Visualizing Large Scale Vehicle Traffic Network Data
A Survey of the State-of-the-art

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Abstract: Analyzing and improving large urban traffic networks is a difficult process due to complex interrelationships between the many variables that impact vehicle traffic behavior. Information visualization techniques can facilitate the tasks of analyzing large amounts of data and of exploring potential solutions to practical traffic problems. Surprisingly, there is a relative lack of investigation focused on how information visualization techniques should be applied and adapted to the field of Traffic Engineering. This paper presents an overview of what has been done on this topic by reviewing the use of information visualization in traffic systems over the years, and highlighting the current state-of-the-art by focusing on several innovative pieces of research. We provide a classification of the reviewed work and identify areas that have been understudied.

1 INTRODUCTION

Large urban areas in many countries suffer from increasing traffic congestion. Such congestion costs money, and impedes the growth of a country. It also affects people's health; for example, vehicles moving at low speed tend to consume more fuel and produce more toxic gases than when traveling faster (Seong et al., 2011). A study conducted in 45 countries on the growth of world income and vehicle ownership forecasted an increase of two billion vehicles by 2030 (Dargay et al., 2007). Therefore, mitigating the urban traffic congestion problem is important for economical and social development, as well as for environmental reasons.

Traffic problems are not simple to solve as they depend on several dynamic and interrelated aspects (urbanism, population distribution, location of workplaces, social, economical and leisure activities, etc.) which are hard to describe and to model in full detail (Button, 2001). As a result, the study of this subject usually involves dividing a traffic problem into steps or stages, in order to facilitate understanding. The famous Four-Step Model (McNally, 2000) is an example. It is comprised of the following steps: trip generation, trip distribution, modal split (trips by car, buses, subway, etc.) and traffic assignment. There are many other ways of analyzing these problems. In general, they can be divided into three major phases: (1) collecting information and describing the network and the travel demands (at different periods of the day and days of the week), (2) defining a traffic assignment model that considers the characteristics of the network and the transportation modes, and (3) experimenting with the model and variations of the network through simulation.

The issues that need to be addressed in each phase have been well studied and a variety of strategies have been devised for dealing with them. For instance, vehicle traffic networks are often modeled using graph theory concepts, while travel demands are usually represented in the form of two-dimensional arrays called origin-destination (OD) matrices, for distinct modes of transportation (car, bus, etc.), periods of the day (rush hours, night time, etc.), and days of the week (Ashok and Ben-Akiva, 1993). Macroscopic, mesoscopic and microscopic methods (either static or dynamic) exist for traffic assignment at different resolutions (Baskar et al., 2009) and each helps to predict vehicle traffic behavior in decision support systems.

However, algorithms and calculations are not sufficient to obtain feedback quickly, and to uncover patterns in the complex data sets collected for and generated by these systems. Thus, tools for visualization are important for such applications.

Information visualization combines aspects of human-computer interfaces, computer graphics and data mining, representing data in a graphical format

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that expands users' visual perception and promotes better understanding of the data (Agrawal et al., 1993; Fayyad et al., 1996). A visualization can support three general activities:

- Exploratory Analysis – finding new knowledge contained in the data through an analytical process that explores visual representation for highlighting trends / patterns that can lead to new hypothesis.
- Confirmatory Analysis – visually demonstrating the validation or rejection of a particular hypothesis.
- Presentation – graphically representing relationships, structures, behaviors, and other intrinsic characteristics to the data.

Given the great advances in the area of information visualization research, surprisingly few studies have focused on the role of visualization in the analysis of traffic problems. There is certainly some form of visualization present in many computational systems that assist in the modeling and the simulation of vehicle traffic. But they have been mostly employed for illustrating a process or a problem. Reported work that does employ information visualization generally does not consider the techniques used *per se*; rather, it assumes that the use of visualization (in some form) yields certain *de facto* benefits.

