Information Systems 57 (2016) 172–194

Contents lists available at ScienceDirect

Information Systems

journal homepage: www.elsevier.com/locate/infosys

Leveraging spatial abstraction in traffic analysis and forecasting with visual analytics

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ARTICLE INFO

Article history:
Received 28 November 2014
Received in revised form
13 August 2015
Accepted 26 August 2015
Available online 6 September 2015

Keywords:
Visual analytics

ABSTRACT

A spatially abstracted transportation network is a graph where nodes are territory compartments (areas in geographic space) and edges, or links, are abstract constructs, each link representing all possible paths between two neighboring areas. By applying visual analytics techniques to vehicle traffic data from different territories, we discovered that the traffic intensity (a.k.a. traffic flow or traffic flux) and the mean velocity are interrelated in a spatially abstracted transportation network in the same way as at the level of street segments. Moreover, these relationships are consistent across different levels of spatial abstraction of a physical transportation network. Graphical representations of the flux–velocity interdependencies for abstracted links have the same shape as the fundamental diagram of traffic flow through a physical street segment, which is known in transportation science. This key finding substantiates our approach to traffic analysis, forecasting, and simulation leveraging spatial abstraction.

We propose a framework in which visual analytics supports three high-level tasks, assess, forecast, and develop options, in application to vehicle traffic. These tasks can be carried out in a coherent workflow, where each next task uses the results of the previous one(s). At the 'assess' stage, vehicle trajectories are used to build a spatially abstracted transportation network and compute the traffic intensities and mean velocities on the abstracted links by time intervals. The interdependencies between the two characteristics of the links are extracted and represented by formal models, which enable the second step of the workflow, 'forecast', involving simulation of vehicle movements under various conditions. The previously derived models allow not only prediction of normal traffic flows conforming to the regular daily and weekly patterns but also simulation of traffic in extraordinary cases, such as road closures, major public events, or mass evacuation due to a disaster. Interactive visual tools support preparation of simulations and analysis of their results. When the simulation forecasts problematic situations, such as major congestions and delays, the analyst proceeds to the step 'develop options' for trying various actions aimed at situation improvement and investigating their consequences. Action execution can be imitated by interactively modifying the input of the simulation model. Specific techniques support comparisons between results of simulating different "what if" scenarios.

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http://dx.doi.org/10.1016/j.is.2015.08.007
0306-4379/

1. Introduction

Data concerning vehicle traffic can be nowadays collected in unprecedented amounts owing to the advances in the sensing technologies. These data offer new opportunities for improving the understanding of traffic properties and enhancing the accuracy of models forecasting traffic situations and their evolution. However, the potential of real traffic data remains largely underexploited. By means of visual analytics methods, we performed a systematic focused study to investigate the potential opportunities offered by traffic data. We found that historical traffic data can not only enable understanding of spatio-temporal patterns of traffic flows and interdependencies between their key characteristics (speed and volume), but they can also be used for building mathematical and computational models capable of forecasting traffic situations and their developments under various conditions. This finding is a result of an evolutionary process of design, implementation, and application of a range of visual analytics methods focusing on movement analysis [2].

Visual analytics [61] is a field of research seeking for ways to synergistically combine the capabilities of computers with the power of human cognition in analyzing massive and complex data. Visual analytics develops integrated methods uniting computational processing with interactive visual interfaces that support human mental processes [40]. In our research on visual analytics of movement [2], we first developed a range of exploratory techniques. They allowed us to spot fundamental patterns of traffic flow dynamics [8] (briefly presented in the next section) that are common for different areas and spatial scales. The next step was development of interactive visual interfaces for representing these patterns by mathematical models [7]. After obtaining such models, a logical next step in our research was to try to use them for traffic forecasting. For this purpose, we devised a lightweight traffic simulation algorithm capable of using previously derived models and developed interactive visual embedding for defining initial conditions, running simulations, and analyzing the outcomes. Since simulations could be prepared and performed very fast, thus allowing interactive operation, we extended the tools with possibilities to imitate various interventions altering network properties and/or traffic routes and investigate their impacts on the traffic situation development, including comparative analysis of various "what if" scenarios.

The contribution of our research is twofold. First, we comprehensively explored the potential opportunities offered by traffic data and demonstrated the possibilities of using them not only for analysis of past situations but also for efficient forecasting and "what if" analysis. Second, we developed an integrated visual analytics framework for traffic analysis, modeling, and forecasting, which supports a seamless workflow involving different analytical tasks. Specifically, our framework supports three major types of analytical tasks ([61], p. 35): assess (i.e., understand the piece of reality represented by available data), forecast (i.e., estimate the properties or behavior of the piece of reality beyond the part represented in the data), and develop options (i.e., find actions that can change the properties or behavior of the piece of reality in a desired way).

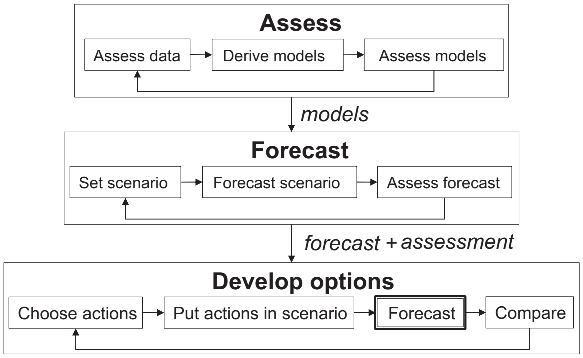

Fig. 1. Three types of visual analytics tasks as stages of a single analytical process.

Although the three types of tasks can be treated as independent activities [61], it is obvious that these can also be stages of a single analytical process, in which 'forecast' builds on results of 'assess' and, in turn, enables 'develop options'. So far, it has not been usual for visual analytics researchers to strive at supporting the whole process comprising all three types of tasks. Our work thus makes a contribution to visual analytics research not only by proposing a set of application-oriented techniques but also by demonstrating a way to support such a process. Although the immediate results of our work are specific to traffic analysis, the experience we gained and the framework incorporating it can be generalized and used by other researchers. The flow chart in Fig. 1 schematically represents a generalized view of an analytical process and exhibits the generic subtasks that need to be supported by visual analytics methods.

At the first stage ('assess'), analysts study available data to understand the phenomena reflected in the data. The understanding gained by the analysts can be seen as a mental model of the phenomenon. It is beneficial for the further analysis to externalize this model, preferably, in a form permitting computer processing. The analysts may derive several models representing different aspects of the phenomenon. Each model must be assessed and validated. At the second stage ('forecast'), the models are used to forecast events and developments that can occur under some conditions of interest. The analysts assess the resulting forecast to see the "capabilities, threats, vulnerabilities, and opportunities" ([61], p. 35) and understand whether the predicted situation or process requires intervention. If so, the analysts proceed to the third stage ('develop options'), in which they choose actions for improving the situation/process and perform the task 'forecast' to see and assess the effects of the chosen actions. The analysts also need to compare predicted results of different possible interventions.

This general scheme can be instantiated for various applications. The generic subtasks need to be specialized for a given application, thereby setting specific objectives for design and development of visual analytics tools.

In this paper, we present an instantiation of the general scheme for vehicle traffic analysis and include a special discussion of possible ways to validate traffic forecasting models using real data. Due to the novelty of our approach