

Article

Collaborative Methods of Resolving Road Graphic Conflicts Based on Cartographic Rules and Generalization Operations

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Abstract: The resolution of road graphic conflicts is a key aspect of map generalization, which involves both scale reduction and the symbolization of map features. This study proposes collaborative methods of road graphic conflict resolution considering different road characteristics. These methods consider both geometric and semantic characteristics, and they incorporate the bend characteristics of roads, the road symbol size, and road semantics. Constrained Delaunay triangulation skeleton lines are used to categorize road graphic conflicts, which are made up of four independent conflict types and four group conflict types. Based on their characteristics, three collaborative methods are designed to deal with the different types of road graphic conflicts: collaboration between deletion and the snake displacement model, collaboration between the snake displacement model and collinearity, and collaboration among simplification, smoothing, and the beam displacement model. Two types of independent conflicts can be processed using only one simple operation. This study summarizes the cartographic rules for resolving road graphic conflicts, and these are used along with geometric features to drive the collaborative methods or one simple operation presented here. The experimental results indicate that the method proposed in this study can effectively resolve road graphic conflicts.

Keywords: cartographic generalization; road graphic conflicts; conflict resolution; cartographic rules; collaborative methods; displacement model



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1. Introduction

Road generalization is an important research direction in the field of map generalization [1–3]. It mainly includes road selection [4,5], road simplification [6,7], road pattern recognition [8], and road displacement [9–11]. Graphic conflicts are drivers of road generalization after road symbolization in the process of reducing the map scale [12]. Graphic conflict resolution is one of the challenges for automatic cartographic generalization [13]. The clear representation of roads on a map necessitates the resolution of graphic conflicts. Displacement is considered the main operation in the resolution of graphic conflicts in map generalization. Ai [14] used the concept of vector fields to execute polygonal target group displacement while considering contextual factors. Burghardt and Meier [15] first introduced the snake displacement model in cartographic generalization for curve displacement, and Bader [9] proposed the beam displacement model. Snake and beam displacement models have been employed to address road and building generalization [10,16–20].

Wang [17] divided displacement methods into continuous geometry and optimization methods. Continuous geometry methods handle spatial conflicts on a case-by-case basis by using a displacement method. Nickerson [21] proposed a road displacement method by using a buffer to detect graphic conflicts. Fei [22] used a displacement operation to resolve graphic conflicts between streets and buildings on a map. Optimization methods resolve graphic conflicts from a global perspective, for example, with the snake and beam

displacement models [16–20]. Ware and Jones [23] used a simulated annealing approach to perform displacement operations and resolve graphic conflicts. Subsequently, Ware, Jones, and Thomas [24] improved this approach by considering generalization operations such as displacement, deletion, exaggeration, and reduction. However, displacement algorithms alone cannot solve all graphic conflicts when there is insufficient map space for displacement.

In recent years, different generalization operators and algorithms have been combined to create effective cartographic generalization approaches driven by map generalization rules, such as a series of collaborative model generalization methods developed based on agent models [25–31]. Li [32] proposed a collaborative method by combining three cartographic generalization operations to resolve the spatial conflicts between buildings and other features in urban villages. Thus, collaborative ideas should be an effective approach to resolving graphic conflicts.

This study proposes collaborative methods for resolving different types of road graphic conflicts. The main contributions of this study are as follows:

- (1) Road graphic conflicts can be automatically categorized into eight types: four independent conflict types and four group conflict types, which provides a basis for their resolution.
- (2) Three collaborative methods were designed to deal with different types of road graphic conflicts, namely, collaboration between deletion and the snake displacement model, collaboration between the snake displacement model and collinearity, and collaboration among simplification, smoothing, and the beam displacement model.
- (3) The cartographic rules for resolving road graphic conflicts are summarized and used to drive the collaborative methods or one simple operation.

This study is organized as follows: the methodology is introduced in Section 2, which includes the recognition and classification of road graphic conflicts, collaborative methods for road graphic conflicts, and cartographic rules for resolving graphic conflicts. The experiments and analysis are reported in Section 3 with experimental illustrations. The main conclusions of the work are provided in Section 4.

2. Methodology

After the map scale is reduced, road graphic conflicts arise when roads are symbolized. Not all road graphic conflicts can be resolved using only one operation [10,17]. Therefore, it is crucial to determine which operation or operations are used to resolve different types of road graphic conflicts. When multiple operations must be used at the same time, these operations must work together to process the data in the road conflict area. The completion of a specific map generalization task often necessitates the combination of several operations [33]. A data processing workflow based on collaborative methods for resolving road graphic conflicts is shown in Figure 1, and the following are the main methods proposed in this study.

- (1) Road graphic conflicts are recognized and classified, and the characteristics of the conflict areas are calculated. According to the average distance between the skeleton lines in road graphic conflict areas, conflicts are classified as independent conflicts or group conflicts, which are each further subdivided into four subclasses based on the relevant characteristics of the skeleton lines in the conflict areas. Each subclass corresponds to a collaborative method or an operation.
- (2) According to the type of road graphic conflict, simple operations are used individually or cooperatively. Simple operations for resolving road graphic conflicts include deletion, displacement, collinearity, smoothing, and simplification. The collaborative methods designed in this study include collaboration between deletion and the snake displacement model, collaboration between the snake displacement model and collinearity, and collaboration among simplification, smoothing, and the beam displacement model. Cartographic rules for resolving road graphic conflicts are established with reference to cartographic specifications and conditions, which establish

correspondences between the type of road graphic conflict and the use of simple operations or collaborative methods.

- (3) It is judged whether there are subsequent graphic conflicts in the generated map, and, if so, it is necessary to rejudge the type of road graphic conflict and continue to resolve it. The process is repeated until there are no subsequent graphic conflicts in the generated map.