The limited application of information visualization to traffic problems is perhaps understandable, since it is not trivial to identify a graphical representation that is appropriate for the type of data and that adequately considers the principles of human perception (Gershon et al., 1998), (Chen, 2005). One major issue is the difficulty in representing multi-attribute data in ways that don't overwhelm our perceptual abilities. This is especially relevant for traffic, where we need to analyze complex data sets over both temporal and spatial dimensions (Boyandin et al., 2011).

This paper surveys the state of the art in the use of information visualization techniques to support modeling, simulation and analysis of urban traffic. Visualizations supporting navigation are not considered here, as our focus is to investigate techniques that help traffic engineers and city government planners improve traffic conditions. In addition, we focus on *urban* traffic networks due to their complexity.

The paper is organized as follows: Section 2 presents the state-of-the-art, describing research that uses information visualization for vehicle traffic modeling, simulation and analysis. Section 3 provides a characterization of the research in this area and identifies some understudied aspects. In Section 4 we draw our conclusions and suggest areas for future work.

2 INFORMATION VISUALIZATION FOR VEHICLE TRAFFIC

Many visualization techniques proposed to support the study of traffic problems have their foundation in well-established fields, most notably Cartography (Taylor et al., 2000; Meyer and Miller, 2001). The majority of visualizations that appear in the traffic engineering literature are common 2D geographic maps, or geographic maps employing a 3D perspective. Standard map features from cartography are widely used, including the division of political regions (suburbs, estates, etc.) by polygonal area features, the use of line features for representing streets, avenues, water channels and rivers, and the use of visual attributes like color, shade and texture to classify or highlight map elements.

Geographic Information System (GIS) and Decision Support System technologies have been applied to traffic engineering to yield modeling and simulation systems that combine georeferenced data with an interactive multiple layer visual representation, for the analysis and planning of traffic networks (Huang and Pan, 2007). Some popular commercial GISs in this category are the software Saturn (Van Vliet, 2013) and Dracula (Liu et al., 2008), TransCAD (Caliper, 2012) and VISSIM (PTV, 2013). Many other traffic modeling systems are also gaining popularity, such as the free software SUMO (Krajzewicz et al., 2013), MITSIM (MitSim, 2013) and PetGyn (Jradi et al., 2009).

Recently, several research projects have explored innovative ways of presenting traffic data. They differ from previous research and from commercial systems in their application of new presentation metaphors and more complex visual approaches, or by being highly interactive. We survey such pieces of work here. They are grouped in this section according to the information visualization classification proposed by (Keim and Kriegel, 1996), to provide a preliminary categorization of the work. This classification includes Geometric Projections (consisting of all techniques that show projections of multidimensional data sets), Pixel-oriented views (which map each data value to a colored pixel), and Hierarchical presentations. Keim et al. also described a Graph-based group, but we have realized that all papers that fall in this category also draw a graph as a geographic projection of a map. Therefore, those papers were classified as belonging to the Geometric Projection group.

2.1 Geometric Projection

As expected, geometric projection remains a key approach for generating interactive visualizations of traffic network data. Increasingly, researchers are applying advanced graphical techniques (animations, perspective transformations, morphing), expanding the expressive power of geometric projections in ways that suit the presentation of traffic flow, multidimensional traffic data, and the complex relationships between network elements (e.g., origins, intersections, destinations).

Cascade on Wheels (Thirion et al., 2008) is a visualization project started during the Visualizar Workshop at the Medialab Prado in Madrid in 2007. The project's main goal was to express the amount of vehicles in big cities using metaphor. Two visualizations were developed and applied to data regarding taxis, buses and light and heavy vehicle flows in the central region of Madrid in 2006.

The first visualization, referred to as Walls Map Piece (Figure 1-(a)), shows traffic data using a wall metaphor. It presents a 2D satellite map of the city, in which it is possible to select streets and visualize their names and traffic data (the amount and type of vehicles) in a given day. By selecting a tool, the visualization then turns into a 3D map with streets raised according to the amount of daily traffic flow in them. Each street segment creates a wall with height proportional to its amount of traffic. The user can rotate the 3D map to view the sides of walls, which show the amount of vehicles of each type using bar charts. A similar approach applied to vehicle crash analysis can be found in (Li et al., 2007).

