data on Table 1 verify (Giannakos, 2010a) the linear relation between substructure's stiffness, $\rho_{substructure}$, and ballast coefficient, C, which is $\rho_{substructure} = C \cdot F/2$ (Giannakos, 2009b), where F is the active seating surface of the sleeper ($F=5700cm^2$). According to Eisenmann et al., (1994), in situ measurements in the Newly-Constructed Lines indicate values of $C=0.60$ N/mm^3, implying a total track stiffness of 171 kN/mm.

Three out of the five layers that constitute the track structure, namely the rail, the sleeper, and the ballast, contribute only 6 to 10% to the total track stiffness. The total track stiffness is mainly affected by the static stiffness coefficients of the pad, ρ_{pad}, and of the substructure, $\rho_{substruct}$. Figure 3 depicts the relation between the static stiffness coefficient of the substructure and (left illustration) the total static stiffness coefficient of the railway track for both ballasted and ballastless tracks and (right illustration) the total dynamic stiffness coefficient of the track. The relevant pad stiffness in both cases is depicted and its influence in the modulation of ρ_{total}. As shown in Figure 3 the total static stiffness coefficient for the case of ballasted track varies from 23.20 to 44.84 kN/mm. On the contrary, the total static stiffness coefficient of the ballastless track equipped with a very resilient fastening obtains values within a very narrow range between 14.83 and 16.90 kN/mm. It is important to note that although the slab track is a much more rigid structure than the ballasted track, the total static track stiffness of slab track is 36% to 62% lower than in ballasted track stiffness. In § 5 below more measured values on track are cited. The stiffer the substructure is, the more decisive is the contribution of the pad stiffness to the total track stiffness modulation.

4. STIFFNESS AND ACTIONS VARIATION ALONG THE TRACK: SLAB - TRANSITION - BALLASTED

The regulations foresees a transition zone between ballasted and slab track of a length that it is travelled in 0.5 second by the train running at the maximum permissible speed, e.g. 250 km/h or 69.44 m/sec, consequently transition zone of 35 m. In the case of Slab Track a very well compacted and constructed substructure is demanded -in order to avoid or minimize the permanent subsidence- and this implies a stiffness coefficient $\rho_{substructure}$ = 86-171 kN/mm for the total length in ballasted, transition and slab track (Giannakos et al., 2011b). In a section of track -let's say- of 50 m length (e.g. 7.5 m ballasted, 35 m transition and 7.5m slab track) the -static and dynamic- stiffness's variation along this section of track is depicted in Figure 4, taking into account two discrete values of $\rho_{substruct.}$=86 and 100 kN/mm considered as the more representative. The values of ρ_{total} have been received from the relevant diagrams in Giannakos et al. (2011b).

