Safety Evaluation: Practical Use Of Collected-Data Vehicle To Obtain Geometric Information Of Existing Roadways

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Synopsis

Roadway geometric data, user behaviour and crash data provide the main input for developing existing highway safety evaluations. In particular, roadway geometric data can be useful in providing quantitative guidance for alignment consistency and for having an initial indication of critical point presence along a road. Researchers in the University of Trieste have already developed some important relationships between the operating speed V85 and the geometric features of a road, introducing the new concept of CCR - curvature change rate - to evaluate the environmental speed of a road section. To determine the CCR, it is important to have geometric information that can be collected from design, but often design is not available. In this case the only way to obtain geometric data is to carry out a road survey.

This paper presents a new methodology to obtain horizontal road information by the elaboration of a dynamic alignment survey. A collected-data vehicle is used to collect three-dimensional data. The vehicle is equipped with a GPS receiver, a vertical gyroscope and a gyrocompass that provides information about the vehicle position (x, y, z coordinates) and orientation (angle of pitch, roll and yaw). Outputs of instruments are used as input data of a software. The developed algorithms produce the main horizontal geometric data (tangent length, tangent azimuth, circular horizontal curve length with relative radius value and centre position, length of spirals).

The algorithms about the location of transition zones between tangent and circular curve are the most interesting and effective. Two different algorithms are used to find geometric data in both of the following cases: tangent to curve transition and spiral transition.

The software was tested for two-lane rural roads in the north - east of Italy, comparing roadway geometric data (algorithm output) with road as-built data. The quality of this comparison was excellent and the difference between calculated and design data was restricted to a small gap.

This effort demonstrates that it is possible to use digital collected-data information to extract important horizontal alignment features and opens the way for use of the developed software in system geometric deficiency and highway safety evaluation.

Safety Evaluation: Practical Use Of Collected-Data Vehicle To Obtain Geometric Information Of Existing Roadways

Roadway geometric data, user behaviour and crash data provide the main input for developing existing highway safety evaluations. As regard user behaviour, the University of Trieste has already studied some relationships in order to link the driver behaviour to the geometric features of the road (Crisman B., Marchionna A., Perco P., Robba A., Roberti R., 2005). The parameter that was chosen to represent user behaviour was the operating speed. On the basis of numerous speed surveys some models were obtained to predict the operating speed of the vehicles as a function of the main horizontal geometric features of the road. In particular, one interesting regression equation was prepared to predict the environmental speed as a function of the CCR (curvature change rate), which represents the general characteristics of an homogenous section belonging to the road. Another two regression equations were prepared to predict the operating speed on the tangents and on the curve as a function of the geometric features of the specific element and as a function of the environmental speed of the homogenous section to which the element belongs. The geometric characteristics of the roads used to develop the prediction models of the operating speed were obtained from the original design plan or from the analysis of the C.T.R.N. (Numerical Regional Technical Cartography). However, when the design plan is not available and the alignment is very long, a new methodology to obtain quick horizontal geometric road information with very high precision could be extremely useful. This new methodology could be useful also to obtain vertical and transversal information when the design plan is not available, as the C.T.R.N. is not able to give this kind of information with an acceptable grade of accuracy.

Moreover, the Road Administrations have also the necessity to know the as-built data of their roads to program the road maintenance and to improve the travelling safety. For this scope a new quick methodology for the reconstruction of the road geometry could be useful to the writing of a road cadastre (Ministry of Public Works, 2001) that, if it was constantly dawned, could be a fundamental device for the improvement of the road safety evaluation.

Some researchers already presented some methodologies for reconstructing the alignment axis (Drakopoulos, Ornek, 2000; Cafiso, Di Graziano, Di Pasquale , 2002), but some problems, as the correct reconstruction of the transition zone, were not solved in a satisfying way.

So, in this paper, a new methodology to obtain geometric road features is presented. Three-dimensional digital information on collected-data vehicle location and orientation were captured using a distance-measuring device (distance travelled), a vertical gyroscope (transverse slope and gradient) a gyrocompass (azimuth) and, in addition, GPS data on vehicle location were captured. Geometric information collected in this manner represents an extremely rich inventory of detailed existing roadway geometry information. The research effort focused on reconstructing continuous roadway geometry information from three-dimensional digital data-base ("raw data") collected at discrete, evenly spaced points along the travelled roadway. The main effort described in the following paragraphs produced some algorithms to process the raw data with an automatic procedure and to obtain as output information the collected-data vehicle path. Following some survey rules described in the next paragraph, the vehicle path can be considered a good representation of the road axis.

Even though an algorithm for the reconstruction of the vertical roadway profile was also prepared, in this paper only the methodology for the horizontal reconstruction is presented.

Finally two practical uses of the collected data are described and the encouraging results obtained for the reconstruction confirm the utility of the software for the automatic determination of the CCR alignment and of the main geometric features of the single road elements.

COLLECTED–DATA VEHICLE FEATURES

The collected-data vehicle (figure 1) used for the road surveys is belonging to the Telegeomatics Excellent Centre of the University of Trieste. The vehicle used is a Mobile Mapping System (MMS). The MMS is a vehicle equipped with some path devices (GPS and odometer) and a series of "cartography sensors" (digital cameras, distance-measuring device, gyroscopes, gyrocompasses). The data of the devices are fused together by the Applanix subsystem to have three-dimensional digital information on the vehicle location in real time and with a high precision quality. The collected-data vehicle is also equipped with two digital cameras that return digital images synchronized with the vehicle location. The data elaboration is organized

in different phases: system preparation (Applanix calibration, definition of the geometric system of instantaneous reference, camera calibration), data collection on the road, data classification, system and coordinates transformation and final information return. The best quality of the MMS is the high level of productivity. To obtain vehicle path information it is necessary only to cover the road in both travelling directions with the sensors active and then the survey is ended. The path information is collected at discrete points along the travelled roadway. The number of points surveyed can be decided before starting the survey with a maximum frequency value of 10 HZ. (Manzoni, 2001; Condorelli, Mussumeci, Parente, Santamaria, 2002).
The MMS gives a lot of information about vehicle location, but for the horizontal geometry road reconstruction only the coordinates x, y, z (H) of the vehicle location, the progressive distance of the vehicle location from a starting point (distance tag) and the instantaneous azimuth (α) of the path (track angle) are used. The accuracy of the measurement is very high and the errors are limited to less than 10 cm for the coordinates x and y, to less than 20 cm for the coordinate z and to less of 0.1° for the azimuth (Manzoni, 2001). An example of the output data of the collected-data vehicle used for the reconstruction is reported in table 1.

Figure 1: the collected–data vehicle

Table 1: output data of the collected-data vehicle

Distance tag [m]	X [m]	Y [m]	H [m]	Track angle [°]
4784,94202	2401181,747	5082297,578	67,683	349,3997803
4785,632723	2401181,635	5082298,258	67,687	349,3724976
4786,325067	2401181,523	5082298,941	67,687	349,3921509
4787,01577	2401181,412	5082299,623	67,69	349,3187561
4788,398816	2401181,185	5082300,989	67,687	349,3288879
4789,0928	2401181,071	5082301,672	67,687	349,3372192
4789,785144	2401180,958	5082302,357	67,685	349,387146
4790,479128	2401180,845	5082303,042	67,682	349,3778992
4791,173112	2401180,732	5082303,727	67,681	349,3751221
4791,865456	2401180,619	5082304,413	67,678	349,3661804
4792,562721	2401180,506	5082305,099	67,675	349,412262

