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Embedding Temporal Display into Maps for Occlusion-Free Visualization of Spatio-Temporal Data

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ABSTRACT

It is often necessary to analyze spatio-temporal data such as traffic flow, air pollution, and vehicle trajectories in a city. A map is often used to show the spatial context while various temporal displays like time series plots can be used to present the changes in the data over time. In this paper, we present a novel visualization that can seamlessly embed temporal displays into a map for occlusion-free visualization of both the spatial and temporal attributes of the data. We first extend the seam carving algorithm to broaden the roads of interest in a map with the least distortion to other areas, and then embed temporal displays into the roads to reveal temporal patterns without the occlusion of map information. We study various design choices in our method, including the encoding of the time direction and temporal display, and conduct two comprehensive user studies to validate our design decisions. We also demonstrate the usability of our approach with case studies on real traffic flow data in a major city.

Index Terms: I.3.5 [Computer Graphics]: Spatio-temporal visualization—Seam carving

1 INTRODUCTION

An increasing amount of spatial-temporal data is becoming available from various kinds of sensors, surveys, and other sources, such as GPS in taxis. Hidden spatio-temporal patterns in these data convey important knowledge for decision making and problem solving. Visual representations of the spatio-temporal data are indispensable for uncovering such hidden patterns.

Many visualization methods have been proposed for spatial temporal data. These methods can be roughly divided into two categories: *linked views* and *integrated views*. The spatial attributes of the data are often visualized with maps while the temporal attributes can be visualized by time series curves, stacked graphs, etc. Linked view solutions put maps into one window and temporal displays into other windows. However, there is always a cognitive and memory burden for users when linking these views and to discover possible correlations. Inspired by *the first law of geography*, which states "everything is related to everything else, but near things are more related than distant things" [32], putting relevant displays close to each other offers clear advantages. Thus, it is desirable to place temporal visualizations near the spatial context that allows users to quickly relate temporal patterns with spatial context. Following this strategy, the integrated view methods integrate temporal visualizations and maps into one display to facilitate the detection of spatio-temporal patterns. However, existing methods either use 3D or directly overlay temporal displays onto a map, which cause occlusion and visual clutter. As collected data are often related to roads (e.g., vehicle or people trajectories, roadside air pollution levels), it is natural to embed temporal displays onto the roads in a map for "in-place" occlusion-free visualization of temporal patterns while preserving the spatial context. This is a nontrivial problem and there are three major obstacles to overcome. First, as roads are usually very narrow strips on a map, the map has to be zoomed into a very high level such that the embedded temporal displays can be perceived by users. Though the most natural way is to zoom linearly, this linear zooming will lose much of the spatial context. Thus, a non-linear zooming method that broadens the roads of interest while preserving other spatial context is needed. Second, as temporal displays often involve a time axis, it is not clear how to encode the flow of time on a road of arbitrary direction. Third, it is not clear what kind of temporal displays are suitable for being embedded on roads.

To address these issues, we present a novel context preserving visualization technique to seamlessly integrate temporal displays into maps for occlusion-free analysis of spatio-temporal data. Our method utilizes the empty road space on the map while minimizing the distortion of other areas. An extended seam carving algorithm is developed to broaden selected road segments and to introduce enough empty space for embedding temporal displays on the map. We also investigate the different choices of encoding time direction for temporal displays overlaid on a road as the road can be of any slope and a conventional time direction that always points from left to right or from bottom to up is not applicable here. There are plenty of ways to represent time direction, for example, text labels, visual symbols, colors, or even animations. We conducted a user study to compare various methods and evaluated their effectiveness and efficiency. To evaluate the strengths and weaknesses of our embedded view, we also conducted a user study to compare our approach with a traditional linked view. Our approach is quite general and different kinds of temporal visualizations (e.g., time series curves, stacked graphs, spiral graphs, and chord diagrams) can be employed with our system. To the best of our knowledge, it is the first comprehensive study on embedding temporal displays onto roads in a map. We demonstrate the usefulness and usage of our methods with case studies on real taxi trajectory data collected in a major city.

The major contributions of our work are:

- An embedded visualization that is intuitive and allows occlusion free and "in-place" exploration of temporal patterns with preserved spatial context.
- A systematic study of some key design choices for our method such as the encoding of time direction.
- A user study to compare our method with a traditional linked view.
- Applications of our method to real traffic data for various analytical tasks.

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2 RELATED WORK

2.1 Time-Oriented Data

Extensive efforts have been put into the development of appropriate visualization methods for time-oriented data in the past few decades. Representative works in this field have been systematically reviewed in [1][2][23]. Here, we only discuss a few widely used methods.

