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RESEARCH

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Commuter Bicyclist Behavior and Facility Disruption

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Cyclists confronted by disruptions to facilities (e.g., dedicated paths, designated lanes) experience disturbances that prompt them to select sub-optimal facilities to avoid disruptions. Cyclists who have ready access to such improved facilities often choose sub-optimal facilities. This project collected a variety of data to help gain a better understanding of commuter cyclist behavior using Global Positioning System (GPS) equipment to record cyclist movements and behaviors. Using GPS units for data collection provides significant data for analysis, however, a substantial and unexpected amount of effort went into determining the best operational use of the GPS units and verifying data collection protocols. Among important findings, results show that as perceived safety decreases, riders appear to be more cautious and move more slowly; however in situations of substantial perceived danger, riders go faster to spend as short a time in unsafe conditions. Cyclists choose these dangerous situations over alternatives because of lessened travel times. The research has been successful in establishing insightful relationships between commuter cyclist behavior and facilities. The methodological results are significant for future work.</td></tr>
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Commuter Bicyclist Behavior and Facility Disruption

Final Report

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Chapter 1 Introduction

Bicycle commuters often encounter disruptions ranging from undesirable circumstances to physical obstacles along their preferred commute route. Some times such disruptions are merely a tight squeeze along a bridge being renovated, but they can range to the complete re-routing of a given facility because of road closure. Cyclists confronted by disruptions to significant improvements (e.g., dedicated paths, designated lanes) experience disturbances that prompt them to select sub-optimal facilities to avoid disruptions. Studying cyclist commuter behavior in relationship to facility disruption provides a basis for prioritizing future infrastructure improvements and understanding the impacts of disruptions. Behavioral factors allow for the generation of disruption types and behavior types that can become critical inputs for improving cycling transportation infrastructure.

The research conducted in this project provides an analysis of cyclist behavior leading to suggestions for prioritizing infrastructure improvements. A pilot study with 15 participants was conducted in the Fall of 2005 and two complete data collection cycles (with 51 participants) were conducted in Spring 2006. Subjects were recruited from neighborhoods in South Minneapolis and prepared daily route log books over a three week period, took part in entry and exit surveys, which included a focus group meeting component to solicit data overall subject insights. During the three week period subjects used GPS-based logging equipment to record fine-scale cycling behavior on their preferred commuting route during the first week and then on an assigned alternate route in the second week. During the third week, each subject independently selected his or her route. For each trip she or he also completed a trip log, part of a dairy, answering questions about their sense of safety, comfort, and confidence. The collected data allows comparisons of behavior in response to interruptions and collect data to aid in determining if interruptions on the preferred or selected routes lead to behavior changes.

Chapter 2 Fall and Spring Studies

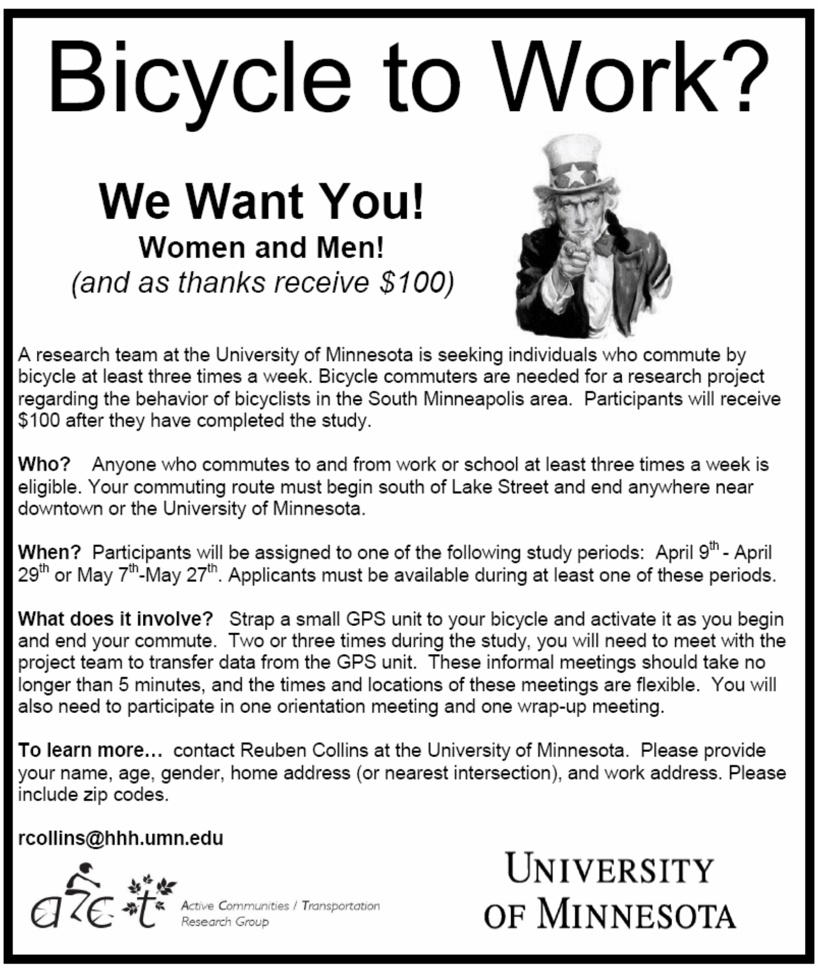
2.1 Overview

In total, three data collection cycles were conducted during this research. The first cycle took place in Fall 2006 and served the role of pilot study, including the assessment and refinement of data collection protocols, the use of GPS equipment, and preliminary assessments of data. The other two data collection studies took place in Spring 2006.

2.2 Subject Recruitment

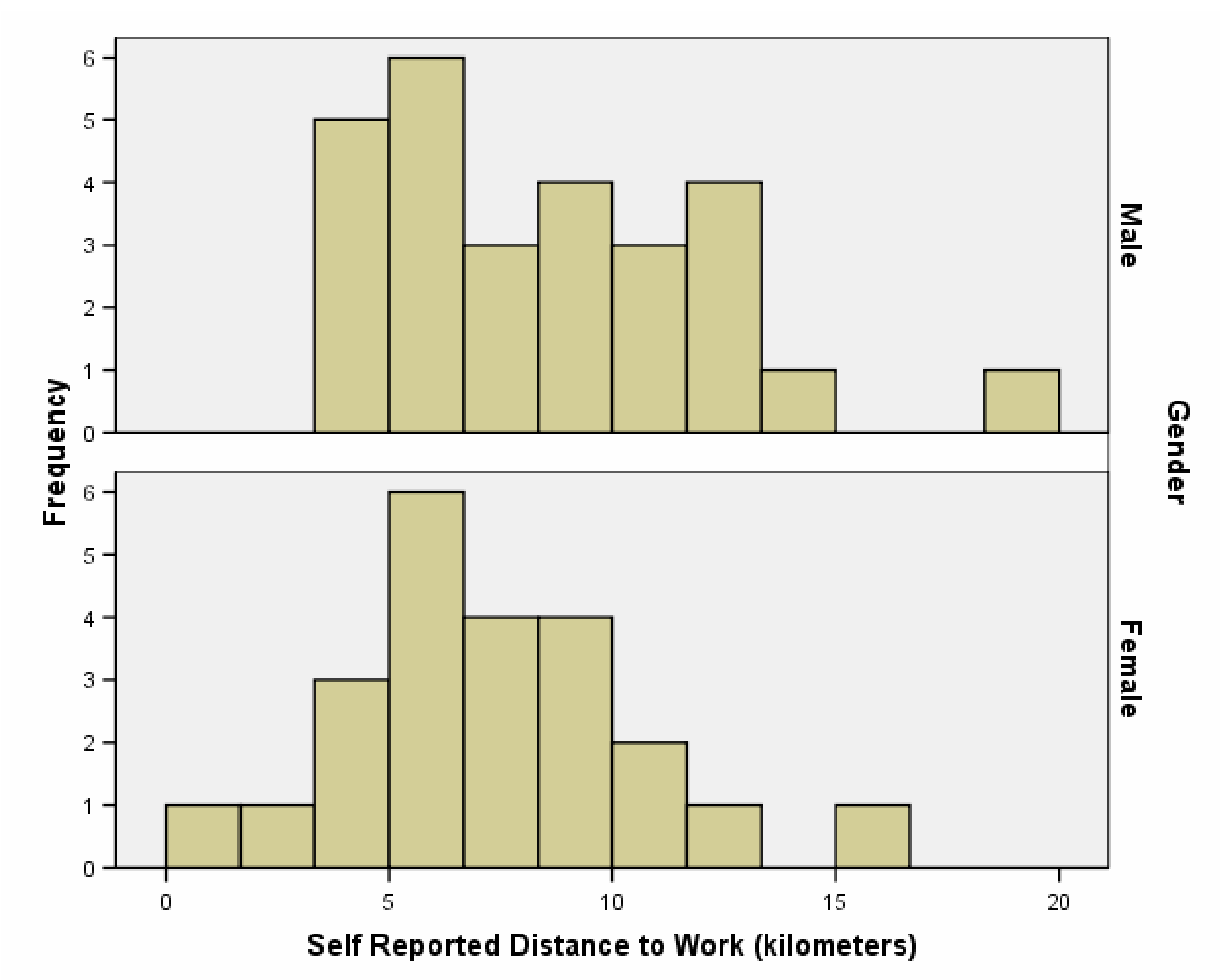
Distribution of the request for participants shown in Figure 2.1 included email lists through various local organizations including Transit for Livable Communities, Twin Cities Bicycling Club, and Minnesota Off-Road Cyclists. Printed copies of the request were also posted at many bicycling sales and repair shops in the Minneapolis area. The most effective form of distribution was the informal and unplanned forwarding of the request for participants between co-workers, friends, relatives, and other acquaintances. The request for participants was distributed first during September, 2005 and again in March 2006.

Figure 2.1 Recruitment of participants



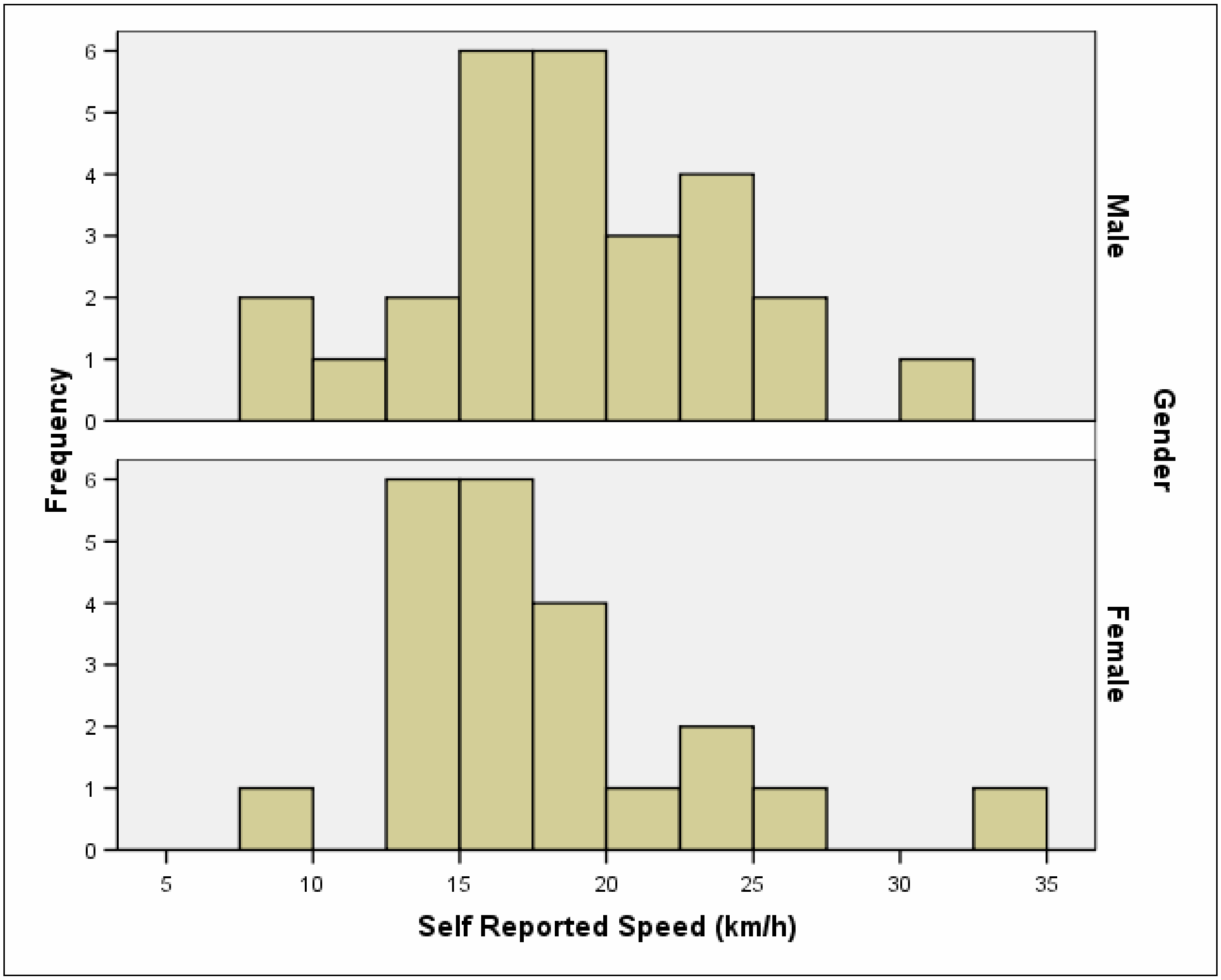
Those interested in participating were directed to email the project coordinator, who received over 200 responses for both periods. Fifteen participants were selected for the Fall pilot study. Fifty-one participants were chosen for the Spring studies based on considerations of gender, age, home location, and work location. Although many more applications were received from males than from females, roughly equal numbers of males and females were chosen (27 male, 24 female). Participants were chosen who lived in “South Minneapolis.” The Spring 2006 selection process also involved a “spatial clustering” approach selecting participants based on proximity to one another. This made it easier later to compare the behavior of individuals on the same or similar routes. All participants had daytime destinations in either downtown Minneapolis or the University of Minnesota, which is located adjacent to the downtown area. Applicants with longer commute distances were favored over those with shorter commute distances. All participants reported that they rode a bicycle to and from work at least three times a week. Participants were also selected in a manner that would introduce a large amount of variance with regard to age. The selection process also ignored bicycling experience or expertise, race, income level, or other socio-economic indicators.