METHODOLOGY OF THE SURVEY

The aim of the research is the determination of the geometric features of an alignment. To achieve this aim, the main concern is to establish the modalities of collecting data, which are fundamental to optimise the final result of the data elaboration.
The quality of the survey data depends on three fundamental variables: the path followed from the collected-data vehicle during the survey, the travel speed of the collected-data vehicle and the frequency of the data collection.
During the survey, the driver of the collected-data vehicle followed, as far as possible, the external white line of the running lane to be sure that all surveyed points belonging to the followed path fell on a line parallel to the real axis of the road. The quality of the survey was certainly improved if the operator followed directly the central line of the road, but this condition was impracticable due to incompatibility and interference of the travelling traffic. However to obviate to the difference between the path of the collected-data vehicle and the real position of the axis of the road that is equal to the width of the lane, one passage of the collected-data vehicle was conducted for each travelling direction. In this way during the phase of elaboration of the collected data, the geometric features of the road axis were obtained considering together the coordinates of all the points of each travelling direction. With this approximation the geometric elements elaborated fall on the geometric axis of the alignment with adequate precision.
Another fundamental variable to obtain a correct reconstruct of the alignment, is the definition of the speed of the collected-data vehicle during the surveys. From the experimental survey conducted, it wasn't possible to determine an optimal speed for the collection. So, based on simple dynamic considerations, it was decided to maintain a constant speed of 30 km/h during the survey. This value of the speed makes it possible to minimize the effects of the imperfection of the road paving on the collected-data vehicle.
The frequency of the data collection is another important parameter that can influence the precision of the reconstruction of the geometric characteristics. During the survey, 10 points per second were collected (frequency of 10 HZ), but this value can be changed on the basis of the operator necessities. Generally, the values of the frequency can influence as the correct identification of the kind of element travelling by the driver (circular curve or tangent) , so the identification of the shorter elements. For these reasons, it isn't possible to define preliminary an optimal frequency of collection. Before starting any new survey it will be necessary to define preliminary the frequency of collection adapted on the basis of the specific geometric features of the road surveyed.
In the experimental surveys that will be described in the following paragraphs of the paper, a frequency of 2 Hz was used to reconstruct the geometric elements. With this frequency of collection and with a speed of the collected-data vehicle of 30 km/h, one point every 4 meters was surveyed.

IDENTIFICATION OF THE SINGLE GEOMETRIC ELEMENTS

If the single points surveyed from the collected-data vehicle (coordinates x, y) are visualized on a computer with a CAD program, it is already possible to have a good representation of the geometry of the alignment. As it is possible to see from the figure 2, the plot of the sequence of the points surveyed makes it possible to perceive immediately the position of the tangents and of the circular curves along the road. But it is not possible from this representation to have precise values of the geometric characteristics of the single road elements. To obtain these values, it was necessary to prepare some algorithms to reconstruct by interpolation the geometry of the surveyed road.
The roads are composed of two fundamental horizontal elements: tangents and circular curves. The new roads have also a third geometric element characterized by a variable value of the curvature: spiral curves.
A software for the automatic recognition of these elements and consequently for the determination of the points belonging to a specific geometric element was prepared. In figure 3 an example of the azimuth variation (α) of the collected-data vehicle path as a function of the covered distance is represented, while in figure 4 the difference of the azimuth for unit of length ($\Delta\alpha$) between two successive surveyed points as a function of the covered distance is represented.
It is very easy to recognize the position of the single geometric elements along the alignment from figure 3. Where the value of α is constant, the vehicle is moving along a tangent, while where the value of α varies linearly, the vehicle is moving along a circular curve. In this graph it is not possible to perceive the errors that could be made during the survey. These errors are more visible in the graph of figure 4. In this second graph the tangents should be characterized by a value of $\Delta\alpha = 0$, while the circular curve should have a constant value of $\Delta\alpha$. Really the imprecision of the survey, caused by the impossibility to follow with precision the white line of the lane, determines the fall of the surveyed points only around the theoretical real values

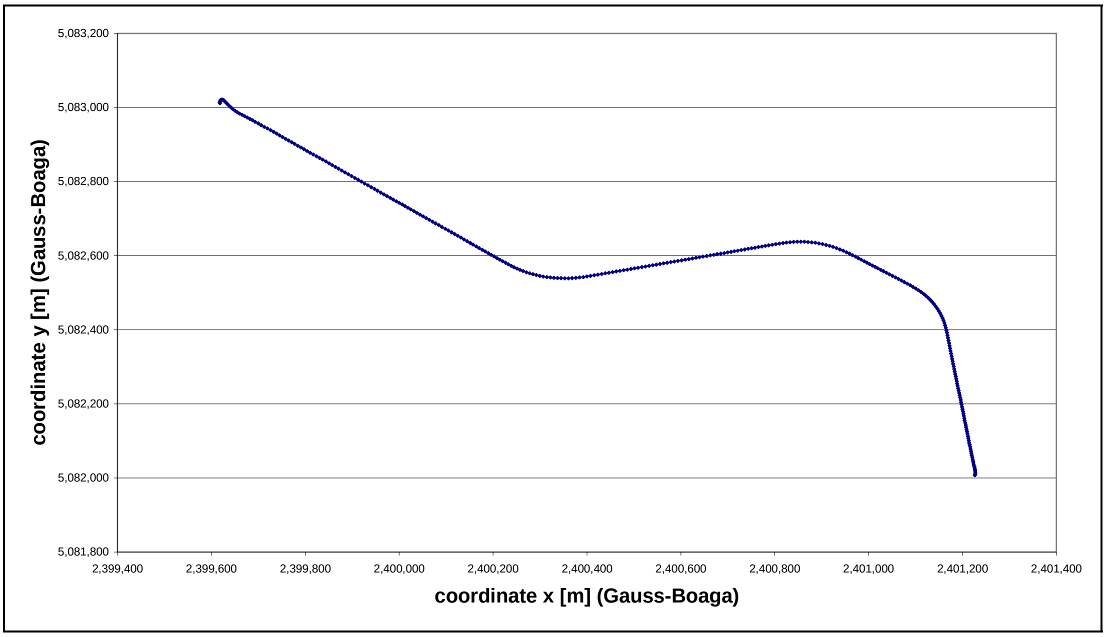

Figure 2: collected-data vehicle path

An algorithm was prepared to identify with an automatic methodology the first and the last points of every geometric element belonging to the alignment. The first step of the algorithm is the calculation of the $\Delta\alpha$ values between each point and the previous one.

$$\Delta\alpha_i = \frac{\alpha_i - \alpha_{i-1}}{d_i - d_{i-1}} \left[\frac{o}{m} \right]$$

