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16. Abstract

Conventional travel-survey methodologies require the collection of detailed activity-travel information, which impose a significant burden on respondents, thereby adversely impacting the quality and quantity of data obtained. Advances in the Global Positioning System (GPS) technology has provided transportation planners with an alternative and powerful tool for more accurate travel-data collection with minimal user burden. The data recorded by GPS devices, however, does not directly yield travel information; the navigational streams have to be processed and the travel patterns derived from it. The focus of this research project is to develop software to automate the processing of raw GPS data and to generate outputs of activity-travel patterns in the conventional travel-diary format. The software will identify trips and characterize them by several attributes including trip-end locations, trip purpose, time of day, distance, and speed. Within the overall focus of the research, this report describes the data collection equipment specifications, data collection protocols, and data formats, and presents a comprehensive synthesis of the state of the practice/art in processing GPS data to derive travel diaries. This synthesis is intended as the basis for developing input specifications and processing algorithms for our software. A second objective of this report is to identify the data requirements for the software development purposes and document the efforts undertaken to acquire the data.

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CONVERSION OF VOLUNTEER-COLLECTED GPS DIARY DATA INTO TRAVEL TIME PERFORMANCE MEASURES:

LITERATURE REVIEW, DATA REQUIREMENTS, AND DATA ACQUISITION EFFORTS

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TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

For nearly fifty years, household travel surveys have been used to document the travel behavior of regional households as part of long-range transportation planning efforts. The survey data are used for general planning and policy analysis, as well as to serve as the foundation for regional travel demand models. Technology advancements have resulted in changes in household travel survey data collection procedures, the most recent being the introduction of Global Positioning Systems (GPS) to record travel patterns. The GPS technology shows promise to minimize costs, while maximizing the volume of travel data collected. However, the data recorded by GPS devices do not directly yield travel information; rather, the outputs from these devices are in the form of navigational streams that have to be processed to derive travel information. The objective of this project is to provide TxDOT with a software and analysis procedure that translates the GPS data into the traditional travel data format.

The purpose of this chapter is to provide a brief summary of how surveys are conducted today, discuss the main concerns regarding household travel survey data, identify how the survey methods and implementation processes have been evolving to address these concerns, and finally, discuss how GPS technology options can be employed to enhance household travel survey data collection efforts. This chapter also identifies the overall objectives of the project.

1.1. Household Travel Survey Methodology

As indicated above, the travel behavior and demographic data obtained through household travel surveys serve as inputs for many transportation planning activities, including the development of regional travel demand models. The process of data collection entails four main steps: (1) random selection of regional households to participate in the survey effort, (2) collection of demographic and work-related information for all household members, as well as information on household vehicle ownership characteristics, (3) provision of materials to help participating households record their travel patterns, and (4) retrieval of the recorded travel data.

The earliest travel surveys were conducted in person, with interviewers collecting demographic information, providing the households with blank trip logs, and returning at a pre-arranged time to retrieve the completed trip logs. As telecommunications technology became more prevalent and telephone ownership became more pervasive, the survey method changed to

the use of telephones to establish contact with the households. Interviewers mailed out blank trip log materials to the households, and the households mailed them back, once completed. In the mid-1990s, technology improvements again resulted in an enhancement, this time with the advent of computer-aided telephone interviewing (CATI) technology. The CATI programs are now commonplace and are used to guide interviewers through the survey administration process by (a) displaying the appropriate survey questions based on responses to prior questions, (b) employing built-in checks to ensure data are complete and consistent, and (c) providing the ability to identify and resolve inconsistent responses (see Weiner, 1999 for a more complete history of US travel surveys).

In terms of the length of the survey period, most travel surveys in the United States are designed to obtain 24 hours of travel data for participating household members. On the other hand, 48-hour, weeklong, or even six-week-long surveys are more commonplace in Europe. Regardless of the length of the survey and the specific data elements obtained, the final survey data are usually provided in four files: household demographic data, person-level demographic data, vehicle information, and travel data. The travel data most commonly include the trip origin and destination, arrival and departure times, mode of travel, and trip purpose. Depending on the reported mode of travel, more detailed information may be collected as well, such as vehicle occupancy, amount paid for parking, and transit route and fare. However, travel route traversed from origin to destination is not a common data item obtained in these surveys.

