Railway Geodesy: The Benefit of Using a Multi-discipline Approach for the Assessment of Track Alignments During Construction

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Key words: track alignment, geodetic surveying, versine measurement, setting out of tracks

SUMMARY

In railway applications, track alignment represents the forming curvature of the running edge of the rails. During construction, alignment measurements are normally obtained with chord measuring systems. When traditional surveying methods are implemented, track alignment is taken at sparse spaced points directly from the versine measurement – i.e., the offset observed at an intermediate point from a straight line chord. In contrast, track recording vehicles either apply the chord measuring technique directly or employ a combination of an inertial/gauge sensing system.

For ballast track sections, deviations in track alignment from the projected track settlement would raise serious concerns for track buckling. This is because any deviation from the nominal geometry reduces the load needed to induce buckling. Today, modern lining systems and automated maintenance procedures are used to restore track surface and alignment. Contrary to the ballast track technique, the connection of the slab track and the underground is rigid. Consequently, adaptations to the nominal geometry after paving over are only possible with additional expenditure. As a result, positional accuracy requirements in slab track projects are very high.

This paper presents the various issues associated with the positioning of rails during the construction of slab tracks and details the observation methods used for measuring track alignment. Furthermore, it discusses the results and the analyses obtained from the implementation of traditional surveying methods and those derived by using a track surveying vehicle during the construction of the new tramway of Athens.

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1. INTRODUCTION AND BACKGROUND

In order to boost the role of the public transport in the metropolitan area of Athens, a new tram system was added recently to the city's transport infrastructure. The construction of the project began in mid 2001 and was completed in time three years later. The modern tram network connects the center of Athens, through urbanized, dense populated areas, with the coast to the south-southwest. From there it branches out along the coastal avenue to serve residential areas laid to the north and recreational areas, beaches and sport facilities laid to the south side of it. It includes 26 km of double tracks on which 35 vehicles serve 47 stops (Figure 1). The numerous constraints imposed by the existing urban planning characteristics of the city infrastructure determined the minimum and maximum values for the horizontal track radius and the longitudinal slope of the track alignment respectively (r=25 m, g= 6%) (Katsios 2003).

Figure 1: The Athens tramway network.

Accurate positioning during track laying was a critical factor to the overall success of the project. To accomplish this goal, stringent quality control procedures were implemented throughout the construction phases of the project. In brief, the positioning tasks pertaining to this project can be divided in six sequential construction stages. At a preliminary stage, a GPS and a precise leveling network were established along the future tram corridor to provide geodetic control for subsequent work. These networks were then suitably densificated to form a geodetic reference that was used for setting out the rails on site. Positioning quality control of rail laying was carried out in three successive steps. Traditional geodetic techniques were implemented in order to compute a set of fundamental track geometry parameters for the entire length of the line. This task was carried out at the construction stage before concreting on site and allowed any misalignments that were identified to be restored to their nominal values. At a post-concreting stage, the rails were surveyed again for a second time. In addition, in order to verify rail laying procedures and to facilitate comparisons in rail positions, additional data were collected with a track vehicle system (KRAB 2002) and compared to those derived with classical geodetic methods.

Among other geometric parameters, track alignment is a critical factor in projects that aim to serve high-speed trains as well as in projects in which a small track radius is applied. This paper is confined in the data collection, the analysis and the comparisons of the results obtained for track alignment based on geodetic methodology and a track recording vehicle system. A full assessment of the procedures and the associated comparisons for the complete set of track surveying data will be presented at a separate study.

2. FUNDAMENTALS OF TRACK GEOMETRY CHARACTERISTICS

Variations in track geometry would raise principal concerns with regard to vehicle's response to derailment and excessive carbody accelerations; and therefore, it needs to be monitored to ensure that safety limits are fulfilled (ECS 2002, El-Siebaie et al 1997). In essence, track geometry is described by the absolute and relative rail locations (Figure 2). Absolute rail positioning refers to the horizontal and vertical displacements of the actual rail locations with respect to their nominal positions (slew and lift). Also, the variation of track curvature defines track geometry in absolute terms (track alignment). Relative rail positioning is described by a number of track surveying parameters. Among others, these include the distance between the two rails (gauge), the inclination of a railway track (cant) and the rate of change of cant (twist).

