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Real-Time Traffic Maps

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in Geography

by

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ABSTRACT

Real-Time Traffic Maps

by

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This dissertation summarizes research investigating the design of real-time traffic maps. As traffic congestion continues to burden our largest cities, and as the Internet continues to grow at a rapid pace, real-time traffic maps have the potential to be among the world's most popular maps. Furthermore, as mobile devices and in-car-navigation-systems begin to connect to the Internet, millions of drivers will access and read these maps on an array of media. This dissertation reports on research aimed to understand as well as enhance the design of real-time traffic maps. The dissertation includes reviews of previous scientific research, as well as several online traffic maps from around the world. The dissertation also introduces new methods to design and empirically evaluate the performance of real-time traffic maps. The design methods are guided by established cartographic principles, as well as the findings of human subjects studies that reveal more intuitive cartographic strategies. The investigation pays particular attention to the influences of cartographic classification, and cartographic symbolization; the findings suggest that both classification and symbolization

significantly influence how map readers perceive and respond to graphical depictions of traffic conditions. With this in mind, the research suggests it is imperative to not only understand the influence of design variables on map perception, but also to, as best as possible, link map design with map-readers' perceptual preconceptions, and preferences. This idea of cognitive congruence represents a new challenge for all kinds of cartographers.

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I. INTRODUCTION

1.1 Introduction

According to the 2004 Urban Mobility Report (Schrank and Lomax, 2004, pg. 1), “Congestion has grown everywhere in areas of all sizes. Congestion occurs during longer portions of the day and delays more travelers and goods than ever before.” The report presents undeniable evidence that the trends across the United States are toward more delays, and more hours on the road. Even the President of the United States believes traffic lays a heavy burden upon our nation. George W. Bush’s proposed budget of the United States Government, fiscal year 2008 (Bush, 2007) includes this:

“Highway traffic congestion is a pervasive problem that affects every American either directly or indirectly. In 2003, drivers in the 85 most congested urban areas in the United States experienced 3.7 billion hours of travel delay and burned 2.3 billion gallons of wasted fuel for a total cost of \$63 billion. In the Nation’s 10 most congested areas, each rush hour traveler “pays” an annual virtual “congestion tax” of between \$850 and \$1,600 in lost time and fuel, spending the equivalent of almost eight work days each year stuck in traffic. In addition to these costs, deterioration in the transportation system makes delivery of goods and services less reliable, has environmental impacts, distorts real estate markets, and robs people of time with their families.”

“In support of a Department-wide effort to tackle congestion in all modes, the 2008 Budget redirects funds to a new \$175 million highway congestion initiative. The program is funded with balances from unneeded Congressional earmarks for highway projects. That strategy would include a broad demonstration of some form of congestion pricing, commuter transit services, commitments from employers to expand work schedule flexibility, and *faster deployment of real-time traffic information*. The goals of the initiative are to test new ways to mitigate congestion, evaluate the benefits and costs of these approaches, and determine if they can be applied in other parts of the country. (Budget of the United States, Fiscal Year 2008, pg. 108)”

One problem is that despite ubiquitous and growing congestion events, drivers still do not have sufficient resources for congestion avoidance. Drivers cannot be certain about where or when congestion events exist along their route. This uncertainty represents a gap in a driver’s cognitive map. Although significant traffic measurement infrastructure is often in place, “relevant” traffic information is rarely delivered effectively to individual commuters. Geographic information is said to be “relevant” when it is informative, timely and enriches an individual’s cognitive map (Raper et al., 2002). As of 2007, the maps included in Advanced Traveler Information Systems (ATIS) fail to effectively communicate relevant congestion information. This dissertation focuses on the role of contemporary cartographic science and technology in the delivery of “relevant” traffic information to drivers in urban environments.

As it relates to transportation science this research is related to Intelligent Transportation Systems (ITS) and ATIS. ITS is the application of computers,

communications and sensor technology to surface transportation. Used effectively, ITS opens the door to new ways of understanding, operating, expanding, refining, reconfiguring and using the transportation system (Intelligent Transportation Society of America, 2002). An important component of ITS is the efficient communication of transportation information. ATIS are the subset of ITS devoted to the provision of transportation information to individual travelers. ATIS are designed to assist drivers in “trip planning, destination selection, congestion avoidance, selection of departure times, route choice, and to assist navigation (Golledge, 2002, pg. 82);” simply put, ATIS should enable intelligent driver decisions. Unfortunately, as they relate to the provision of relevant traffic information, current ATIS are suboptimal. In this transportation science context, this dissertation attempts to lend cartographic support to the graphic depictions of congestion within ATIS.

1.2 Research Goals

Although transportation information by itself cannot solve transportation problems, it can assist applications that do. For this reason it is worthwhile to examine strategies for the efficient delivery of transportation information to human beings. Maps and cartographic visualization constitute important media for communication of spatial information (Tufte, 1990). To this point, limited research has focused on how contemporary cartographic visualization can aide the communication of real-time traffic information. The goals of this dissertation are:

1. To investigate previous research findings, current online traffic map resources, and human responses to traffic map stimuli in order to expose major issues in the design of real-time traffic maps.
2. To design a new data-driven mapping prototype, which is both informed by empirical map design research as well as capable of depicting and delivering streaming Los Angeles traffic information.
3. To conduct a comparative analysis evaluating the performance of the prototype relative to existing traffic mapping systems.

1.3 Research Questions

“The bulk of human travel is repetitive and relatively invariant in time and space. It would be unusual for humans to consult a cartographic map of an environment prior to every trip (Golledge, 2004, pg.6).” One exception to this rule may exist for urban drivers. Highway traffic presents a variable barrier; when and where there is traffic one day, there may not be the next. In terms of Behavioral Geography, traffic introduces a considerable amount of uncertainty into the mental maps of even the most frequent urban travelers. This uncertainty frustrates individual drivers traveling along affected routes. With this in mind, the research questions addressed in this dissertation are:

1. Can we blend previous research findings with results from human subject examinations to better understand how cartographic design influences the perception of traffic maps?

2. How can cartographers apply these findings and harness the strengths of emerging graphics technologies to create an enhanced real-time traffic map?

3. Will this informed real-time traffic map outperform existing “uninformed” traffic maps in terms of clarity, intuitiveness, and user preference?

This dissertation includes a chapter designed to answer each one of these questions. Chapters 3 and 4 explore and reveal some of the influences of map design on the perception of traffic maps. Chapter 5 focuses on new methods to create a prototype traffic map using the emerging vector graphics standard called Scalable Vector Graphics (SVG). Chapter 6 reports on a comparative analysis of the prototype and an existing traffic map. Chapter 7 concludes the dissertation by summarizing the broader findings, and suggesting future directions of related research.

1.4 Relevance of Research/Broader Impacts

Contemporary cartographic displays have the potential to efficiently communicate relevant traffic information to individual drivers. The future of cartographic communication, as well as ATIS is inherently bound to the rapid growth of the Internet, mobile phones, and location-aware computing. There is unbridled potential in this emerging mobile cartographic arena. Unfortunately, current Internet traffic maps fail to meet this potential (Goldsberry, 2005). Applying existing techniques from Geographic Information Science, and Cartography, as well as emerging graphic display strategies to ATIS could benefit frustrated drivers and represent progress within cartographic research. Furthermore, these methods could potentially demonstrate the positive

influence of cartographic research on in-vehicle navigation systems, and ATIS. Since traffic and congestion are problems in many American and international cities, progress toward improved traffic information dissemination is undeniably valuable.

This research also could spark an exciting merger of contemporary cartographic design research and driver workload research. Since it is dangerous for drivers to attend to maps while driving, it is important that future researchers aim to minimize the time spent attending to IVNS. Since maps are an integral part of IVNS, intelligent map design is required to ensure the overall intelligent design of IVNS. Intelligent map design within IVNS can allow successful navigation to destinations without substantial driving task interference (Dingus and Hulse, 1993). Conversely, the consequences of poor map design include an increased risk of driver task interference. The broader impacts of this research include setting a precedent for using the principles of map design in order to reduce driver workload.

This research also facilitates the merger of advanced graphics technologies and telecartography. SVG and XML can potentially benefit Internet cartography and mobile mapping. This research attempts to realize these benefits. This project demonstrates the versatility and unique strengths of SVG and XML, including sleek vector graphics and compact file sizes, as they pertain to telecartography. Potentially, the methods presented here exemplify a new technique for the design and efficient dissemination of real-time mobile maps.

II. MAP DESIGN AND TRAFFIC: BACKGROUND

2.1 Traffic

2.1.1 The American Traffic Problem

Traffic congestion is a significant and growing problem in American cities. The delays associated with congestion reduce the efficiency of American transport, costing us both time and money. Each year researchers at Texas A&M's Texas Transportation Institute produce a detailed Urban Mobility Report; the report includes annual statistics, trends, and analyses of American traffic woes. The most recent reports present undeniable evidence that traffic is a serious and increasing obstacle to transport in the 85 urban areas included in the study. "Despite a slow growth in jobs and travel in 2003, congestion caused 3.7 billion hours of travel delay and 2.3 billion gallons of wasted fuel, an increase of 79 million hours and 69 million gallons from 2002 to a total cost of more than \$63 billion (Schrank and Lomax, 2006, pg. 1)." The 2005 report suggests that the estimated cost of traffic congestion has grown from 12.5 billion dollars in 1982 to 39.4 billion dollars in 1993, and to 63.1 billion dollars in 2003. These costs include the extra fuel consumed during congested travel as well as the hours wasted by congestion. The report presents undeniable evidence that congestion occurs during longer portions of the day, and delays more travelers and goods than ever before.

The Urban Mobility Report mobility report also breaks American congestion down geographically. The findings, not surprisingly, indicate that congestion is most severe in

our largest cities, and that Los Angeles, California has the worst traffic problem in the country. Table 1 details the “key mobility measures” for the 13 “very large” urban areas as reported in the 2005 Urban Mobility Report.

Urban Area	Annual delay per traveler	Rank	Travel Time Index	Rank
Los Angeles-Long Beach-Santa Ana	93 (hours)	1	1.75	1
San Francisco-Oakland CA	72	2	1.54	3
Washington DC-VA-MD	69	3	1.51	4
Atlanta GA	67	4	1.46	5
Houston TX	63	5	1.42	6
Dallas-Fort Worth-Arlington TX	60	6	1.36	19
Chicago IL-IN	58	7	1.57	2
Detroit MI	57	8	1.38	12
Miami FL	51	13	1.42	6
Boston MA-NH-RI	51	13	1.34	21
New York-Newark NY-NJ-CT	49	18	1.39	10
Phoenix AZ	49	18	1.35	20
Philadelphia PA-NJ-DE-MD	38	27	1.32	25

Table 1: The “key mobility measures” for America’s “very large urban areas” (population over 3 million) as reported in the 2005 urban mobility report (values are for 2003 traffic). Annual delay per traveler is the extra travel time for peak period travel during the year divided by the number of travelers who begin a trip during the peak period (6-9 AM, 4-7 PM). Travel Time Index is the ratio of travel time in the peak period to the travel time at free-flow conditions. A value of 1.75 indicates a 20-minute free-flow trip takes 35 minutes in the peak.

Traffic congestion is clearly a very serious and complex problem. There is no singular solution that can eliminate congestion. Common engineering-based approaches

to relieving traffic often involve increasing road capacity, eliminating bottlenecks, and creating intelligent development patterns. This dissertation is concerned only with the provision of relevant traffic information to travelers; one goal of the research is to understand how maps can reduce driver uncertainty and facilitate enhanced wayfinding support.

2.1.2 Traffic Data: Collection And Processing

Klein (2001, pg. 26) describes the process of collecting, handling, and disseminating traffic information. Figure 1 summarizes Klein’s description. This feedback loop includes four nodes: data collection, data processing, data application, and driver behavior.

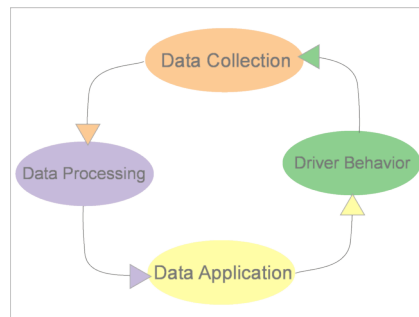


Figure 1: Klein’s feedback loop describing the collection, handling, and disseminating of traffic data. Cartographers can help create map-based data applications to provide commuters with better wayfinding information.

There is an important data distinction between microscopic versus macroscopic levels of traffic measurement (Claramunt et al, 2000). The so-called microscopic level of measurement observes the movements of individual or several individual vehicles in an urban network. Microscopic measurement usually includes GPS units and is

demonstrated in the work of several geographers (Kwan, 2000, Golledge, 1999, Raper, 2000). Meanwhile macroscopic measurement involves measuring states or changes in the traffic properties of the network itself. Macroscopic techniques measure volumes, flows, and speed at fixed points along the network. Urban highway traffic data is most often collected at the macroscopic level using sensors. Different types of sensors exist but Inductive loop detectors (ILD) continue to be the most widely deployed traffic sensors in the United States (Klein, 2001). ILD are made of loops of wire embedded in pavement and connected to a control box where the loop detector data is initially processed. Vehicles passing over an ILD cause a reduction in the inductance of the loop, which in turn enables the measurement of traffic attributes. When properly installed and maintained in good pavement, the inductive loop provides accurate vehicle volume and lane occupancy data needed for most traffic management applications (Klein, 2001).

ILD iteratively collect traffic data at fixed geographic coordinates. These georeferenced point feature data include vehicle speed, vehicle density, and network flow measured at that location. Attribute data collected at points can be easily mapped as dot maps without any sophisticated cartographic transformations. Each dot corresponds to an Inductive Loop Detector location. The ILD's collect the raw data and send it via wire line to a control box where the data are processed. The Data Processing stage involves the input of the field data measured by the road sensors. Before the raw field data can be used in a data application, or a traffic management application, they must be processed. When the sensors are ILD, raw data such as loop

ID and the times each vehicle enters and leaves the loop are sent via wire line to a control box. These raw data are processed, and often aggregated, to create more refined attribute data such as vehicle passage, presence, count, occupancy, time, and flow information.

2.1.3 Intelligent Transportation Systems And Advanced Traveler Information Systems

As suggested by the United States Department of Transportation, “Intelligent Transportation Systems” (ITS) encompass a broad range of wireless and wire line communications-based information and electronics technologies. When integrated into the transportation system's infrastructure, and in vehicles themselves, these technologies relieve congestion, improve safety and enhance American productivity (USDOT, 2007).” Advanced Traveler Information Systems and Advanced Traffic Management Systems are two examples of ITS. In the context of ITS, this dissertation is concerned with effectively designing graphics to communicate information measured by traffic management systems to travelers.

Advanced Traveler Information Systems (ATIS) are a subset of ITS. ATIS employ technology to assist travelers with planning, perception, analysis and decision-making to improve the convenience, safety, and efficiency of travel (Shekhar and Liu, 1994). Common examples of ATIS include variable message signs, in-vehicle-navigation-systems, traffic reports, and real-time traffic maps. Adler and Blue (1998) detail the gradual emergence of ATIS. Their review of research on “driver information technologies” begins in the 1950’s with research mainly focused on improving traveler

safety. Of particular interest to this research they note that “work on traveler information systems focused on using visual displays to provide drivers with traffic condition and diversion information” began with Weinberg et al., (1966), and the Highway Research Board, (1971; 1973). However, this early research into visual displays focused almost entirely on changeable message signs, and not maps.

Substantial ATIS research examines how the availability of traffic information to the driving public influences the performance of the overall system (Al-Deek and Khattak, 1998). This dissertation is less concerned with ATIS as a tool for improving the overall system performance and more concerned with ATIS as a service to individual drivers, designed to improve their confidence and reduce their environmental uncertainty. With this in mind, it is important to examine how design variables influence behavioral responses to traveler information.

2.2 Behavioral Geography And ATIS

The contributions of behavioral geographers and psychologists enable cartographers to design more effective maps. Several researchers have studied map use in a transportation context and their findings are important to this research. Golledge (2002) provides the most thorough examination of behavioral responses to Advanced Transportation Information Systems. Golledge reviews several studies by psychologists, geographers, and transportation scientists, which evaluate how travelers use external sources of information to make wayfinding decisions. Golledge (2002, pg.

83) states, “there is an emerging need to capture the representation of a transportation system in a way that reflects how people perceive it and consequently use it.” If so, cartographers can significantly enhance the effectiveness of these systems by combining perceptual investigations and cartographic principles to the graphic displays of dynamic congestion information. Recent transportation research has favored attention toward driver decisions, but little research has focused on the influence cartographic variables may have on those decisions. ATIS are targeted to assist with trip planning, selection of departure times, route choice, congestion avoidance, and to aide navigation. One goal of ATIS is to reduce driver stress and affect traffic flow by providing in-car, en route, or pre-travel information about hazards such as congestion, construction, or accidents. In this context, the general goal of this dissertation is to inform and enhance the design and delivery of map-based traveler information.

Two categories of influences affect an automobile journey, those within the driver’s control such as departure time or destination location, and those beyond the driver’s control including congestion, construction, or accidents. Traffic maps aim to improve drivers’ controlled decisions by providing them with the relevant information about things beyond their control. Fortunately, as the potential for ATIS to enhance driver behavior has become more apparent, several researchers have studied the impacts of dynamic traffic information on driver behavior. Stopher and Lee-Gosselin (1997) and Mahmassini (2002) both provide thorough reviews of this kind of recent travel behavior research.

Several works have explored humans' responses to dynamic transportation information. Although due to a lack of actual real-world ATIS implementation, many of these findings are based on simulations or Computer Process Models (CPM). The advantage of CPM tests is that they can focus research attention on normally interdependent travel behavior characteristics. Adler (1992), Chen and Mahmassini (1993), Koutsopoulos (1993, 1994), and Schreckenberg (2002) simulate drivers' responses to real-time traffic information. Each investigation notes the presence of ATIS can improve driver behavior, but to this point there is no agreement on exactly *how* access to such information will influence drivers, or the overall system.

Mahmassini (1997) found that simple strategies guide the navigational behavior of repetitive commuters. He suggests that two influences (willingness to change route/departure time, and familiarity with route and traffic conditions) determine the variability of these commuters' behavior. Interestingly, he finds that commuters have "indifference bands" that dictate their tolerance thresholds for congestion. This idea implies that commuters will accept or tolerate some amount of congestion before diverting their planned route, but only to a point. Congestion maps should inform a commuter whether or not current traffic on their route is "tolerable" in this sense; a pre-trip or en route glance at a traffic map should be able to notify the driver of whether traffic conditions are within their specific tolerance, and in turn relax the driver by reducing their environmental uncertainty. It should be noted that different individuals will have different "indifference bands" and even individual tolerances can vary significantly with time-of-day, trip purpose, etc.

The general intention behind providing travelers with external travel information is to benefit route selection and the overall performance of the system. Golledge (2002) proposes that changes in travel aimed at congestion avoidance are guided by the “type, amount, time, and reliability” of the traffic information available to drivers. This research and many other previous studies assume that since current traffic information sources are so sparse that commuters are unable to make the kinds of intelligent decisions that benefit both their travel experience and the system as a whole. Moreover, the emerging technologies capable of delivering this information to commuters must enhance the timeliness, reliability, thoroughness, and types of traffic information availability. Consequently, the role of mobile mapping as an information delivery system cannot be overlooked. A versatile, and portable system design can significantly enhance the delivery of reliable traffic information to commuters in both pre-trip and en route navigational situations.

It is dangerous for people to read maps while driving down a highway. For this reason, we need to consider other methods of information delivery. In the case of en route information delivery, voice directions are probably safer than maps. In their comparison of navigational aids, Streeter et al (1985) conclude that voice directions are superior to maps in cases where travelers are navigating through unfamiliar environments. The disadvantage of voice directions involves inefficiency. Golledge (2002) points out that since vision is the most powerful sense, a graphic communication of location and environment is more efficient than a verbal one. He notes that a map-

reader can understand his place in a quick “glance” while a verbal description of place could take many sentences. Tversky (2002) cites the advantage of the congruence principle of graphics, which states that the content and format of the graphic should correspond to the content and format of the concepts to be conveyed. In this regard (and considering the power of vision), maps, offer more congruent depictions of the visual environment. The congruence principle might also help explain the emergence of oblique perspectives within in-car-navigation-systems. Regardless, a complete traffic information delivery system should provide both graphic and verbal capabilities.

Given that people are beginning to read small digital maps more frequently as they drive, it is important to consider driver workload research. In the context of ATIS, Dingus and Hulse (1993), as cited in the FHWA report on ATIS guidelines (FHWA, 2007), suggest that driver attention should be concentrated on the road as much as possible and that “in-transit” functions of ATIS and IVNS should be limited to those functions that:

- Do not significantly interfere with the driving task.
- Have convenience benefits that outweigh the cost (i.e., required driver resources) of including the function.
- Will be used relatively frequently.

They go on to report that provision of relevant congestion information meets these criteria. Therefore, it is imperative that sufficient thought and design inform the presentation of congestion information so that the benefits of congestion knowledge

can outweigh the costs of driver distraction. Intelligent cartographic design can enhance the efficiency of the delivery of congestion information therein both enhancing the benefits of its presentation while also reducing the costs of driver distraction. This idea relates to recent cartographic research focusing on “perceptual salience.” Lowe (1999) has found that some map-readers extract information based on graphic prominence (perceptually salient) more than they do on thematic relevance. Similarly, Fabrikant and Goldsberry (2005) found that adjusting cartographic variables can significantly alter the output of predictive visual attention models, such as the Itti model (Itti and Koch, 2001). The Itti model strives to identify the focal locations of mammals or robots based on parameters such as color hue, color value, and orientation contrasts at various image scales. It is important to note that these results are limited to computational model output and exclude the enormous influence of cognition on viewing behavior. Nonetheless, poor map designs can increase driver distraction by increasing the time costs of “in-transit” functions such as route selection.

Previous research has studied how and why people choose routes. Econometric models suggest that people often choose routes based on minimal cost strategies. These costs often include, time, distance, or money. Many current routing algorithms, such as the Dijkstra algorithm (Dijkstra, 1959), are based on minimizing costs. Unfortunately, realistic human behavior is often not so simple. Saisa and colleagues (1985) found that this sort of algorithmic behavior is not actually common, and that econometric models of route choice are usually overly simplified. Furthermore, influences such as trip purpose and individual differences have repeatedly been shown

to be major contributors to human routing behavior. Golledge (1995) demonstrates an individual's path selection criteria varies dependent of their trip purpose and their environmental conditions. Current incarnations of ATIS are not sensitive to these influences, and instead offer only simplified routing strategies.

If users disagree with, or have a negative experience with, the embedded routing strategies in an ATIS, there is a danger that they will distrust the system as a whole. Considering the diverse influences of trip purpose and individual differences it may be wise to not include routing strategies in an ATIS. In a system absent of routing algorithms, the information provision becomes the major attraction and the application of this information toward routing is left solely to the user. This design assumes that a user familiar with both his environment and current traffic conditions is capable of making appropriate routing decisions compatible with his comfort and his current trip's purpose. This design could be seen as either respectful of individual and trip purpose differences or as an incomplete system.

In essence this research is concerned with improving travel behavior under variable obstruction conditions. Sometimes roads are blocked, other times they are not. When a traveler is faced with an obstruction, a decision-making process begins. What is the role of ATIS in this decision process? Golledge (2002, pg.110) suggests that an "ATIS should be designed to quickly provide information such that this new decision process does not become onerous." Sholl (1987, 1996) finds that temporary obstructions, such as congestion, represent a gap in an individual's cognitive map; the role of an ATIS

might be to provide relevant information that fills that gap in the user's cognitive map. Furthermore, since Golledge also notes that visual representations are quicker information providers than their auditory counterparts, there must certainly be a role for a well-designed traffic graphic in the decision support functions of an ATIS. If the inclusion of dynamic traffic maps is justifiable, then the next step involves map design.

Too often the demand side of traveler information is neglected for the supply side. In other words the development of ITS, ATIS, and other transportation resources is often done irrespective of important human travel behavior findings. The state of current online dynamic traffic maps also reflects this neglect. For example, the design of the current maps is often based solely on literal representations of the data collection infrastructure. Sigalert.com's Los Angeles map (figure 3) consists of colored dots at sensor locations. The color hue reflects the speed (or the density) that the sensor is currently reporting. The design of the map does not attempt to answer Golledge's call to "represent the transportation system in a way that reflects how people perceive it and consequently use it (2002, pg. 83);" instead it simply presents a literal graphic report of the data collection.

2.3 Map Design And Human Travel Behavior

One core finding in this dissertation is that cartographic design decisions can influence human travel behavior. Unfortunately, to this point not enough research has explored this influence. Three important exceptions are studies by Yarnal and Coulson (1982), Soh and Jackson (2004) and Dilleuth (2005). Each of these studies examines

variability in human travel behavior under a variety of map design conditions. Furthermore, each study illustrates the influence of map design on human navigation.

Yarnal and Coulson (1982) studied three design conditions for Canadian trail maps. Their project investigated how varying trail map designs would influence navigation in a hiking context. The study involved two groups of hikers using a different trail map design; one group used a black and white design, while the other used a colored map that employed hue to differentiate kinds of feature classes (e.g. blue for water, red for trails). Among other findings, Yarnal and Coulson discovered that hikers given the color map used significantly more trails, and hiked for longer durations than their (black-and-white) counterparts.

Soh and Jackson also isolated design variables in a trail map context. Their experiment measured the influence of various terrain representation strategies, including contour lines and shaded relief. Subjects followed trail routes on the maps, and upon completion filled out questionnaires pertaining to the maps. Notably, Soh and Jackson's findings suggest that map design needs to account for different approaches to wayfinding. Their experiment reveals a large amount of individuality when it comes to using marks on a map assists in navigation. For example some individuals rely heavily on estimated distance while others rely more on elevation changes, or other landmark identification strategies. Map designers cannot ignore these differences in wayfinding strategies; a versatile map design needs to accommodate an extremely diverse set of wayfinding techniques.

Dillemuth (2005) further demonstrates map design's influence. Dillemuth examined the specific influence of cartographic generalization on map interpretation and subsequent behavior. Subjects attempted to follow pre-defined routes using mobile digital maps as navigational aids. There were two main design conditions: an aerial photograph, and a more generalized vector-based map. Dillemuth found that this conditional variation "resulted in significant differences in subject performance as related to time to route completion (the generalized map was more efficient than the aerial photograph), amount of zooming (more with the aerial photograph) and number of different zoom levels (more with the aerial photograph), and number of stops subjects made while on-route. Such differences illustrate the importance of appropriately designed maps for mobile devices (Dillemuth, 2005, pg. 86)."

Elsewhere, in a less cartographic context, other research demonstrates the influence of design on human travel behavior. Chrysler et al. (2007), reports on human responses to various approaches to diagrammatic freeway guide signs. The research compares text-based cues versus diagrammatic cues for highway exits, and highway splits. "Results showed that for the left exits the standard text-only signs performed equal to or better than the diagrammatic signs. This performance was true for left lane drops also. For the right exit with optional lane, the standard text signs did well, as did the diagrammatic signs. For freeway-to-freeway splits, standard text signs with two arrows over the optional lane performed better than either style of diagrammatic sign (Chrysler, 2007, pg 34)." This sign-based research presents more strong evidence that design can

steer highway behavior, and should inspire more user-centered design research to ensure wise design.

2.4 Related Cartographic Research

This dissertation is greatly influenced by the last 50 years of cartographic research. This section highlights the most important contributions of cartographic research that have particularly influenced this project.

Many chronicles of cartographic research contributions rightly begin with Robinson's *The Look of Maps* (1952). Prior to his academic career, Robinson practiced cartography in the United States military, where he directed the map division at the United States Office of Strategic Services (OSS). *The Look of Maps*, Robinson's map-less map book was largely culled from his PhD research at Ohio State University; Robinson finished his PhD in Columbus in 1947. The importance of Robinson's subsequent career as a professor of Geography at the University of Wisconsin can hardly be overstated. It is easily argued that his appointment, and research avenues blazed the trail for many of the contributions that in turn directly influenced this dissertation.

From Robinson's obituary, published November 15, 2004 in the New York Times:

In 1963, Dr. Robinson devised his own map projection. He had been dissatisfied with existing projections since his experience as director of the map division of the Office of Strategic Services in World War II.

"I started with a kind of artistic approach," Dr. Robinson said in a 1988 interview in *The New York Times*. "I visualized the best-looking shapes and sizes. I worked with the variables until it got to the point where, if I changed one of them, it didn't get any better."

As Robinson's contributions relate to this dissertation, one of his core assertions stands out: the idea that a map's performance should be measured by the success of its beholders. This was a new idea in the 1950's, and was directly contradictory to the conventional, more "artistic" views of that time. Robinson writes:

"The assumption that effective cartographic technique and its evaluation is based in part on some subjective artistic or aesthetic sense on the part of the cartographer and map reader is somewhat disconcerting. For example, E. Raisz claims that the "effective use of lines or colors requires artistic judgment," and J.K. Wright explains that the suitability of a symbol "depends on the map maker's taste and sense of harmony." Throughout the literature there are numerous assertions regarding the assumed subjective aesthetic and artistic content of cartography."

"There is also considerable tendency to define the subject as a kind of meeting place of science and art. This is exemplified by Eckert. He pleads for artistic imagination and intuition in cartographic portrayal and claims that the inter-action of such talents with scientific geography produces the aesthetic map. There is no question about the importance of imagination and new ideas, but it is equally important that significant processes be objectively investigated, whether it be the visual consumption of a graphic technique or a

process in geomorphology. It can perhaps best be approached by a comparison of the aims, techniques involved, and the results accomplished by each activity. (Robinson, 1952, pg. 16-17)”

Previous to the look of maps, many prominent cartographers offered much more subjective theories of map success. Notably, Raisz, famous for his realistic depictions of terrain, and Eckert both suggested that cartographic success was mostly dependent on the eye of the cartographer. Robinson, on the other hand, advocated a more objective (user-friendly) approach steeped in empiricism and scientific demonstration. The resulting stream of empirical cartographic experimentation produced several lasting cartographic guidelines and principles. Robinson helped initiate university-based academic cartography at American research universities. He led a movement to replace old-fashioned artistic assertions with empirically based justifications; Robinson’s call for empirical cartographic investigations has been answered, as seen in the work of dozens of subsequently influential researchers.

“The Look of Maps put forth the proposition that the function of maps is to communicate with people. This function depends on the visual appearance of map, and this appearance, in turn depends on explicit and implicit decisions made by mapmakers. So to understand and to improve map function, cartographers need to understand the effects of design decisions on the minds of map users (Montello, 2002, pg. 285).”

In the 1950's cartographic research became more scientific and less artistic; important research followed closely behind Robinson's lead. Flannery (Robinson's graduate student at the University of Wisconsin) and Robert Williams (Erwin Raisz's graduate student at Harvard) concurrently investigated the perception of geometric shapes as map symbols. Flannery (1956) used concepts from psychophysics to empirically uncover, and account for, perceptual errors relating to humans' estimation of the areas circular symbols. Williams' 1957 dissertation was called "Statistical symbols for maps: Their design and relative values." Similarly, Waldo Tobler's (1957) masters' thesis empirically evaluated hypsometric colors on terrain maps. These serve as early precedents employing a more scientific approach to map design research.

2.4.1 Analytical And Computer Cartography

"The quantitative revolution" also began in the 1950's. Geographers began to experiment with computers and computational algorithms to automate cartographic operations. Clarke (1990) details the emergence of computational cartography in the United States, and cites Tobler (1959) as the forerunner: "Computer cartography in the United States really dates back to a single article written by a graduate student at the University of Washington, Waldo Tobler. The paper "Automation and Cartography," was published in the Geographical Review in 1959 (Clarke, 1990, pg. 5)."