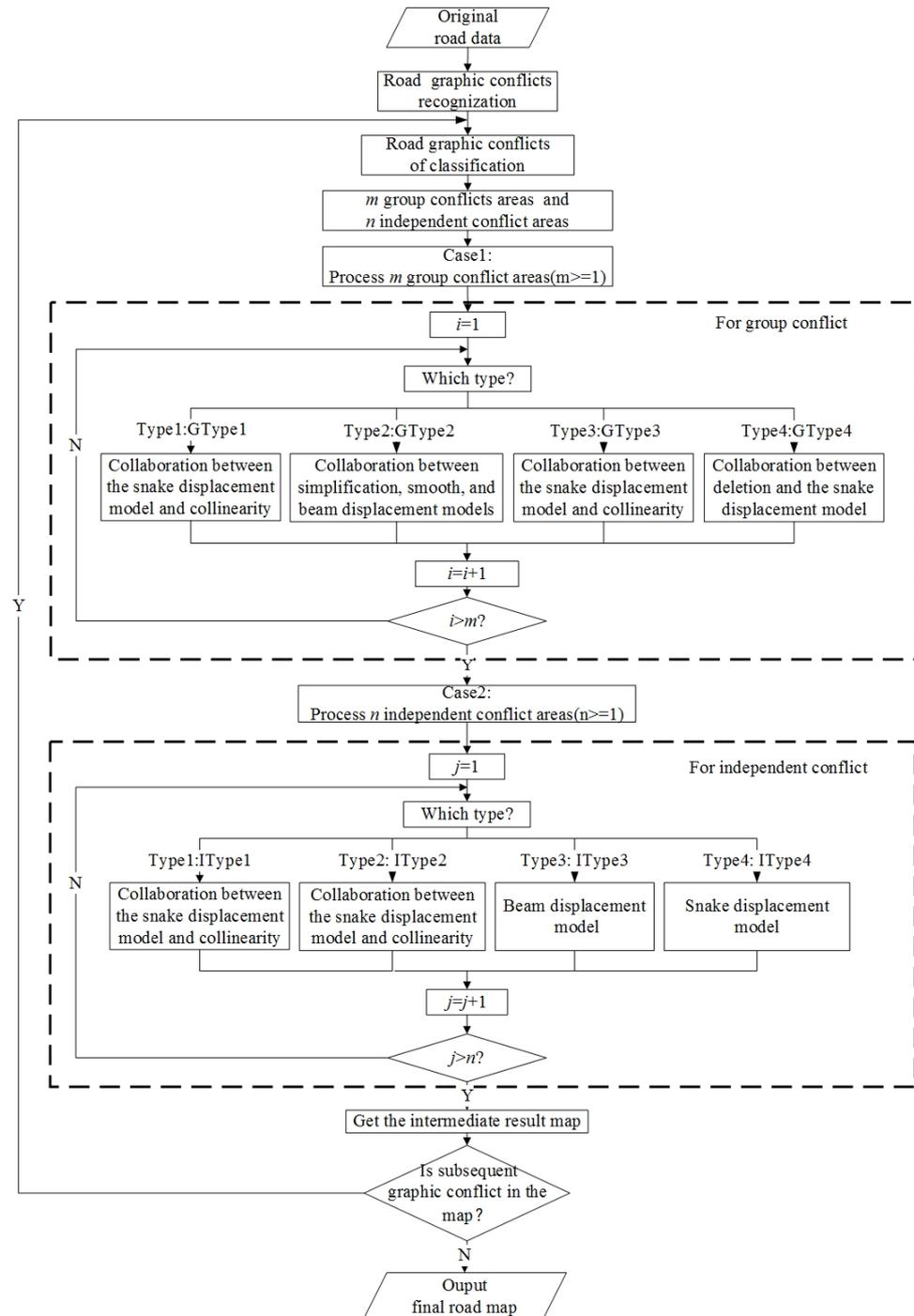


Figure 1. Data processing workflow based on collaborative methods.

2.1. Recognition and Classification of Road Graphic Conflicts

It is necessary to first identify road graphic conflict areas. Constrained Delaunay triangulation (CDT) is widely used in cartographic generalization for neighborhood calculations and spatial conflict detection [34,35]; road graphic conflicts are detected by extracting skeleton lines through CDT, and information on the relevant road characteristics is calculated to assist in the resolution of road graphic conflicts.

2.1.1. Conflict Recognition and Characteristic Information Calculation

Based on the road centerline and the road symbol width, road symbol borderlines can be generated. Using the road centerline and its road symbol borderlines as constraint edges, constrained Delaunay triangulation (CDT) can be applied. Skeleton line extraction methods based on CDT can be used to identify graphic conflicts on roads [10,17]; each road graphic conflict area can be represented by its skeleton line. The triangles in CDT can be categorized into 11 types, as seen in Figure 2, considering the numbers of triangle edges and triangle vertices located on road symbol borderlines or road centerlines. R_{mn} indicates the classification of triangles, where m indicates the total number of constrained triangle edges, and n indicates the n th subtype of the m th type.

All triangles crossed by the skeleton line in a conflict area form a triangular path. If one of two triangles located at the ends of a triangular path belongs to the R_{2n} type, then the triangle is called EnT, the last triangle on this triangular path is called ExT, and all triangles between EnT and ExT along this triangular path are called MT.

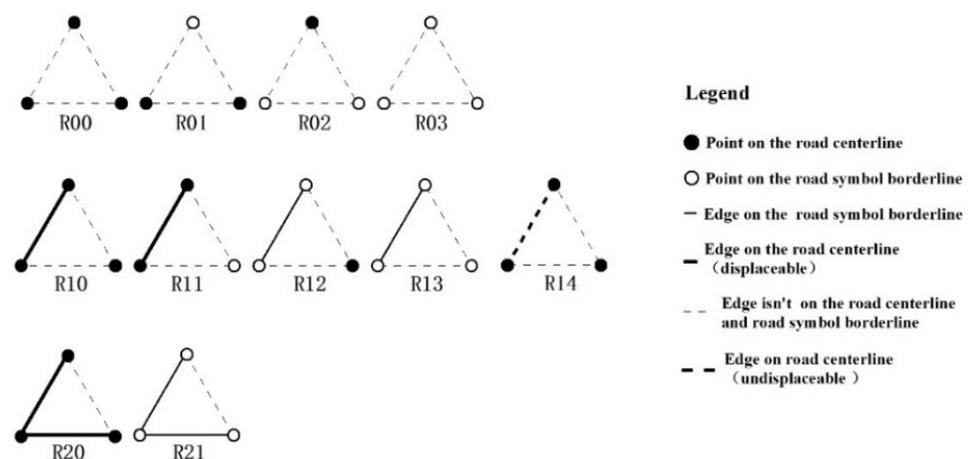


Figure 2. Classification of triangles in CDT for roads.

After extracting a skeleton line in a road graphic conflict area, it is necessary to determine its direction and correlative points. If the endpoint of the skeleton line is not a vertex of triangle R_{2n} , then the perpendicular points from that endpoint to the constrained edges on the left and right sides of that skeleton line must be calculated. For example, as shown in Figure 3a, P_{L1} and P_{L2} are the left correlative points of skeleton line S_1 ; P_{R1} and P_{R2} are the right correlative points of skeleton line S_1 ; and P_L and P_R are the left correlative point and right correlative point of skeleton line S_2 , respectively.

If the endpoint of the skeleton line is a vertex of triangle R_{2n} , the section of the road centerline in the road graphic conflict area represented by this skeleton line is defined as a bottleneck road segment (BRS), whereas the sections of road centerlines in road graphic conflict areas represented by other types of skeleton lines are defined as curved road segments (CRSs). For example, as shown in Figure 3a, the road centerline in the road graphic conflict area represented by S_2 from P_L to P_R is a CRS, whereas those road centerlines from P_{L1} to P_{L2} and from P_{R2} to P_{R1} are BRSs in the road graphic conflict area represented by S_1 .

A polygon enclosed by a road symbol borderline may be connected with two skeleton lines, for example, polygon C_1 in Figure 3a and polygon C_2 in Figure 3b. If the area of this polygon is less than the area threshold, then the main skeleton line of this polygon must be extracted [10,17], and this main skeleton line must be connected with two other skeleton lines connected to this polygon to form a complete skeleton line, such as skeleton line S_0 in Figure 3c. If the area of the polygon is greater than the area threshold, then the main skeleton line of this polygon cannot be extracted, as shown in Figure 3b.

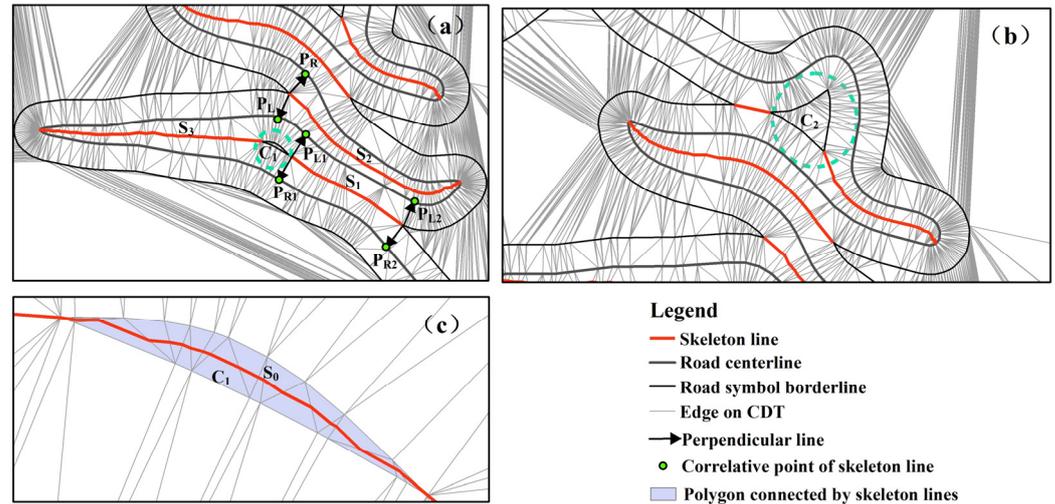


Figure 3. Connection between a bottleneck road segment and a curved road segment. (a) BRS and CRS; (b) the case skeleton lines are not connected; (c) the case skeleton lines are connected.