The second visualization (called Traffic Noise Mixer) makes use of an audio layer combined with a network satellite map (see Figure 1-(b)). The user can interact with the visualization by drawing, dragging and growing circular regions over the map. Sounds with specific frequencies and amplitude are then generated and played, representing the amount and the types of vehicles traveling in the selected regions.

The LIVE Singapore project (Kloeckl et al., 2011), created by the SENSEable City Laboratory at MIT, explores the development of an open platform for the collection, elaboration and distribution of a large and growing number of different kinds of real-time data that originate in a city (e.g., from cellular networks, taxi fleets, public transport, seaports and airports). The platform provides support for generating interactive visualizations employing geometric projections. Some applications built with the LIVE Singapore framework are discussed next.

Members of the LIVE Singapore Project (Kloeckl et al., 2011; Chen et al., 2011) proposed transformations (compression / distension) of a map of Singapore according to the time demanded for traveling between origin-destination of points, in a view called "Isochronic Singapore". About 290 controlling points were defined. Selecting an origin point causes the map to be visually distorted so that the distance from that origin to all destinations in the network is proportional to the travel time between them. The visualization also changes automatically as the observed traffic flows in the network vary during the day.

Figure 1: (a) Walls Map Piece - a 2D/3D map with walls representing streets with dense traffic. The greater the flow of vehicles in a street segment, the higher the corresponding part of the wall. (b) Traffic Noise Mixer. Audible noise is produced in order to indicate the amount and types of vehicle in selected regions. Courtesy of (Thirion et al., 2008).

The Data Lenses visualization(Cruz, 2012) is part of the Live Singapore project as well. It was created to enable precise monitoring of activities of urban public transportation (buses) in Singapore. The visualization uses lenses that work like magnifying glasses (see Figure 2). The users can move the lens or change its properties (like radius and magnification level) to improve perception of a dense information area. It is possible to adjust the lenses to present different layers of information, such as bus lines at each bus stop (in blue), the number of bus passengers, the number of passengers boarding/exiting at the bus stops (in orange) and the total amounts paid for tickets at each bus stop (in red).

Furthermore, the LIVE Singapore visualization called "Traffic Origins" (Kloeckl et al., 2012) aims to identify road events that usually cause congestion. In this visualization, information previously available about road events can be combined with simulation models for better comprehension of traffic conditions

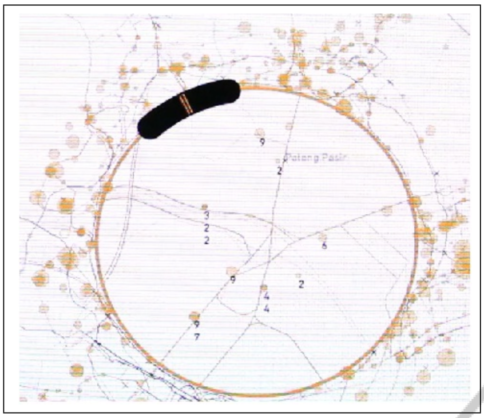

Figure 2: The Data Lenses visualization permits the amplification and suppression of urban traffic data on a map. Courtesy of (Cruz, 2012).

and to predict the impact of traffic interruption in the network. Three types of events can be automatically highlighted in the visualization using colored circles: accidents (in red), intense traffic (in blue) and broken vehicles (in orange). After identifying a region of the map where one of these events occurrs, the visualization emphasizes the color in the nearby streets (inside the circle) to improve perception of their traffic flow speed. The advantage of this techinique is to focus the users attention only on the important occurrences, given by circled events with colored information.

The Web site "Every Death on Every Road in Great Britain 1999 - 2010" (BBC, 2011), produced by the British Broadcasting Corporation (BBC) and released in 2011, uses geometric projection to show the evolution of traffic accidents over time. It presents data and facts about accidents with injuries and deaths on Great Britains roads over a span of eleven years. The visualization resembles a nightly aerial map view, with lights indicating road collisions that caused injuries and deaths.

