USER-DIRECTED GENERALIZATION OF ROADS AND BUILDINGS FOR MULTI-SCALE CARTOGRAPHY

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ABSTRACT

Collecting, processing, and maintaining geographic data for cartographic display are cost- and time-intensive endeavors. While cartographic data is ideally created for a specific or narrow scale range, cartographic demand typically covers a full scale spectrum from neighborhood to globe. Indeed, easy access to the Web has increased demand for multi-scale mapping. To maintain perspective on the effort of generating quality data, automated approaches to generalizing detailed data for display at progressively smaller scales is paramount. Web maps such as Bing Maps, Google Maps, and ArcGIS Online World Streetmap, emphasize the display of roads and streets and ArcGIS Online World Topographic Map includes buildings at the largest scales. A new user-directed solution recently implemented at Esri is designed to generalize road networks and buildings using an optimized approach, working with groups of features contextually to create multi-scale maps for both Web and print output.

1 AUTOMATING GENERALIZATION PROCESSES

Effective cartographic generalisation retains the representative character and intent of individual features and collective and proximate relationships between features. The reduction in target scale minimizes map area for display of features and requires a simplified depiction that retains visual clarity. Achieving this—especially across multiple map themes—is a challenging process that requires subjective decision-making to ensure that the result retains the distinctive patterns and morphology of the original.

The process of cartographic generalization is typically composed of a series of discrete operations performed on a subset of the geographic features in a map. Generalization operators need to work concurrently on whole features, parts of features, and on multiple associated features from different themes to produce a simplified yet characteristic depiction of reality. Although generalization operators have their origins in manual cartography, some generalization operators are easy to perform in a digital environment, such as selecting and excluding insignificant features, reclassifying ordinal data to show less attribution detail, and dissolving adjacent features to one.

In contrast, contextual processes that consider the spatial arrangement and relationships between features in multiple themes are more complex. For example, an aggregate operation—the replacement of many features with a representative feature of increased dimensionality (Roth, 2008)—is difficult to perform in a digital environment because related features must be considered. For example, proper aggregation of a dense dispersal of point buildings to a single built-up area polygon includes a consideration of where streets and rivers lie in relation to the buildings. It is the contextual and subjective characteristics of generalization that make it so difficult to automate and replicate in a flexible, user-friendly framework. (Lee, 2004)

2 TOWARD A USER-DIRECTED SOLUTION

The challenge in developing an effective and commercially viable generalisation solution goes beyond designing algorithms to perform the various generalization operators in isolation. A solution must be able to handle multiple themes simultaneously, and differing (or even opposing) generalisation operations contextually. And perhaps more importantly, a good solution will involve and react to specific directives from the cartographer. Rather than avoid subjectivity, a smart solution allows a user to direct the nature and degree of generalization in a manageable way.

Research has shown that limitations in commercial generalization solutions have included the difficulty of defining parameters to support the complex algorithms and the need for good defaults (Stoter, 2010). A user-directed approach recognizes that the constraints that should be imposed on the generalization operations will likely originate from a mixture of professional design experience and strictly-defined cartographic specifications. It is imperative that a balance be maintained between a solution that is too rigid and one that allows too much user input. The danger in providing a user-directed solution is that too much flexibility and too many options can overwhelm a cartographer and make iterative adjustments nearly impossible to manage as there will be too many permutations to adjust to achieve different results.