Figure 2.2 Self-reported distance to work by gender



Spring data collection occurred in two data collection cycles, the first in April, and the second in May. The April study period consisted of 25 participants (13 males and 12 females) who collected data between 9April and 29 April. The May study consisted of 26 participants (14 males and 12 females) who collected data between 7 May and 27 May.

Figure 2.3 Self-reported speed by gender



In the two Spring 2006 data collection cycles, 27 of the participants were male and 24 female; participant selection attempted to ensure representation of both genders although more males and females had applied. The study participants ranged in age from 23 to 60, with the mean age of 37. In the April 2006 collection cycle 24 participants collected data for the three week period; in the May 2006 collection cycle 26, and one person's collection cycle took place in both April and May 2006. Data from the first week of each Spring collection cycle was received from all participants, while three participants lack data from the second and three from the third week, either due to data loss or the participant dropping out of the study. Four participants are missing one or two weeks of data.

2.3 Participant Meetings

Two meetings were held with participants. The initial orientation meeting collected basic demographic and self-reported commuting cycling information, provided instruction in the use of the GPS units and filling out daily diaries. The meeting began with a project orientation after which all participants were asked to complete a consent form. At the end of each data collection cycle a focus group meeting to discuss participant's experiences and solicit observations agreed to by the group and comments regarding the project organization was held. A closing survey was also conducted. This survey collected a broad range of general questions about behavior, motivations, and perceptions of improvement needs.

The orientation meetings were held at the Hubert H. Humphrey Building on the University of Minnesota Campus during the week prior to each data collection period. Orientation meetings for the Spring collection cycles were held on April 5th, 2006 and May 4th, 2006. Participants were briefly instructed on the goals and design of the research project and their responsibilities throughout the study period. Participants signed a consent form and completed several surveys regarding their demographic information, bicycling habits, and general travel behavior. Each participant was assigned a GPS unit, instructed on its operation, and was given a three week supply of daily log sheets. The project coordinator met individually with several participants who were not able to attend the initial meetings to present the same material.

Each data collection period consisted of three weeks. During the study, participants were required to track all of their bicycle trips to and from work with the GPS unit, and complete a daily log entry for each trip. In addition, the route the participants rode was altered on a weekly basis. The first week of the data collection period, the participants were directed to choose their own route, preferably the route they most commonly ride. This is referred to as their "preferred" route.

During the second week of the data collection period, each participant was assigned two additional routes; during the third week each participant choose their own route. The assigned routes were chosen in such a way as to have as many participants using similar routes as possible. Fourteen corridors, used by a broad range of cyclists, were targeted: West Lakes Trail, Kenilworth Trail, Park Avenue, Portland Avenue, Hiawatha Trail North, Hiawatha Trail South, Minnehaha Ave, West River Road, 15th Avenue, Nicollet Avenue, Franklin Avenue, Hennepin Avenue, Midtown Greenway Trail, and Minnehaha Parkway Trail. Each participant was assigned a route utilizing one or more of the corridors. All of the corridors are either off-street bicycle trails, or urban streets with bicycle lanes except 15th Avenue, Nicollet Avenue, Franklin Avenue, Hennepin Avenue, and part of Minnehaha Avenue.

Periodically throughout the three-week data collection period, the project coordinator met with each of the participants to download the data from the GPS units. Meetings were located at specified times and places both downtown and on the University of Minnesota campus so that participants would not need to alter their bicycling routes to attend the meetings.

At the end of the three-week data collection period, the participants met with the project staff to collect the GPS recievers and debrief. This debriefing was accomplished by asking participants to complete both a structured survey form as well as marking on a map the routes they took and identifying any problem areas encountered in during the study period.

Chapter 3 Project Data

3.1 Subject Behavioral and Focus Group Data

In addition to daily logs, subjects also provided additional data through two surveys and a focus group discussion. The behavioral data collected in the first survey at the initial meeting consists of information on commuting bicycle use throughout the year, bundling with other activities, individual assessment of capabilities, number of other vehicles in the household, number of bicycles in the household, proximity to off-street bicycle trails, use of public transit, type of residence, and household income. A focus group discussion served as a vehicle for eliciting different perceptions of bicycle commuting and attuning participants to the project concern with facility disruptions. The focus group component of the first meeting primarily served, first, to offer us an orientation as to which routes participants regularly choose and might be willing to consider and, second, to motivate participants. A second survey was conducted at the study period's closing meeting. This survey collected a broad range of general questions about behavior, motivations, and perceptions of improvement needs.

3.2 Data Collection

A total of 938 trips were recorded during the two Spring 2006 collection periods. Of these trips, 327 are from the first week, 304 are from the second, and 307 are from the third.

Each participant (51 total) filled out an initial survey and 47 filled out a final survey. 1051 trip reports were received. From the GPS logs, 938 trips were identified. Of these trips, 852 trips identified from the GPS were matched with a trip report.

3.2.1 Coordination and Methodology

During October 2005, a pilot study consisting of 15 participants was performed. It resulted in an equally small number of trips, but was crucial for developing a methodology robust enough for a larger group of participants. This was an opportunity for the research team to become acquainted with the GPS equipment as well as troubleshoot the data collection process. In addition, it provided a small data set that could be explored to determine how to proceed during the Spring data collection period.

Learning to properly configure the GPS units for the reliable collection of data in was a crucial methodological lesson learned during the pilot study. Only approximately 25% of the expected data was collected due to technical problems regarding the proper method of charging the GPS batteries and proper initial configuration of the GPS units. Data was only collected from 8 of the 15 participants. A complete data set was not collected from any of the 15 participants. For the Spring study, aware of these problems, we were able to prepare the units for data collection by following a rigorous charging protocol involving a full five days of charging before distributing the units to participants.

For each trip participants entered data on a pre-formatted diary, which was printed on heavy card-stock. Included on this form were ratings for the participant's feelings towards using the bike to take this particular trip, perceived safety of the route, and the participant's confidence in using the route. Additionally, participants were able to note whether they took any detours, and if any particular conditions, such as green traffic lights or headwinds, aided or hindered their trip. Rider feelings, route safety, and route confidence were all rated on a scale of 1 to 7, with 1 representing positive feelings/high levels of confidence and safety in the route, and 7 representing negative feelings/low levels of confidence or safety in the route. For some trips, participants neglected to provide an evaluation of their feelings, route confidence, or route safety; these were scored as 0 during data entry from the paper diaries.

Throughout the three-week data collection period, the project coordinator met at least weekly with each participant to download the data from the GPS units. Meetings were located at specified times and places both downtown and on the University of Minnesota campus so that participants would not need to alter their bicycling routes to attend the meetings nor interfere with their daily schedules.

At the end of the three-week data collection period, the participants met with the project staff to collect the GPS receivers and debrief. This debriefing was accomplished by asking participants to complete both a structured survey form as well as marking on a map the routes they took and identifying any problem areas encountered in during the study period. These materials were also used for the focus-group discussion that was part of the final meeting.

3.3 Data Processing

The data products generated from this study required a surprising amount of processing. The data products include results from an initial survey, which provides demographic characteristics and self-reported cycling experience and habits; GPS data, which supply a spatial record of each trip; trip logs, which provide participant entered data to a set of questions for each individual trip; final surveys, which provide general feedback on the cycling experience; and, last, a map distributed at the final meeting indicating routes and observations the participants made. The answers from the initial surveys, final surveys and trip logs were encoded into a statistical program. The GPS data was further processed using a Geographic Information Systems software package, using several program scripts to automate much of the processing. However, each trip still had to be pain-staking evaluated to determine if any large errors had slipped through the automated processing. The most methodologically challenging and time-consuming data processing involved the GPS data.

GPS data logged by the GPS units consists of a text file containing a series of comma separated entries, including the date, time, latitude, longitude, elevation, and speed. For our study, we needed to transform this information into a format readily accessible by Geographic Information Systems; initially, shapefiles were created, which were later imported into a geodatabase. The GPS information, as a listing of points, was also transformed into linear information to generate trip length information.

First, the downloaded GPS log was divided into individual trips. This is necessary because the GPS devices record all their data into a single file until data is deleted from the device. When the project coordinator visited each participant, several trips were received as one unit of data. This occurred at least once weekly. If the data recorded should be greater than the device's storage capacity, the first recorded data would be simply overwritten. As mentioned, the processing could be partially automated. Individual trips were automatically identified by examining the time difference between two points in a GPS log; if the time difference was greater than four hours between two points, we assumed that a new trip had begun. Following this automated processing, trips were further separated through a manual inspection of the data; in several cases, the elapsed time between two trips was less than four hours.

Table 3.1 Data collected from a GPS unit over a 24 second period after translation into a text

Date, Time (GMT-06:00) Central Time (DST), Latitude, Longitude, Elevation (m), Heading, Speed (km/hr), GPS Status, Log Type
04/10/2006, 16:08:06, 44.969992, -93.245322, -0.986, 0.00, 0.00, 2, 1
04/10/2006, 16:08:08, 44.969876, -93.245353, -0.869, 0.00, 0.00, 2, 1
04/10/2006, 16:08:10, 44.969236, -93.244108, 230.238, 177.29, 15.90, 3, 1
04/10/2006, 16:08:12, 44.969185, -93.244104, 231.650, 184.71, 14.20, 3, 1
04/10/2006, 16:08:14, 44.969115, -93.244114, 230.981, 182.46, 12.60, 3, 1
04/10/2006, 16:08:16, 44.969051, -93.244122, 232.432, 183.75, 9.40, 3, 1
04/10/2006, 16:08:18, 44.969019, -93.244119, 233.138, 185.04, 4.50, 3, 1
04/10/2006, 16:08:20, 44.969026, -93.244108, 232.392, 235.03, 0.20, 3, 1
04/10/2006, 16:08:22, 44.969038, -93.244108, 232.392, 320.47, 0.00, 3, 1
04/10/2006, 16:08:24, 44.969045, -93.244108, 233.099, 191.57, 0.30, 3, 1
04/10/2006, 16:08:26, 44.969051, -93.244120, 235.259, 214.12, 0.10, 3, 1
04/10/2006, 16:08:28, 44.969050, -93.244131, 238.125, 218.58, 0.10, 3, 1
04/10/2006, 16:08:30, 44.969044, -93.244143, 240.284, 239.69, 0.00, 3, 1

After the break-down into trips, each trip was converted into standard point and line by an involved process working with ArcGIS and Excel to produce geodata. A script was created that transformed the text files for each trip into a similarly named point file. The point files were retained for later analysis and creation of line geodata. Creating lines included both automated and manual removal of data generated when the participant was stopped. Because the units recorded a data point each two seconds, but are only accurate to 3-5 meters, a person stopped appears to be moving erratically within a 3-5 meter box. Most of this points fortunately could be detected automatically and removed. A visual inspection of each trip and comparison to the point data was still required to assure all erroneous points and larger errors in the GPS data were removed. The length of the trips were calculated from the generated lines, and speed was calculated from the time elapsed during a trip. For each week, a representative route reflecting all the trips taken that week was also constructed; this representative route was made to be directly comparable with Metropolitan Council’s transportation geodata. The components of the representative route were classified according to the type of facility present on the component. The classifications were: road; road with bike lane; bike path; and unknown. The unknown category was necessitated by two problems: in certain areas, such as around Lake Calhoun and Lake Harriett, the Metropolitan Council data, roads and neighboring bike paths were indistinguishable from each other and at times participants used unmapped bike facilities, such as the bike paths and sidewalks in Loring Park.