According to Aigner et al. [1], one of the most important characteristics of temporal data is whether the time is linear or cyclical. To visualize linear time, a line chart and its variants are among the most popular methods. Heer et al. compared the traditional line chart and one of its important variations called horizon graph [16]. Javed et al. [19] investigated the efficiency of different line chart techniques for comparison tasks involving multiple time series. Stacked graph is another popular approach to visualize time-series data. Byron and Wattenberg [8] discussed the design decisions and algorithms for stacked graphs. One obvious strength of the technique is that it provides an aggregated view by stacking individual time series on top of each other. But it has been argued that stacked graph is not efficient when it comes to the comparison of different time series plots [10].

In addition to methods dealing with linear time, visualization techniques addressing cyclical time have also been developed. The Spiral Graph [35] is a well-known visualization that reveals periodic patterns in temporal data using a spiral time axis. Animations are also widely used to show the changes of values over time. However, based on a study by Robertson et al. [28], animations may have value for presentations, but are not effective for analytical tasks due to the limits of short-term memory.

2.2 Spatio-Temporal Data

A recent survey by Andrienko et al. [4] raises the need of finding effective visualizations of temporal dimension in geospatial data. The existing work can be roughly divided into two categories: linked views where the spatial and temporal aspects of data are displayed in coordinated multiple views, and integrated views where the temporal information is displayed with geospatial visualization in the same view.

Linked View Linked-view methods have become standard approaches to display temporal and spatial data [4]. Ivanov et al. [18] used several synchronized views, including a timeline, a map, and a camera view, for efficient monitoring of spatio-temporal data collected through surveillance cameras. Andrienko et al. [5] combined a time graph with a map to visualize multiple trajectories. Guo et al. [14] presented a trajectory analytics system with a map view for spatial data and a stacked graph along with a scatter plot for temporal data. Although multiple coordinated views is a powerful visualization technique, a significant limitation to such methods is the cost of screen real estate to show views side-by-side.

Integrated View A well-known technique in geographic applications that integrates space and time in the same view is the famous space-time cube [12][20]. The 3D space-time cube presents space as a 2D map and time as the third dimension. However, this approach does not scale well to a large number of samples due to the occlusion problem in 3D space. Tominski et al. [33] proposed a so-called 2D/3D hybrid display to stack trajectories as bands in the third dimension while time is integrated by appropriate ordering of trajectory bands. However, the view will be severely hindered if one wants to visualize trajectories on multiple roads simultaneously. Liu et al. [21] displayed a circular time axis enclosing a road map to encode both temporal information about trajectories and the spatial context. But the design is limited in the number of roads that can be viewed and only works for cyclical time. Methods that directly embed time series curves on top of their spatial locations in two dimensional maps, such as the embedding of ThemeRiver in a map [2], lead to severe occlusion of other useful map information and visual clutter. Abstraction and aggregation methods can also serve the purpose of integrating space and time. Crnovrsanin et al. [11] proposed proximity PCA to transform spatial information into abstract space and plot proximity spatial information against the time axis. Andrienko et al. [3] discussed possible aggregation methods of movement data. Scheepens et al. [30] presented a density map of traffic data, using color to represent time.

In contrast to the above approaches, our method aims to totally avoid the occlusion problem. It relies on a novel non-linear zooming algorithm to broaden the roads without distorting other areas too much and then overlays temporal displays onto the roads.

2.3 Non-Linear Zooming

Focus+context is a widely used approach in the visualization and computer graphics fields to show the focus and context simultaneously in a single display. Many focus+context techniques and systems, such as fisheye view [13], SignalLens [13], rubber Sheet stretching [29], TreeJuxtaposer [24], LiveRAC [22] , Chronolenses [36], and Sigma Lenses [26] have been developed to visualize data from different problem domains. A handful of recent works also apply focus+context to maps, such as [15][34]. While these techniques achieve the integration of focus regions into surrounding context, they often introduce undesired distortions that make them unsuitable for our analytical tasks. Some recent image retargeting techniques, like seam carving [6], have managed to nonlinearly enlarge or shrink an image without much distortion. Qu et al. [27] used a seam carving-based technique to make selected routes visible in a 3D environment. In this paper, we adopt a similar strategy but deal with a totally different problem. We are more interested in overlaying temporal displays onto roads. Thus, different research issues are investigated in this paper and a more efficient seam carving-based algorithm is developed specifically for our application.

3 DATA AND DESIGN OVERVIEW

3.1 Data

In this paper, we use taxi trajectory data to illustrate the usage of our method. The data used in our experiments contain the trajectories of over 8000 taxis collected in four months in Hangzhou, China. The sampling rate is on average one sample every 20 seconds and the sampling duration is 24 hours each day. Each GPS record consists of 7 fields: (*i*) the ID; (*ii*) the license number; (*iii*) the latitude and the longitude; (*iv*) the status indicating whether the taxi is occupied or vacant; (*v*) the date and time; (*vi*) the direction; (*vii*) the speed.

