Research and Development of Railway Alignment Design System Using FreeCAD Software

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Abstract. This paper explores the functional modules of railway alignment design in the open source FreeCAD software, and makes a foundation development for other railway majors in the open source software. The interactive interface is designed by pyside. The geometric elements of the railway alignment, the coordinates of the main point (ZH, HY, YH, HZ, QZ) and the elevation of end or start point in vertical curve are calculated according to the intersection data, so as to realize the design of the horizontal and vertical section for the alignment. OCC interface is accessed through part module to realize the synthesis of railway baseline. Comparing the baseline generated by FreeCAD with the pile-by-pile coordinates of a project bid section, the coordinate error is less than millimeters, which can well meet the needs of railway construction.

Keywords. FreeCAD, alignment design, BIM.

1. Introduction
In recent years, BIM (Building Information Modeling) [1] technology has developed rapidly, which has brought new vitality to the entire field of infrastructure construction and promoted the transformation and development of the construction industry [2]. At present, China's BIM technology is still immature. It mainly draws on foreign BIM experience and uses relatively mature foreign BIM modeling software. As an important part of the engineering construction field, railway engineering is different from the point-shaped project in the construction field. It has the characteristics of multiple specialties, complex structure, strip-shaped distribution, and large volume. Hence, it requires customized industry-specific BIM software. The railway alignment is the foundation of railway engineering design, and its design efficiency and quality have a significant impact on the entire railway design. At the same time, the railway horizontal alignment and vertical alignment are the basis for other professional BIM design.

The baseline, the spatial curve coupled by the railway horizontal alignment and vertical alignment, is the basis for other professional modeling of railways, and it also defines the reference system of railway linear engineering. The software currently provided for the railway alignment design mainly includes Bentley MicroStation, Dassault Catia, and Dynamo BIM based on Revit for secondary development. The degree of interoperability between different software is low, and it is easy to cause information loss. Therefore, it is difficult to share information. The railway industry has the problems of inability to customize, modularize,
and the high price of software. Open source software is a better attempt to solve these problems [3].

The open source FreeCAD software is relatively mature in 2D and 3D modeling of BIM, with a large user group, continuous optimization of performance, continuous update of the version, and flexible secondary development. However, FreeCAD software currently does not have a BIM design function for railway engineering construction. Therefore, this paper aims to add railway alignment BIM modeling function design in FreeCAD software, and provide railway alignment basis for other professional BIM modeling of railway.

2. FreeCAD Software Overview

FreeCAD is a Qt multi-platform library, python language and OCC (Open CasCADE) 3D parametric open source modeling software jointly developed by Jürgen Riegel, Werner Mayer, Yorick van Havre and others since 2001. Its R&D design has also been affected by Catia V5 software [4]. OCC is a 3D CAD, CAM and CAE development platform, so OCC is the geometric core of FreeCAD modeling. FreeCAD could simulate everything from tiny electronic components to large architectural and civil engineering project models [5]. At the same time, FreeCAD has Open Inventor 3D/Coin 3D library/3D scene rendering and plentiful Python modules.

At present, the main functional modules in FreeCAD 0.19 pre version include Part module, FEM module, Part Design module, Draft module, Sketcher module, Mesh module, BIM module, Arch module, etc. Among them, the BIM module is separated from the Arch module. Figure 1 shows the overall framework of FreeCAD. The Part module is an intermediate bridge between OCC and other modules.

The characteristics of FreeCAD are follows: (1) Multi-platform running, such as Windows, Linux, Mac OS; (2) Console mode can import python module, python and C++ mixed, development flexibility; (3) Parametric modeling; support scripts and macros which can access any part of FreeCAD, including geometry creation and conversion of 2D and 3D graphics scenes; (4) Modular architecture including various plug-ins: CAD, CAM, Robot, FEM, etc.; (5) Support a large number of standard 2D and 3D CAD file format conversion, such as STL, STEP, IFC, DWG, etc. (6) Files in *.fcstd format contain many different types of information, such as geometric figures, scripts or thumbnail icons, etc.; (7) Allowing operations on complex 3D graphics and supports native concepts such as brep, nurbs, booleans operations, etc.