The development of computer cartography continued throughout the 1960's, taking place mostly at universities, and in government agencies. Two significant developments

in computer cartography occurred in the 1960's. First, The Canadian government launched a new program to catalog, and organize large amounts of land use data. The program became known as the Canadian Geographic Information System, and its leader, Roger Tomlinson is credited with coining the (unfortunate) term "Geographic Information System (GIS)." Secondly, in 1964 Howard Fisher started Harvard's Laboratory for Computer Graphics and Spatial analysis; this led to the development of seminal "GIS" software including: SYMAP, GRID, and ODYSSEY. In 1969, one of the participants in the SYMAP project, Jack Dangermond, started the Environmental Systems Research Institute (ESRI). Computer cartography had become "GIS" – whatever that is.

2.4.2 Relevance And Geographic Information

The relevance of the geographic information stored within a map directly relates to the usefulness of that map. "The assessment of the relevance takes place in the information use, i.e. the utility of the retrieved information for the situation at hand (Reichenbacher, 2005, pg.1)." In the case of repetitive urban drivers and maps, the utility of a static paper road map is minimal. What kind of map would be relevant? According to relevance theory, geographic information is relevant when it makes a worthwhile difference to the individual's cognitive map (Wilson and Sperber, 2004). The everyday commuter's cognitive map includes familiarity with his local transportation network and perhaps some ideas about traffic congestion. Raper (2001, pg. 43) contends, "GI can be evaluated at a relevance level where the informativeness

and usefulness of the GI can be assessed through the extent to which it enriches the user's cognitive environment." Furthermore, the extent to which the representational content is informative and relevant to the user is the most fundamental level at which to consider the communication of information (Wilson, 1999). Dervin (1983) suggests that information helps make sense of the world by filling the gaps in our cognitive environment. Given its often unpredictable, and dynamic nature, traffic congestion represents a gap in a driver's cognitive environment; real-time traffic maps can fill this gap by providing information directly relevant to individual drivers. In this sense, the addition of traffic information can make the street map relevant again to everyday drivers. Fortunately, the Internet and the World Wide Web enable cartographers to now distribute more relevant geographic information.

2.5 Maps And The Internet

Clarke (1990) describes the phenomenon of early Internet maps: "consider the daily weather maps distributed by NOAA over the computer networks. Every hour, a new image of North America, admittedly at low resolution but showing up-to-date atmospheric conditions, is posted on the Internet (Clarke, 1990, pg. 9)." Since then, drastically decreased computing costs have enabled billions of computer users worldwide, and the World Wide Web exploded in popularity. In 1993 the world contained 130 web servers, by January 1999 this number climbed to 43.2 million web servers (Peterson, 2003). In 2007, the World Wide Web is the dominant cartographic medium. Although the exact number of maps communicated via the World Wide Web

is hard to estimate, in 1999, MapQuest.com responded to an average of six million requests per day for user-defined maps (Peterson, 2003).

Recent developments in wireless networking, and mobile computing are pushing the emergence of Internet cartography toward a broader array of devices. An increasing amount of PDA's and in-vehicle-navigation-systems offer an important portable digital medium for Internet cartography. These devices are increasingly being connected to the Internet, leading to what is sometimes called "telecartography" or "ubiquitous cartography." These devices are characterized as having small display sizes, and a diverse display capabilities relating to pixel resolutions, color depth, and contrast/brightness limitations (particularly in outdoor viewing situations). Designing maps for this evolving medium is difficult; the designs must adhere to the strange constraints associated with low-bandwidth wireless networks as well as tiny display sizes.

The World Wide Web enables easy distribution of digital maps to billions of potential map-readers. Since the popularization of the Internet in the 1990's billions have maps have been designed for, and shared via the world wide web. Peterson (2003) provides the most thorough review of the emergence of web cartography. The book summarizes conceptual issues such as the cultural effects of web cartography, as well as technical issues such as Internet protocols and file formats. Peng and Tsou also provide a thorough overview of Internet-based "GIS," in their 2003 book aptly titled, "Internet GIS." In the foreword of "Internet GIS," Goodchild notes that Internet GIS

can reduce the significant impediments previously associated with “searching, discovering, retrieving, and reformatting” GIS data sets. Indeed, as it relates to the discovery and retrieval of real-time traffic data for Los Angeles, this research project would be impossible without the recent rise of Internet GIS.

While the preceding decade has witnessed the rapid rises of mobile telephones and the Internet, the next decade will likely witness the confluence of these technologies. The rapidly increasing availability of wireless Internet in more and more places, will make the exchange of digital information even easier than it is now. As the Internet increasingly reaches our phones, and our cars, cartographers have to respond. Clarke (2004, pg. 134) suggests that mobile mapping may represent the “next paradigm in cartography and geographic information science.” Goodchild et al. (2004) also note that a research agenda for mobile mapping is an important component within the future directions of geographic information science. Designing maps for new media is one of the perpetual challenges in cartography. In particular, mobile cartography presents two challenges: it is very difficult for conventional map design, and its depiction strategies, to effectively transition to the small displays currently associated with most mobile devices. The second challenge relates to the mobile user; map designs, and interfaces that are suitable for stationary map users equipped with larger displays, may not be suitable for multi-tasking (driving, walking) mobile map users (Clarke 2001). Reichenbacher (2001) illustrates the basic ideas of mobile cartography, identifies a framework of basic user tasks, and models user contexts within mobile cartographic

settings. The paper also offers an important early demonstration of the flexibility associated with vector graphics formats as it pertains to mobile mapping.

2.6 SVG And Maps

The map design methods included in this dissertation employ Scalable Vector Graphics (SVG). SVG is a World Wide Web Consortium (W3C) recommended standard file format for web graphics and content. SVG is based on extensible markup language (XML) and is “data-driven”. In other words the information contained in a SVG file is decoded by the web-browser on the user’s end to render graphics. SVG applications can populate SVG files with information from streaming databases and a web browser can quickly present that information graphically online. SVG is adopted for three main reasons:

- 1. Vector capabilities** – SVG files are crisper than their image-based counterparts. SVG allows zooming in on graphics without loss of quality. This quality is especially important for map applications. In a GIS context, Tomlin (1990) famously wrote: “Yes raster is faster, but raster is vaster, and vector just seems more correcter.” The ongoing debate remains heated in the GIS community, but with the superior graphical clarity and “zoomability” associated with vector graphics, when it comes to Internet mapping applications, vector formats are usually more desirable.

2. Small file sizes – SVG files are small relative to other display formats. File size is especially important in wireless mobile environments often characterized by low-bandwidth availabilities.

3. Display versatility – SVG files scale to display clearly on mobile devices with diverse screen sizes, pixel resolutions, color depth, CPU power, and memory. These devices include cell phones, PDA's, and In-Car Navigation displays. These kinds of severe display constraints quickly reveal many shortcomings of the raster-based alternatives, especially illegibility.

Until 1999, it was mostly impossible to render vector graphics on the world wide web. As a result the application of vector-graphics and especially SVG to Internet-mapping applications is a recent phenomenon, and remains much more common in Europe than it is the United States. This is unfortunate; delivery of high-quality, sleek vector cartography to the Internet continues to be difficult, and SVG reduces this difficulty. The most common format for the creation of vector-based Internet maps is Flash, a proprietary format begun by Macromedia, now owned by Adobe. Unlike Flash, SVG is open-source, although many prominent graphics-software development companies (Adobe, Apple, IBM, Kodak, Microsoft, Sun Microsystems, Xerox, and others) have helped shape its development. Neumann and colleagues (2005) outline the advantages of SVG for Internet mapping:

“[SVG] opens ways for cartographers to concentrate on content delivery and interactions, still typical with monitor cartography. But with SVG, not only the

visualization is optimized – SVG is an open, object-oriented file-format (not a software!). It is completely based on the XML model. This guarantees a solid and long-term embedding into web-environments and compatibility to other data formats. Thanks to the object-hierarchy it is possible to implement all possible interactions.”

In summary, this dissertation adopts SVG for three core reasons: it is clean and legible, it results in compact file sizes, and this research represents an important test for the feasibility of SVG to facilitate a real-time mapping project. Another goal of this dissertation is to further demonstrate (especially to Americans) that SVG is among the cheapest, most versatile options for Internet cartography.

2.7 Online Traffic Maps

Although, to this point there has been no through examination, some recent cartography and GIS texts have mentioned real-time traffic maps. Usually, these mentions are brief (Miller and Shaw, 2002; Monmonier, 2002; Kraak and Brown, 2000; Peng and Tsou, 2003) and merely overview the status quo of current applications. To this point very little cartographic or GIS research has pointed directly toward the role of maps in ATIS. Furthermore, virtually zero cartographic research has focused specifically on the design of real-time congestion maps. One exception is Summers and Southworth (1998), who speculate on the generation “human-friendly, path-based representations” of real-time network conditions on-the-fly from dynamically updated databases. Summers and Southworth (1998) also suggest that the manner in which

traffic information is supplied to ATIS customers will have influence on its perceived value.

Although it is unclear exactly when the first real-time traffic map arrived on the Internet, trends point to a rapid increase to their prevalence. Goldsberry (2005) inventories the status of real-time traffic maps, examines design approaches, and suggests cartographic improvements. Since then traffic maps have become even more popular. Most notably, in 2007, Google maps added traffic information to its immensely popular Internet mapping application. Users of Google maps are now able to not only route between any two addresses in the United States, they are now able to glimpse at current traffic conditions along their prospective route. As of May 2007, Google Maps' routing engine does not include real-time traffic as a parameter in its routing algorithm, but other services including the somewhat popular software, TeleAtlas are beginning to include current highway velocity as a routing parameter.

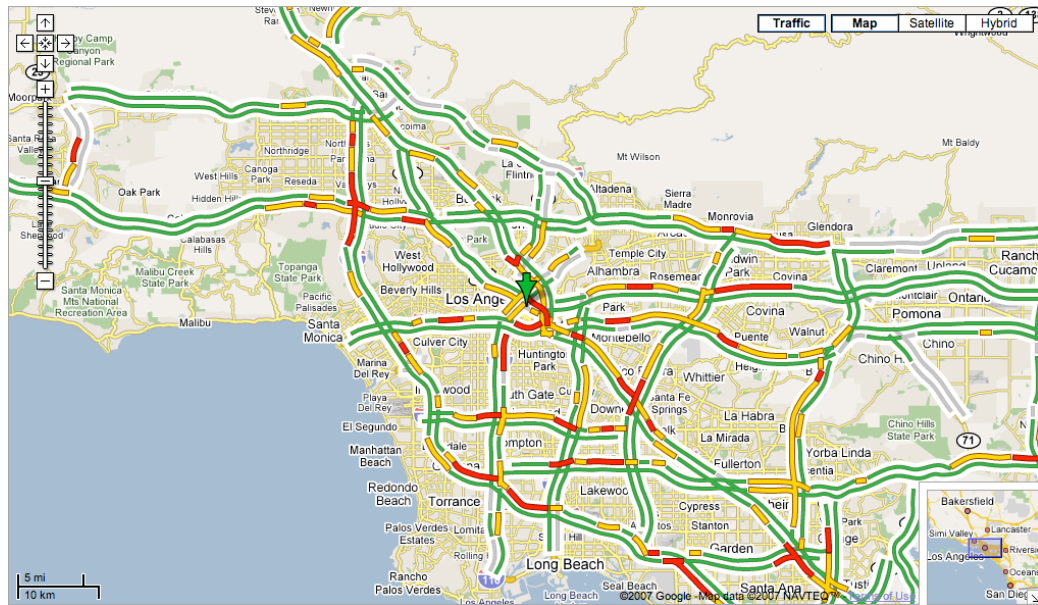


Figure 2: The new, as of 2007, traffic information available within the Google Maps Application. Data is available for several cities in the United States. Unfortunately, the map suffers from common traffic map shortcomings, including: no legend to decode the symbology, obscuring relevant base data with traffic symbols (in this case highway labels), and the misuse of color hue to represent a unipolar quantitative statistic (velocity). Nonetheless, the inclusion of traffic information in one of the more popular web-atlases represents a significant leap for traffic mapping.

These current developments indicate an exciting future for traffic mapping, but it's also important to review the diverse approaches to mapping congestion as a way to inform future designs. Current maps are strikingly inconsistent, and this inconsistency is a clear indicator of a lack of design principles for online traffic mapping. The following section reviews some current traffic maps, as well as their approaches to cartographic design in order to unveil the fundamental design variables associated with real-time

traffic maps. Below, several maps are presented and captioned; each caption includes a profile describing the map's statistical level of measurement, classification scheme, and color scheme.

Los Angeles, California, USA

Author: Sigalert.com

Level of Measurement: Ratio (miles per hour)

Number of Classes: 4

Severe traffic range: 1-14 mph

Color Scheme: Hue-based, stoplight metaphor with an added blue hue between yellow and green.

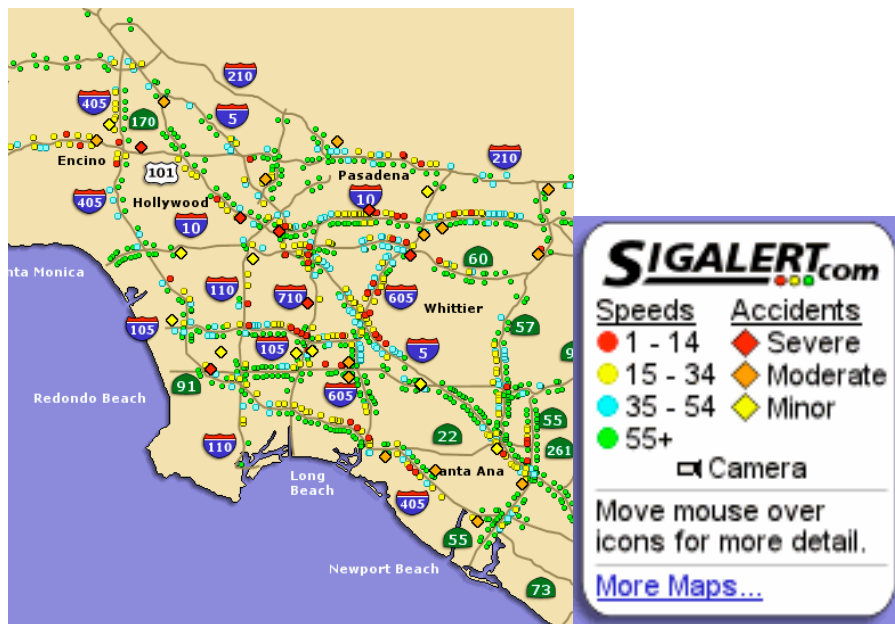


Figure 3: Traffic Map for Los Angeles, California

San Francisco, California, USA

Author: 511.org

Level of Measurement: Ordinal

Number of Classes: 4

Severe traffic term: Stop and Go

Color Scheme: Hue-based, stoplight metaphor with an added black hue to symbolize the most severe congestion group.

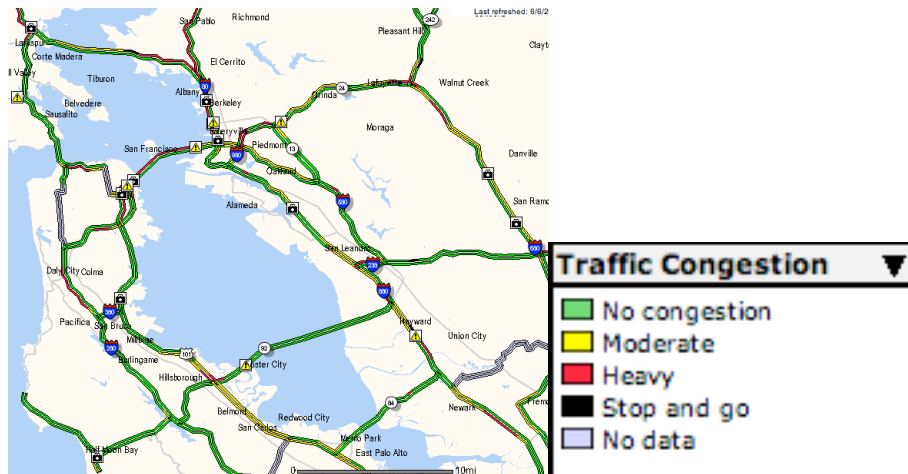


Figure 4: Traffic Map for San Francisco, California

Portland, Oregon, USA

Author: Oregon Department of Transportation

Level of Measurement: Ratio (miles per hour)

Number of Classes: 3

Severe traffic range: 0-25 mph

Color Scheme: Hue-based, stoplight metaphor.

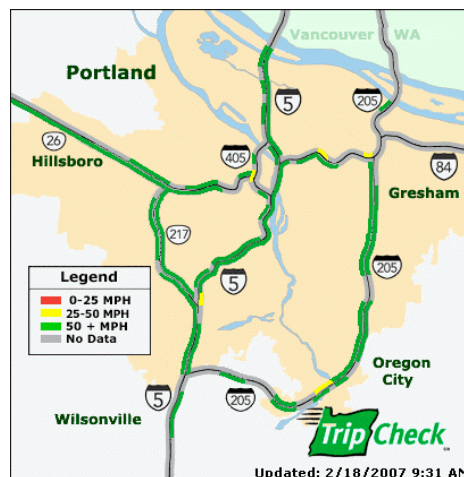


Figure 5: Traffic Map for Portland, Oregon

City: Houston, Texas, USA

Author: Transtar.com

Level of Measurement: Ratio (miles per hour)

Number of Classes: 5

Severe traffic range: 0-20 mph

Color Scheme: Hue-based, stoplight metaphor with an added orange hue between red and yellow, and an added blue hue between yellow and green.

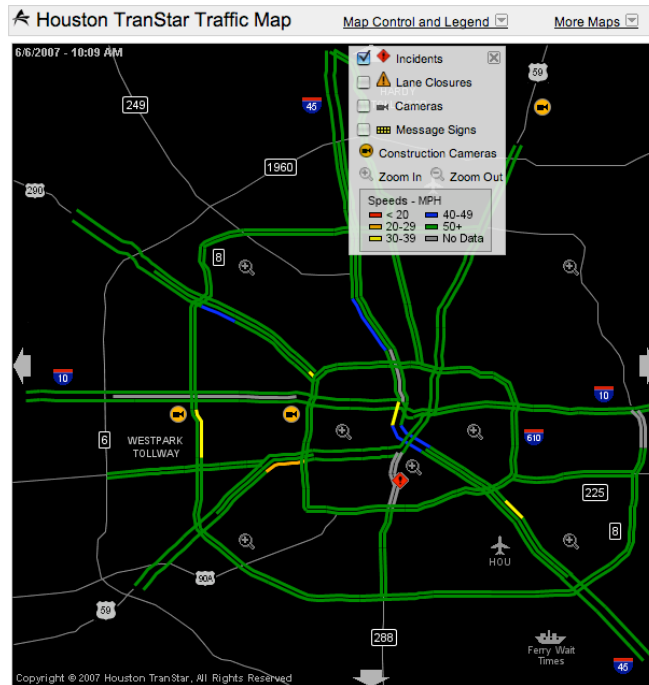


Figure 6: Traffic Map for Houston, Texas

City: Paris, France

Author: Sytadin.tm.fr

Level of Measurement: Ordinal (miles per hour)

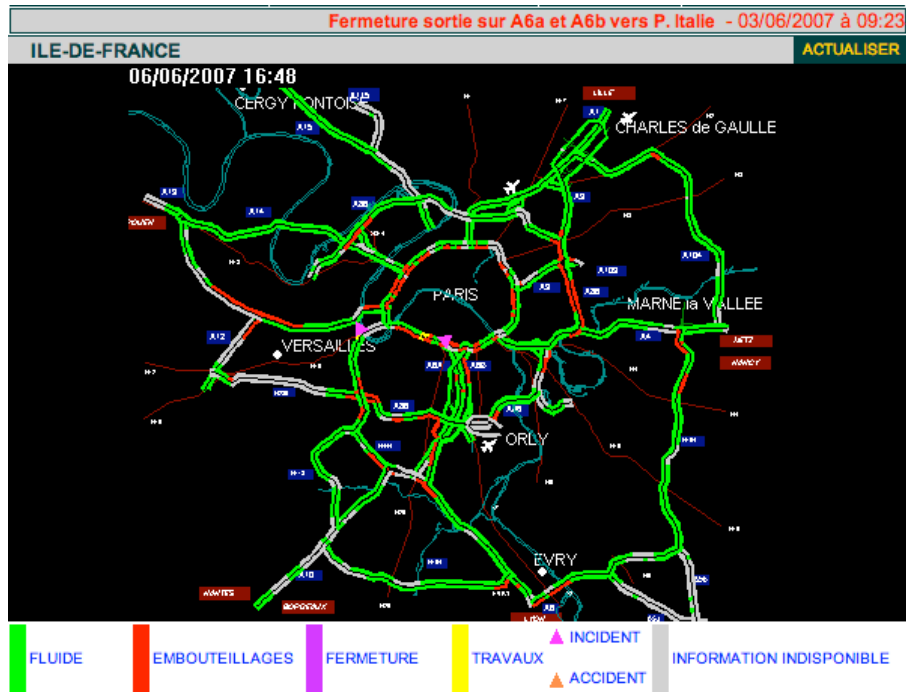
Num

ber of Classes: 2

Severe traffic term: “Embouteillages” (congestion)

Color Scheme: Hue-based, stoplight metaphor,

Translation: Travaux - “work”, Fermeture - “closings”, Fluide – “fluid”



City: Athens, Greece

Author: National Technical University of Athens, Department of Transport Engineering

Level of Measurement: Ordinal

Number of Classes: Unclassed

Severe traffic term: “High”

Color Scheme: Hue-based, spectral: green to red

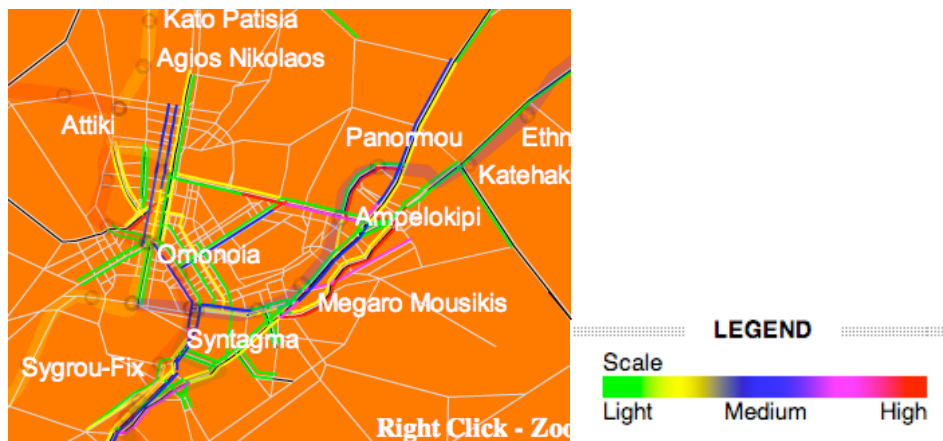


Figure 8: Traffic Map for Athens, Greece

City: Zurich, Switzerland

Author: Zuerittraffic.ch

Level of Measurement: Ordinal

Number of Classes: 3

Severe traffic term: “Stau” (back-up)

Color Scheme: Hue-based, stoplight metaphor

Translation: Frei – “free”, Behindert – “obstructed”, Stau – “back-up”

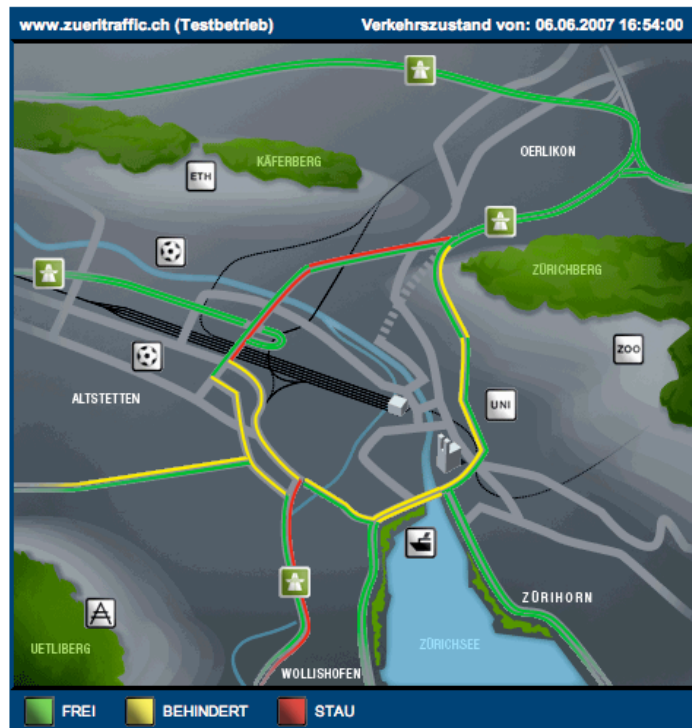


Figure 9: Traffic Map for Zurich, Switzerland

City: Barcelona, Spain

Author: Ajuntament de Barcelona

Level of Measurement: Ordinal

Number of Classes: 5

Severe traffic term: “Congestio”

Color Scheme: Hue-based, stoplight metaphor, with added blue hue to indicate the most fluid conditions, and an added orange hue between yellow and red.

Translation: Molt Fluid – “free”, Fluid – “obstructed”, Dens – “back-up”, Molt Dens – “”, Congestió – “Congested”

Estat del trànsit

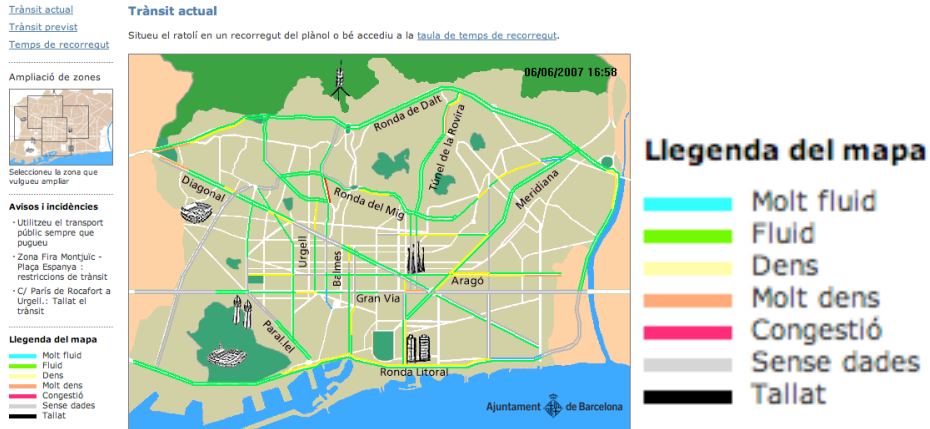


Figure 10: Traffic Map for Barcelona, Spain

City: Toronto, Canada

Author: City of Toronto

Level of Measurement: Ordinal

Number of Classes: 3

Severe traffic term: “Very Slow”

Color Scheme: Hue-based, stoplight metaphor

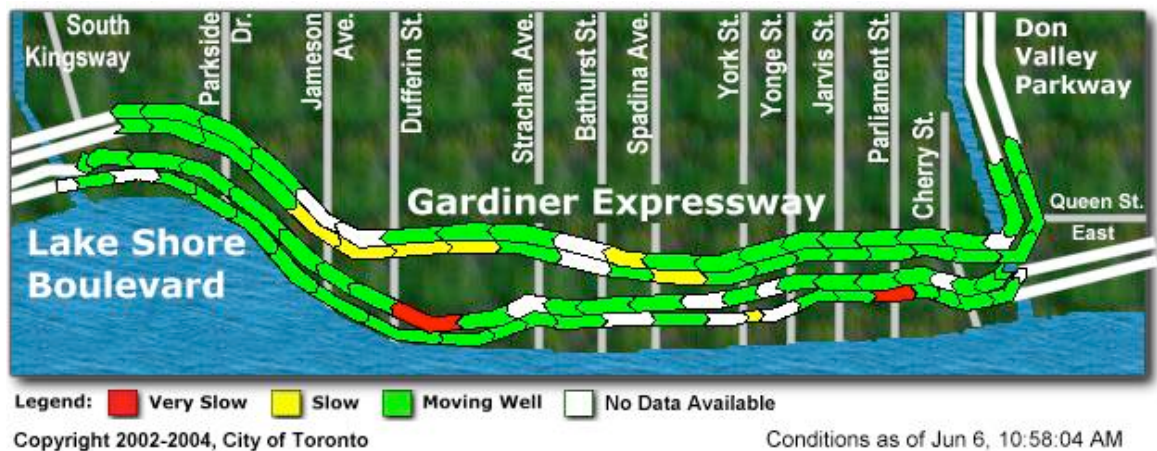
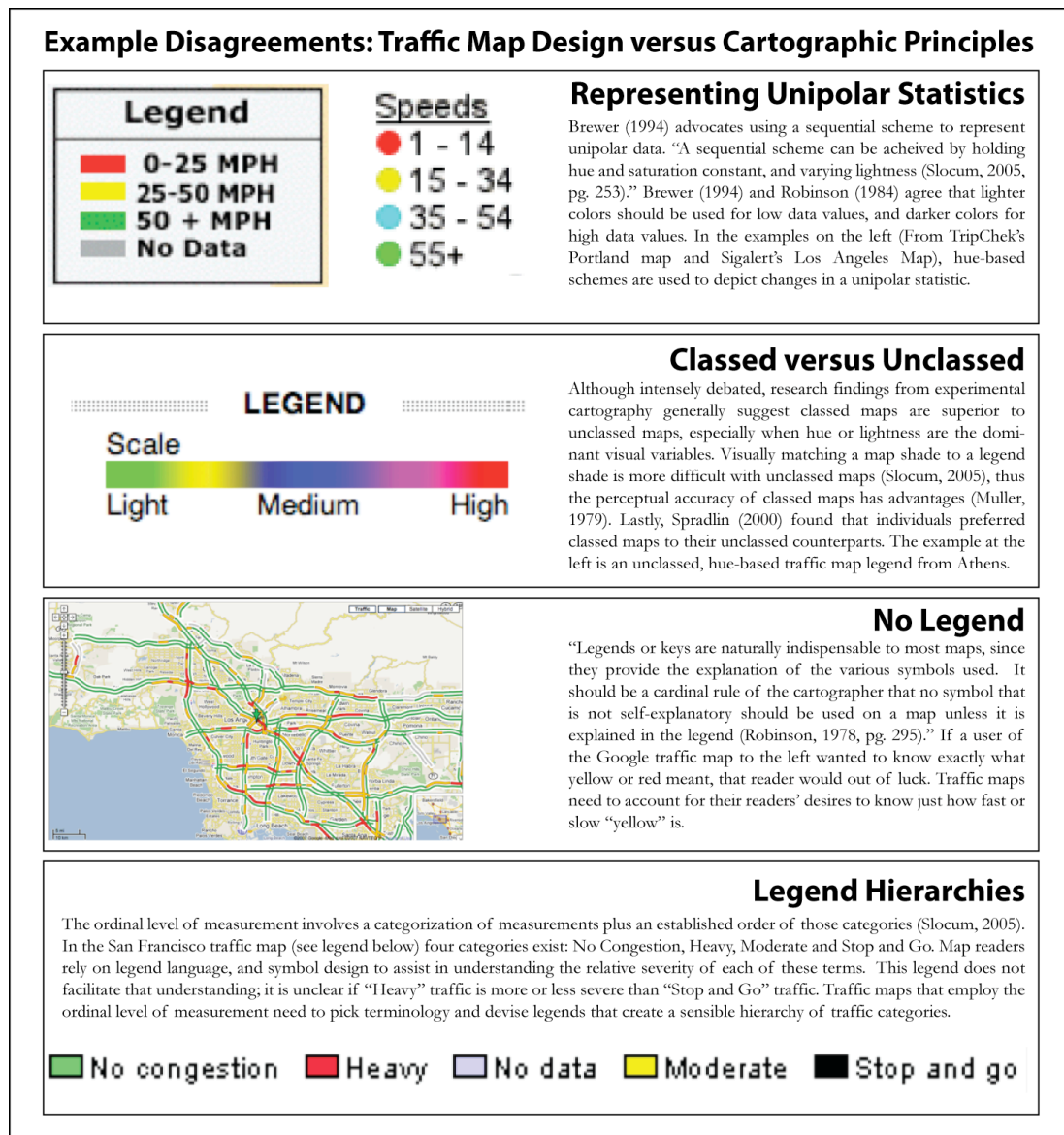


Figure 11: Traffic Map for Toronto, Ontario

2.7.1 Traffic Maps and Cartographic Guidelines

Many of the preceding example of traffic maps do not adhere to cartographic guidelines. This section includes examples of instances in which traffic map design decisions have been inconsistent with established cartographic guidelines; figure 12 summarizes these instances.