An important challenge in travel-survey design is to minimize respondent burden, which plays an important role in determining when to ask specific questions, what level of information detail to collect, and how precisely to elicit information. In fact, between the recruitment interview, recording travel details on the travel day, and providing those details back in the retrieval telephone interview, it is estimated that the average participating household spends at least an hour on the survey process. Recognizing the respondent burden, most surveys are designed to collect only the most critical data elements in as simple a way as is possible.

1.2. Concerns Regarding Household Travel Survey Data

Analysts and modelers who work extensively with travel survey data have raised three major concerns in recent years regarding the completeness and accuracy of household travel survey data. These are: (1) trip underreporting, (2) incomplete, missing, or inconsistent trip

details, and (3) lack of route choice details. Each of these three issues is discussed in turn in the following three sections.

1.2.1. Trip underreporting

For some time, modelers and analysts have been concerned that respondents, either because of inaccurate recall or because of time constraints, do not record all their travel during the assigned travel period. The time burden imposed by the traditional survey method has a direct impact on trip reporting: the more details requested of the respondent, the greater the time and effort required of them (Wolf et al., 2003). Of particular concern are trips that are either short stops made along the way to a main destination (such as stopping to get coffee on the way to work), complete round trips made at the end of the travel day (such as picking up a child at a friend's home), or impulse trips (Bhat and Lawton, 2000; Jones and Stopher, 2003). While at face value, an occasional missed trip may not appear to warrant concern, each missed trip could equate to approximately 200 to 500 missed trips once the survey sample is expanded to the population of interest.

1.2.2. Incomplete, missing, or inconsistent trip details

Stopher and Wilmont (2000) indicate that respondents are sometimes not able to comprehend survey questions, leading to misreported trip information and/or the need for extensive data repair. Further, there is always the danger that the respondent neglected to record critical trip details, such as travel mode, travel times, or trip purposes, when travel data is retrieved from participating households through a mail-back option. However, since the advent of CATI technology, the completeness of the travel data has increased substantially with regard to these data elements. But problems associated with (a) incomplete or missing trips and (b) inconsistent trip information continue to affect survey data quality, as discussed in the next two paragraphs.

The main area where incomplete or missing trip information still adversely impacts the quality of household travel survey data is in location information. Location information is critical in travel-demand modeling, as all trip origins and destinations are assigned to a traffic analysis zone (TAZ). Many TAZs are defined by major roadways or natural features, such as rivers or mountains. Thus, assigning a shopping destination on the wrong side of the road can result in incorrectly assigning one trip (or 200 or 500 trips when expanded) to the wrong TAZ.

Respondents may know how to get to the grocery store, post office, or day care center, but they do not normally know the address details for those particular locations. Many respondents are unaware of crossing geopolitical boundaries such as zip codes or TAZs (Stopher and Wilmont, 2000). In addition, if the location is not one they ordinarily visit, they may have trouble linking it to a specific geographic location.

The concern about inconsistent trip information is primarily associated with the reporting of travel times. There is a tendency among respondents to round times to the closest 5-minute or 15-minute clock time, resulting in a loss in time resolution. For example, there are higher proportions of trip departure and arrivals on the hour, half hour, or quarter hour, rather than the exact minute, say a 7:53 am departure (Battelle, 1997, Murakami and Wagner, 1999).

1.2.3. Lack of route choice details

In balancing respondent burden against obtaining important travel information, most US travel surveys omit questions regarding travel route. In travel forecasting, route choice is implemented using network assignment algorithms. These algorithms are based on the assumption that individuals choose the shortest path for travel. A study undertaken at the University of Wisconsin (Jan *et al.*, 2000) to evaluate route-choice assumptions made in the network assignment component of travel demand modeling indicates that the actual chosen paths are often quite different from the shortest path, even if the travel times along both paths may be comparable. In addition to use in travel forecasting for urban transportation planning, route choice information also becomes important for evaluating the impacts of Advanced Traveler Information Systems (ATIS) on driver behavior, and in air-quality modeling for determining the spatial distribution of emissions over the network (Wolf et al., 1999). As a consequence of the reasons discussed above, it is becoming increasingly important to collect travel route information.