FreeCAD customized function modules only need to be placed in the installation path.../FreeCAD/Mod folder, and then FreeCAD can be run to run the customized function modules. At the same time, FreeCAD supports python or macro customization tools.

![Figure 1. The framework of FreeCAD software [4].](image-url)
3. Railway Alignment Design Algorithm

3.1. Railway Horizontal Curve Design Algorithm

The horizontal curve is the projection of the baseline on the X/Y plane, and consists of a group of orderly, end-to-end horizontal curve segments. The horizontal curve segment includes: 2D straight line segment, 2D transition curve segment, 2D circular arc segment [6]. Among them, the 2D transition curve segment is a curve with continuous curvature set between straight line segment and circular arc segment or between two circular arc segments with different radius. As the curvature changes, the corresponding super high gradually increases, thereby playing a role of transition [7].

Newly-built railways in China generally use a cubic parabola to represent the transition curve. As shown in figure 2, JD is the intersection of the railway horizontal curve; ZH is the intersection of the straight line and the transition curve; HY is the intersection of the first transition curve segment and circular arc; YH is the intersection of the circular arc and the second transition curve segment; HZ is the intersection of the second transition curve segment and the next straight line; QZ is the midpoint of the curve; $\alpha$ is the railway alignment deflection angle; $T$ is the length of the tangent railway alignment; $l_1$ and $l_2$ are the length of the front and back transition curve segment; $R$ is the radius of the circular arc.

![Figure 2. Schematic diagram of transition curve segment.](image)

The calculation equations for the geometric elements of the transition curve are as follows.

\[
\text{Inward distance } \quad p \approx \frac{l_1^2}{24R} \quad (1)
\]

\[
\text{Tangential Offset } \quad m \approx \frac{l_1}{2} \quad (2)
\]

\[
\text{transition curve angle } \quad \beta_0 \approx \frac{90l_1}{\pi R} \quad (3)
\]
The calculation steps of the principal point coordinates of the railway horizontal curve plane are as follows.

**Step 1.** The coordinate calculation equation of ZH point is written as

$$
\begin{align*}
    x_{zh} &= x_i - T_i \cos A_{i-1} \\
    y_{zh} &= y_i - T_i \cos A_{i-1}
\end{align*}
$$

(8)

**Step 2.** The HY point coordinates are solved as follows. The first transition curve has ZH as the origin, the tangent to the ZH point is the \( x \) axis, the vertical tangent is the \( y \) axis, \( l \) is the length of the curve from any point on the transition to the origin (ZH), and \( l_i \) is the length of the front transition curve. \( I \) is a symbolic function. When \( A_i < A_{i-1}, I = 1 \), and when \( A_i > A_{i-1}, I = -1 \).

The local coordinate equation is written as:

$$
\begin{align*}
    x_p &= l - \frac{l^3}{40R^2I_1^3} + \frac{l^9}{3456R^4I_1^9} \\
    y_p &= \frac{l^3}{6RI_1^3} - \frac{l^7}{336R^3I_1^7} + \frac{l^{11}}{42240R^5I_1^{11}}
\end{align*}
$$

(9)

The global coordinate equation is written as:

$$
\begin{align*}
    x_{hy} &= x_{zh} + x_p \cos A_{i-1} + y_p \cos(A_{i-1} + I * \pi/2) \\
    y_{hy} &= y_{zh} + x_p \sin A_{i-1} + y_p \sin(A_{i-1} + I * \pi/2)
\end{align*}
$$

(10)

**Step 3.** HZ point coordinates are written as:

$$
\begin{align*}
    x_{hz} &= x_i + T \cos A_i \\
    y_{hz} &= y_i + T \sin A_i
\end{align*}
$$

(11)

**Step 4.** The global coordinates of the HZ point are written as:

$$
\begin{align*}
    x_{yz} &= x_{hz} - x_p \cos A_i + y_p \cos(A_i + I * \pi/2) \\
    y_{yz} &= y_{hz} - x_p \sin A_i + y_p \sin(A_i + I * \pi/2)
\end{align*}
$$

(12)
where, the second transition curve takes HZ as the origin, the tangent of the HZ point is the x axis, and the vertical tangent is the y axis. The local coordinate equation is the same as the HY point coordinate.

