Computing Challenges in Use of GPS Devices to Understand Travel Decisions

Lisa Aultman-Hall[1], Jianhe Du[2] and Eric Jackson[3]

ABSTRACT

Traveler route choice behavior is the cornerstone of numerous advanced traffic management technologies. Yet, we lack data to describe the route decision making undertaken by drivers. While in-vehicle Global Positioning System (GPS) receivers seem to be a logical means to collect travel data, very few GPS travel route datasets have been collected and analyzed to understand driver behavior. This paper summarizes the findings of several recent field-based research projects which address the methodological issues in use of GPS for travel route data: spatial data typology and conversion; map-matching GPS data to underlying road networks; obtaining comprehensive link travel time data; and missing data issues due to urban canyons. The extent of complications in collecting and using these route data is significant, but this paper demonstrates that the methods to overcome these problems are feasible. Most importantly, these efforts illustrate that datasets of travel routes be collected along known paths for calibration.

KEY WORDS: route choice, GPS, travel data, urban canyons

INTRODUCTION

Traveler route choice behavior is the cornerstone of numerous advanced traffic management technologies. Yet, we lack data to describe the route decision making undertaken by drivers. This lack of data limits our ability to improve route assignment logic in traffic simulation models and regional travel demand planning models. Actual segment-by-segment travel routes are difficult to collect with paper or phones surveys. With the improved accuracy of GPS devices, it is now feasible to use GPS devices, especially passive GPS devices, to collect route data. Recently, researchers are also combining GPS and tailpipe monitoring to more fully consider second-by-second vehicle operations as a predictor of emissions.

However, the application of GPS for travel data is not as straightforward as widely assumed. This is especially true if the data are to be used in the study of route

[1] Associate Professor, Department of Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Road, U-2037, Storrs, CT 06269 aultman@engr.uconn.edu 860-486-2717
[2] Transportation Analyst, Wilbur Smith Associates, 900 Chapel Street, Suite 1400, New Haven, CT
[3] Ph.D. Candidate, Department of Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Road, U-2037, Storrs, CT 06269

choice behavior directly. When the passive GPS devices are used to collect multiple-day travel data, the post-processing of the data is very challenging. Automatic spatial models to identify trip ends and convert point data to link-by-link data are necessary, but also extremely time and resource intensive. Data tabulation is particularly challenging because missing GPS data is spatially correlated in dense urban areas, rather than randomly distributed.

This paper will summarize the findings of several recent research projects conducted at the University of Connecticut which address the methodological issues in use of GPS for travel route data:

- Spatial data typology and conversion;
- Map-matching the GPS data to underlying road networks;
- Estimation of link travel times; and
- Evaluation of the spatial patterns in missing data due to urban canyons.

One unique feature of these methodological analyses is the inclusion of known routes, so that the accuracy of the proposed methods could be measured. In other words, the vehicles with GPS were driven repeatedly on predetermined routes.

BACKGROUND

Commonly available and relatively inexpensive GPS technology has several important advantages for collection of real world travel data. First, GPS allows for significant amounts of travel data to be automatically recorded typically at 1-sec intervals. The equipment is small and can be easily placed in any vehicle to collect routine data from real world subjects or used in controlled travel experiments. Second, GPS positions can be overlayed with Geographic Information System (GIS) databases allowing the road type, traffic control type, and adjacent land use of every spatial location to be quantified.

Over the past decade, several pilot efforts to understand travel patterns using GPS-collected data for transportation planning have been undertaken. In 1996, the Federal Highway Administration (FHWA) collected a travel data set for 100 households in Lexington, KY for all trips taken during one week. The GPS technique showed improvement over traditional survey approaches with respect to inclusion of under-reported trips and capture of certain trip characteristics such as length (Murakami and Wagner 1999). Since that time GPS travel experiments have been undertaken in California, Texas, Arizona and Kentucky.

A major improvement for GPS use occurred in May 2000 when the deliberate scrambling of accuracy, selective availability, was removed by the U.S. Department of Defense. GPS transportation research before that time, focused primarily on the most basic issue: positional accuracy. Given the large errors, significant work was required just to place the vehicle on the right road in a GIS road network database.

