

Article

Development of Motorway Horizontal Alignment Databases for Accurate Accident Prediction Models

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Abstract: The safe and efficient operation of highways minimizes the environmental impact, reduces accidents, and promotes the reliability of the transportation infrastructure, all in support of sustainable transportation. The horizontal alignment of highways holds particular importance as it directly impacts driver behavior, vehicle stability, and overall road safety. In many cases, highway inventory data held by infrastructure operators may contain inaccurate or outdated information. The accuracy of the variables used in crash prediction models eliminates possible bias in the variable estimators. This research proposes a methodology to obtain accurate horizontal geometric features from digital imagery based on the analysis of the planimetry, feature geolocation and centerline azimuth sequence. The reliability of the method is verified by means of numerical and statistical procedures. This methodology is applied to 150 km of motorway segments in Portugal. Although it is found that the geometric characteristics of most of the inventory segments closely matched the extracted alignments, very significant differences are found in some sections. The results of the proposed procedure are illustrated with several examples. Finally, the propagation of error in the determination of the geometric design independent variables in the fitting of the statistical models is discussed based on the results.

Keywords: GIS; highway geometric design; highway inventory; horizontal alignment; motorways; remote sensing; road extraction; safety; sustainable transportation; traffic management



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1. Introduction

The safe and efficient operation of highways is a fundamental cornerstone of sustainable transportation because it minimizes environmental impacts, reduces accidents, and promotes the reliability of transportation infrastructure. Ensuring road safety can help improve connectivity, affordability, livability, accessibility, and economic well-being, contributing to the overall sustainability of transportation [1].

The road system is an essential pillar of the transportation infrastructure. The geometric design of highways encompasses the layout and dimensions of road elements, including horizontal and vertical alignments, cross-sections, intersections, and interchanges. The design output should meet design standards that seek to optimize the traffic flow, minimize the risk of accidents, and accommodate the diverse needs of road users. The horizontal alignment of highways holds particular importance as it directly impacts driver behavior, vehicle stability, and overall road safety [2–4]. The high predictive power of horizontal alignment features in crash prediction models makes it necessary to focus on accurately extracting the sequence of alignments in the horizontal projection [5]. This requires meticulous mapping and analysis of curves, tangents, and transitions in road design, as these elements significantly influence vehicle behavior and crash likelihood. However, in many cases, highway inventory data held by infrastructure operators may contain inaccurate or out-of-date information, which can compromise the reliability of these

models. Research demonstrates that inaccuracies or missing values can significantly impact crash prediction models, leading to erroneous predictions if field validation of inventory data shows significant discrepancies when compared to the original unverified data [6]. Therefore, it is highly recommended to check whether the available alignment data actually correspond to the existing reality. Leveraging advanced technologies, alongside regular updates and validation of highway inventory data, can significantly improve the accuracy of alignment data.

A safety performance function (SPF) is a specific type of accident prediction model that statistically relates the expected number of accidents to the traffic exposure (e.g., traffic volume) and other relevant variables, such as road characteristics. SPFs are typically developed using historical accident data and are most commonly used in the Highway Safety Manual [7]. The accuracy of the independent variables used in an SPF reduces possible bias in the estimators of the variable coefficients, allowing a more accurate diagnosis in the determination of design factors affecting road safety.

Despite the extensive range of SPFs that incorporate road geometric design variables, a significant gap remains in the literature. Numerous approaches have been explored to understand how these design factors affect the accident risk. However, there is a notable lack of research addressing how errors in measuring and determining these geometric variables impact the reliability and accuracy of SPFs. Understanding this relationship is critical, as even minor inaccuracies in geometric data could lead to substantial errors in predicting accident likelihood, thereby undermining the effectiveness of these models in enhancing road safety. The reliability of SPFs is typically estimated through statistical methods, such as cross-validation and sensitivity analysis, which assess the model's consistency and robustness across various datasets. However, it is not possible to properly verify the reliability of an SPF if the accuracy of the model input parameters has not been properly checked.

Based on the above, the aim of this research is twofold. On the one hand, given the possible inaccuracies or outdated information in the highway inventory data held by infrastructure operators, the objective is to develop and validate a method for obtaining the horizontal alignment of motorways with accurate values of the variables that define them in order to support safety performance analyses based on basic geometric design features. On the other hand, the objective is to analyze the effect of errors in the estimation of the geometric design variables on the prediction of accident frequency is pursued. For these purposes, the best features of the various alignment extraction techniques available are applied to obtain the theoretical horizontal alignment of a selection of motorway case studies.

2. Background

Alignment data are required to evaluate the safety performance of the geometric design of a highway in service. These data are generally retrieved from as-built drawings. When alignment data are not available or are unreliable, the sequence of theoretical alignments and their parameters must be derived from other available sources. The alignments thus obtained should maximize the fit of the features deduced from the alternative data sources while satisfying the mathematical boundary conditions between the geometric elements.

The horizontal alignment of a highway is defined by the geometrical projection of its centerline on the horizontal plane. As a first approach in horizontal alignment recreation, the adjustment of highway centerlines has been broached by several authors using cubic splines [8,9]. The goodness of odd-degree piecewise-defined functions (i.e., continuously differentiability of class C^2 , smoothness and simplicity) makes them suitable for the adjustment of centerlines.

As specified in geometric design standards, the horizontal projection of the highway alignment is composed of three types of segments that are seamlessly joined together [10,11]. Tangents are straight alignments, i.e., with zero curvature, which form the alignment support. They are connected by circular arcs, which are segments with constant curvature.

In order to avoid discontinuities in the alignment curvature, the transitions between zero-curvature and finite-curvature segments are, in most cases, made by spirals. The Cornu spiral or clothoid is a curve in which the curvature varies linearly with the distance as follows:

$$A^2 = R \cdot L \quad (1)$$

where A is the spiral parameter, R is the curve radius and L is the length of the spiral. Figure 1 displays the geometric layout of a connection between a tangent and a circular arc through a spiral, along with the location parameters. The curve setback, denoted as ΔR , is the space in which the spiral develops to connect the tangent and the circular arc. The deflection angle Ω_s is the change in heading between the start of the spiral and the point where it joins the circular arc. Expressed in gon, it can be calculated as per:

$$\Omega_s = \frac{100 \cdot L}{\pi \cdot R} \quad (2)$$

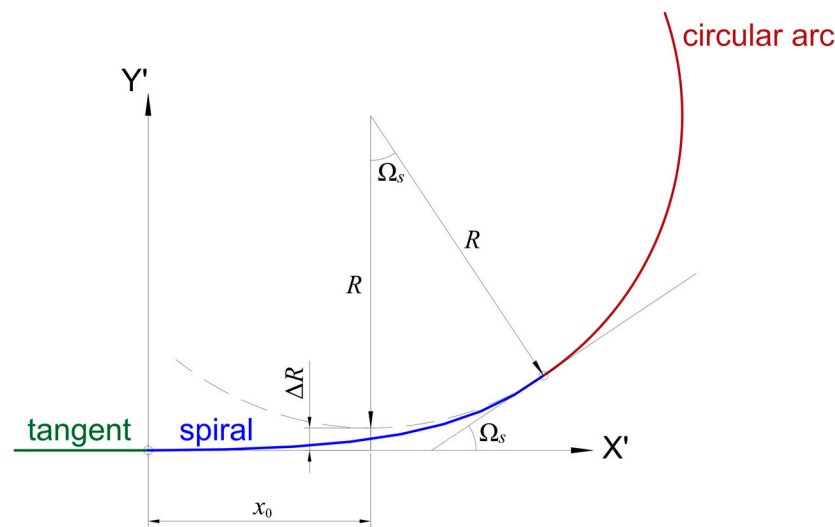


Figure 1. Layout of a spiral transition curve and its parameters between a tangent and a circular curve.