where d_i = progressive distance of the point i in meters

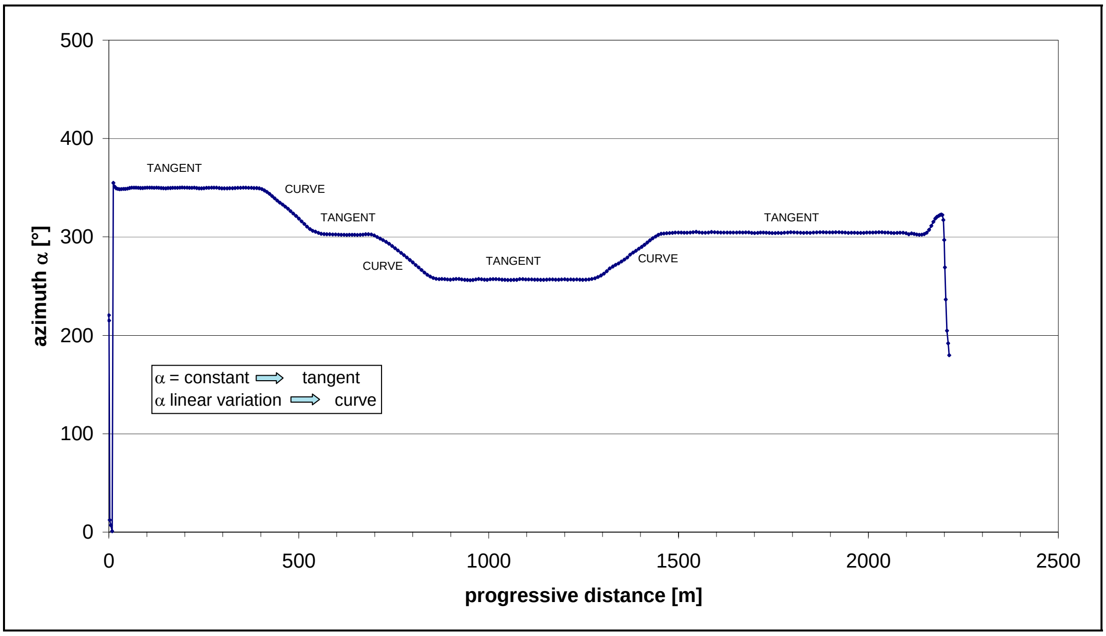

Figure 3: azimuth path of collected-data vehicle

The distance between two successive points is calculated as the difference of the progressive distance values provided by the collected-data vehicle. The local values of $\Delta\alpha$ were compared with two limit values useful to distinguish the circular curves from the tangents. These two limit values were determined since the value of the larger radius of the alignment (R*). All the points characterized by a value of $\Delta\alpha > \Delta\alpha^* = 1/R^* \cdot (360/2\pi)$ belong to a circular curve, while all the points characterized by a value of $\Delta\alpha < \Delta\alpha^{**} = 1/(R^* + \Delta R^*) \cdot (360/2\pi)$ belong to a tangent. The points with a value of $\Delta\alpha$ between $\Delta\alpha^*$ and $\Delta\alpha^{**}$ were not considered in the analysis since they belong to a section of the vehicle path characterized by a variable value of the curvature.

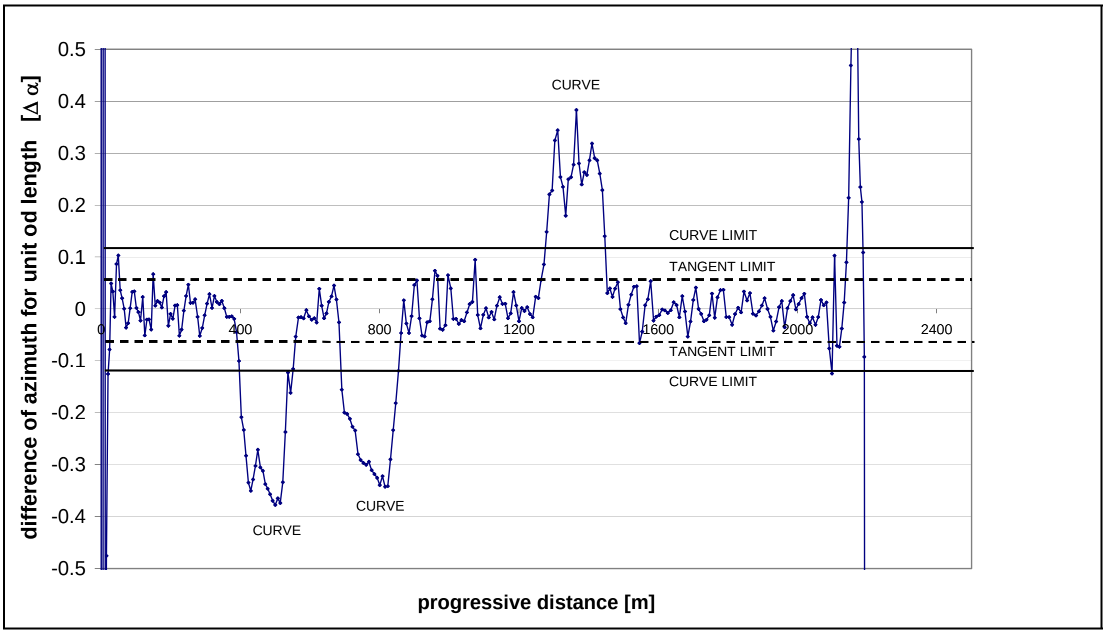

Figure 4: difference of azimuth for unit of length ($\Delta\alpha$) between two successive surveyed points

By means of the experimental surveys described in the next paragraphs, it was observed that this methodology sometimes gives anomalous results. In particular when the radius of the circular curve is higher than 500 m, it can be difficult to recognize correctly the position of the curve inside the alignment. The difficulties probably arose due to the fact that the white lines of the lanes, especially for curves with high radius and short length, can be drawn on the road with a geometry that doesn't respect the axis geometry. Moreover, even if the white line of the curve is perfectly parallel to the axis geometry, probably the collected-data vehicle for curves with high radius and short length is not able to follow with precision the circular path, showing an evident tendency to "cut" the curve, even in very short sections belonging to the curve. These imperfections can lead to the identification of short tangents within the curve and consequently a difficult automatic recognition of the geometric elements belonging to the road.
As regards the tangents, the methodology always gives good results. Only in some sporadic cases erroneous short curves can be found within the tangent, especially when the frequency of the collection data is high and the distance between two consecutive surveyed points is short.
To obviate this problem another algorithm was coupled with the previous one. This new algorithm makes it possible to choose a minimum value acceptable for the length of a geometric element of the road surveyed. If the previous algorithm finds an element with a length shorter than this minimum value, the software rejects this element and considers the relative points belonging to a single element composed on these points and on the points of the previous and of the successive elements. This second algorithm eliminates almost completely the problem of erroneous recognition of a short element within another kind of element, both for the tangents and for the curves. Only in the case of very short curves and with a radius larger than 1000 m does the problem sometimes persist. In this case it might be necessary to insert manually in the software the first and the last points of the uncertain element. These two points can be read from the graph of figure 3 which is the clearer diagram to estimate the point of transition between two different geometric elements.

GEOMETRIC FEATURES OF THE SINGLE ROAD ELEMENTS

After singling out the points belonging to the curves and the points belonging to the tangents, it's necessary to characterize every element of the alignment with its geometric features.
Two different algorithms were prepared to analyse alignments with and without spiral curves.
For both kinds of alignment the algorithm used for the determination of the azimuth and the position of the tangents is the least squares interpolation. For every series of points belonging to a tangent, the parameters "m" and "q" of the generic equation $y = mx + q$, which minimize the distance of the interpolating straight line from the surveyed points, were calculated. Instead, as regards the circular curves, two different algorithms were prepared to determine the geometric features.
In addition a third algorithm was prepared to calculate the value of the radius of the curves only on the basis of the azimuth values.

Alignment without spiral curves:

In this kind of alignment the methodology used to discern the points belonging to the curves from the points belonging to the tangents is the same as that explained in the previous paragraph imposing two limit values for the variable $\Delta\alpha$. The points characterized by an intermediate value of $\Delta\alpha$ belong to the path section that is travelled from the collected-data vehicle in the transition zone between the tangent and the circular curve. These points were eliminated from the analysis since they don't belong to the real geometry of the road, but to the vehicle path.