2.1 An Optimization approach

For the past four years, Esri has been working on an optimized, constraint-based approach to solving generalization problems within a commercial GIS (ArcGIS). The latest release of ArcGIS (version 10) introduced a new generation of generalization tools that leverage an underlying optimizer kernel. The optimization approach seeks to modify geographic features based on a series of pre-defined constraints designed to clarify the display of that data at smaller scales. Examples of constraint are "*a building cannot be closer than the specified distance from another building*" and *"a building cannot move too far from its original location"*. The satisfaction of an individual constraint is improved with one or more corresponding actions. Examples of actions are *"move the building away", "move the building back"* and *"mask the building."* Since constraints often conflict, the optimization approach seeks to find the best overall solution, even if the satisfaction of some constraints must be compromised somewhat. This is consistent with the very nature of cartography which has always required making informed compromises about what to display how on a map at each scale. Any constraint that must not be compromised is defined in the framework as a reflex. Reflexes prevent certain arrangements from existing by applying actions to revert to a previous state. An example of a reflex is "*a building cannot be moved onto a road*." (Monnot 2007). The optimizer employs a *simulated annealing* approach (Kirkpatrick 1983) where conceptual temperature gradually decreases throughout processing. When conceptual temperature is high, a greater degree of change and tolerance of unsatisfactory states is allowed; as temperature decreases, changes are more moderate and constraint satisfaction is more aggressively sought. It is this tolerance and allowance of greater change that prevents the system from getting caught in local minima of progressively poor results. (Monnot, 2007).

2.2 Leveraging the Geoprocessing framework

ArcGIS 10 leverages this optimization approach as the underlying mechanism in an offering of new contextual geoprocessing tools for generalization. Geoprocessing tools released in previous versions of ArcGIS focused on the generalization of features in single themes in isolation, where operations are performed on the geometry of a single layer without regard to symbology or the relationship to other layers. Both types of tools are important components of a generalization workflow built in ArcGIS.

The geoprocessing environment in ArcGIS is well suited to establishing a generalization framework, since it can manage the transformation of data in distinct isolated steps that are represented by individual geoprocessing tools which are directed by data-, scale-, and product-specific variables. These steps can be logically chained together or looped in scripts or models to create a complex workflow that can be applied to a range of data to produce multi-scaled databases for print or screen display. Tasks can be easily repeated sequentially on different groups of features or with different parameters combined in a multitude of ways. Since each input to a workflow can exist as a variable, significant flexibility is achievable. Entire workflows can be automated, or they can be subdivided into smaller pieces with manual editing or verification taking place in between. (Lee 2005.) By introducing generalization tools into this framework as discrete components, highly customized workflows can be built to address the requirements of a wide variety of map specifications and styles.

3 GEOPROCESSING TOOLS FOR GENERALIZATION

The Web has created new demands for Multi-scale mapping. Bing Maps, Google Maps, and Web maps from ArcGIS Online rely heavily on the display of road and street networks as their foundation, with new demands for larger scale data such as individual buildings. ArcGIS Online World Topographic Map includes building footprints for many major cities. For this reason, Esri has focused recent generalization efforts on simplifying road networks and building arrangements and on resolving graphical conflicts associated with their distribution and display at scale. The Thin Road Network and the Merge Divided Roads tools simplify road networks while the Resolve Road Conflicts and Resolve Building Conflicts tools seek to redistribute and reshape roads and buildings to avoid symbol conflicts while retaining characteristic pattern and density. To ensure that each tool works with one another to produce a consistent display, the Propagate Displacement tool propagates positional adjustments made during conflict resolution to proximate features.

3.1 Thin Road Network tool

The Thin Road Network tool eliminates road features from display to create a simplified arrangement of roads that maintains connectivity along with the representative pattern and density of the original arrangement. Flexibility is provided in that significant features can be forced to remain visible, and the visibility of any feature can be easily switched in the results.

No data is moved or deleted in the processing of this tool. The resulting simplified road collection is determined by considering relative road classification hierarchy, significance to the connectivity of the network and local density. Road segments that participate in very long itineraries across the extent of the data, even if they are small, are more significant than those required only for local travel. Road classification is specified by the user as Hierarchy parameter. The desired density of the resulting street network is determined by the user as a Minimum Length parameter. The concept of minimum length corresponds to the shortest segment that is visually sensible to show at scale. This parameter gives the tool a sense of resolution and scale, but does not mean that all segments shorter than this length will be removed. If a segment is short yet significant, it will remain in the output collection. The software user guide includes a table of recommended values for common scales to give users a starting point. Since the results are dictated only by an attribute change to indicate invisibility, it is easy to rerun the tool iteratively to determine the best value for this parameter for a specific data set and scale.