These parameters are related to the spiral length by the following series sum [12]:

$$\Delta R = \frac{L}{2} \sum_{n=0}^{\infty} (-1)^n \frac{\Omega_s^{2n+1}}{(4n+3) \cdot (2n+2)!} \quad (3)$$

The abscissa x_0 is calculated according to the following equation [12]:

$$x_0 = \frac{L}{2} \sum_{n=0}^{\infty} (-1)^n \frac{\Omega_s^{2n}}{(4n+1) \cdot (2n+1)!} \quad (4)$$

2.1. Alignment Recreation

In recent years, the research interest in road extraction techniques from remote-sensing sources has grown, and numerous advances have been made in the field [1–6]. These techniques seek to identify and isolate the road network from a given image to produce digital maps. Furthermore, highway alignment recreation is a specific task requiring greater precision. Particularly, the goal of alignment recreation is to replicate the exact positioning or arrangement of the alignments of a highway, rebuilding the road to follow its original path, and create a digital model representing the alignment.

The process of precisely delimiting which sections of the road centerline correspond to an alignment by determining its ends is known as segmentation. Alignment segmentation can be man-made performed from a centerline using computer-aided design (CAD) applications. However, it is labor-intensive and does not guarantee the accuracy required

for certain purposes. The alignment segmentation can be performed based on curvature data. Garach et al. [8] reported an acceptable accuracy in radii estimation, yet small angle deflection curves or complex curve sequences can hardly be detected using such a procedure. Alternatively, analytical methods have been proposed to deduce the horizontal alignment of highways using heading direction datasets. The heading direction or azimuth refers to the orientation on the horizontal projection of a point on the centerline in relation to the North, and it has several applications in highway alignment analysis [13–15]. First, Karamanou [16] required the user to define the stitching points between alignments from the visualization of the heading direction graph. Later, Gikas and Stratakis [17] proposed a small threshold value of curvature selected subjectively to determine the segmentation after smoothing and filtering the centerline heading dataset. Furthermore, a heuristic method was devised by Camacho-Torregrosa et al. [18] in which the user must mark one spot on each tangent only. This method employs an algorithm to identify the optimal sequence of curves that best fits the heading dataset between two designated points. The curves may include reverse horizontal curves and their corresponding spirals. Two key advantages of this approach are, first, its ability to achieve accurate parameter estimation by avoiding the impact of noise in the curvature data and, second, its ability to handle long sequences of reverse curves. This enables an accurate detection of spirals and small-angle deflection horizontal curves, while also providing a robust procedure for restoring complex sequences of horizontal curves. On the contrary, when reproducing the alignments on the horizontal projection the centerline derived from the procedure gradually deviates from the original roadway on the horizontal projection. Road design commercial software applications offer tools to automatically generate the theoretical alignment that best fits a sequence of surveyed points [19–21].

Trajectories collected by Global Navigation Satellite System (GNSS) receivers installed on surveying vehicles can serve as input data for algorithms that extract the highway centerline [22–24]. Although quite approximate, the data collected using this technique allow to determine the average vehicle path rather than the road centerline [25]. Marinelli et al. [26] adjusted alignments to surveyed data, applying statistical methods to calculate geometric parameters such as the curvature radii and tangent orientations. They compared the precision of the outcome using data from different sensors with as-built alignment data.

Other remote-sensing sources, such as aerial imagery and airborne light detection and ranging (LiDAR), have proved to be very useful in road feature extraction tasks [15,27]. Cai and Rasdorf [22] developed an algorithm to detect road centerlines from LiDAR clouds of points. Based on image analysis, Tsai et al. [28] computed roadway curvature values with high accuracy from images taken by a conventional digital camera mounted on a car using the Canny Edge Detection algorithm.

To deal with the inherent noise and uncertainty in the measurements, Song et al. [29] developed a stochastic curve fitting method based on the maximum likelihood estimation theory. Adjusting the centerline to a sequence of alignments is more difficult on lower-category roads than on higher-category roads, either because the latter have more control over construction or because the former may not have been designed to modern standards [30]. However, curves with smaller radii, frequently found on lower-category roads, and curves with larger deflection angles typically fit better to the centerline [18].

Geographical Information Systems (GISs) provide an efficient and rapid platform for managing road inventories, analyzing accident locations, and evaluating the horizontal alignment of roads [22,31,32]. Aided by GISs, an image analysis approach was proposed by Easa and Dong [33,34] for extracting the elements of simple circular curves and reverse curves using satellite imagery. Software developed for GISs was used by Imran et al. [35] to deduce the alignments in curves without spirals from GNSS vehicle path datasets. Li et al. [36] used GISs to preliminarily detect horizontal curves on low-volume rural highways from polyline feature classes. Bejleri et al. [37] devised a procedure to automatically identify horizontal curves by detecting deflections from straight lines using a vertex deflection angle threshold using roadway centerline networks in GISs as the data source.

In summary, each technique has unique strengths and limitations depending on the specific requirements of the road extraction or alignment recreation task. Curvature-based alignment extraction struggles to detect small deflection angles and complex curve sequences. Alignment extraction using best-fit CAD applications can provide a good starting solution, which can be further improved by using heading direction data due to its greater precision and ability to handle complex sequences. GNSS data are useful for approximating vehicle paths but less accurate for determining the true road centerline. Aerial imagery and LiDAR provide high accuracy in extracting road features but require resource-intensive sophisticated algorithms. Finally, GISs are efficient for managing road inventories and identifying alignments.

References to the error made in the estimation of geometric variables of the alignments are scarce. Based on the analysis of one curve from LIDAR data, Holgado et al. [15] stated that the error in the estimation of geometric parameters with respect to construction project data is less than 2%. Song et al. [29] showed how two different fits to a curve with spirals produce significantly distant points of intersection between the alignments. Concerning how parameter estimation errors might occur and their potential impacts, no research studies have been found. For example, if a curve is incorrectly assumed to not have spirals, an error often found in curve detection, it would affect the estimated radius and other parameters, leading to an overestimation of the true radius when a unique circular arc is fitted to a set of survey points on the curve. However, the extent of this overestimation depends on several factors. The shorter the circular arc, the larger the estimated curve radius; the smaller the deflection angle, the larger the estimated radius; and the longer the spirals, or the greater the circular curve setback, the larger the estimated radius. The accuracy and precision of the survey points will also affect the fitted radius. In addition, if a circular arc is assumed instead of a curve with spirals, the curve length could be underestimated.