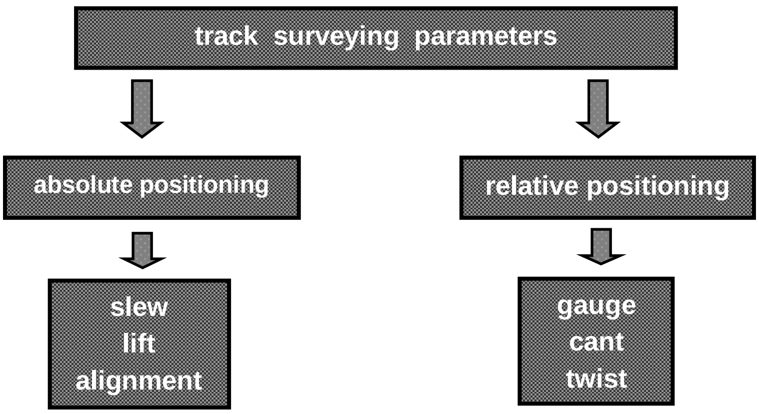


Figure 2: Classification of track surveying parameters.

2.1 Track Alignment

Given a chord between two points in a curve, the perpendicular distance from the chord midpoint to curve is called a versine or alignment measurement. As shown in Figure 3, the sine of angle θ/2 (half the subtended angle) is half of the chord AB of the unit circle. The versine (*versed sine*) of angle θ/2 is the distance CD from the center of the chord to the center of the arc. Thus

$$\text{versine}\left(\frac{\theta}{2}\right) = 1 - \cos\left(\frac{\theta}{2}\right) \tag{1}$$

which, for a given curve radius R and an arc length S is transformed to the equation

$$\text{versine}\left(\frac{\theta}{2}\right) = R\left(1 - \cos\left(\frac{S}{2R}\right)\right) \tag{2}$$

Equation 2 for a spiral curve (clothoid) with parameter A and length L ($RL=A^2$) becomes

$$\text{versine}\left(\frac{\theta}{2}\right) = \frac{A^2}{L}\left(1 - \cos\left(\frac{SL}{2A^2}\right)\right) \tag{3}$$

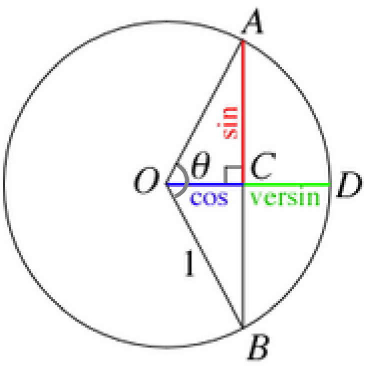


Figure 3: Geometric representation of the versine measurement.

This parameter is used to describe the deviations from straightness of the rail tracks. In fact, for a straight line the versine of any chord is zero, while for a curved track it describes the degree of curvature. More specifically, in circled sections the nominal alignment is a constant value, whereas, in spiral curves the change in curvature is uniform. Existing practice in rail transport extensively employs chord measurements of 10 m for computing track alignment (ECS 2002). Standard 10 m chord observations are suitable to control short wavelength defects that can result in high wheel forces over a short portion of the track. In contrast, longer chord observations (of the order of 30 m or more) are employed to identify longer wavelength track anomalies. These long-wavelength anomalies provide dynamic input to the high-speed passenger trains that can result in unacceptable vehicle accelerations (El-Siebaie et al 1997, Sussmann et al 2003). As discussed in Section 1.0, in this LRT project a low operating speed and a small curve radius were adopted. Hence, the selection of a 10 m chord proved to be sufficient.