1.3. Household Travel Survey Improvements in Response to Concerns

In response to the above concerns regarding trip reporting completeness and accuracy, those conducting travel surveys have responded with improved methods and processes. In this section, a summary of survey improvements in response to each concern is presented. Route choice is not discussed in this section, as most travel surveys still do not seek to obtain that level of information.

1.3.1. Trip underreporting

The issue of trip underreporting in household travel surveys is of substantial concern because, as mentioned above, each missed trip can represent 200 to 500 regional trips when the survey data are expanded. The level of trip underreporting has been reduced through improved survey design as well as through CATI programming, which allows the interviewers to probe for commonly missed trips.

The main methodological improvement in survey design is the move from a trip-based travel diary (asking the respondent to record all trips made) to a place-based or an activity-based travel diary. In the place-based diary, the respondent is asked to focus on all places visited on the travel day, while the activity-based diary asks the respondent to record all activities and their attributes. Both the place-based and activity-based logs have been shown to improve the proportion of incidental trips reported during the travel day (Bhat and Lawton, 2000; Stopher and Wilmont, 2000).

In terms of how the surveys are administered, most firms now allow larger households to mail in the completed travel forms, in order to minimize the potential that respondent fatigue in reporting travel information over the phone may result in trip underreporting. In addition, follow-up calls are undertaken to clarify inconsistencies in the data. Further, most CATI software now permits an interaction between travel records, so that a respondent only has to provide complete address details once, even if a different household member visits the same location. Finally, the CATI program can "copy" travel records among those household members that travel together, thereby reducing the average retrieval interview length from 20 to 25 minutes per person to about 12 to 15 minutes per person, depending on the data elements being collected.

1.3.2. Incomplete, missing, or inconsistent trip details

Aside from the CATI advancements that check for consistent and complete responses, there have also been efforts to replace the paper-based travel diaries with electronic travel diaries (ETDs) and computer-assisted self-interview (CASI) techniques (see Wolf, 2000 and Jones and Stopher, 2003 for details on the evolution of survey administration techniques). A characteristic feature of ETDs and CASI programs is the relative ease with which information can be entered by the respondent. Testing of these user-friendly interfaces with pull-down menu lists and precoded responses suggests that the data obtained is more complete and more accurate than that

written down in the travel diaries. Further, research also suggests that people may be more willing to report certain kinds of behaviors (especially those that are considered socially unacceptable) to a computer rather than writing it down or reporting it orally to an interviewer (Murakami and Wagner, 1999).

With regard to missing or incomplete address (location) information, CATI can be programmed to obtain enough address "clues" that enable the analyst to impute the location. In addition, enhanced CATI programs now allow for integrated geocoding efforts. Thus, the interviewer can locate and confirm a particular location, thereby "filling in the blanks" with the missing address details. However, these approaches are more costly and increase the survey interview length, thereby increasing respondent burden and the corresponding probability that some trips may go unreported.

1.4. Application of GPS Technology to Household Travel Surveys

The above discussion indicates that individual biases, the inability of respondents to comprehend survey diary questions, and the recall and reporting limitations of respondents can critically degrade the quality and quantity of information from conventional self-reported activity/travel surveys. This is primarily because the respondent still needs to expend considerable time and effort in recalling and reporting detailed travel information. Significant advances in survey design methods and effective application of CATI software to minimize data errors have mitigated concerns to some extent, but come at considerable cost. It is in this context that GPS technology offers a valuable alternative to conventional data-collection approaches. Specifically, devices called the "GPS receivers," positioned anywhere on the earth's surface and in view of the GPS satellites, are capable of self-determining their locations with a time-of-day stamp (Wolf, 2004a). Therefore, travel data can be collected by equipping the respondents' automobiles with GPS receivers and recording the position and velocity of the vehicles periodically.

Recent travel-survey studies conducted using in-vehicle GPS devices are presented in reverse-chronological order in Table 1.1. The early studies conducted at Lexington, Quebec City, and Atlanta (see bottom of Table 1.1) were aimed at equipment testing to study the relative performance of different kinds of off-the-shelf GPS devices available in the market. The Lexington study also explored respondent attitudes to the new GPS technology and the

6

willingness to participate in GPS surveys. The primary focus of the rest of the studies in Table 1.1 has been to compare *self-reported* travel patterns from conventional travel surveys with *passively recorded* travel information from GPS devices. Further, all the studies using in-vehicle GPS technology, with the exception of the ones undertaken at Lexington and Ohio, have used *passive* data collection techniques (i.e., the user intervention is limited to, at most, turning the device on and off). Studies conducted in Lexington and Ohio, on the other hand, provided the survey respondents with a non-GPS handheld device to enter information about the trip purpose and identify the passengers in the vehicle in addition to the use of the in-vehicle GPS device that passively records vehicle movement. Overall, Table 1.1 clearly reveals the growing interest in the use of GPS to enhance the completeness and accuracy of travel survey data.