The length of the skeleton line (L_{sk}) and the average width of the road graphic conflict area (W_{sk}) are calculated with Formulas (1) and (2), respectively, in which L_{sk} and W_{sk} depend on the types of triangles crossed by the skeleton line

$$L_{sk} = \sum_{i=1}^j \|N_i N_{i+1}\|, \tag{1}$$

where, $\|N_i N_{i+1}\|$ represents the length of the line connecting point N_i and point N_{i+1} in a triangle, and $1 \leq i \leq j$, where j represents the number of triangles crossed by the skeleton line. For example, as shown in Figure 4, N_1 and N_{j+1} represent the vertex of EnT and ExT in A and B, respectively; N_2 , N_i , N_{i+1} , and N_j represent the midpoint of the edges of EnT, MT, and ExT in A, B, and C, respectively,

$$W_{sk} = \sum_{i=1}^j \frac{\|N_i N_{i+1}\| W_i}{L_{sk}}, W_i = \|W_{i1} W_{i2}\|, \tag{2}$$

where, $\|W_{i1} W_{i2}\|$ represents the length of the line connecting point W_{i1} and point W_{i2} in a triangle. For example, as shown in Figure 4, W_{11} , W_{12} , W_{j1} , and W_{j2} represent the midpoint of the edges of EnT and ExT in A and C, respectively, W_{i2} represents the vertex of MT, and W_{i1} represents the perpendicular point from W_{i2} to the edge of MT.

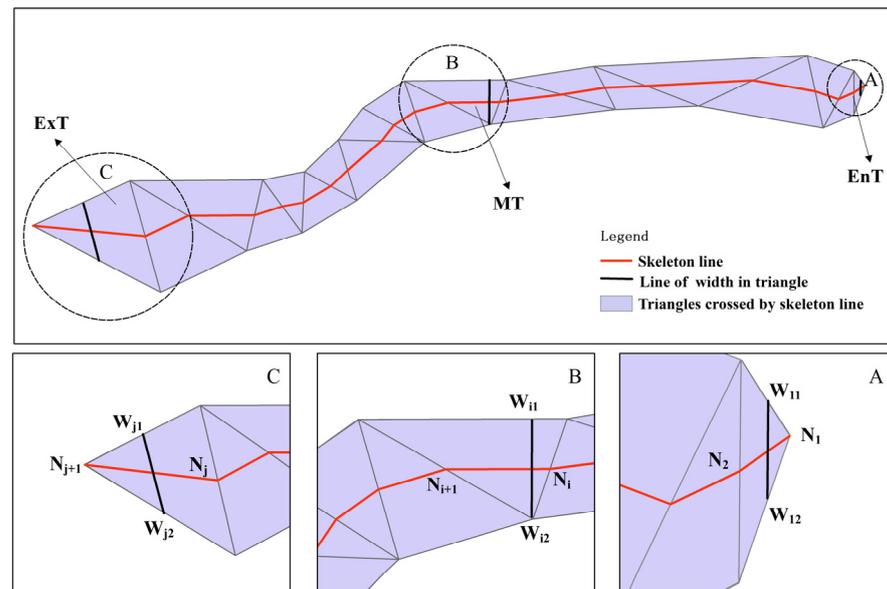


Figure 4. Calculation of the skeleton line length and the average width of a road conflict area. A: EnT; B: MT; C: ExT.

2.1.2. Conflict Types

When graphic conflict areas interact with each other, it becomes necessary to group them together. Whether two graphic conflict areas interact with each other can be determined by the average distance between their two skeleton lines. The threshold of this average distance, T_p , is calculated with Formula (3):

$$T_p = W_{rs} + D_{ms}/2, \quad (3)$$

where W_{rs} represents the width of the road symbol, and D_{ms} represents the minimum distance between map objects. When the distance between the skeleton line of a conflict area and that of a neighboring conflict area is greater than T_p , it is regarded as an independent conflict type (called an IC).

If the average distance between a skeleton line and other skeleton lines is greater than the distance threshold, then the graphic conflict area represented by that skeleton line is an IC. The following are the four different types of ICs:

- (1) For IType1, the first endpoint or last endpoint of the skeleton line is one vertex on the road centerline, and another endpoint is one vertex on the road symbol borderline, as shown in Figure 5a.
- (2) For IType2, the first endpoint and last endpoint of the skeleton line are on the road symbol borderline, as shown in Figure 5b.
- (3) For IType3, the first endpoint and last endpoint of the skeleton line are not on the road centerline and the road symbol borderline. One road segment corresponding to the skeleton line of the conflict area is displaceable, as shown in Figure 5c.
- (4) For IType4, the first endpoint and last endpoint of the skeleton line are not on the road centerline and the road symbol borderline. Two road segments corresponding to the skeleton line of the conflict area are displaceable, as shown in Figure 5d.

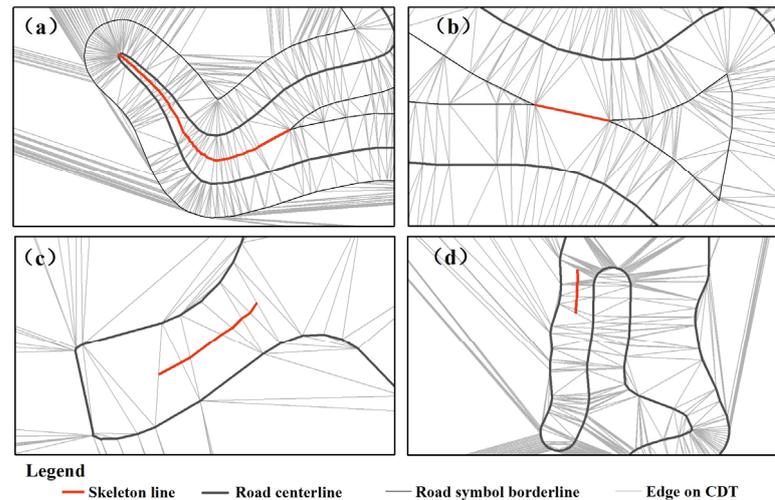


Figure 5. Independent conflict types: (a) IType1, (b) IType2, (c) IType3, and (d) IType4.

If the average distance of a skeleton line from other skeleton lines is smaller than the threshold value, then the graphic conflict areas represented by these skeleton lines are a group conflict and are called GC. If any two adjacent skeleton lines are among all the skeleton lines in a GC area and a correlative point of one of two adjacent skeleton lines lies between two correlative points of the other skeleton line, then this GC area is called a collinear curved group; otherwise, this GC area is called a non-collinear curved group. For example, as shown in Figure 6a, a correlative point P_{L1} of one skeleton line S_1 is between two correlative points P_{L2} and P_{R2} of the other skeleton line S_2 ; therefore, it is a collinear curved group. There are four types of GCs, which are as follows:

- (1) If the GC area is a collinear curved group and the number of skeleton lines is even, it is GType1, as seen in Figure 6a.
- (2) If the GC area is a collinear curved group and the number of skeleton lines is odd, it is GType2, as seen in Figure 6b.
- (3) If the GC area is a non-collinear curved group, it is GType3, as seen in Figure 6c.
- (4) If there are both non-collinear curved and collinear curved groups in the GC area, it is GType4, as seen in Figure 6d.