2.2 Track Alignment Measuring Methods

Depending on the special requirements of a project, mid-chord offset measurements can be made by theodolite surveying as well as with automatic track geometry vehicles. Versine measurements based on traditional surveying methods employ angle and distance observations made from reference points established nearby or within the work area, to predefined and suitably marked points at regular intervals along the track. Based on these measurements, the coordinates of the points involved in the process can be computed. The coordinates of these points are then used to produce measures of alignment at the midpoints of the specified chords. Given the high accuracies that characterize modern theodolite / EDM systems this method can produce remarkably good results (Lewis 2002). However, the drawback to the method is in the small sampling interval. Versine estimates can only be taken at discrete points; and therefore, the method is not considered suitable for exhaustive quality control, unless the construction program does not allow for a track recording coach to run freely on the line prior to concreting.

Track recording vehicles for computing alignment are of two types. The first type employs a combination of an inertial accelerometer and a gauge sensing system, and those, which measure the versine of the forming curvature on the chord. When an inertial system is used, the signal from the accelerometer is processed to yield the lateral path in space taken by the moving vehicle. This information is then combined with the gauge measurements to form the alignment of each individual rail. Automated recording systems under the second category compute the versine measurement on a three-point asymmetric chord. The raw observations are then decomposed to their original sinusoid components by applying a Fast Fourier Transformation (FFT). Finally, the processed versine values are recalculated in the spatial domain and they are represented in a form of mid-chord offsets with multiple chord lengths (KRAB 2002).

3. TEST DATA, RESULTS AND ANALYSES

3.1 Observation Techniques and Test Data Description

In order to comply with existing practice, as well as in order to compensate for operational efficiency and cost, a strategic decision for collecting alignment measurements at rail segments of 5 m was made at an early stage of this project. Under this observation scenario the rails were marked up and numbered with sustainable paint at opposite locations every 5 m along the track as shown in Figure 4. Then, in order to compute the rail positions at the specified check points, surveying observations were made from the geodetic control stations / reference points, which were established along the track site. In order to minimize errors pertaining to the measurement process (e.g. errors due to leveling / centering of the instrument), the observation program specified that, from each reference point it should be observed as many check points as possible. Furthermore, the observation program provided that for every group of check points observed from a reference point, at least the first and the last two of them had to be re-observed from the preceding and following reference points respectively. This observation scheme ensured that every versine measurement could be computed by using observations made solely from a single reference point; and hence, the risk of inducing errors associated to the measurement process was minimized significantly. In accordance to common practice versine measurements were taken 1,59 cm below of the top of rail. To accomplish this task an iron-made part was made especially for setting up the EDM unit reflector at the prescribed rail location – see Figure 5.

Figure 4: Rail marking on site.

Figure 5: Observation set up.

As stated in Section 1.0, in this project versine measurements based on conventional surveying techniques were taken twice – at the construction stages just before and after concreting on site. In addition, at a post-concreting stage, the rails were surveyed again by using the KRAB rail coach (KRAB 2002). This system employs the three-point asymmetric chord technique for computing track alignment. In this article, the results and the analyses obtained for a typical section 120 m long are discussed. More specifically, a mixed curve comprising of circled, spiral and straight line segments was chosen. The geometric details of each one of the analytical functions involved in the dataset examined are given in Figure 6.

3.2 Results and Analyses of Alignment Measurements

In this study, test data evaluation is based on the statistical analysis and the comparisons derived from the nominal alignment values and those that were surveyed in the field. Figure 6 depicts the nominal alignment values for the dataset in question. In accordance to Section 2.1, the nominal alignment for the circled and spiral segments is computed by equations 2 and 3 respectively, whereas, the same parameter for the straight-line section equals zero.