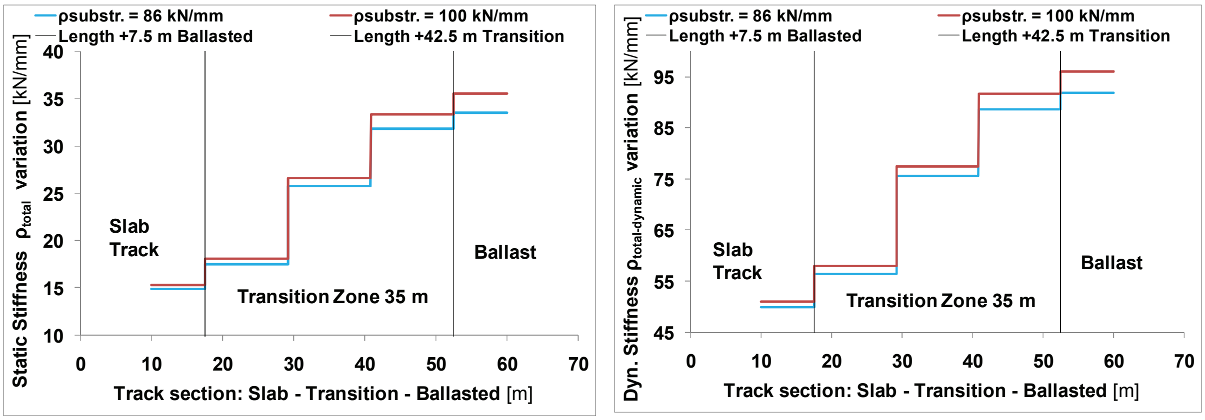

Fig. 4. Stiffness's variation along a 50m track section: Slab **(last 7.5 m)** - Transition **(35 m for Vmax=250 km/h)** - Ballasted **(last 7.5 m)**, for the two more characteristic values $\rho_{substruct.}$: 86 and 100 kN/mm: (left) the static stiffness ρ_{total} and (right) the dynamic stiffness $\rho_{total\text{-}dynam.}=h_{TRACK}$.

For the actions/reactions on the track panel at each support point of rail (fastenings' position or sleeper), the four methods for the estimation of loads on railway track presented above, were programmed in a computer code and parametric investigations were performed by varying the total static track stiffness, ρ_{total}. This methodology was applied for slab track - transition zone - ballasted track, assuming maximum axle load 225 kN, maximum operational speed 250 km/h (mixed traffic of passenger and freight trains), Non-Suspended Masses 7.5 kN/wheel, UIC 60 rail (60 kg/m), maximum cant deficiency 160 mm, distance of the vehicle's centre of gravity from the rail running table 1 m, average condition of the rail running table with corresponding coefficient k_1=9 (for more details see Giannakos et al., 2009d, and Giannakos, 2010b), and wheel diameter 1m (33.86 in.). For the slab track W15 fastenings were considered consisting of a combination of two rail pads: Zwp104 and Zw687a. For the ballasted track W14 fastening with pad Zw700 Saargummi was considered. For the transition zone of 35m (divided in three sub-sections of equal length 35/3~11.67m) three "transition" pads were considered (all of them Saargummi): Zw104/27.5, Zw104/40 and Zw104/55. The static pads' stiffness ρ_{pad} were calculated from the load-deflection curve of each pad, assuming equilibrium between the five "springs" of the track and using the trial-and-error method. The correspondent actions on track panel were calculated -according to the four methods- for the more characteristic value of $\rho_{substructure}$=100kN/mm and the results are plotted in Figure 5.

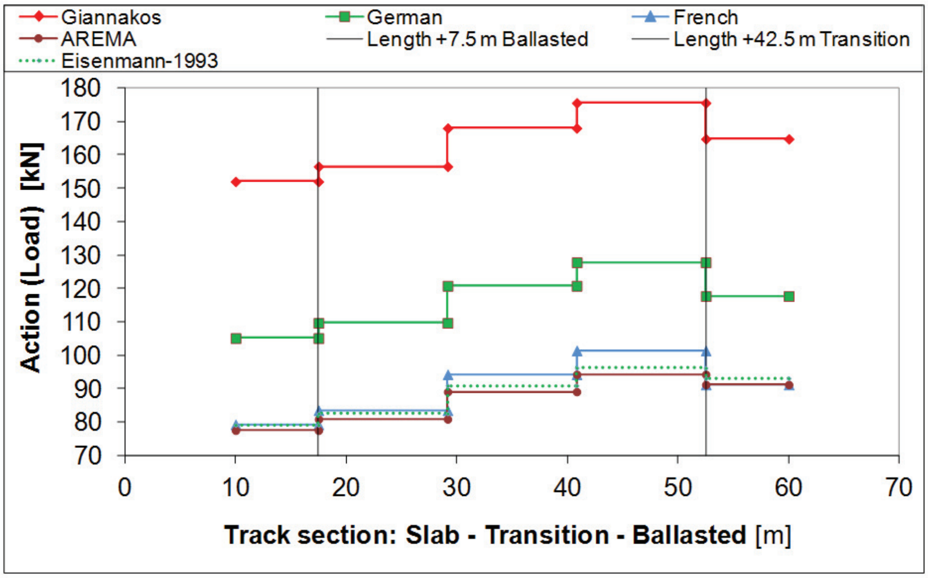

Fig. 5. Variation of Actions on the track panel along a 50m track's section for $\rho_{substructure}$=100 kN/mm: Slab (with W15+Zw104/22.5) - Transition Zone (W15 clip + three types of pads Zw104/27.5, Zw104/40 and Zw104/55) - Ballasted (W14 clip + Zw700 Saargummi). The values of the actions have been calculated with four methods cited in: two equations cited in German literature, the old German method and Eisenmann-1993, French literature, AREMA and Giannakos (2004).