Processing and automation

Because of limitations of the GPS data we opted to process and maintain three data sets for different archival and analytical purposes. The first data set was a file for each participant trip of all GPS points. This is the source for a detailed inspection of route behavior. This data was the basis for producing a data set with great accuracy, a line data set that recorded the movements of each participant on a single trip. This data set was simplified (cartographic generalization) to produce the third data set—a less accurate representation of a single trip suitable for graphics and small-scale comparisons.

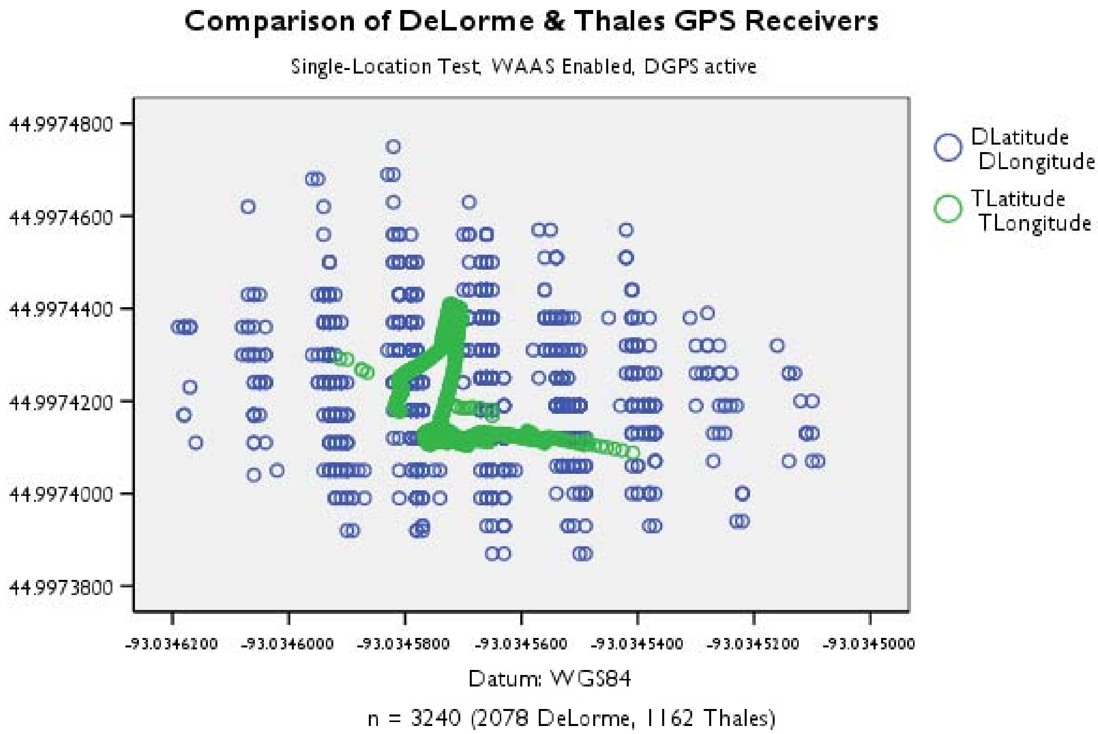
Simplification (Cartographic Generalization)

For simplification we used a tool provided by ESRI in the ArcGIS software package and specified a tolerance of 0.00015 decimal degrees. This tool works iteratively from start to finish of each individual line data set, removing all points within the defined tolerance before moving to the next point along the line that is outside the tolerance. This process can result in some loss of detail and a small amount of arbitrary movement of point locations. Unfortunately, this tool lacks a facility to interpolate locations from a nexus of points and no GIS tool in ArcGIS offers a capability to “lock” the locations of points for processing.

Limitations

As figures in appendix A evidence, converting GPS data to tracks that record the movement of individual cyclists for analysis, is still complex. Clearly there are some tracks which must be removed because their location is erroneous, for example, a track that runs through the building to the West of 20th Street. The spatial error in other tracks also must be verified to assure that the quality of the data is considered in analysis. Our strategy for simplifying lines reduces their accuracy, but we believe is consistent with the relative inaccuracy of the GPS data. Certainly, for detailed analyses, the inaccuracies are likely cumulative and the final accuracy of the detailed data is likely between 3 to 8 meters. To assess the possibility of improving this accuracy we looked into the use of higher accuracy GPS equipment. In appendix D we include a paper authored by Jason Menard who worked on assessing the accuracy of the data collected with the low-cost GPS units used by participants in this research with high accuracy, survey quality GPS equipment. This equipment produces more accurate results, but the complexity, size, and weight of these devices precludes their use in this study.

Figure 3.1 This comparison shows the difference between a high accuracy GPS receiver (Thales) and the DeLorme receivers used for collecting participant data. The coordinate values are decimal degrees.



Chapter 4 Analysis

4.1 Preliminary Analysis (Fall Study data)

The analysis of the fall study data revealed some interesting behaviors and patterns that we elected to focus on in the Spring study. These include the relationships of speed and safety, comfort, and confidence, use of similar facilities, choice of longer routes even when improved facilities were in the proximity of the participant's origin, destination, or route. The small amount of data collected in the fall with sufficient to suggest interesting relationships between travel speed and safety: participants were faster on safer routes but also quite fast on routes they described as unsafe routes. We also started to recognize the use of the same facilities even if participants had different origins and destinations. Finally, we began to note from this preliminary analysis that participants were preferring routes up to 31% longer than the shortest-path route from origin to destination. This brief summary of issues is enhanced in the following section of the report.

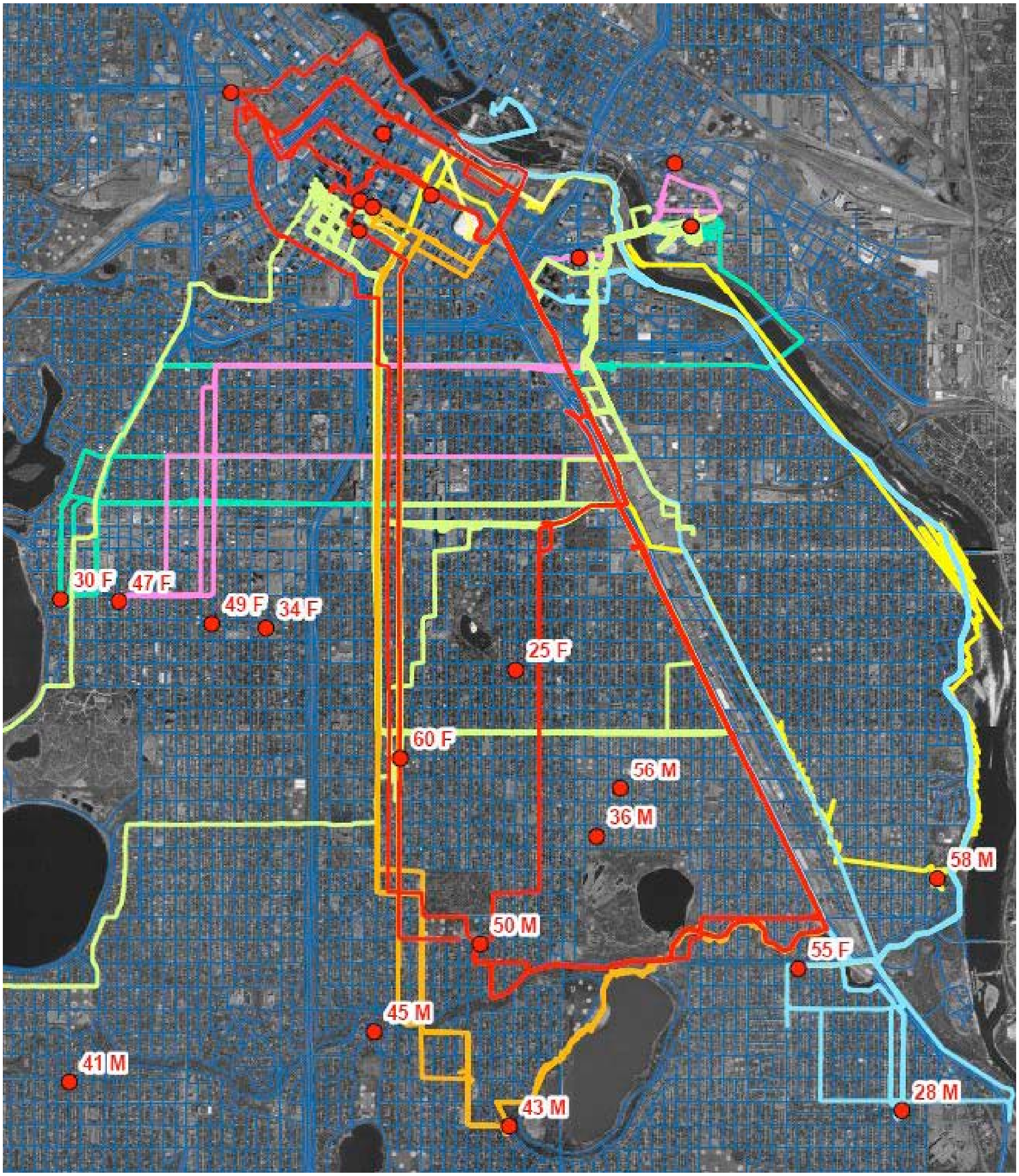


Figure 4.1 The 110 trips taken by 15 participants in fall 2005. Ages and genders are indicated along with the approximate location of their residences. Note the use of several facilities by the same riders

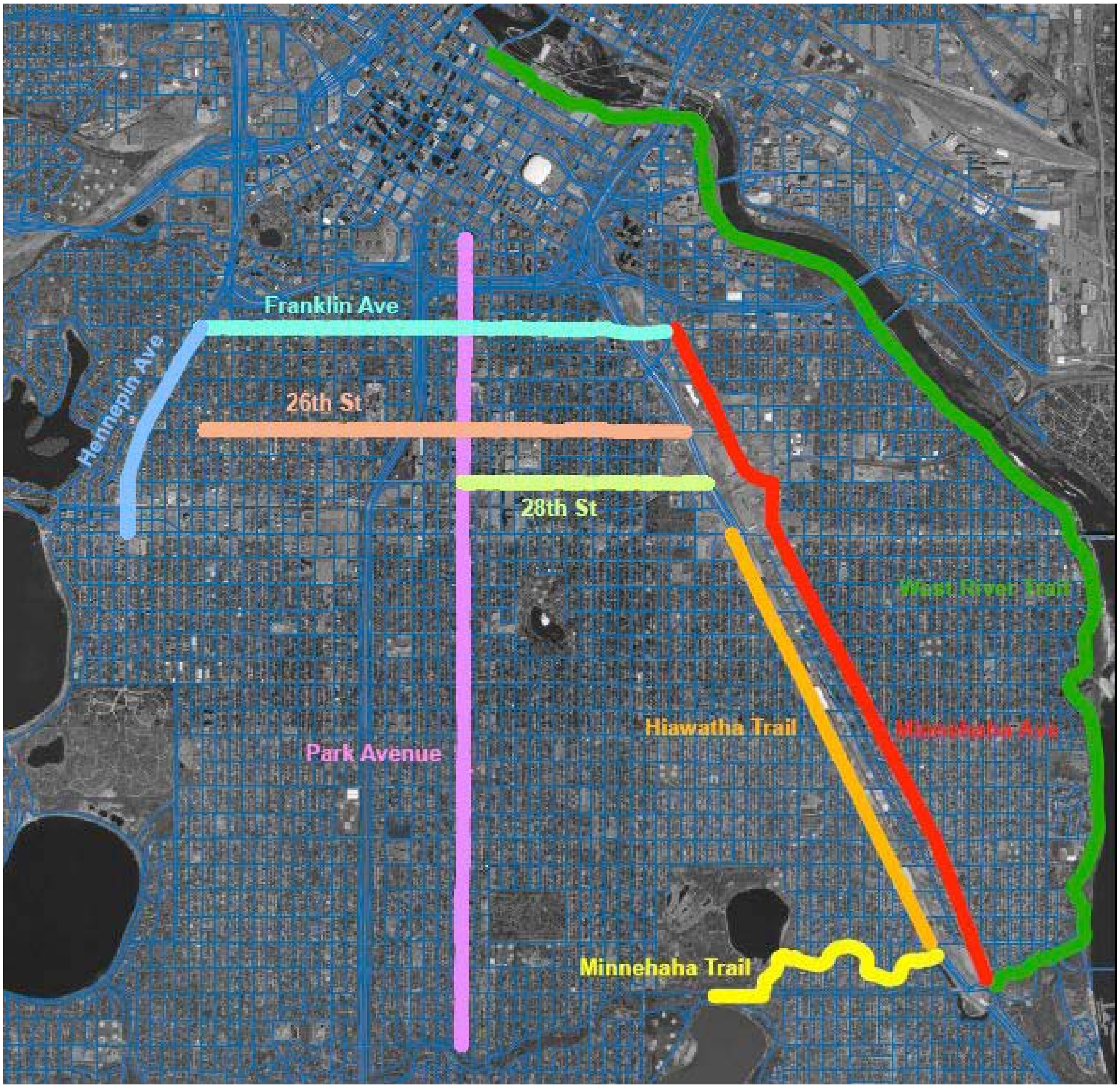


Figure 4.2 Corridors used by Fall 2005 participants

4.2 Main Analysis

With the benefit of a tried and tested protocol, data procedures, and methodology, the data collected in Spring 2006 can be more exhaustively and reliably analyzed. The 852 trips with a distinct match between GPS data and daily log from 51 participants assure these results are statistically significant. Of these trips, the overall average trip taken was 6.44 miles (10.36km) long at 12.08 miles per hour (19.60 kph). Trip distances ranged from 1.19 miles (1.92km) to 15.53 miles (24.99 km), and the maximum trip speeds was 21.28 mph (34.25 kph); due to the methodology used in identifying trips, minimum trip speed is difficult to quantify- one trip can include multiple components that are separated by up to four hours, and trip speed is calculated from total trip duration.

