Non-Connective Linear Cartograms for Mapping Traffic Conditions

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Cartograms have the advantage of bringing a greater visual impact to map readers. Geographic locations or spatial relationships of objects are intentionally modified to suit the attributes pertaining to objects. In area cartograms, it is the size of the object that is intentionally modified, while in linear cartograms it is the length or direction that is intentionally modified. Traffic conditions in urban transportation networks are very dynamic phenomenon as they change through time. During highly congested hours, travel speeds are low, and travel times are long, and vice versa. In previous studies, traffic conditions were visualized by color and width of road segments. In this paper, non-connective linear cartograms are introduced as a way to represent traffic conditions. Non-connective linear cartograms are linear cartograms that do not show the connectivity between line segments. Lengths of road segments are modified to represent a specific theme in traffic conditions. When the length of road segments represents the congestion level, longer segments indicate higher congestion levels, meaning near road maximum capacity. When the length of the segments represents the travel speed, longer segments indicate higher travel speed and, therefore, shorter travel time. When the length of the segments represents the travel time, longer segments indicate longer travel time, and therefore lower travel speed. In the non-connective linear cartograms, lengths of line segments are not limited to the physical length of represented road segments. The flexibility of adjusting it makes length of line segment a visual variable just like color and width of line segment. All three visual variables work together to create dramatic visual effects and attract greater attention from readers.

Keywords: non-connective linear cartogram, traffic congestion, travel speed, travel time, urban transportation network

INTRODUCTION

A map is "graphic representation, drawn to scale and usually on a flat surface, of features ... of an area of the Earth …" (Encyclopedia Britannica 2008). Most maps are created according to geographic locations of features and spatial relationships between them, though projections may bring inevitable distortion when transforming from 3D space to 2D space (Tobler 1986; Bugayevskiy and Snyder,1995; Iliffe 2000). In addition to objects representing real world features, attributes (characteristics or themes of objects) are elements often seen on maps. Thematic maps emphasize spatial patterns of attributes (Tyner 1992; Slocum et al. 2005). A method of disseminating attributes is the use of labels. Figure 1 is an example map

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showing the average travel speed in mph (mile per hour) in Salt Lake City, Utah. Other methods of disseminating attributes include the use of visual variables, such as color or width of line segments. However, under some circumstances, showing attributes as labels or visual variables is not practical or efficient enough to disseminate the spatial distribution of such attributes. The attributes themselves are of more importance or concern than the object that carries them (Monmonier 1996). Cartograms may be created based on the attribute, rather than geographic locations or spatial relationships (Muehrcke and Muehrcke 1998; Campbell 2001; Slocum et al. 2005), and therefore have the advantages of emphasizing attributes over geographic locations or spatial relationships.

"The attributes themselves are of more importance or concern than the object that carries them."

The urban transportation network is one of the features within which attributes (such as congestion levels, travel speed, or travel time) are of more importance or concern than road segments themselves. Local commuters who are already familiar with the street network know the connectivity between road segments. What matters to these commuters is the congestion level (or travel speed, travel time, etc.) during traffic rush hours (MTA-LAC 2006). Maps created from previous studies focusing on modeling and simulating dynamic urban traffic conditions do not create a visual effect that allows map readers to easily comprehend the spatial pattern of traffic conditions.

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This paper presents a new approach to visualizing traffic conditions with non-connective linear cartograms. The following sections will examine types of cartograms; review maps created from previous transportation studies; and point out weaknesses on previous maps, advantages of non-connective linear cartograms, and how they are created. The final three sections will introduce non-connective linear cartograms showing congestion level, travel speed, and travel time, respectively.

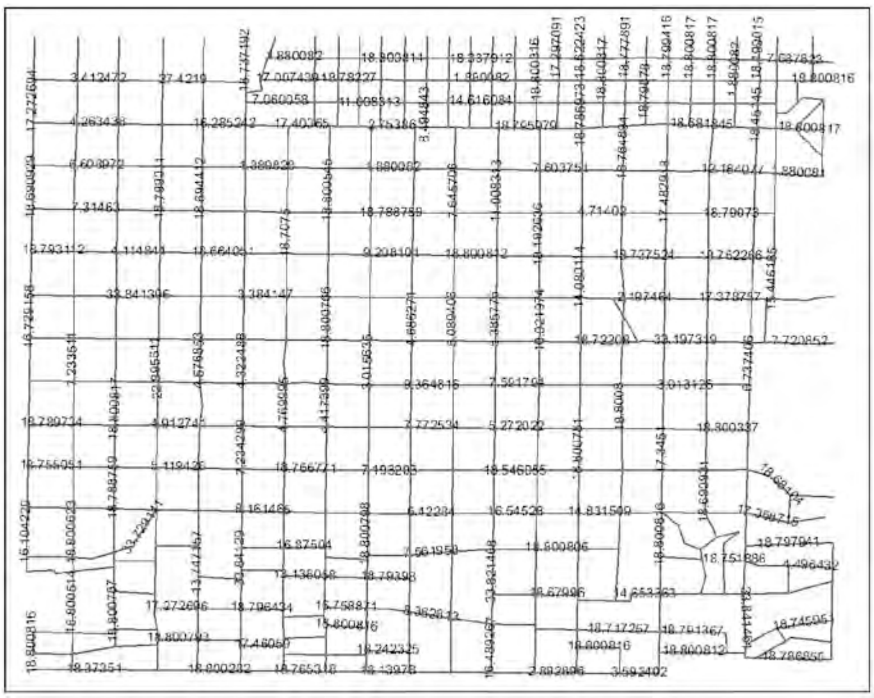


Figure 1. An example map showing traffic speed in mph with labels in Salt Lake City, Utah.

Cartogram

A cartogram "purposely distorts geographic space based on values of a theme (e.g., making the size of countries proportional to population" (Slocum et al. 2005). In its common use, a cartogram "does not depict geographic space, but rather changes the size of objects depending on a certain attribute" (Cartogram Central 2002a). Distortion, in turn, creates unexpectedly strong visual impacts (Tyner 1992; Clarke 1995; Dorling and Fairbairn 1997; Tobler 2004). There are area cartograms focusing on areal features and associated attributes and linear cartograms focusing on linear features and associated attributes. Most cartogram research is focused on area cartograms. Depending on the types of distortions, area cartograms can be grouped as contiguous cartograms, non-contiguous cartograms, pseudo-cartograms, or Dorling cartograms (Tobler 1986; Dorling 1993; Muehrcke and Muehrcke 1998; Campbell 2001; Cartogram Central 2002a; Slocum et al. 2005). For contiguous cartograms, continuity is preserved while shape is distorted. For non-contiguous cartograms, shape is preserved while continuity is distorted (Slocum et al. 2005). For Dorling cartograms, neither shape nor continuity is preserved; instead, non-overlapping symbols like circles are used. The sizes of these symbols are proportional to the mapped variable (Dorling 1993). Pseudo-cartograms are sometimes called pseudo-continuous cartograms. Though they may look like contiguous cartograms, neither shape nor continuity is preserved. Polygon sides are often straightened and aligned with gridlines in order to accurately represent relative directions (Tobler 1986).

"Distortion, in turn, creates unexpectedly strong visual impacts."