2.2. Geometric Design and Safety

The segment length is the main independent variable expressing exposure to the risk of accident occurrence. The segment length was found to affect the fitness of multivariate crash prediction models as longer segments aggregate more crash data and therefore enhance the model's goodness of fit [38]. However, to assess the effect of specific alignment features on road safety, the segment definition must be based on the feature location.

Geometric design variables have been found to be strong explanatory factors in crash prediction functions [39]. The relationship between road curvature and accident rates has been studied extensively. Concerning horizontal curves, most models show that larger curve radii and smaller deflection angles generally result in fewer crashes [40,41]. Slight variations in curvature have been found to correlate positively with the frequency of crashes [42]. Small curve radii combined with sight obstructions have a negative impact on safety [43].

The analysis of highway design consistency is also closely related to obtaining the geometrical parameters of road alignments. This analysis seeks to ensure that drivers predict road geometric conditions, reducing driving errors and improving overall safety. The operating speed, defined as the speed at which drivers are observed operating their vehicles under free-flow conditions, plays a crucial role in the analysis of design consistency [44]. To estimate the safety implications of poor design consistency, operating speed prediction models should be developed based on the alignment features, mainly the curve radii, curve deflection angles and tangent lengths. Consistent highway design helps in reducing unexpected events and ensures that driver expectations are met [45,46]. Several measures of geometric design consistency, such as the speed reduction on curves, have been statistically linked to accident frequency in such a way that consistent designs correlate with fewer accidents [31,47,48].

3. Materials and Methods

Figure 2 illustrates the process followed and the inputs used to obtain the alignment database. First, a road centerline is manually sketched as a polyline on a satellite image for each motorway roadway following the inner edge road markings. The polyline consists of a string of straight segments and its vertices define a sequence of (x_i, y_i) Universal Transverse Mercator (UTM) coordinates. The vertices serve as a basis to deduce the stationing according to the equation that follows:

$$\Delta s_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \quad (5)$$

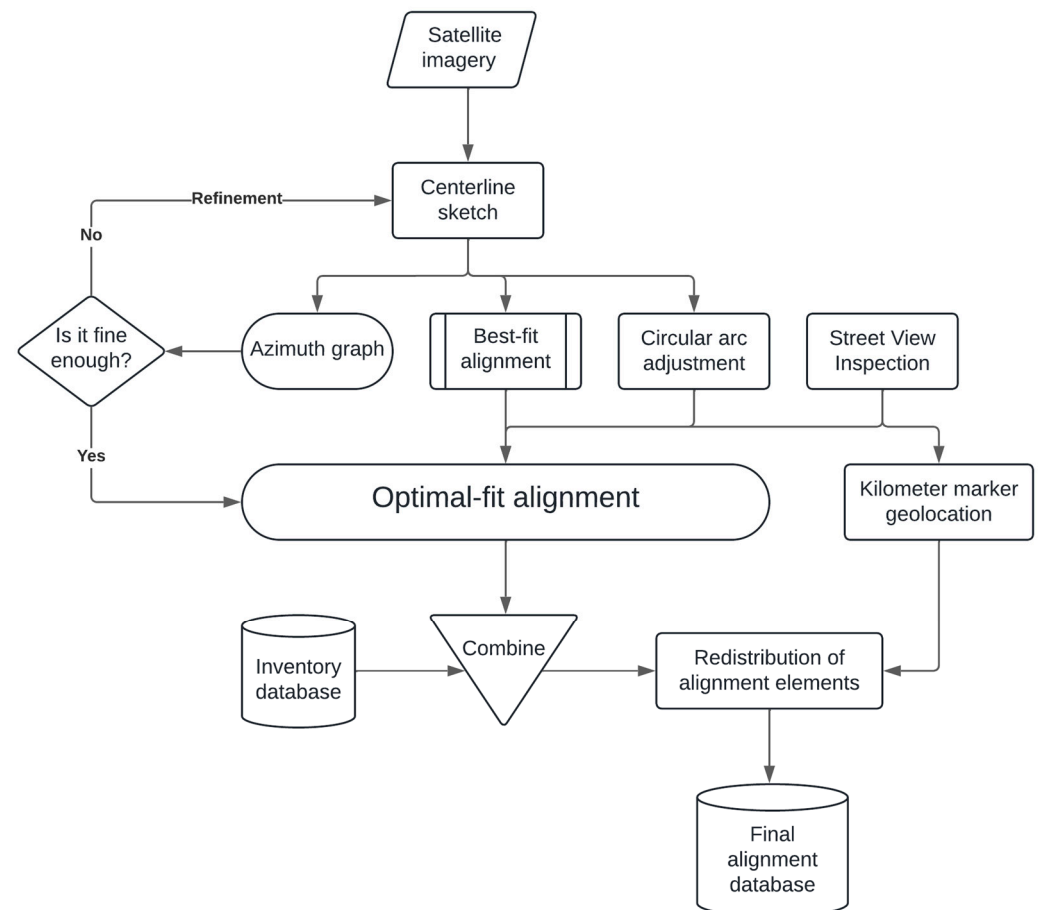


Figure 2. Flowchart of the procedure to obtain the final alignment database.

The UTM coordinates of the points marked on the image are exported to produce an azimuth graph. Each point is associated with two azimuth values θ_i , approach and departure, which are calculated as follows:

$$\theta_i = \begin{cases} \text{atan}\left(\frac{y_{i+1}-y_i}{x_{i+1}-x_i}\right), & |x_{i+1} \neq x_i \\ \pm 100, & |x_{i+1} = x_i \end{cases} \quad (6)$$

In this study, as in most highway geometric design projects, the unit utilized to measure the azimuth angles is the gon, corresponding to one-hundredth of a right angle. A centerline polyline defined with high precision ensures a trustworthy reconstructed alignment outcome. Therefore, the polyline sketched is refined in such a way that the deflection angles between successive points do not exceed 2 gon, and with no change in

the sign of the azimuth variation $\Delta\theta$ is produced. Using the azimuth profile, the radius of a curve can be estimated from the slope of the regression line β as per the equation:

$$R = \frac{200}{\beta \cdot \pi} \quad (7)$$

Three geometric design software alignment recreation tools have been initially tested: AutoDesk Civil3D 2022, Bentley OpenRoads Designer 2023 and Card-1 (version 10.0). These tools can produce a centerline output with a satisfactory fit in a wide range of cases. However, sequences of unlikely alignments may be retrieved, depending on the quality of the input data. For example, some of the software suites may have a tendency to return sequences of compound curves with similar radius values instead of a single-radius curve with spirals or to ignore low-deflection angle curves. The best-fit tool of AutoDesk Civil3D was ultimately selected for inclusion in the process due to its greater functionality and versatility. For these reasons, the proposed procedure not only takes advantage of the capabilities of alignment recreation tools but also combines centerline azimuth data with alignment adjustment on the horizontal projection.

A MATLAB (version R2019b) routine for fitting a set of points on a plane based on least square fitting was adapted from an existing script to examine the curve radii obtained from the azimuth series [49]. The method minimizes the sum of squared radial deviations. The points examined for each curve were those approximately leaning at a constant angle.