In general, the rides are fairly homogenous. There are minor variations in both trip speed and length by gender; males travel slightly further and faster than females, as shown in table 1. Table 2 shows average length and speed of trip by age; participants 30 years old or younger tended to have a shorter trips than people older than 30, and participants between 31 and 40 years old had the fastest and longest trips, though the speed variation was again small. One interesting trend is that as trip length increases, speed gradually increase; This may be because it is the males who make longer and faster trips, or because riders are making longer trips using dedicated facilities, which may allow faster transport.

The average trip speeds vary according to a participant's willingness to bike, their confidence in the route they will bike, and their perceived safety of the route are shown in Table 3. Interestingly, the unrated trips are consistently slower than average. With all of the above variables, over 90% of the trips were rated 1,2 or 3; the small number of trips rated 4,5, and 6 make interpreting the results over the entire range difficult. For each of these variables, approximately 10 trips for each category were not ranked; this is in addition to the 80 trips that lack daily logs. Out of the three variables, perceived route safety provides the easiest trend to understand; as the perceived safety is lessened, riders appear to be more cautious and move more slowly. This trend holds for all but the most unsafely ranked conditions; anecdotal evidence has indicated that in this situation, riders may go faster to spend as short a time in the unsafe conditions. There is a basic relationship between route confidence and average trip speed in the data; as confidence in the route taken decreases, trip speed also decreases. Finally, the relationship between trip speed and rider confidence is unusual. The speed of a trip seems to be a function of how strongly a rider feels about taking the trip, and secondarily related to the type of feeling. If the rider is extremely positive (1 or 2) or negative (5 or 6) about the trip, the trip speed is quicker. Negative feelings towards the rides also generate slightly higher speeds than positive feelings; as with route safety, riders with a negative feelings may be trying to shorten the duration of the trip.

Participants were grouped based on geographic location, corresponding roughly to the following Minneapolis neighborhoods: Calhoun-Isles and Southwest west of the Lakes Calhoun and Harriett; Calhoun-Isles and Southwest east of Lakes Calhoun and Harriett (including the Lyndale neighborhood of Powderhorn Park); west Powderhorn Park/Nokomis; east Powderhorn Park/Nokomis; and Longfellow south of Lake St. Table 4 presents the average distance and speeds by region. Average trip speed was slightly higher for those living in the western and eastern neighborhoods (12.20 mph for the westernmost riders, 12.58 for the easternmost), while those living in the middle neighborhoods experienced fairly uniform trip speeds. This pattern is consistent with the use of dedicated bike paths that lead to downtown Minneapolis, which exist at the eastern and western regions of the study area. Trip lengths also vary between regions. The westernmost region had the longest average distance; this is in line with the circuitous nature of the Lakes trails and Kennilworth trails. The riders living between the Lakes and 4th Ave South on average lived the closest to downtown; this probably accounts for the low distances. Many participants in the two eastern middle regions (between 4th Ave and 21st Ave and between 21st Ave. and Hiawatha) were asked to use facilities farther away from their residence than other neighborhoods, leading to somewhat increased distances. For example, people living between 21st Ave and Hiawatha were asked to use the Park/Portland bike lanes one week and West River Parkway the next; this adds distance to their trips over using Hiawatha, which for most is their closes facility. The residences of the western-most region benefited from the Hiawatha and Minnehaha Avenues' non-standard direction, creating a diagonal that shortens their distance between both the University and downtown and their residences.

Table 4.1 Gender differences in Spring 2006 average trip lengths and speeds

Gender	Mean Trip Length (km)	Mean Trip Speed (kph)
Female	10.03	18.17
Male	10.67	20.45

Table 4.2 Age differences in Spring 2006 average trip lengths and speeds

Ages	Mean Trip Length (km)	Mean Trip Speed (kph)
23 – 30	8.05	19.17
31 – 40	11.99	20.02
41 – 60	10.90	19.07

Table 4.3 Matrix showing average trip speed according to trip-specific behavioral variable

	Average Trip Speed by Trip-specific Rated Category (kph)			
Rating	Feelings on taking the trip	Route Confidence	Route Safety	
0	18.60	18.57	18.59	No Response
1	20.10	19.76	19.96	Better
2	19.52	18.99	19.41	
3	18.62	19.01	19.04	
4	18.93	19.83	18.88	
5	19.76	16.42	18.38	
6	20.73	18.56	18.72	Worse

Table 4.4 Distinction between participants coming from various areas in average speed and average distance are noticeable

Location of Residence	Number of Trips	Avg. Speed (kph)	Avg. Distance (km)
West of Lakes	215	19.63	11.62
East of Lakes, west of 4th Ave	210	19.28	9.00
East of 4th Ave, West of 21st Ave	213	19.36	11.27
East of 21st Ave, West of Hiawatha	168	19.17	10.49
East of Hiawatha	132	19.88	8.98

4.3 Focus Group Discussions

The results from the Spring focus groups are significant in that they complement the quantitative and hybrid quantitative and qualitative analysis. They also help understand the mindset of participants. Because of the number of questions, space precludes a detailed analysis. The interested reader can find an overview of responses in the appendix B.

Figure 4.3 Qualitative Questions for Spring 2006 Focus Group Meetings

Qualitative Questions for Spring 2006 Focus Group Meetings

- Which routes for commuting from South Minneapolis to Minneapolis downtown or the U of M campus are under-developed?
- Which recent bicycling specific improvements have been the most beneficial?
- What could the city do to improve bicycle commuting facilities?
- What are the key factors in choosing your bicycle commuting routes?
- Why (if ever) do you change your bicycle commuting routes?
- When you choose not to commute by bicycle, what are the main reasons?
- When you choose not to commute by bicycle, on which modes of transportation do you rely?
- What type of bicycle facilities are available at your place of employment/school (e.g. bicycle racks, showers, lockers, changing rooms, air pumps, etc.)
- How would your bicycle commuting be different if more or less facilities were available?
- Why did you initially begin commuting by bicycle?
- Why do you continue to cycle to work?
- What else effects your decision to commute by bicycle (e.g. support from family, membership in club, friends who bicycle to work)?

We think the comments offered by participants are insightful, but may represent, in spite of our efforts to select participants from a broad spectrum of Minneapolis, a more active and engaged portion of the bicycle commuting population. The bias may mean that, on the one hand, these perspectives tend to exaggerate situations. This highlighted sensitivity leads to a stronger weighting, on the other hand, of factors that the less engaged cycling population may perceive to be among the strongest influences on their choice of commuting transportation modes. This note could be verified through a larger analysis of cycling attitudes among Twin Cities inhabitants.

The focus groups for the Spring 2006 studies were held at the end of each three-week study period. Participants returned the GPS units in addition to taking part in an exit interview and focus group discussion. The results from the Spring focus groups are significant in that they complement the quantitative and hybrid quantitative and qualitative analysis. They also help understand the mindset of participants. Because of the number of questions, space precludes a detailed analysis.

Focus group participants were given a single sheet map of S. Minneapolis and asked to use highlighters to indicate the routes the regularly used and affix post-it notes with comments to indicate where they would like to make comments about facilities. A great number of comments were recorded that range from observations about rough pavements, dangerous crossings, high traffic volumes, to comments about conditions in neighborhoods. The significance of the comments was not determined. We asked participants to provide this information as a means of gaining closure on the data collection process and a vehicle for us to augment the data we had collected using GPS and other surveys.

These comments offer valuable insights into the analyses of cyclists when considering route alternatives. Additionally, some of these comments may be helpful to planners considering bicyclists in the planning process. For example, the five post-its from one participant offer the following:

- dotted blue is my usual route home
- Lyndale wasn't too bad if I went before 7 am; bad at rush and midday
- Lyndale was a bit faster, but not enough to be worth the the traffic
- Lyndale was far too dangerous to ride home
- Blaisdell to the Greenway has a bad connection

In general, focus groups flagged the following intersections and roads as dangerous:

- Minnehaha/Franklin
- 46th Street between Hiawatha and Minnehaha
- Riverside
- Crossing 35W by 36th or 28th
- Portland because of traffic's high speed
- Park Ave. near Lake Street
- Lake Street between Pillsbury and Park is in an unsafe neighborhood
- Northbound on Hennepin is dangerous on-ramp to I94
- Franklin between 35W and 11th Avenue
- Street around the Metrodome
- Minnehaha/Lake

Additional comments of relevance include:

- Hiawatha is too noisy and takes to long to cross
- Hiawatha crossings are not aligned with the bike paths
- Turning left on Minnehaha is difficult
- The Hiawatha bike trail is too windy with nothing to block the wind
- Rough pavement on Nicollet between 40th and Lake
- These comments should be considered in conjunction with responses to other surveys questions about route choice behavior.

Chapter 5 Summary and Outlook

5.1 Key Findings

The research has been successful in establishing insightful relationships between commuter cyclist behavior and facilities that point to much more complex and nuanced relationships. However, because of the complexity of data processing, the major outcome is perhaps at this point the methodology, which can be used for other studies. Indeed, this research has only scratched the surface of the relationship between behavior in a two-fold manner: the detailed evaluation of collected data and the development of follow-up research. The four main outcomes we can reliably present are:

1. Safety is the key determinant of bicycle commuter speed

Participating cyclists travel faster, on average, when they feel safer. The perceived safety of a route is clearly an important determinant of an individual cyclist's sense of safety. The resulting increase in speed makes safer routes more attractive. An even more insightful and interesting result is that cyclists, on average, are also faster when they feel unsafe. A route's lack of safety influences cyclists desire to complete the route quicker, hence the increases in speeds compared to routes on which cyclists feel moderately safe.

2. Commuter cyclists gravitate toward similar facilities

Cyclists with similar origins or similar destinations gravitate towards the same facilities over significant portions of their routes. While they may not use the facility over the same distance, results indicate that the choice of facilities is mainly influenced first by perceived safety of a route and closely followed by comfort and confidence. However, great individual discretion in route choice remains due to these very same factors as well as individual considerations, e.g., desire to vary a route on a windy day.

3. Longer routes are the norm

Regardless of the proximity of improved facilities, commuter cyclists choose longer routes, compared to the hypothetical shortest route between origin and destination. Improved facilities may exacerbate this tendency, but the data we have collected is not clear enough for a unequivocal statement of that nature. The choice of longer routes is influenced by safety, comfort, and confidence factors. Variability in traffic volumes over the course of a day is also an important factor considered by participating cyclists. The choice of route considers spatial and temporal factors.

4. GPS units are effective data collection devices, GPS data processing remains complex

Low-end GPS units designed for data collections are extremely valuable for data collection. Because of variability in accuracy and resulting errors that are extremely difficult to automatically detect and resolve, great effort is necessary to review participant data and edit out obvious errors and clear up minor problems. This workload is easy to underestimate.