Since the removal of selective availability, positional accuracy has greatly improved and is not an issue for vehicle tracking (Ochieng and Sauer 2002 and Adrados et al. 2002). However, the use of GPS in a moving vehicle will always represent measurement accuracy problems that cannot be completely overcome. Indeed, survey quality GPS is now possible using carrier phase GPS receivers and differential correction. But even as the price of high-end GPS receivers comes down, facilitating widespread use in vehicles, accurate measurements will always be hampered by the movement of the vehicle. As the vehicle moves, its lock on satellite signals changes, and obstructions such as tree canopies, buildings, or overpasses prevent continuous data collection.

In addition, the vehicle environment makes the problem of temporal delay in obtaining a GPS measurement even more significant. The positional accuracy of a receiver is usually reported for a steady-state stationary condition (less than 15 m for the units used in these studies). Because this error in absolute position results from clock errors and atmospheric conditions, GPS measures of relative position from point to point are much more accurate and allow velocity measurements which are accurate to 0.1 knots at steady state velocity (for the GARMIN 16-HVS unit). Of course vehicles in the transportation system rarely travel at steady state, and acceleration and deceleration is frequent.

Smoothing may be an appropriate method to address GPS accuracy issues for average travel time estimation. Some researchers have considered the accuracy of GPS for velocity and acceleration estimation within the context of air quality and fuel consumption (Hellinga and Chan 2002, Greaves and Somers 2003). Both have demonstrated that use of smoothed GPS data provides improvements over average speed-based techniques for these applications. However, many remaining challenges for use of GPS for travel route data cannot be addressed with smoothing.

EQUIPMENT

Figure 1 GeoStats GeoLogger GPS Receiver

A mid-range self-contained GPS receiver designed specifically for in-vehicle data collection was used in all of the field-based work described here: the GeoLogger (Geostats) is shown in Figure 1. This receiver was designed for use in travel habit research and transportation planning surveys. This unit requires a 12-volt vehicle power socket as a power source. The Geologger is capable of recording data in its 4MB memory at one or five-second intervals. For this study, the rate of one record per second was used. This receiver is a stand-alone unit; there is no differential correction used in the data collection.

Table 1 contains the receiver specifications as reported by the manufacturers. The reacquisition time refers to the time that it takes a receiver to regain a position based on satellite signals once the signal has been lost. The reacquisition time is very important for this research since signals are blocked by obstructions or lost as the vehicle moves. A time gap of two seconds could cause an unreasonable velocity or acceleration to be calculated, which is critical for the emissions related work.

Table 1 GPS Receiver Information

Position Accuracy	< 49 feet
Velocity Accuracy (steady state speed)	0.44 mph
Reacquisition Time	< 2 sec

SPATIAL DATA TYPOLOGY AND CONVERSION

One fundamental problem in use of GPS for travel route data is the mismatch of GPS point data to the linear representation of the link segments in a transportation network. Currently, errors which will never be completely eliminated in the GPS collected points as well as the base linear networks make the process of matching the GPS data onto the network complicated. In many cases, humans are needed to directly transform the GPS point data into a representation consisting of network line segments for analysis. This is not practical on a large scale for full transportation networks where a large number of vehicles are being tracked.

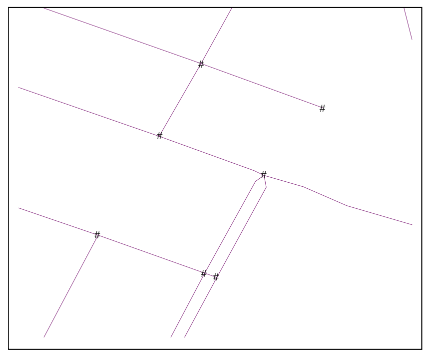
Figure 2 Link and Node Network

The data points collected by a GPS receiver in a vehicle traveling in a transportation system are single points in space. Networks of roads, rivers, railway lines, pipes or transmission lines on the other hand are represented as lines in a GIS or other network database. Often referred to as links and nodes, a linear feature such as a road is represented in a network as a link that joins two nodes as shown in Figure 2. In a road network, the link represents the road segment that goes from one intersection to the next. Even though in reality the road has a width dimension, in the network model, it is a one dimensional line. The attributes of the network link are stored on this line segment in the GIS or other computer program which is used for route analysis or optimization. Therefore, in order to consider the route a vehicle is using, the GPS point data must be translated onto the line network. In a network model, that route then consists of, or is represented by, a series of consecutive links. When collected by a GPS receiver, an actual route traveled by a vehicle consists of a series of points that may or may not fall along the lines the vehicle traveled in the network. Given urban canyons or tree canopies, as well as the movement of the vehicle these points might be separated by significant time and distance.