The majority of area cartogram research has focused on contiguous cartograms, especially developing algorithms on automatically creating them, because of the complexity of maintaining the continuity (Dougenik et al. 1985; Edelsbrunner and Waupotitsch 1997; House and Kocmoud1998; Kocmoud and House 1998; Keim et al. 2002; Gastner and Newman 2004; Keim et al. 2004; Keim et al. 2005; Inoue and Shimizu 2006). In addition, creating area cartograms using commercial geographic information system (GIS) software has attracted interest from cartogram researchers in recent years (Jackel 1997; Du and Liu 1999; Wolf 2005). Area cartograms are often used to present election results (Haro 1968; Kocmoud and House 1998; Fabrikant 2000, 2004; Gastner et al. 2005) or social-economic data, such as population (Haro 1968; Kocmoud and House 1998; Cartogram Central 2002b; Newman 2006; ODT Inc. 2007).

Little attention was given to the creation and application of linear cartograms, sometimes called distance cartograms (Campbell 2001) or distance-by-time cartograms (Tyner 1992). Compared to the classification of area cartograms based on continuity of polygons (contiguous area cartogram or non-contiguous area cartogram), linear cartograms could be identified as connective linear cartogram or non-connective linear cartogram based on connectivity of line segments. Connective linear cartograms preserve connectivity but distort line shapes. In such linear cartograms, route connectivity is preserved (lines connecting to other lines are still connecting to them), but direction and length of route segments are intentionally distorted. Furthermore, the lengths of route segments are not proportional to any attribute associated with these transportation routes. Simplicity and appearance are the main concerns of these linear cartograms. They are mainly used to conceptually present unique transportation routes (e.g., MTA-LAC 2008; Transport for London 2008; Washington Metropolitan Area Transit Authority 2008a), driving distance and driving time maps (e.g., AAA 2004), or airline route maps (e.g., Delta Airlines 2008). On the other hand, non-connective linear cartograms preserve line shapes but dis-

". . . non-connective linear cartograms preserve line shapes but distort connectivity."

tort connectivity. In such cartograms, lines may not connect to other lines as they are supposed to. Instead, lines at their original shapes are shrunk according to the mapping variable and shown at a representative location to identify their original locations.

"When cartograms do not show the correct geographic locations or spatial relationships, it is necessary to show a map drawn to scale of the study area for reference."

When cartograms do not show the correct geographic locations or spatial relationships, it is necessary to show a map drawn to scale of the study area for reference. The study area is a portion of Salt Lake City, Utah. Figure 2 shows all of the road segments in the study area. It is a grid-like transportation network, which is commonly seen in many cities in the USA. Because of the regular shape of lines, it is easier for readers to recognize individual roads even after they are distorted or shortened. In this figure, the lengths of road segments are proportional to their actual length. Widths of road segments, however, are the same throughout the study area, regardless of their actual widths and road classes.

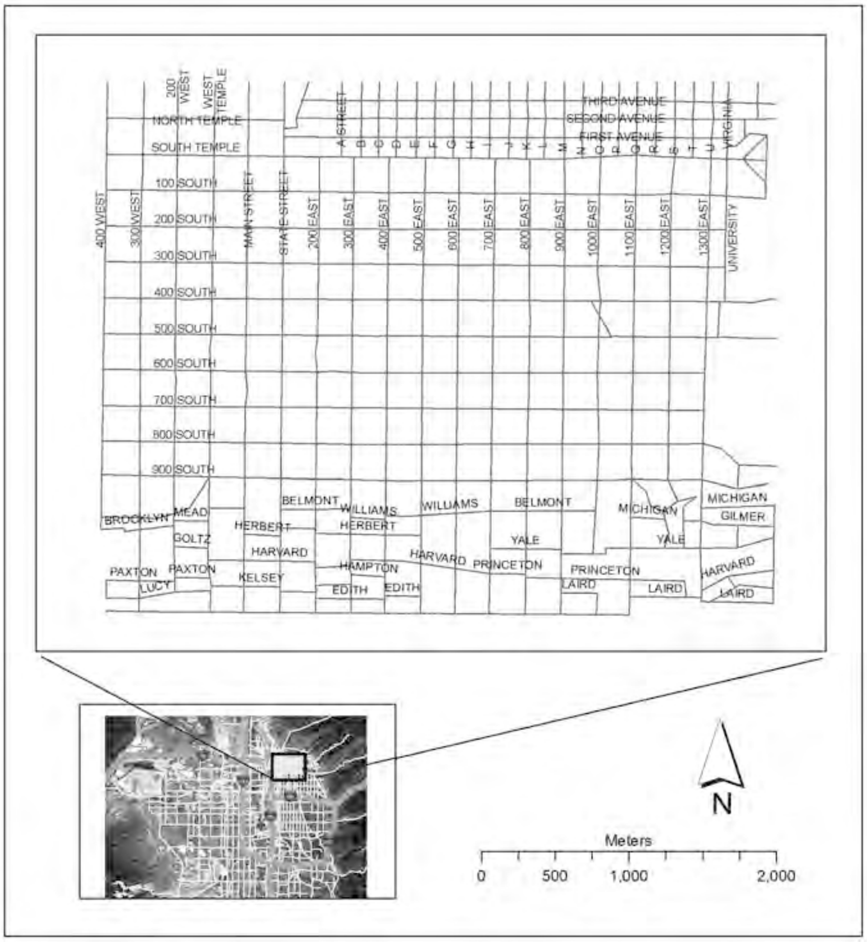


Figure 2. Transportation network in the study area: Salt Lake City, Utah. (see page 70 for color version)

Previous Maps for Traffic Conditions

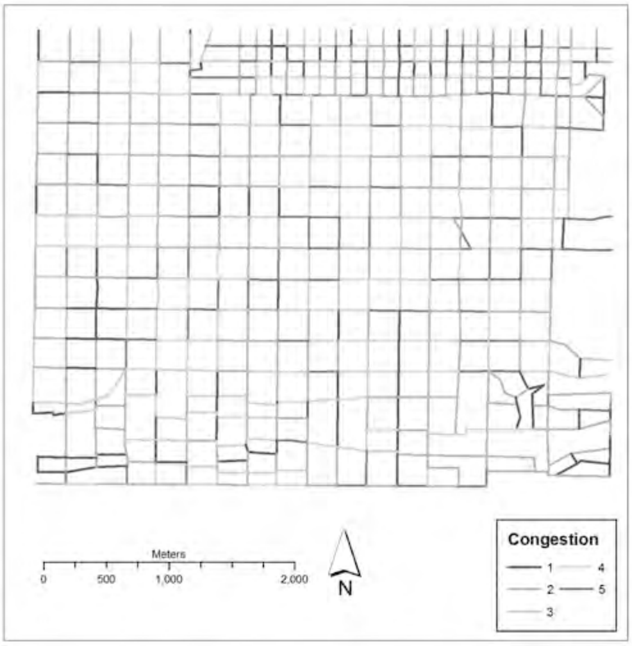
Traffic congestion is an indication of the relationship between the current traffic flow and the maximum capacity of a road segment. Simply speaking, the current traffic flow could be described as the current amount of cars traveling freely at the speed limit, while the maximum capacity could be described as the maximum amount of cars travelling freely at the speed limit. The congestion level can then be expressed as a ratio of the current traffic flow over the maximum capacity. It is easy to observe from daily traffic flow in urban areas that traffic congestion is inevitable, and it is dynamic through time. Though traffic congestion is complicated in nature, many studies have used various models and approaches to simulate traffic flow through time (Friesz et al. 1996; Chen 1998; Ran and Boyce 1996; Miller and Shaw 2001). A more recent study concluded that the level of congestion changes, not only from time to time, but also from road segment to road segment. At a given time, Main Street may be more congested than First Street. Five minutes later, it may not be so. It is not surprising to learn that in traffic rush hours, timing is more important than time (Wu 2004).