Next, a visual inspection of the roadway navigating through Google Street View was conducted to verify the existence of low deflection angle curves detected in the azimuth profiles, checking if the roadway indeed appears to bend (Figure 3). At street level, parallel lines such as the road edges and lane markings appear to converge as they extend into the distance. This convergence helps the observer perceive the roadway direction and any deviations from straightness, making it easier to detect changes in direction. From this reasoning, it can be verified that there is a reverse small-angle deflection curve in the area highlighted in Figure 3.

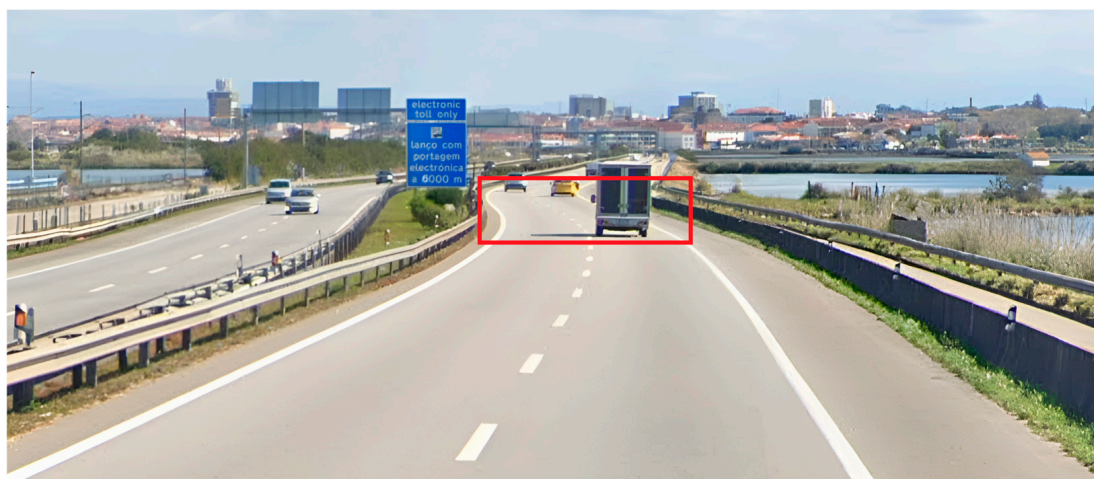


Figure 3. Roadway visual inspection of low-deflection angle curves (source: Google Street View).

It is important to note that the optimal-fit alignment might not meet the standards in terms of either the individual parameters or the relations between some of them. However, the goal in this step is to extract the existing sequence of alignments.

The last stage consisted of the geolocation of the hectometric signposts, which was performed with the help of satellite imagery and navigation with Google Street View. The distance between hectometric signposts along the centerline of the optimal fit alignment was measured, which was often not exactly 100 m. From their position, the redistribution of the alignment elements was calculated proportionally, assigning the stationing of stitch

points between a tangent and a curve, and between two curves, in such a way that spirals were considered together with the corresponding arc as a single curve.

The combination of the analysis of the azimuth graph, the Civil 3D best-fit alignment tool, the circular arc adjustment and the Google Street View inspection allowed us to obtain the optimal fit horizontal alignment, which is a theoretical alignment in which all the design parameters are defined as meeting the mathematical constraints.

Highway inventories typically use kilometer markers as a reference. Moreover, crash locations are linked to the kilometer markers. In certain zones, right-of-way restrictions or relief constraints force designers to decouple the two roadways of the motorway so that each centerline runs independently along a certain section. As kilometer markers must be placed at the same position on both roadways, these sections are prone to contain inconsistent geometric data in inventories if the same geometric design variables are indicated for both roadways. As a result, kilometer markers are mere reference points rather than reliable landmarks for measuring lengths. For these reasons, the alignment ends must be associated with kilometer markers, which might not match the real alignment length.

The methodology described above was applied to 150 km of motorway segments in Portugal. These motorways are the A29 between the cities of Porto and Aveiro, and the A25 between Aveiro and Viseu. These motorways have two separate roadways, total control of accesses, and intersections with other roads at different levels. The motorways analyzed have hectometric signposts on both roadways, from which the position of the alignment ends can be associated to a kilometer point. The inventory database is based on those hectometric signposts.

4. Results and Discussion

4.1. Obtaining the Optimal Fit Alignment

In this section, a comparison between the outcome of the alignment extraction methods and the existing inventory database is provided. Table 1 presents the number of alignments according to the inventory database, those obtained by the proposed method, and the matching alignments. It contains the data broken down by type of alignment, considering the spirals within the same curve as the corresponding circular arc. As a first approximation, matching alignments are considered those that share more than 50% of their length in common in both databases. The column of matching alignments indicates the number of alignments that are found in both the database and the outcome of the method proposed under this criterion. According to the data shown in the table, important differences exist in terms of the number of alignments between the outcome of the alignment extraction methods and the existing inventory database. Although the inventory database contains more alignments than the number of alignments extracted with the procedure presented, some segments were missing in the inventory database. Moreover, the mismatched alignments correspond to either missing alignments or duplicated alignments in the inventory database, and to differences in the alignment sequences between the inventory and the extracted alignment. The matching tangents represent 79.4% of those in the inventory database, the matching curves 98.7% of those in the inventory database and the total matching alignments 91.0% of those in the inventory database.

Table 1. Number of alignments of the case studies.

Alignments	Inventory Database	Extracted Alignment	Matching Alignments
Tangents	214	199	170
Curves	318	349	314
Total	532	548	484

Next, a comparison of the length, curve radii, and deflection angle of the matching alignments was conducted to verify the parameter values of the alignments obtained with the method presented. Figure 4 shows histograms of the differences in length of

the matching alignments, the differences in radii and the differences in deflection angles. T-tests for paired samples were performed to determine whether there are significant differences between the parameters of the alignments in the inventory database and their counterparts in the matching extracted alignments. The difference in length was not found to be significant at the 95% confidence level. The differences in the curve radii were also not found to be significant between the matching curves of two databases at the 95% confidence level. The differences in curve deflection angles were not found to be significant either at the 95% confidence level.

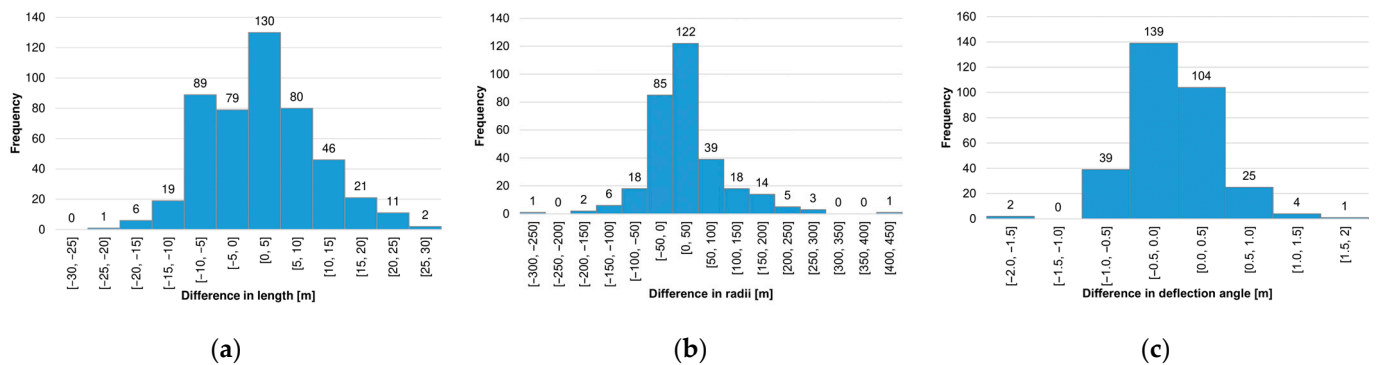


Figure 4. Histograms of the differences between the alignment parameters of the inventory database and the extracted alignments: (a) differences in length; (b) differences in curve radii, and (c) differences in curve deflection angle.