Other research has considered technical challenges involved in generating traffic visualizations employing geometric projection. For example, the work of Chen et al. (Chen et al., 2008) considers the difficulty in modeling large meshes of roads. In this context, they proposed a system to assist the user on modeling/drawing a road network using stress fields.

As another example, Sewall et al. (Sewall et al., 2011) present a hybrid model that combines continuum (macroscopic) and agent-based (microscopic) methods for efficient and effective traffic simulation and visualization of large-scale networks in real time. In general, macroscopic methods are faster but do not capture individual vehicle behaviors precisely. On the other hand, microscopic methods are more flexible for modeling traffic elements in detail, but demand extra processing power. In their approach, a large network can be divided into several small regions and each region can be simulated by either the microscopic or macroscopic method. This hybrid model allows a fine-grain detail of a network region of interest, while simultaneously keeping the simulation of the remaining part of the network with the continuum method. Traffic data from the different methods are interchanged.There are other papers with similar visualizations (Kim et al., 2009; Mahut and Florian, 2010; Svennerberg, 2010; Buch et al., 2011).

Other research has deeply integrated visualization tools into traffic analysis system. The CityMotion Project (Silva et al., 2010) was developed by researchers of the University of Coimbra, MIT and the University of Porto, between 2007 and 2010. Their goal was to build knowledge infrastructure, computational models and user applications that allow access to real-time information about the state of transportation-related resources as well as to do predictions regarding their future state.

One of the CityMotion subprojects is called "Visualizing the Circulatory Problems of Lisbon" (Cruz and Machado, 2011). That project resulted in alternative visualizations to identify bottlenecks in a road network based on a metaphor of the circulatory system of a living being. The scenario is Lisbon in 2009 with data from 1,534 vehicles. They presented two types of visualizations inspired by basic biology.

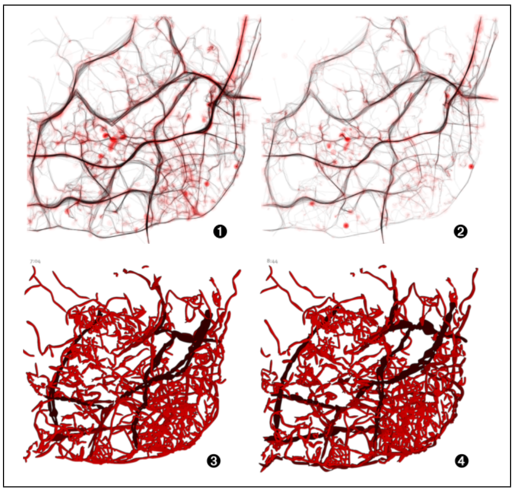

Figure 3: Images (1) and (2) represent clots in Lisbon at 9am and 7pm, respectively. Images (3) and (4) show blood vessels in Lisbon at 7:04 am and 8:44 am. Courtesy of (Cruz and Machado, 2011).

In the first visualization, shown in images (1) and (2) of Figure 3, blood clots (as red circles) represent zones of slow traffic. The diameter of the clots is inversely proportional to traffic speed.

In the second visualization, shown in images (3) and (4), color and the size of blood vessels change according to the number of vehicles and the average transit speed in each road.

In both visualizations, traffic in low speed tends to darken the related blood vessel, representing blood stagnation. In contrast, if the traffic speed is high, the blood vessel is painted in lighter color.

The “Pulse of the City” (Reades, 2011; Reades, 2012) is an animated view developed by Jonathan Reades[1] that also applies the circulatory system metaphor. It shows the usage of public railway transportation lines in London, presenting railway lines over a cartographic map with a dark background. As time passes and commuters travel in the railway system, railway line segments increase in thickness according to their use. If a railway segment that had many passengers before becomes less used, its thickness shrinks to normal size. Since the animation covers many days and periods of the day, even with rush hours, the resulting visual effect is of a living circulatory system that pulses with blood.