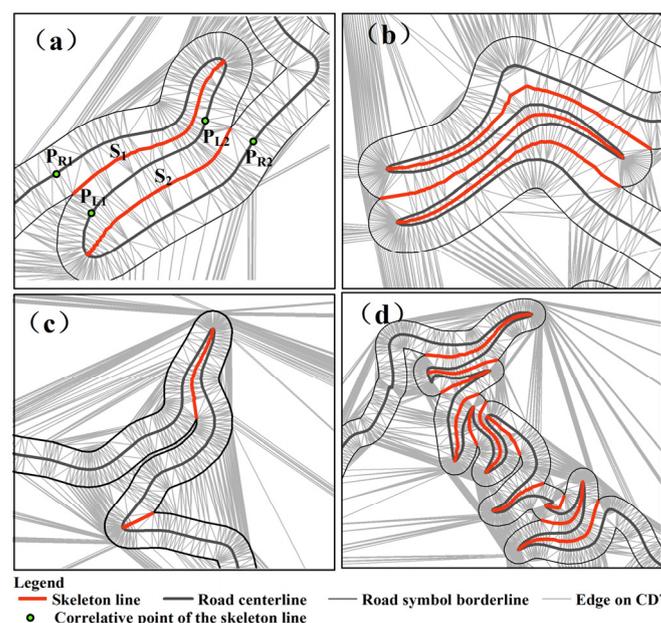


Figure 6. Group conflict types: (a) GType1, (b) GType2, (c) GType3, and (d) GType4.

2.2. Collaborative Methods

It is necessary to choose a collaborative method according to the type of graphic conflict. Three collaborative methods are proposed in this study: collaboration between deletion and the snake displacement model, collaboration between the snake displacement model and collinearity, and collaboration among simplification, smoothing, and the beam displacement model.

2.2.1. Cartographic Rules for the Resolution of Road Graphic Conflicts

Cartographic rules can be used to guide conflict resolution; they include the order of handling different conflicts, the order of applying operations, the conditions of using operations, and the constraints on mapping specifications. Li [36] proposed a classification scheme for map generalization operators considering the geometric properties of map objects. Regnauld and McMaster [37] provided a framework for map generalization operators. Stanislawski et al. summarized the map generalization operators associated with network generalization [13]. Simple operations and their corresponding algorithms for resolving road graphic conflicts selected in this study are shown in Table 1. The cartographic rules used in this study for road graphic conflict resolution are summarized in Table 2. For example, when dealing with different types of independent conflicts, it is necessary to follow R_{S1} and R_{S2} to determine which conflict area should be dealt with in which order. When dealing with different types of group conflicts, R_{O1} – R_{O3} can be used to decide which collaborative method should be selected.

Table 1. Simple operations and the corresponding algorithms.

Operations	Algorithm
Smoothing	Peak (from ArcGIS)
Displacement	Snake [17], beam [10]
Collinearity	Collinearity method [17]
Simplification	Algorithm proposed in this study
Deletion	Algorithm proposed in this study

Table 2. Cartographic rules for road graphic conflict resolution.

Number	Description of Cartographic Rules
R_{S1}	If \exists IType1 and \exists IType2, then IType2 should be processed first.
R_{S2}	If \exists IType3 and \exists IType4, then IType4 should be processed first.
R_{S3}	If \exists IC and GC, then GC should be processed first.
R_{O1}	If $W_{rs} <$ the required width of a GC $<$ the maximum allowable displacement threshold, then operation = collaboration between the snake displacement model and collinearity.
R_{O2}	If the required width of a GC $>$ the maximum allowable displacement threshold and the current width of a GC $<$ W_{rs} , then operation = collaboration among simplification, smoothing, and the beam displacement model.
R_{O3}	If the required width of a GC $>$ the maximum allowable displacement threshold and the current width of a GC $>$ W_{rs} , then operation = collaboration between deletion and the snake displacement model.
R_{O4}	If L_{sk} in CRS $<$ W_{rs} , then operation = displacement; otherwise, operation = collaboration between the snake displacement model and collinearity.
R_{O5}	If \exists IType3, then operation = beam displacement; if \exists IType4, then operation = snake displacement.
R_{C1}	If operation = displacement, then the displacement magnitude is <0.5 mm.
R_{C2}	If \exists any graphic conflict, then $D_{ms} < 0.2$ mm.

2.2.2. Collaboration between Deletion and the Snake Displacement Model

If the width of a group conflict area is not sufficient to resolve a graphic conflict based only on the displacement operation and the length difference of the skeleton lines in this group conflict area is larger than a certain threshold, then the deletion operation and the snake displacement model must be used in collaboration.

The skeleton line set of this group conflict area is represented as $S = \{S_1, S_2, \dots, S_n\}$, and n represents the number of skeleton lines in this group conflict area. A subset of the vertexes on the road centerline is represented as $V = \{V_0, V_1, V_2, \dots, V_n, V_{n+1}\}$, where V_0 and V_{n+1} represent the correlative points of S_1 and S_n on this road centerline, respectively, according to the method mentioned in Section 2.1.1. V_1, V_2, \dots, V_n represent the respective intersections between the road centerline and each skeleton line S_i ; $V_{i(i+1)}$ represents the midpoint on the road centerline between V_i and V_{i+1} ($1 \leq i \leq n$); a set of the midpoints is represented as $V_{\text{mid}} = \{V_{12}, V_{23}, \dots, V_{(n-1)n}\}$. For example, as shown in Figure 6a, $S = \{S_1, S_2, S_3, S_4, S_5, S_6, S_7\}$, $V = \{V_0, V_1, V_2, V_3, V_4, V_5, V_6, V_7, V_8\}$, and $V_{\text{mid}} = \{V_{12}, V_{23}, V_{34}, V_{45}, V_{56}, V_{67}\}$. The current width (W_c) and the required width (W_r) of this group conflict area are calculated with Formula (4) and Formula (5), respectively:

$$W_c = \sum_{i=1}^n W_{sk(i)}, \quad (4)$$

$$W_r = n * (W_{rs} + D_{ms}), \quad (5)$$

where $W_{sk(i)}$ represents the average width of this group conflict area through which the i -th skeleton line passes, as mentioned in Section 2.1.1. W_{rs} represents the width of the road symbol, and D_{ms} represents the minimum spacing distance determined by rule RC2.

The length difference of these skeleton lines is expressed as the standard deviation (σ_L), which is calculated with Formula (6):

$$\sigma_L = \sqrt{\frac{\sum_{i=1}^n (L_i - \bar{L})^2}{n}}, \quad (6)$$

where the set of lengths of these skeleton lines in this group conflict area is represented as $L = \{L_1, L_2, L_3, L_4, \dots, L_n\}$, L_i represents the length of the i -th skeleton line, and \bar{L} represents the average length of these skeleton lines. The maximum displacement distance (D_{md}) can be determined by rule RC1. If $W_r - W_c > D_{md}$ and if σ_L is larger than a certain threshold, then the width of this group conflict area is not sufficient to resolve the graphic conflict based only on the displacement operation, and the deletion operation and the snake displacement model must instead be used in collaboration.

The deletion operation involves deleting part of a road centerline, which is the road segment that corresponds to the shortest skeleton line and its adjacent skeleton line in the group conflict area.

Because the visual symmetry of road bends should be considered from the perspective of visual perception, it is assumed that S_m is used to represent the shortest skeleton line in $\{S_1, S_2, \dots, S_n\}$, and its adjacent skeleton line is S_{m-1} or S_{m+1} . The three cases for deleting this road segment are as follows:

- (1) If $1 < m < n$, then it is necessary to select the adjacent skeleton line of S_m . If $L_{m-1} < L_{m+1}$, then the selected adjacent skeleton line is S_{m-1} ; otherwise, the selected adjacent skeleton line is S_{m+1} . For example, if S_5 is the shortest skeleton line, the road segment that corresponds to S_5 is the road centerline from V_{45} to V_{56} , as seen in Figure 7a. If S_4 and S_6 are the skeleton lines adjacent to S_5 , S_6 is selected as S_5 's adjacent skeleton line, as $L_6 < L_4$. The road segment that corresponds to S_6 is the road centerline from V_{56} to V_{67} , as seen in Figure 7a. Therefore, the road segment from V_{45} to V_{67} in Figure 7a is deleted.
- (2) If $m = 1$, then the only adjacent skeleton line of S_1 that can be selected is S_2 , and the road segment from V_0 to V_{12} is deleted.