2.8 Design Issues With Traffic Maps

Traffic maps are a unique combination of thematic maps and reference maps. Traffic map-readers will make wayfinding decisions based on two sets of information, the thematic traffic statistics and the reference street/highway network. The cartographers designing traffic maps have to balance the figure-ground relationship between the traffic symbology and the base data. It is the interaction of these two layers that provides decision support for the map reader. In the above maps there is a lot of diversity, especially as it relates to the design of the traffic symbology. The next section outlines the main design decisions that have critical influence on the depiction of velocity data within traffic maps.

2.8.1 Point Symbols Versus Segment Symbols

The first main decision is a question of cartographic representation. Velocity data is almost always measured at points along a network (usually by Inductive Loop Detectors). Despite this point-based measurement strategy, for the sake of clarity most traffic maps represent these measurements using segments; each detector influences a surrounding segment of the highway. The alternative strategy, as seen in Figure 3, simply depicts velocity values at dots corresponding to each detector location. This, although fiercely loyal and accurate, results in a crowded graphic with countless dots about intricate network links; this is especially problematic at or near complex interchanges, features that are intrinsically related to, and often the cause of congestion.

Therefore, again evidenced by the above maps, the more popular strategy involves assigning a segment of influence to each detector. Although countless interpolation techniques are available, most maps simply assign this area of influence by dividing the space between detectors in half so that each detector's influence spans the segment connecting the point halfway between the detector to the point halfway between the detector and the next detector in front of it. In a less popular alternative segment-based approach, a detector's influence spans from its own location to the location of the next detector down the road. In either segment-based approach the segment itself becomes the symbol. The appearance of that symbol is determined by the subsequent decisions involving classification and symbolization.

2.8.2 Classed Versus Unclassed

The classification debate has resulted in many publications in cartographic journals. Notably, an early set of discussions in the 1970's, surrounding choropleth map design, explored classed maps versus their unclassified counterparts. Tobler (1973) introduces the idea of unclassified choropleth maps. This introduction was greeted immediately by Dobson's (1973) rebuttal, and thus began a series of ongoing explorations into the influences, justifications, and intrinsic errors of class intervals. Generally speaking, unclassified statistical maps attempt to link a visual variable (size, hue, saturation, etc.) associated with a map symbol to match proportionally with the measured statistical value for each geographic unit of measurement. This technique is most successful when the geographic units are modeled as points, and the visual variable, size is adjusted

relative to some quantitative statistical value, resulting in the very popular “proportional symbol map.” Similarly, wind maps commonly relate the visual variables “orientation” and “size” to create vectors depicting the magnitude and directionality of winds.

The Athens traffic map, in figure 8, is perhaps the world’s only unclassed traffic map; the map uses proportional variations of hue (rather unsuccessfully) to depict automobile velocity. This is problematic for a few reasons. First it violates the cartographic principle stating that the visual variable hue should not be used to depict differences in quantitative measurements. Secondly, one reason size-based proportional symbol maps are sometimes deemed superior to their classed counterparts is that readers’ can easily extract actual data values by measuring a symbols area is relating it legend symbols. With hue or lightness this advantage is virtually lost. Third, the limitations associated with both the human-perceptual system as well as output devices such as monitors or printers (Brewer and Pickle, 2002) essentially create classes on their own. In the realm of traffic maps, this third reason is particularly pertinent. In the emerging era of ubiquitous computing, map-readers are likely to view traffic maps on a diverse array of mobile devices often characterized by limited color depth, brightness, and contrast abilities. Unclassed maps place an increased burden on the map-reader, and the weight of this burden increases when compounded by the limitations of mobile map-reading. This added burden is minimized when quantitative data is broken up into groups, therein limiting the number of symbols a device (printer, monitor, PDA, etc.) must render, and a reader must differentiate and understand.

2.8.3 How Many Classes?

When creating a classification scheme for a traffic map, a primary decision involves selecting how many classes will exist on the map. In other words, how many groups will the velocity data be divided into? To be loyal to the stoplight metaphor, the map would have three classes, fast (green), medium (yellow), and slow (red). Previous research (Miller, 1956; Cromley, 1995) endorses five to seven classes for a static choropleth map, and two to three classes for dynamic maps (Harrower, 2003). In the above examples, the number of classes ranges from 2 (the Paris map) to 5. No research has ever asserted that there is a consistently optimal number of classes applicable for thematic maps. This dissertation investigates the role of classification, including the number of classes, on the perception of traffic maps.

2.8.4 Where To Place The Breaks?

There are seemingly countless algorithms and approaches to assist cartographers in dividing a data set into classes. As cartographers have sought scientific reasoning behind thematic map design, these classification techniques have appeared in scores of publications. Jenks and Caspall (1971) offered a seminal early investigation into the influence of classification on static choropleth maps. But despite 35 years of research and thorough reviews of this research (Evans, 1977; Brewer and Pickle, 2002; Slocum, 1999), the selection of class intervals remains a murky subject. Similar to the selection of the number of classes, there is no “be-all, end-all” method for the selection of a method to place class divisions. Perhaps the best advice relating to traffic data comes from

Cromley (1995), who suggests that exogenous class breaks are best for map series'. "Exogenous classes are determined using criteria relevant to the data topic, but external to the examination of the data distribution (Brewer and Pickle, 2002, pg. 664)." Exogenous approaches have two advantages over "data-distribution-based" approaches: they facilitate the creation of a "matched legend" (A matched legend is simply a consistent legend that applies to multiple maps) and they enable the cartographer to place class breaks at meaningful locations. Applying a data-distribution-based method such as quantiles or nested means classifications to a streaming data set causes dynamic class breaks. In other words, since the data set is perpetually evolving over time, a quantile-based scheme would result in a legend with perpetually shifting class breaks. Previous research has suggested this phenomenon hinders the accurate identification and/or comprehension of trends within geographic data sets (Dixon, 1972).

Exogenous classing methods may be superior to data-distribution-based methods for classification of streaming traffic data sets because they produce more simple, and more meaningful legends. Exogenous classification places the onus on the cartographer to make sensible "manual" class breaks. Since exogenous classes are determined using criteria relevant to the topic, the next step for exogenous velocity classification is to identify sensible locations along a velocity number-line. In other words, which velocity values represent the border between "major" and "moderate" congestion? "moderate" and "minor"? When we examine the above traffic maps from around the world we discover little agreement.

A core task facing traffic map designers is to identify sensible class break locations for the classification of velocity. A logical way to identify these breaks is to survey potential map-readers and apply their preferences to the map's classification. Remember Golledge's (2002, pg. 83) statement, "there is an emerging need to capture the representation of a transportation system in a way that reflects how people perceive it and consequently use it." It is important that the classification scheme matches up with, as much as possible, the viewing public's notions about traffic. The theory being that if you survey enough potential readers you can identify a convergence linking popular relationships between velocity and traffic severity. It boils down to one simple question: How do drivers/map-readers relate velocity measurements to congestion severity? At what average velocity does highway traffic reach different thresholds? Is 50 miles per hour a "free-flow" condition or a "minor traffic" condition? Is 35 miles per hour a "severe," "moderate," or "minor" traffic condition? At face value this may seem like an extremely minor decision, but the findings from this dissertation indicate that it is not; this dissertation demonstrates that classification greatly influences traffic map interpretation, and (potentially) subsequent wayfinding behavior.

2.8.5 How To Symbolize?

Along with classification, symbolization encompasses another set of important cartographic decisions. This dissertation also explores how symbolization variables influence the perception of traffic maps. As it relates to transportation, semiology is clearly important. In our society red is a powerfully salient signifier, especially on the

road. We use red to color our ambulances, fire engines, our stop signs, “do not enter” signs, and of course, the “red light.” With this in mind, traffic map-readers are naturally alarmed by red. Wise cartographers have long taken advantage of semantic associations in maps (cyan for water, green for parks). Perhaps this is why the stoplight metaphor is so popular in traffic map design. It is immediately intuitive; it gives readers a cognitive head start. American drivers are thoroughly pre-conditioned to associate red hues with stopping, yellow with slowing, and green with going. Unfortunately this violates two dearly beloved cartographic principles: first we should not depict changes in a quantitative statistics using qualitative variation in hues, and second we should avoid using red and green in the same color scheme because a sizable portion of human beings are afflicted by red-green colorblindness. So this presents quite the cartographic quandary; do we take advantage of the powerful cultural metaphor to optimize the intuitiveness of the map thus violating lessons from cartography 101, or do we adhere to cartographic principles and risk a less intuitive design that even colorblind readers can decipher? This dissertation argues that we can only justify the answer to that important question with empirical evidence. Chapter 3 includes an investigation aimed to assess the intuitiveness of both symbolization approaches.

III. INTUITION AND TRAFFIC MAP DESIGN

3.1 Introduction

“The Look of Maps put forth the proposition that the function of maps is to communicate with people. This function depends on the visual appearance of map, and this appearance, in turn depends on explicit and implicit decisions made by mapmakers. So to understand and to improve map function, cartographers need to understand the effects of design decisions on the minds of map users (Montello, 2002, pg. 285).”

This chapter summarizes two studies that investigate how cartographic design variables influence the perception of traffic maps. Chapter 3.2 summarizes a pre-test involving 48 human participants. The pre-test explores the intuitiveness associated with a set of symbolization and representation conditions. Chapter 3.3 reports on a study developed subsequent to the pre-test that further examines symbolization and also explores the influence of cartographic classification on traffic-map-reading.

3.2 – Pre-test: Representation, Symbolization

This section details a human-participants examination assessing how cartographic representation and cartographic symbolization influence the perception of traffic maps. The goals of the pre-test are the following:

- To determine whether or not cartographic representation and cartographic symbolization influence the intuitiveness of traffic maps.

- (If there is an influence) To identify which velocity depiction strategies result in the most intuitive maps.

3.2.1 Background

Chapter 14 of *Analytical and Computer Cartography* (Clarke, 1990) is called “Designing the Map.” This chapter outlines some of the states and transformations in the mapping process. The author notes that the symbolization transformation is especially important “because the transformation determines not only the esthetic look of the map, but also how effectively it communicates the map’s spatial information content to the user or interpreter (Clarke, 1990, pg. 279).” So to paraphrase Montello (2002) in the terminology of Clarke, to understand and improve map function cartographers need to understand the effects of the symbolization transformation.

Figure 13, from Clarke (1990) depicts this transformation.

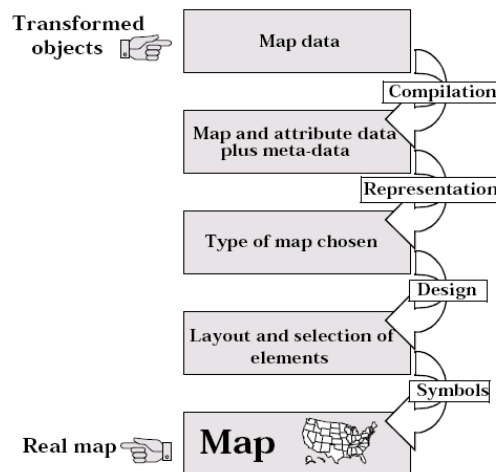


Figure 13: This figure was taken from of *Analytical and Computer Cartography* (Clarke, 1990, pg. 281). This pre-test explores the influences of representation and symbolization on traffic maps.

Clarke's symbolization transformations bridge the gap between raw map data, and a finished map. In between the map data and the final map product there are four interim phases: compilation, representation, design, and symbol selection. The first phase, compilation, requires the cartographer to essentially get his ducks in a row. The compilation step involves things like matching scales, projections, and data formats, as well as evaluating data sources and reliability. The second phase is representation. "The representation phase is one in which the cartographer has to choose the type of map that is to be produced (Clarke, 1990, pg. 282)." The third phase is constructing a design framework using an appropriate group of cartographic elements. The last phase in the symbolization transformation is the actual selection of the graphic symbols for inclusion on the map. "The output from this stage is a real map (Clarke, 1990, pg. 282)." The investigations described in this chapter explore the influences of the second and fourth phases as they relate to traffic maps.

There are a few categories of maps. There are reference maps, image maps, navigational maps and numerous types of what Robinson (1966) called "special purpose maps", but are now commonly referred to as thematic maps. The idea of cartographic representation methods being synonymous with the selection of map type is popular in thematic cartography (Clarke, 1990; Dent, 1999; MacEachren, 1992; Robinson, 1984; Slocum et al, 2005). Chrisman (1999) succinctly demystifies the "anti-entropic feat" of converting raw data into more useful information. Often this conversion results in a thematic map. Thematic maps include choropleth maps, dot density maps, proportional symbol maps, isopleth maps, and many others. The selection of the representation

method depends largely on data characteristics. As it pertains to traffic mapping, cartographic representation largely is concerned with representing velocity measurements along highways. Highway velocity data is most commonly measured at what Claramunt (2000) termed the “macroscopic” level; sensors measure traffic variables at fixed geographic locations (points) around the highway network. Given this point based measurement approach, two types of representation commonly result:

- Point-based: The map reflects the data collection architecture, modeling the measurement locations as dots placed on the graphic to correspond to their location in geographic space.
- Segment-based: These maps transform the point measurements by representing each detector location using a segment. In other words, each detector influences a segment of highway. This is the most common representational approach. These maps can be static or animated.

The pre-test investigates whether or not these two representation strategies will cause any differences in participant performance. Figure 14 shows examples of both types of representation.



Figure 14: The two types of representation, "dot" on the left, and "segment" on the right

The last phase in Clarke’s symbolization transformation is the selection of the graphic symbols for inclusion on the map. On traffic maps, symbols are generally used to depict velocity values and accident locations. This research is mostly concerned with

the depiction of velocity measurements. The legends of existing traffic maps demonstrate a diverse set of symbolization approaches. Although, the red-yellow-green stoplight symbolization is very popular, it may not be the wisest choice. The pre-test examines the feasibility of alternate approaches that may be less intuitive but adhere more closely to cartographic principles. With this in mind, one goal of the pre-test is to analyze how intuitive various approaches to velocity symbolization are.

3.2.2 Methods

48 participants participated in the pre-test. The participants were all undergraduate students at the University of California, Santa Barbara. The participants viewed traffic maps and performed tasks relating to traffic map interpretation. The study included 4 symbolization conditions and 2 representation conditions, resulting in a set of 8 unique conditions; each participant was exposed to only 1 of the 8 conditions. The participants performed identical map tasks, and answered identical questions pertaining to traffic maps all based on actual traffic data. The maps consisted of a fictional network overlaid by the traffic symbology. Figure 15 depicts the 8 map conditions.

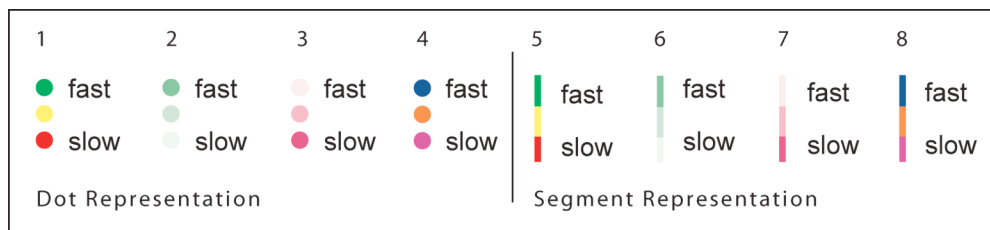


Figure 15: The eight conditions of the pre-test. There are four symbolization conditions and two representation conditions.

The experiment was presented on 8.5x11 inch pieces of paper, and participants used pens to indicate their answers. The first page included a brief introduction to the experiment, stimuli, and instructions on how to complete the various map tasks. Pages 2 through 10 of the experiment each included a map task. These pages all had a task listed at the top of the page (e.g. Trace the fastest route from location “G” to location “C”) and an accompanying map that was approximately 7.5 inches wide and 6 inches tall. Figure 16 is an example map from the pre-test. The eleventh page of the experiment packet included a post-test survey involving 6 statements with accompanying 5-point Likert scales, which participants used to express their level of agreement with each statement.

There were three kinds of map tasks included in the pre-test: routing tasks (4), congestion identification tasks (1), and comparisons of travel time (4). The routing tasks asked participants to trace the “fastest” route between a given origin-destination pair. Participants used their pencils to trace their routes directly onto the map page. The congestion identification task simply had participant mark three areas on the map that they perceived to be congested. The last set of tasks had participants estimate and compare travel times for two network segments; participants estimated whether it would take longer to get from A to B or from B to A, given a the traffic conditions. In summary there were 9 total map tasks in the pre-test so subjects’ task scores could range from 0 to 9.

Trace the fastest route from "G" to "C"

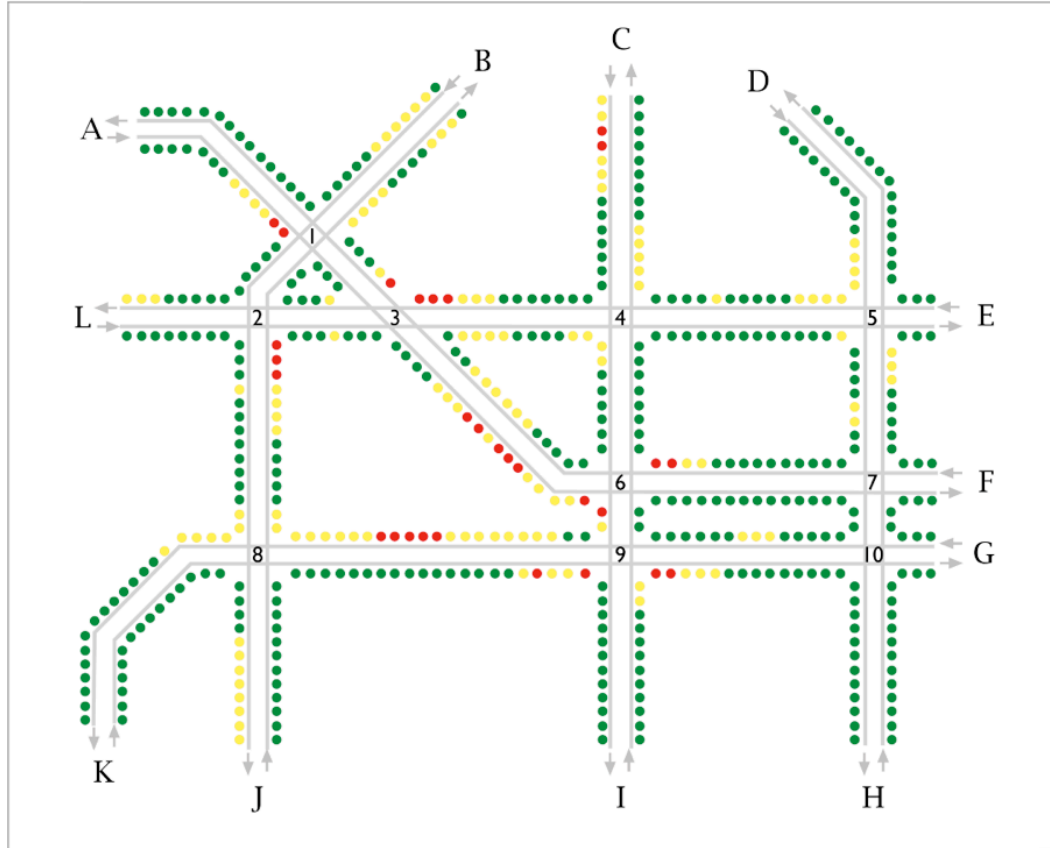


Figure 16: An example map stimulus used in the map task section of the pre-test. This example comes from the "stoplight" symbolization / dot representation condition.

Pre-test: Testing the Intuitiveness of Traffic Maps - "Legend-less" Map Tasks

4 routing tasks, 1 identification task, 4 comparison tasks, 4 Likert Statements

48 subjects, 8 design conditions - each subject was exposed to only one condition

Identical sequencing for the 9 tasks, and 4 Likert statements

Each task has a correct response

Section 1: Routing Tasks

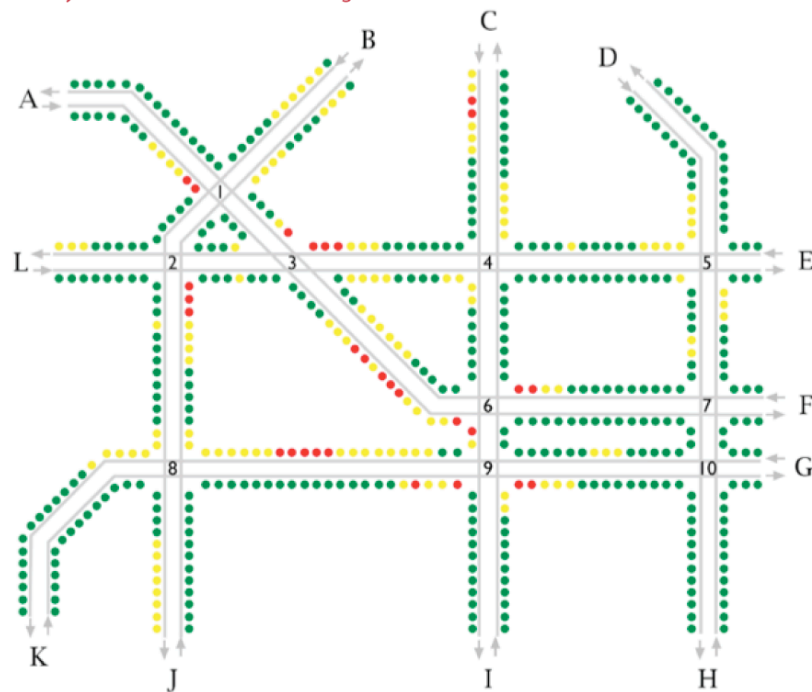
1. Trace the fastest route from "G" to "C"
2. Trace the fastest route from "E" to "J"
3. Trace the fastest route from "L" to "G"
4. Trace the fastest route from "K" to "D"

Section 2: Traffic Identification Tasks

5. With your pen, identify 3 areas of traffic congestion on the map

Section 3: Travel Time Comparison Tasks

6. Do you believe it would take longer to travel from "6" to "7" or from "7" to "6?"
7. Do you believe it would take longer to travel from "3" to "6" or from "6" to "3?"
8. Do you believe it would take longer to travel from "8" to "9" or from "9" to "8?"
9. Do you believe it would take longer to travel from "3" to "4" or from "4" to "3?"



Section 4: Likert Statements (5-point scale)

1. The maps were intuitive and easy to use:
2. If the map had a legend, I would have been more confident about my answers:
3. The maps were confusing and hard to use:
4. I feel confident about my answers:

Figure 17: A summary figure detailing the design and sequence of the pre-test.

The goal of the experiment was to uncover performance differences between these 8 conditions; which of the eight participant groups would perform best/worst? In order to test for intuitiveness, the maps within the experiment did not contain legends. In other words, the participants did not have access to a key to decode the map symbols; they were forced to rely on their intuition. The study was designed to test the hypotheses that groups of users faced with different representation and symbolization conditions, will produce significantly different test results; some groups will outperform other groups in terms of their abilities to perform a set of map tasks.

3.2.3 Results

The results echo the assertions of Robinson and Montello; the function of these maps indeed depends on design decisions made by mapmakers. There were significant performance differences among the eight participant groups. Although, there was not significant influence caused by the representational variation, the symbolization conditions resulted in drastic performance differences. Figure 18 presents the findings from the task-based portion of the test; scores are out of a possible 9.

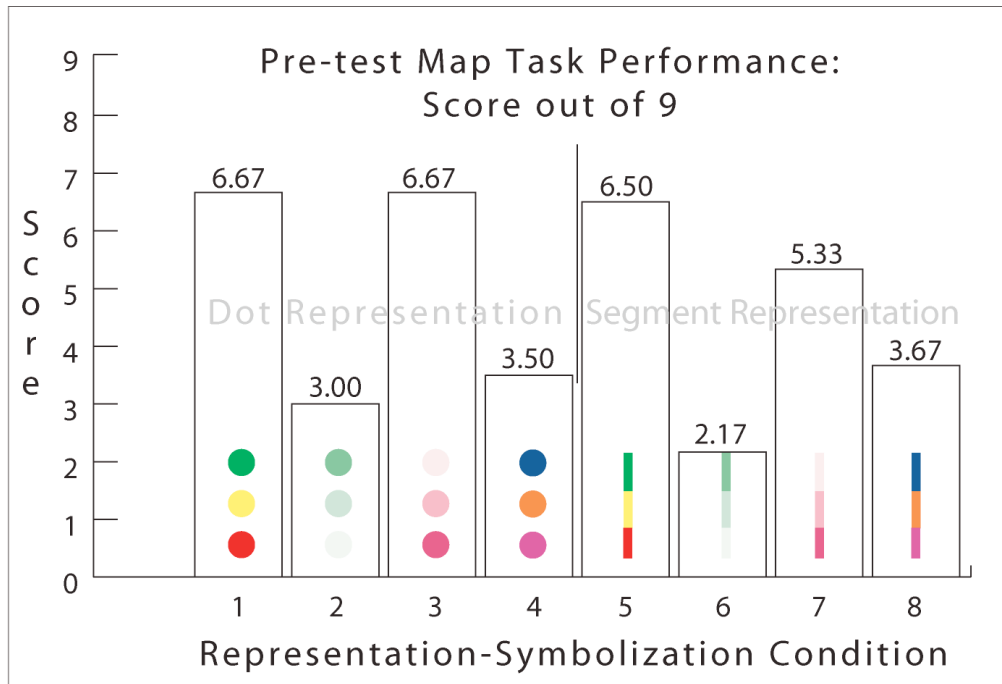


Figure 18: Results for the 8 conditions: Mean task scores (out of a possible 9)

When we isolate cartographic representation, the findings indicate the four dot-based groups performed marginally better than their segment-based counterparts. Four groups correctly responded to over half of the tasks, the other four groups were not very successful. Of the successful groups the top two, conditions 1 and 3, involved dot-based scheme, while the other two, 5 and 7, involved segments. The four groups that inaccurately responded to over half of the map tasks were identically split, two dot-based groups, and two segment-based groups.

Unlike the representation condition, the symbolization condition produces conditionally dependent results. Participants in the “stoplight” (red-yellow-green) condition (conditions 1 and 5) performed best on the map tasks, slightly better than the red sequential groups (conditions 3 and 7). Together the stoplight, and red-sequential

groups performed much better than the other groups. There is a considerable gap separating these groups from the underperforming groups; the green sequential groups (conditions 2 and 6) performed the worst, slightly worse than the random hue groups (conditions 4 and 8).

If we aggregate the results by combining symbolization conditions across the representation conditions we end up with four twelve-participant symbolization conditions. In this case, the findings indicate two of the four symbolization conditions succeed, and two fail. Figure 19 depicts these aggregate findings; the scores are out of 18.

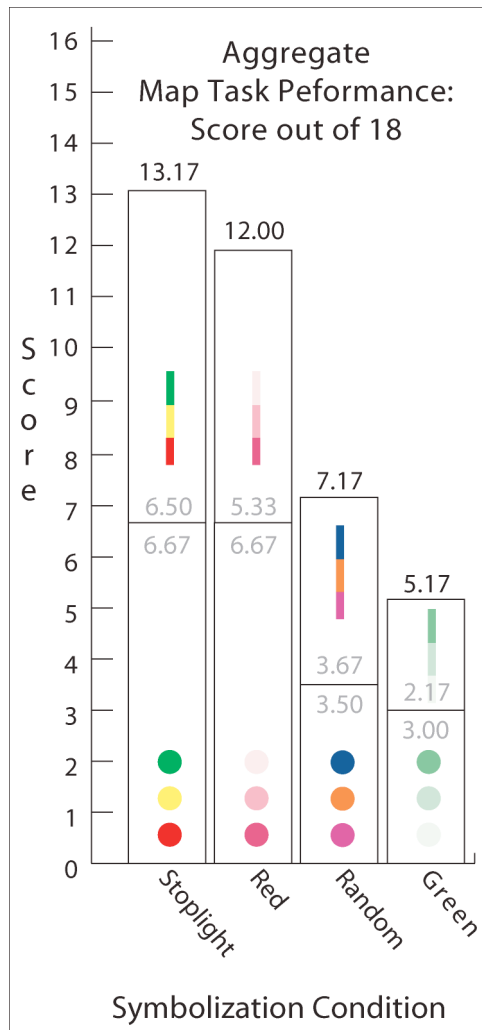


Figure 19: Scores from the pre-test aggregated across representational conditions. 12 participants viewed each symbolization condition, and those in the stoplight, and red sequential groups vastly outperformed those in the random hue and green-sequential groups.

The results of the pre-test indicate that symbolization has a significant influence on the intuitiveness of the map, which in turn influences a map-reader's ability to complete map tasks. The effects of representation, at least in this dot versus segment experiment, are not nearly as important.

3.2.4 Pre-test Analysis

The pre-test described in this chapter was designed to test the following two hypotheses:

1. Different representation conditions will elicit significantly different user task performance scores
2. Different symbolization conditions will elicit significantly different user task performance scores

The study described in this chapter was designed to test four hypotheses. Paired t-tests are employed to test each hypothesis. T-ratios are expressions of differences between two groups. Each group in this experiment has the same number of samples. The goal of the analysis is to determine whether or not there are significant differences between groups. The t-test sets up a sampling distribution of differences and determines whether the differences between two groups' samples are indicative of "significance." The null hypothesis states equal means; there is no significant difference between the two groups. If the t-statistic is greater than the critical value (critical values of t decrease as the number of samples and the degrees of freedom increase) then we can reject the null hypothesis, and accept the alternative hypothesis stating different population means. This type of analysis is vulnerable to type I and type II errors. The likelihood of a type I error, incorrectly rejecting the null hypothesis, is equivalent to the alpha value in the t-test, often set to 0.05, or 5%. The exact likelihood of type II error, not rejecting the null hypothesis when we should, is unknown. Type II error would potentially occur in this research due to small sample sizes. For example, the analysis of

performance metrics for the stoplight and the red sequential map, suggest accepting the null hypothesis. There is a risk that this finding is incorrect and map readers performances are significantly influenced by these conditions; this is an example of type II error.

The participants' scores (out of 9) from the task portion of the pre-test served as a proxy for performance. The null hypotheses are that the performances of the subjects will not depend on map design conditions. Using paired t-tests it was found that performances did not significantly depend on the representation conditions, but did depend on symbolization conditions. Below is a summary of the hypothesis testing for the representation conditions:

Analysis of "dot representation" versus "segment representation:"

1. Null Hypothesis: The mean performance value of the segment representation population is equal to the mean performance value of the dot representation population.
2. Alternative Hypothesis: The mean performance values of the two populations are significantly different
3. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population's standard deviation is unknown
4. Significance level: alpha equals 0.05
5. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 23
6. Critical region: $t_{0.05} \geq |2.07|$. Since the alternative hypothesis is non-directional the critical region consists of all values greater than or equal to 2.07 or less than or equal to -2.07
7. Results:

t-Test: Paired Two Sample for Means

	<i>dot</i>	<i>segment</i>
Mean	4.96	4.42
Variance	5.09	7.12
Observations	24.00	24.00
df	23.00	
t Stat	0.96	
P(T<=t) two-tail	0.34	
t Critical two-tail	2.07	

8. Decision: Since the obtained t statistic does not fall within the critical region we fail to reject the null hypothesis

Table 2 summarizes the results for the paired t-tests with alpha set to 0.05 for the four symbolization conditions.