While the circulatory system metaphor is one specific approach, a range of projects more generally apply deformation and color to highlight areas of concern in traffic visualizations. Another visualization from the CityMotion project is “Morphing City” (Cruz, 2011), which presents a map whose lines are deformed (compressed or distended) if the current flow speed on the road is lesser or greater than the average global speed. Color assists in the interpretation of the map as well: deformations that compress the view are assigned cold colors, while warm colors are applied for expansions. The Morphing City visualization enables rapid identification of critical points since areas with intense traffic are highlighted by warmer colors and appear to expand in comparison to other routes.

Seong et al. (Seong et al., 2011) use Geometric Projection to model and map noise produced by urban traffic in Fulton County, Georgia, USA. They created a visualization where decibel ranges are represented by colors: buildings with low noise level are shown in green, high levels of noise appear in red, and there is a color scale indicating intermediate levels. A range of visualizations considering noise and air pollution have been considered in other research (Tsai et al., 2009; Elbir et al., 2010; Pamanikabud and Tansatcha, 2010; Zannin et al., 2013), most employing some form of geometric projection.

In our review, we also found some projects that aim to visualize origin-destination matrices using a combination of geometric projections and other techniques, including graph-based approaches. The work of Boyandin et al. (Boyandin et al., 2011) is one example. It highlights the limitations of geometric projections alone when applied to temporal origin-destination datasets. The paper then introduces an interactive visualization called Flowstrates (Figure 4), which presents two different geometric maps with a heatmap in the center, using color to represent demand over time. Similar visualizations are presented in (Wood et al., 2011).

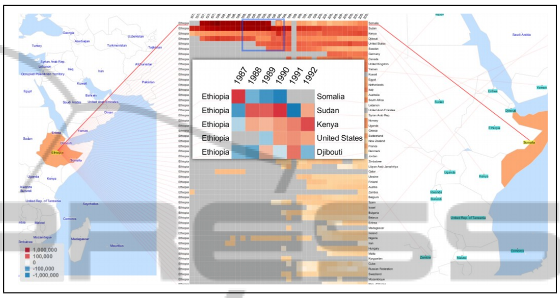

Figure 4: The image represents the annual number of refugees of Ethiopia. Each column in the heatmap (between two maps) indicates temporal scale. In this example Somalia is the country which receives more refugees (hot colors represents a big density, when cool colors is small).

In another project (Wood et al., 2010), the authors draw OD matrices as colored cells and lines over a cartographic map, according to the density of trips between the OD pairs. In addition, Gunay (Gunay, 2009) shows OD matrices using Wavelets transformations in order to highlight similarity in data.

2.2 Pixel-oriented

In this section we discuss recent work that employs a pixel-oriented approach. Just as with graph-based examples, this also is done in a manner that integrates with a geometric projection.

The work of (Xie and Yan, 2008) presented spatial patterns of traffic accidents in roads. A variation of the Kernel Density Estimation (KDE) technique was developed that smooths density surface of spatial point events over a 2D geographic space. The new approach was implemented in the ESRI ArcGIS environment and tested with traffic accident data from 2005 in Bowling Green, Kentucky, USA, provided by the Kentucky State Police Department. The researchers found that the new KDE was more effective than the standard method for estimating traffic accident densities.

In order to help understand the results, the authors used a map visualization, as shown in fig 5. Figure 5-(a) highlights the density of accidents by varying the thickness of roads in the positions where there are

[1]http://vimeo.com/user11576485/pulseofthecity

many accidents. This is carried out a smoothing procedure that expands and connects points of the network if they are already close to each other and there is a high number of accidents in them. Figure 5-(b) presents the same data but uses a 3D perspective to show traffic accident densities (the higher the density, the higher the peak over an area).