We first calibrate the coordinates of each road segment on the map and use polygons to represent them, thus getting the position information of each road segment. We next extract the GPS samples that are close to each road segment and compute the number of taxi, the average speed, and the average driving time for both directions in different time periods, e.g., one hour or one day.

3.2 Design Goals

The general goal of our system is to support analysis of temporal patterns in the preserved spatial context of road maps. To be more precise, when analyzing temporal patterns of attributes on a certain road, we want to be able to take into account the neighborhood information, such as whether the district that the road cuts through is commercial or residential, and what the typology of the road network around the road is. We find that the following four types of tasks are commonly performed in spatio-temporal analysis:

Synoptic Characterization (T1) Estimate the trends and variations of attributes over different time periods in a large spatial area. Example questions include: what is the variation of average traffic flows from one region to another over a week? What is the actual route taken by most traffic from one region to another?

Local Characterization (T2) Estimate the trends and variations of attributes over different time periods in a local area. Example questions include: What is the temporal pattern of traffic along each side of a specific road? Does the attribute value exhibit imbalance in two directions?

Pattern Detection (T3) Locate a specific pattern of attributes in its occurring spatial and temporal positions. An example is to detect the location and hour of traffic congestions by looking for a high number of vehicles at a very low speed.

Pattern Comparison (T4) Compare the patterns of attribute values across different time intervals and different spatial regions.

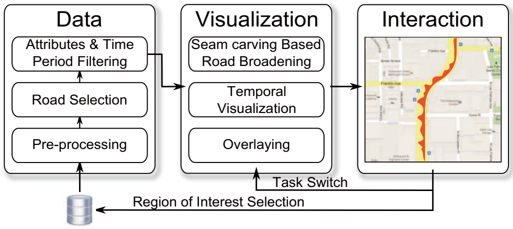


Figure 1: System Overview. The data module allows users to preprocess and filter data. The visualization module supports the overlaying of temporal displays onto roads that are broadened by our extended seam carving algorithm. The interaction module provides rich user interactions to facilitate various analytical tasks.

Based on the tasks we want to perform, we have identified three goals for our method:

The design should put temporal displays close to the spatial context without occlusion of other map information (G1). This goal aims to help users conduct Tasks T1, T2, and T3. As these tasks need to link temporal displays and spatial context, we use a non-linear zooming algorithm to expand a road in a map and then overlay the temporal displays on the road for “in-place” analysis.

The design should be simple and intuitive (G2). Spatio-temporal analysis is a common task conducted by everyone in everyday life, as a result, we want the method to be used by a large audience. Since we do not assume the background of end users, our design should have high intuitiveness and simplicity. To achieve this goal, we considered a variety of design choices for certain key issues in our method, conducted user studies to evaluate their intuitiveness and effectiveness, and compared our method with a well established linked view method.

The design should facilitate the spatio-temporal data comparison of multiple roads at different times (G3). This goal aims to help users perform Task T4. To achieve this goal, our system supports the expansion of multiple roads in a map and shows the temporal displays of these roads simultaneously. In addition, we provide a side-by-side view of traffic flow in two directions along a road for comparison.

3.3 System Overview

Figure 1 shows the overview of our system. It consists of three major components. The data component allows users to load, process, and filter spatial-temporal data. During the pre-processing, a variety of statistical information, such as traffic volume and speed, are computed, as discussed in section 3.1. Then roads of interest can be selected by users by clicking on both ends of the road segment or brushing on it. Users can further filter data with a time period or other data attributes. After that, the data will be sent to the visualization component for display. In this component, the selected roads will be automatically broadened with our extended seam carving algorithm and various temporal displays can be conveniently overlaid onto the roads for further analysis. Finally, users can interact with the system to perform analytical tasks.

4 EXTENDED SEAM CARVING ALGORITHM

In this section, we describe our extended seam carving algorithm which is tailored for the map application and is much faster than the original algorithm. The seam carving algorithm [6] needs an importance value computed by the energy function for each pixel on the map, then it applies an image operator called seam carving to enlarge or shrink an image by inserting or deleting a seam that is a path of connected low energy pixels. The effectiveness of different image energy functions is also discussed in [6].

Road Importance Value Computing Map images are quite different from normal images, like scenery or portrait, as they have obvious similar patterns, such as roads. To calculate the energy of each pixel and speed up this process, we adopt the $e_{HoG}(I)$:

$$e_{HoG}(I) = \frac{|\frac{\partial}{\partial x}I| + |\frac{\partial}{\partial y}I|}{max(HoG(I(x,y)))} \qquad (1)$$

which is defined in the original paper [6], and can prevent the seam from crossing the edge of the roads in our situation. But to increase the speed, we use an 8-bin histogram with a 4×4 computing window instead of an 11×11 window because the width of a road is usually only a few pixels on a typical map.

