VISUALIZATION OF DYNAMICS
IN LINEAR REFERENCED TRANSPORTATION DATA

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ABSTRACT:

Linear referencing represents locations along routes, linear features with an established measurement system, using relative positions. It allows locating events along routes without segmenting it, and has been applied to manage linear features in transportation and utility. In transportation, dynamics in variant attributes such as speed limit, number of lanes, surface material, and traffic accidents, are often saved in event tables. Although events can be displayed via dynamic segmentation, there are difficulties in handling dynamics or changes in events. For example, it is hard to distinguish multiple resurfacing events over time at one location. When variant attributes are associated, dynamic segmentation split a route into short segments and the display can be greatly slowed down. In this study, I explore alternative approaches, including dynamic segmentation with temporal offset in 2-dimesional (2D) and 3-dimensional (3D) view, and animation for visualization of dynamics in linear referenced transportation data. In the first approach, temporal offset is introduced as a relative time axis. The older an event is, the closer it is to the route. This method works in the same way for one or variant attributes without over-segmentation. Using dynamic segmentation with temporal offset, it is not only fast in visualizing dynamics across different attributes, but also straightforward for visual analysis of the history in transportation data. The 3D view approach treats the time in transportation data as the third dimension in the space. Compared to dynamic segmentation with temporal offset in 2D, the 3D view is better for areas with dense linear features. Dynamics in both 2D and 3D view can be animated. In summary, this study provides alternative visualization for dynamics in linear referenced transportation data. Moreover, these approaches are not limited to transportation data but can be applied toward general dynamics in linear referencing.

1. INTRODUCTION

Transportation plays an important role in economic development and daily life. Because of its importance, US government reauthorized $244.1 billion for highways and public transportation, which is the largest investment on public surface transportation in US history (Pack, 2010). The money will be invested in transportation infrastructure, research, policy, data, information system, and etc. Among researches in transportation, challenges have been identified in visualization including temporal visualization of dynamic geographic data (Pack, 2010).

Geographic data have three components: location, themes, and time. The space is usually represented in a 2-dimension (2D) or 3-diemnsion (3D) coordinate system. In transportation, most data are located on or along roads - linear features. It's convenient and efficient to represent the location using relative distance along the roads (Guo and Kurt, 2004; Zhu and Li,, 2008). For example, interstate highways have mile posts every 0.2 mile. Mile posts are used in accident report, navigation, and etc. When the location is represented in a linear referencing system, the themes and the time are stored in event tables and displayed on-the-fly via dynamic segmentation.

Although events in linear referencing can be displayed via dynamic segmentation, there are difficulties in handling dynamics or changes in events, especially when there are temporal overlaps between events. For example, it is hard to distinguish different resurfacing events over time at one single location. Further, when multiple themes are mingled, dynamic segmentation splits a route into short segments and the display can be magnificently slowed down.

This study aims to explore alternative approaches to visualize dynamics in transportation data, which are spatially represented in a linear referencing system rather than in a traditional 2D or 3D coordinate system. It examines the problems/difficulties in displaying the time using dynamic segmentation, and proposes a 2D and a 3D methods for visualization of dynamics in transportation data. Animation in the 2D and 3D views are described in general.

The remainder of this section explains linear referencing and reviews related work on temporal visualization of geographic data. Section 2 presents alternative approaches to visualize dynamics in transportation data. Section 3 makes conclusions and discusses future work.

1.1 Linear Referencing

Linear referencing system represents locations along routes with relative positions (ESRI, 2009). A route is based on a line, a straight or curved line in a 2D planar or 3D geographic coordinate system. It has a unique identifier and an established measurement system. A measurement system has an origin and can be in Euclidian distance or relative distance, i.e. time distance.

Figure 1 gives an example of a route - *Route1* in a linear referencing system. *Route1* is based on a curved line. Its measurement system is labelled beneath the line. Event A and B are a point and a line on *Route1*, respectively. Event C is a point off *Route1*. In a traditional coordinate system, a point is defined as one (x, y) coordinate pair, and a line is stored as a series of (x, y) coordinate pairs. In a linear referencing system, a point is defined by the route identifier and one measurement (RID, m), and a line is represented by the route identifier and a from-measurement and a to-measurement (RID, f_m, t_m). When a location is not exactly on but a little off from a route, such as point C in Figure 1, an offset distance is introduced (RID, m, offset). In Figure 1, point A is at (*Route1*, 15) and line B is recorded as (*Route1*, 20, 30). Suppose point C is 10 meters away from *Route1*, then it is at (*Route1*, 34, 10). *Note:* The measurement value of 34 and the offset value of 10 are usually in different unit, i.e. 34 in miles and 10 in meters.