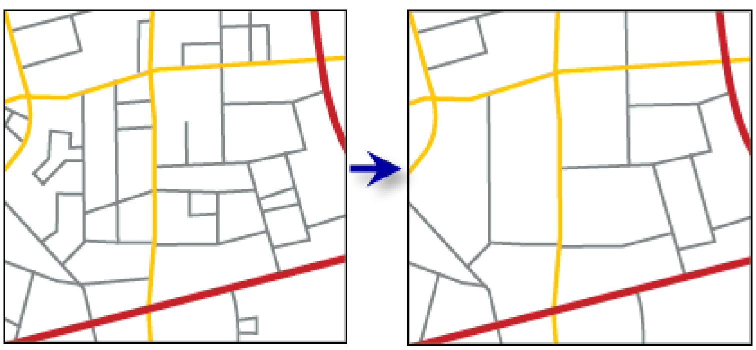

Fig. 1 – Thin Road Network tool eliminates relatively insignificant road segments

3.2 Merge Divided Roads tool

The Merge Divided Roads tool creates a single road from a matched pair of parallel-trending, equal classification roads. This is particularly useful when data has been collected as separate lanes in a highway, or for multiple lane boulevards that should be depicted as a single feature at reduced scales. A merge only occurs when roads are of equal classification and within a user-specified distance apart. Optionally, the degree of movement, or displacement, that takes place can be captured as a separate output feature class and used in the Propagate Displacement tool to reestablish spatial relationships among merged roads and adjacent features.

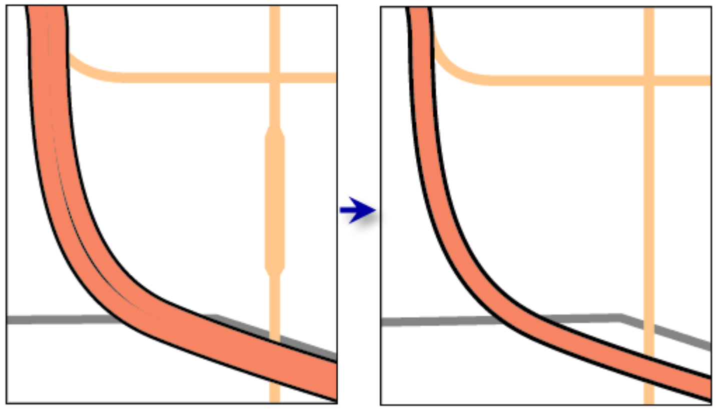

Fig. 2 – The Merge Divided Roads tool creates single road features in place of divided roads

3.3 Resolve Road Conflicts tool

The Resolve Road Conflicts tool separates roads that graphically conflict when symbolized at scale. Graphic overlaps typically occur when road data is displayed at a scale smaller than it was created at. When an appropriate line symbol is applied, adjacent roads may conflict with one another. Road classification is defined through attribution which is fed to the tool as an input parameter. This hierarchy dictates which features will remain in place (or move a relatively small amount) at the expense of others which must be moved and reshaped somewhat more to accommodate them. The tool separates multiple highway lanes and boulevards, exaggerates roundabouts, and widens gaps between highways and exit ramps. Like the Merge Divided Roads tool, the degree and direction of displacement can be stored in polygons which can be used to propagate this movement to spatially related features.