	Random Hue	Green Sequential	Red Sequential
Stoplight	$t(11) = 4.24 \ p < .005$	$t(11) = 6.37 \ p < .001$	No Significant Differences
Red Sequential	$t(11) = 3.74 \ p < .005$	$t(11) = 4.16 \ p < .005$	
Green Sequential	No Significant Differences		

Table 2: A summary of results from paired t-tests comparing the results from the task portion of the pre-test. The stoplight and red sequential symbolization conditions resulted in significantly higher task scores than the green sequential and the random hue conditions.

Analysis of “stoplight metaphor” versus “random hue:”

9. Null Hypothesis: The mean performance value of the stoplight metaphor population is equal to the mean performance value of the random hue population.
10. Alternative Hypothesis: The mean performance values of the two populations are significantly different
11. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population’s standard deviation is unknown
12. Significance level: alpha equals 0.005
13. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 11
14. Critical region: $t_{0.05} \geq |3.50|$. Since the alternative hypothesis is non-directional the critical region consists of all values greater than or equal to 3.50 or less than or equal to -3.50
15. Results:

t-Test: Paired Two Sample for Means

	<i>stoplight</i>	<i>random</i>
Mean	6.58	3.58
Variance	2.45	3.72
Observations	12.00	12.00
df	11.00	
t Stat	4.24	
P(T<=t) two-tail	0.0014	
t Critical two-tail	3.50	

16. Decision: Since the obtained t statistic falls within the critical region we reject the null hypothesis

Analysis of “stoplight metaphor” versus “green sequential:”

17. Null Hypothesis: The mean performance value of the stoplight metaphor population is equal to the mean performance value of the green sequential population.
18. Alternative Hypothesis: The mean performance values of the two populations are significantly different
19. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population’s standard deviation is unknown
20. Significance level: alpha equals 0.001
21. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 11
22. Critical region: $t_{0.01} \geq |4.44|$. Since the alternative hypothesis is non-directional the critical region consists of all values greater than or equal to 4.44 or less than or equal to -4.44
23. Results:

t-Test: Paired Two Sample for Means

	<i>Stoplight</i>	<i>Green seq</i>
Mean	6.58	2.58
Variance	2.45	2.45
Observations	12.00	12.00
df	11.00	
t Stat	6.37	
P(T<=t) two-tail	0.00005	
t Critical two-tail	4.44	

24. Decision: Since the obtained t statistic falls within the critical region we reject the null hypothesis

Analysis of “stoplight metaphor” versus “red sequential:”

25. Null Hypothesis: The mean performance value of the stoplight metaphor population is equal to the mean performance value of the red sequential population.
26. Alternative Hypothesis: The mean performance values of the two populations are significantly different
27. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population's standard deviation is unknown
28. Significance level: alpha equals 0.05
29. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 11
30. Critical region: $t_{05} \geq |1.80|$. Since the alternative hypothesis is non-directional the critical region consists of all values greater than or equal to 1.80 or less than or equal to -1.80
31. Results:

t-Test: Paired Two Sample for Means

	<i>Stoplight</i>	<i>red sequential</i>
Mean	6.58	6.00
Variance	2.45	5.27
Observations	12.00	12.00
df	11.00	
t Stat	0.92	
P(T<=t) two-tail	0.38	
t Critical two-tail	1.80	

32. Decision: Since the obtained t statistic does not fall within the critical region we fail to reject the null hypothesis

Analysis of “red sequential” versus “random hue:”

33. Null Hypothesis: The mean performance value of the red sequential population is equal to the mean performance value of the random hue population.
34. Alternative Hypothesis: The mean performance values of the two populations are significantly different
35. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population's standard deviation is unknown
36. Significance level: alpha equals 0.005
37. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 11
38. Critical region: $t_{005} \geq |3.50|$. Since the alternative hypothesis is non-directional the critical region consists of all values greater than or equal to 3.50 or less than or equal to -3.50
39. Results:

t-Test: Paired Two Sample for Means

	<i>red sequential</i>	<i>random hue</i>
Mean	6.00	3.58
Variance	5.27	3.72
Observations	12.00	12.00
df	11.00	
t Stat	3.75	
P(T<=t) two-tail	0.00	
t Critical two-tail	3.50	

40. Decision: Since the obtained t statistic falls within the critical region we reject the null hypothesis

Analysis of “red sequential” versus “green sequential:”

41. Null Hypothesis: The mean performance value of the red sequential population is equal to the mean performance value of the green sequential population.
42. Alternative Hypothesis: The mean performance values of the two populations are significantly different
43. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population’s standard deviation is unknown
44. Significance level: alpha equals 0.005
45. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 11
46. Critical region: $t_{0.05} \geq |3.50|$. Since the alternative hypothesis is non-directional the critical region consists of all values greater than or equal to 3.50 or less than or equal to -3.50
47. Results:

t-Test: Paired Two Sample for Means
mean score out of 9

	<i>red</i>	<i>green</i>
Mean	6.00	2.58
Variance	5.27	2.45
Observations	12.00	12.00
Pearson Correlation	-0.05	
Hypothesized Mean Difference	0.00	
df	11.00	
t Stat	4.16	
P(T<=t) two-tail	0.0016	
t Critical two-tail	3.50	

48. Decision: Since the obtained t statistic falls within the critical region we reject the null hypothesis

Analysis of “green sequential” versus “random hue:”

49. Null Hypothesis: The mean performance value of the green sequential population is equal to the mean performance value of the random hue population.
50. Alternative Hypothesis: The mean performance values of the two populations are significantly different
51. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population’s standard deviation is unknown
52. Significance level: alpha equals 0.05
53. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 11
54. Critical region: $t_{0.05} \geq |2.20|$. Since the alternative hypothesis is non-directional the critical region consists of all values greater than or equal to 2.20 or less than or equal to -2.20
55. Results:

t-Test: Paired Two Sample for Means

	<i>green</i>	<i>random</i>
Mean	2.58	3.58
Variance	2.45	3.72
Observations	12.00	12.00
df	11.00	
t Stat	-1.13	
P(T<=t) two-tail	0.28	
t Critical two-tail	2.20	

56. Decision: Since the obtained t statistic does not falls within the critical region we fail to reject the null hypothesis

3.2.5 Pre-test Discussion

Cartographic principles, and topical relevance are the two sources that enable cartographers to create intuitive symbolizations. The conditions in the pre-test exemplify these two sources. Velocity is a “unipolar” quantitative variable; cartographic principles suggest that sequential color schemes (such as the red and green conditions in the pre-test) are most appropriate for unipolar data. Cartographers should adjust a color’s value, while keeping hue mostly steady, to effectively imply quantitative variability. Furthermore, the darkest colors should indicate higher quantities, while

lighter tones should be used to imply smaller amounts. Consequently, the symbolization condition most loyal to cartographic principle in this test is the green condition; dark green is associated with the highest velocities, and light green with the lowest. It is noteworthy then that the green condition, the most cartographically adherent approach, performs poorly.

Why are these results particularly poor ambassadors for cartographic principles? The answer, I believe, has to do with the relationship that links the statistic and the theme of traffic maps. Velocity, the unipolar statistic consistently equated with congestion on traffic maps, has an inherently contradictory relationship with the map theme (traffic congestion); if velocity is high, congestion is low and if velocity is low, congestion is likely high. This inverse relationship between the variable leads to a breakdown in cartographic principle. In fact when such a relationship exists the wise thing to do might be to invert the color scheme so that lighter tones signify higher data values, and darker tones signify lower data values. Another example of this phenomenon is a map depicting “hours of sunlight around the world” where darkness would be more logically linked to smaller quantities of the variable.

These results are poor despite the greenish hue commonly associated with “go” – shouldn’t dark green intuitively mean “more speed” than a much lighter green? The results indicate no, suggesting green on its own is not a powerful enough semantic association to overcome whatever dominant preconceptions readers have about traffic.

The stoplight metaphor violates cartographic principles but adheres to culturally relevant preconceptions map-readers associate with driving speed. American drivers

semantically associate the red-yellow-green hues with the stoplight, one of our more powerful and ubiquitous traffic signals. The results evidently demonstrate that despite not having access to a legend, the map-readers in the stoplight group seem to decode the map's symbology with ease.

The stoplight metaphor cannot explain the success of the red group. Participants exposed to the red-sequential scheme performed very well without a legend. The red sequential symbolization scheme uses dark red symbols to signify low velocity measurements, and light red symbols to denote higher values. Like the stoplight metaphor, this approach breaks cartographic rules but still succeeds with map-readers. Lowe (1999) finds that a large group of map-readers “extract” based on perceptual salience instead of thematic relevance. In other words, many “novice” map-readers simply attend to the boldest symbology on the map. This puts added onus on cartographers to ensure that the thematically relevant information is appropriately prominent, graphically speaking (Fabrikant and Goldsberry, 2005). In the case of the green versus red condition, salience may be of primary importance. With a white background, the darkest features create high-contrast, salient zones on the map, while the lighter tones are almost camouflaged against the ground. Therefore, traffic events (i.e. areas of low velocity) are perceptually salient on the red sequential map, and relatively subdued on the green map. This effect is compounded by the frequency of salient symbols within each graphic. Under normal flowing conditions, or average congestion conditions, a vast majority of velocity symbols on a traffic map will be of the “high velocity” or “free flow” variety. If these symbols are the most salient symbols in

the scheme then the map-reader will be faced with a barrage of symbols indicating normal conditions.

Traffic maps are similar to weather maps; they both overlay quantitatively dynamic thematic measurements atop a set of stationary geographic reference layers (base data). Both maps' messages rely heavily on the interaction of the thematic information with the base data, a classic "figure-ground" situation. As it relates to perceptual salience, the traffic map could take a lesson from conventional weather maps. The conventional radar map depicting precipitation conditions employs no symbols to indicate a lack of precipitation (The lack of a symbol is a symbol itself). Perhaps traffic maps should do the same; when there is free-flow traffic, apply an invisible symbol, therefore reserving all of the visible traffic symbology for congested conditions. Within the pre-test, the red sequential condition most closely approximates this approach. Most current traffic maps, based on the stoplight metaphor, use rather salient green symbols to depict free-flow conditions (analogous to no rain) and are forced to amp up the bright red symbols to depict congested locations (analogous to precipitation). The weather-map approach effectively draws the readers' attention immediately to precipitation-affected areas without having to employ bright red hues (which are reserved for the most severe storms). Furthermore, the no-symbol-for-no-rain approach drastically reduces the clutter caused by the thematic symbology, granting more display space to the geographic references in other layers. These benefits could logically be echoed within traffic maps.

The results of the pre-test suggest that both the stoplight and the red-sequential approach are intuitive to map-readers. Chapter 3.3 further investigates these two design approaches as well as examining the influence of cartographic classification on traffic maps.

3.3 Experiment: Symbolization and Cartographic Classification

This section outlines an experiment designed to investigate how symbolization and classification variables influence the perception of traffic maps. The experimental design closely mimics the design of the experiment in chapter 3.2. This time 58 undergraduate students from UCSB participated in the test.

The goal of this investigation is to:

- Further evaluate the symbolization transformation by continuing to compare the stoplight approach with the red-sequential approach.
- Determine what influence cartographic classification of velocity data has on the perception and use of traffic maps.

3.3.1 Background

As described in chapter 2, and demonstrated in chapter 3.2, map design decisions can drastically alter the perception of geographic information. As it relates to traffic maps, the influence of design is still not understood. This study attempts to remedy that by focusing on the influences of symbolization and classification on human perception of traffic graphics.

Chapter 3.2 demonstrates the symbolization influence, but that investigation ignored the drastic influence of classification. Every traffic map employs some form of cartographic classification. Figures 3 - 11 include a subset of the world's traffic maps; they reveal a wide array of classification approaches. Since most traffic maps use velocity as a measure of "traffic," classification in traffic maps really comes down to how we create classes of velocity measurements. We can distinguish classification approaches based upon the statistical level of measurement included on the legend. Some maps employ an ordinal level measurement, as seen in figure 4 meaning that traffic data is classed using terms such as "free flow" "moderate" "minor" "stop and go" and "blocked" – a good ordinal scheme has a clear order, yet lacks quantitative cues that facilitate more mathematical analysis. But, the more popular approach to traffic mapping applies the ratio level of measurement; velocity data is naturally measured at the ratio level (miles per hour) and this approach creates a set of classes based on numerical ranges, as seen in figure 3 of velocity measurements.

One common problem with traffic maps is tied directly to the "level of measurement" decision; the ordinal level of measurement necessarily results in ambiguous terms used to describe traffic flow. For example, in the 511.org map of San Francisco traffic (figure 4), there are four classes included on the legend: "No Congestion," "Moderate," "Heavy," and "Stop and Go." This approach immediately is vulnerable to two perceptual issues. First, what do these terms mean exactly, and second, what is their order of severity. The map-reader may want to know exactly how slow, or how congested "Moderate" traffic is versus "Stop and Go." This is especially

true if the reader is going to be making critical wayfinding decisions based upon time constraints, these ordinal approaches hinder quantitative map reading. Secondly, the ordinal approach often employs a set of traffic adjectives lacking an inherent order. This is again exemplified by the San Francisco map (figure 4); is “Stop and Go” traffic more or less severe than “Heavy” traffic? Map readers (as demonstrated in the chapter 4) can be confused by these terms.

Symbolization and classification go hand-in-hand; the number of classes of data on a map directly influences the number of unique symbols on that map. Previous research indicates that the optimal number of classes for static thematic maps is between 5 and 7 (Miller, 1956), and 2 or 3 for animated thematic maps (Harrower, 2003). This study examines how different classification schemes influence map perception.

3.3.2 Methods

58 participants participated in the study; they were all undergraduate students from the University of California, Santa Barbara. They ranged in age from 18 to 25 with a mean age of 21.1. There were 34 males and 24 female participants. 38 participants reported that they owned their own vehicles, and 41 of the 58 indicated they “regularly” drive on freeways. The participants viewed traffic maps, performed map tasks, and answered questions related to their perceptions of traffic. The test contained three main sections: a routing section, a traffic description section, and a post-test section. The protocol for each section is described below:

1. The Routing Section: Similar to the pre-test, participants were given a fictitious network along with dot-based representations of traffic conditions and asked to trace “the fastest” route between an origin-destination pair. Unlike the pre-test, the maps included a legend as well as a scale, and participants were also asked to estimate the length of the route, the average velocity of the route, and the travel time of the route. In summary “the routing section” included five such origin-destination tasks, each with four responses, resulting in a total of 20 user responses for the section.

2. The Traffic Description Section: This section asked participants to select terms from multiple-choice lists that best described the traffic conditions at certain locations around the network. There were 5 locations clearly marked on the maps, and separate choice sets associated with each location. This section resulted in five responses from each participant.

3. The Post-test Section: This post-test questionnaire included 6 Likert scale questions similar to those in the pre-test. This section was designed to elicit the participants’ opinions about the map stimuli. The questionnaire also asked participants about their experiences driving on highways, whether they owned cars, and where they were from.

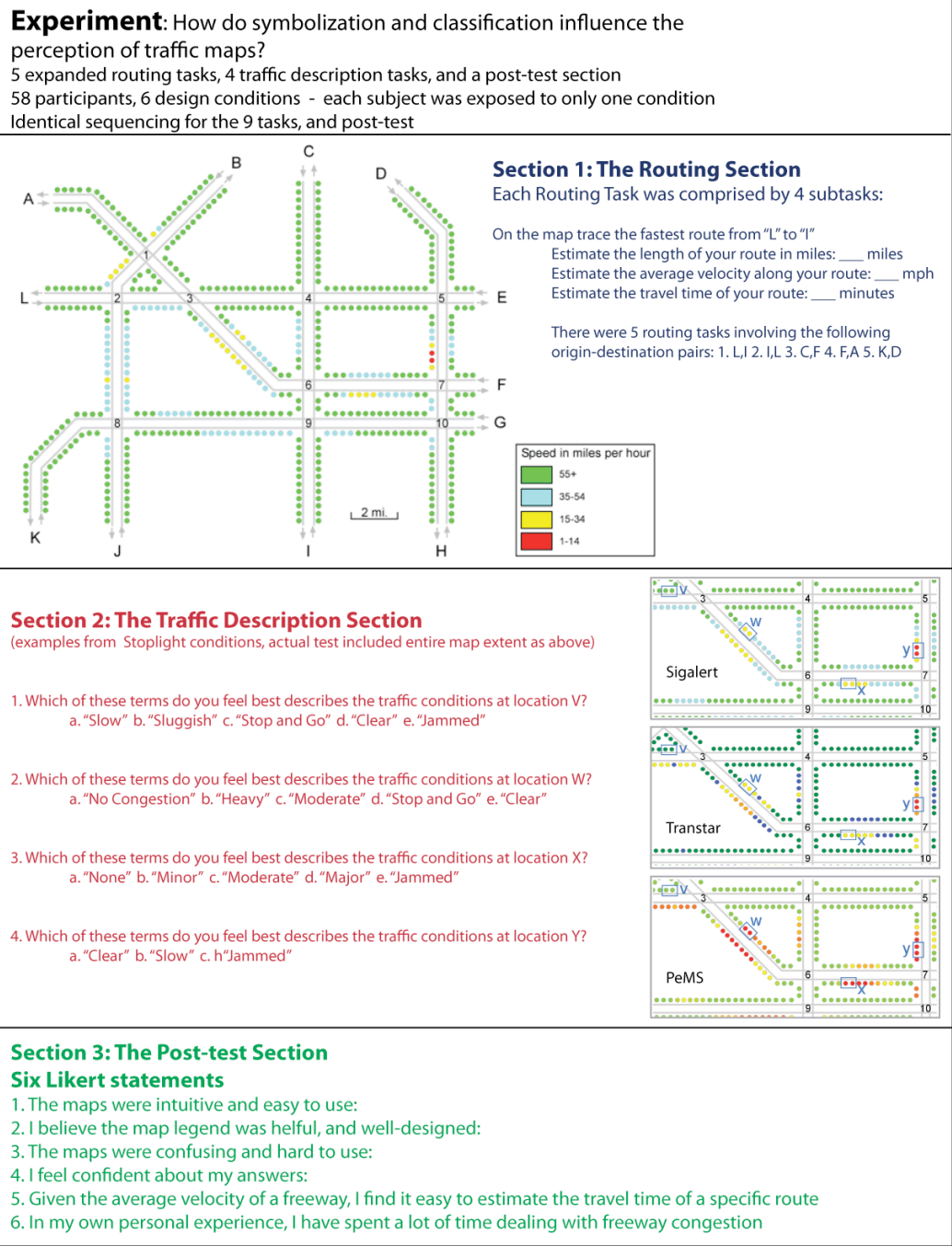


Figure 20: An overview of the experiment.

3.3.2.1 Conditions

Similar to the pre-test the study employs a “between” design, meaning each participant is exposed to only one condition, and the results can be analyzed across groups of participants. The experiment includes 3 classification conditions, and two symbolization conditions. The symbolization conditions (“stoplight” and red sequential) were chosen because of their superior performances in the pre-test. The classification conditions are each sourced from a different online traffic map (Transtar’s Houston traffic map, Sigalert.com’s LA traffic map, and PeMS’ Los Angeles traffic map). These schemes were chosen because of the diversity of their approaches. The Sigalert map uses a 4-class approach, Transtar a 5-class approach, and PeMS employs a 6-class approach. Figure 21 summarizes these three classification schemes.

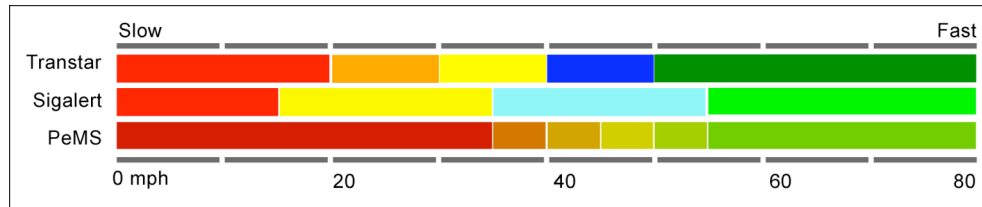


Figure 21: The classifications, and symbolizations of the three traffic maps, depicted along a number line

3.3.3 Results

This section details the results of the experiment.

3.3.3.1 The Routing Section

Participants responded to four types of tasks in this section of the test: route selection tasks (Part A), estimated geographic distance tasks (Part B), estimated average

velocity tasks (Part C), and estimated travel time tasks (Part D). The results for the routing sections are presented below using similar divisions.

PART A - Route Selection:

Each participant responded to five unique route selection tasks. Participants selected the “fastest” route in 180 out of 299 responses, just over sixty percent of the time. This means that participants failed to derive the correct route over forty percent of the time. Of the five routing tasks, the accuracy rate of the responses ranged from 50% (route 3) to 78.3% (route 2). The results are not conditionally dependent; participants’ success rates were consistent across all conditions.

PART B - Estimation of Geographic Distance:

This task had participants estimate the distance of the route they had just traced for the routing question. The map included a simple graphic scale bar. Participants accurately estimated the length of routes. The mean and median responses were consistently close to actual distances,

PART C - Estimation of Average Velocity:

Participants were next asked to estimate the average velocity along their route. The map includes a dot-based representation of loop detectors conveniently spaced out equally along the network. The task requires participants to assess the velocity symbols along their route, and estimate the average velocity, in miles per hour, of their chosen route. Figure 22 summarizes the responses of the subset of participants who correctly

identified the fastest route. Across all conditions participants significantly underestimated the average velocity along the route. The magnitude of this effect is conditionally dependent. This effect is caused by cartographic design decisions: the influence of classification, and the presentation of that classification in the legend is the apparent cause. The Transtar classification produces the most severe underestimates. The underestimation effect is extremely consistent; only 1 response out of 180 overestimated the velocity for any of the routes. This means that 179 out of 180 responses underestimated the average velocity of the route. Figure 22 summarizes the prevalence of velocity underestimation. To this point we may have identified prevalent tendencies to underestimate route distances, and severely underestimate average velocity.

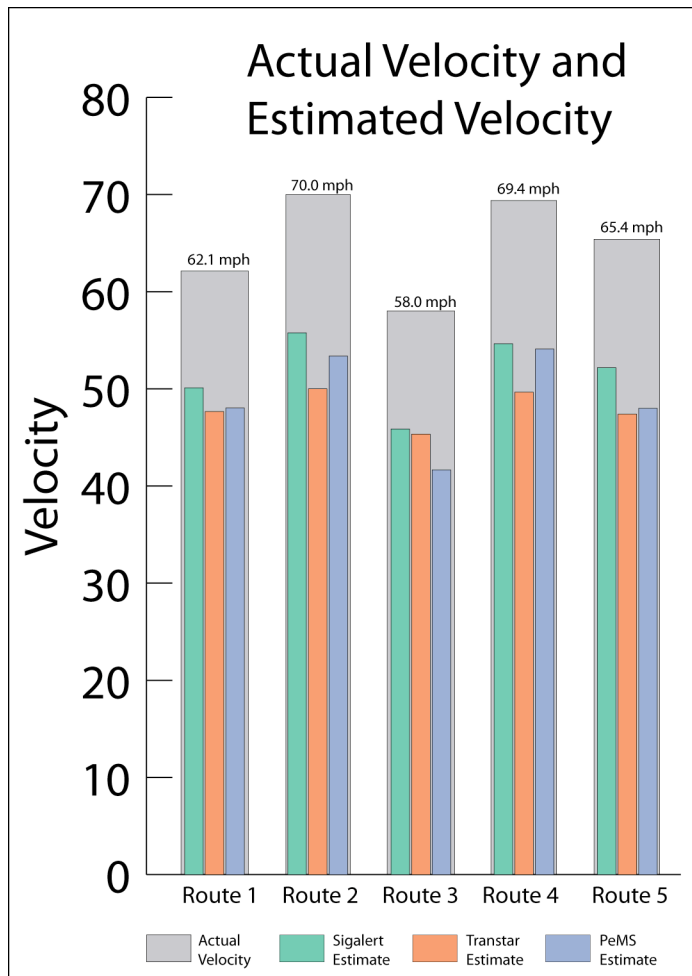


Figure 22: Actual velocities versus mean velocity estimates of the participants

PART D: Estimation of Travel Time

The fourth part of the routing estimation section involved the estimation of travel time. In the previous three parts of this section, participants estimated a fastest route, that route's geographic distance, and the average velocity along that route. The final task is then to estimate the travel time, in minutes of that route. One obvious way to derive travel time involves simple arithmetic using average velocity and geographic distance

(dividing distance by velocity), parameters the participants previously produced in parts B and C of the routing estimation section.

Participants neither underestimated nor overestimated travel times on a consistent basis, and the results were not conditionally dependent. The mean response underestimated travel time in two cases, and overestimated travel time in the three other cases. Table 3 summarizes the findings from part D, relating actual travel times of the routes with the mean responses of the participants.

Route Number	Actual Travel Time	Mean, Median, Standard Deviation: T.T. Estimate
1	24.4 minutes	21.8, 20, 9.2 minutes
2	21.7 minutes	20.3, 20, 10.8 minutes
3	19.6 minutes	22.9, 20, 14.6 minutes
4	24.6 minutes	29.2, 28, 16.7 minutes
5	34.0 minutes	46.7, 35, 82.2 minutes

Table 3: Actual travel time versus mean estimated travel times for each of the five routes

3.3.3.2 The Traffic Description Section

This section of the test asked participants to select the adjective from a list that they felt best described the traffic at a designated location. The designated location was denoted using a box drawn around a pair of detectors symbols. There were four of these locations dispersed around the map, resulting in four individual questions. The

four locations included one area of very low velocity, one area of high velocity, and two areas in between. Table 4 summarizes the mode responses within each condition.

Detector Values	Sigalert Condition	Transtar Condition	PeMS Condition
15, 15 (mph)	“Jammed”	“Jammed”	“Jammed”
33, 32 (mph)	“Moderate”	“Moderate”	“Heavy” “Major” (Tie)
34, 33 (mph)	“Moderate”	“Moderate”	“Jammed”
70, 70 (mph)	“Clear”	“Clear”	“Clear”

Table 4: Mode responses to the terminology questions.

PART A – Free Flow Conditions

The first question within the traffic description section asked participants to select the term, from a list of five terms, that best described the traffic at location V. Location V is an area of two loop detectors each reporting a velocity of 70 miles per hour, free flowing conditions. Across all three conditions, this velocity is symbolized using the most favorable symbol, green in the stoplight metaphor, and the lightest tone in the sequential schemes. Not surprisingly, a vast majority of participants described the conditions as “clear” given the choices of: slow, sluggish, stop and go, clear, and jammed. This result was not conditionally dependent.

PART B – Ambiguous Conditions

Questions 2 and 3 of the traffic description section asked participants to choose terms to describe traffic at velocities between 32 and 34 miles per hour. This area is given extra attention because it is characterized by diverse symbolization approaches across the conditions. Looking again at Figure 23 this diversity is obvious. For example a 34mph measurement would be categorized within the most severe class using the PeMS scheme, and categorized in the heart of the middle class using the Transtar scheme.

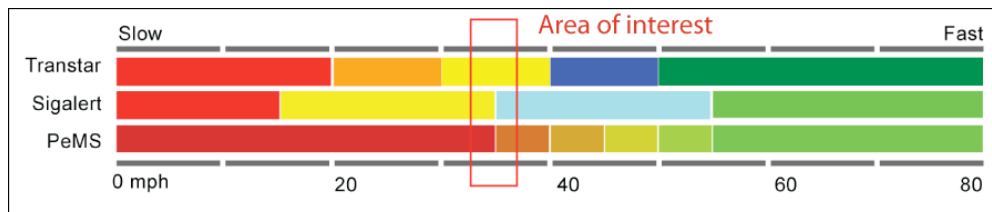


Figure 23: The number line graphic with the area of interest highlighted.

Question 2 within the traffic description section asked participants to select the term that best described traffic at area W, where two detectors are measuring 33 and 32 miles per hour respectively. The list of terms from question 2 was: “no congestion,” “moderate,” “heavy,” “major,” and “jammed.” The results were conditionally dependent. Figure 24 includes 3 pie charts, one for each condition depicting the distribution of participant responses.

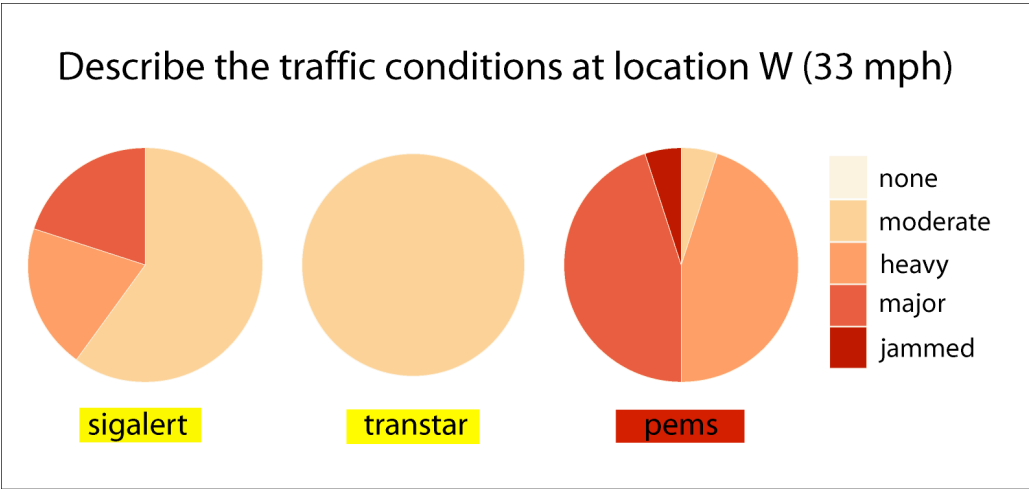


Figure 24: Pie charts showing the distributions of responses of the participants in each of the 3 conditions. The question asked participants to choose which term best described the traffic at location W.

Question 3 within the traffic description section asked participants to select the term that best described traffic at area X, where two detectors are measuring 34 and 33 miles per hour respectively. The list of terms from question 3 was: “none,” “minor,” “moderate,” “major,” and “jammed.” The results were conditionally dependent. Figure 25 includes 3 pie charts, one for each condition depicting the distribution of participant responses.

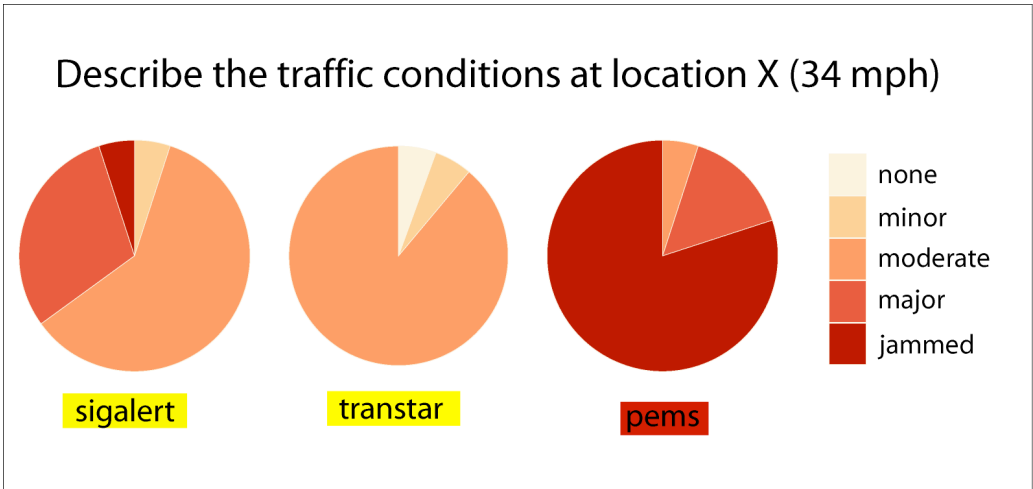


Figure 25: Pie charts showing the distributions of responses of the participants in each of the 3 conditions. The question asked participants to choose which term best described the traffic at location X

PART C – Congested Conditions

Question 4 within the traffic description section asked participants to select the term that best described traffic at area Y, where two detectors are each measuring 15 miles per hour respectively. The area is clearly congested and each scheme symbolizes these detector locations using its most severe symbol. The list of terms from question 4 was: “clear,” “slow,” and “jammed.” The results were not conditionally dependent, an overwhelming majority of participants selected “jammed” to describe this area.