To determine the geometric features of the circular curves it is necessary to impose three conditions to solve the generic equation of the circumference:

$$(X - X_0)^2 + (Y - Y_0)^2 = R^2$$

where X_0, Y_0 = coordinates of the centre; R = radius of the circumference

The first two conditions are obtained imposing the tangency between the two approach tangents and the circular curve. These conditions are defined making equal the distance between the centre X_0, Y_0 and the two straight lines $Y=m_1+q_1$ e $Y=m_2+q_2$ to the radius R.

$$\frac{|m_1 \cdot X_0 - Y_0 + q_1|}{\sqrt{m_1^{\,2} + 1}} = R; \qquad \frac{|m_2 \cdot X_0 - Y_0 + q_2|}{\sqrt{m_2^{\,2} + 1}} = R;$$

If these equations are written in matrix form, we have:

$$\begin{vmatrix} m_1 & -1 \\ m_2 & -1 \end{vmatrix} \cdot \begin{vmatrix} X_0 \\ Y_0 \end{vmatrix} = \begin{vmatrix} R \cdot \sqrt{m_1^{\,2} + 1} - q_1 \\ R \cdot \sqrt{m_2^{\,2} + 1} - q_2 \end{vmatrix};$$

Imposing then:

$$\begin{vmatrix} m_1 & -1 \\ m_2 & -1 \end{vmatrix} = \underline{M}; \qquad \begin{vmatrix} \sqrt{m_1^{\,2} + 1} \\ \sqrt{m_2^{\,2} + 1} \end{vmatrix} = \underline{MM}; \qquad \begin{vmatrix} q_1 \\ q_2 \end{vmatrix} = \underline{Q};$$

and making explicit the coordinates X_0 , Y_0, we obtain:

$$\begin{vmatrix} X_0 \\ Y_0 \end{vmatrix} = \underline{M}^{-1} \cdot R \cdot \underline{MM} - \underline{M}^{-1} \cdot \underline{Q} = R \cdot \underline{A} - \underline{B} = R \cdot \begin{vmatrix} A_1 \\ A_2 \end{vmatrix} - \begin{vmatrix} B_1 \\ B_2 \end{vmatrix};$$

In the end, two equations, in which the coordinates X_0 e Y_0 are expressed as a function of the radius R, are obtained:

$$X_0 = R \cdot A_1 - B_1; \qquad Y_0 = R \cdot A_2 - B_2;$$

Inserting these two expressions in the generic equation of the circumference and developing it as a function of R:

$$R^2 \cdot (A_1^{\,2} + A_2^{\,2} - 1) - 2 \cdot R \cdot (A_1 X + A_1 B_1 + A_2 Y + A_2 B_2) + B_1^{\,2} + X^2 + 2XB_1 + Y^2 + B_2^{\,2} + 2YB_2 = 0;$$

All the terms A_1, A_2, B_1, B_2 are a function of the geometric parameters m_1, q_1, m_2, q_2 of the approaching straight lines and so they are well-known terms. A first approximation value of the radius of the circular curve R_0 can be calculated inserting into the equation the coordinate X, Y of one of the points belonging to the series surveyed along the circumference.

The following general expression can be obtained developing the equation written above as a Taylor series around the first approximation solution R_0 and stopping the development at the first term of the equation:

$$g\left(X_i, Y_i, R_0\right)+\left(\frac{\partial g}{dR}\right)_0 \cdot \Delta R = \nu_i$$

where ν_i = errors to minimize

ΔR = increase to give at the radius R_0 to minimize the errors ν_i

$$\left(\frac{\partial g}{dR}\right)_0 = 2 \cdot R_0 \cdot (A_1^2 + A_2^2 - 1) - 2 \cdot (A_1 X_i + A_1 B_1 + A_2 Y_i + A_2 B_2)$$

The expression above can be written in a matrix form:

$$\underline{L} + \underline{TT} \cdot \Delta R = \underline{\nu}$$

where: $\underline{L} = \begin{vmatrix} g\left(X_1, Y_1, R_0\right) \\ .... \\ g\left(X_n, Y_n, R_0\right) \end{vmatrix}$; $\underline{TT} = \begin{vmatrix} 2 \cdot R_0 \cdot (A_1^2 + A_2^2 - 1) - 2 \cdot (A_1 X_1 + A_1 B_1 + A_2 Y_1 + A_2 B_2) \\ .... \\ 2 \cdot R_0 \cdot (A_1^2 + A_2^2 - 1) - 2 \cdot (A_1 X_n + A_1 B_1 + A_2 Y_n + A_2 B_2) \end{vmatrix}$;

$\underline{\nu} = \begin{vmatrix} \nu_1 \\ .... \\ \nu_2 \end{vmatrix}$;

To find the value of ΔR that minimizes the errors ν_i can be found by imposing $\sum \nu_i^2 = \min$. In matrix form the expression can be written in the following way:

$$\underline{\nu}^T \cdot \underline{\nu} = \left(\underline{L} + \underline{TT} \cdot \Delta R\right)^T \cdot \left(\underline{L} + \underline{TT} \cdot \Delta R\right) = \min$$

To found the value of ΔR that minimize the expression written above, the value of the first derivative has to be calculated and this value has to be imposed equal to zero.

$$\frac{\partial\left[\left(\underline{L} + \underline{TT} \cdot \Delta R\right)^T \cdot \left(\underline{L} + \underline{TT} \cdot \Delta R\right)\right]}{d\Delta R} = 0;$$

$$\underline{TT}^T \cdot \underline{TT} \cdot \Delta R = \underline{TT}^T \cdot \left(-\underline{L}\right)$$

$$\Delta R = \left(\underline{TT}^T \cdot \underline{TT}\right)^{-1} \cdot \underline{TT}^T \cdot \left(-\underline{L}\right)$$

The calculated value of ΔR makes it possible to improve the first approximation value of the radius R_0. The final value R is the radius which is able to guarantee the tangency between the circumference and the two approaching tangents and at the same time to minimize the distance between the surveyed points and the calculated circumference.

$$R = R_0 + \Delta R$$

Finally the coordinates X_0, Y_0 of the centre of the circumference can be calculated inserting the value of R inside the expressions written above.

Alignment with spiral curves:

In the case of alignment with spiral curves, the reconstruction of the main geometric features of the circular curve – radius, coordinates of the centre, length – is more complex. All the elements characterized by a fixed value of the curvature are included between two elements characterized by a variable value of the curvature.

The individuation and the successive geometric reconstruction of the elements characterized by a variable value of the curvature are, also in the simpler cases, very difficult to obtain. So the methodology to recognize the geometric features of the alignment provides a first step to determine separately the characteristics of the tangents and of the circular curves and then a second step to determine mathematically the spiral parameters on the basis of the shifting from the next two elements. As described in the previous paragraphs, the least square interpolation was used to determine the azimuth of the tangents calculating the straight line that minimizes the distance from all the points surveyed belonging to the tangent. A different algorithm, in respect of the previous one, was developed to determine the characteristics of the circular curves. In this case, the accompanying conditions of tangency between tangents and circular curves are missing and the circumferences are completely free in space. The only condition that can be used to find the geometric features of the curves is the minimization of the distance of the surveyed points from the generic circumference.
The algorithm for the determination of the features of the circular curves can determine the three parameters "a, b, c" of the circumference written in the following form:

$$X^2 + Y^2 + a \cdot X + b \cdot Y + c = 0;$$

The condition of the passing of the circumference in three points (first, middle and last points of the series of points belonging to the circular curve) permits the determination of three parameters of a first approximation a_0, b_0, c_0. The general equation of the circumference written as a Taylor series - stopping the development at the term of first grade - around the first approximation solution can be written in the following form:

$$g(X_i, Y_i, a_0, b_0, c_0) + \left(\frac{\partial g}{da}\right)_0 \cdot \Delta a + \left(\frac{\partial g}{db}\right)_0 \cdot \Delta b + \left(\frac{\partial g}{dc}\right)_0 \cdot \Delta c = \nu_i$$

where $\left(\frac{\partial g}{da}\right)_0 = X_i;\quad \left(\frac{\partial g}{db}\right)_0 = Y_i;\quad \left(\frac{\partial g}{dc}\right)_0 = 1;$