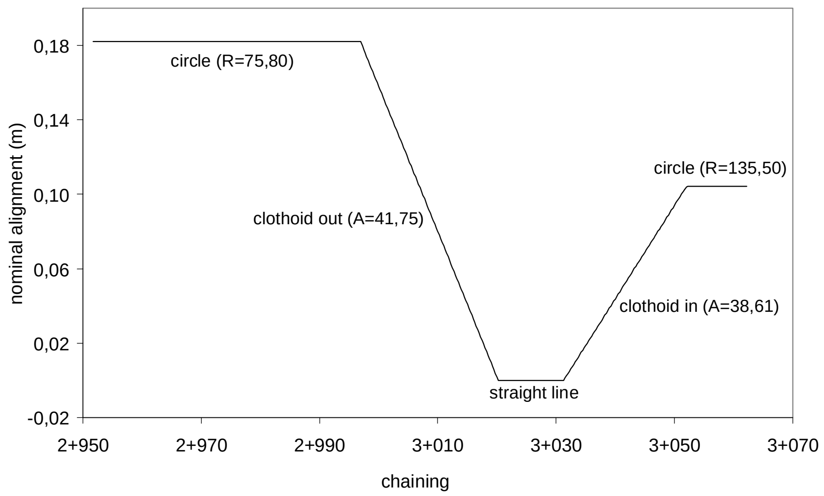


Figure 6: Nominal alignment and design geometry elements.

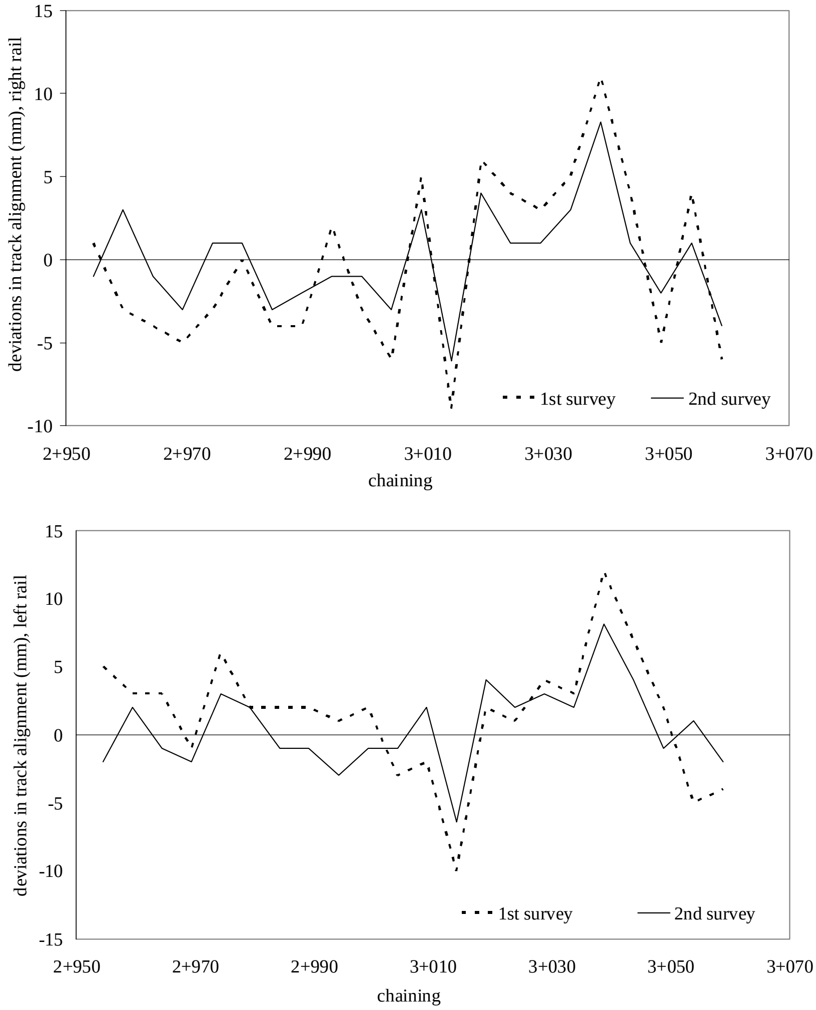
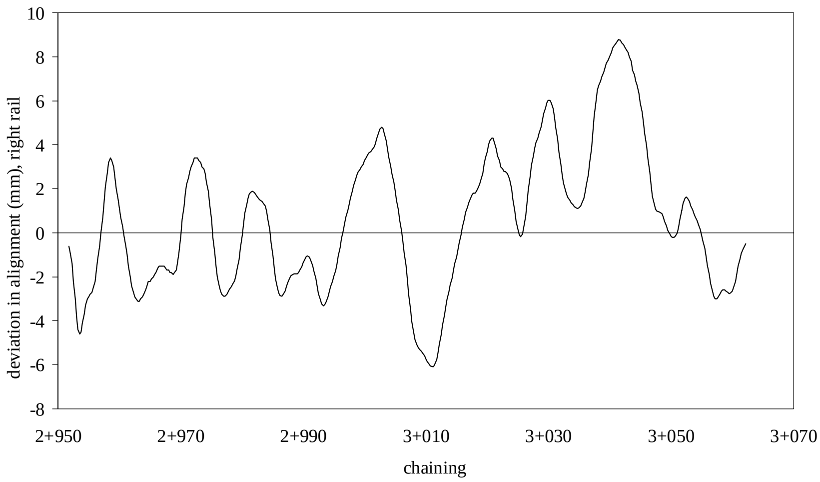