This research leads to significant other outcomes that still require additional analysis beyond this project or analysis deploying new techniques. They include:

- Navigation of intersections varies tremendously. Complex intersections with non-standard signaling stand out as very treacherous places for cyclists leading to a variety of unsafe behaviors, (e.g., riding against the flow of traffic, crossing lanes mid-intersection.
- Gender differences seem to have only modest influence on speed and distance among participants. Further, the perception of safety, comfort, and confidence shows little difference between male and female participants. After nightfall, women indicate a much greater perception of a loss of safety along many routes, no matter what improvements have been made (e.g., along the Midtown Greenway) and plan their travel accordingly, often accepting a decrease in safety due to higher traffic volumes in exchange.
- Cyclists prefer dedicated bicycling facilities but are extremely conscious of diminished quality (e.g., broken asphalt, conflicts with pedestrians) and will opt for a better-kept facility with higher traffic volume if perceived to be faster or in better condition.

The results of this research are perhaps most significant from a general methodological view point as this type of study has never before been attempted on this scale to our knowledge. This research combines well-tested time-space diary research methods into cyclist's travel behavior with high-accuracy GPS to identify factors influencing route choice and choice of facilities to support informed transportation planning decisions. Though many studies of bike route choice and bicycle travel behavior make extensive use of GIS, no published research utilizing WAAS-augmented GPS technology has reached the literature. Despite this, planners need accurate cyclist travel behavior data to make informed decisions regarding facility management, infrastructure improvements, and the impacts of disruptions on cyclist commuting. The use of WAAS-enabled GPS data equipment allows study participants to collect realtime data that accurately reflects their spatial behavior in a manner that time-space diaries are incapable of providing. We feel that the addition of GPS tracking to the traditional method of using time-space diaries to track spatial behavior enhances both methods—GPS logs record spatial behavior in an absolute fashion that a time-space diary is incapable of, while diaries add a sociocultural component to the GPS data that it would otherwise lack. Based on our results, is seems that larger studies would be quite feasible using similar technology.

The small GPS receivers we used in this study compare quite favorably in performance with higher-performance mapping-grade GPS receivers, recording accurate points in high-multipath situations such as under dense tree canopies and next to tall buildings. In many cases, it appears that the use of mapping-grade GPS confers no additional advantage over consumer-grade WAAS-enabled receivers. Based on this level of performance, we were able to discern relatively fine-grained changes in the use of facilities, resolving a cyclist changing from a bicycle lane to an adjacent bicycle path when the two were less than 3 meters apart, using 0.3-meter USGS aerial imagery.

Similarly, using small GPS units to collect spatial behavior data also allows for the collection of other data as well. When logging points, the units record data every two seconds, permitting research to calculate the speed of travel at any given point along a trip. These data combined with the position data, can permit researchers to study cyclist behavior in a number of situations, including negotiating high-traffic facilities and complex intersections.

Thus the use of small WAAS-enabled GPS receivers provided researchers with considerable advantages for the study of spatial behavior. The units are lightweight and easily mounted on a bicycle, record positions accurately to within 3 meters, and can store up to 50,000 points; about 27 hours' worth of continuous data collection. However, like all GPS receivers, they can be susceptible to multipath effects, especially around very tall buildings, and produce unreliable results. While the GPS dataloggers we used had a very limited interface; only one button and two lights, this limitation caused confusion among study participants since it was difficult to know when the device was tracking satellites, or indeed, even if it was powered on.

Small WAAS-augmented GPS receivers have the potential to revolutionize how research into spatial and travel behavior is conducted. Since such receivers can be mounted on almost anything, and even worn by pedestrians, it is now possible for researchers to obtain highly precise positions with accuracies under three meters—accuracies that were difficult to achieve with GPS even ten years ago without professional-grade equipment and significant processing. As this study continues, future research will explore the integration of the qualitative travel diary data with specific trips recorded by GPS, as well as developing models to predict how facilities impact cycling behavior.

In summary the general methodological issues to consider in the use of GPS equipment to assess individual commuter behavior are:

1. Data Processing requires detailed and repetitious hands-on review and editing
The GPS data suffers from inaccuracies and errors that cannot be automatically detected. The interactive review and resolution of inaccuracies and errors is exceedingly involved and time consuming.

2. No data collection of specific disruptions
We rely on analysis of GPS data and daily logs to determine disruptions. This has its limitations. With this collection of disruption information, we were unable to specifically identify different behavioral responses to unexpected behaviors. We can graphically point to distinct behavioral differences in navigating complex intersections, lack, however, the resources for a systematic analysis.

3. Facility networks have limited indicators of bicycle improvements
The street network data used for this study lacks consistent and clear indicators of bicyclist facility improvements. The development of a street network that accurately records cyclist facility improvements and their conditions would have been a great aid.

Figure 5.1 Challenges for resolving change of facilities

5.2 Outlook

We are working currently on two publications. One highlights the methodological issues and the other focuses on analytical issues.

Finally, this research has only scratched the surface in a two-fold manner: the detailed evaluation of collected data and the development of follow-up research can and should occur now. This also includes possibilities for a number of student projects exploring and evaluating the data, for example comparing how different participants negotiated intersections and if we can identify facility and behavioral typologies.

With the data sets from Spring 2006, a variety of research projects are conceivable relying solely on the behavioral and GPS data resources. A few we wish to highlight include:

1. Data mining of locational and behavioral data

A project using geospatial data mining techniques and approaches could more readily analyze the rich but volumous data resources for relationships between speed, behavior at intersections, daily logs, and general behavioral data for participants.

2. Intersection analysis
The rich data from GPS recording of individual travel at intersections coupled with behavioral data could be analyzed to develop a typology of intersections as a well a typology of intersection navigation.

3. Route variability
The variability of routes among commuter cyclists with nearby origins and destinations could be studied more thoroughly and put into relationship with daily logs, weather changes, etc.

All of these examples also could benefit from additional data collection. Additional projects that focus on these specific opportunities, if possible, would offer great returns for increasing our understanding of commuter bicyclist behavior and facility disruption.

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Appendix A Maps

Figure A.0.1 Home and Work Locations of Spring 2006 Participants

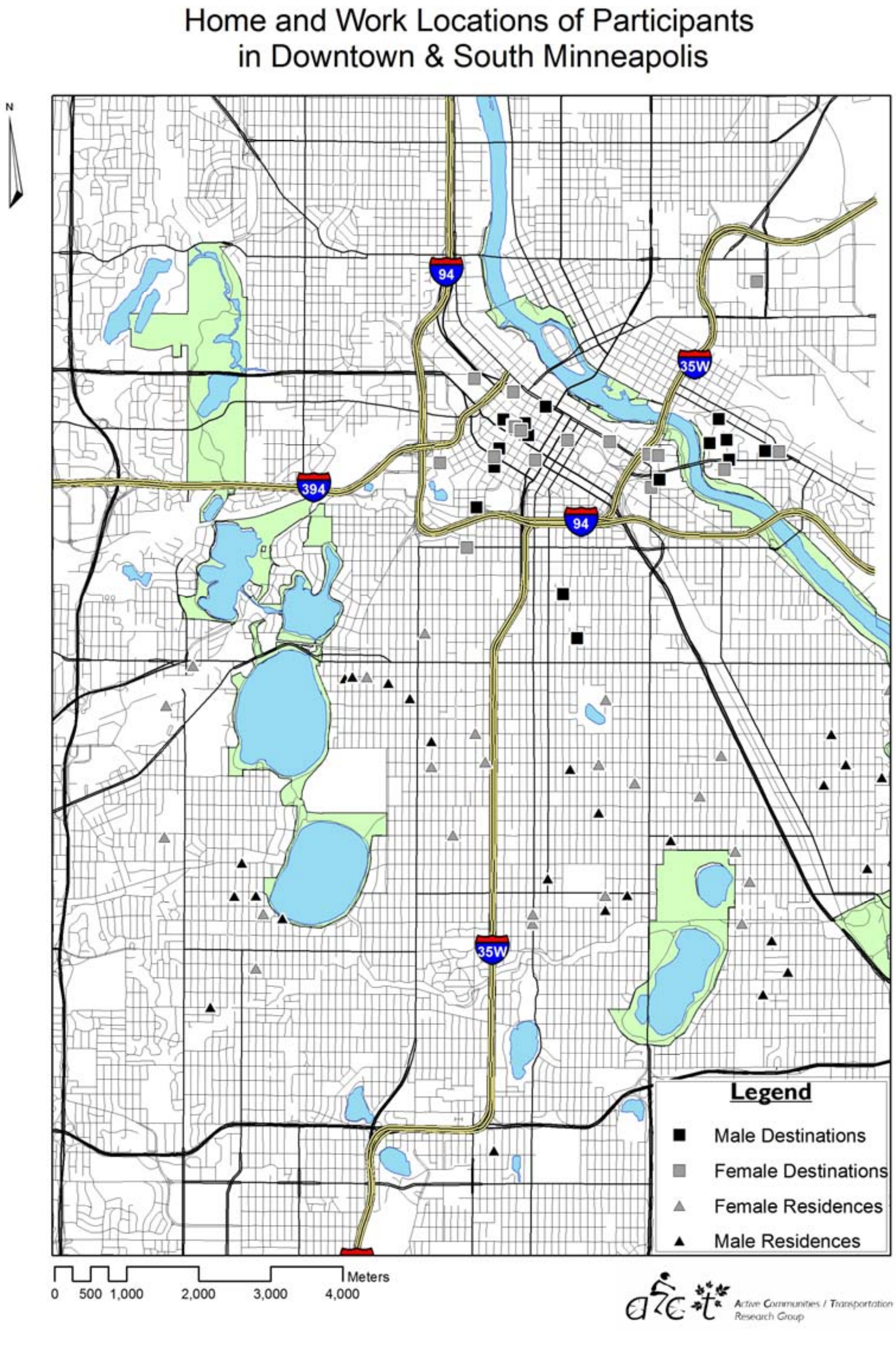
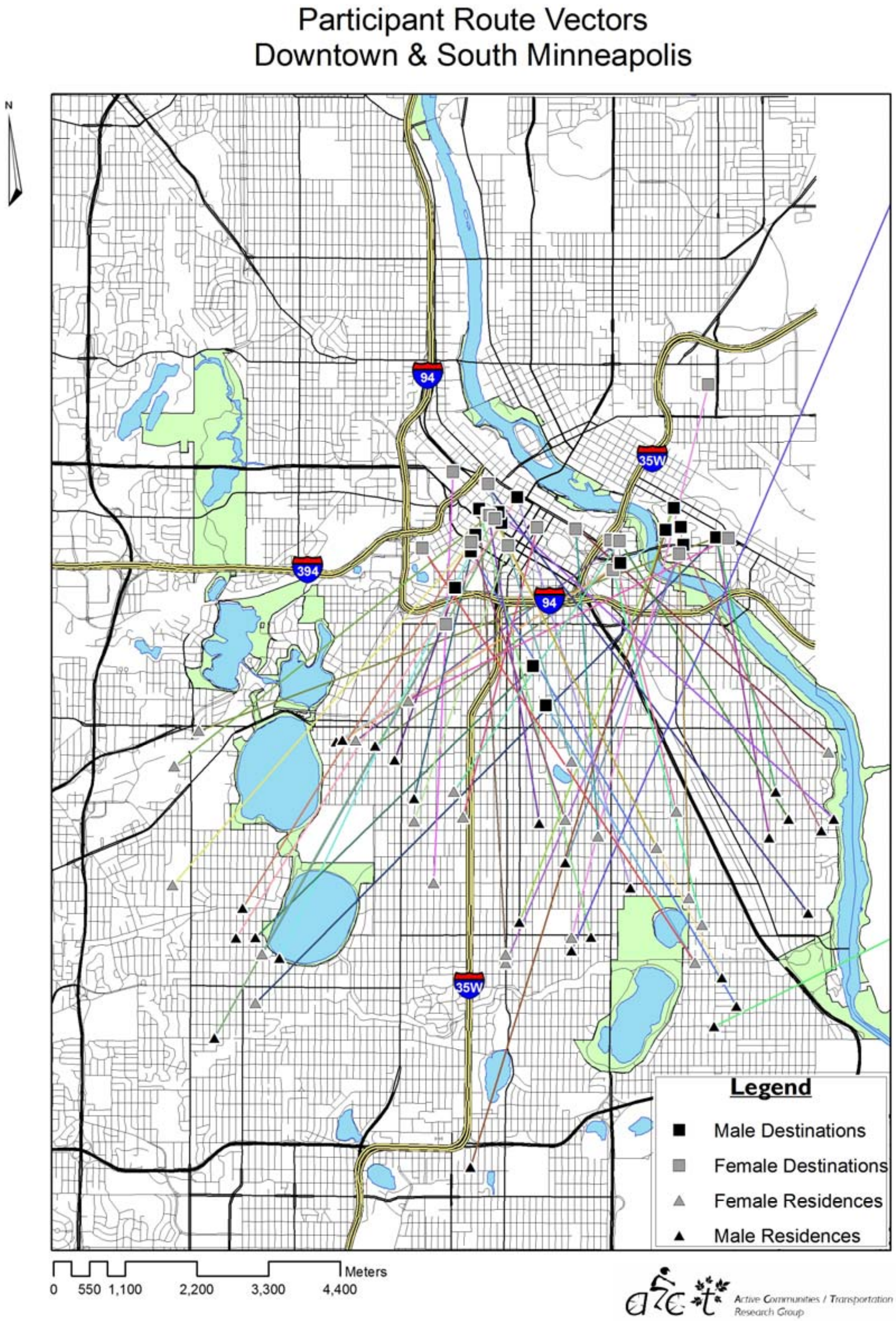


Figure A.2 Participant Route Vectors



Appendix B Survey Instruments

Initial Survey

Participant ID #____________ **Initial Participant Survey**

Age_____________ Gender________________

1. How far is your (one-way) bike commute to work (in miles)? ___________miles

2. How long does this take you on average? ______________minutes

3. What is the longest time it takes? Why? ___________minutes. What are some of the circumstances that contribute towards it being longer in time? ____________________

4. On average, how many times per week do you **bicycle to work**…

_____In January

_____In February

_____In March

_____In April

_____In May

_____In June

_____In July

_____In August

_____In September

_____In October

_____In November

_____In December

Do you go shopping or do other things on your bike commute?