3.2. Railway Vertical Curve Design Algorithm
The railway vertical curve is an elevation curve that unfolds along the railway horizontal curve, which is composed of a set of orderly, end-to-end vertical curve segments. Vertical curve segment is divided into three types: straight line segment, circular arc segment and parabolic segment [8].

In the design process of the railway vertical curve section, generally in order to simplify the calculation, the circular arc section and the straight line section are generally connected in order to form the vertical curve segment. As shown in figure 3, A is the starting point of the circular arc segment; B is the end point of the circular arc segment; R is the arc radius; BP is the grade change point; \( \alpha \) is the slope angle; \( i_1 \) is the back slope; \( i_2 \) is the front slope; \( \omega \) is the slope difference between front and back. In FreeCAD, a vertical curve is drawn on the XOZ plane, the x axis is the continuous mileage, and z is the elevation.

![Figure 3. Schematic diagram of vertical curve.](image)

The geometric elements of the vertical curve are calculated as follows.

\[
\omega = i_2 - i_1 \quad (13)
\]

where, \( \omega \) is the variable slope angle. When it is greater than 0, it is a concave curve; when it is less than 0, it is a convex curve.

Vertical curve length \( L = Ro \omega \) \quad (14)

Tangent length \( T = L/2 \) \quad (15)

External distance \( E = \frac{T^2}{2R} \) \quad (16)

The mileage of the starting point A of the circular arc is calculated as follows.

\[
z_{yk} = BPK - T \quad (17)
\]

The mileage of the end point B of the circular arc is calculated as follows.
The longitudinal distance \( y \) of any point on the vertical curve is calculated as follows.

\[
y = \frac{x^2}{2R}
\]  

(19)

where, \( y \) is the longitudinal distance of the calculation point, and \( x \) is the difference between the mileage of the calculation point and the starting point of the vertical curve.

The calculation steps for the design elevation of any point on the vertical curve are as follows.

**Step 1.** The tangent elevation is calculated as follows.

\[
H_0 = H_{JD} - (T - x) \cdot i
\]  

(20)

where, \( H_{JD} \) is the elevation of the variable slope point, \( H_0 \) is the tangent height of the calculated point, and \( i \) is the longitudinal slope.

**Step 2.** The calculated design elevation is as follows.

\[
H = H_0 \pm y
\]  

(21)

where, \( H \) is the design elevation, and \( \pm \) indicates the uneven curve.

### 3.3. Baseline Algorithm

The baseline defines the reference system of railway linear engineering, which is formed by coupling the horizontal curve and the vertical curve [6]. The coupling algorithm is to cut from the mileage corresponding to the horizontal curve, stretch the cut curve plane along the z-axis into an infinite surface, and then use the edge generation algorithm. Define the range (mileage) corresponding to the value range (elevation) on the surface, and find the curve on the surface, which is the baseline.

### 4. Program Design and Implementation

#### 4.1. Framework Design

The railway alignment design function module adopts python secondary development as a whole, and its alignment geometric interface is realized by OCC. In FreeCAD, customize BaseLineWorkbench, that is, a railway alignment work module. The module has four functions, which are horizontal curve, vertical curve, baseline, and mileage design. The first three functions are to complete the geometric interface of OpenCasCADE in the FreeCAD source code. The Python console access the interface of the horizontal curve, vertical curve, railway baseline, through the Part module, namely Part.createObjectHorizontal, Part.createObjectVertical, Part.composeBaseline, and returns the wire geometry type. The program interface is implemented by Pyside.