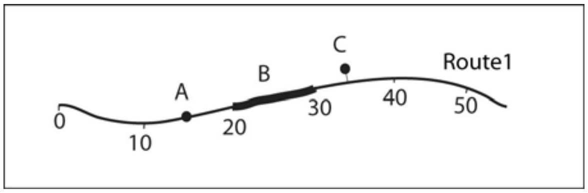

Figure 1. A route in a linear referencing system

In transportation, mile posts along interstate highways can be employed as a measurement system. By referencing to the mile posts, a collision can be reported at mile post 17.6 on I-29 South or (I-29S, 17.6); and a traffic congestion or a road work may be recorded between mile posts 17.6 and 19.2 on I-29 South, which is (I-29S, 17.6, 19.2).

In linear referencing, data of the same theme along routes, i.e. surface material and conditions, are stored in event tables. Each record in an event table represents a point or a line event. To visually display events from an event table onto a map, a process called dynamic segmentation is hired to render points or lines on-the-fly (ESRI, 2009). The term, dynamic segmentation, is derived from the idea that lines need not be split or segmented each time a theme value changes.

Linear referencing allows locating events along routes without segmenting it, and has been applied to linear features including transportation, river/streams and utilities (Zhu and Li, 2008). In transportation, dynamics in variant themes such as speed limit, number of lanes, surface material, and traffic accidents, are often saved in event tables and displayed via dynamic segmentation. Figure 2 presents a route with surface material, number of lanes, and speed limit information. Figure 3 shows change in surface material over the time. The route in Figure 2 and 3 is based on a curved line like the one in Figure 1, but simplified as a straight line for illustration.

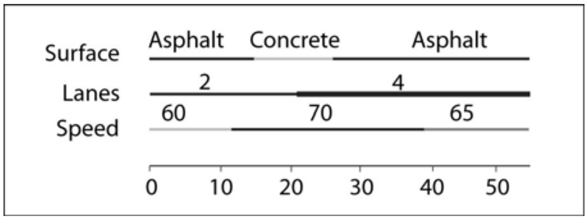

Figure 2. Multiple themes of a route

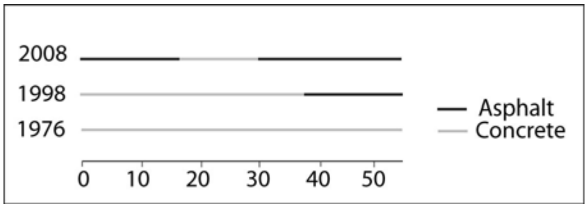

Figure 3. Status of surface material on a route

For linear features, such as roads, pipelines, and streams, linear referencing systems have advantages over the traditional 2D or 3D coordination systems. First, linear referencing avoids splitting a linear feature into small pieces. Second, there is no duplication of coordinate pairs between overlapping lines or points, which are common in highway assets. However, there is a problem when variant themes as in Figure 2 or dynamics of one theme over time, i.e. surface material in Figure 3, are rendered on one single map. Lines overlap and it is difficult to tell them apart. This problem is serious especially for temporal transportation data as in Figure 3. There is a great need of alternative visualization for temporal transportation data in linear referencing system.

1.2 Related Work

Time has been studied in geographic information science (GIScience) (Hägerstand, 1970; Langran, 1992; Goodchild *et al*, 2007) and computer science, specifically the database community (Allen, 1984; Snodgrass, 2000). The database community models changes in non-spatial data with timestamps at the table-, record-, or attribute-level (Kimball Group, 2000). These concepts have been adopted in representing dynamics in geographic data by the GIScience community. For example, the sequential snapshots approach adds timestamp at the table level (Armstrong, 1988). Because of difficulties in modelling temporal geographic data, most temporal researches in GIScience focused on spatiotemporal data representation (Peuquet and Duan, 1995; McIntosh and Yuan, 2005; Goodchild *et al*, 2007). This is also true for geographic information system (GIS) application in temporal transportation system (Wang and Cheng, 2001; Koncz and Adams, 2002; Zhu and Li, 2008). So far, there are limited studies in the literature on visualization of temporal geographic data (Guo and Kurt, 2004; Zhu and Li, 2008). Visualization of sptiotemporal data are often discussed as part of a temporal GIS system (Le, 2005).

Kraak (2003) presented alternative visualization approaches to Minard's map of Napoleon's 1812-1813 March on Moscow. Among the seven alternative graphs, four are temporal. For example, Kraak (2003) applied small multiples of time series in one map. He used time as one axis in a 2D coordinate system in a second map. Kraak treated time as the third-dimension in a space-time cube in the third map.