Additionally, the images in our application are very special. For example, the color representing roads is always monotonous. To improve the efficiency and robustness of our algorithm, we directly pick out the color representing roads (e.g., yellow or orange on Google Standard Maps) and take advantage of it in our algorithm. The accumulation of minimum energy C for all possible connected seams can be conveniently computed using dynamic programming:

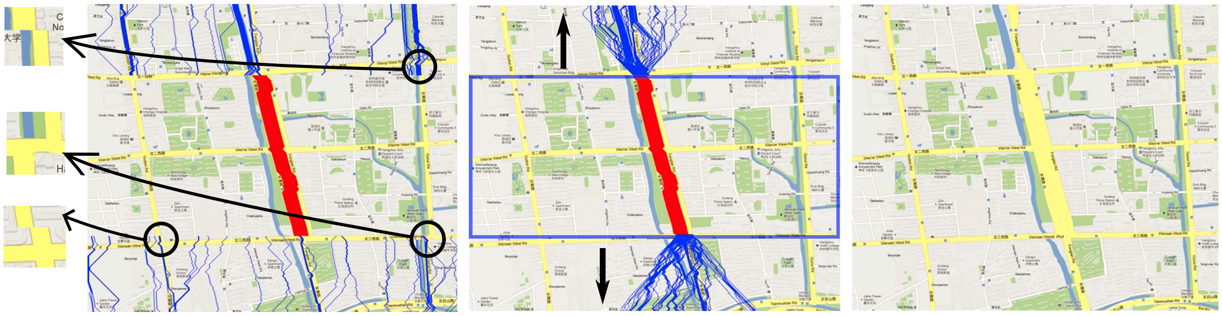
$$C(i,j) = e(i,j) + min(C(i-1,j-1), C(i-1,j), C(i-1,j+1))$$
$$e(i,j) = \begin{cases} energy(P(i,j)) & P(i,j) \text{ is not a pixel on road} \\ 0 & P(i,j) \text{ is a pixel on road} \end{cases} \qquad (2)$$

where $P(i,j)$ is a pixel in row i and column j, and $e(i,j)$ represents the energy of $P(i,j)$.

Seam Segment Selection In our algorithm, due to the map images (e.g., google maps) we use, we do not need to store the geometry coordinates of each road segment. Users simply click on the start and end points of one road segment and our algorithm will then find two kinds of seam segments automatically: one seam segment for broadening the selected road while skirting the text or icon on the road and the other for retargeting other parts of the map to an appropriate size while minimizing the distortion (See Figure 2 (b)). Our algorithm starts by finding the optimal seam from the start point to the end point of the road. Thanks to the lower energy of the road, it can always find a seam path on the road in the first iteration regardless of whether the road is straight or zigzag. Next, we set the energy of the pixels on that path to zero, so that the iterations followed will always find the same seam due to the low energy. Beyond the start and end points of the road, our algorithm will also separately find the optimal seams from the start point and the end point to each boundary of the map, and thus avoid the skewing of the road and other parts of the map (See Figure 2 (a)).

Improved Seam Carving Once we have obtained the seams for different parts of the map, we can run the seam carving algorithm for each seam segment. In the seam carving process, a seam representing a pixel-wide empty space line is inserted into the map. The time complexity of the seam carving is linear in the number of pixels and most of the time is spent on computing the energy of each pixel. As the resolution of a map is usually very high, we need to extend the seam carving to speed up the road broadening by exploiting the specialty of the map.

Our goal is to broaden the selected road to a certain width instead of retargeting the whole image to a certain size. Thus, once the optimal seam on the road is found in the first iteration, we regard



(a) (b) (c)

Figure 2: Extended seam carving algorithm. (a) Uncontrolled seam carving on the map causes offsets, especially at the cross. (b) The optimal seam finding direction for the rest of the map to avoid offsets among the broadening area and retargeting areas that results in (c).

that seam as the optimal seam for the subsequent iterations. Consequently, there is no need to compute the energy for each pixel of the whole horizontal or vertical part of the map that contains the road. If the length of the road equals the width or height of the map, our algorithm only needs to compute the energy of each pixel once, and the remaining operations are the horizontal or vertical translation of the parts outside the road. Therefore, our algorithm would be quite efficient when opening a long road on a big map. As a road junction is not always vertical or horizontal, to avoid distortion at the junction between the road and other parts of the map, we need to dynamically increase or decrease the value of the start and end positions of the road according to the road slope.

The performance of the seam carving is always a big issue. However, a lot of analytical tasks are routine tasks. For example, an officer in a city transportation department routinely checks certain roads every day. In previous literature [6], the authors adopted a seam index strategy to speed up the image retargeting process. Here we adopt a similar cache scheme which saves the seam when the road is broadened the first time, and it will be much faster when users attempt to broaden the same road again. Once the cached seam is loaded, there is no need to compute the accumulated energy, which is quite time-consuming. All we need to do is memory operation, namely, shifting pixels. We have tested the performance of this seam cache scheme, and it takes less than 1 second to broaden a road by 75 pixels in a map image of 1500×1500 resolution, which is higher than a general display resolution.