The equation can be written in a matrix form:

$$\underline{L} + \underline{TT} \cdot \underline{\Delta S} = \underline{\nu};$$

where $\underline{L} = \begin{vmatrix} g(X_1, Y_1, a_0, b_0, c_0) \\ .... \\ g(X_n, Y_n, a_0, b_0, c_0) \end{vmatrix};\qquad \underline{TT} = \begin{vmatrix} X_1 & Y_1 & 1 \\ ... & ... & ... \\ X_n & Y_n & 1 \end{vmatrix};\qquad \underline{\Delta S} = \begin{vmatrix} \Delta a \\ \Delta b \\ \Delta c \end{vmatrix};$

The vector $\underline{\Delta S}$ can be calculated imposing $\sum \nu_i^2 = \min$ and equal to zero the first derivate of the addition:

$$\underline{\Delta S} = \left(\underline{TT}^T \cdot \underline{TT}\right)^{-1} \cdot \underline{TT}^T \cdot \left(-\underline{L}\right)$$

The final values of the parameters that define the circular curve can be calculated summing the vector $\underline{\Delta S}$ to the vector of first approximation $\underline{S_0}$:

$$\begin{vmatrix} a \\ b \\ c \end{vmatrix} = |S_0| + |\Delta S| = \begin{vmatrix} a_0 \\ b_0 \\ c_0 \end{vmatrix} + \begin{vmatrix} \Delta a \\ \Delta b \\ \Delta c \end{vmatrix}$$

The values of the radius and of the centre of the circumference can be calculated from the parameters a, b, c.

$$X_0 = -\frac{a}{2};\qquad Y_0 = -\frac{b}{2};\qquad R = \sqrt{X_0^2 + Y_0^2 - c};$$

The values of the parameter A and of the length L of the spiral curves can be calculated if the geometric characteristics of the tangents and of the circular curves are known. With the value Δs of the shifting of every circumference from the approaching tangents, it can be possible to calculate the geometry of the elements characterized by a variable value of the curvature:

$$L = \sqrt{24 \cdot R \cdot \Delta s}\,; \qquad A = \sqrt{R \cdot L}\,;$$

Determination of the radius value on the base of azimuth data:

Another methodology was prepared to determine the radius of the circumference in both the cases analysed (without and with spiral curves). The value of the radius can be calculated considering the variation of the azimuth of the vehicle path along the covered distance (figure 3). Moving along a circumference, the collected-data vehicle follows a path with a constant curvature and this means that the variation of the azimuth for unit of covered distance is constant. The errors made during the survey, caused by the imprecision of the vehicle path and possibly by the imprecision of the white line drawing, don't make it possible to obtain a perfect linear relationship between the vehicle azimuth and the covered distance. A least square interpolation permits the calculation of the value of the angular coefficient of the interpolating straight line that represents the variation of the azimuth path for units of covered distance (figure 5).

$Y = m \cdot X + q\,;$ where $m = \dfrac{\alpha_i - \alpha_{i-1}}{d_i - d_{i-1}} = \Delta\alpha \left[\dfrac{o}{m}\right]$ with d_i = progressive distance of the point i

The value of the circumference radius is obtained from the reverse of the angular variation expressed in radiants.

$$R = \frac{1}{\Delta\alpha} \cdot \frac{360}{2\pi}[m]$$

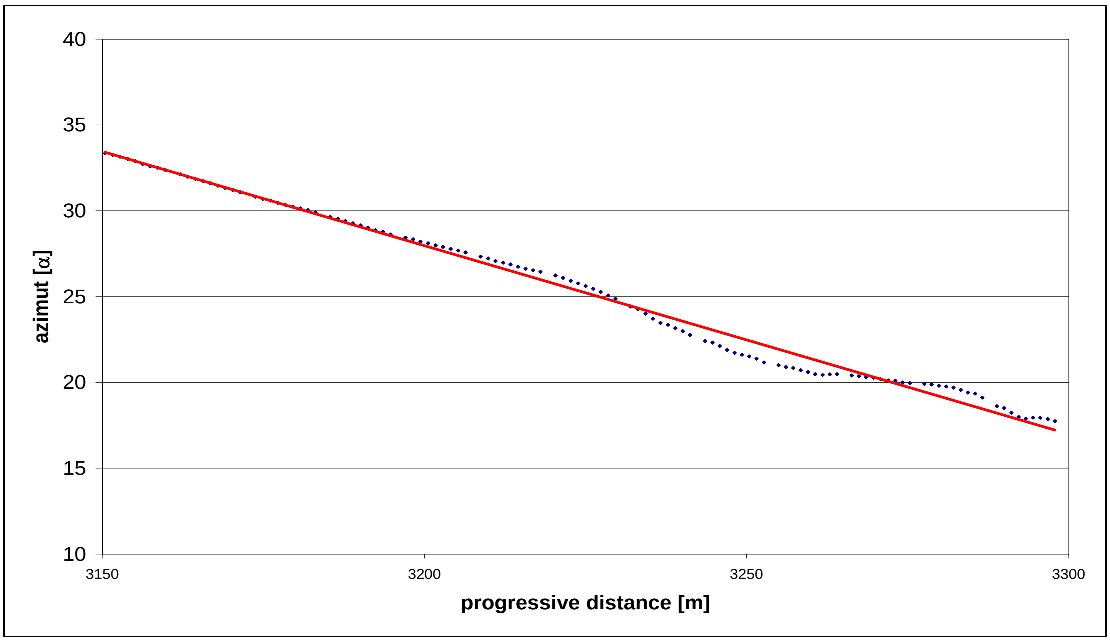

Figure 5: azimuth as a function of the progressive distance on a circular curve

EXPERIMENTAL SURVEYS:

Survey n°1:

The methodology of reconstruction presented in the previous paragraphs has been applied to some practical cases.

The first two-lane rural road studied is the S.P.18 in the province of Gorizia in the north-east of Italy. The section analyzed is about 2200 meters long and has a paved cross section of 6.5 meters (two lanes of 3.00 meters with two paved shoulders of 0.25 meters). The horizontal signs are composed of two white borderlines and one central white line. The alignment is characterized only by the presence of tangent to curve transitions without spiral curves. The three circular curves within the section analyzed are characterized by a value of radius of about 200 m and the section is also characterized by the presence of two sag curves and one crest curve to allow to the alignment to pass over the highway below. Figure 6 presents a map of the surveyed road, while figure 7 shows a photo of the site.