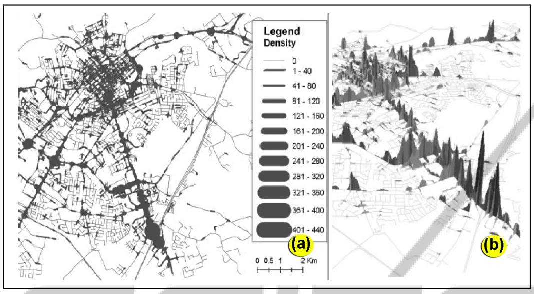

Figure 5: Visualizing traffic accident densities. The image (a) indicates traffic accident densities by expanding and connecting nearby points. Other presents this data in a 3D view using height to indicate density. Courtesy of (Xie and Yan, 2008).

Other visualization approaches based on variations of KDE can be found (Ha and Thill, 2011; Liu et al., 2012; Wang et al., 2009; Mesbah et al., 2012).

2.3 Hierarchical

Wood et al. (Wood and Dykes, 2008) explore the use of treemaps for variable selection in spatial-temporal data. Their study focuses on a dataset consisting of 90 million georeferenced vehicle locations from a courier fleet. The data was collected during 18 months and each location contains its geographic position (given by GPS), timestamp, vehicle type (including van, large van, motorbike, large motorbike and bicycle) and travel speed. The goal of that study was to demonstrate that treemap visualizations can help users identify useful patterns in the data and to select information for further analysis.

The researchers present two approaches for visualizing the dataset. In the first one shown in Figure 6-(a), the data is hierarchically organized according to vehicle type, day of the week (from Monday to Sunday) and hour of the day (24 hours in total). In the lowest level of the hierarchy, each treemap rectangle has an area proportional to the volume of vehicles (according to the corresponding type, day of week and hour). Color intensity is also used for mapping the average speed of these vehicles.

In the second approach, illustrated in Figure 6-(b), a map of the city is divided into a grid of rectangular regions. Each cell of the grid contains a treemap

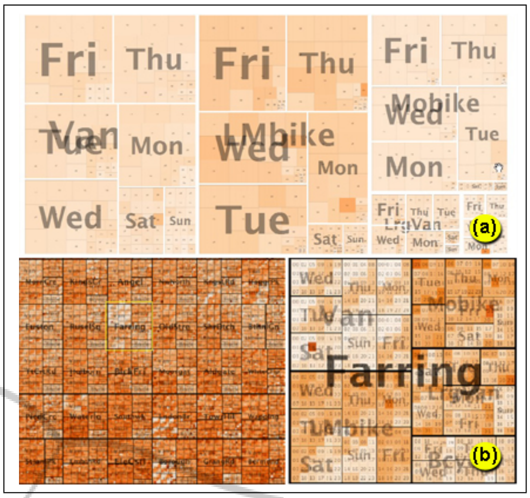

Figure 6: (a) Treemap showing traffic data classified by transportation mode, day of week and hour of the day. The rectangles are ordered by size from top-left to bottom-right for each level of the classification. (b) An area of London divided into cells of 1km square each (left). In each cell there is a treemap of the hierarchically ordered vehicle data. The image on the right is a zoomed view of the "Farring" cell. Lighter colors indicate that vehicles traveled at a lower average speed. Courtesy of (Wood and Dykes, 2008).

presenting data from that region, hierarchically organized as before. Color intensity indicates either traffic volume or average speed in each small rectangle at the lowest level of the hierarchy.

Despite being used for visualizing data for a courier fleet, the same approaches can be applied to other traffic data in a straightforward way.

3 CHARACTERISTICS AND UNTREATED ASPECTS

As we have seen, current traffic network visualization research is heavily oriented toward geometric projection-based approaches. We can characterize the visualization techniques we have discussed according to different criteria so that it becomes easier to compare them as well as to identify as-yet-unexplored avenues for traffic visualization. We propose here two major criteria for vehicle traffic related visualizations:

- Type of data. The visualizations are grouped according to the main type of traffic data they present. These types include, but are not limited to the following: O-D matrices, rigid network infrastructures (such as roads, bridges and intersections), flexible elements of the network (that can be changed with little or no infrastructural intervention, such as lane direction, maximum speed limits, signal settings, turning restrictions, parking authorizations, trip and parking tolls, etc.), flow measurements or flow estimations, and meaningful high level data such as information about car accidents and other events. One can see that such data can be naturally organized into levels in a hierarchical multilayer way, as is usually done in geographic information systems. Therefore, we can further classify a traffic visualization according to whether it was designed for presenting a given layer of data or a combination of them.