1. Never
2. Seldom
3. Often
4. Frequently
5. Every time

5. Please assess your level of comfort/experience bicycling by checking the statement you most closely associate with:

    1. Only on off-street paths
    2. A variety of conditions but prefers riding off-street paths
    3. A variety of conditions but prefers riding off-street paths and on-street bike lanes
    4. In *light* traffic without on-street bike lanes
    5. In *heavy* traffic without on-street bike lanes

6. On average, how often do you bicycle **each week** during the summer months (regardless of purpose; the above question was just for going to work)? _________

7. How many vehicles in working order does your household own? _____

8. How many bicycles in working order does your household own? _____

9. How close is your home to the NEAREST off-street bicycle trail? For example, the type of trail we are referring to is the Midtown Greenway, Cedar Lake Trail, Luce Line Trail, or the Southwest LRT Trail. (*Check only one*.)

    1. Less than ¼ mile (less than four blocks)
    2. Between ¼ and ½ mile (four to six blocks)
    3. Between ½ mile and ¾ mile (six to eight blocks)
    4. Between ¾ mile and 1 mile (eight to ten blocks)
    5. More than 1 mile
    6. I know where the trail is, but don't know how far it is from my home.

7. I don't know where any bicycle trail is located. [
OVER]

10. Did you ride public transit (bus, light rail) in the past 7 days?

1. Yes ➔ ➔
2. No

> a. What was your PRIMARY reason for riding public transit in the past 7 days? (*Circle one.*)
>
> 1. To get to work

11. When did you move into your current residence? Month__________ Year________

12. How would you describe the type of housing unit in which you currently live? (*Circle one.*)

1. Duplex
2. Townhouse
3. Single-family detached house
4. Apartment/Condo
5. Other (*please specify*) __________________________

13. Do you rent or own your residence? (*Circle one.*)

1. Rent 2. Own

14. What is the nearest INTERSECTION to your current address (for example, South Street S and 54th Avenue W) and the city, state, and ZIP code?

____

City / State / ZIP: ________________________________

15. Do you have a valid driver's license?

1. Yes ➔ ➔
2. No

> a. How many motor vehicle trips did YOU make in the past 24 hours (a good way to think about this is the number of times you had to park your vehicle or start the ignition)?
>
> ________ Motor vehicle trips

16.For statistical purposes, please circle the category that best describes your current household income, including the combined earnings and other income of all household members who contribute to the household budget? (*Circle one*.)

1. Less than $20,000
2. $20,000 to $39,999
3. $40,000 to $59,999
4. $60,000 to $79,999
5. $80,000 to $99,999
6. $100,000 to $119,999
7. $120,000 or more

17. Feel free to provide us with other comments about your choices relating to daily travel.

Thanks again for your help.

Daily Log

Each daily log was produced on both sides of a heavy-weight colored paper for participants. These log "cards" were each half of an 8.5" X 11" sheet of paper in size.

Daily Log (for each leg of your commute)

Participant ID#:___ Today's Date:______ Start Time of Commute:______am/pm End Time of Commute:_______am/pm

Current Temperature (°F):_______ Current Weather Description:_______________________________________

What are your feelings toward cycling to work/home today (circle one number)?

Enthused/There is great weather	1	2	3	4	5	6	I am lacking energy/This is a drag

Are there specific events/instances/issues that you wish to share that describes your above response?

How confident do you feel about your route today (circle one number)?

Know exactly the streets/intersections	1	2	3	4	5	6	I really don't know this route at all

If applicable, what features are you uncertain about?

After You Ride:

Did you feel safe on your route today?

Yes, safe in all conditions	1	2	3	4	5	6	Many places on this route were scary

If applicable, where and why was this route unsafe today?

Did you deviate from your route or stop for any reason, planned or unplanned? Why?

Name the positive characteristics of this route:

Name the negative characteristics of this route:

Final Meeting Survey Questions

General

What obstacles were most significant when planning your routes? (paving, construction, traffic, perceived danger, other:, space for comments)

What obstacles were most significant when riding your routes? (paving, construction, traffic, perceived danger, other:, space for comments)

What do you think the city needs to do about improving bike commuting facilities? (space for response)

How did your participation in this research alter your bicycling? (space for response)

Did weather impact your cycling? (space for comments)

Were there any special circumstances that impacted your bike routing (Yes/No, space for comments)

How did the GPS equipment work for you? (Add space for comments)

Focus Group Discussion

Which routes for commuting from South Minneapolis to Minneapolis downtown or the U of M campus are under-developed?

Which improvements do you think help the most?

What are the key factors in choosing your commuting routes?

Why do you change your commuting routes?

When you choose not to commute by bicycle, what are the main reasons?

Wrap-up

How do you think this research project could better establish the factors that influence the routes cyclist use when commuting?

How would you characterize the interactions with the research team?

What was the most interesting and most difficult parts of participating in the project?

Appendix C Project Terminology

Route – A route is a designated series of roadways, bicycle lanes, trails, or sidewalks linked together that a bicyclist can use to travel from one location to another. A route may be assigned or chosen by the bicyclist.

Actual Shortest Route – Shortest route used by a particular bicyclist.

Theoretical Shortest Route - The route consisting of the shortest network distance between two locations. This route may or may not ever be used by a bicyclist for various reasons. This route excludes highways or other facilities that cyclists cannot travel.

Preferred Route – The route chosen by a bicyclist most frequently during the study period. The route used during week one of the study period is usually the preferred route.

Stated Route – A route that a participant reports to have bicycled, which is not verified by GPS data.

Assigned Route – A route the project coordinator asks the participant to utilize if safety and comfort permits..

Route Variable – Route variables are both microscopic or macroscopic in nature and apply to all bicyclists using a particular route segment. Examples include pavement quality, potholes, traffic control devices, facilities available along route, prevailing traffic patterns, and traffic volumes.

Corridor – Multiple bicyclists riding on the same series of roadways, bicycle lanes, or trails constitutes a corridor. Corridors may be established artificially by assigning multiple bicyclists to a route they might otherwise not use, or may be identified visually by observing travel. The Midtown Greenway is a prime example of a corridor in our study area.

Segment – A portion of a route used by a particular bicyclist.

Trip – The travel from one address to another address, usually in one closed period.

Trip Chain – A series of linked trips, for example a bicyclist traveling home going to shop for groceries and continuing from there home.

Travel Characteristics – Attributes that describe one or more participants travel behavior. A travel characteristic may change within a given trip. Examples include facilities used and speed traveled.

Documented Trip – Complete and reliable GPS data has been collected for the trip.

Partially Documented Trip – Incomplete or unreliable GPS data has been collected for the trip.

Facility – infrastructure used for bicycle travel, such as a bicycle lane, trail, bridge, or neighborhood street.

Problem Intersection – An intersection of two or more streets or facilities. They may be uncommon with regard to scale, multi-modal conflict points, awkward geometry, impedance of sight or visibility, or other uncommon circumstances. An example is the intersection of Hiawatha, Franklin, Minnehaha, and 20th Avenues.

Disruption – A location where a facility is interrupted. Examples include construction, large puddles/mudholes, facilities in disrepair (large potholes), problem intersections, conflict points with other travel modes, or disconnects between trail sections.

Attitudinal Variables – Self-reported perceptions or values held by individual bicyclists regarding travel behavior.

Travel Behavior – A broad term used to describe characteristics generally observed of a particular bicyclist regarding route choice, route preference, speed, and other variables.

GPS Point – The location of a bicyclist at a specific point in time as defined by the GPS data.

GPS Track – Straight lines connecting ALL points in chronologically within a given trip.

False Spur – A cyclist initially travels in a particular direction, then backtracks after realizing they have made an incorrect route choice decision. They pose an interesting problem for analyzing trip distances and times.

Clump – A messy "hairball" of crossing lines in a trip created when the GPS unit is collecting data while the bicyclist is stopped or traveling at extremely slow speeds. Clumps may occur at three locations: the origin or destination of the trip, or somewhere in the middle. Whenever possible, groups of points located at the beginning or end of a trip should be removed before points are connected to form lines to avoid creating clumps. Clumps occurring in the middle of a trip are generally due to the bicyclist stopping at an intersection.

Simplified Line – The line created by connecting GPS points is "simplified" using the ArcGIS script "Simplify Line Tool." Simplifying the lines has two purposes: removing clumps from the middle of trips, and generalizing the trip data to obtain a more accurate measurement of trip length by removing inaccuracies of the GPS data.

Appendix D Guide to Using the BlueLogger GPS Unit

The GPS is only collecting points when the GREEN light is flashing!
The GPS must be plugged in for recharging when not in use or data will be lost!

Turning the Unit On:
Press and hold the power button for 2-4 seconds (until the GPS/Battery LED blinks green once), then release the power button. If you hold the power button down too long, the GPS may turn off when the button is released.

Turning the Unit Off:
Press and hold the power button for 2-4 seconds (until the GPS/Battery LED blinks green once), then release the power button. The device is off when both LEDs are no longer lit.

Bluetooth LED:

- Solid Red = Low Battery
- Flashing Blue = no Bluetooth Connection
- Solid Blue = Bluetooth Connection

GPS/Battery LED:

- Flashing Green = 3-D Fix. Collecting Data Points, (please allow up to 60 seconds start-up time)
- Flashing Orange & Red = charging & 3-D Fix
- Solid Red = Charging Battery

Charging the Unit:
Please charge with the unit on **Sunday night only**. Make sure that the unit is not next to an open window where it may begin collecting data. Make sure the green light is not flashing while it is charging.

Appendix E GPS Device Accuracy Comparison

The following is a draft paper written as a journal article submission.

Using the Global Positioning System to Track Bicycle Commuters' Spatial Behavior

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Abstract

This paper aims to demonstrate that the use of GPS receivers as a means to collected data on the spatial behavior of commuting bicyclists is feasible and produces high-quality data. The Active Communities/Transporation Research Group recently outfitted 55 bicycle commuters with WAAS-enabled GPS dataloggers between April and May 2006 to identify the types of facilities cyclists favor and the variables that influence route choice. As part of this research, our results suggest that the new generation of small WAAS-enabled GPS receivers can serve as an excellent platform for tracking bicycle commuters' travel behavior. Moreover, such receivers can reliably show cyclists' specific choice of facilities and response to disruptions to a much finer degree than was previously possible, and their performance compares with that of much more costly mapping-grade receivers. [130 words]

Introduction

As commuting to work by bicycle and cycling in general becomes more and more popular, planners must consider the needs of bicyclists for prioritizing future infrastructure improvements. To this end, the Active Communities/ Transportation Research Group at the University of Minnesota is attempting to analyze the spatial behavior of cyclists to identify the types of facilities commuting cyclists favor, how they choose their routes to and from work, and the kinds of disruptions that force cyclists onto suboptimal routes to avoid them. Studying cyclist commuter behavior provides a basis for future infrastructure improvements and understanding the impacts of disruptions on daily commutes and urban traffic flow.

The study of human spatial behavior and its theoretical underpinnings has been actively developed for over 30 years (Hägerstrand 1970, Chapin 1974, Parks & Thrift 1980, Pred 1981). Studies in this field, notably Parkes & Thrift (1980) and Hanson & Hanson (1981) have generally been limited to questionnaires and travel diaries, and rely on the participants' own perceptions and desire to faithfully record how they negotiate space and spend their time in their daily lives. This technique is very useful in that the diaries can record behavior patterns that are otherwise impractical to observe (Thornton, Williams & Shaw 1997).