Table 1.1 GPS Travel Survey Studies using In-Vehicle Devices

Study	Year	Sample Size	Survey Period	References
Kansas City Regional Survey	2004 (Feb-Apr)	548 vehicles from 294 households	1 day	Wolf (2004b)
Tyler/Long View Household Travel Survey	2003 (Sep-Nov)	646 vehicles from 367 households	1 day	Wolf (2004b)
St. Louis Regional Survey	2002 (Sep-Nov)	666 vehicles from 313 households	1 day	NuStats (2003a, 2003b)
SCAG Vehicle Activity Survey	2002 (Sep-Oct)	111 vehicles from 67 households	10 days	Stiefer *et al*. (2003); Wolf (2003)
Sydney Pilot Study, Australia	2002 (Apr-July)	32 vehicles from 27 households	1 day	Stopher *et al.* (2003)
Laredo Household Travel Survey	2002 (Mar-May)	348 vehicles from 187 households	1 day	Wolf (2003)
Ohio Household Travel Survey	2002 (Feb-July)	236 households (avg. of 2 vehicles per HH)	3 days	Pierce *et al.* (2003)
The Tracer System Informal Pilot	2002	4 volunteer drivers	many days	Marca *et al.* (2002)
SCAG (Los Angeles) Household Travel Survey	Sep 2001 - Mar 2002	1217 vehicles from 820 households	1 day	Wolf (2004b)
Pittsburgh Household Travel Survey	2001 (Oct-Dec)	149 vehicles from 74 households	1 day	Wolf (2003)
California Statewide Household Travel Survey	2001 (Feb-Oct)	920 vehicles from 517 households	1 day	NuStats (2002); Wolf *et al.* (2003); Wolf (2004b)
Intelligent Speed Adaptation Study, Borlange, Sweden	June 2000 - Mar 2002	186 vehicles	>= 30 days per vehicle (50,000 vehicle days in all)	Axhausen *et al.* (2004)
Baton Rouge, Louisiana	2000 (Apr)	16 vehicles	2-3 days	Bachu *et al.* (2001)
Atlanta*	2000 (Mar-Apr)	30 vehicles	3 days	Wolf (2000)
Japanese Study	1999 (Jan and Mar)	15 drivers (Jan survey) 28 drivers (Mar.survey)	1 week	Ohmori *et al.* (2000)
Quebec City	Dec 1998 - Mar 1999	3 vehicles (of researchers)	1-2 weeks per vehicle (49 days overall)	Doherty *et al.* (1999)
Austin Household Travel Survey	1997-1998	356 vehicles from 200 households	1 day	Casas *et al.* (1999)
Lexington	Fall, 1996	100 vehicles from 100 households	6 days	Battelle (1997)

* A larger study was undertaken in 2001 (Wolf, 2003)

In addition to the use of in-vehicle GPS devices for travel data collection, some research studies have developed and deployed wearable, personal, or handheld GPS units in travel surveys to collect data on personal travel using any mode of travel. Recent travel surveys using handheld or personal GPS devices are presented in reverse-chronological order in Table 1.2.

Table 1.2 GPS Travel Survey Studies using Personal/Handheld Devices

Study	Year	Sample Size	Survey Period	Reference
Atlanta Route Study	2002 (Nov-Dec)	57 persons	7 days	Wolf (2003)
London Study	2002 (Sep-Nov)	154 persons	3 day	Steer Davies Gleave (2003)
Atlanta Physical Activity Study	2001-2002	542 persons	2 day	Wolf (2003)
Battelle's PTU Development and Testing Study	2000	6 Battelle staff members	2-3 days	Battelle (1997)
Netherlands Pilot Study	Winter 1998-Spring 1999	151 persons	4 days	Draijer et al. (2000)

In the rest of this report, our focus will be on the use of *passive in-vehicle GPS devices* in which the user intervention is limited to, at most, turning the device on and off. Such passive in-vehicle GPS-based travel surveys offer the following advantages over conventional data-collection approaches:

1. GPS devices can collect data passively and directly record it on electronic media with little or no intervention from the user, thereby reducing respondent burden substantially. Consequently, when correctly processed, the GPS technology can address trip underreporting and can also be effectively used for multiday travel data collection.