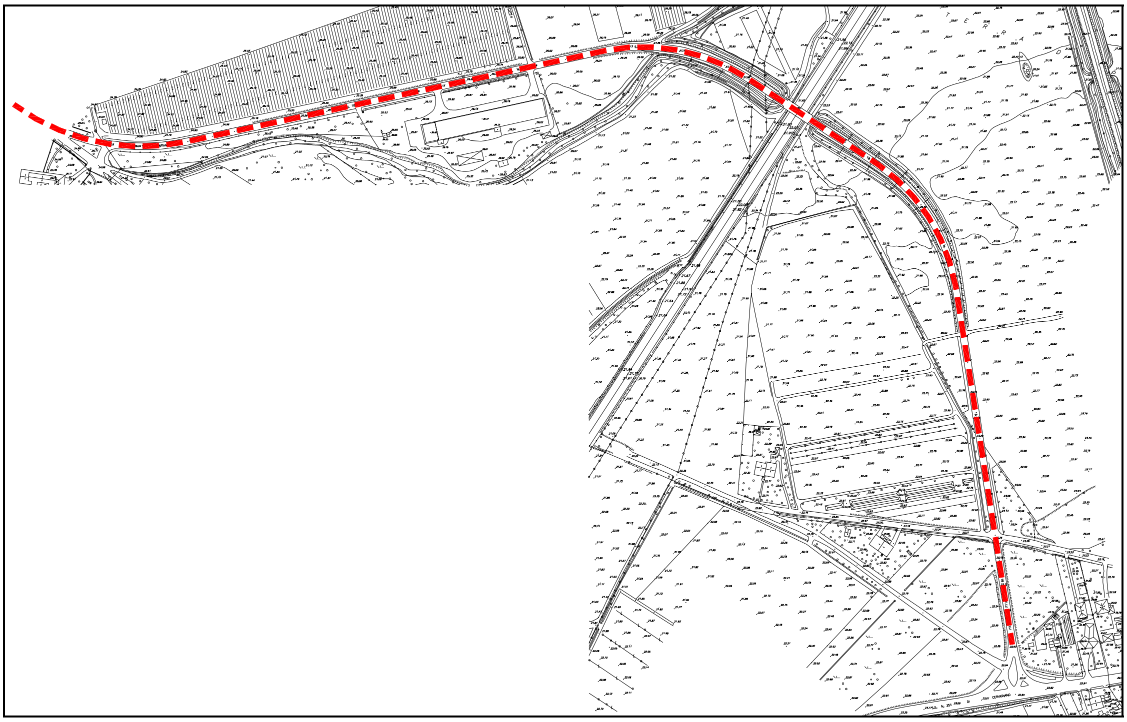

Figure 6: the surveyed road map

Figure 7: a surveyed road photo

The collected-data vehicle traveled along the alignment surveyed in both the travelling directions and always followed the external white line of the carriageway. Both paths, in one direction and in the other one, were reconstructed. The speed of the collected-data vehicle was about 30 km/h and the frequency of collection was set up on 10 Hz, so one point every 0.85 meters was surveyed. To reconstruct the geometry data not all the points surveyed were considered, but only one point in every ten to optimize the operations of recognition of the single geometric elements. Some points belonging to the vehicle path are visualized in figure 8.

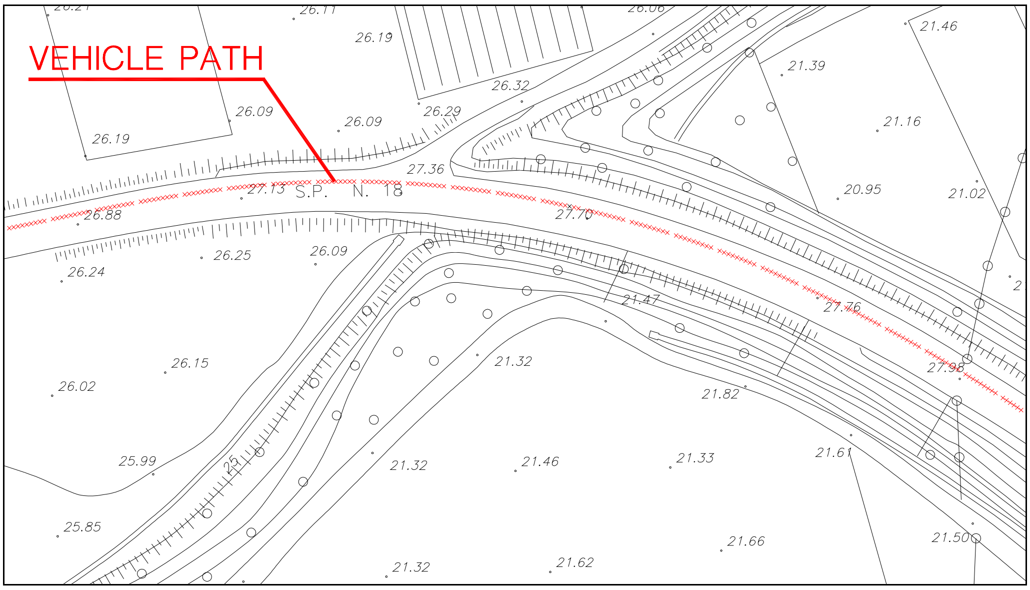

Figure 8: surveyed points of the vehicle path

The first reconstruction regarded only the points belonging to one travelling direction. The analysis data was carried out, as explained in the previous paragraphs, at two different moments. At first the points belonging to the tangents were divided from those belonging to the curves. Two limit values were taken for the value $\Delta\alpha = (\alpha_i - \alpha_{i-1})/d$ on the basis of the larger radius. The higher value of $\Delta\alpha$ ($\Delta\alpha^*$) was taken as equal to 0,115 °/m (corresponding to an instantaneous value of the radius of 500m), while the smaller value of $\Delta\alpha$ ($\Delta\alpha^{**}$) was taken as equal to 0,057 °/m (corresponding to an instantaneous value of the radius of 1000m). All the points, where $\Delta\alpha$ was higher than $\Delta\alpha^*$, were classified as points belonging to a circular curve, while all the points characterized by a value of $\Delta\alpha$ smaller of $\Delta\alpha^{**}$ where classified as points belonging to a tangent. The intermediate values of $\Delta\alpha$ were calculated for points belonging to a path section characterized by a variable value of the curvature (transition sections) and they were not considered in the successive analysis.
The automatic methodology prepared has given good results for the recognition of the single geometric elements along the alignment, indicating no inconsistency in their continuity.
The second phase of the software regards the geometric reconstruction of every horizontal element indicated. Also this second phase has given good results. A comparison between the calculated values and the real data obtained from the analysis of a detailed photogrammetry in scale 1:1000 (figure 9) revealed a very small gap between the two values.

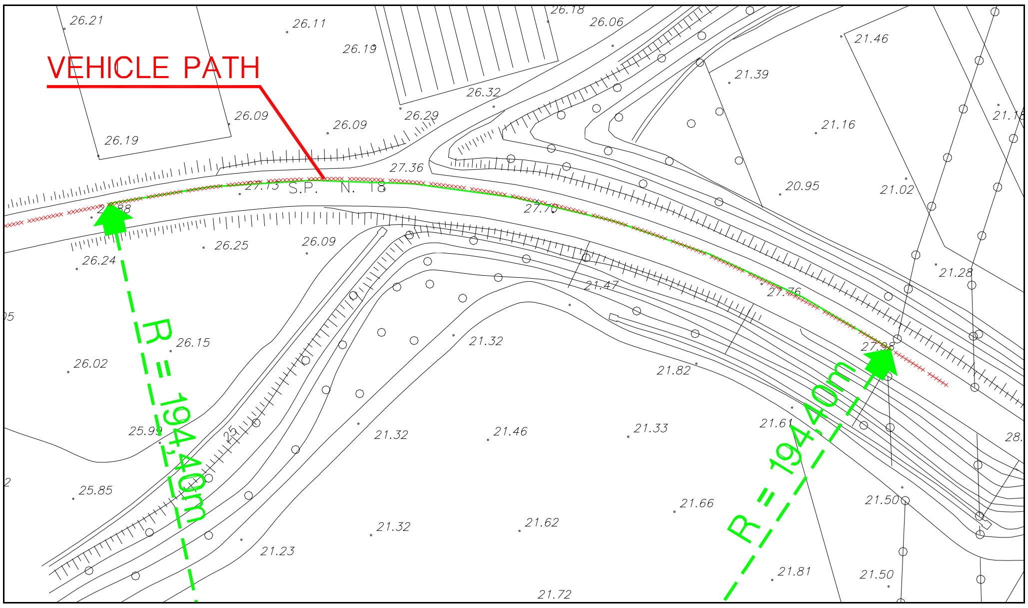

Figure 9: example of reconstruction of a circular curve

An example of the circular curve that minimizes the distance from the points belonging to the vehicle path and that at the same time satisfies the tangency condition with the two approaching tangents is reported in figure 9.
In the tables 2 and 3 the calculated values and the real values are reported for comparison.