The root mean square error (RMSE) was computed for each of the three variables as an additional metric to compare the values obtained in the extracted alignment with the values of the counterpart matching alignments from the inventory database using the formula shown below:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (8)$$

where n is the sample size, y_i is the value of the variable in the inventory database for the i -th alignment and $\hat{y}_i$ is the counterpart value of the extracted alignment. The results are shown in Table 2. The average percentage error (APE) has also been calculated for each of the three variables, and the results are also shown in Table 2:

$$APE = \frac{100}{n} \sum_{i=1}^n \frac{|y_i - \hat{y}_i|}{\hat{y}_i} \quad (9)$$

Table 2. Metrics for assessing the estimation accuracy of the alignment variables.

Metric	Length	Radius	Deflection Angle
RMSE	8.72 m	54.82 m	0.448 gon
APE	2.54%	5.61%	0.67%

The results shown in Table 2 indicate that the deflection angle values are the most accurate and the radius values are the least accurate. It should be noted that the error in the estimation of the alignment variables is in any case below 10%.

As seen previously, part of the sample of motorway sections in the inventory database contains information of high accuracy for the development of an SPF, while the rest contains information that differs significantly from the results obtained with the presented method.

The differences found between the inventory and the horizontal alignment are illustrated with an example section showing the difference between the alignment inventory and the reconstructed alignments. Figure 5 shows a sequence of azimuth values obtained from the centerline sketched on the image for one roadway, and the subsequent extracted

alignments on the A25 motorway. The former corresponds to the black line with steps. The latter includes horizontal blue lines representing tangents, inclined green straight lines representing circular arcs, and purple parabolas representing spirals. A curve with unsymmetrical spirals was adjusted from station 1+836 to 2+798, describing a turn of 41.6 gon. This sequence of alignments could be adjusted without difficulty using the best-fit alignment tool. Then, several small-angle deflection curves are observed. The first of these extends from stations 4+040 to 4+303, with no transition curves and with a deflection angle of only 4 gon. However, given that this alignment is connected to two tangents with a considerable length, the best-fit alignment tool was able to correctly identify the bend. Otherwise, the error in planimetry would be very large. Next, a reverse curve composed of two small-angle deflection curves is observed between stations 5+184 and 5+528. This is an alignment sequence to which the best-fit tool typically fails to adjust since the approach and departure tangents have approximately the same heading direction and, therefore, the planimetry error is low. As a result, these alignments required the azimuth graph and the circular adjustment to be extracted. It can also be noticed that the first curve of the sequence was adjusted with small transition curves at both ends, whereas the second one was adjusted without spirals. The completion of the sequence required a short interim tangent to connect both curves. Finally, a reverse curve is found between stations 5+800 and 6+112. In this case, only the first curve was adjusted with an approach transition curve. The other ends were adjusted without transition curves.

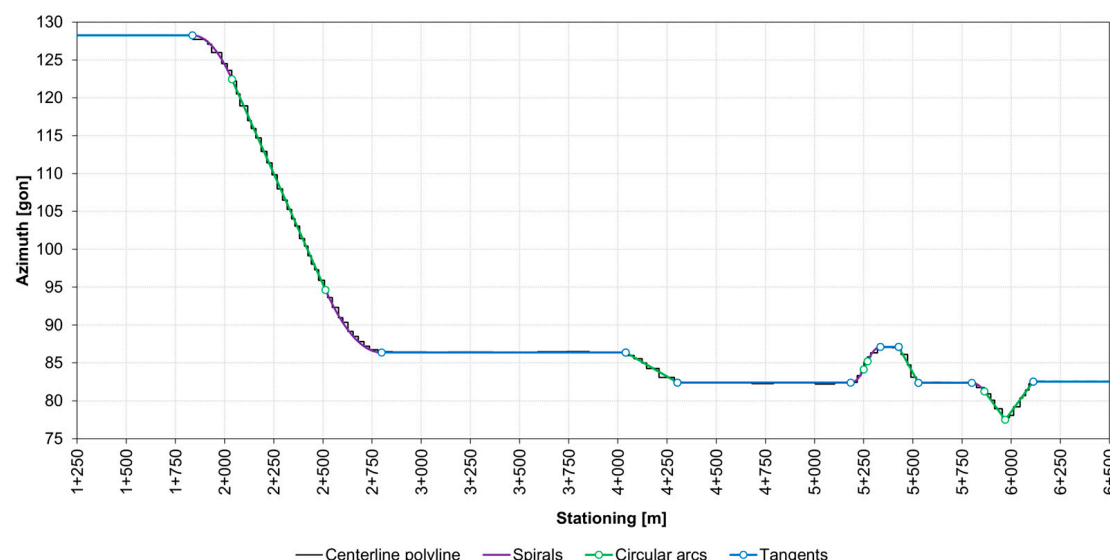


Figure 5. Azimuth graph of a motorway section obtained on the satellite image and its optimal-fit alignment.

Figure 6 displays the curvature graphs as per (a) the inventory database and (b) the optimal-fit alignment of the same section. According to the alignment inventory, there is a curve between stations 1+476 and 2+250 with identical transition curves on both curve ends, whereas the analysis of the azimuth sequence shows that this curve is located 360 m ahead and the spirals are unsymmetrical. The rest of the section shows much more noticeable differences. According to the inventory database, there are three curves located between stations 2+400 and 3+700, while the analysis of the azimuth sequence reveals that none of these actually exist. Although the following curve is found in both the inventory database and the optimal-fit alignment, their parameters differ significantly. The radius, length and especially the location do not coincide. According to the inventory, from station 4+500, there are two curves with radii of 1100 m and 800 m. The analysis of the azimuth sequence reveals that there are actually two reverse curves, each consisting of two small-angle deflection curves. The curve radii do not match in any case.