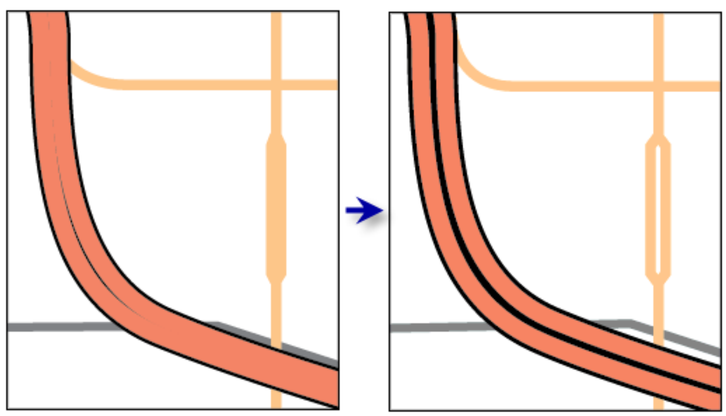

Fig. 3 – The Resolve Road Conflicts tool displaces graphically conflicting roads

Although the Merge Divided Roads and Resolve Road Conflict tools are in effect opposites of one another—the former collapses and the latter displaces— they can often coexist within the same workflow. It may be appropriate to merge boulevards but exaggerate the spacing between separate lanes of a divided highway. Or if the data is to be displayed at multiple scales, it may be appropriate to exaggerate lane spacing with the Resolve Road Conflicts tool at larger scales but collapse them to a single line with the Merge Divided Roads tool at smaller scales. Specific control over generalization processes is possible in the geoprocessing framework by inputting differing subsets of data into a complex workflow made up of individual generalization tools chained together.

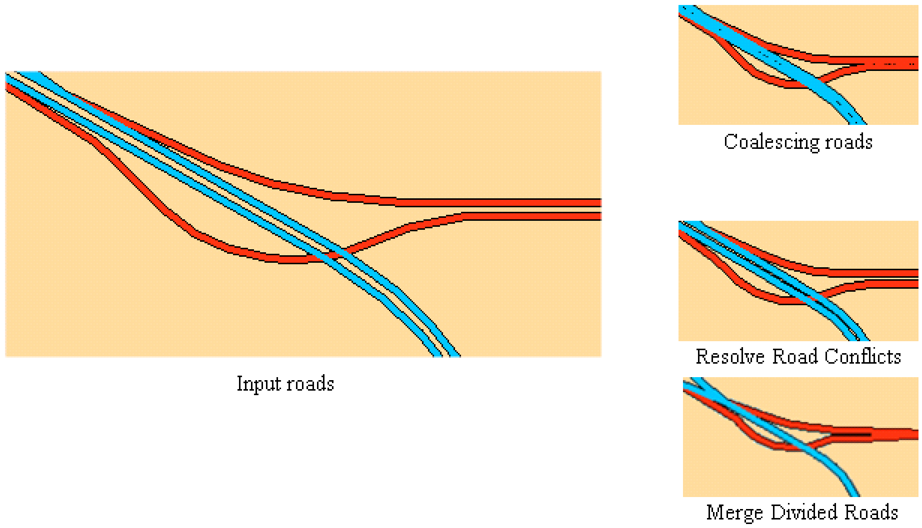

Fig. 4 – When symbolized roads are displayed at a smaller scale they may begin to coalesce. Users can exaggerate spacing between lanes with the Resolve Road Conflicts tool or to collapse dual lanes to a single line with the Merge Divided Roads tool.

3.4 Propagate Displacement tool

The Propagate Displacement tool reestablishes the spatial relationship between features by propagating the conflict resolution displacements made by the Merge Divided Roads or the Resolve Road Conflicts tools to proximate features. The user can choose to make these propagated movements either solid—where the entire feature is translated to a new location—or elastic—where a large complex feature is reshaped proportionally to account for the positional changes. An automatic option allows the tool to make this choice dependent on the morphology of each feature.

The location of input features are adjusted based on the vector displacements contained in the displacement features output by the Merge Divided Roads and Resolve Road Conflicts tools. Adjustments are a compromise of all displacements, such that large displacements that occurred quite near an input feature will have more influence than smaller displacements further away. Conceptually, this action is similar to a rubber-sheeting process that moves features in various directions by various amounts to fit them back to the spatial relationship that they originally had with the roads.

In the diagram on the left, below, the yellow polygons are displacement polygons output by the Resolve Road Conflicts tool. The diagram on the right shows how buildings, railways, hydrology, and vegetation features have been adjusted slightly as dictated by the displacement polygons.