- (3) If $m = n$, then the only adjacent skeleton line of S_n that can be selected is S_{n-1} , and the road segment from $V_{(n-1)n}$ to V_{n+1} is deleted.

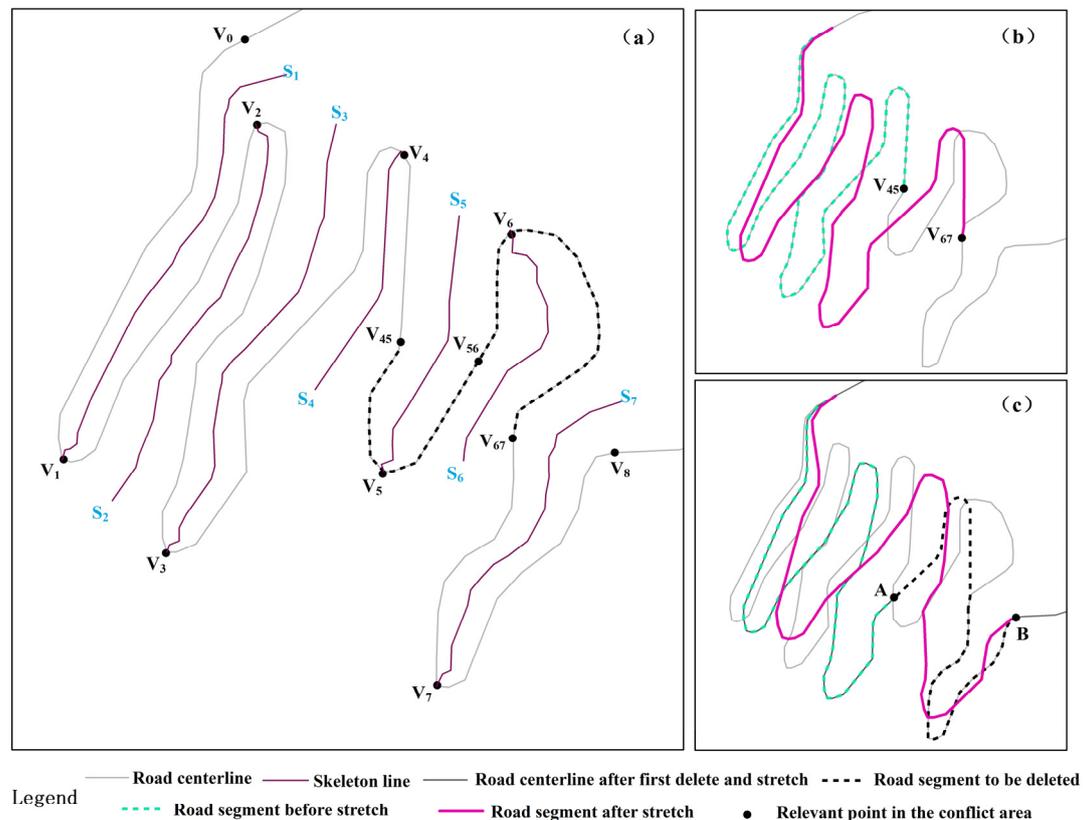


Figure 7. The process of collaboration between the deletion operation and the snake displacement model: (a) finding the first deleted road segment; (b) the first collaboration between the deletion operation and the snake displacement model; (c) the second collaboration between the deletion operation and the snake displacement model, A represents the midpoint of two intersections and B represents the correlative point of the skeleton line.

To maintain the graphic characteristics of the remaining road segments in the group conflict area, the snake displacement model [17] is used to stretch these segments. The stretching direction is determined by comparing the W_r values of the two road segments on either side of the deleted road segment. If the W_r value of one road segment (RS) is larger than the other, the direction of the stretch is from the road segment (RS) to the other road segment. For example, the stretching direction is from V_{45} to V_{67} in Figure 7b. Sometimes only one collaboration between the deletion operation and the snake displacement model is not sufficient to meet the requirement of resolving a graphic conflict; therefore, the collaboration must be used several times, and the number of iterations (N_{it}) of this collaboration can be calculated with Formula (7). For example, Figure 7c is the result after the second collaboration, where the stretching direction is from point A to point B:

$$N_{it} = \lceil (W_r - W_c) / W_{rs} \rceil, \quad (7)$$

where W_c and W_r are calculated with Formula (4) and Formula (5), respectively.

If σ_L is less than a certain threshold, after determining N_{it} , the road segment on one side in the group conflict area is arbitrarily deleted, and then the remaining road segment is stretched.

2.2.3. Collaboration between the Snake Displacement Model and Collinearity

If the difference between the required width and the current width of a group conflict area is less than the maximum displacement distance, then a collaboration between the snake displacement model and collinearity is used.

The skeleton line set of this group conflict area is represented as $S = \{S_1, S_2, \dots, S_n\}$, and n represents the number of skeleton lines in this group conflict area. A subset of the correlative points of skeleton lines on the road centerline is represented as $R = \{R_1, R_2, R_3, \dots, R_{2n}\}$. The two methods for the collaboration between displacement and collinearity are as follows:

- (1) If the correlative point of one skeleton line is not between the positions of two correlative points of another skeleton line, then the collinearity [17] is used to resolve the conflict represented by each skeleton line according to the road symbol width. For example, in Figure 8a, R_3 is not between R_1 and R_2 , and R_2 is not between R_3 and R_4 . To ensure that a smoother connection can be made at the correlative points, it is necessary to use the displacement operation for displacement propagation after the collinearity, as seen in Figure 8b. The snake [17] model is used to deal with non-collinear portions of road segments that are connected to correlative points of a skeleton line, as seen in Figure 8b.

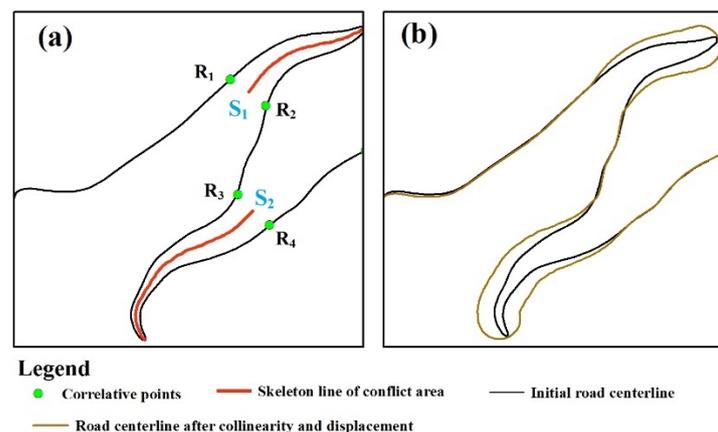


Figure 8. Collaboration between the snake displacement model and collinearity. (a) extraction of skeleton line of conflict area; (b) collaboration between the snake displacement model and collinearity.

- (2) If the correlative point of one skeleton line is between the positions of two correlative points of another skeleton line (e.g., R_2 is between R_1 and R_3 in Figure 9a), then the snake displacement model [17] is used to displace one of the two neighboring skeleton lines (e.g., S_3 is displaced to S_3' in Figure 9b). The parallel line AB of skeleton line S_4 is obtained according to the width of the road symbol. O is the nearest point from endpoint E of S_3 to AB in Figure 9c; P is the nearest point from point B to skeleton line S_3' ; and C and D are endpoints of S_3' in Figure 9d. The line PD is shifted to let P coincide with point B, and then it is connected with OB so as to obtain line S_3'' in Figure 9e, and the collinearity [17] operation is applied to S_3'' and S_4 . The snake [17] model is used to deal with non-collinear portions of road segments that are connected to correlative points of a skeleton line. For example, R_1 and R_4 are correlative points, as shown in Figure 9f.