"It is not surprising to learn that in traffic rush hours, timing is more important than time."

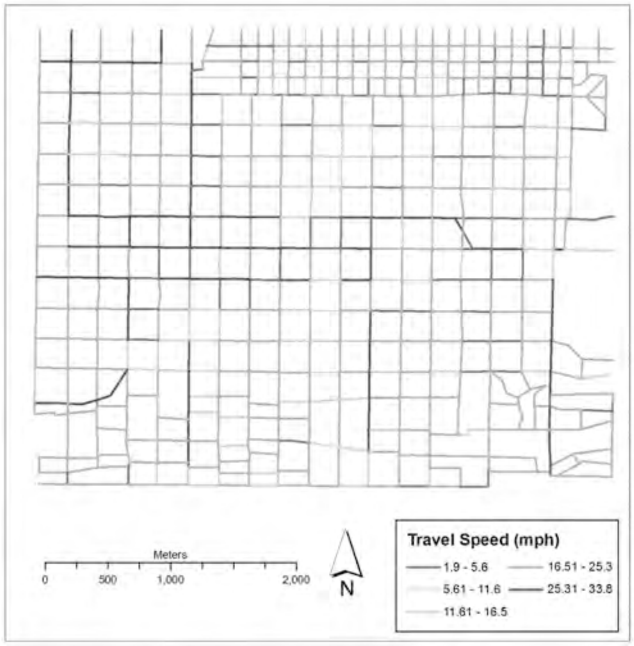
Traffic congestion affects travel speed and travel time. High levels of traffic congestion are near the maximum capacity of a road segment, and therefore lead to lower travel speed and longer travel time, and vice versa. Visualization of such in previous studies included using various colors or grey levels to show levels of congestion, travel speeds, and/or travel times (MTA-LAC 2006; Miller and Wu 2000; Miller et al. 1999). Re-makes of maps from previous studies (showing traffic conditions using various colors or grey levels) can be found in Figure 3. Figure 3 (a) shows traffic congestion level per road segment by multiple colors, Figure 3 (b) shows travel speed (mph: miles per hour), and Figure 3 (c) shows travel time (minutes). There are five levels of congestion; level 1 is the least congested with the current traffic flow less than 20% of the maximum capacity, level 2 is less than 40%, level 3 is less than 60%, level 4 is less than 80%, and level 5 is the most congested with the current traffic flow more than 80% of the maximum capacity. Differently from original maps, a spectral color scheme is used. A sequential color scheme, either lightness-based or saturation-based, may make some color lighter or more saturated than others (Slocum et al. 2005). Using lighter or more saturated colors on linear features (especially thin or short lines) tends to make them difficult to see or almost invisible in some cases. To ensure every line is clear and visible, a spectral color scheme is used in this illustration. Moreover, the red color is intentionally used to represent slower traffic (higher congestion level, lower travel speed, or longer travel time) because the color red in traffic lights indicates stop which naturally links to slower traffic from a color-association viewpoint. This, however, leads to a reversed color sequence in travel speed (red for high congestion level values, high travel time values, but low travel speed values). As one may observe from Figures 3 (a), (b), and (c), they present a similar general pattern, but not exactly the same (red color in congestion level may not necessarily be red in travel speed nor travel time). This occurs because the classifications on congestion level, travel speed, and travel time are different from each other. The congestion level ranges from 1 (least congested) to 5 (most congested), travel speed ranges from 1.9 mph to 33.8 mph with class boundaries set at 5.6, 11.6, 16.5, and 25.3 mph, while travel time ranges from 0.03 minutes to 10.2 minutes with class boundaries set at 0.2, 0.4, 1.5, and 3.6 minutes. Each variable is individually classified by the Natural Breaks (Jenks) classification method with 5 classes in ArcGIS software.

"Using lighter or more saturated colors on linear features (especially thin or short lines) tends to make them difficult to see or almost invisible in some cases."

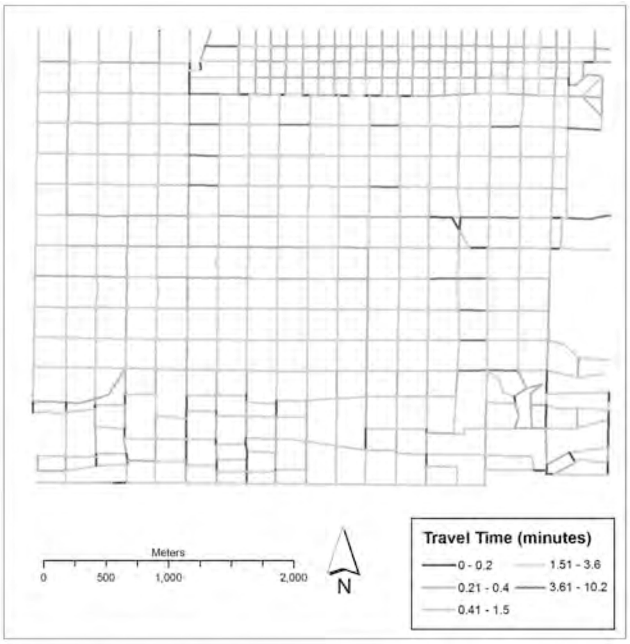
In other studies, width of road segments are modified to show the variable of interest (Wu and Hung 2000; Wu et al. 2001; Wu and Miller 2002). Re-makes of maps from previous studies (showing traffic conditions using road segments with various widths) can be found in Figure 4. Figure 4 (a) shows the traffic congestion level per road segment by multiple colors and widths, Figure 4 (b) shows travel speed, and Figure 4 (c) shows travel time. In addition to the color choice and color association as used in Figure