Road Width Our system allows users to manually adjust road widths to an appropriate size. In addition, users can change the default width in the system configuration.

Another important parameter to consider when deciding on road width is the aspect ratio of the embedded time series chart. According to the *banking to 45 degrees* technique [9], a fixed road length with a 45 degree aspect ratio determines the corresponding road width. While an optimal aspect ratio maximizes the perception of trends in data, the resulting variation of road width makes the comparisons of absolute attribute values at different roads difficult.

Figure 3 shows one result after applying our extended seam carving algorithm and also compares it with traditional linear zooming. From the figure, we can clearly see that if we want to achieve the same road width using linear zooming, much of the spatial context, such as the region highlighted in the black rectangle, will be pushed out of the display window.

5 VISUALIZATION DESIGN

After the roads are broadened by our extended seam carving algorithm, we can now overlay various temporal displays onto the road. However, there are still some major design issues to be addressed.

(a) (b) (c)

Figure 3: Comparison of our algorithm with linear zooming. (a) A map with a road and a region of interest highlighted in the black rectangle. (b) The result after broadening the road by 50 pixels. (c) The result after linearly enlarging the whole image by 300%.

5.1 Time Direction

Embedding temporal displays on roads raises the question of how to indicate the direction of time flow. As the road on which the time series is overlaid can be of any slope, the conventional default encoding where time flows from left to right does not apply. Figure 4 illustrates various design choices considered in our system.

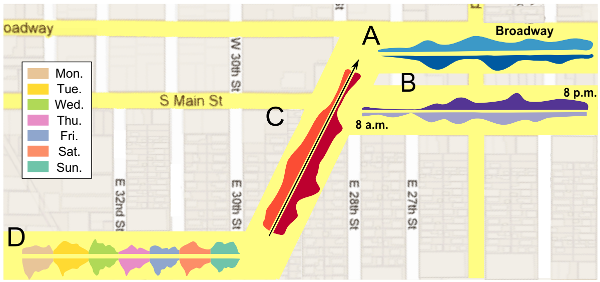


Figure 4: Different encoding methods for time direction using road name (A), text labels, such as date and time (B), visual symbols, such as arrow (C) and color (D).

Default Direction In principle, we can encode time direction based on the Cartesian Coordinate System, i.e., the direction of time flow is left to right for horizontal roads and bottom to top for vertical roads. This is sufficient for most cases since urban road layouts are often regular. For roads of other slopes, we can choose a direction based on the angle between the road and the horizontal axis. For example, if the angle between the road and the horizontal axis falls between -45 degree to 45 degree, the time direction is from left to right. Otherwise, the direction is from bottom to top. Though intuitive and natural, this approach is problematic under special circumstances. For example, a road with a 43 degree slope may adopt left-to-right orientation while a road with a 47 degree slope will be bottom-to-top; a slight change in slope leads to a dramatic flip of time flow direction.

Possible Visual Cues For these special cases, additional visual cues are required to indicate time direction. We have considered

(a) (b) (c) (d) (e)

Figure 5: Different temporal representations embedded in broadened roads. (a) Temporal visualizations including Time series curves, ThemeRiver, and spiral graph. (b) and (c) demonstrate the comparison of heatmaps on normal and broadened roads. (d) and (e) show the comparison of the direct overlaying method and our embedded view.

using text labels, visual symbols, colors, and animations in our system.

Text Label A straightforward way to solve the ambiguity of time direction is to directly label the date and time alongside the temporal pattern. Text label is also good for presenting temporal display with different time range. However, directly labeling on the roadside will occlude surrounding map information. If the labels are to be placed inside the broadened road along the time axis, we face a trade-off between the space taken up by the text and the legibility of the label.

Visual Symbol A handful of conventional symbols for encoding direction exists and we can plot them as glyphs on top of our temporal visualization. A time axis with an origin and arrow is simplest, most non-pervasive, and most natural way to indicate direction. A plus or minus sign can also be used. Besides the obvious strength of being conventional and intuitive, these approaches have the merit of not using additional visual channels of the temporal displays. Nonetheless, they take up extra spaces and cause visual clutter at the road intersection.

Color Possible ways to exploit the color channel of the temporal design include the use of saturation, opacity, or a sequential color scheme to indicate time direction. The advantage is that color is effective for human perception, but it requires more use of the visual channel.

Animation Animation can be used in two different ways. First, animation can represent the flow orientation of time while displaying all temporal information. Second, we may directly animate the time-varying data. We argue that the first approach creates distraction for the users and the second method introduces cognitive burden.