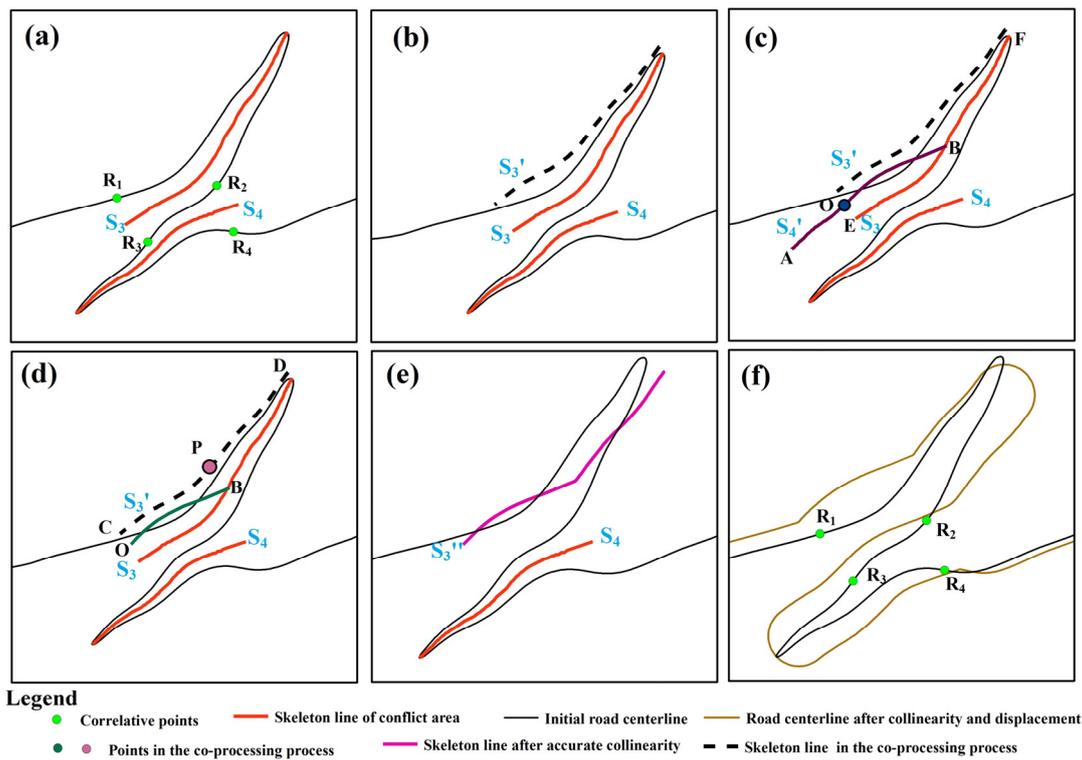


Figure 9. Collaboration between the snake displacement model and collinearity. (a) extraction of skeleton line of conflict area; (b) displace one of the two neighboring skeleton lines; (c) the parallel line AB of skeleton line S_4 is obtained; (d) get the nearest point P from point B to skeleton line S_3' ; (e) obtain line S_3'' ; (f) the collinearity operation is applied to S_3'' and S_4 , and the snake model is used to deal with non-collinear portions of road segments.

2.2.4. Collaboration among Simplification, Smoothing, and the Beam Displacement Model

If the width of a group conflict area is not sufficient to resolve a graphic conflict based on collaboration between displacement and collinearity or collaboration between deletion and the snake displacement model, then the simplification operation and collaboration must be used.

The skeleton line set of this group conflict area is represented as $S = \{S_1, S_2, \dots, S_n\}$, and n represents the number of skeleton lines in this group conflict area. A subset of the vertexes on the road centerline is represented as $V = \{V_0, V_1, V_2, \dots, V_n, V_{n+1}\}$, where V_0 and V_{n+1} represent the correlative points of S_1 and S_n on this road centerline, respectively, according to the method mentioned in Section 2.1.1; V_1, V_2, \dots, V_n represent the intersections between the road centerline and each skeleton line S_i . The two cases for the simplification operation are as follows:

- (1) If n is even, all road segments in the road graphic conflict area are deleted, and then the two correlative points of the outermost skeleton line on the road centerline are connected. For example, as shown in Figure 10a, a part of the road centerline from the correlative point V_0 of skeleton line S_1 to the correlative point V_5 of skeleton line S_4 is deleted in the group conflict area, and then V_0 and V_5 are connected; the result is shown in Figure 10b. After the simplification operation, if there are sharp corners at the connection of the road centerline, then the smoothing operation is used to remove them.

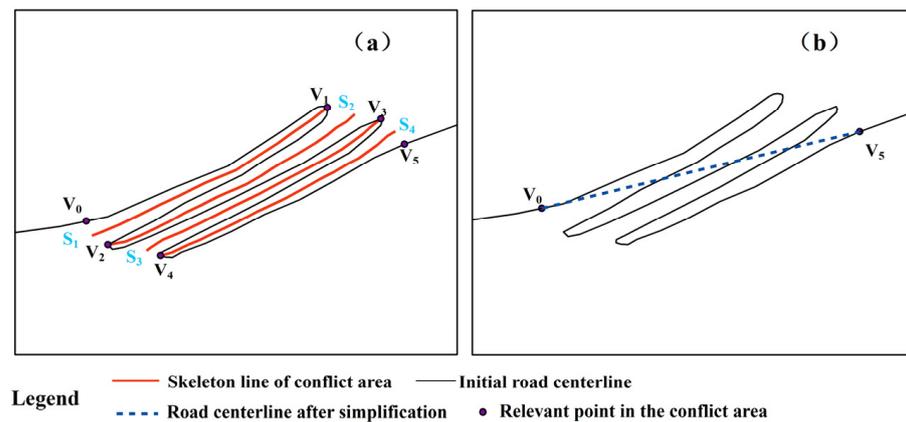


Figure 10. Process of simplification and its collaboration: (a) extraction of skeleton line of conflict area; (b) simplification and its collaboration.

- (2) If n is odd, the road segment from the first intersection to the last intersection in the group conflict area is deleted, and then the two intersections are connected. For example, in Figure 11a, a part of the road centerline from V_1 to V_3 is deleted, and then V_1 and V_3 are connected in the group conflict area. After the simplification operation, if there are sharp corners at the connection of the road centerline, then the smoothing operation is also required to remove them, as seen in Figure 11b. If there are still conflicts after simplification, the beam displacement model [10] is used with collaborative displacement to expand the width of the external space and resolve the conflict, as seen in Figure 11c.

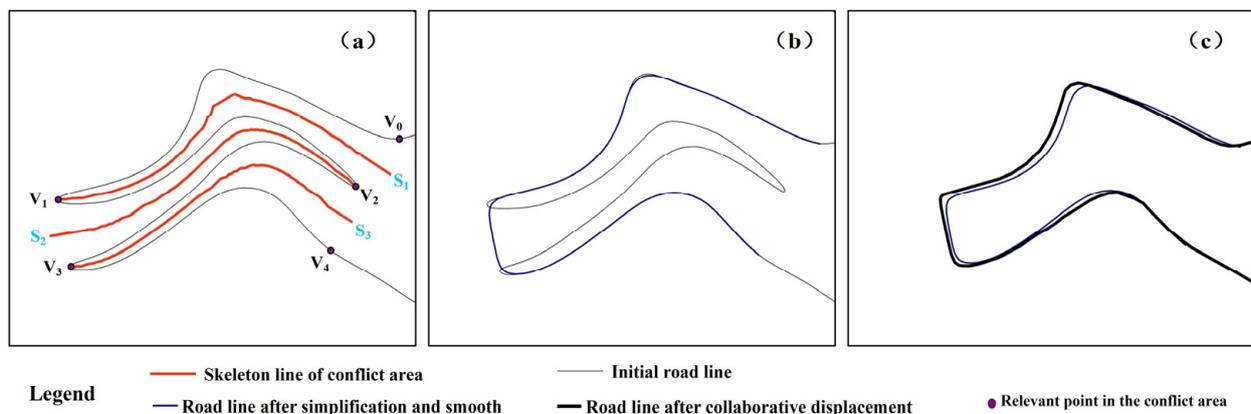


Figure 11. The process of simplification and its collaboration: (a) conflict area, (b) simplification and smoothing operations, and (c) the beam displacement model for collaborative displacement.