(a) *Showing traffic congestion level (see page 71 for color version)*



(b) *Showing travel speed (see page 71 for color version)*

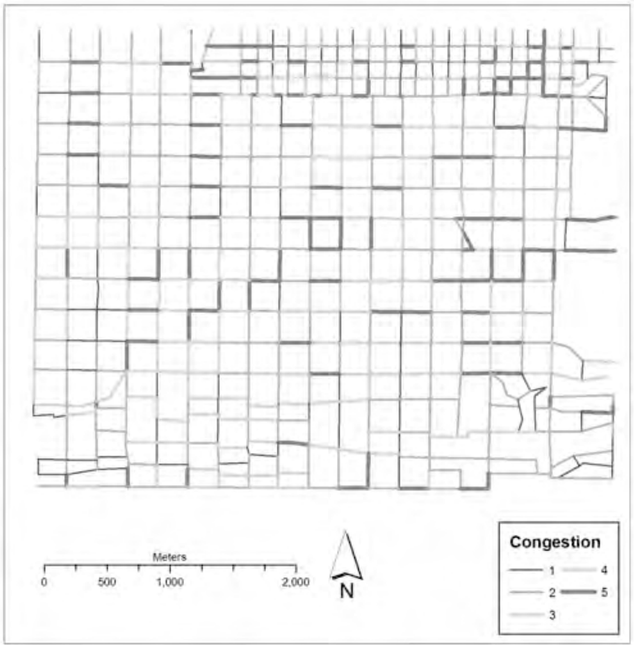


(c) *Showing travel time (see page 71 for color version)*

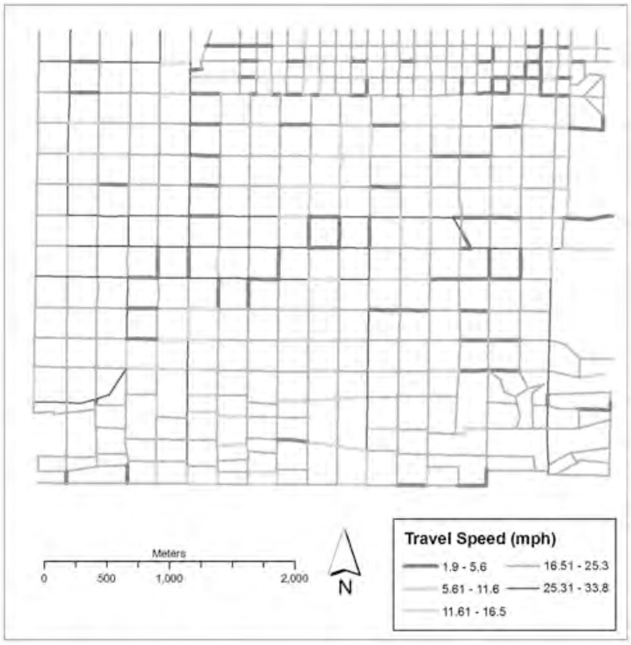
Figure 3. Maps showing traffic congestion by different indicators per road segment by different colors.

3, wider lines are used for slower traffic (higher congestion level, lower travel speed, or longer travel time) to create a visual effect of crowdedness.

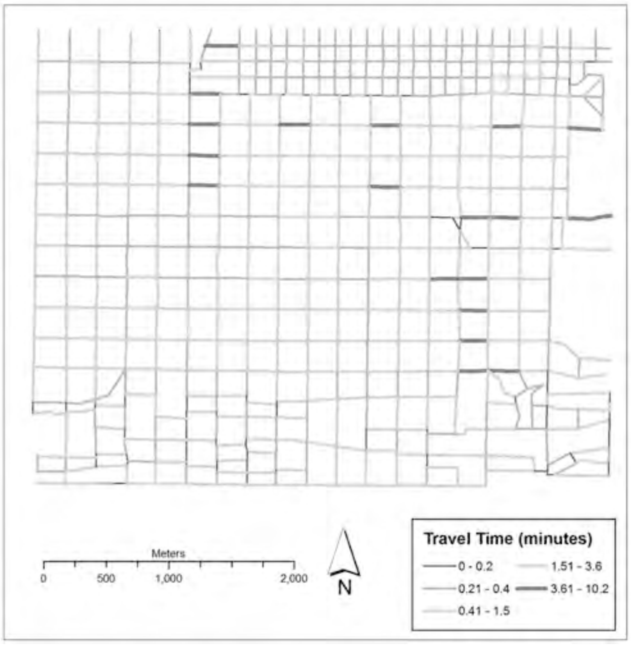
Ahmed and Miller (2007) proposed a time-space transformation to depict the free-flow travel time. Similar to linear cartograms, they used lengths of line segments to represent travel times. Though lengths of line segments may change, they chose to preserve connectivity between lines correctly (lines are still connected to other lines). As a result of such,



(a) *Showing traffic congestion level (see page 72 for color version)*



(b) *Showing travel speed (see page 72 for color version)*



(c) *Showing travel time (see page 72 for color version)*

Figure 4. Maps showing traffic congestion by different indicators per road segment by multiple colors and multiple widths.

features were moved away from their geographic locations and formed time-space locations. These time-space locations were superimposed on geographic locations, and vectors were drawn from geographic locations to time-space locations to show the displacement pattern. In such visualization, road segments were not drawn to scale. Furthermore, road intersections were not drawn to their geographic locations. For readers who want to identify road intersections, it is very confusing and challenging.

Traffic Conditions by Non-Connective Linear Cartogram

Advantages of Non-Connective Linear Cartogram

Though traffic conditions were visualized in previous studies, there is room to improve. In Figure 1, traffic conditions (average travel speed) are shown as labels which are then attached to each line segment. Readers have to examine the numbers in order to get information out of the map. Though this is an effective method to show quantitative traffic conditions for individual road segments, it is not suitable to represent a comprehensive view of the entire transportation network. In addition, labels themselves take up space in the map. This method may inevitably make the map crowded because of a large amount of labels. In Figure 3, traffic conditions (congestion level, travel speed, and travel time) are shown with various colors. Unfortunately, colors themselves do not show any numeric associations. It is the order of these colors in the legend that relates the numeric meanings to the reader. Thus, legends have to be studied in order for readers to understand meanings of various colors. In Figure 4, in addition to colors, widths of line segments are used to show traffic conditions. Comparing to Figure 3, this approach improves numerical association, but not much. In addition to problems with use of colors, there are drawbacks or limitations on use of widths. Lines cannot be drawn too wide. Otherwise, the whole map will look crowded and, in turn, difficult to be read. The resultant map from the time-space transformation approach proposed by Ahmed and Miller (2007) is quite similar to linear cartogram, connective linear cartogram to be exact. Their transformation created severe distortions as seen from their map. More specifically, their transformation modified lengths of road segments and moved road intersections away from their geographic locations on their map. Because of these distortions, the map is quite confusing even for readers who are familiar with the study area.

"Unfortunately, colors themselves do not show any numeric associations. It is the order of these colors in the legend that relates the numeric meanings to the reader."

To better visualize traffic conditions on maps, this paper presents a new approach using non-connective cartograms. The transportation network in the study area will be shown symbolically. Road segments are represented by line segments. Lengths of line segments are not proportional to their actual lengths. Instead, they are proportional to the mapping variable; in this paper it is congestion level, travel speed, or travel time. Lengths of line segments may be drawn independently from their physical lengths of the represented road segments. Therefore, length itself is a visual variable for line segment, just like color or width of line segment. To create a better visual effect, all three visual variables of line segment (length, width, and color) are utilized. Also because lengths are adjusted, line segments may not connect to other line segments. In other words, connectivity between road segments is not preserved. To some degrees, non-connective linear cartograms work like non-contiguous area cartograms in that lengths (or sizes) of mapping units (lines versus polygons) are independent from their physical lengths (or sizes) and could be used as a means to show the variable of interest.

"Lengths of line segments are not proportional to their actual lengths. Instead, they are proportional to the mapping variable . . ."