2. The location of activities and travel is determined with very high spatial accuracy, especially after the termination of selective availability in May 2000 (selective availability (SA) refers to the intentional degradation of GPS spatial accuracy). Thus, the trip-end locations from GPS surveys are more accurate than the reported locations in conventional surveys.

3. GPS-recorded trip timing data (i.e., time of day of start and end of trips and travel times) are more accurate than estimates and approximations obtained from conventional surveys, and do not suffer from round-off errors.

4. GPS technology makes it possible to collect information on the travel route, important travel information not obtained from current survey techniques.

5. Trip speeds are recorded as actual observations, rather than being calculated as part of the post-collection processing.

6. Trip distances can be computed accurately using the detailed position data along the length of the trip.

Overall, it is apparent that almost all the information that can be obtained from conventional travel surveys (and more) can be derived from passively collected GPS data. However, despite the several advantages of the GPS survey approaches as discussed above, there are several issues that need to be addressed for effective use of this new technology for household travel survey data collection. These are:

1. The GPS data are collected in the form of navigational streams (i.e., periodic recordings of position and velocity). Substantial processing is necessary to convert these streams into the conventional travel-diary format for subsequent use of the data for modeling purposes. Further, the automation of the processing requires operational definitions of trips and stops. This in turn determines the set of trips and stops that can be identified from the recorded navigational streams. However, the success of past research in identifying reported trips from the GPS navigational data streams is very encouraging. For example, in the St. Louis study (NuStats 2003a, 2003b), about 91% of the trips reported via a conventional CATI survey were also identified from the GPS data, and in the California study (Wolf et al., 2003), 1625 of the 1736 (93.6%) CATI-reported trips were successfully matched to trips identified from GPS data.

2. Equipment specifications (such as errors in position and velocity computations), operational shortcomings (e.g., loose cabling and loss of signal in regions of dense tree cover) and respondent error (e.g., forgetting to power on the unit) impact the quality and quantity of the GPS data collected.

3. Trip-purpose information is unknown. This needs to be elicited from the respondent directly or derived using the GPS data in conjunction with supplemental land use and network data.

4. The vehicle occupancy levels are unknown; the driver and the passengers in the vehicle cannot be identified. Such information, if needed, has to be elicited from the respondents directly.

5. The derived trip diary is an accurate record of the sequence of vehicle trips and not the person trips. The derived destinations are vehicle trip-end locations. The computed travel times represent the in-vehicle times and do not include the possible walk times to/from the vehicle. The actual person trip-end destinations and arrival/departure times associated with those destinations are unknown or must be imputed in the absence of additional input from respondents.

1.5. Research Objectives

The discussion presented in the previous section highlights the feasibility of the use of GPS technology for improving the accuracy and completeness of travel surveys. On the other hand, it is also evident that the use of passive GPS devices for data collection shifts considerable burden from the respondent to the analyst. Therefore, the success of this new technology as a travel survey instrument depends on the ability of the analyst to derive meaningful trip information from the navigational data streams of GPS devices. All the studies listed in the previous section have used a mixture of manual and automated procedures for processing GPS data to derive trip information. In general, these studies have also been largely successful in identifying CATI-reported trips from the GPS data streams, but little research has been conducted to date on what the GPS-identified trips that are missing in the CATI data actually represent.

In a recent review of the state-of-the-art and emerging directions in the application of new technologies in travel surveys, Wolf (2004b) observes that "recent trends indicate that someday GPS may be used to replace some or all components of the traditional travel survey data collection methods". In such a scenario, in which the data will be collected from several hundreds of vehicles and/or for multiple days (as opposed to the conventional single-day approach), there would certainly be a need for robust and efficient algorithms and software for

analyzing GPS data streams. Toward this end, the current TxDOT-funded research proposes the development of a prototype software tool labeled the "GPS-Based Travel-diary Generator" (GPS-TDG) that automates the process of converting navigational data streams collected passively from in-vehicle GPS devices into an electronic activity-travel diary. Within this broad goal, there are four specific objectives for the software:

1. Identify vehicle trips and characterize each trip in terms of attributes such as trip-end location, trip purpose (or activity type at destination), time of day, duration, distance, and speed. The derived sequence of trips with all the relevant trip attributes will be written to an output file in the conventional travel-diary format.