3. Experiments and Analysis

3.1. Experimental Data and Related Parameters

Experimental data on Sichuan Province, China were downloaded from OpenStreetMap (OSM) at <https://www.openstreetmap.org/> (accessed on 2 May 2024). The scale of these experimental data was 1:10,000, as shown in Figure 12. Figure 13 shows the road map after symbolization, and the width of the road symbols on the map was from 0.6 to 1.2 mm for different types of roads. The total length of road centerlines in the experimental dataset was 24.36 km on the Earth. The scale of Figure 13 is 1:50,000.

The software for the methods proposed in this study was developed using C# in vs 2015 and the ArcGIS Engine, and the hardware was a PC with Windows 10 OS and an Intel(R) Core(TM) i5-4460 CPU (3.20 GHz). The total runtime of this software for processing these experimental data was 378 s.

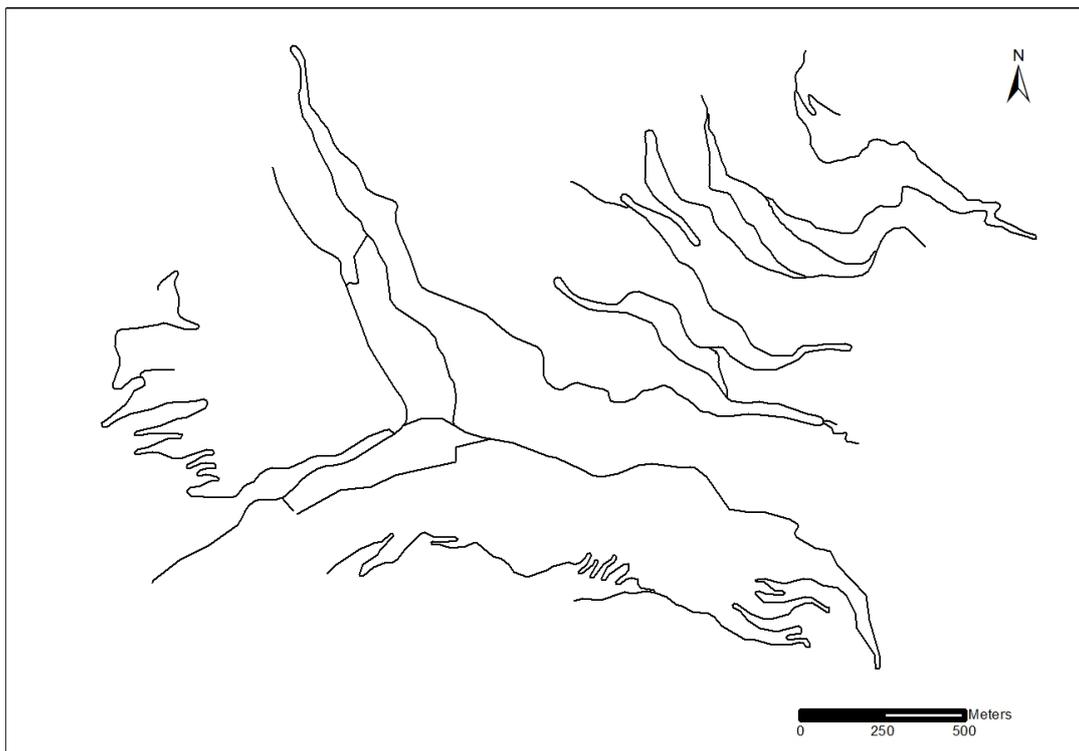


Figure 12. Experimental data.

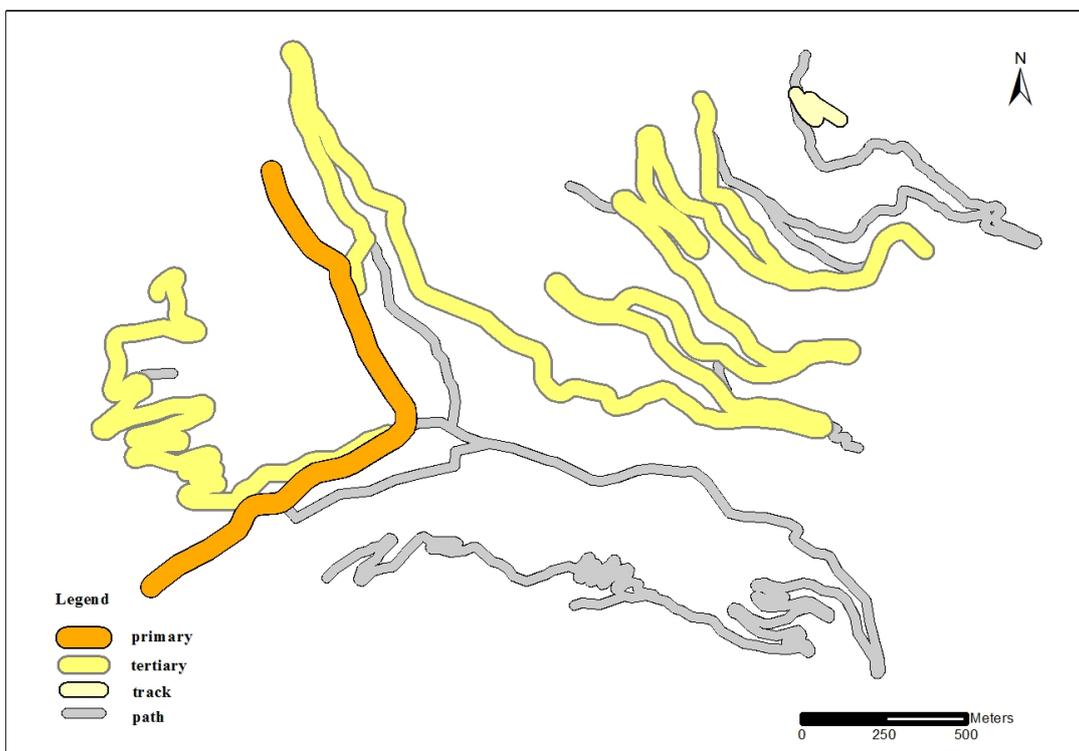


Figure 13. Road map after symbolization.

3.2. Experimental Results and Analysis

Figure 14 shows the skeleton lines that were extracted in the road graphic conflict areas in the experimental data. There were eight group conflict areas and nine independent conflict areas, as shown in Figure 14. The group conflict areas in Figure 14 were resolved

with the three collaborative methods, and the independent conflict areas were resolved through collinearity and displacement. The final road map is shown in Figure 15.