Non-connective cartograms have the potential to better visualize traffic conditions, based on problems observed from previous studies. The mapping variable is represented by one or more of the visual variables of the line segments; there is no need for labels. Therefore, this eliminates labels and free up space to avoid crowdedness caused by labeling. By choosing a saturation-based color scheme, the degree of saturation may also be used to represent the value of the mapping variable. Therefore, colors do have a quantitative association, or at least an ordinal meaning. Not every line segment is connecting to other line segments. Some lines are short. These short lines free up space for other map elements. Even though other lines are drawn at a relatively large width, there is space for such wide lines. Therefore, wide lines will not cause unpleasant crowdedness. Road segment connectivity is not presented in non-connective linear cartograms; adjustments on lengths will not affect the locations of road intersections. Road intersections are shown at their geographic locations (though in cartograms presented by this study, road intersections are not mapped). Therefore, there is less confusion for readers.

Calculation and Classification of Traffic Conditions

The congestion level was calculated following previous work by Miller et al. (1999), Miller and Wu (2000), Wu et al. (2001), and Wu and Miller (2002). Their work produced five congestion levels, level 1 being the most congested with more than 80% of the maximum capacity of travel volume on the road, level 2 with more than 60%, level 3 with more than 40%, level 4 with more than 20%, and level 5 being the least congested with less than 20% of the maximum capacity. From a cartographic viewpoint (Slocum et al. 2005); however, it is preferable for high levels to represent high data values. Therefore, their work was modified to produce a reversed order (level 5 being the most congested while level 1 is the least congested), so that higher congestion levels are associated with higher percents of maximum capacity. Lengths of line segments are proportional to their data value and are calculated by the following equation:

". . . however, it is preferable for high levels to represent high data values."

$L = r * (f / 5)$ (equation 1)
where L is the length of a line segment in a non-connective linear cartogram,
r is the original length of a line segment, and
f is the traffic condition value (congestion level, travel speed, or travel time) with ranges between 1 and 5.

The following sections and linear cartograms depict the traffic conditions (congestion level, travel speed, and travel time) in the time interval 1, the beginning of the analysis time period (4 pm). They are created by Visual Basic (VB) scripts in ArcGIS software. The VB scripts read in the polyline shapefile and break down the connectivity between lines by converting the entire shapefile to a collection of graphics. Each graphic then represents an individual line segment in the transportation network, and equation 1 is applied to each graphic to adjust the length according to the variable of interest. The graphic is then assigned a pair of coordinates that illustrates the center of the represented line segment. ArcMap software draws it on the map area according to these assigned coordinates. At the time when the manuscript is written, the VB scripts only perform the conversion, length-adjusting, and coordinates-assigning tasks. Before running the VB scripts, the traffic conditions have to be manually classified, and widths and colors manually chosen.

"Higher congestion levels (higher data value, slower traffic) are represented by longer segments."

Non-Connective Linear Cartogram for Congestion Level

Figure 5 shows non-connective linear cartograms, indicating the levels of traffic congestion. The lengths of road segments are modified according to their congestion levels. Higher congestion levels (higher data value, slower traffic) are represented by longer segments. As in non-contiguous area cartograms, a drawn-to-scale map (Figure 2) should be used for reference. In addition, colors and widths are used here as well to enhance visual effects. In Figure 5 (a), all road segments are shown with the same color, black defined as (0%, 0%, 0%) in the RGB color model, and the same width (2 points). Only the length is used as a visual variable. It is a fairly straight and plain non-connective linear cartogram: longer segments indicate higher data values (high congestion levels in this figure, which indicate slower traffic), and vice versa. In Figure 5 (b), widths are the same throughout the study area, but colors are different according to the congestion levels. A saturation-based sequential color scheme with green as the hue is chosen because of color association (green means go and red means stop in traffic lights). Furthermore, desaturated greens (green without saturation, brighter green) mean faster traffic (lower congestion levels), while saturated greens mean slower traffic (higher congestion levels). In this color sequence, the desaturated green on the lower data value end is defined as (0%, 100%, 0%), while the saturated green on the higher data value end is defined as (40%, 60%, 40%). This creates a visual effect that roads with faster traffic are shown by brighter greens. In Figure 5 (c), colors are the same throughout the study area (black), but widths are different according to the congestion level. Longer segments are wider (3.5 points) and shorter segments are thinner (1.5 points). This creates a visual effect that roads with slower more crowded traffic conditions (higher congestion levels, longer line segments) are shown with thicker lines. In Figure 5 (d), both widths and colors are different according to the congestion level, as explained above. Overall, Figure 5(d) has the most dramatic appearance among the four linear cartograms in this figure. It combines the two mapping techniques used in (b) and (c) and uses all of three visual variables (length, width, and color) to provide a more dramatic visual effect. Roads with faster traffic (lower congestion levels, lower data values) are shown brighter, lighter, and shorter, while roads with slower traffic are shown darker, heavier, and more crowded.

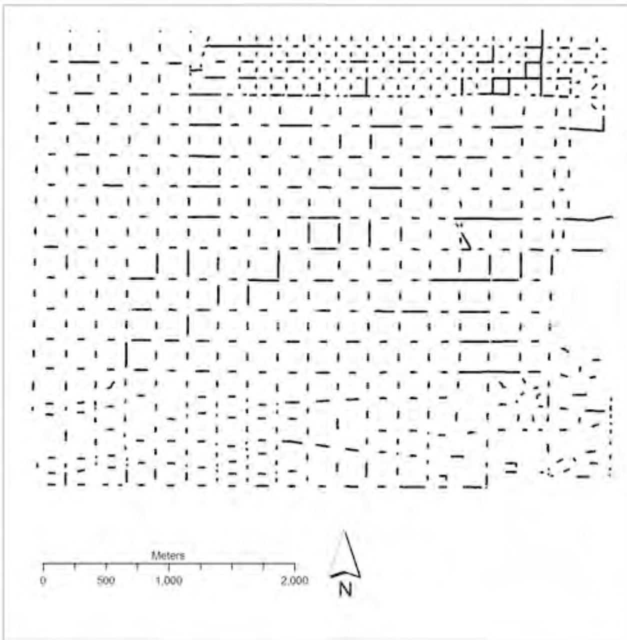
"A saturation-based sequential color scheme with green as the hue is chosen because of color association (green means go and red means stop in traffic lights)."

Non-Connective Linear Cartogram for Travel Speed

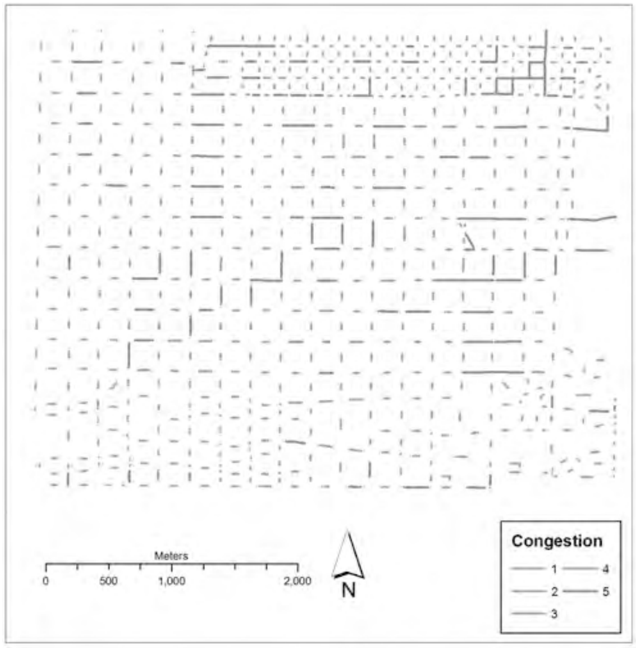
Figure 6 shows non-connective linear cartograms indicating the travel speed. Lengths of road segments are proportional to their travel speeds, calculated by the same manner as in equation 1. In general data association, higher data values (higher travel speeds, faster traffic) are represented by longer segments. As in Figure 5, colors and widths are used to enhance the visual effects. In Figure 6 (a), all road segments are shown with the same color and the same width; only the length of a road segment is used as a visual variable. In Figure 6 (b), widths are the same throughout the study area, but colors are different according to the travel speed. Again, a saturation-based sequential color scheme with green as the hue is used, as explained previously. Brighter greens are intentionally used on roads with faster traffic (higher travel speed, higher data values). In Figure 6 (c), colors are the same throughout the study area, but widths are different according to the travel speed. Wider lines are used for higher data values (higher travel speed, faster traffic). In Figure 6 (d), both widths and colors are different according to the travel speed.