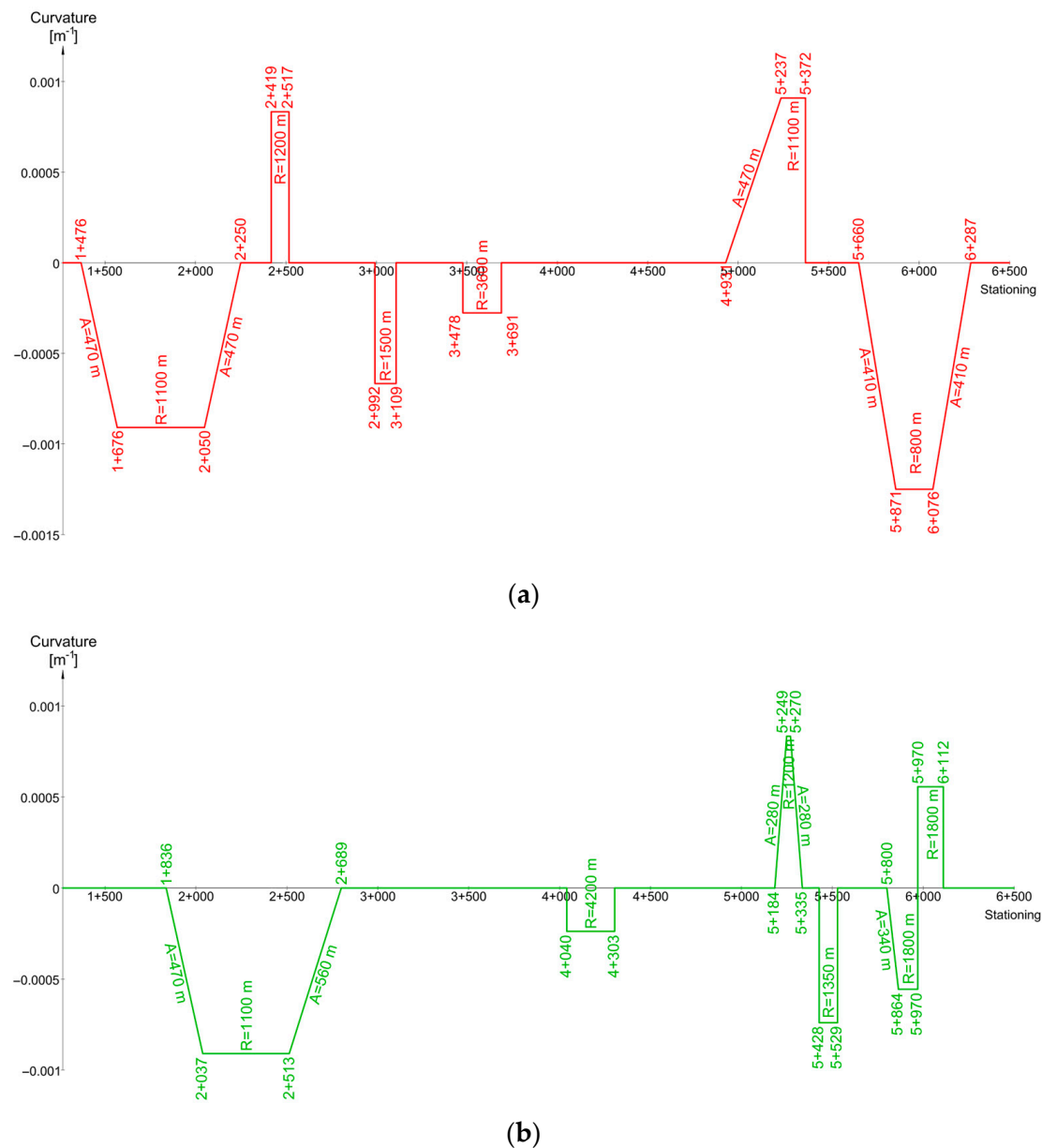


Figure 6. Curvature graph: (a) according to the inventory database; and (b) extracted optimal-fit alignment.

In terms of the motorways analyzed, several sections can be found where the centerlines of each roadway are independent. Although this is not frequent, the different alignment features should be considered in the accident databases for each independent roadway, even though the differences may seem small, to ensure accurate crash prediction models. The case studies found both sections where the inventory was considered to match the existing alignments and sections where the clearly different characteristics of each roadway were not differentiated. Figure 7 illustrates a section of the A25 motorway where the roadways diverge over a short distance and then rejoin, running completely parallel again. The parameters of horizontal alignment elements such as the lengths and radii of curves vary from one roadway to another in this section.

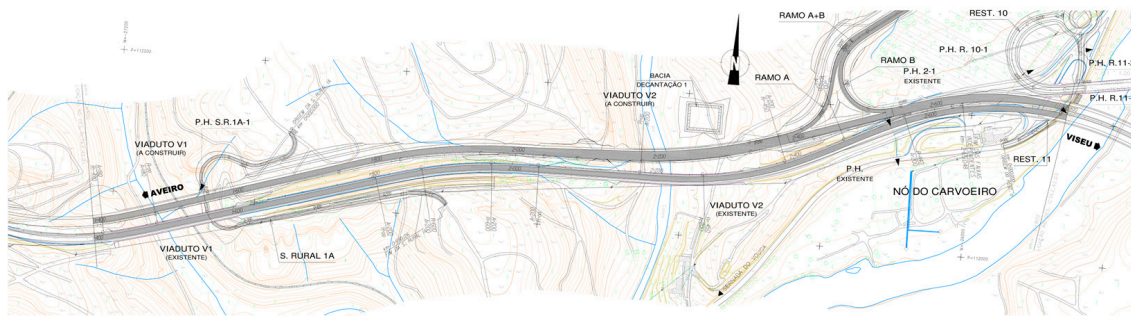


Figure 7. Section where the roadways diverge over a short distance and then rejoin.

4.2. Impact of Variable Accuracy on Crash Prediction Models

Crash prediction models have been adjusted from the final alignment database in the case studies using the geometric design features extracted. The objective is to estimate the effect of the error in estimating the geometric design parameters on the accident prediction.

Generalized linear models have been used to link the independent variables with the crash count in the period 2015–2018. The number of accidents is modeled as a negative binomial variable since the data distribution exhibits over-dispersion [50]. The link function predicts a number of accidents equal to or greater than zero according to the exposure variables, and it is linearizable in order to estimate the coefficients, with a mathematical expression as follows [51]:

$$\hat{E}[Y] = \alpha_0 \cdot AADT^{\alpha_1} \cdot L^{\alpha_2} \cdot \exp(\alpha_3 \cdot x) \quad (10)$$

where $\hat{E}[Y]$ is the estimated number of crashes in four years; L is the segment length; $AADT$ stands for the annual average daily traffic; x is the geometric design independent variable; and α_i are the model estimates. The 548 motorway segments extracted were used to adjust the models. Three geometric design variables have been used to create variables to be incorporated into the models: segment length, curve radius and deflection angle (Table 3). According to Equation (8), the natural logarithm of the segment length is incorporated into the model as an exposure measure, along with the natural logarithm of the AADT. To include tangents and curves likewise in the model, the variable curvature was calculated as the inverse value of the curve radius. The deflection angle (Def_angle) was taken directly from the final alignment database, and the curvature change rate (CCR) was computed as the ratio of the deflection angle to the length.

Table 3. Model variables used to fit the SPFs.