Recently, the transportation community recognized the challenges of visualization in transportation, including visualization of dynamics in transportation data, visualization of temporal massive data, 3D visualization, and spatiotemporal trend analysis (Pack, 2010). Since time is critical to transportation, the time rather than the space or the themes is treated as an important variable in research examples from the Center for Advanced Transportation Technology Lab (CATT Lab) at the University of Maryland presented. For example, researches at the CATT Lab applied linear timeline to discover critical information in an accident, a cyclical time graph for exploration of events in transportation, and an a 4D animation for real-time visualization (Pack, 2010). Linear time views the time as a straight directional line from the past through the present and to the future. Cyclical time emphasizes the repeating cycles in time. An analog clock is good metaphor for cyclical time in minutes and hours.

2. METHODOLOGY

Visualization of geographic data is constrained by data representation at certain degree. In this section, we first examine characteristics of dynamics in transportation data. Next, we present a temporal framework for transportation data in linear referencing system. Finally, we explore visualization approaches alternative to the traditional dynamic segmentation.

2.1 Characteristics of Dynamics in Linear Referenced Transportation Data

Transportation data can be spatially represented in either a traditional 2D or 3D coordinate system or in a linear referencing system. Since most highway assets and events take place along highways, it is convenient and efficient to adopt linear referencing for transportation data. This practice has been pretty common to most state department of transportation in the US (Koncz and Adams, 2002; Zhu and Li, 2004).

Transportation data are more dynamic compared to most others, especially the base geographic data such as elevation. On one hand, transportation data usually changes faster and more frequently. For example, a traffic accident happens in seconds; and congestions take place for minutes to hours. On the other hand, there is a broad range of temporal resolution in transportation. For instance, a traffic camera or camcorder records in sub-seconds; while a road work may last for days, months, or years. Once built, a highway functions for a long time, i.e. more than forty years. Over the years of operation, segments of the facilities wears out and needs resurfacing; speed limit must be adjusted for safety consideration; additional lanes are added after urban sprawl; and road conditions deteriorate slowly over time and are improved right after resurfacing. In general, temporal resolution in transportation data can be high/fine, i.e. seconds, or low/coarse, i.e. years. Change in transportation data may be slow or abrupt.

Linear time and cyclical time coexist in temporal transportation data. At a high temporal resolution, traffic pattern repeats day by day, with rush hours on weekdays. At a low temporal resolution, highway quality changes from excellent through good to poor over years, which is linear; and after resurfacing, it becomes excellent again and a similar cycle repeats.

In this study, we focus on linear time in highway assets and events at a relatively coarse temporal resolution. Hopefully, the proposed visualization approaches will help discover cyclical time in the dynamics. For example, we may notice, via visual analysis of road conditions in linear time, that certain road segments have a shorter cycle and need more frequent maintenance. Such knowledge can assist in transportation planning and management.

2.2 Representation of Temporal Transportation Data in Linear Referencing

Transportation data has the same three components: location, themes, and time, as with general geographic data. With linear referencing system, dynamics in transportation data can be conceptualized as point or line events, and logically stored and managed using a relational database management system (RDBMS). E.g.

Point event:

$$\{ID, (RID, m), \{theme_i, value_i\}, (f\_t, t\_t)\} \qquad (1)$$

Line event:

$$\{ID, (RID, f\_m, t\_m), \{theme_i, value_i\}, (f\_t, t\_t)\} \qquad (2)$$

where ID = unique event identifier
RID = unique route identifier
m = measurement value
$theme_i$ = the ith theme
$value_i$ = the ith theme value
f_m = the from measurement value
t_m = the ending measurement value
f_t = the beginning time of the event
t_t = the ending time of the event

When multiple themes of a feature have different spatial or temporal component, each theme should be managed in a separate table.

The interval time, (f_t, t_t) may be simplified as an instant time, (t), if the temporal scale is small. The concept of temporal scale is borrowed from the general term of scale in the space. E.g., a building is cartographically represented as a point at a median scale and a polygon at a large scale. Similarly, a traffic accident could be described as a line event at a large temporal scale, i.e. minutes, or as an instant point event at a small temporal scale, i.e. days. For transportation data, a line event at a large temporal scale does not have to be longer in duration than a point event at a small temporal scale. For example, a road work may take several days or months but modelled as a point event at a small temporal scale, i.e. 1-year temporal resolution; while a traffic accident, which lasts for only several minutes but still can be treated as a line event at a large temporal scale, i.e. 1-minute temporal resolution.