"In general data association, higher data values (higher travel speeds, faster traffic) are represented by longer segments."

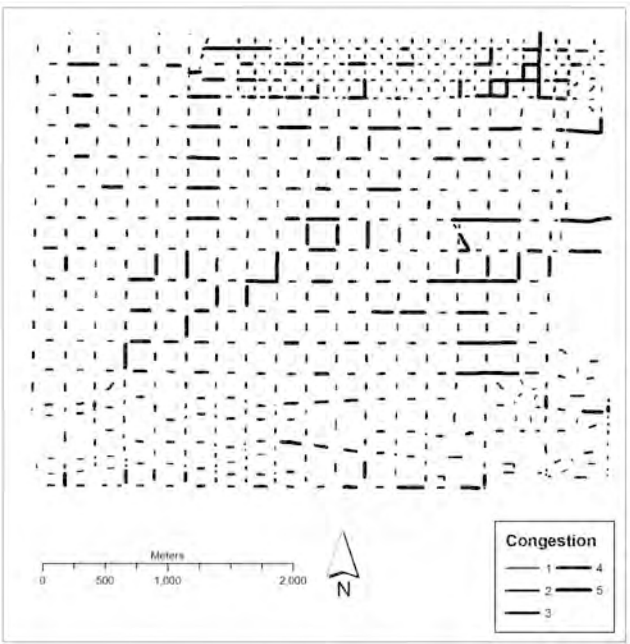
As one may note from comparisons between Figures 5 and 6, there are some similarities but also some differences. There are three visual variables used here: length, color, and width of line segment. Figures 5 (d) and 6 (d) will be used as examples for comparisons between visual effects created by congestion levels and travel speeds. In terms of length alone (disregarding color and width), it is proportional to its own data value. These two figures almost present a reversed pattern: longer segments in one are found with shorter segments in the other. This occurs because of general



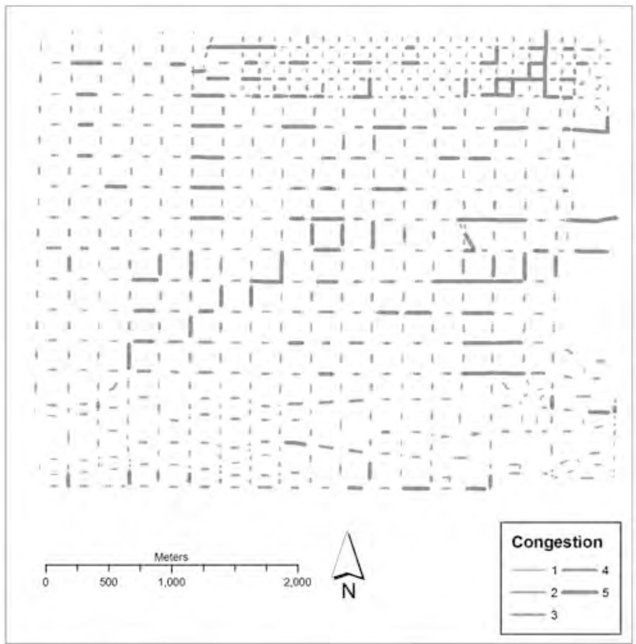
(a) All road segments are shown with the same color and the same width.



(b) All widths are the same, but colors are different according to the congestion level. (see page 73 for color version)



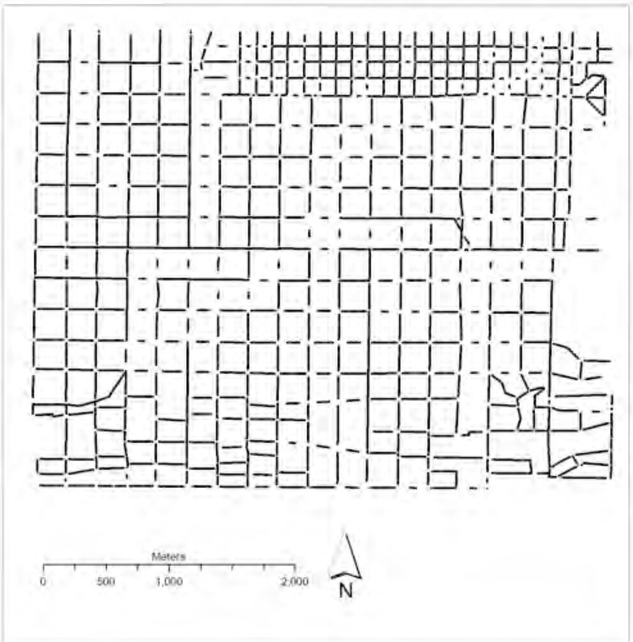
(c) All colors are the same, but widths are different according to the congestion level.



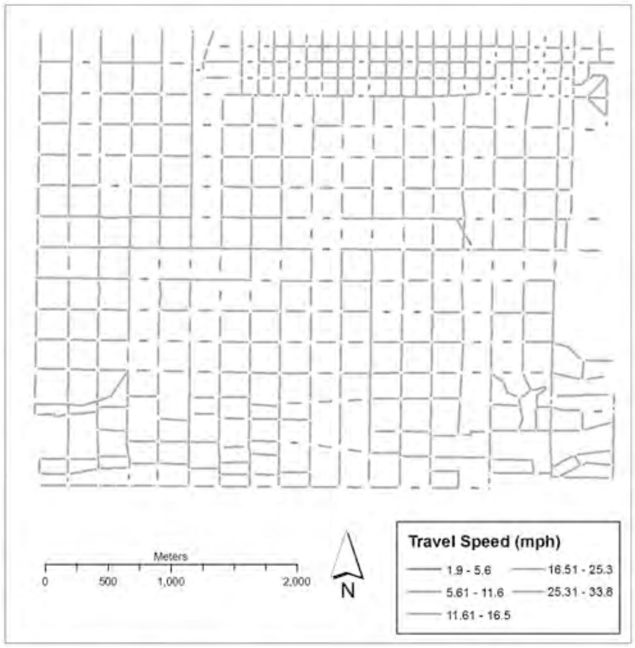
(d) Both widths and colors are different according to the congestion level. (see page 73 for color version)

Figure 5. Non-connective cartograms showing traffic congestion level.