Table 2:calculated and real geometric values of the tangents

TANGENT	Calculated values				Real values			
	L [m]	m (tgα)	α [°]	q [m]	L [m]	m (tgα)	α [°]	q [m]
1	341,92	-6,234	-80,88	20.050.192,79	338,57	-6,264	-80,93	20.131.758,56
3	130,49	-0,659	-33,38	6.663.804,38	156,50	-0,658	-33,33	6.650.325,75
5	403,60	0,217	12,24	4561531,15	422,19	0,216	12,19	4.563.994.72

Table 3: calculated and real geometric values of the curves

CURVE	Calculated values				Real values			
	L [m]	X_0 [m]	Y_0 [m]	R [m]	L [m]	X_0 [m]	Y_0 [m]	R [m]
2	148,823	2.400.987,17	5.082.371,13	180,51	146,562	2.400.990,82	5.082.372,51	180,00
4	163,580	2.400.852,60	5.082.443,13	194,40	147.119	2.400.855,16	5.082.449,95	190,00
6	178,052	2.400.258,92	5.082.293,49	214,70	185,081	2.400.264.70	5.082.331.87	215,00

It's important to emphasize that the length of the geometric elements is calculated by the use of another algorithm. This algorithm is able to determine for each couple of tangent-curve the tangency point on the basis of the geometric features of the tangent and of the curve. Naturally this new point is not within the series of points surveyed from the collected-data vehicle. The length of the single geometric element is calculated as a difference in the progressive distance of the two new calculated points at the extremity of the element.
As regards the tangents in table 2 it can be observed that the difference between the calculated azimuth value and the real value is very small. The maximum gap is equal to 0,05°, which means it has a transversal error in the determination of the tangent position of about 8 cm along a distance of 100 m.
The geometric features of the circular curves are also determined with very good precision, especially as regard the values of the radii. The maximum gap found for the curve radius is about 4 meters for a curve of 190 meters (error of about 2%). Small gaps are obtained also for the coordinates of the centre (maximum difference equal to 6 meters for the coordinate Y of the curve 4). Only for curve 6 the differences between the calculated and the real values of the coordinates X_0, Y_0 are more relevant, especially as regard to the Y value. But curve 6 is not within the detailed cartography (scale 1:000) and so the cause of the gap can be found in the real value which was determined from a less detailed cartography (C.T.R.N. – Numerical Regional Technical Cartography).
A second analysis regarded the points belonging the return direction and the results were compared with the values obtained from the first analysis (one way direction). In table 4 the calculated values obtained for both travelling directions are reported. From table 4 it can be observed that the values reconstructed in the two different travelling directions are extremely similar. The only noticeable difference regards the length of the various geometric elements which is equal in the worst case to approximately 16 meters. But, if this difference is compared with the distance between the two successive surveyed points which is equal to approximately 8,5 meters, it is clear that this gap becomes less relevant.
A last analysis regarded the contemporaneous use of the surveyed points in both travelling directions for the determination of one geometric axis that was as far as possible coincident with the real axis of the alignment. The points belonging to one precise geometric element was determined separately for both the travelling directions. Only at the moment of the reconstruction they were considered together. The characteristic values obtained from this analysis present very small differences if compared with the values obtained separately from the two travelling directions. The difference is so small that it isn't possible to define in advance if the result of this analysis taking all the points together is better or worse in respect of the previous two.
The geometric characteristics of tangent 5 and of curve 6 are reported in table 5.

Table 4: calculated geometric values obtained for both travelling direction

TANGENT 1	Length [m]	m (tgα)	q [m]	α [°]
One way	341,9209	-6,233554	20050192,79	-80,8861
Return	322,047	-6,171343	19900805,46	-80,7958
CURVE 2	Length [m]	X_0 [m]	Y_0 [m]	Radius [m]
One way	148,8227	2400987,174	5082371,131	180,5151
Return	152,063	2400987,063	5082370,844	179,1773
TANGENT 3	Length [m]	m (tgα)	q [m]	α [°]
One way	130,4854	-0,65857	6663804,377	-33,3677
Return	114,195	-0,657374	6660932,475	-33,3199
CURVE 4	Length [m]	X_0 [m]	Y_0 [m]	Radius [m]
One way	163,5801	2400852,603	5082443,127	194,4025
Return	157,162	2400852,053	5082439,321	196,119
TANGENT 5	Length [m]	m (tgα)	q [m]	α [°]
One way	403,6035	0,217052	4561531,147	12,24623
Return	417,29	0,217823	4559679,742	12,28838
CURVE 6	Length [m]	X_0 [m]	Y_0 [m]	Radius [m]
One way	178,0521	2400258,921	5082293,495	214,7019
Return	166,228	2400259,672	5082290,61	215,3458

Table 5: geometric features in one way, return and both directions

POINTS	TANGENT 5		CURVE 6		
	m (tgα)	q [m]	X_0 [m]	Y_0 [m]	Radius [m]
One way	12,2462	4561531,147	2400258,920	5082293,494	214,70
Return	12,2883	4559679,742	2400259,672	5082290,609	215,34
Both directions	12,2900	4558942,566	2400260,354	5083391,552	215,29

The software elaborated is able to determine the main geometric features of the single roadway elements. From these data it's possible to obtain very easily a general parameter for the geometric characterization of single sections belonging to the road alignment. This parameter is the CCR (curvature change rate) and it can be useful for the determination of the environmental speed in speed prediction models. The CCR is the summation of the deflection angles (α) of the successive elements of the horizontal alignment per unit of kilometres. The software elaborated is able to calculate this value when the azimuth values of the tangents belonging to the alignment are known. For S.P. 18 the value of the CCR calculated by the software is 87.06 [gon/km].

Survey n°2:

The second experimental survey concerned a two-lane rural road that links Cimpello to Sequals in the province of Pordenone in the north-east of Italy. The road has a cross section of 10,50 m with two lanes of 3,75 m and two paved shoulders of 1,50 m. The road is about 27 km long and is characterized by a series of long tangents linked by circular curves with a very large radius (from a minimum value of 480 m to a maximum value of 2000 m). The spiral curves are always inserted between two consecutive elements with different constant values of the curvature. The cross environment is flat along the entire alignment. The central white line and the white borderlines that divide the lanes from the paved shoulders are always well marked on the pavement.
In this test also, the collected-data vehicle followed the external white line during the survey. It traveled along the alignment in both travelling directions keeping a constant speed of about 40 km/h and surveying the vehicle position with a frequency of 10 Hz (one point every 1,2 meters). Only one point in every five was utilized for the element reconstruction.
The automatic recognition of the tangents and curves position in general gave good results but in some specific cases correct recognition was difficult due to the individuation of some short elements within another kind of element (for example short pieces of tangents where it was clear that all the points surveyed were belonged to a single circular curve). The presence of curves with very large radius and short length made the determination of a limit $\Delta\alpha$ value to recognize the right position of all the circular curves along the alignment

difficult. In particular, as the radius of the curves increased, the automatic recognition of the points belonging to the curves was correspondingly difficult. This problem probably emerges, as already explained in the previous paragraphs, due to the imperfect drawing of the external white line and due to the difficulty of the collected-data vehicle to follow the white line when the variation of the azimuth for unit of length is very small. The algorithm, which makes it possible to choose the minimum length of a single geometric element, has limited the problem, but in some isolated cases it was necessary to insert manually in the program the progressive distance of the first and last points of the element. The progressive distances were read from the graph of figure 11.
The reconstruction of the geometric parameters was conducted using the algorithms described in the previous paragraph for the alignment with spiral curves. In this experimental survey, both the methodologies presented were used for the reconstruction of the circular curves. At first the geometric parameters were reconstruct minimizing the distance of a general circumference from the points belonging to all circular curves (without imposing the tangency with the adjacent tangents); then only the radius of the curves was obtained considering the azimuth variation for unit of length along the curves of the vehicle path. The calculated values were compared with the as-built data obtained from the original road design. The calculated data for the tangents were extremely similar to the as-built ones and they are not tabled in this paper. Instead in table 6 the calculated and the as-built data of the first 6 curves of the alignment are compared.
As can be seen from table 6, the errors in the determination of the radius values can vary within a large range. These errors are included in a range which varies from 2 to 33 % for the first methodology (Taylor series), while they are included in a range which varies from 0 to 17 % for the second methodology (angular coefficient of the straight line interpolating the surveyed points).
The errors naturally increase as the radii become higher and the lengths of the circular curve become shorter.