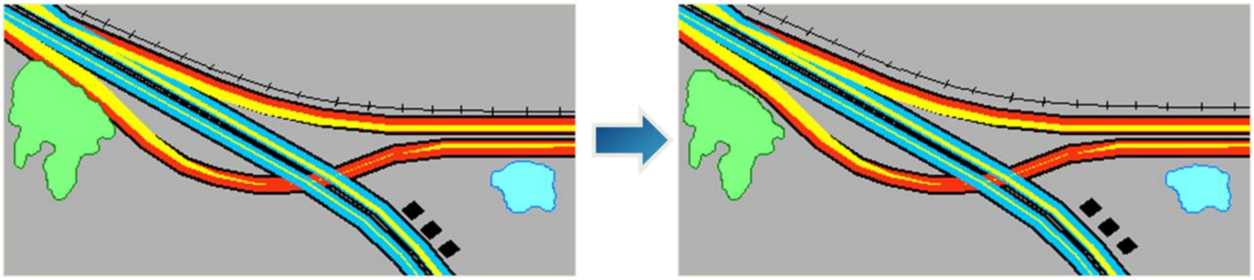

Fig. 5– The Propagate Displacement tool reestablishes spatial relationships after conflict resolution

3.5 Resolve Building Conflicts tool

The Resolve Building Conflicts tool seeks to eliminate graphic conflicts between buildings and between buildings and specified barrier features through elimination and transformation when these features are symbolized at scale. Elimination and transformation choices are dictated by constraints to preserve characteristic pattern arrangement and relative density of the buildings as much as possible. Buildings can be optionally oriented and positioned relative to the barrier features and multiple barrier layers can be considered simultaneously. Barriers typically include roads and streets, but can also include other layers like rail, hydrography, utilities, or administrative boundaries. Point and polygon building geometry can be assessed together. Before conflicts are assessed, polygonal buildings are enlarged to a minimum size specified by the Minimum Allowable Building Size parameter to ensure that legibility or map specification requirements are respected.

A Hierarchy Field parameter allows the user to specify a classification of buildings if one is available. If this parameter is not specified, buildings will be assigned a relative importance based on the size of the building and proximity to barriers. Larger buildings closer to more than one barrier will be assessed as more significant than smaller buildings relatively far from a barrier. A partial classification, where only some buildings have been attributed can be used. In this case all unattributed buildings will have a relative significance calculated. Culturally significant buildings can be forced to stay visible by attributing them with a lock value so that they will not be masked by the tool. A locked building is considered locally important, so nearby buildings may be compromised more than they would if that building was not forced to stay visible.

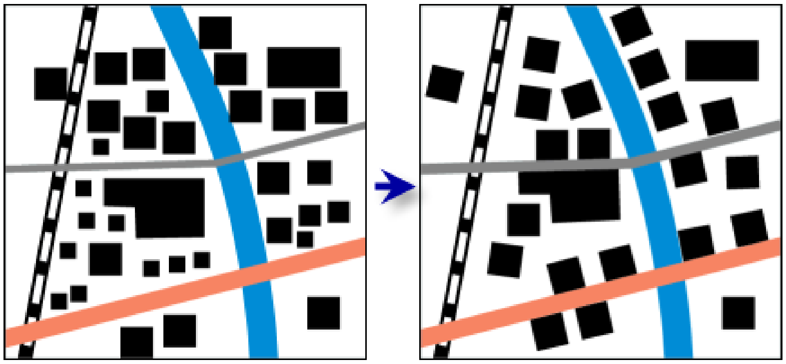

Fig. 6 – The Resolve Building Conflicts tool resolves conflicts among graphically conflicting buildings and barriers and manages user-specified orientation and gap settings

4 WEB MAPPING APPLICATION

Esri created a workflow leveraging this generalization framework to produce a Web map service of Hamilton County, Indiana at a contiguous scale spectrum from neighborhood streets and buildings to a view of the entire county. The Web map service was implemented to test and verify the generalization results as well as a proof of concept of the workflow as a superior alternative to the standard simplification provided by simple feature selection.

The following are results from the Web service cached at scales of 1:9,028, 1:18,056, 1:36,112, and 1:72,224 to conform to the tiling schema used by Google Maps, Bing Maps and ArcGIS Online.