Relying on Existing Map Features We find that our problem of encoding time direction is similar to some problems studied in the field of cartography. Effective determination of the time direction for a road with an arbitrary slope is an instance of a larger problem in cartography and geovisualization research: finding a one dimensional direction in a two dimensional network. Linear designations, namely placing names for geographical objects with a linear or ribbon-like shape [17], share similar design considerations regarding text orientation. While a large number of guidelines exist [17][31], the rule-of-thumb is to place text progressing from left to right. For vertical situations, text are rotated from the horizontal position and whether it runs from bottom to top or from top to bottom does not have a significant impact [7].

Inspired by this, our final design assigns time direction according to the orientation of the text name label of the road. This option has two obvious advantages. First, because it relies on existing map features, it perfectly satisfies our design principle of minimal occlusion or distortion. Second, from the perspective of the users, associating street names orientation with time direction is simple to learn and easy to apply.

Table 1 summarizes and compares different schemes for encoding the time direction on a road. They all have their advantages and disadvantages. Which one to use depends on the application, the familiarity of users with our system, and the space capital available for the visualization.

Name	Intuitiveness	Extra Space	Ambiguity	Accuracy
Default	Medium	No	Yes	Medium
Text Label	High	Yes	No	High
Visual Symbol	High	Yes	No	High
Color	Medium	Yes	Yes	Medium
Animation	High	No	No	Medium
Road Name	Medium	No	Yes	High

Table 1: Comparison of different schemes to encode time direction.

5.2 Temporal Display

Another design choice is to decide which temporal displays are suitable for being overlaid on the roads in a map. There is one road characteristic that cannot be changed by broadening: long but narrow. The ratio and limited width are the major constraints for our design choices. First, line charts and its variations such as horizon graph should have no problem with our scheme. Second, Themeriver can also be used. But to overlay Themeriver on a road, we need to make sure the road is adequately broadened so each layer is visible to users. Third, visualization of cyclical temporal pattern such as radial view can be overlaid on the road, but it is not easy to recognize unless the road is broadened to a huge width. However, radial view such as chord diagram is quite suitable for presenting the interchange of traffic flow in the intersections of multiple roads. These three temporal display are demonstrated in Figure 5 (a).

Heatmap is also a choice. However, overlaying heatmap on roads to present the traffic flow either causes occlusion or may be too narrow to perceive (shown in Figure 5 (b)). Figure 5 (c) displays the traffic flow on a broadened road. The flows in both directions can be better perceived and the display doesn't cause occlusion. Figure 5 (d) and (e) compare our method with the direct overlaying method. For the four vertical roads in the map, our method makes their comparison easy and efficient. However, other useful map information is occluded by the time series curves directly overlaid on the map.

5.3 User Interactions

Apart from basic user interactions in map navigation and data selection, we support a further set of interactions to facilitate analysis.

Brushing and Filtering Users can directly brush any road segments on a map and then these segments will be broadened by the extended seam carving algorithm. Users can filter out data of interest by time interval in the time series curve and the corresponding segments will be highlighted for all curves on the map.

Overlaying We support additional overlaying of optional labels, including date time text labels, time axis, data value axis, traffic direction indicators, and user-specified texts.

Road Width Control To find the most appropriate width of a given broadened road, users can first select a road and then perform zooming to continuously enlarge or shrink the road.

6 CASE STUDIES

In this section we demonstrate the usage and effectiveness of our method by applying it to real traffic data collected in Hangzhou, China.

6.1 Case 1: Synoptic View of the West Lake District

Figure 6: A synoptic view of the traffic volume in the West Lake District allows quick detection of interesting patterns and easy comparison between multiple roads.

This example demonstrates possible findings that could be obtained at the synoptic level. Typically, in the beginning, an analyst wants to get a synoptic view of the overall traffic conditions in a certain district and then further pursue interesting patterns spotted in the view. Figure 6 shows a synoptic view of the West Lake District in Hangzhou with line charts encoding one-week traffic volumes on each road segment. The green parts indicate the time series curves of the traffic on the right lanes (right side of the direction of the arrow) and the orange ones are for the left lanes.

The following patterns can be observed. First, traffic imbalance can be observed and compared intuitively. Road A and B in the figure are two example of roads with a high degree of imbalance regarding traffic directions. An investigation of the map reveals that Road A and B are one-way streets. Direct embedding of temporal data on the associated road shows a clear advantage for this task.

Second, different roads have different pattern shapes. The shapes on Road A and B indicate that the traffic volumes during morning rush hours are almost the same as those in the evening. But the shapes on other roads, like Road C, D, and E, show that traffic volumes during evening rush hours are much higher than those in the morning. The immediate association of these patterns to the map tells us that the areas near Road C, D, and E are residential sections, and it may tell that people prefer to take taxis when they get off work on Friday.

In contrast, if the analyst uses a linked view system, he/she will have to first record the patterns for each road by examining all the time series and then associate the recorded patterns to places on the map in order to perform such spatio-temporal analysis.