Variable	Units	Min. Value	Mean Value	Max. Value
Length	m	15	496	2212
AADT	Veh./day	3145	10,069	23,517
Curvature	km ⁻¹	0	0.9836	5.5556
Def_angle	gon	0	24.71	157.79
CCR	gon/km	0	47.41	285.19

In order to achieve a balance between simplicity and explanatory power, three parsimonious generalized linear models (GLMs) have been adjusted with R-Studio software (version 1.3.959). The first model, denoted as Model 1, incorporated the length, the segment and the curvature of the segment. Substituting the curvature with the inverse value of the curve radius, the equation that predicts the number of accidents in four years is expressed below:

$$\hat{E}[Y] = \alpha_{0,1} \cdot AADT^{\alpha_{1,1}} \cdot L^{\alpha_{2,1}} \cdot \exp\left(\frac{\alpha_{3,1}}{R}\right) \quad (11)$$

The estimates $\alpha_{i,1}$ and the level of significance of the fitted model are presented in Table 4. All the variables included were found to be significantly different from zero at the 95% confidence level.

Table 4. Summary of Model 1 incorporating the segment length and the curvature.

Variable	Estimate	p-Value
Intercept	−15.93311	$<2 \times 10^{-16}$
Ln_length	0.77581	$<2 \times 10^{-16}$
Ln_AADT	1.25123	$<2 \times 10^{-16}$
Curvature	0.22183	1.05×10^{-5}

The second model, denoted as Model 2, incorporated the length of the segment and the deflection angle of the segment (Ω). Equation (12) predicts the number of accidents in four years from the AADT, the length and the deflection angle of the segment:

$$\hat{E}[Y] = \alpha_{0,2} \cdot AADT^{\alpha_{1,2}} \cdot L^{\alpha_{2,2}} \cdot \exp(\alpha_{3,2} \cdot \Omega) \quad (12)$$

The estimates $\alpha_{i,2}$ and their level of significance are presented in Table 5. All the variables included in this model were found to be significantly different from zero at the 95% confidence level.

Table 5. Summary of Model 2 incorporating the segment length and the deflection angle.

Variable	Estimate	p-Value
Intercept	−15.424745	$<2 \times 10^{-16}$
Ln_length	0.654792	3.45×10^{-15}
Ln_AADT	1.280247	$<2 \times 10^{-16}$
Def_angle	0.007292	3.33×10^{-5}

The third model, denoted as Model 3, included the segment length and the CCR. The number of accidents in four years is predicted by Equation (13), where the CCR is replaced by the ratio of the deflection angle divided by the segment length.

$$\hat{E}[Y] = \alpha_{0,3} \cdot AADT^{\alpha_{1,3}} \cdot L^{\alpha_{2,3}} \cdot \exp\left(\frac{\alpha_{3,3} \cdot \Omega}{L}\right) \quad (13)$$

The estimates $\alpha_{i,3}$ and their level of significance are presented in Table 6. In this model, all the variables included were found to be significantly different from zero at the 95% confidence level.

Table 6. Summary of Model 3 incorporating the segment length and the CCR.

Variable	Estimate	p-Value
Intercept	−15.986354	$<2 \times 10^{-16}$
Ln_length	0.768374	$<2 \times 10^{-16}$
Ln_AADT	1.26248	$<2 \times 10^{-16}$
CCR	0.004515	9.66×10^{-6}

It should be noted that the parameters obtained for the models fitted are consistent with similar models in the literature. First, all the exposure variables have positive values of the estimates. In all cases, the models indicate that the accident frequency increases as the traffic volume increases and as the segment length increases. Also, the positive correlation between the curvature, deflection angle, and CCR and the accident frequency is consistent with similar models and logical expectations.

Based on the adjusted crash prediction models, an error propagation analysis was conducted to determine how the error in determining the geometric design variables impacts the crash prediction output. Evaluating error propagation in a model equation involves determining how the uncertainty in the input variables affects the uncertainty of the output. As an initial approach, uncorrelated and independent errors were assumed. Equation (14) provides the expression to obtain the relative value of the propagated uncertainty Δy_j of the output of a SPF as a function of the partial derivative of the model function with respect to one of the geometric design input variables x_i , the model function itself $y_j(x_i)$ and the value of the error for that input variable Δx_i [52].

$$\Delta y_{j,i} = \frac{\frac{\partial}{\partial x_i} [y_j(x_i)]}{y_j(x_i)} \Delta x_i \quad (14)$$

Applying the expression of Equation (14) to the model that includes the curvature variable (Table 4) to obtain the output error produced by an error of 10% in the estimation of the curve radius, as measured in km, the following expression is obtained:

$$\Delta y_{1,R} = \frac{\alpha_{0,1} \cdot AADT^{\alpha_{1,1}} \cdot L^{\alpha_{2,1}} \cdot \frac{-\alpha_{3,1}}{R^2} \cdot \exp\left(\frac{\alpha_{3,1}}{R}\right)}{\alpha_{0,1} \cdot AADT^{\alpha_{1,1}} \cdot L^{\alpha_{2,1}} \cdot \exp\left(\frac{\alpha_{3,1}}{R}\right)} \cdot 0.1 \cdot R = \frac{-0.1 \cdot \alpha_{3,1}}{R} = \frac{0.0222}{R} \quad (15)$$

The result is a relationship that is inversely proportional to the radius of the curve and is independent of the segment length and the AADT. Substituting the result of Equation (15) with different values for the curve radius and taking into account the 10% reference error in the radius value mentioned above, the error in estimating the accident frequency is -5.6% for curves with 400 m radius and -1.1% for curves with 2000 m radius. It can therefore be said that the error propagation in the radius estimation in this SPF is limited.

If Equation (14) is developed for the model that includes the curvature variable to obtain the output error produced by an error of 10% in the estimation of the segment length, the following result is obtained:

$$\Delta y_{1,L} = \frac{\alpha_{0,1} \cdot AADT^{\alpha_{1,1}} \cdot \alpha_{2,1} \cdot L^{\alpha_{2,1}-1} \cdot \exp\left(\frac{\alpha_{3,1}}{R}\right)}{\alpha_{0,1} \cdot AADT^{\alpha_{1,1}} \cdot L^{\alpha_{2,1}} \cdot \exp\left(\frac{\alpha_{3,1}}{R}\right)} \cdot 0.1 \cdot L = 0.1 \cdot \alpha_{2,1} = 0.0776 \quad (16)$$

The result is a constant value of 7.8%. Therefore, in this case, the propagated error is smaller than the estimation error of the segment length.

In the case of the Model 2, using Equation (14) and considering an error of 10% in the estimation of the deflection angle Ω , the error propagation is:

$$\Delta y_{2,\Omega} = \frac{\alpha_{0,2} \cdot AADT^{\alpha_{1,2}} \cdot L^{\alpha_{2,2}} \cdot \alpha_{3,2} \cdot \exp(\alpha_{3,2} \cdot \Omega)}{\alpha_{0,2} \cdot AADT^{\alpha_{1,2}} \cdot L^{\alpha_{2,2}} \cdot \exp(\alpha_{3,2} \cdot \Omega)} \cdot 0.1 \cdot \Omega = 0.1 \cdot \alpha_{3,2} \cdot \Omega = 0.000729 \cdot \Omega \quad (17)$$

The result is linearly related to the deflection angle and is independent of the segment length and the AADT. The error value is 0.4% for curves with a 5 gon deflection angle and 7.3% for curves with a 100 gon deflection angle.