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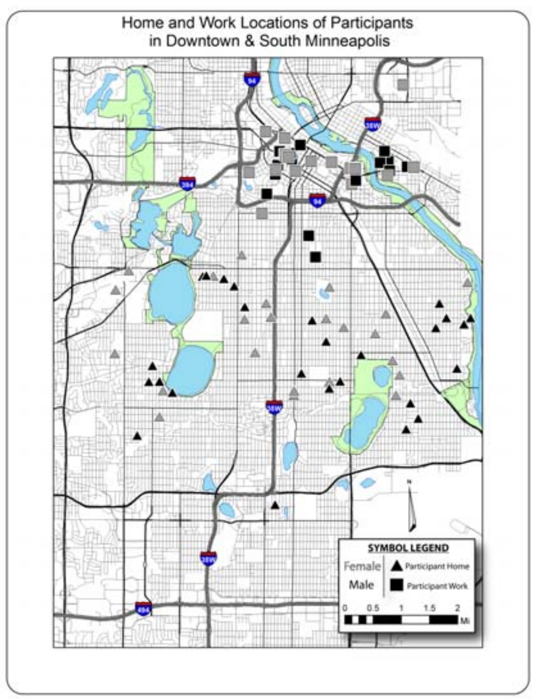
However, with the advent of Geographic Information Systems (GIS), and the widespread use of the Global Positioning System (GPS), it has become possible for researchers to track subjects and their spatial behavior much more accurately than was possible 30 years ago, though the time-space diary is still very useful to record subject's non-spatial behavior and attitudes. The use of this technology for studying cyclists' spatial behavior is still in its infancy; studies using GPS to collect data on spatial behavior have generally been limited to studies tracking the movement of vehicles (Zito *et al* 1995, Quiroga & Bullock 1998), and or to assist blind or visually impaired pedestrians (Golledge *et al* 1991). Likewise, GIS has frequently been applied to the problem of studying cyclists' spatial behavior to excellent effect, but thus far the use of GPS to track individual trips has been limited (Dill & Carr 2003, Nelson & Allen 1997, Aultman-Hall *et al* 1997).

This project attempts to combine tracking cyclists' commuting behavior with GPS technology, while continuing to utilize time-space diary techniques to assess and explain the behavioral factors exhibited with the GPS tracking data. GPS is rapidly coming into its own as a research tool for high-resolution tracking, and has been used to track pedestrian spatial behavior in urban environments (Shoval & Isaacson 2006), and variations in route choice in motor vehicles (Jan *et al* 2000). However, GPS has not been well-studied as a research platform for bicycle behavior. The results of our research suggest that the new generation of small WAAS-enabled GPS receivers can serve as an excellent platform for tracking bicycle commuters' travel behavior, and can reliably show cyclists' specific choice of facilities and response to disruptions to a much finer degree than was previously possible with consumer-grade GPS receivers affordable enough to deploy to large numbers of research volunteers.

Methodology: GPS Methodology in Brief

GPS data for the project was collection in two periods during April and May 2006. The April study consisted of 25 volunteers (12 females and 13 males). The May study consisted of 30 volunteers, evenly split between males and females. Volunteers were chosen from a pool of over 200 applicants living in south Minneapolis, identifying applicants who lived near one another on a street map of the City of Minneapolis though a visual clustering method. All volunteers lived in clusters spread across south Minneapolis, and commuted by bicycle at least three times a week to destinations in downtown Minneapolis, or the University of Minnesota near the downtown area. Preference was given to those with longer commutes. In addition to selecting volunteers who lived near one another in south Minneapolis, participants were informally

Figure 1: Map of Study Area



selected to provide a wide variety of ages for the volunteer pool. No preference was given for volunteers with a perceived bicycling skill or for socio-economic variables of any kind, and such data was not collected.

Each study period for the project lasted three weeks. For each bicycle trip to and from work, volunteers recorded details about the cycling conditions that day on a daily log, as well as collected GPS data using a small GPS receiver attached to their bicycle. The route each volunteer took to and from work was changed on a weekly basis. For the first week, participants were asked to take their "preferred" route to and from work. For succeeding weeks, each volunteer was assigned a new route each week by project staff, with the route assignments developed to encourage volunteers to use similar routes along fourteen study corridors. Each of the corridors consisted of off-street bicycle trails, or in many cases urban streets with designated bicycle lanes. Participants met with project staff very briefly each week to receive new route assignments and to download their collected GPS points into a handheld computer. The GPS receiver records positions every two seconds into a log file stored in the unit's flash memory, which can be downloaded to any Bluetooth-enabled PDA or laptop. Points were then run through a number of geoprocessing scripts in Python to remove excess points caused by short stops and traffic lights, then converted into ESRI shapefiles for display and analysis in ArcGIS 9.1.

Discussion of Equipment

The project took advantage of a new generation of small GPS receivers. Each participant in the project was issued with a DeLorme BlueLogger GPS receiver, a very small 12-channel WAAS-enabled unit that fits easily in the palm of the hand and weighs less than 100 grams. The unit has no output screen, it is simply turned on and it begins to record points into internal memory. The receivers data from the units is transferred remotely using a Bluetooth connection to a PDA or laptop computer. Participants turned the unit on, waited several seconds for the unit to warm up, and rode normally with the unit attached to the handlebars of their bicycles.

Figure 2. DeLorme EarthMate BlueLogger GPS used in project

The GPS receivers recorded the volunteer's position and elevation every two seconds, to an accuracy of roughly three meters. Since a point is collected at set intervals, these data also allow for the calculation of velocity. Each week, study participants met with the project coordinator to download the stored GPS data from the units for processing. The units' cost, size and ease-of-use made collecting GPS data much easier than would be possible with GPS receivers in the past.

How GPS Works: NAVSTAR System

The Global Positioning System, formally known as the NAVSTAR Global Positioning System, is developed and funded by the US Department of Defense (DoD). NAVSTAR is an acronym standing for NAVigational System using Timing And Ranging. Originally deployed for the US military, GPS is now firmly entrenched in the private sector with millions of public and private users worldwide.

The system is operated by the US Air Force and is comprised of three segments; the control segment, the space segment, and the user. The spaceborne segment is comprised of the 24 satellites of the nominal GPS constellation arranged in circular 12-hour orbits at an altitude of 10,900 nautical miles (20,200 Km) above Earth. The satellites are arranged in six orbital planes spaced 60 degrees apart and tilted 55 degrees off the Earth's equator. Each orbital path has four GPS satellites, thus four or more satellites are usually visible from any point on the Earth at any one time (Hofmann-Wellenhof 2001: 12)

The control segment consists of the Master Control facility in Schriever Air Force Base in Colorado, plus five monitor stations and four ground antennas spread over the planet. The monitor stations track the signals from the entire GPS constellation, which are forwarded to Master Control and used to update individual satellites through the ground antennas.

The user segment is comprised of the GPS-using community. GPS receivers use the signal from four or more GPS satellites to provide precise timing and highly accurate estimates of position and velocity (Hofmann-Wellenhof 2001: 11-24)

How GPS Works: How GPS Points are Calculated

While the details of how the global positioning system works are complex, the principles on which it functions are simple. GPS receivers calculate the distance from each GPS satellite in the local sky by measuring the time it takes for the GPS signal to travel from the satellite to the receiver. This process is called trilateration. Each satellite carries four internal atomic clocks, and broadcasts the current time, satellite position and ephemeris data for the GPS constellation, and system status messages as part of its signal to earthbound GPS receivers (FRD 2001: 3-5, US Coast Guard 1995, Hofmann-Wellenhof 2001: 76).

The system has two levels of service, the Standard Positioning Service (SPS) used by the civilian world, and the Precise Positioning Service (PPS) used by the military, which is inherently more accurate than SPS. Currently the system uses two L-band frequencies, L1 and L2. (1575.42 and 1227.6 MHz). The Coarse Acquisition (C/A, also called Civilian Access) code available to civilians as part of the SPS is transmitted around the L1. The PPS is based on L2, which carries the P/(Y) code, and can be broadcast as the unencrypted P code or the encrypted Y code, which requires a military receiver to decode. The P code itself is not classified (Hofmann-Wellenhof 2001: 75, US Coast Guard 1995)

Based on the C/A code from the GPS satellites in orbit, the receiver calculates the distance to each satellite using the time lag from when the signals were sent from the satellite to when they are received, and then adjusts for ionospheric disturbances to the signal and the rotation of the earth. This produces a *pseudorange*, calculated via a PRN, or pseudo-random noise code transmitted by the GPS satellite. C/A PRN code chips are 1.023 bits in length with a period of one millisecond (Hofmann-Wellenhof 2001: 76). This code is unique to each satellite, though each satellite uses the same L1 frequency using CDMA techniques, very similar to how cellular phone signals use the same frequency. The GPS receiver then matches the PRN to a code chip in its memory and uses a scoring system to synchronize them until the two millisecond code chips match.

Using the pseudoranges for each of the satellites in view, the GPS receiver uses a process called trilateration to determine its location on the Earth. Since the direction and distance to each satellite is known from its pseudorange, the GPS receiver is at the intersection of four imaginary spheres around each satellite. Since each GPS satellite has four atomic clocks on board, which are kept synchronized by the US Department of Defense and the exact time is broadcast as part of the GPS signal, the much less accurate clock in the GPS receiver is able to adjust its clock to focus the intersection of the spheres' radii to within 13 meters horizontally and 22 meters vertically on the surface of the Earth (FRD 2001: 3-6).

WAAS Augmentation

While a 13-meter level of accuracy for base civilian GPS signals is adequate for most uses of GPS, tracking spatial behavior of cyclists in an urban environment requires more precise positioning. Under development to assist in aviation navigation, the wide-area augmentation system (WAAS) supplements the spaceborne GPS signal with a series of 25 ground stations that compare the GPS signal to geodetically known points. The stations then send corrections over landline to a master station, which retransmits a unique corrected GPS signal to each of four orbiting WAAS satellites, which in turn broadcast a corrected signal to WAAS-enabled GPS receivers. The WAAS signal serves three purposes. It provides additional ranging for GPS receivers, it provides GPS satellite integrity data, and most importantly, it provides wide-area differential corrections to the SPS signal.

The WAAS signal dramatically improves the horizontal accuracy of the SPS to 2 and 3 meters from an average SPS accuracy of 13 meters, making WAAS-enabled GPS units feasible for tracking bicyclists' choice-of-route in urban settings (FRS 2001: 3-17).

Sources of Error: GPS Error

GPS signal propagation is significantly affected by travel through the atmosphere, and such errors are one of the main GPS error factors that WAAS corrects for. As GPS signals travel down to the Earth from space, the layers of the atmosphere, particularly the ionosphere, refracts and slightly delays them. This delay interferes with the range solutions from the GPS receiver on the ground and the satellite, resulting in positional errors of several meters. WAAS corrects for this by determining how the atmosphere is interfering the signal in a region, and then providing realtime correction data to WAAS-enabled receivers via its own satellites.

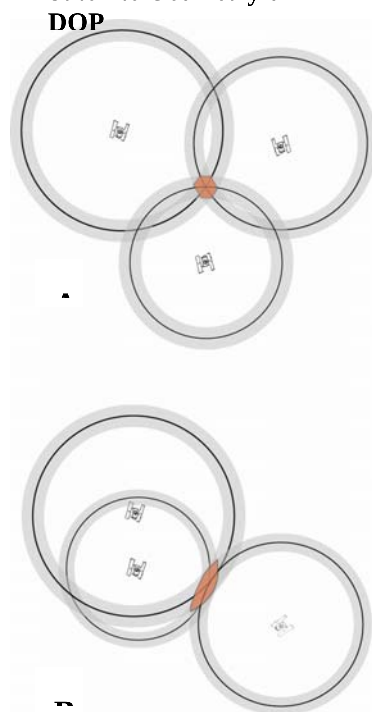
However, WAAS does not correct for other common sources of GPS error, such as GPS points collected during a cold start of the receiver. Receivers turned on after being off for several days (or even hours), or moved more than 500 miles use outdated satellite ephemeris data, which initially can cause poor position solutions until the almanac is updated through the GPS signal.

Likewise, multipath error, or interference caused by signal reflection off surfaces near the receiver is a common problem as well, especially in urban environments and under thick tree canopies. Since reflecting off surface can increases the distance from the satellite to the receiver, multipath errors can affect the accuracy of positions by artificially increasing the pseudorange. Most modern receivers are able to filter out the majority, but not all multipath effects through advances in GPS antenna design and signal processing (Hofmann-Wellenhof 2001: 129-130).