3.3.3.3 The Post-test Section

This section describes participant feedback garnered from the final part of the test. The feedback section includes six Likert scale responses, and four background questions. “Likert scales require respondents to express their degree of agreement or disagreement with a series of statements (Montello, 2006, pg. 87).” Below is the summary of the Likert statements as well as their responses (Potential Likert responses range from 1 to 5 with 1 meaning “strongly disagree, and 5 meaning “strongly agree”):

1. The maps were intuitive and easy to use.
2. I believe the map legend was helpful, and well designed.
3. The maps were confusing and hard to use.
4. I feel confident about my answers.

5. Given the average velocity of traffic on a freeway, I find it easy to estimate the travel time of a specific route.
6. In my own personal experience, I have spent a lot of time dealing with freeway congestion.

INDEX: A summary value of a participants' opinion about the map; it is the sum of statements 1, 2, and 4 (positive statements about the map design) minus the value from 3 (negative statement about the map design).

<i>Statement</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>	<i>6</i>	<i>INDEX</i>
Overall	3.81	3.96	2.04	3.58	3.30	3.39	9.32
Overall	3.93	4.13	1.90	3.83	3.53	3.62	10.00
Stoplight							
Overall	3.67	3.78	2.19	3.30	3.04	3.12	8.56
Sequential							
Sigalert All	3.75	4.15	2.15	3.45	3.10	2.89	9.20
Sigalert	3.70	4.20	2.20	3.70	3.40	2.70	9.40
Stoplight							
Sigalert	3.80	4.10	2.10	3.20	2.80	3.11	9.00
Sequential							
Transtar	3.94	4.00	1.72	3.78	3.39	3.78	10.00
All							
Transtar	4.20	4.20	1.50	4.10	3.80	4.20	11.00
Stoplight							
Transtar	3.63	3.75	2.00	3.38	2.88	3.25	8.75
Sequential							
PeMS All	3.74	3.74	2.21	3.53	3.42	3.53	8.79
PeMS	3.90	4.00	2.00	3.70	3.40	4.00	9.60
Stoplight							
PeMS	3.56	3.44	2.44	3.33	3.44	3.00	7.89
Sequential							

Table 5: Mean Likert responses for each condition.

The final questions of the questionnaire asked respondents about their driving habits and their sources of traffic information. 70 percent of the participants indicated that they owned their own cars and 76 percent indicated that they “frequently” drive on freeways. As for their primary source of traffic information, exactly half of the respondents indicated they “don’t use traffic information,” and only 13 percent of the participants indicated they downloaded traffic information from the Internet or mobile devices.

3.4 Discussion

The pre-test and the experiment described in this chapter demonstrate that map design decisions influence the utility of traffic maps. Some approaches outperform others. Since traffic maps are growing in popularity, and have the potential to be among the world’s most frequently viewed maps, it is imperative that they are designed properly. This section discusses the findings of the tests described earlier in this chapter.

The pre-test demonstrates that some approaches to symbolization are more intuitive than others. The results suggest that cartographers should consider semantic associations when devising color schemes. As it relates to traffic mapping, the stoplight metaphor proved to be the most intuitive symbolization strategy despite violating cartographic principles. This shows that topical context and semantic associations are vastly important in map design. Cartographers and other graphic designers need to consider the role of metaphor closely in the design phase.

3.4.1 Colorblindness and Traffic Maps

The stoplight scheme performed well in both tests, but important questions relating to colorblindness remain. Red-green colorblindness affects millions of people worldwide; these people would have trouble differentiating stoplight-themed traffic symbols. Not only do sufferers of red-green colorblindness have trouble distinguishing red and green hues, many also have similar trouble with yellow. Figure 26 depicts this effect as seen through the eyes of a reader with two of the most common color-viewing deficiencies: Deuteranopia, and Protanopia, each known to affect 1 percent of males (Cassin and Solomon, 1990). The top four rows of color in image A of Figure 26 are of obvious importance to the stoplight metaphor. Unfortunately, these are the exact same colors that many colorblind map readers have the most trouble distinguishing. Chapter 5.3.5 of this dissertation suggests a compromised symbolization approach that attempts to maintain the intuitiveness of the stoplight scheme, while not being quite so vulnerable to colorblindness.



Figure 26: Image a depicts the colors of the spectrum as viewed without a deficiency. Image B portrays the same set of colors as seen by a sufferer of Deuteranopia. Image C portrays the spectrum of colors as seen by a sufferer of Protanopia.

3.4.2 The “Everything’s Okay” principle

Another pitfall of the stoplight symbology involves graphical clutter. The maps used as stimuli in both tests described in this chapter are all simplified. They contain extremely simple (and schematic) road networks and virtually zero typography. This simplification helps isolate certain cartographic variables for analysis but is unrealistic. Realistic traffic maps include entire layers containing highway symbols, and several place name labels. Users of traffic maps rely on highway symbols and other labels to determine where congestion is (and isn’t); these layers are key for wayfinding. The stoplight symbolization, as it relates to perceptual salience, results in fairly salient symbols for every traffic condition. The red symbols denoting severe congestion are only slightly more prominent than the green symbols denoting a lack of congestion. This approach reduces the status of congestion (relative to no congestion) within the visual hierarchy and also barrages traffic-map-readers with more symbols than are necessary. The stoplight approach to traffic mapping would be analogous to a radar-based weather map using prominent symbols to depict areas with zero precipitation. Radar-based weather maps generally depict no precipitation using no symbol, accomplishing two things: allowing the reader to more clearly see the base data in these unaffected areas, and to promote the status of precipitation events within the visual hierarchy.

The red sequential approach, which also performed well in the pre-test, offers a more congruent approach to the conventional radar map. The red sequential approach depicts areas affected by severe traffic using dark red hues (similar to the stoplight

method), but unaffected areas using no symbol at all; this allows the reader to focus on base data in unaffected areas and promotes the status of traffic events within the visual hierarchy. This suggests an “everything’s okay” principle for mapping, which advises cartographers to not barrage map-readers with symbols indicating normalcy. In terms of salience, the “everything’s okay” principle states that cartographers should depict normalcy using the least salient symbols therein promoting the salience of affected places by default. This principle applies to all maps containing “affected” and “non-affected” places.

3.4.3 Estimation of Average Velocity

The routing section of the experiment exposes some interesting perceptual influences of cartographic classification. In particular, the estimation of average velocity section produces highly conditionally dependent results. Perhaps the most significant finding suggests that the participants overly weighted the lower threshold of the high-velocity class when calculating average velocity. Figure 27 contains each conditions’ legend. The “free flow” class in the Transtar condition is different than the others; while the Sigalert and PeMS classifications place their highest thresholds at 55 miles per hour, Transtar’s is at 50 miles per hour. While at first this difference may seem minute, the results suggest that it is not. While all participants consistently underestimated average velocity along the routes, the Transtar condition produced the most severe underestimates. It is unclear if this effect is an artifact of the classification or the design of the map legend; perhaps the effect would diminish if the upper class included a range (50-85) instead of a “+” sign. Regardless, current maps, including those inspiring the

three conditions of this experiment, commonly use “>,” or “+” signs in their legends. The results of this research clearly indicate this is misleading map-readers. Average free flow velocity on unencumbered highways in California is about 68 miles per hour, yet map-readers apparently underestimate free flow velocities when confronted with these legend designs. More research is needed to pinpoint the exact cause, it may be either the classification scheme, but it is more likely the presentation of that scheme within the legend.

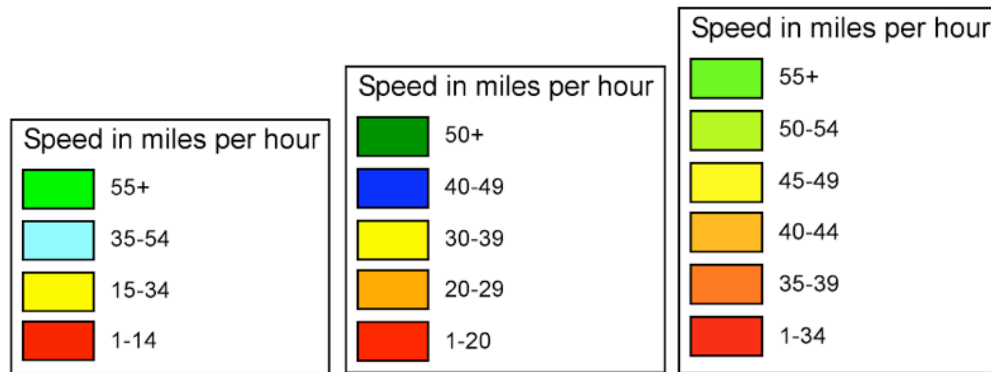


Figure 27: Legends from left-to-right Sigalert, Transtar, and PeMS

3.4.4 Classification and Traffic Description

Two questions within the “traffic description” section elicit important results. Questions 2 and 3 expose drastic differences across the classification conditions. Figures 24 and 25 summarize the feedback from these questions. The PeMS group consistently describes traffic in more severe terms than the other groups, while the Transtar group consistently chose less severe traffic adjectives than their counterparts. These are obvious artifacts of classification. Both question 2 and question 3 asked participants about areas with average velocities between 32 and 34 miles per hour.

Classifying numerical data destroys many of the numerical relationships present in raw data observations. As classes of numerical data span wider swaths along a number line, the amount of numerical precision decreases. Observations within large classes can deviate significantly from their class mean. Such is the case with the most severe class on the PeMS classification (1-34 mph). This class depicts areas of 1 mile per hour traffic and areas of 34 miles per hour traffic identically. In other words, despite its six-classes, the PeMS classification seems to equate 34 miles per hour with the most severe traffic congestion. The upper bounds for the severe classes in the Sigalert and Transtar maps are 14 and 20 miles per hour respectively. In fact, both the Sigalert and Transtar maps place 34 mph measurements near the center of their classification schemes (35mph is the center of Transtar's middle-class, and centerline of the Sigalert scheme). When the effects of these classification differences are compounded by culturally significant symbolizations the resulting maps signify very different messages to map-readers.

Every participant in the Transtar condition selected "moderate" to describe traffic at location W depicted in question 2. Conversely, only 1 participant in the PeMS condition selected "moderate;" 9 PeMS participants chose the term "heavy," 9 others chose the term "major," and 1 chose the term "jammed." It is easy to imagine how this discrepancy would manifest itself in wayfinding behavior; fewer drivers would adapt their wayfinding behavior when confronted with "moderate" conditions then would when facing "heavy" or "major" conditions.

Question 3 in the traffic description section reiterates this influence. This time participants were asked to describe conditions at location X (34, and 33 mph). Once again, there is drastic conditional dependence; a vast majority of the PeMS participants describe the conditions as “jammed,” while a majority of participants in both other conditions chose “moderate.” Together, the results of questions 2 and 3 in the traffic description confirm that classification has a pronounced influence on the perception of traffic maps, and potentially the subsequent travel behavior.

3.4.5 User Feedback

According to the user feedback, participants preferred the stoplight maps to the sequential maps. The Likert responses indicate that of the design conditions (3 classification conditions x 2 symbolization conditions) the Transtar stoplight design was most preferred. As a whole, this group responded more favorably than any other on all four of the Likert responses (Likert questions 1-4). Figure 28 depicts the summary Likert scores of the six design conditions.

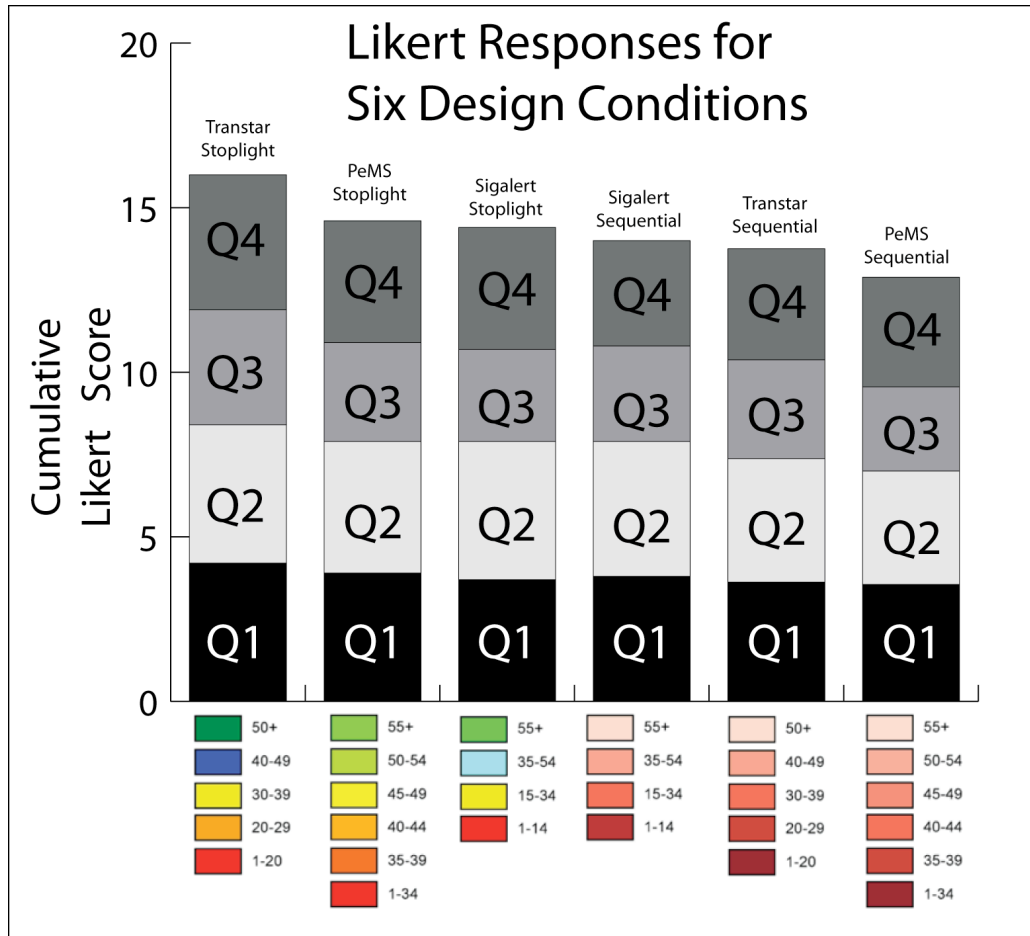


Figure 28: A stacked bar graph depicting the mean response values for Likert questions 1-4. Higher numerical responses indicate larger agreement with positive statements about the map. Conditions are arranged from high-score to low-score along the x-axis.

Each stoplight design scored more favorably than every sequential design. This is noteworthy; it seems to suggest a genuine and consistent user preference for this hue-based approach to symbolization. Although it flies in the face of cartographic principle there is no denying that this study presents evidence advocating the stoplight metaphor. The result also reveals a big question in user-centered mapmaking: what do you do if the results of the user-tests suggest cartographic techniques that violate our precious guidelines? Such is the case in this study. The results from the pre-test indicate that both

the stoplight and the red sequential symbolizations are most intuitive, but upon closer examination, the stoplight scheme performs best.

The Likert feedback presents a quantitative measure of participants' opinions. Although these quantities should be taken with a grain of salt, these measures offer an important compliment to the task-based findings presented earlier in the chapter. These quantities reflect how users consciously FEEL about the maps; the performance measures offer no such insight.

3.5 Limitations

The findings of this chapter are limited due to several factors, including the following:

Sample Size: The experiments described in sections 3.2 and 3.3 have sample sizes of 48 and 58, respectively. If more people had participated in the experiments, the results could be more meaningful. The sample sizes are relatively small due to the availability of volunteer participants; many potential subjects are unwilling to “donate” their time to graduate student research.

Sample Quality: The participants in both experiments represent an extremely limited subset of the population at large. For the sake of availability and convenience, all the participants were undergraduate students at UCSB. I acknowledge that this group is:

- **Young:** Young people may drive differently (Faster, for instance) than society at-large. The subject pool failed to include any middle-aged or elderly drivers. The behavioral responses and attitudes of college

students are likely different from those of senior citizens, and these differences may have significantly altered the findings of this research.

- Well-sighted: Young people tend to have stronger, healthier eyes that are less prone to colorblindness and other visual impairments that make map reading more difficult. Only one participant reported that they were colorblind. If the subject pool had included more visually impaired participants, the results may have differed.

Analysis:

The results of the analysis are limited by confidence intervals, and the likelihood of statistical errors. Specifically, the repetitive rejections of the null hypotheses in section 3.2.4 are vulnerable to type I error. Similarly accepting the null hypotheses with an alpha of .05 introduces the possibility of type II error. Both types of error are inherent risks of inferential statistics, but must be acknowledged as limitations.

Experimental Design

An additional set of limitations results because of the format of the experiment. Specifically, the design of the stimuli, the content of the stimuli and the media used to communicate the stimuli all present limitations relevant for both sections 3.2 and 3.3. The stimuli were designed to depict a fictitious highway network along with simulated traffic data. Although the data is sourced from actual traffic measurements, its depiction along with that of the network is simplified. In order to simplify calculations of correct answers, a “curve-less” schematic network was used. The schematic network

facilitates precise distance measurements. Unfortunately, this depiction is not an accurate depiction of realistic freeways. Freeway networks, and road maps contain curves and are much more complicated than the fictitious network used in these experiments. Similarly, the traffic depictions are simplified; traffic measurement infrastructure is not regularly or evenly placed along freeways. In their natural, realistic state, measurement devices such as inductive loop detectors (ILD) are placed irregularly. The stimuli present dots (to represent fake detectors) in a perfectly regular, symmetric form; like the schematic network depiction, this artificial regularity enables more certainty and precision in correct answer calculations. Real-world ILD placement is characterized by large gaps, and broken detectors; these characteristics if included in the stimuli would have made the stimuli more realistic, but would have also reduced the certainty of the calculations.

The Stimuli also fail to represent a real geographic location. In order to prevent the mental maps, or prior contextual knowledge from biasing subject feedback a fictitious network was generated. I adopted this approach to prevent the results from being contaminated by contextual biases caused by prior geographic knowledge. Realistic traffic map users will often be familiar with the geographic context of the network. Their wayfinding decisions stem from a combination of pre-existing cognitive maps and the real-time conditions depicted in the maps. In order to isolate the influences of cartographic design on traffic maps, it was mandatory that the potentially large influences of contextual biases be accounted for in the stimuli design stage.

The test was administered on sheets of 8.5 x 11-inch pieces of paper. This is not a realistic medium for real-time mapping. Most real-time traffic maps are viewed on computer screens, so the most realistic medium for a traffic map experiment would employ digital displays. Unfortunately, collecting participant data via computers can be burdensome. Specifically, the routing questions in both experiments had participants draw their chosen routes directly on the map. This is much easier to do with a pen than it is with computers. Similarly, paper testing allowed me to collect data from large groups of people at once. In short, paper was chosen for convenience, and the ability to collect lots of data easily, but it is less realistic than digital media.

A better test is possible; it would take more time, more money, and more participants. The strength of the results would benefit from a larger subject pool that would reduce the likelihood of type I errors as well as more clearly identify patterns or behaviors of traffic map-readers. Similarly, with additional time and money the digital stimuli could have been designed and administered on either computer displays or some other mobile computing device. Ideally, traffic map use would be tested on a variety of devices including desktop computers, mobile phones, PDA's, and in-vehicle-navigation-systems. The robustness of this kind of experiment was beyond this scope of this research.

3.6 Conclusion

The pre-test and the main experiment described in this chapter both indicate that design decisions influence the perception of traffic maps. This chapter summarizes studies that expose the specific influences of representation, symbolization, and classification. The results suggest that classification and symbolization both have significant influence on readers' perceptions while the two representation methods tested do not.

Cartographic classification influences how readers perceive traffic. Thematic maps rely on abstract symbology to communicate the spatial distribution geographic information. Thematic map-readers decode symbols to uncover meaning. The "key" to this decoding process is in the map's legend; here, like in a dictionary, terms are defined. But the results also point out a less understood effect of thematic legends. Especially in the case of ordinal or numerical data sets, thematic legends include some inherent hierarchy; some symbols denote "more," some symbols denote "less." This hierarchy by itself is quite influential. The results in this chapter show that readers are greatly influenced by a given symbol's location within this hierarchy. Particularly in the traffic description section, we see readers equating traffic severity with this hierarchical structure. It is almost as if a five-class classification of numerical or ordinal data

becomes the proverbial “scale from 1 to 5.” Some readers inevitably reduce the level of measurement of whatever statistic is being classified to this scale. This effect might be called “ordinalization;” in the case of velocity data, which is naturally at the ratio level of measurement, we see readers more swayed by the ordinal set of symbols than they are by the raw statistical information. This is what classification does, it “ordinalizes” a continuous number line into a sort of “scale from 1 to 5.” The classification method of the cartographer determines where numerical values fall on that scale. This is why the PeMS participants consistently regard 33mph as a “5” on this scale, while Transtar participants consistently 33mph conditions as a “3.” As soon as a cartographer classifies numerical data, he/she must understand he is not only reducing its level of measurement, but also steering readers’ perceptions because the classification thresholds are directly tied to legend hierarchies, and subsequent symbolization strategies.

The effect of legend hierarchies is apparent when we evaluate the traffic description results across symbolization conditions. By and large within a given classification condition, participant groups behaved similarly regardless of which symbolization (stoplight or red sequential) they viewed. This means that in the traffic description test participants were more swayed by the influence of classification than they were by symbolization. The findings suggest the following problem solving technique for this section: Readers first identify the symbols in the area of interest, look to the legend, identify the identical symbol in the legend, then choose which term based on that

symbol's place on the traffic "totem pole" created by the classification scheme. The pie charts in figure 24 clearly indicate this "totem pole" effect.

Map classes MEAN something to the reader; therefore it is important that they are based on something meaningful. Some thematic maps conveniently have natural divisions relevant to their data topic. For example in degrees Celsius, zero and one hundred degrees provide meaningful break points. But when there are no convenient thresholds, it is up to the cartographer to create them. It is evident from the diversity in current approaches that there is no obvious solution to this problem. This is why it is important to survey potential traffic-map readers to uncover how people relate velocity to traffic severity. We can use survey data to help locate, or at least approximate meaningful divisions along the velocity continuum. This same approach could apply to other commonly mapped variables such as precipitation, temperature, or census statistics. While classification algorithms such as quantiles, or equal intervals facilitate certain types of spatial analysis, it is also important to consider topical meanings that may conform more closely to cultural meanings. Cartographers frequently take advantage of cultural meaning in the symbolization phase of map design; they should consider it in the classification phase too.

Symbols on maps also mean things to readers. Cartographers are often wise to craft symbols in a way that reduces the cognitive load of decoding. Maps with logical symbol design are easier to read. The little airplane to denote an airport, the interstate shield symbol to depict an interstate highway, and using cyan for water are each examples of logical, metaphorical symbol design. It is evident from the uniformity of existing

approaches that many people find the stoplight metaphor quite intuitive; this research confirms that. There is no question that most readers can immediately infer what red, yellow, and green mean on traffic maps. The question is: Do the advantages of the stoplight metaphor, specifically intuitiveness, outweigh the disadvantages? The main disadvantages involve colorblindness and a tendency to violate the “everything’s ok” principle by prominently depicting unaffected areas.

It’s easy to combine the strengths of the stoplight and red sequential approaches into a happy medium where cartographic principles are not violated, yet we can still employ the semaphore metaphor. By replacing the green symbol with a clear, or invisible symbol we can reduce graphic clutter and immediately promote the salience of affected areas. This also makes the progression along the legend more adherent with Bertin’s principles. The evolution of the symbols from clear to yellowish to reddish is much more of a “sequential” color scheme. Chapter five describes the creation of a new traffic map prototype that employs this exact idea; unaffected areas are not symbolized. Chapter six describes a study that measures users’ performances using the prototype versus existing more loyal stoplight designs.

IV. TRAFFIC SURVEY

CHAPTER 4 - SURVEY

4.1 Introduction

This chapter reports on a second survey of 58 subjects aimed to reveal how people relate velocity measurements with traffic congestion. The participants filled out the short two-page questionnaire summarized below. The goal of this chapter is to demonstrate that cartographers can inform classification decisions with user feedback. The questions below are each designed to elicit quantitative relationships linking common expressions of congestion (mph, terminology) to participants' perceptions of congestion. I believe traffic mapping could benefit from these kinds of surveys, and although this survey is brief, and limited to 58 participants, it stands as a proof-of-concept for "user-informed" classification.

Traffic survey

Please take a few minutes to complete this survey. It will help me compile some background information for my PhD research. Thank you very much!

1. What do you think the average velocity is for automobiles driving along a freeway with absolutely no traffic congestion? _____ mph
2. What do you think the average velocity is for automobiles driving along a freeway with:
 - Minor traffic congestion _____mph
 - Moderate traffic congestion _____mph

- Major traffic congestion _____mph
3. Assuming you were driving on a freeway and in a hurry, which kind of traffic conditions do you believe would slow you down more?
- A) “Stop and Go” traffic conditions
- Or
- B) “Heavy” traffic conditions
4. Rank the following terms in order from 1 to 4 from LEAST severe to MOST severe as they relate to freeway traffic congestion, with 1 being the LEAST severe and 4 being the MOST severe:
- Stop and Go _____
 - Heavy _____
 - No Congestion _____
 - Moderate _____
5. Imagine you are about to embark on a drive from point A to point B. The drive will require you to travel exclusively on freeways. Without any traffic the trip from point A to point B will take you about 20 minutes. In your opinion how long would this same trip take under consistently “congested” conditions? _____ minutes
6. Imagine you are about to embark on a drive from point C to point D. The drive will require you to travel exclusively on freeways. Without any traffic the trip from point C to point D will take you about 25 minutes. In your opinion how long would this same trip take under consistently “heavy traffic” conditions? _____minutes
7. Imagine you are about to embark on a drive from point J to point K. The drive will require you to travel exclusively on freeways. Without any traffic the trip from point J to point K will take you about 30 minutes. In your opinion how long would this same trip take under consistently “minor traffic” conditions? _____ minutes
8. Imagine you are about to embark on a drive from point Y to point Z. The drive will require you to travel on freeways. Without any traffic the trip from point Y to point Z will take you about 40 minutes. In your opinion how long would this same trip take under consistently “stop and go” conditions? _____ minutes
9. How often do you drive in freeway traffic?
- A) Never
- B) Rarely

- C) At least once a month
- D) At least once a week
- E) Several times per week

10. Do you ever consult sources of traffic information such as radio or television reports?

11. Are you familiar with real-time traffic maps? YES or NO

12. Have you ever used a real-time traffic map? YES or NO

12A. If so, how often do you use them?

- A) Almost Never
- B) Rarely
- C) Every once in a while
- D) Frequently
- E) All the time

12B. What website do you visit to view real-time traffic maps? _____

Personal information:

Gender: M or F

Age: _____

Major: _____

Do you own a car? Yes No

Surveys of map-readers can help inform map design. This research attempts to link survey feedback to specific map design decisions. Although the sample in this survey may not be an optimal cross-section of potential traffic map users, the guiding

principles could certainly apply to a more thorough sample pool. The idea is to use surveys to reveal popular perceptions and then apply these revelations to cartographic classification.

The goal of this particular survey was to uncover perceptions relating traffic congestion with both velocity (in miles per hour) and commonly used traffic terminology such as “stop and go,” or “heavy.” The idea is derive average velocities associated with varying severities of traffic to help logically classify velocity measurements on traffic maps. The diversity of current classification approaches on existing maps indicates a lack of common ground; the survey approach can help us arrive at a convergence and down the road could even lead to a standard for traffic map classification.

4.2 Survey Methods and Results

The 58 subjects were all undergraduate students at the University of California, Santa Barbara enrolled in the Geography of Surfing in the Spring Quarter of 2007. The ages of the subjects ranged from 18 to 24 years old, with a mean of 19.4 years old. 41 subjects were male, 17 were female. The students were from a diverse set of majors including biology, economics, film studies, communications, and many of the students had undeclared majors.

42 of the 58 subjects indicated that they owned their own vehicle. When asked how frequently they “drove in freeway traffic,” 2 subjects indicated “never,” 23 subjects indicated “rarely,” 10 subjects indicated “at least once a month,” 13 subjects indicated

“at least once a week,” and 10 subjects indicated “several times per week.” 16 of the 58 subjects indicated that they “consult sources of traffic information such as radio or television reports,” while 22 of the 58 reported that they were “familiar with real-time traffic maps.” 16 of 57 subjects indicated that they had used a real-time traffic map. Only 2 subjects indicated that they “frequently” used real-time traffic maps, and 4 subjects said they used them “once in a while.” Within this subject pool, the most popular real-time traffic map is the Sigalert.com map, with 5 subjects indicating they use Sigalert. 2 subjects indicated they use real-time traffic maps from the California Department of Transportation.

The survey was presented to the participants on 1 piece of 8.5 x 11 inch piece of paper. There were questions on both the front and the back of the page. Participants indicated their answers with pens. The test was administered in a large classroom, participants were seated at desks while they took the survey, and instructed not to ask questions or talk to one another. The survey had three distinct sections; each section and its results are described in detail below:

4.2.1 The Velocity Section

The first section of the survey asked the subjects about average velocities “for automobiles driving along a freeway” under the following conditions: “absolutely no traffic,” “minor traffic congestion,” “moderate traffic congestion,” and “major traffic congestion.”

Within the velocity section, subjects were asked two questions, and provided the following responses:

1. What do you think the average velocity is for automobiles driving along a freeway with absolutely no traffic congestion? _____ mph

Mean: 75.25 mph

Median: 75 mph

Standard Deviation: 4.93

2. What do you think the average velocity is for automobiles driving along a freeway with:

- Minor traffic congestion _____ mph

Mean: 65.30 mph

Median: 65 mph

Standard Deviation: 7.42

- Moderate traffic congestion _____ mph

Mean: 52.98 mph

Median: 55 mph

Standard Deviation: 11.81

- Major traffic congestion _____ mph

Mean: 28.36 mph

Median: 25 mph

Standard Deviation: 17.46

4.2.2 The Terminology Section

The second section of the survey asked subjects to rank the following terms (commonly used on traffic maps) in order of severity: “Stop and Go,” “Heavy,” “No Congestion,” and “Moderate.” These terms were taken from the Bay Area traffic map

created by 511.org (Figure 29). The goal was to determine whether or not subjects would consistently identify the correct order of these adjectives. Along with symbolization strategies, and legend design, it's important for cartographers when using the ordinal level of measurement to imply congestion hierarchies by using language with a clear order. Ordinal ambiguity can lead to confusion and misinterpretation.

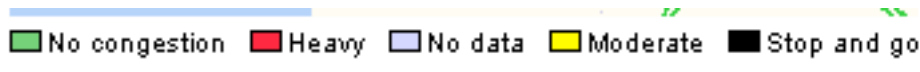


Figure 29: The legend from the Bay Area traffic map created by 511.org. There is an ambiguous order to the terms caused by poor legend design, symbolization, and poor choice of language.

The Terminology Section included two questions, and users provided the following feedback:

3. Assuming you were driving on a freeway and in a hurry, which kind of traffic conditions do you believe would slow you down more?