Considering Equation (14) to deduce the error propagation produced by a 10% error in the estimation of the segment length, results in:

$$\Delta y_{2,L} = \frac{\alpha_{0,2} \cdot AADT^{\alpha_{1,2}} \cdot \alpha_{2,1} \cdot L^{\alpha_{2,2}-1} \cdot \exp(\alpha_{3,2} \cdot \Omega)}{\alpha_{0,2} \cdot AADT^{\alpha_{1,2}} \cdot L^{\alpha_{2,2}} \cdot \exp(\alpha_{3,2} \cdot \Omega)} \cdot 0.1 \cdot L = 0.1 \cdot \alpha_{1,2} = 0.06548 \quad (18)$$

The result is a constant value of 6.5%. Consequently, the propagated error is less than the estimation error of the segment length.

In the third model, the result of applying Equation (14) with an estimation error of 10% in the deflection angle Ω is:

$$\Delta y_{3,\Omega} = \frac{\alpha_{0,3} \cdot AADT^{\alpha_{1,3}} \cdot L^{\alpha_{2,3}-1} \cdot \alpha_{3,3} \cdot \exp\left(\frac{\alpha_{3,3} \cdot \Omega}{L}\right)}{\alpha_{0,3} \cdot AADT^{\alpha_{1,3}} \cdot L^{\alpha_{2,3}} \cdot \exp\left(\frac{\alpha_{3,3} \cdot \Omega}{L}\right)} \cdot 0.1 \cdot \Omega = \frac{0.1 \cdot \alpha_{3,3} \cdot \Omega}{L} \quad (19)$$

$$\Rightarrow \Delta y_{3,\Omega} = \frac{0.000452 \cdot \Omega}{L} \quad (20)$$

The result of the accident frequency prediction error in this case depends on two variables. It is directly proportional to the value of the deflection angle and inversely proportional to the segment length. The contour plot in Figure 8a represents the relative error propagated to the accident prediction output as a function of both variables. Each line is annotated with the error associated with the accident prediction according to the values of the variables on the axes. The vertical axis represents the segment length, and the horizontal axis displays the deflection angle, each of them for the range of values in the sample of motorway alignments. It can be observed that the value of the maximum error in accident prediction is 0.05%, and it is obtained for the segments with a length of about 100 m long and curves with a deflection angle of almost 120 gon.

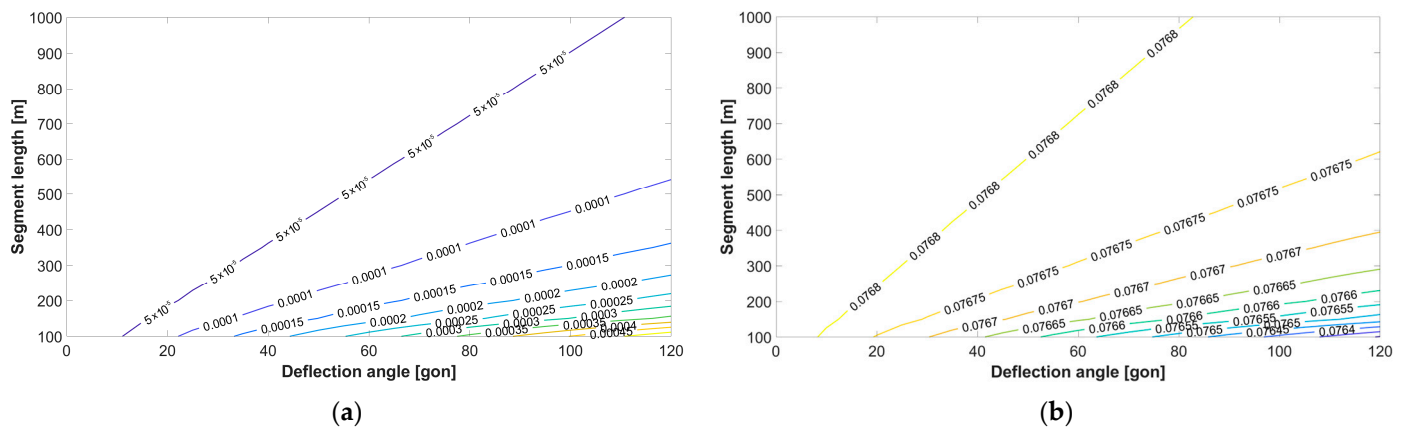


Figure 8. Relative error in accident prediction of Model 3: (a) produced with an estimation error of 10% in the deflection angle Ω ; and (b) produced with an estimation error of 10% in the section length L .

Also, in the third model, applying Equation (14) with an estimation error of 10% in the section length L results in:

$$\Delta y_{3,L} = \frac{\alpha_{2,3} \cdot L^{\alpha_{2,3}-1} \cdot \exp\left(\frac{\alpha_{3,3} \cdot \Omega}{L}\right) - L^{\alpha_{2,3}-2} \cdot \alpha_{3,3} \cdot \Omega \cdot \exp\left(\frac{\alpha_{3,3} \cdot \Omega}{L}\right)}{L^{\alpha_{2,3}} \cdot \exp\left(\frac{\alpha_{3,3} \cdot \Omega}{L}\right)} \cdot 0.1 \cdot L \quad (21)$$

$$\Rightarrow \Delta y_{3,L} = 0.1 \cdot \frac{\alpha_{1,3} \cdot L - \alpha_{3,3} \cdot \Omega}{L} = \frac{0.0768 \cdot L - 0.000452 \cdot \Omega}{L} \quad (22)$$

The contour plot in Figure 8b illustrates the relative error propagated to the accident prediction according to the result of Equation (22) for the ranges of the segment length and deflection angle in the motorway alignment sample. This shows that the relative error propagated is almost constant at 7.7% and increases slightly with an increasing segment length and a decreasing deflection angle.

5. Conclusions

In this study, a procedure to develop motorway alignment databases for SPFs has been devised. The analysis of the available data showed that it is essential to check the validity of the data used, as they may contain inaccurate or outdated information. The methodology presented in this document combines the advantages of azimuth diagrams and alignment best-fit software to retrieve the alignments of motorway sections. Other auxiliary tools have also been used, such as the adjustment of circular curves in planimetry, for the adjustment of the existing horizontal alignment in singular sections.

A total of 150 km of motorway segments in Portugal were studied under the methodology proposed. This methodology has been validated, observing that the main parameters of the alignment extraction present no significant differences with respect to those of the inventory database in matching alignments. Two patterns were found in the sections where the extracted alignments did not match those of the geometric design inventory. First, total discrepancy in all the variables. Second, sections where the roadways diverge for a certain distance due to right-of-way restrictions and then rejoin, running completely parallel again. In addition, the procedure developed has been used to recreate the alignments that had been found to be incorrect in the inventory. The methodology proposed allows highway administrators to correct these inaccuracies in their inventories.

Finally, the propagation of error in the determination of the independent variables in the fitting of SPFs is discussed based on the results of the extracted alignments. The geometric design features (curve radii, deflection angle and segment length) were used to calculate the curvature, the deflection angle and the segment length and included in the parsimonious GLM. The results indicated that the relative error propagated to the accident frequency is reflected in either a slightly smaller error or a very limited error for the models fitted in the range of values of the sample. In addition, future research should explore how errors in estimating the geometric parameters of alignments arise and examine any potential relationships between these errors.

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