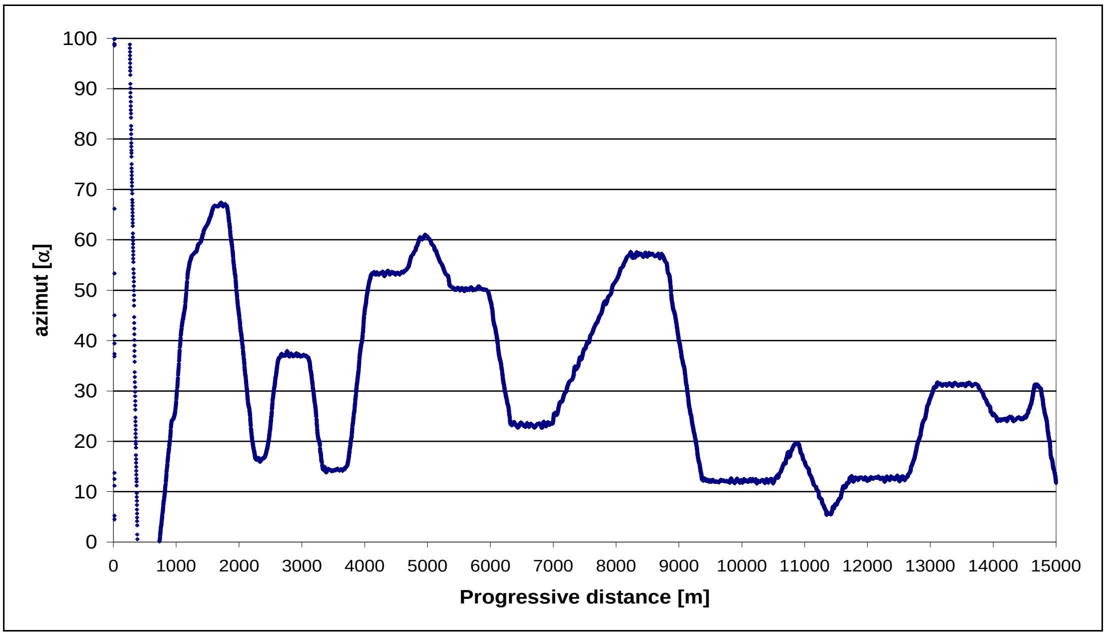

Figure 11: azimuth of the vehicle path

Table 6: comparison between as-built and calculated data

CURVES	AS-BUILT DATA				CALCULATED DATA			
					Taylor			Least square interpolation
	L [m]	R [m]	X_0 [m]	Y_0 [m]	R [m]	X_0 [m]	Y_0 [m]	R [m]
3	324,31	480,00	2.343.897,74	5.092.036,93	499,30	2.343.886,93	5.092.053,19	480,51
4	74,74	480,00	2.344.874,18	5.091.929,17	406,20	2.344.812,24	5.091.965,41	503,07
5	89,70	500,00	2.344.431,50	5.092.943,85	473,70	2.344.456,68	5.092.931,32	486,08
6	230,29	500,00	2.345.509,51	5.093.067,12	491,06	2.345.503,91	5.093.070,86	494,85
7	229,80	2000,00	2.345.840,13	5.092.168,52	2.661,74	2.347.179,55	5.091.598,90	2.334,65
8	312,19	2000,00	2.345.105,86	5.095.776,16	2.091,53	2.345.062,00	5.095.854,93	2.130,09
9	273,36	750,00	2.346.342,33	5.095.156,94	723,42	2.346.365,73	5.095.139,42	729,27

For the first 6 curves of the alignment, the parameters of the spirals were also calculated. These parameters were calculated from the shifting between the circular curves and the adjacent tangents using the algorithms presented in the previous paragraphs. In table 7 as-built and calculated parameters are presented. Also the lengths of the spiral curves are reported.

Table 7: as-built and calculated data for spiral curves

CURVE	AS-BUILT DATA					CALCULATED DATA				
	R [m]	A1	L1 [m]	A2	L2 [m]	R [m]	A1	L1 [m]	A2	L2 [m]
3	480,00	219,09	100,00	219,09	100,00	499,30	162,39	52,81	147,07	43,32
4	480,00	219,09	100,00	219,09	100,00	406,20	248,48	152,00	219,71	118,84
5	500,00	234,52	110,00	234,52	110,00	473,70	259,86	142,55	245,47	127,20
6	500,00	234,52	110,00	234,52	110,00	491,06	294,18	176,23	282,31	162,30
7	2000,00	200,00	20,00	200,00	20,00	2.661,74	661,63	164,64	525,17	103,62
8	2000,00	300,00	45,00	300,00	45,00	2.091,53	375,87	67,55	409,81	80,30
9	750,00	246,00	80,69	246,00	80,69	723,42	345,57	165,08	245,89	83,58

As can be seen from table 7, the calculated geometric characteristics of the spirals can also differ from the as-built data in a relevant way. These differences arise as a consequence of the fact that the collected-data vehicle is not moving along the road axis during the survey, but along an external white line that can't have the same geometric parameter as the spiral curves drawn on the axis. Another reason for these differences can be found in the drawing of the white line which probably has a different geometry in respect of that of the design plan. Moreover, the calculated parameters A and the calculated lengths L of the spirals depend heavily on the geometry of the near elements and so a small error in the determination of these elements can influence also strongly the correct reconstruction of the spiral curve features.
Therefore the methodology presented for the reconstruction of the geometric parameters is not still able to reconstruct correctly the features of the elements characterized by a variable value of the curvature. Perhaps with a larger sample of surveyed roads, the algorithms used in this phase could be improved to minimize the difference between the as-built data and the calculated data.

CONCLUSION

The knowledge of existing roadway geometry is a fundamental parameter to find geometric deficiency along an alignment and to evaluate adequately existing roadway safety. The methodology proposed in this paper is an interesting way to obtain geometry information starting from a dynamic road survey. The dynamic road survey is carried out by a collected-data vehicle that gives accurate discrete data about its location and its orientation along the alignment. These data are input data of a software that is able to capture the position of single geometric elements along the alignment individuating the points belonging to the tangents and to the curves. At a later time another algorithm is able to attribute the geometric features of each road element. Two different algorithms were prepared in the case of alignment with or without spiral curves and this fact makes it possible to optimize the result of the reconstruction. Generally the methodology gives very good results and shows only a small difference with the as-built data used for the comparison. Some problems emerge only for the reconstruction of the geometry of the curves, especially when the radius of the circular curves is higher than 1000 m and the circular curves are short. An attempt to reconstruct the spiral curves was made, but the results show that it's very difficult to determine the right values of the parameter A and of the length of the spiral curves.
The methodology of reconstruction proposed gives excellent result as regards the use of these data for the prediction of the operating speed as a function of the geometric characteristics of the road. Probably if these data were used for the writing of a Road Cadastre, it would be necessary to enlarge the sample of roads surveyed to optimize the algorithm elaborated and to have a clearer view of the errors made in the reconstruction.
Finally, the continuation of this research will be focused on the study of the vertical and transversal reconstruction of the road environment. A module of the software to analyze the vertical radii of the road has just been prepared, but some problems, such as the reconstruction of the vertical radius of the curves when they are very short and very wide are still being studied. When all the modules are ready, the software will provide an excellent device for the three-dimensional reconstruction of the alignment, thus making an important contribution to the developing of the highway safety evaluation.

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