In current practice, the beginning time of an event, f_t, is used for transportation data; and the ending time, t_t, is often not stored. This is mainly because there is always a theme value for a line event. For example, a road segment always has a surface material and a speed limit. When one theme is updated after an event, the previous value expires and the ending time of the previous is the same as the beginning time of the new event. On the other hand, temporal resolution in current practice is relatively coarse. A road work lasting for several days or months are recorded in one year in current practice. In other words, the temporal dimension is usually generalized in transportation data management.

2.3 Alternative Visualizations of Dynamics in Linear Referenced Transportation Data

Transportation assets and events are usually stored in event tables and displayed on-the-fly via dynamic segmentation in current practice. Although transportation data are dynamic in nature, the time dimension is not explicitly displayed in existing dynamic segmentation. For example, events in Figure 3 are rendered as four overlapping lines after dynamic segmentation (Figure 4). This brings difficulties in query. Further, temporal information in transportation data is lost.

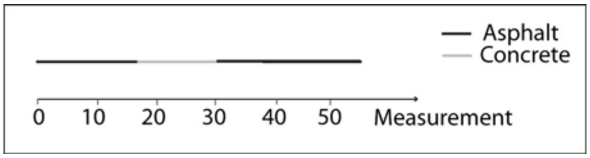

Figure 4. Surface material after dynamic segmentation

2.3.1 The 2D-View

In this alternative 2D approach, we introduce an explicit time axis perpendicular to a route within the 2D space (Figure 5). A route is simplified as a straight line in this graph. The horizontal axis is the measurement established with the route, and the vertical axis is the linear time axis. The origin is not (0, 0) but (0, 1970) or any other appropriate number of user's choices. For each route, there is such a vertical time axis in addition to the measurements. Because the horizontal measurement and the vertical time axis are different, the time axis can be adjusted in terms of initial value and interval to meet the visualization needs.

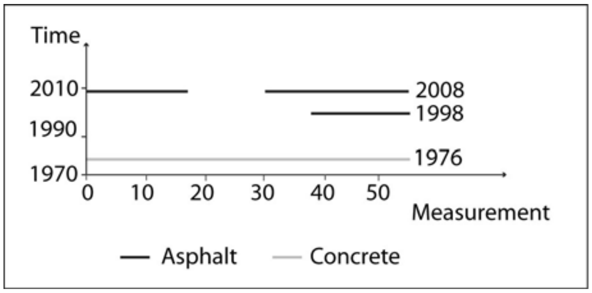

Figure 5. The 2D-view of the surfacing event

This approach takes advantage of the fact that linear referencing compresses the traditional 2D coordinate system to 1-dimension (1D). The reduced spatial dimension is utilized for the time. All line events in Figure 5 are separate in the 2D-view. An order pair (x, y) in a traditional 2D coordinate system refers to a static point, while an ordered pair (m, t) in Figure 5 corresponds to a temporal point on the route.

Fundamentally, the 2D-view is similar to the spatiotemporal framework called based-state-with-amendments (Langran, 1992). Both begin with a base state, and model events or changes over the time. The 2D-view and the based-state-with-amendments approach differs in the representation of spatial data. In the 2D-view, point/line events are in a linear referencing system; while in the based-state-with-amendments approach, geographic data are in a traditional 2D or 3D coordinate system. In terms of visual analysis, the 2D-view for temporal transportation data in linear referencing system has an advantage over the based-state-with-amendments approach. In the 2D-view, point/line events are separate and parallel to the routes. This makes it straightforward for human eyes to find a status at a specific time.

Figure 6 presents the result of visual analysis of lines from Figure 5. The dashed lines do not exist physically but are imagined in the visualization process. Area a and c refers to road segments that are concrete in 1976 and resurfaced with asphalt in 2008. Area b refers to a segment with concrete surface since 1976. Area d and e reveals that road segment was concrete in 1976 and resurfaced two times with Asphalt. The two resurfacing events along line (38, 55) suggest that segment has a much shorter cycle on road condition and needs resurfacing frequently.

The 2D-view can be rendered by modifying existing dynamic segmentation process. To be specific, we convert the beginning time of an event, f_t, to an offset. An offset determines how far a point/line event is away from the route. In this way, earlier events are displayed closer to the route, and later ones are rendered far away.