Intuitively it seems that "snapping" the GPS points to the nearest line segment would allow the analyst to translate the points into lines so they could be analyzed. Unfortunately, however there are gaps in the GPS data so links are missed and at intersection points might be snapped to intersecting roads. However, even if incredibly accurate GPS points could be obtained for the moving vehicle, the ability to translate the points onto the network would be further hampered by the quality of the line networks available. Road networks are typically derived from the center lines of streets taken from paper maps, satellite images or digitizing. Even road networks developed with GPS have some error and it is only recently that agencies are developing these higher quality networks.

Furthermore, even if the lines representing the network segments were placed at the actual accurate center of the road, in reality the road is not one dimensional; it has width. Vehicles do not travel on the center line but across the whole width of the road in various lanes. On a major eight lane roadway as much as 50 feet might separate the edge of the curb lane from the center line of the road. Therefore, GPS points collected from traveling vehicles even if perfectly accurate may fall off of the center lines in a perfectly accurate network file. Frontage roads that closely parallel major arterials or freeways in urban areas create problems. So while it may seem reasonable to "snap" points to the nearest line, this is simply never going to be enough of a methodology to translate GPS collected data into useable vehicle route data in a network configuration. It is necessary to develop a more rigorous procedure using spatial models to map GPS points onto network lines.

MAP-MATCHING THE GPS DATA TO UNDERLYING ROAD NETWORKS

One recent study (Du et al. 2005) focused on the development of the spatial models to match GPS point data to underlying linear links. It also included the evaluation of model accuracy and performance using objective metrics and known travel routes. This is a notable difference between this study and others. Therefore, unlike previous travel behavior studies where the actual routes used by participants are unknown, the accuracy of the models for map matching can be evaluated through comparison between predicted routes and the known real routes in this research is possible.

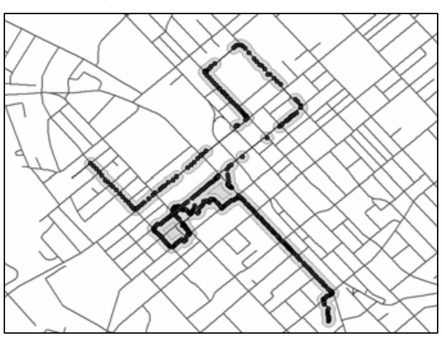

Figure 3 GPS Data on Network

Figure 3 illustrates the type of challenges encountered. In this figure, the black points have been collected by in-vehicle GPS and the grey buffered areas are a set distance from these points. Algorithm development required very careful selection of buffer sizes. If the buffer distance is too large, too many links are included, especially in closely spaced grids networks such as downtowns. The buffer distance of 150 feet was found to be optimal.

TRAVEL TIME DATA

Link travel times, especially real-time travel times, are a fundamental factor for studying travel behavior and route choice because minimization of travel time has been treated as the most important criterion for routing decisions in the majority of situations (Abdel-Aty et al. 1995 for example). Link travel times are also essential for the operation of traffic management and intelligent transportation systems. While it seems straightforward to calculate route travel times from GPS travel speed, challenges exist for this computation as well.

It would be ideal if link travel times on the road links in the entire network were known. Unfortunately, it is impractical to collect travel time data on each individual road link during all time periods. The in-vehicle GPS used for a travel survey when participants undertake routine travel has some advantages over other methods: they collect data on all types of links (arterials through local roads) at many different times of day (not just peak periods), while detectors and dedicated travel time probes are typically only deployed on major routes at peak hours. However, GPS observations are a small non-random sample. Link travel times are known to be complex dynamic functions that vary with demand volume. Travel times differ throughout the day and by day of the week and are affected by traffic control. Limited GPS data simply may not be representative.

Most previous research has been aimed at estimating the link travel times on only one or more arterial roads where GPS probe data were collected. The mean difference between the predicted travel time and the observed travel time ranges from 2% to 26% (Du and Aultman-Hall 2006). There have been virtually no real-world data collections aimed at a full urban area and studying route choice behavior where estimation of average link travel times over the network is imperative. In a recent University of Connecticut study (Du and Aultman-Hall 2006) link travel times were estimated for the whole road network with sparse probe data distributed in the city (10-12 receivers at one time) over a long time period (the data collection was 16 months) where the probe data came from real-world travel. This is typical of the type and level of GPS deployment we are likely to see in coming years in an increasing number of household travel surveys. A Classification and Regression Tree (CART) method was used to categorize the links by minimizing variances of the observed speed ratios (observed speed to free flow speed) in category and maximizing variances of the ratios among categories.