At 1:9,028 scale, no generalization was needed to display the data which had been captured at approximately 1:2,000 scale.

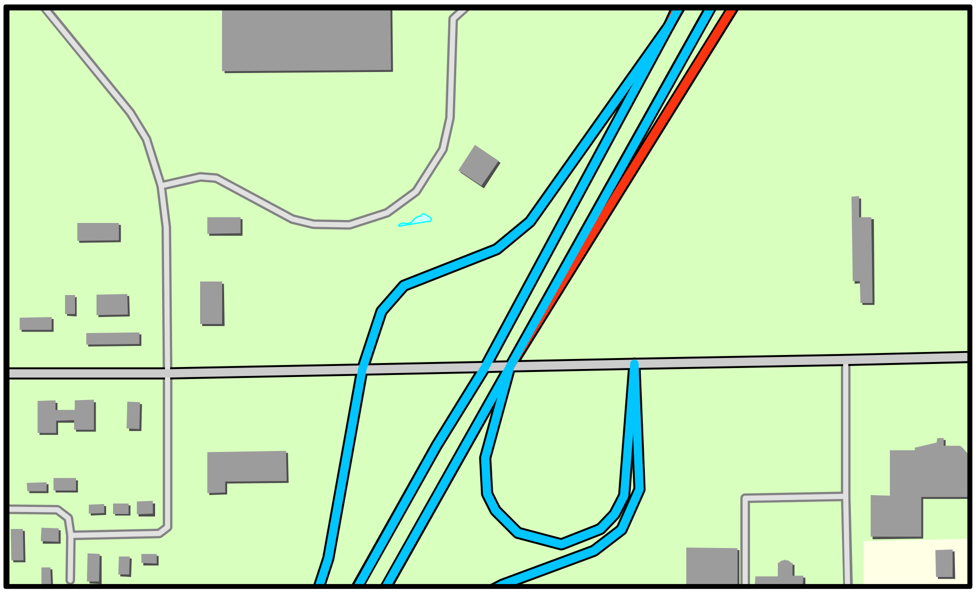

Fig. 7 – A portion of Hamilton Count, Indiana at 1:9028 scale

At 1:18,056 scale, a model composed of a sequence of geoprocessing tools was run to generalize the roads and buildings. First, the Simplify Building tool was run with a tolerance of 7m to simplify the building footprints. The Thin Road Network tool was run next, with a minimum distance of 200m, specifying that road segments below 200m in length are no longer visually significant at this scale. The Resolve Road Conflicts tool was run next to ensure that there were no coalescing parallel roads. And displacement resulting from that conflict resolution step was then propagated to the simplified buildings with the Propagate Displacement tool, to ensure that spatial relationships were preserved. Finally, the Resolve Building Conflicts tool was run to enlarge buildings to a minimum size of 20m (in both dimensions), to resolve conflicts between buildings, roads, and other buildings. Additionally, parameters were set to orient adjacent buildings to roads and ensure a minimum 5m gap from them.