6.2 Case 2: Temporal Visualization for Navigation

This example demonstrates how a user can interact with our system to choose a better route to drive from one place to another. Figure 7 shows that the user just selects Position A and Position B, and then we can present the traffic flow for each road segment on which the time series curve indicates the traffic flow towards the destination instead of a two-way traffic flow. In Figure 7, we calculate the average time consumed by taxis for each road segment (from one crossing to the other crossing) on all previous Fridays and draw the timer series curves on the road. If a user wants to go from Position A to B on Friday evening, we can see that green route is a promising one, and the blue route is quite suitable for driving in the morning.

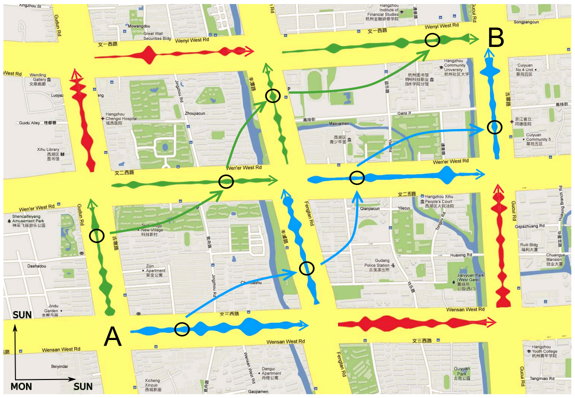


Figure 7: Time series curves representing the time consumed by taxis on each road segment of one Friday in one-way direction from location A to B. Different time saving routes could be found out at different times in a day.

7 USER STUDIES

We have evaluated the usability of our design with two controlled user studies. The first study addresses the design option of encoding the time direction while the second study is concerned with the performance of our method versus a linked view method.

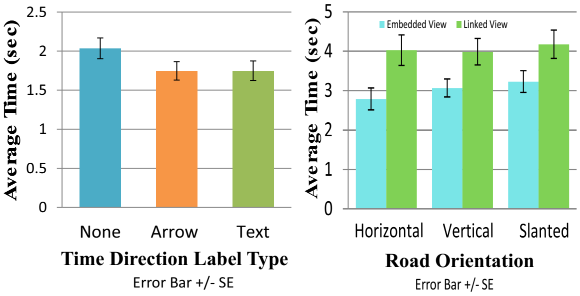
7.1 Experiment 1: Time Direction

To evaluate the design options for encoding time direction when time series curves are embedded on arbitrarily oriented roads, we designed the following experiment. We compared the usability of three methods: time direction is explicitly labeled by an axis, time direction is explicitly labeled by text, and time direction is implicitly labeled by road name orientation. The response accuracy, response time and preference ratings were recorded. The experiment aims to address the question: *How does the choice of the three methods affect the response time or accuracy?* We hypothesized that the explicit labeling methods are expected to outperform implicit labeling one, but these three methods do not vary significantly in time or accuracy.

Method The experiment used a within-subject design with 5 repeated trials for each condition. In each trial, subjects were given a picture with a time series curve embedded into a broadened road. The time series curve might contain no direction labels, a time text label, or a time axis label, respectively. The subjects were instructed to click on the approximate location where the time flow started. They were informed to complete each trial as fast as possible without hurting accuracy. The three conditions appeared in random order.

The figures for all three representations were generated using the same map and the same dataset. To avoid memorization, the map was flipped horizontally or vertically for different conditions.

We recruited 23 unpaid (14 male, 9 female) undergraduate or graduate students from various majors. Among the subjects, only one indicated frequent exposure to time series representations, four indicated that they had seen or used time series representations from time to time, and the remaining had rarely worked with time series representations. We designed an interactive Web-based experiment interface using JavaScript and deployed the generated experimental materials on it, and response time was recorded in milliseconds.



(a) (b)

Figure 8: Charts show the mean response time (a) and subjective user ratings (b) for the user study with no label, a time text label, and a time axis label to indicate time direction.

Result and Discussion Figure 8 (a) shows the statistics for the study. For all conditions, the response accuracy reached 100% for every participant, so we focused on the analysis of the response time. Overall, participants spent 2.03 seconds in the no label condition (SD = 0.64), 1.75 seconds in the axis label condition (SD = 0.56) and 1.75 seconds in the text label condition (SD = 0.60). We used 3 Representations (None, Arrow, Text) Repeated Measure Analysis of Variance (RM-ANOVA) test to analyze the response time data. RM-ANOVA revealed a significant effect for Representations (F(2,44) = 21.32, $p<0.001$). Pair-wise comparisons showed that the response time for the no label condition was indeed slower than the axis label condition ($p<0.001$) or the text label condition ($p<0.001$), but the response time was not significantly different across the axis label and the text label conditions ($p = 0.9$).

The results prove that adding additional visual cues does lead to significantly faster task completion. However, the results confirm our hypothesis that these three choices are comparable in response accuracy.