- Target task. In this case, the visualizations are classified according to the kind of task(s) they are intended to support. We envision three types of tasks. The first is simply to present traffic data for overall understanding and for pattern identification. This involves showing the data and possibly allowing interaction to control the visualization attributes, or to apply filters. The second type of task is to input data. Although user interface components like dialog boxes, tables and text fields could be used for inputting data into a traffic system, we mean here a more intuitive and visually-oriented way of entering information by direct manipulation of the elements of a visualization. The third type of task is to simulate and optimize traffic behavior through the exploration of multiple scenarios of the network and traffic conditions. This task is very common in decision support systems for traffic engineering. We can say that it involves an aggregation of the previous two tasks in order to allow the user to pursue a more complex goal. Similarly to the first classification criterion, this second one is not mutually exclusive in its options, allowing the presence of two or all three target tasks simultaneously.

We analyzed the visualizations reviewed in Section 2 according to these criteria and presented the result in Table 1.

Note that it is possible to characterize the views according to the type of visualization approach too (2D, 3D, treemap, etc.) and by the interaction techniques used. We consider these other criteria useful, but mainly to further differentiate visualizations that have already been classified by the other means.

One of the main observations from our survey of the field of visualizing vehicle traffic data and traffic problems is that there are many combinations of the two criteria proposed above for which no visualization technique is currently available. Furthermore, there has been no systematic study that demonstrates how to build good visualizations for variations of data type and target task.

Table 1: Characterization of the reviewed visualizations.

	Type of Data					Target Task		
Projects	OD Matrix	Network Infrastrucure	Flexible network elements	Flow	High Level Meaningful Data	Data Presentation	Inputting Data	Simulation and Exploration
(Waze, 2013)		x		x	x	x	x	x
(Zannin et al., 2013)		x		x	x	x		x
(Cruz, 2012)		x		x	x	x	x	
(Reades, 2012) II		x		x		x	x	
(Liu et al., 2012)		x		x		x		
(Mesbah et al., 2012)		x	x	x		x		x
(Seong et al., 2011)		x		x		x		x
(Sewall et al., 2011)		x	x	x		x		x
(Reades, 2011)		x		x		x	x	
(Cruz, 2011)		x	x	x		x	x	
(Kloeckl et al., 2011)		x		x	x	x		x
(Chen, 2011)		x		x		x	x	x
(Boyandin et al., 2011)	x			x		x		
(BBC, 2011)		x		x	x	x	x	
(Ha and Thill, 2011)		x		x	x	x		
(Elbir et al., 2010)		x		x	x	x		x
(Wood et al., 2010)	x	x		x		x		
(Silva et al., 2010)	x	x		x	x	x	x	x
(Kim et al., 2009)			x	x	x	x		x
(Wang et al., 2009)		x		x		x	x	x
(Outram et al., 2009)		x		x	x	x	x	
(Tsai et al., 2009)		x		x	x	x		
(Wood and Dykes, 2008)				x		x		
(Jradi et al., 2009)	x	x	x	x		x	x	x
(Xie and Yan, 2008)		x		x	x	x		x
(Thirion et al., 2008)		x		x		x	x	
(Chen et al., 2008)		x	x			x		
(Madsen et al., 2007)		x		x	x	x		x
(Tang and Wang, 2007)		x		x	x	x	x	x
(Li et al., 2007)		x		x	x	x		x
(Wang, 2005)		x	x	x		x	x	x
(Elbir, 2004)	x			x	x	x		
(Borho, 2003)		x	x	x		x	x	x
(Brandt et al., 2003)		x		x	x	x		
(Claramunt et al., 2000)		x	x	x		x	x	x