A) **“Stop and Go”** traffic conditions
Or

B) **“Heavy”** traffic conditions
Response: 33 subjects chose “Stop and Go,” while the other 25 subjects chose “Heavy”

4. Rank the following terms in order from 1 to 4 from LEAST severe to MOST severe as they relate to freeway traffic congestion, with 1 being the LEAST severe and 4 being the MOST severe:

- Stop and Go _____
- Heavy _____
- No Congestion _____
- Moderate _____

Response: 33 subjects provided the following order: “No Congestion,” “Moderate,” “Heavy,” and “Stop and Go.” 22 other subjects ranked the terms this way: “No Congestion,” “Moderate,” “Stop and Go,” and “Heavy.”

4.2.3 The Travel Time Index Section

The third section asked subjects to quantitatively estimate delays in travel time caused by various severities of congestion. The goal of this section was to uncover relations pertaining to traffic congestion with a metric other than velocity. Travel time is a common expression of distance in our society, and using simple arithmetic we can compare how people relate travel time, velocity, and common terms used to describe congestion.

The Travel Time Index Section asked subjects four questions, and subjects provided the following results:

9. Imagine you are about to embark on a drive from point A to point B. The drive will require you to travel exclusively on freeways. Without any traffic the trip from point A to point B will take you about **20 minutes**. In your opinion how long would this same trip take under consistently “**congested**” conditions? ____ minutes

Mean Response in Minutes: 37.23 = 1.86 TTI

Median Response in Minutes: 35 = 1.75 TTI

10. Imagine you are about to embark on a drive from point C to point D. The drive will require you to travel exclusively on freeways. Without any traffic the trip from point C to point D will take you about **25 minutes**. In your opinion how long would this same trip take under consistently “**heavy traffic**” conditions? __ minutes

Mean Response in Minutes: 51.34 = 2.05 TTI

Median Response in Minutes: 50 = 2.00 TTI

11. Imagine you are about to embark on a drive from point J to point K. The drive will require you to travel exclusively on freeways. Without any traffic the trip from point J to point K will take you about

30 minutes. In your opinion how long would this same trip take under consistently “**minor traffic**” conditions? _____ minutes

Mean Response in Minutes: 37.5 = 1.25 TTI

Median Response in Minutes: 36.25 = 1.21 TTI

12. Imagine you are about to embark on a drive from point Y to point Z. The drive will require you to travel on freeways. Without any traffic the trip from point Y to point Z will take you about 40 minutes. In your opinion how long would this same trip take under consistently “**stop and go**” conditions? _____ minutes

Mean Response in Minutes: 81.03 = 2.03 TTI

Median Response in Minutes: 75 = 1.88 TTI

4.3 Survey Discussion

Although a pool of 19-year-old surfing students at UCSB may not represent an optimal cross-section of traffic map-readers at large, their feedback is nonetheless helpful. The feedback from this survey can be used to help classify velocity data for traffic mapping. This section describes the cartographic utility of the survey feedback.

The results from the terminology section reveal some dangers with ordinal traffic terms. 33 subjects indicated that they felt “stop and go” conditions were more severe than “heavy” conditions, while 25 subjects suggested the opposite. The Bay Area traffic map, created by 511.org, uses both of these terms in a 4-class ordinal classification scheme. Independent of cues garnered from symbolization and legend design, the feedback from this survey indicates that there is not much of a difference in readers’

perceptions of “stop and go” and “heavy” conditions. Feedback from the travel time section further supports this finding; the derived mean travel time index for “heavy” traffic is 2.05 and for “stop and go” traffic is 2.03. These values are essentially identical, meaning these subjects find these terms to both convey very similar severities of traffic. Ordinal traffic terms should must have an obvious order with evident steps between them. Related terms like “minor, moderate, and major” are likely superior in this regard.

The velocity and travel time sections of the survey aimed to uncover more quantitative findings. Feedback from question 1 can be used to set more realistic numerator for a travel time index. Travel time index can be calculated by dividing a free flow velocity by a congested velocity. The group of subjects returned a mean of 75.25 miles per hour for question 1, suggesting that they estimate flow to travel about 75mph when there is “absolutely no traffic.”

The feedback from question 2 allows for the calculation of travel time indices for “minor,” “moderate,” and “major” traffic congestion. By dividing 75.25 by 65.30 we can derive a group travel time index of 1.15 for “minor” traffic congestion, and derive similar values of 1.42, and 2.65 for “moderate,” and “major” respectively. We can also use these values to classify velocity in a fashion that corresponds to this group of respondents. So, although this survey pool is a poor cross-section of society at large, an expanded survey pool could produce more valid results applicable to a broader swath of readers.

Given the mean responses for question 2 (“minor” = 65, “moderate” = 53, “major” = 28), we can create a classification scheme that would apply specifically to this group

of readers. Figure 30 summarizes the classification process. By placing class breaks halfway in between the mean responses we end up with four classes. These four classes approximate a velocity classification scheme based on the survey feedback. This survey technique is a novel way to approach classification. Previous research (Jenks and Caspall, 1971; Evans, 1977) has explored classification algorithms such as nested means, equal intervals, and quantiles, and found that different algorithms are necessary due to diverse map audiences, and purposes. For example Brewer and Pickle (2002) determined that human subjects prefer quantile classifications when comparing two or more choropleth maps. However, no research to this point has focused on the perceptions of potential map-readers as a source for classification on thematic maps.

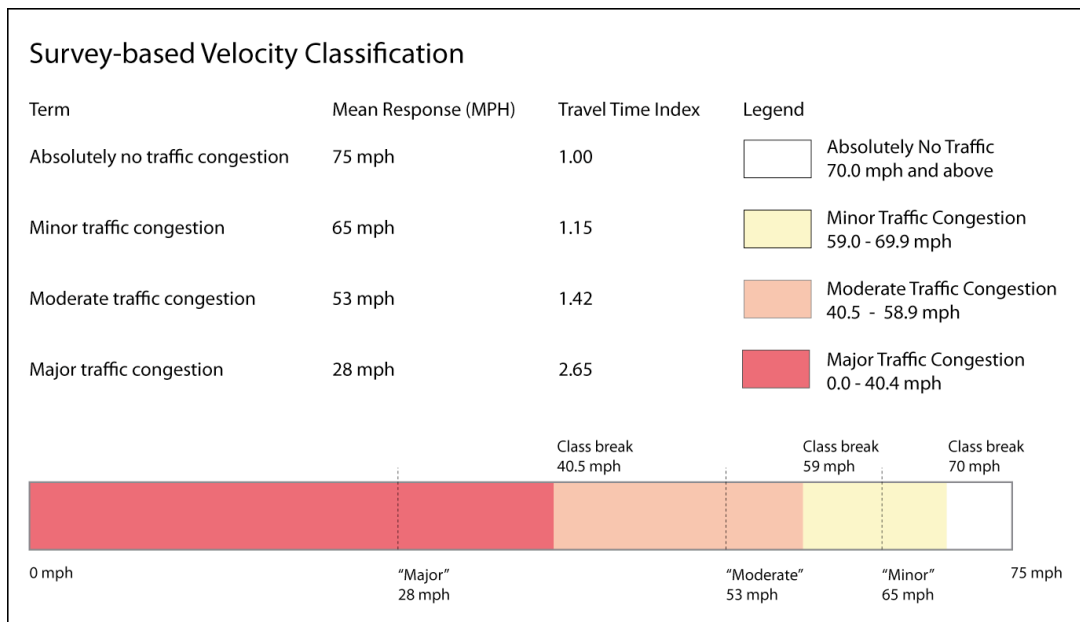


Figure 30: A User-informed classification scheme for traffic maps. The results from a questionnaire can be used to create class breaks for thematic maps. In this case class breaks are placed halfway in between mean responses to survey responses. The resulting may be more congruent with the traffic perceptions of the participants than other schemes.

V. A NEW TRAFFIC MAP

CHAPTER 5 – A NEW TRAFFIC MAP

5.1 Introduction

Along with exploring major design issues relating to traffic maps, a core goal of this dissertation is to apply research findings toward the construction of a new user-informed traffic map. This chapter demonstrates how we can apply user feedback to inform cartographic design. The new map's design is based on the findings of Chapters 3 and 4. The new map also represents a proof-of-concept designed to demonstrate the feasibility of Scalable Vector Graphics (SVG) to deliver vector-based, compact real-time traffic maps to the Internet.

5.2 Background

This dissertation addresses problems associated specifically with cartographic displays within Advanced Traveler Information Systems (ATIS). Maps included in ATIS need to be clear, legible, portable, and versatile. With the growth of In-Car-Navigation Systems and wireless communications, there is an increasing need to make the production and dissemination of mobile traffic maps more efficient. Current maps are not properly designed. Although there has been a wealth of ATIS research, there is a surprising gap regarding the graphic communication of information to travelers.

One goal of cartography is to achieve graphic clarity. Cartographers strive to accurately present thematically relevant geographic information to map-readers. Recent cartographic research has explored the idea of salience in maps. In a map context, salience refers to graphic prominence or obviousness. For centuries, mapmakers have aimed to make thematically relevant information appropriately salient. Lowe (1999) found that map-readers tend to primarily extract perceptually salient information rather than thematically relevant information. The goal of the cartographer then would be to pair thematically relevant information with perceptually salient graphic characteristics. From an ATIS standpoint, a transportation map needs to efficiently present map-readers with salient representations of relevant network characteristics. These characteristics include base map features such as nodes and links, as well as important dynamic features such as congestion events and accidents. Dynamic traffic maps need to clearly depict traffic conditions to travelers in pre-trip as well as en route situations. Current maps (Figure 31) create clutter by failing to pair thematically relevant network characteristics with perceptually salient graphic elements. These maps are difficult to read and the most relevant information is often hard to discern (Goldsberry, 2005). Cartographers can enhance the clarity of traffic maps in two ways: first, by improving the convergence of thematic relevance and perceptual salience, and secondly, by reducing the graphic prominence of less pertinent information. One goal of the prototype's design is to increase clarity in real-time traffic maps by prioritizing the graphic prominence of relevant features while minimizing the distracting influences of irrelevant information.



Figure 31: Sensor locations in Los Angeles; the green symbols are salient, yet only indicating “normal” conditions

One way to elevate network characteristics like nodes and links, is to employ a schematic map design. Egenhofer (1991) claims that topological diagrams more accurately mimic the way that humans cognize spatial environments. Although, this seems to contradict the congruence principle of graphics, perhaps it suggests a cognitive congruence principle in which the content and format of the graphic should correspond to the cognitive format of the entity to be conveyed. The Beck map of the London Underground might be an example of this cognitive congruence. The graphic is half schematic diagram and half map. Beck, an electrical draftsman, created unprecedented clarity in the system map by prioritizing the topological connectivity of the system and dismissing the geographic duplication as secondary. Initially, Beck’s map was disregarded because it contained no consistent cartographic scale, but in 1933 the first Beck map was published, and Harry Beck was paid five pounds (Short, 2003). The map now serves as a defining symbol of the Underground, is printed over 60 million times each year (Short, 2003), and Beck’s technique has proven to be very popular.

Prior to the Beck map, maps of the underground were much more traditional. These maps emphasized geographic direction, and distances between stations. It was fairly radical to challenge these conventions. But, Beck must have noticed that the old underground maps were saturated with thematically irrelevant information. By

removing the irrelevant information, and distorting the geographic distance and directions, Beck created a clear, efficient schematic diagram of a transportation network. Can Beck's ideas improve mobile maps of highway networks in southern California? Can purposeful stretching and thoughtful eschewing simplify the complicated geographic details of the freeway network and enhance the clarity and efficiency of mobile maps included in ATIS? Montello (2005) suggests that maps used for navigation do not need to communicate complete metric information. Specifically, when the map is used to navigate on a constrained path network system, navigators might only want to know the topology of nodes and links. If so, then schematic maps such as the Beck map, should be evaluated for highway map applications. The dangers of the schematic map include over-interpretation. Berendt et al, (1998) warn that some map-readers display distorted spatial knowledge as a result of schematic maps that stretch and eschew geographic distances and directions. Further research is needed to quantify the extent of these distortions; Battersby's (2007) dissertation includes methods to assess mental map distortion caused by map projections could be translated to similarly assess mental map distortion caused by schematic network maps.

Beck's diagram has been described as a "postmodern map" (Cummings and Wilson, 2002), and this research wonders if this "postmodern" cartography represents an example, incidental as it may be, of an answer to Golledge's (2002) call for network depictions to mimic the cognitions of the map reading public. Beck, as an electrical draftsman, created the diagram to mimic electrical circuit diagrams of the day, but in doing so also diagrammed his conception of the network. Fortunately, his conception

of the network has been very useful to millions of travelers. Harry Beck, perhaps unknowingly and accidentally, created one of the most important network maps in history.

Dynamic traffic maps also need to be portable. In an era of emerging wireless communications, it is important for information designers to acknowledge the constraints of telecommunications infrastructure. In this regard, mobile map designers need to account for efficiency, as it pertains to information passage. Specifically, it is important that mobile ATIS maps account for file size and bandwidth in the design stage. Current maps often employ sub-optimal image-based data formats resulting in large, “clunky” files that require greater amounts of bandwidth and longer download times. In this sense, current maps are not appropriately portable. This chapter proposes methods that employ vector data formats, which result in clearer, more portable maps (smaller file sizes).

Lastly, with increasing amounts of mobile device diversity, it is important that ATIS maps are versatile. The maps must be designed in such a way that they are legible on a large array of devices including desktop computers, laptops, PDA’s, INVS displays, and cell phones. These devices represent both the core of ATIS communication and an important new challenge for cartographers. Current image-based map displays are not scalable and therefore perform poorly on devices with diverse screen sizes, color capabilities, and pixel resolutions. The methods outlined in this chapter include the use of Scalable Vector Graphics (SVG), a format designed with this kind of versatility in mind.

SVG is a file format designed to distribute vector graphics on the World Wide Web. Although recent research has demonstrated SVG's ability to support Internet maps, it remains surprisingly unpopular in the American cartographic community. A vast majority of Internet vector maps here are created with Flash, a proprietary format now owned by the Adobe Corporation. The prototype created as a part of this dissertation proves that a new generation of vector-based real-time Internet maps can be created using SVG, a free-of-charge, and standards-based open-source format less vulnerable to proprietary influences.

5.3 Map Design Methods

This section describes the creation of a prototype map designed in accordance with the findings of Chapters 3 and 4 as well as the survey reviewed in this chapter. The new map is also designed in accordance with previous research findings to improve graphic performance online, in wireless environments, and on small displays.

5.3.1 Data Handling

Real-time traffic maps require real-time traffic data; this section describes the processes involved with acquiring and manipulating streaming traffic data for map production. This project uses data from the California Freeway Measurement Project (PeMS). Together with the California Department of Transportation, PeMS collects and maintains real-time traffic data sourced from the state's thousands of inductive loop detectors. Inductive loop detectors are essentially coils of wire buried in the freeway pavement; when a vehicle passes over the ILD it disturbs the inductance of the circuit,

and the timing of this disturbance is used to measure velocities. The result of PEMS' ILD measurement infrastructure is a dynamic database stored in Berkeley, California. The prototype interfaces with this database to iteratively retrieve data updates via File Transfer Protocol (FTP). My colleague, Andreas Neumann and I coded the a script designed to retrieve the compressed District 7 (Los Angeles County) file from the PeMS FTP server, "unzip" the file, and store it locally for subsequent cartographic operations. Here is the code:

```
#first download the data

$status = system("wget -P /Users/kirkgoldsberry/Desktop/diss/
ftp://var_kpg109:a5r\!fpsy\@128.32.48.245/D7/Data/5min/5minagg_latest.txt.gz");
if ($status != 0) {
    die "something went wrong with downloading the traffic data!\n";
}

#unzip the data

$status = system("gzip -d -f /Users/kirkgoldsberry/Desktop/diss/5minagg_latest.txt.gz");
if ($status != 0) {
    die "something went wrong with unzipping the data!\n";
}

#open text-file

open(TRAFFICFILE, "</Users/kirkgoldsberry/Desktop/diss/5minagg_latest.txt") || die "could not open traffic textfile for
reading!";

open(OUTFILE, ">/Users/kirkgoldsberry/Desktop/diss/trafficdata.js") || die "could not open outfile for writing!";

my $line;
my @data;
my $i;

my $datetime = <TRAFFICFILE>;
```

```

#cut off the carriage return/linefeed
chomp($datetime);
print OUTFILE "myMapApp.trafficDate`Time = \"$datetime\";\n";
print OUTFILE "myMapApp.trafficData = new Array();\n";

while(<TRAFFICFILE>) {
    $line = $_;
    chomp($line);
    @data = split(/,/,$line);
    for($i=0;$i<=$#data;$i++) {
        if (length($data[$i]) == 0) {
            $data[$i] = "undefined";
        }
    }
    print OUTFILE "myMapApp.trafficData[$data[0]] =
{flow:$data[1],occupancy:$data[2],speed:$data[3],vmt:$data[4],vht:$data[5],q:$data[6],travel_time:$data[7],delay:$data[8],numsamples:
$data[9],pctobserved:$data[10]};\n";
}

close(OUTFILE);
close(TRAFFICFILE);

```

The result of this script is an automatically updated, locally stored traffic data file containing velocity data for each of Los Angeles County’s Inductive Loop Detectors (ILD); here is an example of the output:

```

myMapApp.trafficDate`Time = "07/09/2007 07:25:00";
myMapApp.trafficData = new Array();
myMapApp.trafficData[717935] =
{flow:115,occupancy:.0716,speed:59.1,vmt:63.25,vht:1.1,q:59.1,travel_time:undefined,delay:.1,numsamples:0,pctobserved:0};
myMapApp.trafficData[717622] =
{flow:278,occupancy:.0652,speed:63.2,vmt:222.4,vht:3.5,q:63.2,travel_time:undefined,delay:.1,numsamples:9,pctobserved:25};

```

```

myMapApp.trafficData[765151] =
{flow:undefined,occupancy:undefined,speed:undefined,vmt:undefined,vht:undefined,q:undefined,travel_time:undefined,delay:0,num
samples:0,pctobserved:0};
myMapApp.trafficData[718126] =
{flow:465,occupancy:.1442,speed:40.7,vmt:344.1,vht:8.5,q:40.7,travel_time:undefined,delay:3.16,numsamples:0,pctobserved:0};
myMapApp.trafficData[759385] =
{flow:115,occupancy:.0716,speed:59.1,vmt:14.375,vht:.2,q:59.1,travel_time:undefined,delay:.02,numsamples:0,pctobserved:0};
myMapApp.trafficData[767395] =
{flow:undefined,occupancy:undefined,speed:undefined,vmt:undefined,vht:undefined,q:undefined,travel_time:undefined,delay:0,num
samples:2,pctobserved:0};
myMapApp.trafficData[764669] =
{flow:115,occupancy:.0716,speed:59.1,vmt:54.05,vht:.9,q:59.1,travel_time:undefined,delay:.08,numsamples:0,pctobserved:0};
myMapApp.trafficData[760812] =
{flow:190,occupancy:.0657,speed:65.6,vmt:309.89,vht:4.7,q:65.6,travel_time:undefined,delay:0,numsamples:20,pctobserved:100};

```

The above code includes a time stamp and data from eight ILD for July 9th, 2007 at 7:25AM. Each ILD record includes a unique identifier, and ten measurements, table 6 defines each measurement:

<i>Measurement Term</i>	<i>Definition</i>
VDS_ID	Unique station identifier
FLOW	Flow (vehicles/5-minutes)
OCCUPANCY	Average occupancy as a percentage (0 - 1)
SPEED	Flow-weighted average of lane speeds
VMT	Total vehicle miles traveled over this section of freeway
VHT	Total vehicle hours traveled over this section of freeway
Q	Measure of freeway quality (VMT/VHT)
TRAVEL_TIME	Not in use
DELAY	Vehicle hours of delay
NUM_SAMPLES	# of samples received in the 5-minute period
PCT_OBSERVED	Percentage of individual lane points from working detectors that were rolled into the station's 5-minute values.

Table 6: Terms and definitions for PeMS database fields.

This sets the stage for subsequent cartographic design procedures that will represent, classify and symbolize the velocity data. These procedures are described in the following sections.

5.3.2 Base Map Design

The prototype includes an octilinear schematic base map of Los Angeles County freeways. Octilinear diagrams contains lines drawn in one of eight directions, each oriented at some multiple of 45 degrees. The schematic octilinear map is chosen because it emphasizes the network's node-and-link topology. Although schematic maps like this eschew geographic congruence and may cause distorted mental maps (Montello, 2002) they reduce the prominence of geographic minutiae within the visual hierarchy. This allows depictions of the overlaying thematic symbology to more easily achieve perceptual salience. In terms of figure-ground, by reducing the prominence of the graphic's ground, we elevate the salience of the graphic's figure by default. Thus, the traffic symbols can achieve salience without extreme applications of visual variables. The thematic traffic symbology on many current traffic maps has to overcome overly salient base map depictions. This phenomenon explains the large, saturated and bright symbols we see on many of the world's traffic maps. Figure 32 includes a portion of the schematic base map used in the prototype. With a few exceptions in downtown Los Angeles, the network intersections are loyal to their original locations, but the links between the intersections are generalized to adhere to octilinear constraints. The most potent way to reduce an element's place within a graphic's visual hierarchy is to simply eliminate it altogether; this relates to the fundamental ideas of cartographic selection.

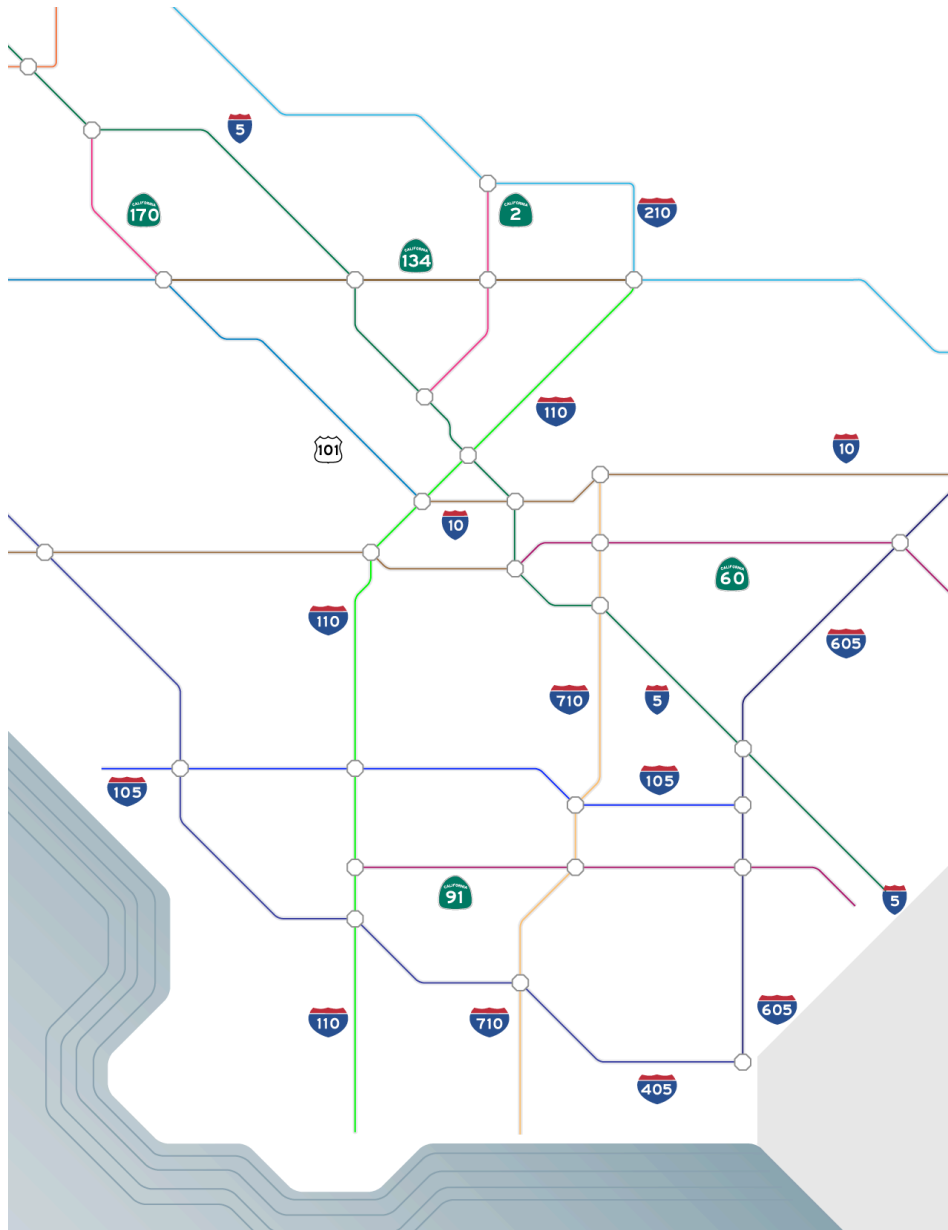


Figure 32: Los Angeles freeways depicted in an octilinear diagram.

5.3.3 Representation

Chapter 3 investigated whether subjects preferred dot-based or segment-based representations of traffic, but the results indicate no preference. Due to this finding and

surprisingly irregular placement of ILD (figure 33) about the Los Angeles freeways, the prototype employs a segment-based representation. In the segment-based approach each ILD influences a segment of a highway, and sets of these segments comprise network links. As velocity measurements are classified and symbolized each segment becomes a meaningful symbol in itself. The result is a more continuous, but more uncertain depiction of velocity than the dot-based approach.



Figure 33: From the PeMS website, an image demonstrating the irregular placement of ILD on the Los Angeles freeways. ILD are not equally separated along the highways, which is not a bad thing. The density of ILD is higher along busier sections of the f



Figure 34: A highly zoomed in image of the segment-based representation. In this image, the variable length of the blue segments is a reflection of the irregular placement of the ILD along US 134 near Burbank, California.

5.3.4 Classification

This dissertation examines the classification of velocity on traffic maps. Chapter 3 reveals that subjects performed map tasks marginally better with fewer classes. This result along with Harrower's (2002) assertion that dynamic maps should only contain a few classes inspired a four-class approach for the prototype. This dissertation finds no significant evidence that advocates a certain number of classes for traffic maps nor does it make any assertions pertaining this important design decision. However, it is important that traffic maps not have too many or too few classes. Using common sense, and previous cartographic research guidelines, it is not a bold assertion to suggest two-classes is too few. Harrower (2003) suggests that dynamic maps should have two or three classes, and choropleth research has advocated 5-7 classes (Slocum et al., 2005). Since real-time traffic maps are somewhat dynamic, technically they are "animated" since a new frame is presented every five minutes, the prototype adopts a compromised approach employing 4 classes, meeting halfway between harrower's advice and conventional choropleth research. Also, of the existing real-world maps surveyed in chapter 2, the median class value is 4.

Classification of the velocity data occurs using JavaScript. The classification and symbolization occurs in these lines of code:

```
if (myMapApp.trafficData[id].speed) {  
    if (myMapApp.trafficData[id].speed <= 20) {  
        lineColor = "rgb(203,24,29)";  
    }  
    else if (myMapApp.trafficData[id].speed > 20 && myMapApp.trafficData[id].speed <= 35) {  
        lineColor = "rgb(251,106,74)";  
    }  
}
```

```

    }
    else if (myMapApp.trafficData[id].speed > 35 && myMapApp.trafficData[id].speed <= 45) {
        lineColor = "rgb(252,174,145)";
    }
    else if (myMapApp.trafficData[id].speed > 45) {
        lineColor = "rgb(251,251,251)";
    }
}

```

This example results in a four-class map with breaks at 20, 35, and 45 miles per hour. The symbol colors are specified using red, green, and blue specifications.

5.3.5 Symbolization

The four-class classification scheme requires four unique symbols. The findings in chapter 3 suggest that the stoplight metaphor creates the most intuitive traffic maps. Unfortunately, as discussed in chapter 3, this symbolization approach violates two significant cartographic guidelines. By replacing the stoplight's green hue with a clear or invisible symbol we are left with a more cartographically obedient symbolization that is still fairly intuitive. The prototype employs a version of this compromised stoplight metaphor that is more sequential in nature, and less vulnerable to colorblindness. Figure 35 includes the four-class color scheme used in the prototype.

The green hue within the stoplight scheme disrupts a potential sequence that involves a gradual evolution of the visual variable, lightness. Previous cartographic research has indicated that people can easily associate varying lightness values with varying quantities of a statistic. With this in mind, the problem with the stoplight

metaphor is that there is no consistent directionality in lightness changes as we progress from low velocity values to high velocity values; the lightness values are lowest toward the yellow center of the scheme, almost creating an unintentional diverging color scheme. This is more evident when we reduce these gradients to grayscale, as seen in Figure 36.

This variation in lightness is important for two reasons: salience and contrast. With a light-colored background darker symbols are naturally more perceptually salient which causes the stoplight symbolization to produce highly salient marks for both low and high values of the variable, while symbols in the middle are demoted within the visual hierarchy. A unipolar sequential statistic should not only be depicted with a sequential color scheme, there also should be a corresponding sequence in perceptual salience along the legend's progression. This way, the reader can subconsciously equate graphic prominence with statistical value. The stoplight scheme fails to facilitate this equation. Along the same lines, mobile computing is characterized by bright reading environments that can make reading an LCD display particularly difficult. Insufficient contrast amounts within a map's symbolization scheme can make certain symbols hard to read, or even invisible.

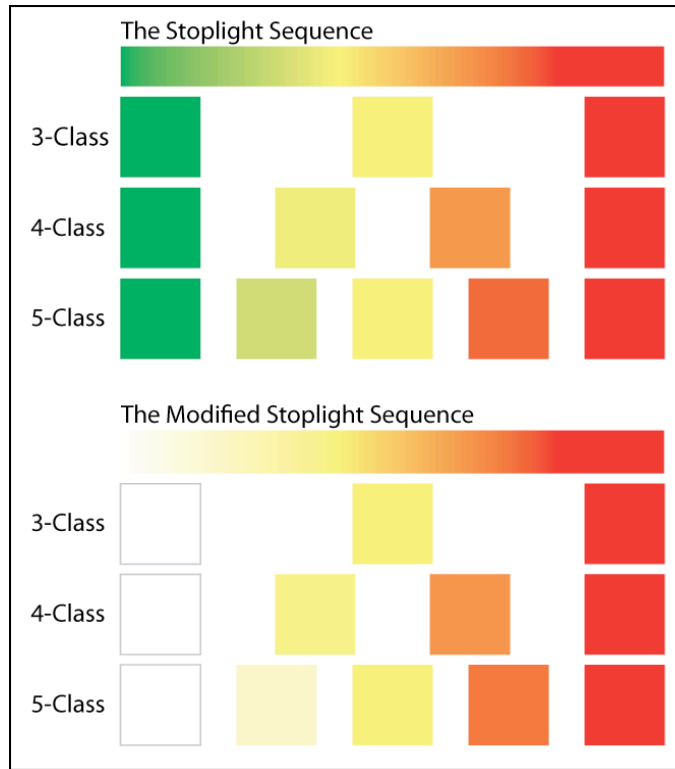


Figure 35: Removing the green hue from the stoplight sequence allows for a more sequential graduation of symbols.