7.2 Experiment 2: Embedded View versus Linked View

It is difficult to fairly compare our method with other integrated views. First, it is not easy to get the implementations of some methods. Second, the design goals are quite different. Our method aims to totally avoid occlusion that is undesirable for some applications. Thus, we compare our method with a standard link view scheme (i.e., the map is in one window and time series curves in another window) which also does not have an occlusion problem.

Similar to the user study conducted by Dmitry et al. [25], we evaluated the effectiveness of our design with the linked view by running an experiment to address the following questions: *How does the choice of the embedded view or the linked view affect task completion time or accuracy? How does the orientation of roads in the embedded view or the linked view affect estimation time and accuracy?*

We hypothesized that the embedded view would result in faster task completion than the linked view because the temporal information is directly associated with the corresponding spatial context. However, for the roads that are not horizontal, we expected longer response times for the embedded view due to the mental reorientation of temporal information. With respect to accuracy, the error rate should be comparable in both methods.

Method In each trial, the subjects were given a picture, on which three selected roads were labeled Z, T, and R respectively. The picture either contained three time series curves embedded in these three roads, or displayed three time series graphs on the right hand side of the map with clear labeling. The participants were instructed to click on the road with the highest attribute value in a specified date. We asked the subjects to answer the question as quickly as possible without hurting accuracy. The maps used in both methods were of the same size. In other words, the bounding box containing the linked view GUI were larger than the ones for the embedded view.

In the experiment, we tested the embedded view and the linked view graphs with horizontal, vertical, or slanted roads in a within-subjects scheme. For each condition, the trials were repeated five times. In generating the graphs for the experiment, we used the same map and the same dataset for both the embedded view and linked view methods. With respect to road orientation, the three roads in each trial were in the same orientation category. To control the practice effect, we asked the subjects to practice as many times as they like for each graph type or road orientation until their performance became steady. Correct answers were given for practice trials but not for test trials.

We recruited 12 unpaid postgraduate students (6 male, 6 female) from engineering majors. Three of the participants reported using time series curves frequently, two indicated that they had seen time series curves from time to time, and the remaining had rarely used time series curves.

Result and Discussion Figure 8 (b) shows the statistics for the study. Overall, the average response time was 3.03 seconds (SD = 0.84) for the embedded view method and 4.37 seconds (SD = 1.11) for the linked view method. We conducted a 3 Orientations (Horizontal, Vertical, Slanted) × 2 Techniques (Linked View, Embedded View) Repeated Measure ANOVA to analyze the response time data. Our analysis revealed a significant effect on the response time for both Techniques (F(1,11) = 11.598, $p<0.01$) and Orientations (F(2,22) = 4.531, $p<0.05$), but did not find significant interaction for Techniques × Orientations. Pair-wise comparisons of Orientations found a significant difference between Horizontal roads and Slanted roads ($p<0.01$), while the other pairs did not have significant differences. The results confirm our hypothesis regarding the effects of different methods or orientations on response time.

As for response accuracy, the overall average was 98.8 % for the linked view method and 99.4 % for the embedded view method. RM-ANOVA did not have a significant effect on the methods or orientations.

8 DISCUSSIONS

From the experiments, we can see that our methods have clear advantages though our technique sacrifices a little space for context. Compared with linked views, our method displays the temporal information and the spatial context together and thus there is no need for users to switch from one view to another, which taxes their memory and causes cognition burden. Compared with the existing integrated views, our method has no occlusion, which makes it very suitable for analysis of multiple roads simultaneously. Compared with linear zooming, the extended seam carving algorithm can retain more spatial context with little distortion.

In the previous sections, our discussion is primarily based on straight roads that are neither too long nor too short. It can be argued that embedding time-series on roads of unusual shapes or lengths poses special challenges. For curved or circular roads, we can either reshape the time axis according to the road shape or straighten the road with some distortion. For roads that are too long or too short, we can apply different zooming levels and display temporal displays only when the zooming level is appropriate. Under circumstances when the shape or length of the road does not allow an appropriate embedding of temporal displays, traditional linked views or other integrated methods may be more efficient and we can complement our view with these methods.

9 CONCLUSION

In this work we presented a novel visualization solution that allows analysis and presentation of spatial and temporal data as an inseparable whole. By direct overlaying of time series visualizations on broadened roads, we achieve a seamless combination of space and time with no occlusion and minimal distortion. By carefully choosing visual encoding methods for time direction, we have ensured that occlusion is minimized yet maintains intuitiveness and accuracy. The usability of our system has been demonstrated by two case studies using real-world traffic data and the effectiveness and efficiency has been proven by a user study against a conventional linked view design.

There are multiple possible avenues for future work. It would be useful to conduct a user centered experiment to evaluate the usability of different temporal visualizations embedded on broadened roads. It would also be interesting to apply this approach to data from different problem domains.

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