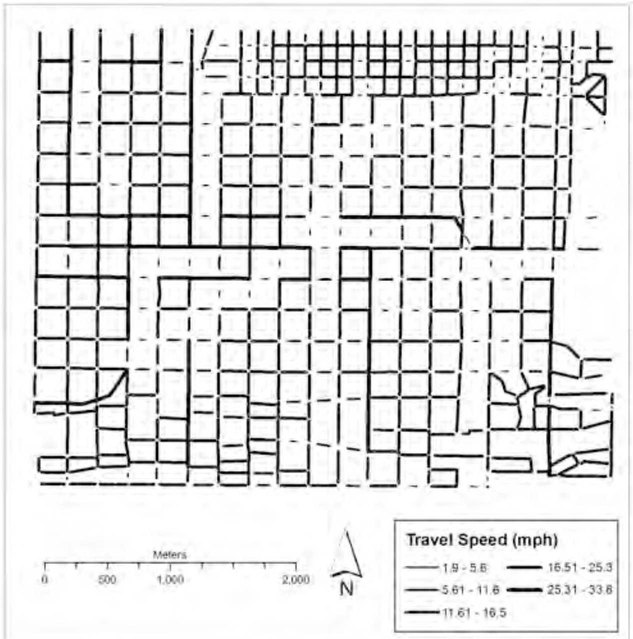
data association (larger data with longer lines) and the variable of interest here. In Figure 5 (d) with congestion levels, faster travel is represented by lower congestion levels, lower data values, and, therefore, shorter line segments. However, in Figure 6 (d) with travel speed, faster travel is represented by higher travel speeds, higher data values, and, therefore, longer line segments. In terms of width alone (disregarding length and



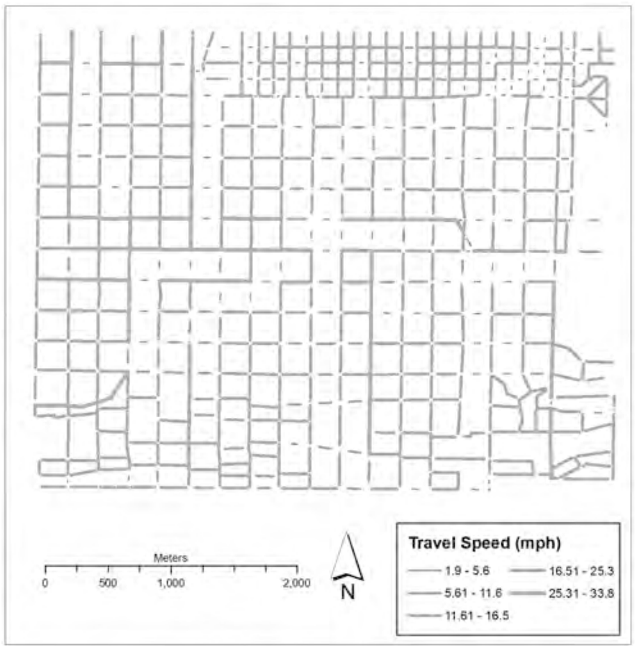
(a) All road segments are shown with the same color and the same width.



(b) All widths are the same, but colors are different according to the travel speed. (see page 74 for color version)



(c) All colors are the same, but widths are different according to travel speed.



(d) Both widths and colors are different according to travel speed. (see page 74 for color version)

Figure 6. Non-connective cartograms showing travel speed.

color), it is again almost a reversed pattern between these two figures because of the general data association (larger data with wider lines) as explained previously. In terms of color alone (disregarding length and width), it is not a reversed pattern. Instead, it is almost an identical pattern between these two figures. Color association could be done independently from data association. Desaturated greens are intentionally used for faster travel. As one may notice from the figure legends, desaturated greens are for lower data values (faster travel) in Figure 5 (d), but higher data values (also faster travel) in Figure 6 (d). Therefore, they both have a visual effect that brighter greens mean faster travel.

Non-Connective Linear Cartogram for Travel Time

Figure 7 shows non-connective linear cartograms indicating the travel time. Lengths of road segments are proportional to their travel times. Higher data values (longer travel times, slower travel) lead to longer segments. As was done in Figures 5 and 6, colors and widths were used here as well to enhance visual effects. In Figure 7 (a), all road segments are shown with the same color and the same width. In Figure 7 (b), widths are the same throughout the study area, but colors are different according to the travel time. Again, a saturation-based sequential color scheme with green as the hue is used, as explained previously. Brighter greens are intentionally used on roads with faster traffic (lower travel time, lower data values). In Figure 7 (c), colors are the same throughout the study area, but widths are different according to the travel time. Wider lines are used for higher data values (higher travel time, slower traffic). In Figure 7 (d), both widths and colors are different according to the travel time.

"Contributions of these cartograms are the ability to use length of line segment as a visual variable (just like color or width) to create dramatic visual effects."

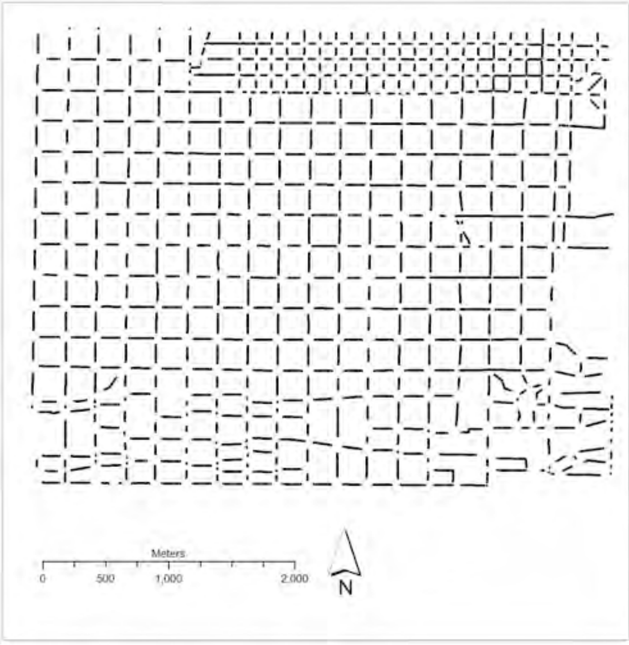
Figure 7 shows a similar general pattern as the one observed in Figure 5, but not a perfect match. Normally, higher congestion levels indicate lower travel speed and longer travel time. However, travel time depends on not only the congestion level, but also the distance (the actual length of the road segment). Not every road segment in the study area has the same actual length. The same congestion level may not necessarily lead to the same travel time. In addition, data classification may also play an important role in the overall pattern. These three variables (congestion level, travel speed, and travel time) are classified independently from each other by the Natural Breaks (Jenks) method in ArcGIS software.