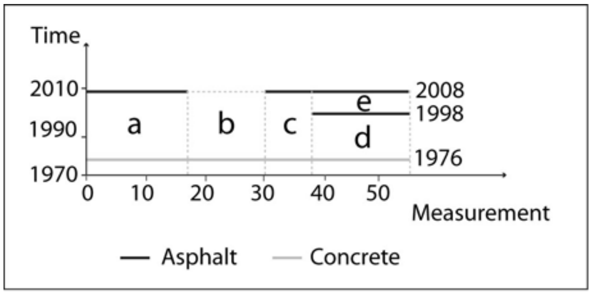

Figure 6. Visual analysis in the 2D-view

The 2D-view expands the time dimension and allows separating each event. This approach works well for one theme. For multiple themes, such as speed limit, surface material, and road quality, different symbols or multivariate symbols should be used.

Since the 2D-view displays temporal transportation data off the routes, it occupies space in the 2D space. It is not appropriate for urban area at a small spatial scale. Temporal line events could block neighboring streets and mess up the map.

2.3.2 The 3D-View

The 3D-view is similar to the 2D-view. Both methods introduce a time axis perpendicular to a route. The only difference is the direction of the time axis. In the 2D approach, the time axis and the route are within a traditional 2D space. In the 3D view, the time axis and the route are not within a 2D but a 3D space.

Figure 7 illustrates the difference on the direction of the time axis between the 2D- and 3D-view. In Figure 7, the cube refers to a traditional 3D space. The first dimension, measurement, represents a simplified route based on a straight line. The second and third dimension represents the time axis in the 2D-and 3D-view, respectively. In this cube, the 2D visualization of temporal transportation data takes place in the bottom face; while the 3D-view displays in the front face. Other than that, there is no big difference between the 2D- and the 3D-view.

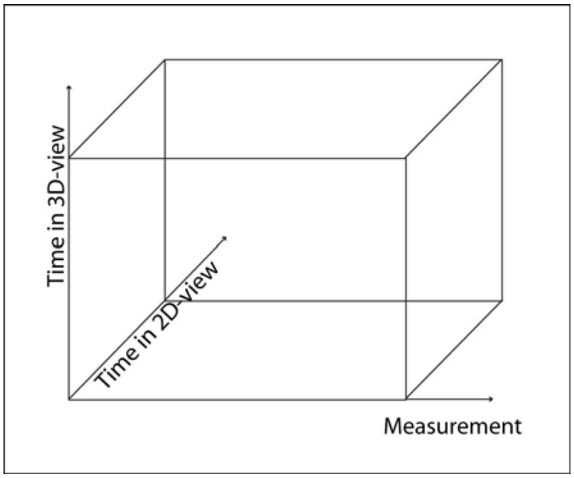

Figure 7. The time axis in the 2D- and 3D-view

The 3D-view overcomes two shortcomings related to the 2D method. First, it does not display events in the 2D space, thus will not interfere with other feature near the roads. Second, the time has been visually represented as the third dimension in a 3D space-time cube in the literature (Thrift, 1977; Kraak, 2003). This makes the 3D-view familiar and acceptable to map readers.

Regarding implementation, the 3D-view cannot directly utilize the existing dynamic segmentation process, which displays point/line events in the 2D space. A 3D version of dynamic segmentation should be developed for the 3D-view.

2.3.3 Animation

Animation is efficient in visualizing dynamics in geographic data (Kraak and Klomp, 1995; MacEachren, 1995). Both the 2D- and the 3D-view can be displayed in an animation. Compared to general geographic data in a traditional 2D or 3D space, there is nothing specific to temporal transportation data in a linear referencing system. Therefore, details in an animation design are not further addressed in this section.

3. DISCUSSION AND CONCLUSIONS

In summary, dynamics in linear referenced temporal transportation data can be visualized alternatively in the 2D- and the 3D-view, either on a static map space or in an animation. These methods introduce a time axis, which is treated as the second or the third dimension in a 3D space, and successfully avoid the problem of overlapping of point/line events in existing dynamic segmentation. Moreover, alternative approaches introduced in this research are not limited to transportation data but can be applied toward general dynamics in linear referencing.

The 2D-view is relatively easy to implement by modifying existing dynamic segmentation. This method is appropriate for highways, but not good for dense streets in urban area since neighboring features might be blocked. The 3D-view overcomes the shortcomings in the 2D-view, but needs a 3D version of dynamic segmentation for implementation. Dynamics in both 2D and 3D view can be animated.

In the future, an interactive tool should be designed to allow users to enter parameters for the time axis in the 2D- and 3D view. For instance, users should be able to specify the initial value, time interval, and temporal scale of the time axis. We will also explore web services based on the 3D-view. When integrated with other GIS web services , i.e. Google Maps, it will allow visualization of dynamics in linear referenced transportation data via Internet applications.

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5. ACKNOWLEDGEMENTS

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