Sources of Error: GPS Mission Planning

Although the nature of the GPS constellation ensures that at least four satellites will be visible above 15º elevation at any one time, the relative positioning of the satellites in the sky has a great deal to do with the accuracy of the position solution a GPS receiver finally calculates. The reason for this lies with the trilateration method the receiver uses to solve positions. If the satellites are more or less evenly distributed throughout the sky, the point of intersection of the pseudoranges for each satellite will be small, and the position solution that the GPS receiver derives from this arrangement of the GPS constellation will be accurate.

Figure 3. Effect of Satellite Geometry on DOP



On the other hand, if the GPS satellites are arranged roughly in line with the receiver, the area of intersection of the pseudoranges on the ground for each satellite is potentially large, and the subsequent position solution will be less accurate. Moreover, this problem can be enhanced by large objects, such as tall buildings, that block the signal for individual satellites entirely. In cases such as this, unreliable points can be collected even under excellent satellite conditions.

This issue of satellite geometry can be critical for interpreting data from cyclists' riding at all times of the day and in all conditions. Satellite geometry affects the accuracy of points rider collect on their trips and can cause systemic errors in data collection at certain times of the day when satellite conditions are poor. Since the orbits of GPS satellites are very well known, many GPS receiver manufacturers also publish mission planning software that allows users to view the configuration of the constellation over any location at any time. The effect of satellite geometry on the accuracy of positioning can be summarized by Dilution of Precision (DOP) factors. DOP is a scalar that represents the role of satellite geometry on the position accuracy, represented as a ratio:

$$\sigma = DOP \times \sigma_O \tag{1}$$

where σ is the standard deviation of position accuracy, and σ_O the standard deviation of measurement accuracy (Wells *et al* 1999: 4.22). In practical terms, DOP is a function of satellite geometry; a high DOP stems from a poor arrangement of satellites, generally grouped together in one section of sky. Low DOPs come from satellites well-spaced throughout the visible sky. Any accuracy error in measurement is multiplied by the DOP factor to get the effective positional error. In general, the lower the DOP, the more accurate the position fix. DOP factors below 4 are desirable, above 5 are suspect, and above 8 are completely unreliable for accurate positioning. DOP has several forms, defined by the coordinates it measures.

Table 1: Dilution of Precision (DOP) variants		
VDOP	Vertical Dilution of Precision	Vertical accuracy
HDOP	Horizontal Dilution of Precision	Horizontal accuracy
PDOP	Positional Dilution of Precision	Horizontal and vertical positional accuracy
TDOP	Time Dilution of Precision	Time accuracy
GDOP	Geometric Dilution of Precision	3D coordinates, plus time.

For purposes of tracking cyclists' spatial behavior, the DOP figure of interest is GDOP, since the timestamp on each GPS point collected by a cyclist's receiver allows the calculation of velocity. While the relative positions of GPS satellites in the sky is outside the user's control, DOP factors can help users understand and manage the error stemming from satellite geometry on a day-to-day basis, especially when incoming data from cyclists is inexplicably poor.

Sources of Error: Error Budgets

Though GPS has become increasingly accurate since its inception in the 1980s, the system still remains subject to error. The rough breakdown of error for the GPS, the error budget, is summarized in Table 2.

Table 2: Sources and Levels of Uncorrected GPS Error

Source of Error	**Approximate Error Level**
Ionospheric interference	±5 meters
Tropospheric interference	±0.5 meters
Calculation & rounding errors	±1 meters
Ephemeris data errors	±5 meters
Clock drift, satellite & receiver	±2 meters
Multipath effects	±1 meter
Total	~14.5 meters

Note that this does not include error introduce through poor satellite geometry. However, WAAS-enabled receivers differentially correct for much of this inherent system error, by comparing the corrected WAAS signal to the incoming GPS signal, eliminating much of the atmospheric, ephemeris and clock error, thus increasing the accuracy of position fixes to around three meters (FRS 2001: 3-17).

All GPS receivers are subject to these errors, but the more sophisticated mapping and survey-grade receivers minimize these errors by combining differential correction (usually from WAAS) and measuring the carrier phase of the L1 signal, or in the case of highly accurate instruments comparing the L1 and L2 carriers. These techniques produce sub-meter position accuracies, and are generally not necessary for tracking the spatial behavior of commuting cyclists. Indeed, the performance of mapping-grade GPS receivers with sub-meter accuracy compares favorably with small, user-friendly WAAS-enabled GPS dataloggers.

Results

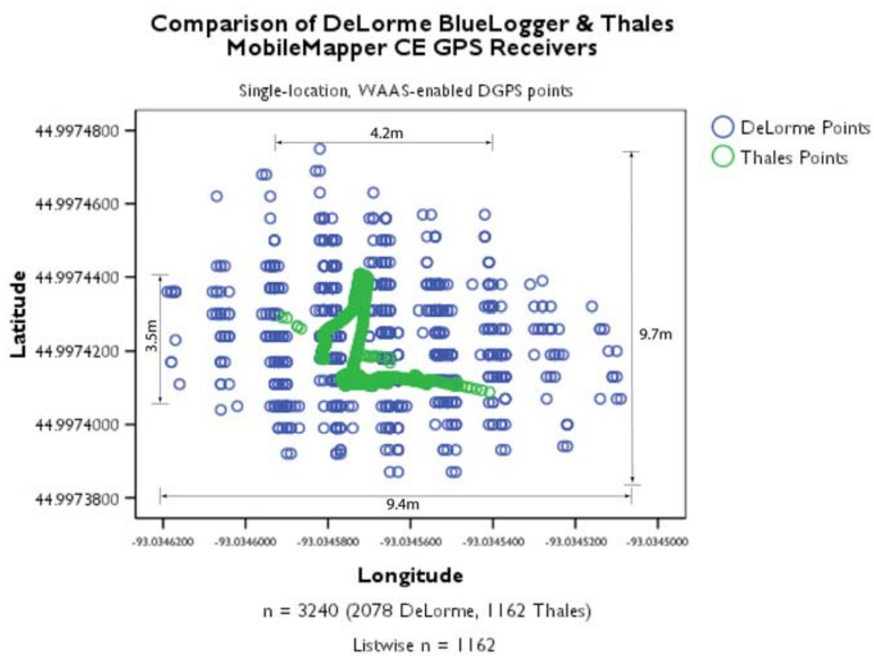
GPS receivers have become increasingly small over time, but until the removal of Selective Availability in 2000, and the recent introduction of WAAS augmentation to the SPS, the accuracy of handheld units was insufficient to track cyclists on the move, especially in an urban setting. Users of traditional consumer GPS receivers need training in the use of the unit, and some understanding of how GPS works.

However, the small WAAS-enabled units used for this research were small enough to attach to the handlebars of participants’ bicycles, and quite accurate when corrected by WAAS, with 2 to 3-meter accuracy. The DeLorme BlueLogger has a single button to turn the unit on and off, and two lights; one to indicate GPS positions are being recorded, and another to indicate a Bluetooth connection to a PDA or laptop computer. These units require very little understanding of GPS, and almost no training to use properly once they are configured. This makes tracking cyclists with accurate GPS much more feasible than was previously possible. Handheld receivers with similar accuracy require more training for volunteers to use and have more features that increase the cost of the unit. Likewise, submeter-accurate mapping-grade receivers cost far too much to issue to volunteers, require a significant understanding of GPS, and tend to be unwieldy for attaching to a bicycle.

Figure 4. Thales MobileMapper CE GPS Receiver

To assess the accuracy of the BlueLogger units, and the viability of using GPS to track bicycling commuters, we compared the performance of the BlueLogger to that of a Thales MobileMapper CE receiver. The Thales unit is a submeter accurate WAAS-enabled mapping-grade receiver that measures the L1 carrier phase variance to increase accuracy in addition to differentially correcting the incoming GPS signal with WAAS. This device is significantly larger and heavier than the DeLorme, and while it has many features and uses ESRI ArcPad software, it is not easily accessible to a casual user. It is also quite expensive, prohibitively so to issue MobileMapper units to 25 cyclists at a time. However, the Thales unit does provide an excellent baseline for assessing the accuracy of points collected with the DeLorme BlueLoggers.

Figure 5



We collected data simultaneously at a single location with both the BlueLogger and the MobileMapper CE. Figure 5 represents a scatterplot overlay of 1162 points from both receivers. The points overall are grouped quite tightly over a roughly 81- square meter area. In comparison, the Thales data are spread over a roughly 4x4-meter area. This is not unusual for points collected for periods over one hour, even with differential correction. While the BlueLogger points are spread evenly over the entire area, the data collected by the Thales receiver are much closer together, and display the variability in GPS positions even with very precise equipment. Table 3 shows descriptive statistics for each receiver's respective datasets. The Thales unit is roughly twice as accurate as the DeLorme unit, and the much lower standard deviations from the Thales receiver keep points more focused on a single location.

Table 3: GPS Comparison Descriptive Statistics

	N	**Range**	**Min**	**Max**	**Mean**	**SD**	**Variance**
DeLorme Latitude	2077	.000088 ..	44.997387	44.997475	44.997423624	.000013194	.0000
DeLorme Longitude	2077	.000122	-93.034631	-93.034509	-93.03457218	.000020181	.0000
Thales Latitude	1161	0000320	44.9974088	44.9974408	44.997419126	.0000095188	.0000
Thales Longitude	1161	0000503	-93.0345912	-93.0345408	-93.034572751	.0000061588	.0000
Listwise N	1161						

Figure 6. Differences in facility use detected with high accuracy GPS equipment

Though a single-location comparison shows that submeter-accurate GPS receivers are significantly more precise than WAAS-enabled receivers alone, their respective accuracies are not completely dissimilar. When comparing their performance in tracking cyclists, the data collected by the BlueLogger largely falls within the area of expected WAAS accuracy around the submeter path. This suggests that a relatively inexpensive WAAS-enabled GPS can serve almost as well as a much more expensive receiver.

Testing the BlueLogger under field conditions shows similar results. In this case, data was captured on a moving bicycle using a BlueLogger receiver under heavy tree cover, which created significant multipath effects. The route taken along the Mississippi River in Saint Paul has both a bicycle lane and a bicycle path. A path in ArcGIS 9.1 (Figure 6) derived from points collected from a BlueLogger clearly demonstrated was able to resolve relatively fine-grained changes in route and facility on a USGS 0.3m digital orthophotoquad. Figure Z shows the rider's route moving from the bicycle lane on the street, to the adjacent bicycle path, a distance of about 1.5 meters. In many places along the street, the bicycle lane and path are 2 meters or less apart, and data collected by the BlueLogger successfully resolved which facility the cyclist was using with little ambiguity.

Indeed, it seems clear that using low-cost WAAS-enabled GPS receivers can provide accurate data to track not only commuting cyclists' day-to-day spatial behavior, but also which specific facilities cyclists are using within a confined area. It is also possible that such receivers can perform better under such conditions than can higher-performance mapping and survey-grade receivers. Since the emphasis with high performance units is accuracy, many units only differentially correct positions when conditions are ideal for submeter accuracy. When conditions do not meet the unit's tolerance, the unit does not collect DGPS points at all. This creates a situation of "diminishing returns", when the highly precise positions of mapping-grade receivers do not necessarily provide more information about spatial behavior or route choice than does much less expensive and easier-to-use consumer-grade WAAS-enabled receivers, which are quite accurate and more suited to collecting data on a moving bicycle.

Conclusions

This research combines well-tested time-space diary research methods into cyclist's travel behavior with high-accuracy GPS to identify factors influencing route choice and choice of facilities to support informed transportation planning decisions. Though many studies of bike route choice and bicycle travel behavior make extensive use of GIS, no published research utilizing GPS technology has reached the literature.

With the advent of WAAS and the removal of Selective Availability, the Global Positioning System has come into its own. In the late 1990s, GPS accuracy was limited to roughly 100 meters in any direction without significant processing in a receiver that could be mounted on bicycle. By 2003, with WAAS augmentation and the US Government's decision to discontinue Selective Availability, GPS accuracy was increased to less than 3 meters, making high-resolution tracking of travel behavior possible for researchers.

The results of this research show that the new generation of small WAAS-enabled GPS receivers are quite adequate for high-resolution tracking of cyclists' spatial behavior. Moreover, though receivers capable of submeter accuracy could certainly be used, such equipment will not necessarily guarantee more accuracy. Indeed, the BlueLogger resolved a cyclist switching from one adjacent facility to another during a trip, and reliably showed which facility was in use along a multifacility route.

Small WAAS-augmented GPS receivers have the potential to revolutionize how research into spatial and travel behavior is conducted. Since such receivers can be mounted on almost anything, and even worn by pedestrians, it is now possible for researchers to obtain highly precise positions with accuracies under three meters—accuracies that were difficult to achieve with GPS even ten years ago without professional-grade equipment and significant processing. The challenge to geographic information science will be to develop techniques to integrate high-resolution GPS data into the existing body of method and theory in spatial behavioral research.

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