Figure 4 is a class diagram of the entire program design. _HorizontalLine and _VerticalLine inherit the Component class in the Arch module. This class mainly performs operations such as occ interface call, parameterized geometry, and adding related attributes. The _viewProviderHorizontalLine and _viewProviderVerticalLine classes provide FreeCAD geometric display, such as linear size, color, etc. TransitionCurveFeature is the calculation of horizontal curve geometric elements and principal point coordinates, and VerticalCurveFeature is the vertical curve geometric elements and mileage calculation. makeHorizontalLine and makeVerticalLine mainly deal with parameters, create new FeaturePython objects and assign geometric values. The HorizontalTaskPanel and VerticalTaskPanel classes implement the interactive interface of Axure prototype design in the task panel in FreeCAD. Alignment2DVerticalCmd
and Alignment2DHorizontalCmd are mainly interface functions used to add functions to the FreeCAD custom Baselineworkbench. Mileage class is a mileage design.

![Class structure diagram](image)

**Figure 4.** Class structure diagram.

### 4.2. Interface Design

The interface is defined using the PySide module (figure 5). The interface contains two parts, one is the parameter input part, and the other is the parameter list. The parameter input part is to input data through the interface and then add it to the parameter list. Import external data can also be used in the parameter list, such as *.csc, *.txt, *.xlsx and other data formats. At the same time, the input data can be exported into other data formats. In the parameter list, you can view all the elements of the intersection point, such as the length of the tangent line, the length of the transition curve, the value of Inward distance, the outer distance and other elements.
4.3. Key Algorithm Implementation

In the key algorithm of the railway alignment, the flow diagram of the horizontal curve geometry and vertical curve geometry is shown in figure 6. According to the equation of the horizontal curve, the x and y coordinates of the ZH, HY, YH, HZ point are calculated. the point between ZH and HY is transition curve segment; between HY and YH is circular arc segment; between YH and HZ is transition curve segment; between HZ and next ZH is line segment. The transition curve is three times parabola.

Figure 5. Interactive interface design.

Figure 6. The flow chart of the horizontal and vertical curve.
According to equation 9, the local coordinate calculation is calculated according to a certain distance. Then use equation 10 to get the corresponding geodetic coordinates to get equidistant scattered points on the transition curve. According to the discrete point interpolation, the B-spline curve is fitted to generate the transition curve. Finally, the line segment, the transition curve segment, and the circular arc segment are connected in order to form the horizontal curve, as shown in figure 7.

![Figure 7. The horizontal curve.](image)

On the basis of the horizontal curve, the vertical curve is drawn in the XOZ plane. The mileage is x and the elevation is z. According to the equation, the start and end points of the circular arc segment in the vertical curve are calculated. The start point (A) and the previous end point (B) are connected to form a line segment, and the between the start point (A) and the end point (B) is a circular arc segment. Finally, the line and the circular arc are connected in order to form the vertical curve, such as figure 8.

![Figure 8. FreeCAD schematic diagram of the curve](image)

The design of the mileage system is as follows. On the basis of the horizontal curve, input the starting mileage and the chain scission parameters. The mileage of the entire railway alignment is calculated, and the chain scission parameters are added as attributes to the alignment attributes. The display of mileage pile number is only related to the horizontal curve, as shown in figure 9.
According to the baseline algorithm, select the horizontal curve geometry and vertical curve geometry. Then transfer the Part.composeBaseline interface to couple into a spatial curve. Convert the FCStd format of the baseline to the kmz format and display it in Google Earth (figure 10).

5. Application Case

This article uses the horizontal curve parameters of a project bid mileage K66+100~K129+154.304 and the vertical curve parameters of K85+305~K109+950 as the test data. The K86+00~K108+00 railway alignment design coordinates provided by the project department are used to verify the accuracy of the. The test data is input into the program, the baseline is drawn and the coordinates of each pile are calculated. Comparing with the pile-by-stake coordinates provided by the bidding project, the mean value of X error is 0.1mm, and the RMSE is 0.0001. The mean error of Y is 0.1 mm, and the RMSE is 0.0001. The mean error of the elevation Z is 0.005 mm, and the RMSE is 0.0002. This shows that the error between the pile-by-stake coordinates of the baseline drawn in FreeCAD and the design coordinates provided by the project team is about 0.1 mm, and the error of the z-coordinate is negligible, and the accuracy can well meet the needs of engineering construction. Table 1 lists the coordinate error comparison of the transition curve between K86+240~K86+640.
6. Conclusion
This paper investigates the realization of the railway alignment design system of the open source software FreeCAD. Using python and occ for secondary development in FreeCAD, the railway alignment design system is completed. FreeCAD customizes the workbench, and the functional designs are added, such as horizontal curve, vertical curve, baseline etc. The baseline generated by FreeCAD can satisfy the railway engineering construction very well. It provides a positioning reference for the professional BIM models of railways such as bridges, subgrades and tunnels for the realization of the railway alignment.