The models were successful at estimating the average link travel time for arterials and collectors at approximately the same accuracy level of other previous research which was corridor focused. The models could not account for the complete variability in link specific travel times within a given time period (from minute to minute for example) or between individual drivers who have different speed and other habits.

MISSING DATA AND URBAN CANYONS

Even if the GPS point data can be converted to link-typology and travel times estimated with GPS data, the urban canyon remains the largest problem for travel route collection. Urban canyons usually correspond with the locations where we are in the most need of traffic analysis. Some researchers are considering use of cell-phones with GPS for data collection in these areas. This allows the in-vehicle device to use cell towers for position triangulation within urban canyons. While this approach seems appropriate in very large cities such as New York where cell phone infrastructure is very dense, it may not be a good solution in smaller urban areas. Furthermore, certain legal issues over the proprietary information belonging to cell phone companies may stifle advances.

Certainly the urban canyon problem has been widely studied. But the location and spatial distribution of missing GPS data was particularly interesting to our research group because we were concerned that missing GPS data are correlated with different types of travel, and thus tailpipe emissions. In 2004, a route was chosen for investigation in Hartford, Connecticut (city population 121,000; county population 1,183,110). The route encompasses a range of roadway and driving conditions.

Section one (Figure 4 – 33.4 miles, 65 mph) of the test route runs along Interstate 91 from Hartford to Enfield, CT. Here satellite signal obstruction was minimal. Section two (Figure 5) is located in downtown Hartford, CT where the effects of satellite obstruction from tall buildings compromise GPS receivers. The downtown section of this route is only 2 miles of the total route, the other 10 miles in this section is designated as an urban arterial. This 10 mile section has a moderate right of way and buildings lining the roadway do not reach more than 3 stories high. Section three (Figure 6 – 16.2 miles, maximum speed 40 mph) runs along a state highway from Hartford to Avon, CT. While one portion of the route is classified as an urban arterial, the other is designated as a rural arterial due to the limited residential access and rural nature of the roadway.

An undergraduate student from the University of Connecticut was recruited and instructed to drive as he would during normal day-to-day driving conditions. The data from a total of three runs are used in this analysis resulting in a total of 197.28 miles of data.

The GPS data collected on the test route was categorized by the spatial definitions that were outlined in Figures 4 through 6 (downtown, rural arterial, urban arterial, and interstate). For each of these categories an analysis was conducted to determine the number of missing data points (Table 2). In addition to missing data, the GPS receiver may record a position point, but report an erroneous or unrealistic velocity. Velocity readings were labeled unrealistic based on the previous second. For example, there were 48 records in the downtown section where the velocity changed greater than 62 mph (100 km/h) in one second. Any records where the velocity changed more than 10 mph per second (16 km/h) were removed from the dataset. Table 3 contains the results from this secondary analysis.

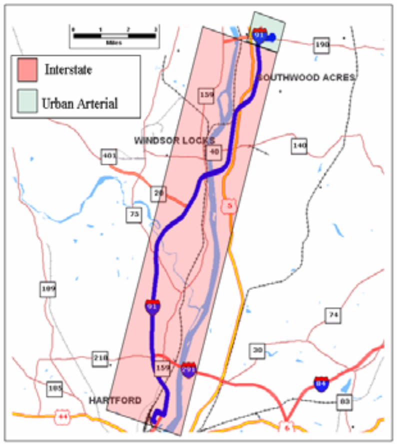

Figure 4 Test Route – Interstate

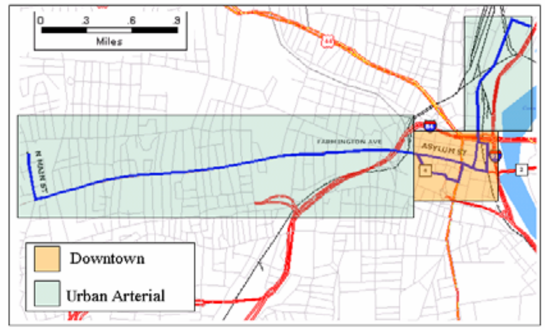

Figure 2 Route – Downtown Section (Test Route in Blue)