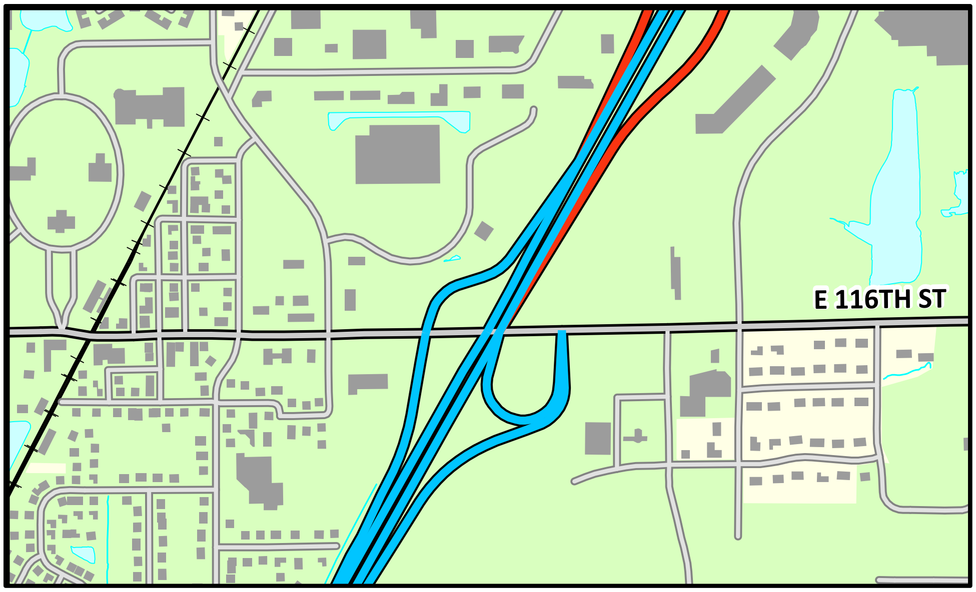

Fig. 8 – A portion of Hamilton Count, Indiana at 1:18,056 scale

At 1:36,112 scale, the original buildings were used as an input, but this time simplified with the Simplify Building tool at a tolerance of 30m. Using the original large scale roads, the Thin Road Network tool was run to remove extraneous segments. This time the minimum distance was set to 500m. Resolve Road Conflicts was run next, followed by the Propagate Displacement tool to propagate and displacements to nearby buildings. The Resolve Building Conflicts tool was run on the simplified buildings, using both roads and hydrology as barriers this time. Buildings were still set to be oriented to the roads with a 5m gap, but no orientation was specified with respect to the hydrology. To account for the smaller scale, the minimum building size was enlarged to 30m and the allowable gap between buildings specified as 20m.

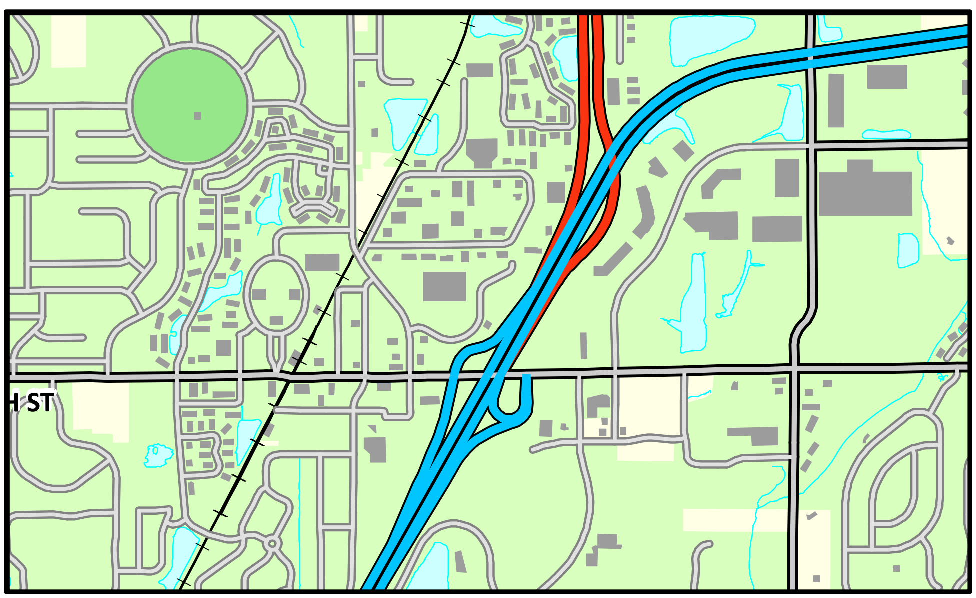

Fig. 9 – A portion of Hamilton Count, Indiana at 1:36,112 scale

At 1:72,224 scale, buildings were eliminated from the display. The road network was thinned using a minimum distance of 1200m, and then the Merge Divided Roads tool was run on the result to display the major highways with a single line only. Finally, the Resolve Road Conflicts tool was run to ensure that there were no remaining graphic conflicts with the roads.