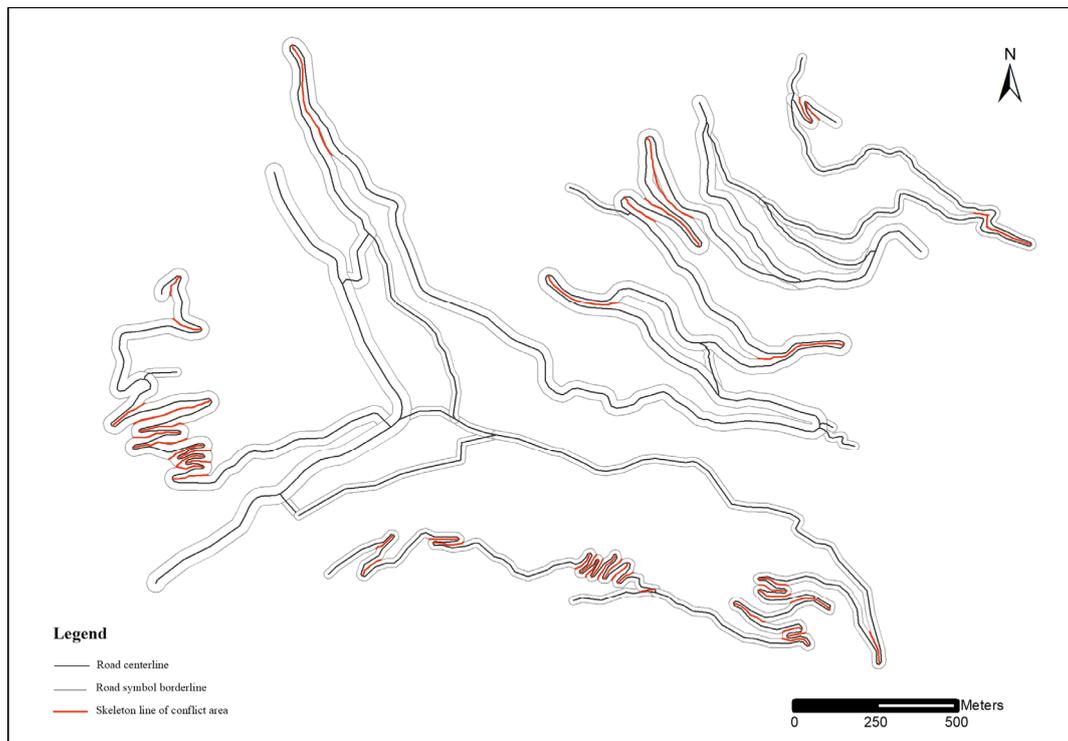


Figure 14. Map of road graphic conflict areas.

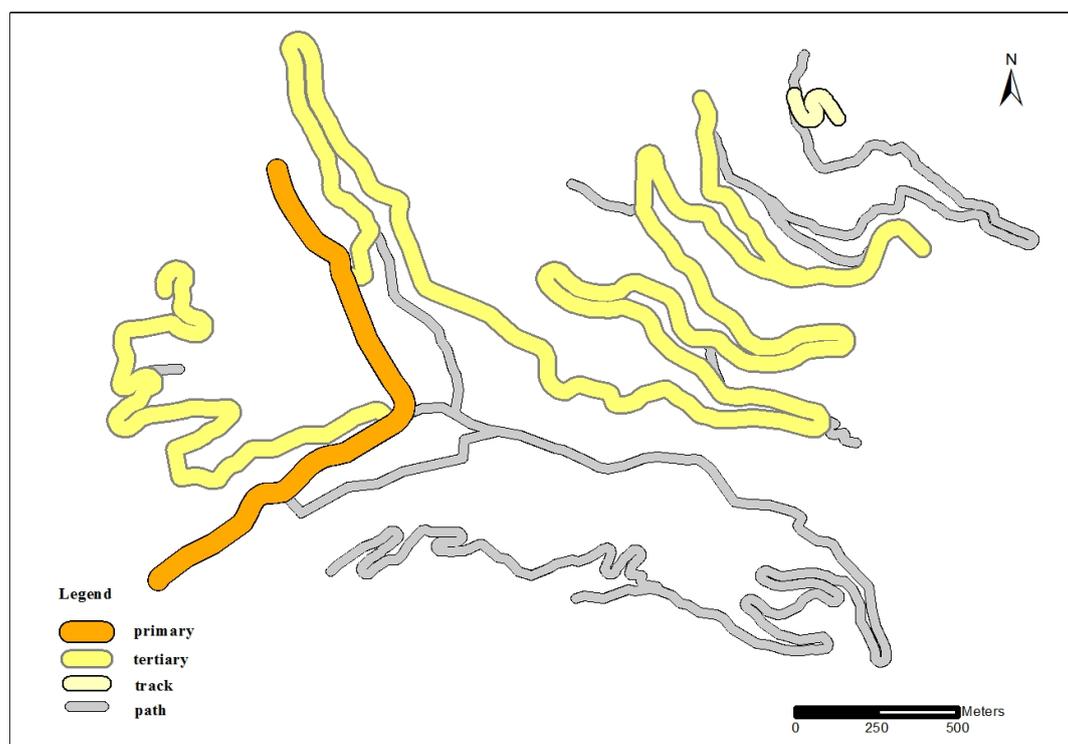


Figure 15. The final road map.

The experimental results in Figure 15 meet the requirements for visual clarity, and there are no visual conflicts. Some indicators were used to evaluate the degree of conflict

resolution: the displacement magnitudes of the vertexes, the coalescence strength, and the shape measures of the roads.

- (1) The displacement magnitudes of vertexes: The specification in [38] requires that the maximum displacement magnitude of vertexes is from 0.5 to 1 mm on a map, but the maximum displacement magnitude of vertexes in this experimental result was <0.3 mm.
- (2) Coalescence strength: After calculating the total actual area (A1) of buffers of roads on the map at a scale of 1:50,000 and the total ideal area (A2) of map symbols for these roads, the coalescence strength can be represented as $1 - A1/A2$ [39]. The coalescence strength of this road map was 0.003, which was smaller than 0.02, thus meeting the requirements for mapmaking [39].
- (3) Shape measures of the roads: Shape measures include the number of bends, the number of extremal points, and the curvature [40]. A comparison of these three shape measures of these roads in this experiment is shown in Figure 16. In Figure 16, A represents the number of shape measures of road objects after resolving road graphic conflicts, and B represents the number of shape measures of the original road objects. $|1 - A/B|$ can explain the degree of change in these three indicators, which was 0.0491, 0.0644, and 0.0461, respectively, in this experiment; these values were very small.

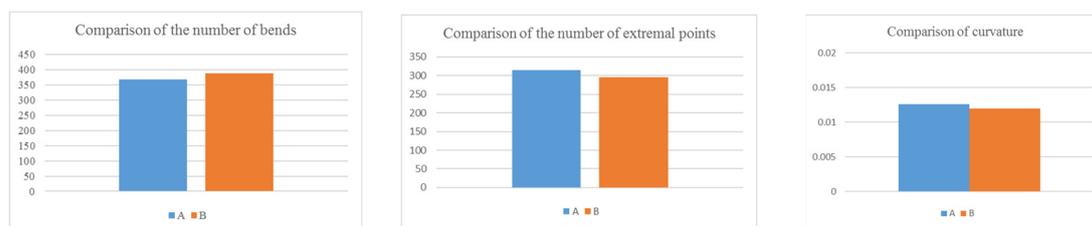


Figure 16. Comparison of road shape measures. The values on the horizontal axis represent the shape measure of the road objects after and before resolving road graphic conflicts. The values on the vertical axis represent the number of shape measures.

4. Conclusions

The collaborative methods proposed in this study can effectively resolve road graphic conflicts and are guided by cartographic rules. Based on the characteristics of road graphic conflict areas, three collaborative methods were designed to deal with different types of road graphic conflicts: collaboration between deletion and the snake displacement model, collaboration between the snake displacement model and collinearity, and collaboration among simplification, smoothing, and the beam displacement model. Qualitative and quantitative analyses of the experimental results showed the proficiency of these collaborative methods in resolving road graphic conflicts. The road shape features were adequately maintained.

These new methods for resolving road graphic conflicts should be further researched while considering geospatial contextual information, such as the spatial relationships between roads and other map features. More types of graphic conflicts between roads and other map features should be considered, and more collaborative methods for resolving these new graphic conflicts need to be investigated.

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