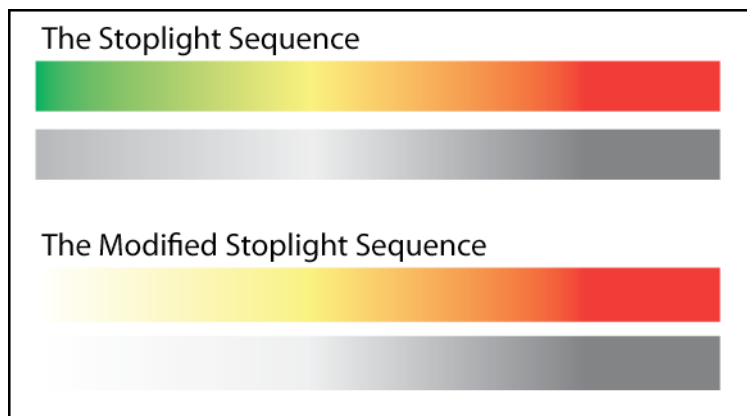


Figure 36: Changes in the visual variable, lightness are revealed upon grayscale conversion. If users subconsciously relate lightness with quantity then the stoplight sequence is suboptimal. The modified stoplight sequence, absent the green hue, includes a linear

5.4 Map Design Results

The map design phase consisted of data handling, base map design, and thematic cartographic design decisions involving representation, classification and symbolization. The end result of the map design process is a single SVG file. The file contains the map as well as some interface controls developed by Andreas Neumann at ETH in Switzerland. Figures 37 - 40 include screen captures of the completed application.

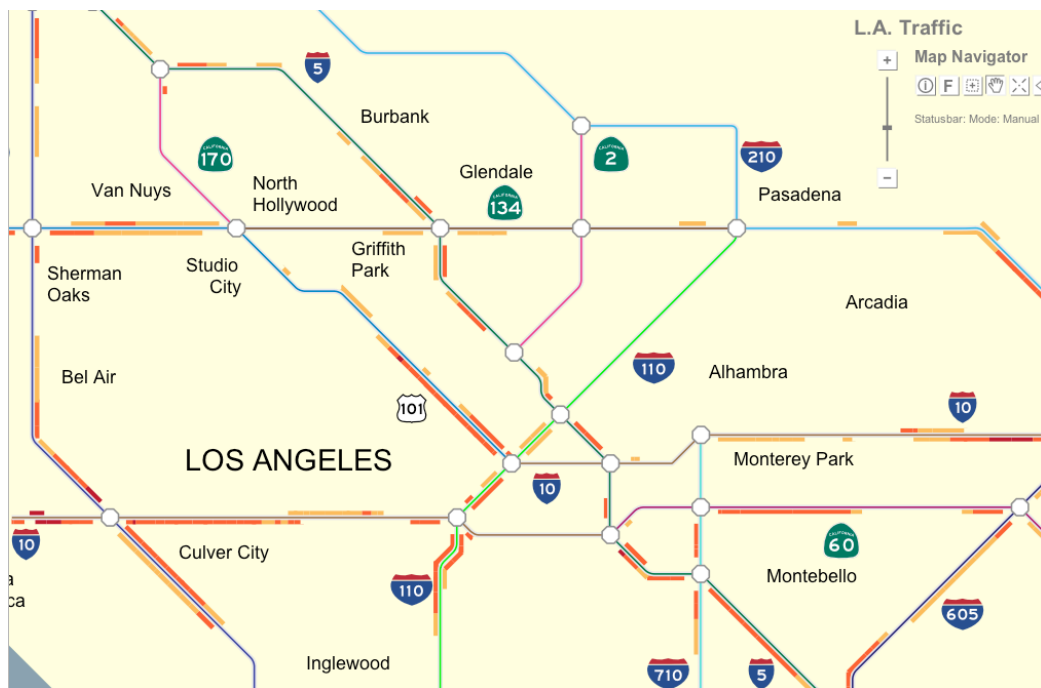


Figure 37: The prototype

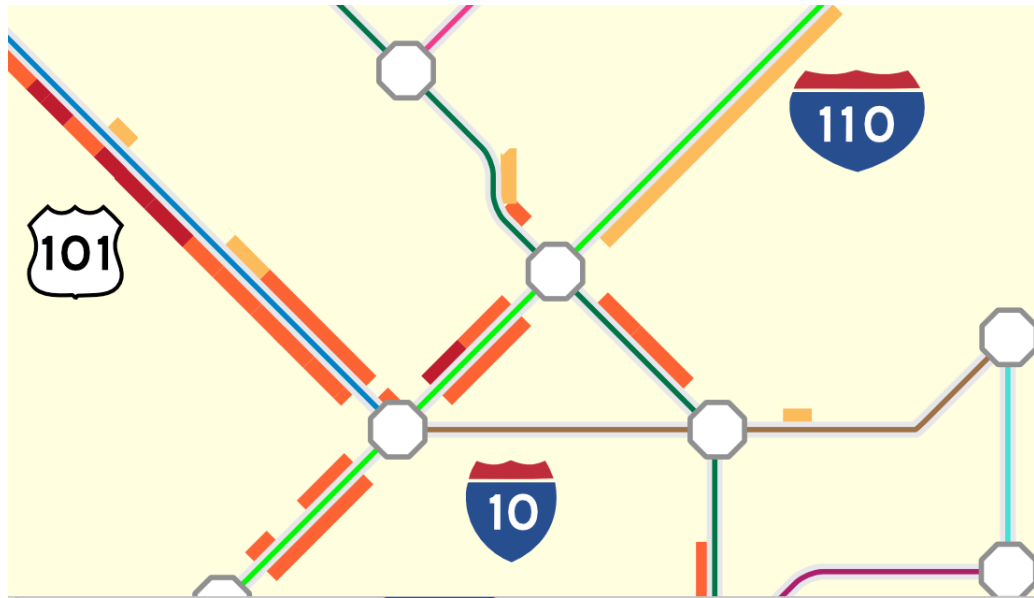


Figure 38: A close-up view of the prototype. Vector graphics render objects very cleanly at all zoom levels.

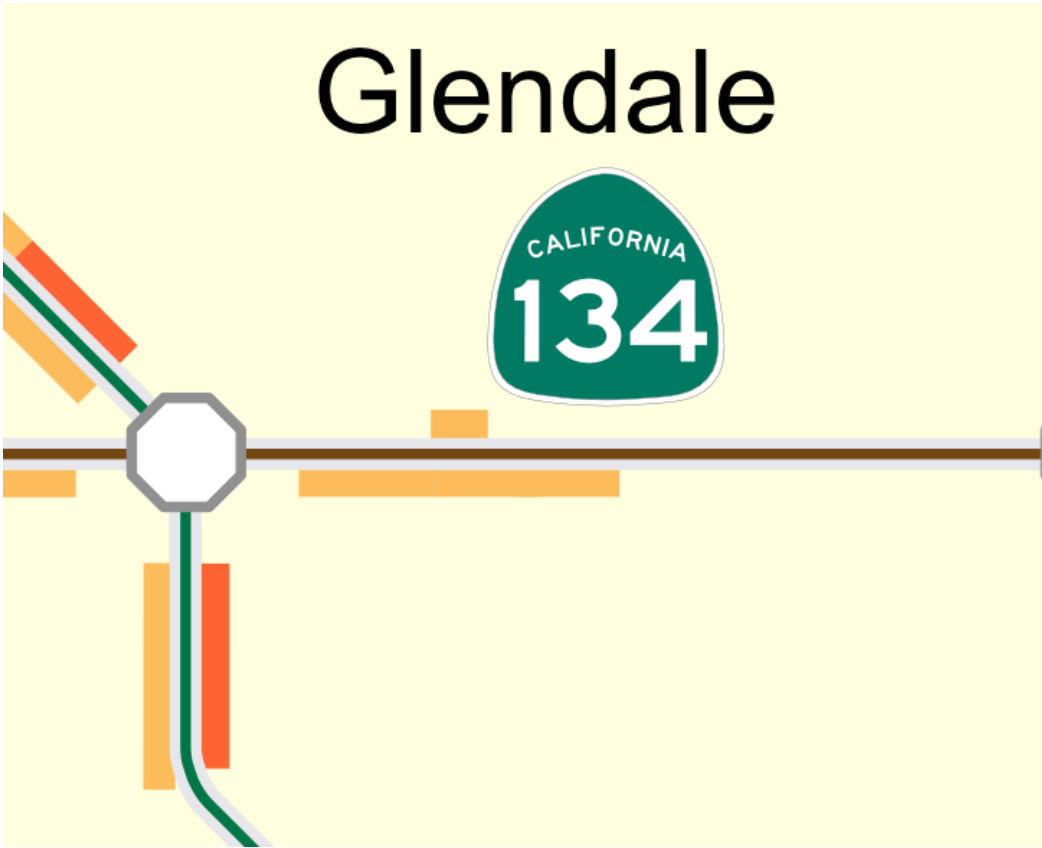


Figure 39: A highly zoomed in image of the prototype

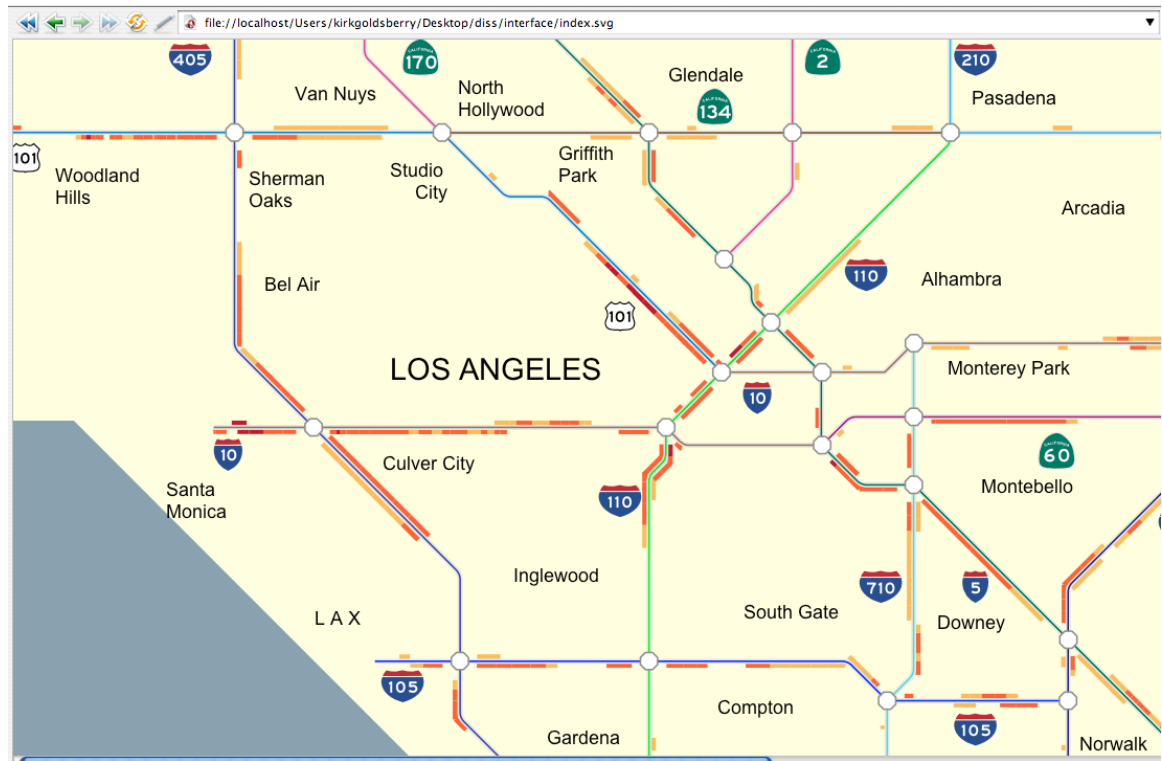


Figure 40: The prototype within a browser window.

5.5 Discussion

The new map is noteworthy for two main reasons: it employs a vector-based, compact file format, and it is informed by both cartographic principles and the results of user testing. Previous designs, such as Sigalert.com's design employ suboptimal raster-based file formats, which are particularly inefficient for network representations. Similarly, existing designs violate tried and true cartographic principles and do not account for important constraints such as limited bandwidth and small displays, that characterize contemporary mobile computing environments.

The user feedback included in chapters 3 and 4 helps justify the cartographic design decisions present in this chapter. In particular the symbolization results from chapter 3, suggested the color scheme employed in the prototype. Similarly, although based on a unique, and limited demographic the survey techniques in chapter 4 can enable a more logical approach to velocity classification, one of the more important traffic mapping decisions.

VI. ASSESSING THE PROTOTYPE VERSUS SIGALERT.COM

6.1 Introduction

This dissertation includes the development of a prototype traffic map for Los Angeles, California. Chapters 3 and 4 explored perceptual issues associated with traffic map reading, and chapter 5 successfully applied the findings from chapter 3 and 4 toward the construction of a prototype. This chapter discusses a study comparing the usability of my prototype and the popular Los Angeles traffic map created by Sigalert.com. The study was designed to explore two research questions:

1. Will users perform map tasks better using the prototype map or using the Sigalert map?
2. Will users prefer the prototype map over the Sigalert map?

Since the prototype is informed by the findings discussed earlier in this dissertation and adheres to established cartographic principles it is predicted that participants using the map will:

1. Perform map tasks *more accurately* using the prototype map than they will using the Sigalert map.
2. Report they felt *more confident* about their answers when using the prototype than when using the Sigalert map.
3. Complete map tasks *more quickly* using the prototype than they will using the Sigalert map.
4. Favor the design of the prototype over that of the Sigalert map.

6.2 Methods

6.2.1 Participants

19 subjects participated in the study. 18 of the participants completed a background questionnaire describing their background, and other relevant characteristics (1 subject failed to complete half of the background questionnaire). The participants were all undergraduate students at the University of California, Santa Barbara, and included 12 males and 6 females. The ages of the participants ranged from 19 years old to 25 years old. The mean age of the participants was 21.0 years, with a standard deviation of 1.57. 15 participants indicated that they owned their own vehicles, and 9 of them indicated they were from the Los Angeles area. 14 of the participants said they had “a lot” of experience driving on the Los Angeles freeways. All of the participants indicated they had some experience driving in traffic; of all the respondents, 7 indicated they drive in freeway traffic “several times per week,” 6 indicated “at least once a week,” 4 indicated “at least once a month,” and 1 indicated “rarely.” (0 indicated “never”)

In terms of experience with traffic maps, 14 participants said they were familiar with real-time traffic maps, and 11 indicated that they had previously used one. Of those 11, 1 indicated they “almost never” use them, 3 indicated they “rarely” use them, 5 said they use them “every once in a while,” and 2 said they use them “frequently.” When asked to name which website they visit to view real-time traffic maps 4 indicated they

visit Sigalert.com, 3 indicated Google, 2 indicated the CalTrans website, 1 indicated Yahoo, and 1 subject failed to name a site.

6.2.2 Design

For this study, every subject completed the exact same tasks on the exact same set of stimuli. The experiment contained four sections: a background traffic questionnaire, a Sigalert task portion, a prototype task portion, and a post-test survey. Although the tasks and stimuli were identical, there were 2 sequences of the test: 10 participants completed the prototype task portion prior the Sigalert task portion, and 9 participants completed the Sigalert task portion prior to the prototype task portion to account for the risk of sequential biases.

A pair of identical task-based sections, one for each map condition, followed the background questionnaire. Each task section consists of 7, 3-part questions. The first part of each question asks subjects to perform a map task relating to traffic conditions depicted on an accompanying map. 10 locations, each at a major freeway junction were each labeled with large capital letters (Figure 41). For the 6 travel-time comparison tasks subjects determined whether it would “faster to travel from location C to location E or from location E to C.” The seventh task asked participants to rank four freeway segments in order of travel time from shortest, to longest.

After completing a task the subjects provide two subsequent pieces of information: their level of confidence about their answer, and the exact time that they completed the task. Confidence level is recorded using a 5-point Likert scale, with 1 denoting “very

unconfident,” and 5 indicating “very confident.” Also, by referring to a projected digital clock (hrs:mins:secs) at the front of the room, subjects record the exact time they complete each question, which facilitates a basic time-to-completion calculation for each map task. Here is an example question:

3. Given the traffic conditions on the accompanying map, do you believe it would be faster to travel from location C to location E or from location E to location C?
 - a. It would be faster to travel from C to E
 - b. It would be faster to travel from E to C

How Confident are you about this particular answer?

1 2 3 4 5

very unconfident

very confident

Reference the clock projected at the front of the room and please record the time you completed question 3: ____:____:____



Figure 42: The Sigalert-based stimulus

The study included two map conditions, the prototype condition and the Sigalert condition. The 10 locations used in each condition were identical but different identification letters were used for each of the conditions. Letters A through K were used within the prototype condition, while letters M through W were employed in the Sigalert condition. Furthermore the tasks were identical, meaning that subjects were asked to perform identical map tasks in both conditions. For example, question 3

(above) asks subjects about locations C and E, but that same question also appears in the Sigalert condition, but the letters in that case are P and R (Figure 43).



Figure 43: The same area, as depicted by the Sigalert design and the prototype.

After completing the task portions of the experiment, subjects completed a post-test survey. The goal of the survey was to elicit subjects' opinions about the usability and design of both maps. Unlike previous experiments in this dissertation, this study exposed participants to multiple design variables, and then asked them which they favored. Subjects expressed degrees of agreement with a set of eight statements using 5-point Likert scales.

The experiment was presented on 8.5 x 11 inch pieces of paper, and participants used pens to indicate their answers. The first and second pages of the experiment included the background traffic questionnaire. This was followed by the task sections which each consisted of 3 pages of questions stapled to the fourth page which included the map that the participants used to answer the task questions. Each map, was printed in color and was approximately 7" by 7" centered on the page. The last two pages of the experiment packet included the post-test survey. The experiment was conducted on two separate occasions in small classrooms on the campus of UCSB. The subjects were seated at desks and instructed not to ask questions or consult with one another.

6.3 Results

6.3.1 Sigalert Task Results

19 subjects completed 10 map tasks within the Sigalert condition. Of those 10 map tasks 7 had a definitive correct answer. The mean score, out of 7, within the Sigalert condition was 3.79 with a standard deviation of 1.13. On the 5-point confidence scale (1 indicating no confidence, and 5 indicating extreme confidence) the mean response was 3.65 (Standard deviation = 0.51). The mean time-to-completion was 34.3 seconds (Standard deviation = 7.20 seconds).

6.3.2 Prototype Task Results

19 subjects completed 10 map tasks within the prototype condition. Of those 10 map tasks 7 had a definitive correct answer. The mean score, out of 7, within the

prototype condition was 4.58 with a standard deviation of 2.14. On the 5-point confidence scale (1 indicating no confidence, and 5 indicating extreme confidence) the mean response was 3.97 (Standard deviation = 0.27). The mean time-to-completion was 34.2 seconds (Standard deviation = 8.4 seconds). Figure 45 summarizes the task accuracy results for both conditions.

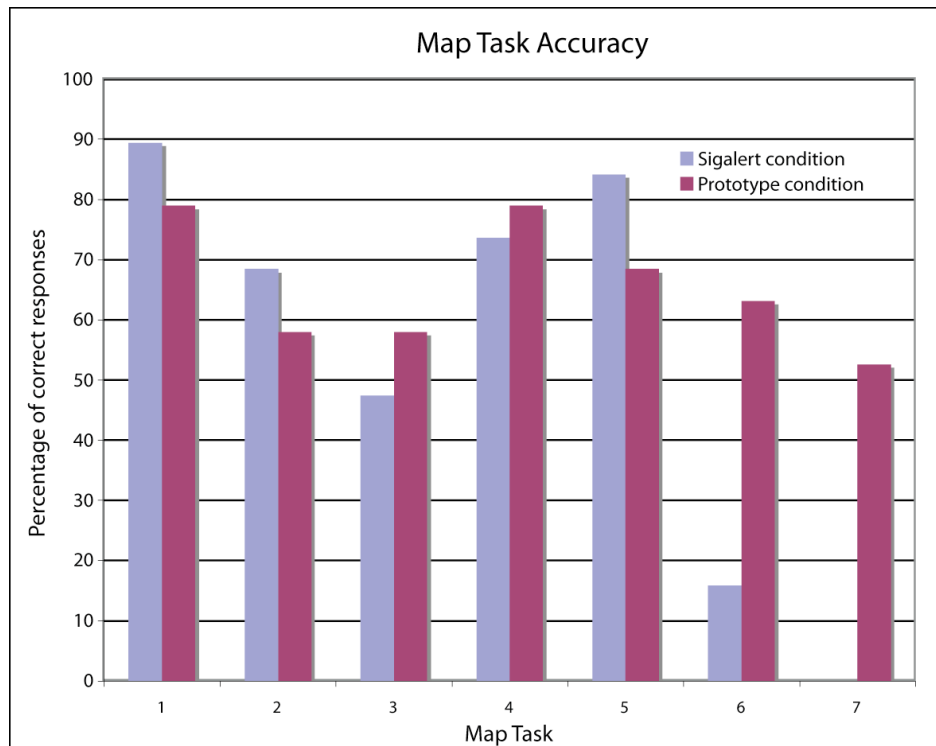


Figure 45: Task performance - percentage of correct responses for each task. 0 participants correctly completed the 7th task in the Sigalert condition. Tasks 1-6 involved determining which of 2 highway segments would take less time to traverse. Task 7 involved ranking 4 routes in terms of travel time from shortest to longest; no participants responded correctly to task 7 within the Sigalert condition.

6.3.3 Post-test Results

The post-test consisted of the following 8 statements, and generated the following mean responses on the 5-point Likert scale (1 indicating strong disagreement, and 5 indicating strong agreement):

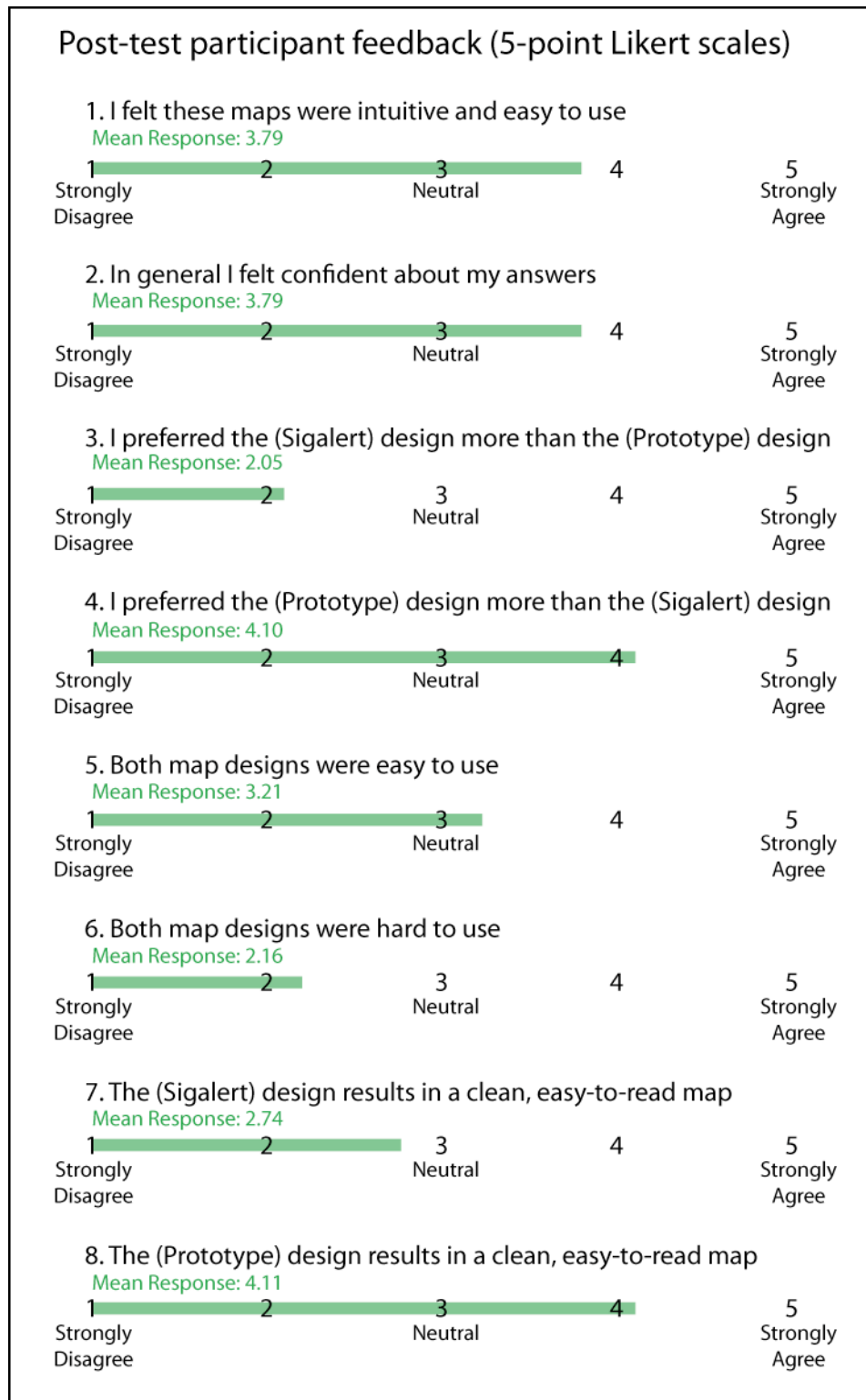


Figure 46: Post-test participant feedback

The ninth question in the post-test asked participants which map design they liked “better;” 4 subjects indicated they preferred the Sigalert design, 15 subjects indicated that they liked the prototype’s design better. The tenth question asked participants which map was easier to read. 5 participants indicated they felt the Sigalert map was easier to read, 14 participants indicated they felt the prototype was easier to read.

6.4 Analysis

The study described in this chapter was designed to test four hypotheses. Paired t-tests are employed to test each hypothesis. T-ratios are expressions of differences between two groups. Each group in this experiment has the same number of samples ($N=19$). The term “degrees of freedom” refers to the number of independent observations on which a parameter is based; for this analysis it is always equal to the number of observations within a condition minus one. The goal of the analysis is to determine whether or not there are significant differences between groups. The t-test sets up a sampling distribution of differences and determines whether the differences between two groups' samples are indicative of "significance." The null hypothesis states equal means; there is no significant difference between the two groups. If the t-statistic is greater than the critical value (critical values of t decrease as the number of samples and the degrees of freedom increase) then we can reject the null hypothesis, and accept the alternative hypothesis stating different population means. This type of analysis is vulnerable to type I and type II errors. The likelihood of a type I error, incorrectly rejecting the null hypothesis, is equivalent to the alpha value in the t-test, often set to

0.05, or 5%. The exact likelihood of type II error, not rejecting the null hypothesis when we should, is unknown. Type II error would potentially occur in this research due to small sample sizes. For example, the analysis of time-to-completion metrics for the prototype and the Sigalert map, suggest accepting the null hypothesis. There is a risk that this finding is incorrect and time-to-completion metrics are significantly influenced by these conditions; this is an example of type II error. The paired t-tests are applied to test the following four hypotheses (in roman numerals)

- I. Users will perform map tasks more accurately with the prototype map than they will with the Sigalert.com map.

The results from the task portions of the study enabled testing of the first hypothesis. Mean task scores serve as a proxy for task performance. The mean score out of 7 tasks for the prototype was 4.58, and was 3.79 for Sigalert. Using a paired t-test it was found that participants performed significantly better using the prototype map than they did when using the Sigalert map, $t(18)=1.8, p < 0.05$. The t-statistic was 1.8 and the critical value was 1.7, thus we can disprove the null hypothesis stating equal means in favor of the alternative hypothesis stating a higher mean for the prototype population.

Analysis of Performance:

1. Null Hypothesis: The mean task score (out of 7) of the Prototype population (from which the sample was drawn) is equal to the mean task score of the Sigalert population.
2. Alternative Hypothesis: The mean task score of the prototype population (from which the sample was drawn) is greater than the mean task score of the Sigalert population
3. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population's standard deviation is unknown
4. Significance level: alpha equals 0.05
5. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 18

6. Critical region: $t \geq 1.73$. Since the alternative hypothesis is directional the critical region consists of all values greater than or equal to 1.73

7. Results:

t-Test: Paired Two Sample for Mean Performance Scores

Performance Score = # of correct responses out of possible 7

	<i>Prototype</i>	<i>Sigalert</i>
Mean	4.58	3.79
Variance	4.59	1.29
Observations	19.00	19.00
Pearson Correlation	0.46	
df	18.00	
t Stat	1.81	
P(T<=t) one-tail	0.04	
t Critical one-tail	1.73	

8. Decision: Since the obtained t statistic falls within the critical region we reject the null hypothesis

II. Users will express more confidence about their answers when using the prototype than they will with the Sigalert.com map

The second hypothesis involves confidence. Will subjects express more confidence about the answers they attained when using the prototype than those attained when using Sigalert? Confidence expressions were quantified using 5-point Likert scales, and the mean prototype confidence response was 3.97 and the mean Sigalert confidence was 3.65. Using a paired t-test it was found that participants reported significantly higher confidence levels using the prototype map than they did when using the Sigalert map,

$t(132)=3.08, p < 0.05$. The t-statistic was 3.08 and the critical value was 1.66 effectively discounting the null hypothesis of equal means.

Analysis of Confidence:

1. Null Hypothesis: The mean confidence value of the prototype is equal to the mean of the Sigalert population.
2. Alternative Hypothesis: The mean confidence value of the prototype is greater than the mean of the Sigalert population
3. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population's standard deviation is unknown
4. Significance level: alpha equals 0.05
5. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 132
6. Critical region: $t \geq 1.66$. Since the alternative hypothesis is directional the critical region consists of all values greater than or equal to 1.66
7. Results:

t-Test: Paired Two Sample for Mean

Confidence Responses

Respondents estimated

confidence on a scale from 1

to 5 after completing each task

	<i>PROTOTYPE</i>	<i>SIGALERT</i>
Mean	3.97	3.65
Variance	1.12	1.49
Observations	133.00	133.00
Pearson Correlation	0.47	
df	132.00	
t Stat	3.08	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.66	

8. Decision: Since the obtained t statistic falls within the critical region we reject the null hypothesis

III. Users will perform map tasks more quickly with the prototype than with the Sigalert map.

The third hypothesis states that users will perform map tasks quicker with the prototype. Both the Sigalert and prototype task sections of the experiment recorded 7 time-to-completion measurements for every subject, resulting in a total of 133 time-to-completion observations for each map condition; the mean time-to-completion was 34.3 seconds within the Sigalert condition, and 34.8 seconds within the prototype condition. The third hypothesis is not accepted; these participants did not use significantly less time completing map tasks when using the prototype.

Analysis of Time-to-completion:

1. Null Hypothesis: The mean time-to-completion value of the Prototype population is equal to the mean time-to-completion value of the Sigalert population.
2. Alternative Hypothesis: The mean time-to-completion value of the prototype population from which the sample was drawn is less than the mean of the Sigalert population
3. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population's standard deviation is unknown
4. Significance level: alpha equals 0.05
5. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 133
6. Critical region: $t \leq -1.66$. Since the alternative hypothesis is directional the critical region consists of all values less than or equal to -1.66
7. Results:

t-Test: Paired Two Sample for Mean Time-to-completion values

	<i>PROTOTYPE</i>	<i>SIGALERT</i>
Mean	00:34.2	00:34.8
Variance	00:00.0	00:00.0
Observations	133.00	133.00
Pearson Correlation	0.04	
df	132.00	
t Stat	-0.30	
P(T<=t) one-tail	0.38	
t Critical one-tail	1.66	

8. Decision: Since the obtained t statistic does not fall within the critical region we accept the null hypothesis

IV. Users will favor the design of the prototype over the design of the Sigalert map.

The fourth hypothesis surmises that participants will express a preference for the prototype over the Sigalert map. Feedback from the post-test indicates the participants, in fact, did express a preference for the new map. Statements 7 and 8 in the post-test explicitly commented on the designs of both maps:

7. Map Design I [Sigalert] results in a clean, easy-to-read map: 2.74
8. Map Design II [Prototype] results in a clean, easy-to-read map: 4.11

Using a paired t-test it was found that participants significantly preferred the cleanliness and legibility of the prototype map, $t(18)=3.8, p < 0.01$; the t-test of these distributions gives a t-statistic of 3.8 and a critical value of 2.55, therefore discounting

the null hypothesis of equal means. According to these results, and questions 9 and 10 of the post-test, which explicitly asked about their preferences, these participants favored the design of the prototype.