Discussion and Summary

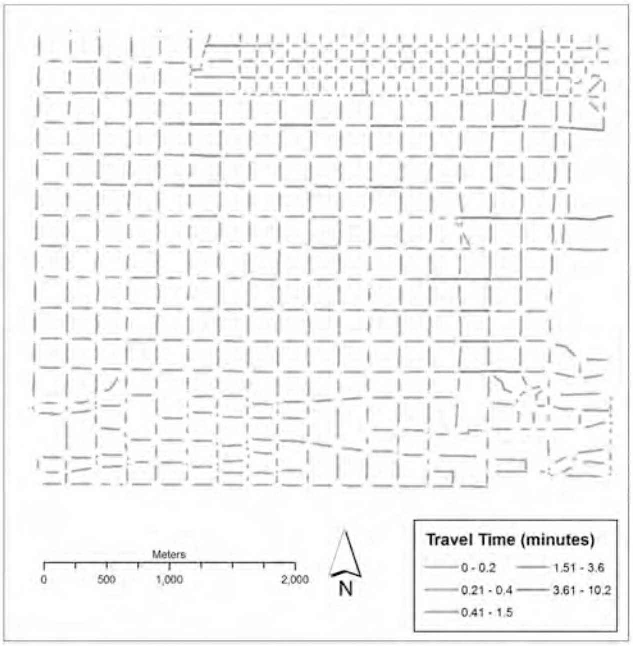
Three variables of traffic conditions are presented by non-connective linear cartograms: congestion level, travel speed, and travel time. For each variable, four cartograms are created. Contributions of these cartograms are the ability to use length of line segment as a visual variable (just like color or width) to create dramatic visual effects. Lengths of line segments on the map are not limited to the physical length of the represented real-world road segments; they could be modified according to the mapping variable. Among the four cartograms for each variable of interest, one is a plain linear cartogram with uniform width and uniform color (for example, Figure 5 (a)), one is with uniform width but various colors (for example, Figure 5 (b)), one is with various widths but uniform color (for example, Figure 5 (c)), and the last one is with various widths and various colors (for example, Figure 5 (d)). It is the one with various widths and various colors that brings the most visual impact because all three visual variables are utilized. In Figure 5 (d), it is easy to see desaturated green roads. In traffic signals, green means go. The color is so designed that desaturated green lines indicate faster traffic, while saturated green lines indicate slower traffic.

"Color choice is a difficult task in map-making."

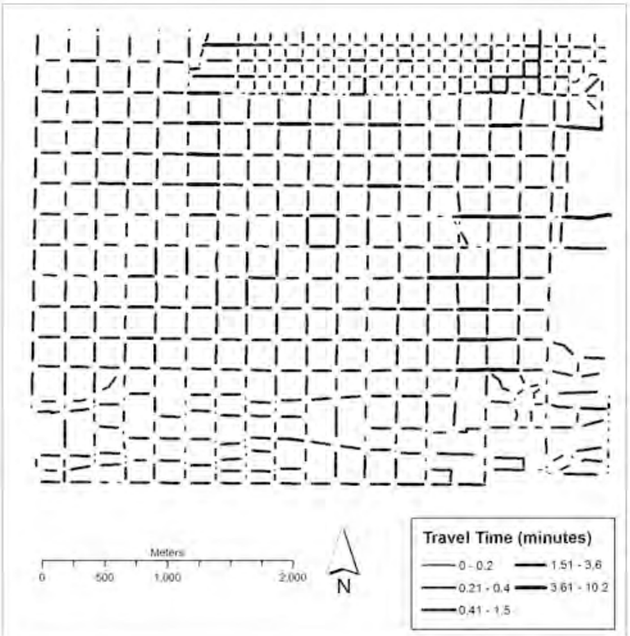
Color choice is a difficult task in map-making. A saturation-based color scheme is chosen in this study because of color association in traffic lights. It is natural to choose green as the hue for maps depicting traffic conditions. Unfortunately, there are not many choices on levels of saturated



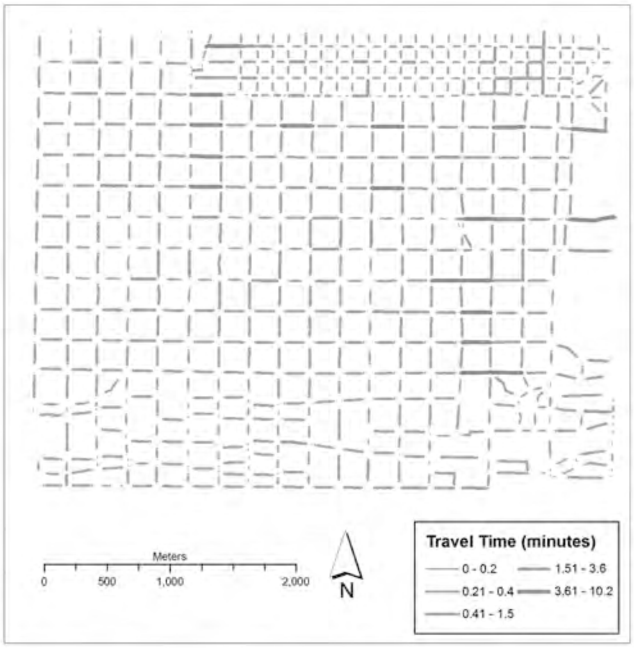
(a) All road segments are shown with the same color and the same width.



(b) All widths are the same, but colors are different according to the travel time. (see page 75 for color version)



(c) All colors are the same, but widths are different according to the travel time.



(d) Both widths and colors are different according to travel time. (see page 75 for color version)

Figure 7. Non-connective cartograms showing travel time.

greens while maintaining the visibility of some extremely short line segments. It is noticed from these cartograms that it is not easy to distinguish greens with different levels of saturations from each other. Fortunately, the use of width as another visual variable helps to mitigate this difficulty.

It is also interesting to notice the varied visual effects created by different variables of interest. Congestion level and travel speed are two commonly used variables in describing traffic flows. They may, however, create two almost reversed patterns as explained in previous sections. Readers are encouraged to examine the legend carefully before attempting to interpret these cartograms.

Cartograms should be used with caution. Non-connective linear cartograms do not suit street networks with long streets far away from each other or with irregular patterns. They are better suited to networks in which segments and interconnections are dense and plenty because road intersections may be used as reference points in most readers' mental image of a given area. The street network in Salt Lake City, Utah, is a grid-like network where most road segments are short and straight and are well aligned in an east-west or north-south direction. Though line segments are not connected to others and road intersections are not shown as points, they are still recognizable and easily linked to their represented road segments in the real world.

"Cartograms should be used with caution. Non-connective linear cartograms do not suit street networks with long streets far away from each other or with irregular patterns."

Though non-connective linear cartograms are created, the whole process has room for improvement. First of all, manual tasks are involved in several steps, such as data classification of travel speed and travel time, line width choices, line color choices, etc. These could be automated by VB scripts with or without some graphic user interface. Secondly, travel speed and travel time are quantitative data at the ratio level of measurement (Slocum et al. 2005). They are classified to five classes, to be consistent with five congestion levels. It would be interesting to explore the possibility of using non-connective linear cartograms to represent raw (not classified) travel speed or travel time. Thirdly, a computer animation to show dynamics of traffic conditions as lengths of line segments gradually changes as time progresses into traffic rush hours. Fourthly, different colors may be used on these cartograms. Currently, it is not easy to distinguish greens with different levels of saturation. Fifthly, these non-connective linear cartograms have not been verified on their practical values yet. It would be helpful to have a user survey on commuters who are familiar with the study area. However, the practical value of these cartograms should be separated from the accuracy of the model to simulate traffic conditions.

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