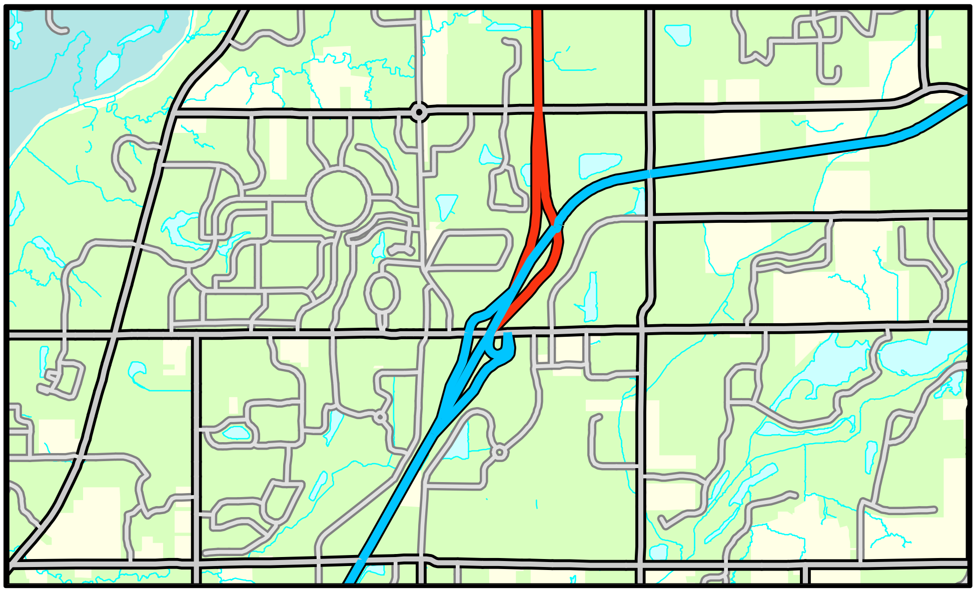

Fig. 10 – A portion of Hamilton Count, Indiana at 1:72,224 scale

The results demonstrate improved scale transitions across all scale ranges, yet changes between interim scaleappear minimal. This is essential for maintaining a seamless experience when zooming in a Web map. Relative density and pattern of both the road and buildings are maintained while simultaneously thinning and displacing features at smaller scales.

That is not to say that there is not room for improvement. There are numerous components of this workflow that could be refined upon and improved. Iterative attempts to refine parameter values would likely result in an even more seamless transition between scales. Including more layers in the processing would also improve the map. For example, railways are shown on this map, but were not considered in the conflict resolution process.

Even with enhancements to the workflow, there are still some aspects of the results that are not yet ideal. In particular, roads that form a small loop tend to be overlooked by the road thinning process, leaving too much detail in these areas. Likewise, traffic circles are not thinned properly either. Complex intersections with long exit/entry ramps tend to be difficult arrangements for the tools to handle gracefully. The resulting arcs and joins are not as smooth as they should be. Examples of these issues are evident in the images above. Development continues in these arenas to deliver improvements in a future release of the software.

5 CONCLUSION

The demands from both Web and print map requirements have been a valuable testing environment. Using this framework, Esri created a workflow to produce a Web map service of Hamilton County, Indiana. The Web map service was implemented as both a test of the tool results and as a proof of concept as to the improvements that could be seen in Web maps when using sophisticated, automated generalization models. Results demonstrated that improvements could be made at the larger scale levels making the zooming operations more seamless, with less obvious scale jumps.

The tools that Esri has released demonstrate a practical application of an optimized generalization framework that balances flexibility and usability in a commercially available software package designed for cartographers with a wide range of skills.

6 FUTURE RESEARCH

The geoprocessing tools recently developed for generalization are considered a first step in providing a robust yet flexible contextual generalization solution in ArcGIS. Research continues in how to adapt these processes to a nationwide or even global dataset. An awareness that other themes, particularly hydrology and physiography, could strongly benefit from a similar approach is under consideration (Brewer, 2009.)

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