Analysis of Preference:

1. Null Hypothesis: The mean Likert response for post-test question 7 is equal to the mean of the mean Likert response to post-test question 8.
2. Alternative Hypothesis: The mean Likert response for post-test question 8 is greater than the mean Likert response to post-test question 7.
3. The paired t-test is chosen because we are dealing with a normally distributed variable in which the population's standard deviation is unknown
4. Significance level: alpha equals 0.01
5. Sampling distribution: The sampling distribution is the Student t-distribution with degrees of freedom = 18
6. Critical region: $t \geq 2.55$. Since the alternative hypothesis is directional the critical region consists of all values greater than or equal to 2.55
7. Results:
 - t-Test: Paired Two Sample for Mean Likert Responses

Question 8 asked about the prototype, Question 7 asked about Sigalert

	<i>QUESTION</i> 8	<i>QUESTION</i> 7
Mean	4.11	2.74
Variance	0.88	0.98
Observations	19.00	19.00
Pearson Correlation	-0.33	
df	18.00	
t Stat	3.80	
P(T<=t) one-tail	0.00	
t Critical one-tail	2.55	

8. Decision: Since the obtained t statistic falls within the critical region we reject the null hypothesis

6.5 Discussion

The study described in this chapter aimed to address two central research questions:

1. Will users perform map tasks better using the prototype map or using the Sigalert map?
2. Will users prefer the prototype map to the Sigalert map?

The results from the study suggest that the second question is yes, while the answer to the first question is mostly yes. In terms of time-to-completion the results across conditions suggest no significant difference; mean time-to-completion values are nearly identical across conditions for every map task (Figure 47).

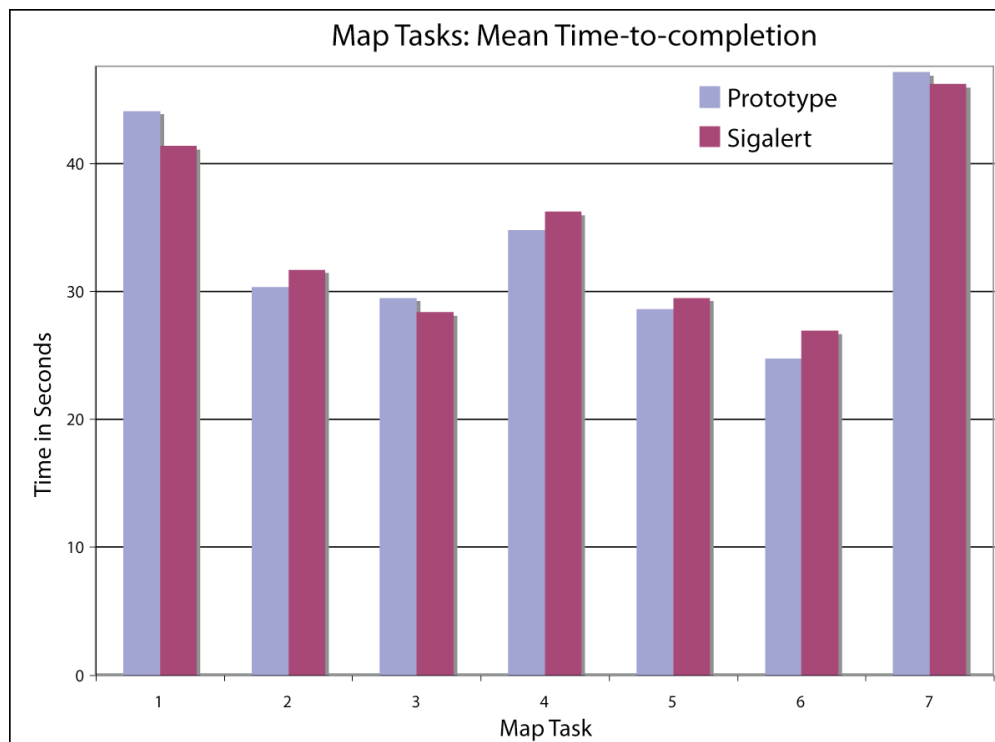


Figure 47: Time-to-completion means for each map task.

Aside from time-to-completion however, the other metrics used to evaluate these map conditions (accuracy, confidence, and preference) each significantly favor the prototype map. This is good news for cartography; the map that subscribes more closely to cartographic principles outperforms a map that does not adhere to conventions.

As they relate to the map theme of traffic congestion, these results take on a more specific relevance. Traffic map reading is difficult; in order to make navigation decisions, readers are required to assess the severities and spatial distributions of the thematic traffic information while also performing the kinds of wayfinding traditionally associated with conventional road maps. This is an arduous task. The generally poor results on the map tasks (Participants scored a 4.58/7 in the prototype condition, and 3.79/7 in the Sigalert condition.) indicate this difficulty. For this reason it is imperative that the designs of traffic maps reduce the arduous cognitive burdens associated with traffic map reading, not increase them.

The results from this study indicate that cartographic design decisions significantly influence that burden; map design clearly influences readers' abilities to decipher real-time traffic maps. The way the information is presented influences how it is understood. Research within transportation science, specifically within Intelligent Transportation Systems and Advanced Traveler Information Systems, has mostly neglected issues related to information design. They commonly emphasize collection strategies, the construction of delivery channels, and behavioral responses (Golledge, 2002) to information, but to this point the research has mostly ignored what happens

within the delivery channels, and how the design of traveler information can “make or break” its utility. For example, Al Deek and Khattak’s (1998) assertion that the presence of real-time traffic information may not affect overall system performance is questionable since it neglects the idea that the design of information will significantly influence its utility. We cannot really assess how the presence of traveler information will influence an entire population of agents until we understand how the information will influence an individual agent. Chrysler and colleagues (2007) research into how road sign design can steer driver behavior is an important precedent; although limited to the design of highway signage, her work empirically demonstrates that various depictions of transportation information will result in significant behavioral differences. Aside from this work, there is a surprising lack of transportation research concerned with the link that connects graphic design and travel behavior. This study demonstrates that different approaches to map design significantly influence an individual’s interpretation of that information. As our society aspires toward an era of more in-vehicle-navigation-systems that enable more real-time traveler information delivery it is important that due attention is paid to the design (and its influence) of the graphic channels that deliver us from ignorance, confusion, illegibility, and wayfinding mistakes.

VII. CONCLUSION AND FUTURE DIRECTIONS

7.1 Conclusions

This dissertation was centered around three core goals:

1. To investigate previous research findings, current online traffic map resources, and human responses to traffic map stimuli in order to expose major issues in the design of real-time traffic maps.
2. To design a new data-driven mapping prototype, which is both informed by empirical map design research as well as capable of depicting and delivering streaming Los Angeles traffic information.
3. To conduct a comparative analysis evaluating the performance of the prototype relative to existing traffic mapping systems.

7.1.1 Traffic Map Design Issues

A very limited amount of previous research has addressed the design of real-time traffic maps. The diverse array of design strategies in the “real-world” offers stirring evidence of a lack of traffic map design guidelines. The most glaring inconsistency involves classification. Many maps employ ordinal classifications that rely on ambiguous descriptors such as “moderate,” “major,” or “light.” The very popular Google traffic

map does not include any legend at all; it relies solely on an undefined red-yellow-green scheme to depict velocity data. A reader interested in knowing just what yellow *means* is out-of-luck. Even when designers group quantitative velocity measurements into classes, there remains a stark amount of inconsistency. Chapter 3 demonstrated that this inconsistency can and will result in varying perceptions of traffic severity.

Symbolization is also an interesting traffic map issue. The most intuitive, and most popular symbolization scheme, the stoplight metaphor, violates cartographic conventions and is likely illegible to colorblind readers. The red-yellow-green combination proved to be the most intuitive in chapter 3, but not much more intuitive than the red sequential scheme. Even without a legend to decode the symbology, participants completed traffic evaluation tasks almost as well with the red scheme as they did with stoplight scheme.

7.1.2 A New Traffic Map

Chapter 5 of this dissertation summarized the construction of a new kind of traffic map. The results are encouraging. The prototype system successfully accesses and downloads real-time traffic data from the PeMS database, but more importantly, the application of vector graphics enables a cleaner, more versatile display; this is especially pertinent as we are increasingly accessing maps on smaller displays in mobile settings. Along the same lines the schematic representation of the freeway network simplifies the depiction, allowing users to focus on the most relevant network characteristics and traffic events.

The compromised stoplight scheme, which replaced the green hued symbol with a clear, invisible symbol accomplishes three things:

1. It is intuitive to readers while not violating established cartographic principles that advocate the use of lightness-based sequential color schemes to represent unipolar quantitative data.
2. It elevates the salience of congested areas, therein adhering to the “everything’s ok” principle discussed in Chapter 3 (3.4.2).
3. It is more compatible with red-green colorblindness than the traditional stoplight approach.

7.1.3 Evaluating The New Traffic Map

The results presented in chapter 6 suggest that the prototype may be superior to the popular Los Angeles traffic map created by Sigalert.com. With the exception of time-to-completion, the other metrics used to infer performance, task accuracy, confidence, and personal opinions each favored the prototype map. Although the sample of participants was extremely limited (UCSB undergraduate students), the results are still very encouraging. At best, the results suggest that the prototype is a superior map to the Sigalert map. At least, the results indicate that significantly better traffic maps are possible. In general, however, it is hard to quantitatively compare two maps. I am very hesitant to assert that any map can be empirically deemed superior to another. One set readers will prefer one design to another design, but another set will feel the opposite way; the 12th century monk and poet John Lydgate once said, “You can’t please all of

the people, all of the time.” Or as Abraham Lincoln famously paraphrased Lydgate “You can’t fool all of the people all of the time.” Well, the results from this dissertation imply that your map can’t please all of the people, all of the time. But map design is not, and never will be a matter of universal acceptance. Optimal map designs are those that are able to both please the maximum while disturbing the minimum. Map designers can only hope to approach that optimal status.

7.2 Future Directions

Overall, I consider the design of the prototype a success, yet I believe the following additions would significantly enhance its performance:

1. Incident data: The addition of the California Highway Patrol incident data would improve the map. This dissertation does not address accident data, its acquirement, or its representation. A complete traffic map must inform its readers about important events such as car accidents, and lane closures, that can often trigger severe congestion events. The prototype is incomplete in this regard.
2. Typography: Since traffic maps are a unique blend of thematic and reference maps, typography is important. Readers of traffic maps blend information from the thematic traffic layers, and the network layers, with labels from the type layers in order to orient themselves, and assess the traffic conditions along their route. The prototype has particularly limited typography; it is fairly sparse, and it does not react or redraw upon zooming/panning operations. The typography in the prototype should be enhanced to account for user-driven changes of map extent and/or scale; labels should never be truncated at the map’s edge, nor should the type grow or shrink in size as the map scale changes.

3. Interoperability: Although many mobile computing devices can decode SVG, further work is needed to evaluate the performance of the prototype on mobile phones, PDA's, and In-vehicle-navigation-systems. These devices present large challenges to dynamic maps, and it is important that future cartographic research investigates map use on mobile devices, and in real-world environments. The stimuli used in the studies in this dissertation were unrealistic in that they were printed on paper, and larger than most mobile maps. Paper maps generally have a higher resolution (300 dots per inch) than digital maps (72 dpi to 144 dpi). Further, there are different interaction strategies between paper maps and mobile maps. Map readers physically adjust themselves or the printed map in order to facilitate basic interactions such as zooming, panning, or rotating, but these same operations often require human-computer interaction – which is very demanding while also driving a car.

On a broader level, this research reveals the need for more investigations pertaining to:

1. Map use: As Clarke (2004, pg. 134) suggests that mobile mapping may represent the “next paradigm in cartography and geographic information science,” this research avenue must account for how people view maps in mobile settings and how cartographic design must evolve to adapt to this new, and very popular type of map consumption. The results from chapter 6 indicate that participants were taking on average more than thirty seconds to complete map tasks. Although this finding may not be exactly accurate for the general public or for mobile map settings it is noteworthy nonetheless; if users are taking even 5 or 10 seconds to refer to a traffic map while they are driving, that would be very dangerous. Previous research has suggested that in-vehicle-navigation-systems should employ sound, in the name of safety, to communicate dynamic information. But as more and more automobiles are manufactured with screens in their dashboards it is unreasonable to expect that maps will not continue to

be integral part of IVNS. Furthermore, visual maps are the most congruent depictions (Tversky, 2002) of the visual environment, and since our eyes are such powerful sensors, it would be foolish to eliminate maps from IVNS altogether. Therefore, future research should focus on how maps can safely be integrated into IVNS. This safety research includes room for a more specific cartographic research question: How can we design maps for IVNS so that they are as efficient as possible? How can we improve reader performance and reduce time-to-completion metrics for the most common IVNS map tasks, such as orientation, routing, landmark identification, or distance estimation?

2. Traffic Mapping: I believe traffic maps have the potential to be among the most frequently used maps in the world. Traffic burdens are increasing, not just in America, but also internationally. Similar to weather maps, traffic maps offer depictions of “relevant” and “up-to-the-minute” conditions to a readership that could realistically be include many million map readers on a daily basis. For this reason alone, traffic map design research is justified. Traffic mapping research includes 4 important sub-fields:

- a. Data Collection: What’s the best way to collect real-time traffic data? The data in this project stems from Inductive Loop Detectors, a useful yet archaic technology that is costly, and requires perpetual upkeep to maintain good data collection. Claramunt (2000) distinguishes between “microscopic” and “macroscopic” data collection strategies; macroscopic collection measures traffic flow at fixed network locations, while microscopic collection tracks agents’ individual progress through the network. Macroscopic collection requires a robust set of expensive, troublesome detectors such as ILD to collect a sufficient set of data, and the data is only accurate at finite detector locations. Increasingly, data from microscopic collection is being collected by spatially-aware mobile devices. Future traffic mapping research needs to develop a framework

that will filter streaming microscopic traffic data into functioning real-time traffic databases.

- b. Data processing: So-called “real-time” traffic maps are generally not “real-time.” In the case of the PeMS database, which I used for this project, data is collected but aggregated to 5-minute averages. In essence when readers look at a real-time map they are often not looking at depiction of traffic conditions at that exact time. Furthermore, if I am at Los Angeles International Airport (LAX), and I am using a traffic map to pick my favored route to Burbank, I don’t really care about what the traffic near Burbank is like now as much as I care about what the traffic near Burbank will be like when I get there. Future research could combine real-time traffic data, traffic forecasting models, and visual models of mobility (such as isochrones) to create a more relevant traffic map.
- c. Representation: Television news often includes animated traffic maps. These maps adhere more closely to the congruence principle (Tversky, 2002) than their static counterparts that dominate the Internet. The results from chapter 3 indicate participants performed equally with segment-based and point-based traffic representations. The research did not investigate animated depictions of traffic flow. Future research needs to explore the viability of animated traffic maps as well as other representational strategies that may prove to be more intuitive than current depictions.
- d. Classification: If we continue to use velocity measurements as a proxy for traffic congestion, then we have to reach a better understanding of how to classify those measurements. The results from chapter 3 indicate that the thresholds separating severities of traffic significantly influence how readers perceive congestion. A good place to start may

involve a simple binary traffic classification; if we were to create a traffic map of just two-classes, congested, and not congested, where would the threshold be? How could we make a sensible division that would correspond with the preconceptions of a large group of readers? Could we survey potential map-readers to identify a logical division between congested and not congested? User-based classification strategies might offer a new approach to thematic map classification, but more research is needed to determine the feasibility and utility of such an approach.

- e. Symbolization: What's the best way to symbolize real-time velocity conditions? Perhaps the most depressing finding of this research for cartographers is that participants performed better using the red-yellow-green stoplight metaphor than they did with any of the other symbolization conditions. But, this finding is really important; in this test at least, this finding demonstrates that some semantic associations, or metaphor-based symbolizations are more efficient than schemes that are much more adherent to the principles of cartographic science (Bertin, 1983). Cartographers should always consider cultural metaphors when devising symbolization schemes; recent cartographic symbolization literature has mostly neglected this idea, and this is evident in this literature's most prized symbolization utility, ColorBrewer (Brewer, 2002). Future research, and cartographic instruction should explore how the visual variables can be manipulated to take advantage of the cultural metaphors. For example, sequential schemes still have a dominant hue, and choosing that hue based on cultural semiotic relevance (Green = money) can enhance the efficiency of thematic maps.
- f. Cognition: By far the most complex factor in designing good maps involves the human mind, and how it perceives and understands

graphics. Future research needs to bridge the gap between cartography and cognition. More specifically, it is important to bolster our understanding of how and why certain map designs (of the same data set) are more intuitive, or “easier-to-read” than others. Cartographers should continue to work with psychologists to enhance this line of research.

3. **Advanced Traveler Information Systems:** Maps are a core component of ATIS, yet hardly any attention within the ATIS community is paid to the designs of traveler information. Previous research has demonstrated that map design can influence all kinds of travel behavior (Soh and Jackson, 2004) but more studies are needed to help us really understand the complex links that connect graphic variables, and cartographic design decisions to map interpretation as well as travel behavior. The transportation community should encourage the contributions, and integrate the findings of Geographic Information Science to enhance ATIS research.
4. **Behavioral Cartography:** The findings of this research and other previous research (Yarnal and Coulson, 1982; Dillemath 2005) demonstrate that map design influences human travel behavior. It is important to understand how and why certain map designs will influence behavior differently than other designs. This type of research might best be called “Behavioral Cartography;” it represents the confluence of cartographic design, behavioral geography, transportation science and psychology.

These and other research avenues could profoundly expand the findings discussed in this dissertation and other areas of Geography.

REFERENCES

511.org (2007). 511 Traffic Home.

Adler, J. L. and V. J. Blue (1998). "Toward the design of intelligent traveler information systems." *Transportation Research Part C: Emerging Technologies* 6(3): 157-172.

Adler, J. L., W. W. Recker, et al. (1992). Using interactive simulation to model driver behavior under ATIS. Berkeley, UCTC.

Al-Deek, H. and A. Khattak (1998). "A combined traveler behavior and transportation system performance model with ATIS." *Transportation Research A* 32(7): 479-493.

Barcelona, A. d. (2007). Barcelona Traffic Map. Barcelona. 2007.

Berendt, B., R. Rauh, et al. (1998). Spatial Thinking with Geographic Maps: An Empirical Study. *Herausforderungen an die Wissensorganisation: Visualisierung, multimediale Dokumente*. H. Czapski, H. P. Ohly and S. Pribbenow. Würzburg, Internetstrukturen: 63-74.

Bertin, J. (1983). *Semiology of Graphics: Diagrams, networks, maps*. Madison, WI, University of Madison Press.

Brewer, C. (1994). Guidelines for use of the perceptual dimensions of color for mapping and visualization. *Color Hard Copy and Graphic Arts III*. J. Bares. Bellingham, WA, USA, International Society of Optical Engineering: 54-63.

Brewer, C. A. (2002). "ColorBrewer."

Brewer, C. A. and L. Pickle (2002). "Evaluation of Methods for Classifying Epidemiological Data on Choropleth Maps in Series." *Annals of the Association of American Geographers* 92(4): 662-681.

- Bush, G. W. (2007). Proposed Budget of The United States Government, Fiscal Year 2008. O. o. M. a. Budget.
- Cassin, B., S. Solomon, et al. (1990). Dictionary of eye terminology. Gainesville, Fla., Triad Pub. Co.
- Chen, P. S. T. and H. S. Mahmassani (1993). "A dynamic interactive simulator for studying commuter behavior under real-time traffic information supply strategies." *Transportation Research Record* 1413: 12-21.
- Chrisman, N. (1999). "A Transformational Approach to GIS Operations." *International Journal of Geographic Information Science* 13(7): 617-637.
- Chrysler, S. T., A. A. Williams, et al. (2007). Driver Comprehension of Diagrammatic Freeway Guide Signs. TTI. T. T. Institute, TTI.
- Claramunt, C., B. Jiang, et al. (2000). "A new framework for the integration, analysis and visualization of urban traffic data within geographic information systems." *Transportation Research Part C*: 167-184.
- Clarke, K. C. (1990). *Analytical and Computer Cartography*. Englewood Cliffs, NJ, Prentice-Hall.
- Clarke, K. C. (2001). *Cartography in a Mobile Internet Age*. Proc. of the 20th International Cartographic Conference, Beijing, China.
- Clarke, K. C. (2004). "Mobile Mapping and Geographic Information Systems." *Cartography and Geographic Information Science* 31(3): 131-136.
- Cromley, E. K. and R. G. Cromley (1995). "An analysis of alternative classification schemes for medicals atlas mapping." *European Journal of Cancer* 32A(9): 1551-1559.
- Cummings, S. and D. C. Wilson (2002). *Images of strategy*. Oxford, Blackwell.

- Dent, B. (1999). *Cartography, Thematic Map Design*. Boston, WCB McGraw-Hill.
- Dervin, B. (1983). An overview of sense-making research: Concepts, methods, and results to date. International Communication Association Annual Meeting, Dallas, TX.
- Dijkstra, E. W. (1959). "A Note on Two Problems in Connexion with Graphs." *Numerische Mathematik* 1: 269-271.
- Dillemath, J. (2005). Human-map interaction for mobile cartography. *Geography*. Santa Barbara, UCSB. Master's Thesis.
- Dixon, O. M. (1972). "Methods and progress in choropleth mapping of population density." *The Cartographic Journal* 9(1): 19-29.
- Dobson, R. and F. W. Young (1972). On the perception of a class of bilaterally symmetric forms, Psychometric Laboratory, University of North Carolina.
- Egenhofer, M. J. (1991). Reasoning about binary topological relations (extended abstract), National Center for Geographic Information and Analysis, University of California Santa Barbara.
- Evans, I. A. (1977). "The selection of class intervals." *Institute of British Geographers Transactions, New Series* 2(1): 98-124.
- Fabrikant, S. I. and K. Goldsberry (2005). Thematic relevance and perceptual salience of dynamic geovisualization displays. 22nd ICA/ACI International Cartographic Conference, A Coruna, Spain.
- Flannery, J. J. (1956). *The Graduated Circle: A description, analysis, and evaluation of a quantitative map symbol*, University of Wisconsin, Madison.
- Goldsberry, K. (2005). Limitations and Potentials of Real-Time Traffic Visualization. International Cartographic Conference, A Coruna, Spain, ICA 2005.

- Golledge, R. (1999). *Human Wayfinding and Cognitive Maps. Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes*. R. Golledge. Baltimore, MD, USA, Johns Hopkins University Press.
- Golledge, R. G. (1995). Defining the criteria used in path selection. *International Conference on Activity based Approaches: Activity Scheduling and the Analysis of Activity Patterns*. Also printed as a University of California Transportation Center Work Paper, UCTC No. 278., Eindhoven University of Technology, The Netherlands.
- Golledge, R. G. (2002). Dynamics and ITS: Behavioral responses to information available from ATIS. In *Perpetual Motion: Travel Behavior Research Opportunities and Application Challenges*. H. S. Mahmassani. New York, Pergamon: 81-126.
- Golledge, R. G. and T. Garling (2004). "Cognitive Maps and Urban Travel." *University of California Transportation Center*(601): 9.
- Goodchild, M. F., D. M. Johnston, et al. (2004). *Distributed and Mobile Computing. A Research Agenda for Geographic Information Science*. R. B. McMaster and E. L. Uery. Boca Raton, Florida, CRC Press: 257-286.
- ITSA (2002). *National Intelligent Transportation Systems Program Plan: A Ten-Year Vision*. ITS America. ITSA. Washington D.C., Intelligent Transportation Society of America.
- Itti, L. and C. Koch (2001). "Computational modelling of visual attention." *NATURE REVIEWS NEUROSCIENCE* 2(3): 194-203.
- Jenks, G. F. and F. C. Caspall (1971). "Error on choropleth maps." *Annals of the Association of American Geographers* 61(2): 217-244.
- Klein, L. A. (2001). *Sensor Technologies and Data Requirements for ITS*. Boston, Artech House.

- Koutsopoulos, H. N., T. Lotan, et al. (1993). A driving simulator and its application for modeling route choice in the presence of information. 72nd Annual Meeting, Transportation Research Board, Washington, DC.
- Koutsopoulos, H. N., T. Lotan, et al. (1994). "A driving simulator and its application for modeling route choice in the presence of information." *Transportation Research C* 2(2): 91-107.
- Kraak, M.-J. (2000). *Web Cartography*, Taylor & Francis.
- Kwan, M.-P. (2000). "Interactive Geovisualization of Activity-Travel Patterns using Three-dimensional Geographical Information Systems: Methodological Exploration with a Large Data Set." *Transportation Research Part C*: 185-203.
- Lowe, R. K. (1999). "Extracting Information from an Animation during Complex Visual Learning." *European Journal of Psychology of Education* 14(2): 225-244.
- MacEachren, A. (1992). "Visualizing uncertain information." *CARTographic Perspectives* 13: 10-19.
- Mahmassani, H. S., Ed. (2002). *In Perpetual Motion: Travel Behavior Research Opportunities and Application Challenges*. New York, Pergamon.
- Mahmassani, H. S. and Y.-H. Liu (1997). *Day-to-day dynamics of commuter route choice behaviour under real-time information*. Center for Geographic Education: The First Assessment: Research in Geographic Education, Southwest Texas State University, San Marcos, TX.
- Miller, G. A. (1956). "The magical number seven, plus or minus two: Some limits on our capacity for processing information." *Psychological Review* 61: 81-97.
- Miller, H. J. and S.-L. Shaw (2001). *Geographic Information Systems for Transportation*, Oxford University Press.
- Monmonier, M. S. (2002). *Spying With Maps*. Chicago, University of Chicago Press.

- Montello, D. R. (2002). "Cognitive Map-Design Research in the Twentieth Century: Theoretical and Empirical Approaches." *Cartography and Geographic Information Science* 29: 283-304.
- Montello, D. R. (2005). Navigation. *The Cambridge Handbook of Visiospatial Thinking*. P. Shah and A. Miyake. Cambridge, Cambridge University Press: 257-294.
- Montello, D. R. and P. C. Sutton (2006). *An introduction to scientific research methods in geography*. Thousand Oaks, Calif., Sage Publications.
- Muller, J. C. (1979). "Perception of continuously shaded maps." *Annals of the Association of American Geographers* 70(1): 107-108.
- NATUA (2007). *Athens Traffic Map*. Athens, National Technical University of Athens, Department of Transport Engineering, 2007.
- ODOT (2007). *TripCheck*, Oregon Department of Transportation, 2007.
- Peng, Z.-R. and M.-h. Tsou (2003). *Internet GIS: distributed geographic information services for the internet and wireless networks*. Hoboken, N.J., Wiley.
- Peterson, M. P. (1995). *Interactive and Animated Cartography*. Englewood Cliffs, N.J., Prentice Hall.
- Peterson, M. P. (2003). *Maps and the Internet*, International Cartographic Association.
- Raper, J. (2000). *Multidimensional Geographic Information Science*. London, Taylor and Francis.
- Raper, J., J. Dykes, et al. (2002). "A Framework for Evaluating Geographical Information." *Journal of Information Science*(28): 39-50.

- Reichenbacher, T. (2001). *The World In Your Pocket - Towards a Mobile Cartography*. Proc. of the 20th International Cartographic Conference (CDROM), Beijing, China.
- Reichenbacher, T. (2005). "The concept of relevance in mobile maps." *Location Based Services & Telecartography*.
- Robinson, A. H. (1952). *The Look of Maps*. Madison, WI, University of Wisconsin Press.
- Robinson, A. H. (1966). *The Look of Maps*. Madison, The University of Wisconsin Press.
- Robinson, A. H., R. D. Sale, et al. (1984). *Elements of Cartography*. New York, Wiley.
- Saisa, J., A. Svensson-Garling, et al. (1985). "Intra-urban cognitive distance: the relationship between judgments of straightline distances, travel distances, and travel times." *Geographical Analysis* 18: 167-174.
- Schrank, D. and T. Lomax (2004). *The 2004 Urban Mobility Report*. T. A. M. U. System. College Station, TX, Texas Transportation Institute.
- Schrank, D. and T. Lomax (2006). *The 2005 Urban Mobility Report*. College Station, TX, Texas Transportation Institute: 91.
- Shekhar, S. and D. R. Liu (1994). *Genesis and Advanced Traveler Information Systems (ATIS): Killer Applications for Mobile Computing*. National Science Foundation MOBIDATA Workshop.
- Sholl, M. J. (1987). "Cognitive maps as orienting schemata." *Journal of Experimental Psychology: Learning, Memory, and Cognition* 13(4): 615-628.
- Sholl, M. J. (1996). *From visual information to cognitive maps. The Construction of Cognitive Maps*. J. Portugali. Dordrecht, Kluwer Academic Publishers: 157-186.

- Short, J. R. (2003). *The world through maps: a history of cartography*. Toronto; Buffalo, Firefly Books.
- Sigalert.com (2007). Sigalert.com. 2007.
- Slocum, T. A. (1999). *Thematic cartography and visualization*. Upper Saddle River, N.J., Prentice Hall.
- Slocum, T. A. and T. A. Slocum (2005). *Thematic cartography and geographic visualization*. Upper Saddle River, NJ, Pearson/Prentice Hall.
- Soh, B. K. and T. L. Smith-Jackson (2004). "Influence of Map Design, Individual Differences, and Environmental Cues on Wayfinding Performance." *Spatial Cognition and Computation* 4(2): 137-165.
- Spradlin, K. L. (2000). *An evaluation of user attitudes toward classed and unclassed choropleth maps*. Geography. Lawrence, University of Kansas. MA.
- Stopher, P. R. and M. Lee-Gosselin (1997). *Understanding Travel Behaviour in an Era of Change*. New York, Elsevier Science Ltd.
- Streeter, L. A., D. Vitello, et al. (1985). "How to tell people where to go: Comparing navigational aids." *International Journal of Man - Machine Studies* 22: 549-562.
- Summers, M. and F. Southworth (1998). "Design of a testbed to assess alternative traveler behavior models within an Intelligent Transportation System architecture." *Geographic Systems* 5(1-2): 91-116.
- Sytadin.tm.fr (2007). Paris Traffic Map. 2007.
- TOBLER, W. (1959). "AUTOMATION AND CARTOGRAPHY." *GEOGRAPHICAL REVIEW* 49(4): 526-534.
- TOBLER, W. (1973). "CHOROPLETH MAPS WITHOUT CLASS INTERVALS." *GEOGRAPHICAL ANALYSIS* 5(3): 262-265.

- Tobler, W. R. (1957). An empirical evaluation of some aspects of hypsometric colors, University of Washington, Seattle.
- Tomlin, D. (1990). Geographic Information Systems and Cartographic Modelling. Englewood Cliffs, NJ, Prentice-Hall.
- Transtar (2007). Houston Traffic Map, Transtar. 2007.
- Tufte, E. R. (1990). Envisioning Information. Cheshire, CN, Graphics Press.
- Tversky, B. (2002). "Animation: Can it facilitate." International Journal of Human-Computer Studies 57(4): 247-262.
- USDOT (2007). ITS Overview, United States Department of Transportation. 2007.
- Wilson, D. and D. Sperber (2004). Relevance Theory. L. Horn and G. Ward: 607-632.
- Wilson, T. D. (1999). "Models in Information Behavior Research." Journal of Documentation 55: 249-270.
- Yarnal, C. M. M. and M. R. C. Coulson (1982). "Recreational Map Design and Map Use: An Experiment." The Cartographic Journal 19(1): 16-27.
- Zuerittraffic.ch (2007). Zurich Traffic Map. 2007.

Appendix

[Appendices typically contain supporting material such as data sheets, questionnaire samples, illustrations, maps, charts, etc. Students may need to photocopy some items at less than 100% in order to fit them within the margins. Other oversize items may be folded to fit within the margins or may be put in special pockets in the back.]