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| Mileage stake | Design coordinates (m) | FreeCAD coordinates (m) | Errors (m) |
|---------------|------------------------|-------------------------|------------|
|               | X                      | Y                       | Z          |
| K86+240       | 2806615.8089 497976.9115 29.1450 | 2806615.8085 497976.9113 29.1452 -0.0004 -0.0002 0.0002 |
| K86+260       | 2806597.8208 497968.1690 29.0520 | 2806597.8205 497968.1688 29.0518 -0.0003 -0.0002 -0.0002 |
| K86+280       | 2806579.8488 497959.3937 28.9580 | 2806579.8485 497959.3935 28.9583 -0.0003 -0.0002 -0.0003 |
| K86+300       | 2806561.8920 497950.5873 28.8650 | 2806561.8917 497950.5872 28.8649 -0.0003 -0.0001 -0.0001 |
| K86+320       | 2806543.9495 497941.7516 28.7710 | 2806543.9492 497941.7515 28.7714 -0.0003 -0.0001 0.0004 |
| K86+340       | 2806526.0207 497932.8884 28.6780 | 2806526.0204 497932.8882 28.6780 -0.0003 -0.0002 0.0000 |
| K86+360       | 2806508.1047 497923.9993 28.5850 | 2806508.1044 497923.9991 28.5849 -0.0003 -0.0002 -0.0005 |
| K86+380       | 2806490.2007 497915.0860 28.4910 | 2806490.2004 497915.0859 28.4911 -0.0003 -0.0001 0.0001 |
| K86+400       | 2806472.3079 497906.1504 28.3960 | 2806472.3075 497906.1502 28.3976 -0.0004 -0.0002 -0.0004 |
| K86+420       | 2806454.4254 497897.1940 28.3040 | 2806454.4251 497897.1938 28.3042 -0.0003 -0.0002 0.0002 |
| K86+440       | 2806436.5224 497888.2187 28.2110 | 2806436.5221 497888.2185 28.2107 -0.0003 -0.0002 -0.0003 |
| K86+460       | 2806418.6881 497879.2260 28.1170 | 2806418.6878 497879.2259 28.1173 -0.0003 -0.0001 0.0003 |
| K86+480       | 2806400.8316 497870.2179 28.0240 | 2806400.8313 497870.2177 28.0238 -0.0003 -0.0002 -0.0002 |
| K86+500       | 2806382.9822 497861.1958 27.9300 | 2806382.9819 497861.1957 27.9304 -0.0003 -0.0001 0.0004 |
| K86+520       | 2806365.1389 497852.1616 27.8370 | 2806365.1386 497852.1615 27.8369 -0.0003 -0.0001 -0.0001 |
| K86+540       | 2806347.3009 497843.1170 27.7430 | 2806347.3006 497843.1168 27.7435 -0.0003 -0.0002 0.0005 |
| K86+560       | 2806329.4673 497834.0636 27.6500 | 2806329.4670 497834.0635 27.6500 -0.0003 -0.0001 0.0000 |
| K86+580       | 2806311.6373 497825.0032 27.5570 | 2806311.6370 497825.0030 27.5566 -0.0003 -0.0002 -0.0004 |
| K86+600       | 2806293.8100 497815.9374 27.4630 | 2806293.8097 497815.9373 27.4631 -0.0003 -0.0001 0.0001 |
| K86+620       | 2806275.9846 497806.8680 27.3700 | 2806275.9843 497806.8679 27.3697 -0.0003 -0.0001 -0.0003 |
| K86+640       | 2806258.1602 497797.7966 27.2760 | 2806258.1599 497797.7965 27.2762 -0.0003 -0.0001 0.0002 |
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