Figure 7: Nominal minus geodetically derived track alignment estimates.



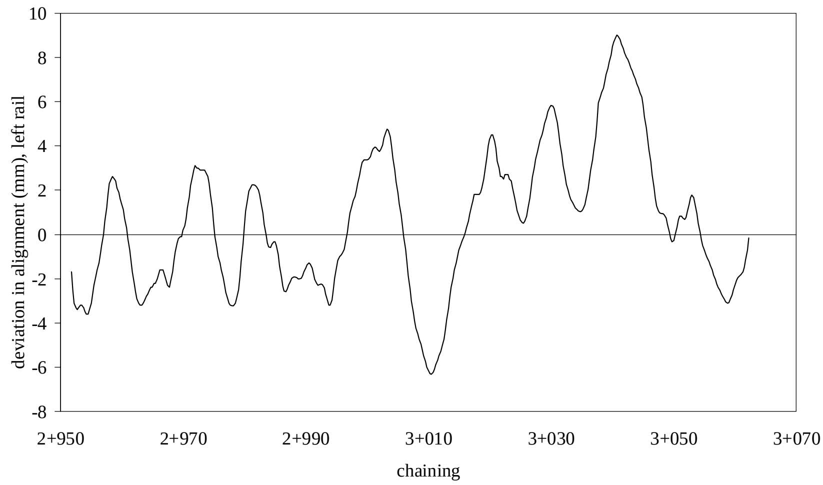


Figure 8: Nominal minus track recording vehicle derived alignment estimates.

Figure 7 contains the differences between the nominal alignment values and those values that were computed by means of tacheometric surveying for the left and right rails. More specifically, the dash line shows the results obtained from the first survey (i.e. before concreting on the site was applied), while the solid line depicts the results obtained on the finished line (i.e. after adjustment in rail laying positions was applied and concreting on site was finished). From these diagrams a number of conclusions can be made. The first thing to note is that the differences computed at the first and second surveys exhibit a similar trend. Moreover, as expected, in the final check their magnitude has been significantly reduced – especially, for the points that indicate maximum values in the first survey (CH:3+010 and CH:3+040). The next point to note is the strong correlation between alignment errors and track geometry. In particular, maximum values are observed in those sections that spiral curves were applied (CH: 3+005-3+015 and CH: 3+040-3+050). This can be possibly explained by the fact that clothoids geometry is complicated; and hence, these sections are difficult to be bent and to be laid precisely (Gikas and Soilemezoglou 2003).