Another important observation is that, for many tasks and data types for which supposedly reasonable visualization techniques have been applied, the visualizations are revealed to be ineffective or inefficient in some common cases. For instance, a traditional way of denoting flow orientation on streets and turning permissions/restrictions on intersections is by drawing arrows that indicate the flow directions. However, when the network is large, it becomes practically impossible to visualize these details in a cartographic map. Interactive zoom can solve this problem, but at the expenses of compromising perception of the complete network. Also, it does not allow effective simultaneous visualization of multiple detailed regions of the network. Innovative pieces of research as the work done by Sewall et al. (Sewall et al., 2011), that uses augmented reality over a 2D network map to present animations of vehicles moving, would offer flow direction perception while preserving full-picture zoom level. However, this approach demands high processing power, does not show the network characteristics in regions where there is absence of flow, and does not provide a good visualization of flow orientation at intersections with many crossings and turning permissions.

The Flowstrates approach (Boyandin et al., 2011), as another example, improves the understanding of Origin-Destination matrices, but has several limitations. There is a lot of visual overlapping when the number of selected OD pairs increases. Furthermore, it does not show how OD demands translate into real traffic flow, particularly when considering an urban traffic network, with many possible flow paths.

In general, the existing visualizations suffer from two main problems: visual overlapping as the size of the data set steadily increases, and an inability to present different types of data in an integrated way (network structures, OD demands, traffic flow, etc.). It is also difficult to develop a "robust" visualization that produces visually acceptable results for all traffic scenarios, since we are dealing with very dynamic systems in which small changes of the network structure may result in totally different flow behavior.

Finally, the majority of traffic-related visualizations and interaction techniques considered to date were designed with traditional mouse+keyboard or touchscreen configurations in mind. Few researchers are investigating the use of novel HCI approaches, going beyond the simple dualities of large/small screens and touch/indirect interfaces to build on the frontier and explore how techniques from augmented reality, tangible, mobile and ubiquitous computing can play a role.

Some interesting examples are emerging in the processes of collecting traffic data. For example, the Copenhagen Wheel Project (Outram et al., 2009) consists of an electric wheel extension (called "hub") that transforms any ordinary bike into a hybrid e-bike with a motor, batteries, GPRS, and sensors for torque, moisture, carbon dioxide, temperature and noise. While a bicyclist follows their route, the sensors collect information and send them to an iPhone every two seconds via Bluetooth.

Copenhagen Wheel is one example of a larger trend toward *Crowdsourcing* traffic network data (Howe, 2006; Weissman and Villalobos, 2012). Waze (Waze, 2013) is an application for mobile devices that allows traffic information to be shared, such as locations with congestion, accidents, objects on a track, as well as tips and warnings. It has been reported that the use of such software can help in better choices of route (Chen et al., 2012; Talele et al., 2012).

In future, systems that exploit crowdsourcing, open data, and heterogeneous data sets will need to manage information that is not always complete, correct or provided at the same level of granularity. This will also impact on how to best visualize and interact with the data.

4 CONCLUSION

We have reviewed the research on information visualization applied to vehicle traffic problems and data in order to show the state-of-the-art in this field.

We then proposed a characterization approach for traffic-related visualization methods. Based on our review and on the characterization criteria, one can see that there still lacks much investigation of interactive visualization methods for certain tasks and types of traffic data. Furthermore, a range of emerging HCI techniques has not generally been employed by researchers working in this domain. We have also identified two main limitations with current approaches: visual overlapping and poor integration of different forms of traffic network data. Our paper is a step towards better understanding these challenges, by reviewing the state-of-the-art in this field and by situating the existing research within our categorization scheme. Nevertheless, there is still much to investigate and to define in this area.

For future research, we suggest:

- more exploration of techniques for integrating multiple views, each optimized for specific types of network data;
- consideration of 3D interaction techniques to mitigate the problem of visual overlapping;
- expanding the characterization scheme to include interactive techniques and conceptual approaches for inputting data;
- further exploring interactive visualizations for the task of inputting different types of traffic-related data; and
- adapting emerging HCI techniques to traffic-related visualization in decision support systems.

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