The embedded track give very low actions on track compared to the slab and ballasted high-speed tracks due to the very low speeds consequently the results are not presented in the figures (see Giannakos, 2010a). The following main points are noteworthy: (a) In all sections slab - transition - ballasted, Giannakos (2004) method predicts higher loads on the support points than the other three methods presented in this paper. This is because the static component of the total load acting on the sleeper is derived from a distribution through the $\bar{A}_{dyn}$ and a probability of occurrence 99.7% is used for the increase of the dynamic component of the load not distributed to the adjacent sleepers, (b) the loads on the superstructure of the slab track are lower than in the case of the ballasted track even though the former is a more rigid system due to the higher elasticity (minor stiffness coefficient) of the relevant fastenings and pads, (c) the total stiffness of track -both static and dynamic- is smoothly changing from lower in slab track to higher (stiffer) in ballasted track through the transition zone and (d) the actions/reactions on each support point of the rail (sleeper or fastening) are abnormally changing from lower in slab track, increasing in transition zone and then lowering in ballasted track. The (d) point shows towards a more attentive scheduling and design of the transition zone elasticity (stiffness) and in the case of Greek railway network we proposed not to use Zw104/55 pad, so to divide the transition zone in two equal sections with the use only of the Zw104/27.5 and Zw104/40 pads.

The average stress, $\bar{p}_{ballast,}$ can be used qualitatively as a "decision criterion" and not quantitatively, since in practice there is no uniform support of the sleeper on the ballast, or uniform compaction of the ballast and the ground, there are faults on the rail running table, imperfections on the wheels etc.:

$$\bar{p}_{ballast} = \frac{R_{\max}}{F_{eff-sleeper}} = \frac{R_{\max}}{L_{eff-sleeper} \cdot b_{sleeper}} = \frac{R_{\max}}{\left(L_{sleeper} - e\right) \cdot b_{sleeper}} \quad (15)$$

where R_{max} the maximum action on the sleeper derived from each method, $F_{sleeper}$ = effective sleeper seating surface, $L_{sleeper}$ = sleeper length, e = track gauge, $L_{eff-sleeper}$ calculated from Equation (16) with the assumption that the center of the sleeper is unsupported, $b_{sleeper}$ = sleeper width at the seating surface.,

$$L_{eff\text{-}sleeper} = \left(L_{sleeper} - e\right) \quad (16)$$

The main issue is the determination of the confidence level (possibility of occurrence) in calculation of the stresses that yields results close to the measured values on track. Eisenmann (1988) proposes a probability of occurrence 68.3% for the substructure (t=1) and 68.3% ÷ 99.7% for the stress on ballast and also a probability of occurrence of 68.3 % to 95.5 % instead of 99.7 % has been proposed also (Giannakos, 2004, 2010a, Giannakos et al., 2009c).

5. CONCLUSIONS

In this paper the static and dynamic stiffness's variation and the actions' variation at each support point of the rail for the case of slab track - transition zone - ballasted track are presented. The embedded track presenting lower values of actions is not presented since ballasted and slab tracks are more decisive in track's dimensioning. Four existing methods are used for the estimation of the loads on the track: two equations cited in German literature, the old German method and Eisenmann-1993, the AREMA, French, and Giannakos (2004) method. These methods are used to calculate the actions with appropriate confidence levels and consequently the mean stress on the substructure could be calculated, since the mean stress acting on the substructure of the railway track is one of the main factors influencing the dimensioning of the layers the track and its behaviour over time. A parametric investigation is performed for the more characteristic track stiffness and the results from the four methods are compared.

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