Figure 8 presents the deviations in track alignment in the same section computed by using the track geometry trolley. The apparent smooth character in the results is indicative of the high sampling interval (0,25 m) of the recording vehicle. Moreover, if Figure 8 is examined in combination with Figure 7 it is immediately evident that these two independently derived estimates follow the same pattern and they are of the same magnitude – indicating that the surveying techniques and the procedures applied are correct. Finally, what is of great importance to note is the fact that the absolute values of the differences are within generally accepted specifications (ECS 2002). More specifically, from Figures 7 and 8 it can be clearly seen that they vary between –3 mm to 3 mm and that only occasionally reach 8 mm.

The results presented here come from a very limited set of observations. However, statistical analysis of the results derived, spanning the entire data volume, support the general conclusions drawn in this study. Figure 9 presents a summary of the deviations in track alignment (nominal minus geodetically computed values) for the entire length of the tramline. The sample comprises about 5200 points (26 km / 5 m). Given the low operational speed adopted in this project, the specified limits for track alignment (at a confidence level 99%), range from 4 mm for a track radius more than 400 m, to 10 mm for a track radius 60 m or less. Therefore, from Figure 9 it can be concluded that normal distribution is fulfilled and that just 1,5% of the residuals marginally exceed the specified standard deviation. The apparently large distribution of the differences is due to the large proportion of geometric elements with a small track radius.

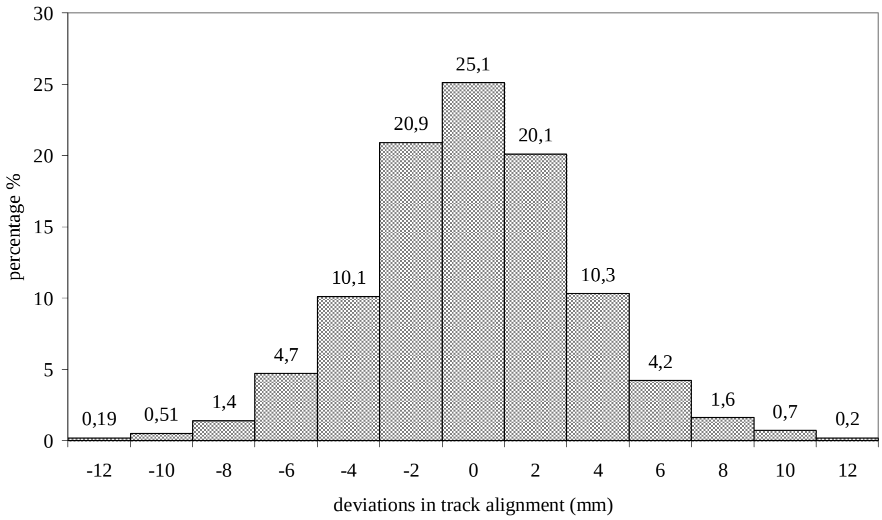


Figure 8: Distribution of track alignment deviations.

4. CONCLUSIONS

In railway systems, derailment and carbody accelerations are the principal concerns in vehicle response to track geometry variations. Among other parameters, track alignment plays a significant role in controlling surface geometry. In this study, a summary of the various methods used for computing track alignment during construction of the slab track was given.

Analysis of a complete set of real data showed that the geodetically derived estimates compare very well (both in trend and in magnitude) with those obtained with a track measuring trolley. Field observations and data analysis were based on the selection of the standard 10 m chord. However, further analysis with a 20 m chord (in those sections that a large track radius was applied), did not reveal the existence of longer wavelength track anomalies. Finally, both methods indicated that maximum deviations in track alignment occur in spiral sections – suggesting that, in order to fulfill track geometry safety criteria special precautions need to be taken during geodetic observations and setting out or rails.

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BIOGRAPHICAL NOTES

Vassilis Gikas joined as a lecturer the National Technical University of Athens in 2004. His previous appointments include a research position in the Department of Geomatics at the University of Newcastle upon Tyne, UK. In the past he served the offshore industry in the UK and the USA as a navigation and positioning specialist and more recently, he served the private sector in a series of surveying and transportation engineering projects under the same capacity. His principal areas of research include navigation, high precise GPS and surveying engineering applications.

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