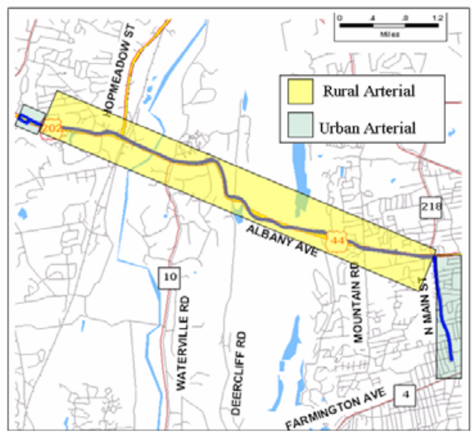

Figure 6 Test Route - Rural Section (Test Route in Blue)

Table 2: Missing GPS Data Point Analysis

Area	Number of Records	Number Missing	Percent Missing
Downtown	**2638**	**238**	**9.02**
Urban mixed landuse	9371	15	0.16
Interstate	4681	16	0.34
Rural Arterial	3975	7	0.18
TOTAL	**20665**	**276**	**1.34**

Table 3: Missing and Erroneous GPS Data Point Analysis

Area	Number of Records	Number Missing	Percent Missing
Downtown	**2638**	**319**	**12.09**
Urban mixed landuse	9371	78	0.83
Interstate	4681	98	2.09
Rural Arterial	3975	25	0.63
TOTAL	**20665**	**520**	**2.52**

These erroneous velocities mentioned earlier are suspected to be caused by inaccurate positions being reported by the GPS receiver with is common with multipath errors in urban canyons. Therefore, an addition analysis was conducted to determine the level of accuracy in GPS position relative to the 4 classifications outlined above. To do this ArcGIS was used to calculate the distance between each GPS data point and the known test route or road that the vehicle was traveling. The average distance or departure from the test route and the standard deviation of that departure distance was calculated for each of the road categories (Table 4). Be aware that the underlying GIS centerline network is not perfect and the vehicle was certainly not driving on the center line, but the quality of the road network layer is consistent throughout the dataset. This problem can be seen spatially in Figure 6.

Table 4 GPS Point Data Departure Distance From Known Route

Area	Number of Records	Mean Departure Distance (ft)	Standard Deviation of Departure (ft)
Downtown	2638	52.1	60.9
Urban mixed landuse	9371	17.3	13.7
Interstate	4681	26.9	23.7
Rural Arterial	3975	21.0	16.2
TOTAL	**20665**	**25.3**	**29.80**

Tables 2 through 4 show that the downtown area has considerably larger GPS data problems than any of the other road types. By calculating the distance from recorded GPS points to the known route, this analysis shows that data collected in the downtown area has the largest error in positional accuracy. Urban canyons are a known major problem in GPS travel data collection. Future research is being conducted into the effects of urban canyons biasing in-vehicle GPS data and impacting emissions measurements. Methods that account for the non-random nature of the missing data are being developed to fill gaps in GPS datasets.

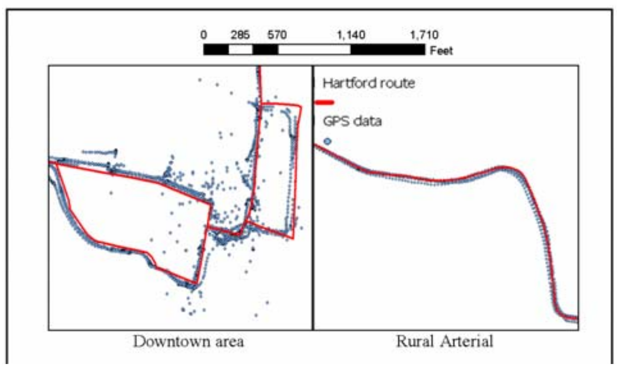

Figure 7 GPS Data Dispersion in Downtown

CONCLUSIONS

There is an assumption within both the transportation and academic communities that GPS is a mature technology with natural applications in travel data. Among other functions, GPS is in successful use to navigate automobiles, to track commercial vehicles such as buses, planes and trucks, as well as for field data collection of information describing transportation networks such as roads, pipelines and waterway characteristics. However, the fundamental problems for use of GPS as an accurate and reliable research instrument for travel data remain. There is a need for more open discussion of the impact of inaccuracies as well as reliable methods to minimize their impact. The research summarized here has an important factor in common: in-vehicle GPS data was undertaken on known routes. This allowed the magnitude of errors to be calculated and the methodologies developed had accompanying goodness of fit measures. Much more work of this type is needed.

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