2. Enable the visualization of travel patterns on a GIS platform.

3. Aggregate the derived diary data to generate vehicle trip tables (by trip purpose and time of day).

4. Compute interzonal network performance measures such as travel times, speeds, and distances by time of day from the derived diary data.

1.6. Focus and Structure of the Report

The primary aim of this report is to present a comprehensive synthesis of the state of the art/practice in collecting and processing GPS data. This synthesis forms the basis for developing input specifications and processing algorithms for the GPS-TDG software. A second objective of this report is to identify the data requirements for software development purposes and document the efforts undertaken to acquire the data.

The rest of this report is organized as follows. Chapter 2 describes the structure of the navigational stream outputs from GPS-based travel-data recording devices. This chapter also discusses supplemental data that are commonly used along with the GPS navigational streams to derive the travel patterns. Chapter 3 presents the various processing steps that need to be undertaken to convert the raw GPS data into a travel-diary format. The algorithms and methods adopted by past studies for each of the processing steps are also described in this chapter. Chapter 4 identifies the data requirements for the design and development of the proposed GPS-TDG software. Efforts undertaken to date to acquire these data are also described. Finally, Chapter 5 presents the summary and conclusions.

CHAPTER 2 DATA FOR TRAVEL-DIARY GENERATION

Passive GPS data collection of travel produces streams of navigational data through periodic recordings of the position and velocity of equipped vehicles. To facilitate the use of this data for subsequent analyses, travel-demand modelers and planners need the travel information to be converted into a conventional trip-diary format (i.e., a sequential listing of all trips undertaken, with each trip characterized by attributes such as purpose, time of day, trip-end locations, distance, and duration). This translation from GPS navigational streams to trip sequences requires an understanding of the GPS equipment specifications, data collection protocols, and output formats. Also, it is important to note that secondary data, such as respondent characteristics, roadway network characteristics, and regional land use patterns, can be used in conjunction with the GPS data to enhance the process of trip-diary generation and to determine attributes such as trip purpose, which cannot be determined from the GPS data alone.

The objective of this chapter is to present an overview of the GPS outputs and other secondary data that have been used in prior studies to convert the navigational streams of data into a trip-diary format. Section 2.1 focuses on the GPS equipment, data collection protocols, and the formats of the recorded navigational streams. Section 2.2 describes supplemental data that have been used by analysts for enhancing trip identification and characterization. Finally, Section 2.3 focuses on the data requirements for validating the algorithms developed for trip-diary generation.

2.1.   Equipment and Data Collection

The equipment used in GPS travel data collection typically has two main components: (1) a GPS antenna and receiver and (2) a data-logging device that records the GPS data. The GPS receiver/antenna specifications are described in Section 2.1.1. The standard formats of the outputs from the GPS receivers are next discussed in Section 2.1.2. Section 2.1.3 provides an overview of the data-logging devices, their operational characteristics, and the data recording formats and rules. Finally, in Section 2.1.4, two different data collection protocols are presented.

2.1.1.   GPS Receiver/Antenna Specifications

There are three important GPS receiver/antenna specifications that are particularly relevant to the current study from the standpoint of the quality and completeness of the travel

data collected. These are (1) the signal acquisition time, (2) position and velocity accuracy, and (3) the update rate.

The *signal acquisition time* is the time required by the GPS device to obtain a positional fix after being powered on. Most GPS devices today have a rated signal acquisition time of 15–45 seconds (Stopher, 2004). However, this specification assumes that the device is stationary for this (15–45 seconds) period of time, which is generally not the case in travel survey applications. Further, the signal acquisition time also depends on how long the device was powered off before reactivation. For short durations of power off ("warm starts"), the signal acquisition is generally quicker. However, for long durations of power off (of the order of several hours, "cold starts"), the signal acquisition time can be much longer. It has been found that, in situations in which the vehicle is driven almost immediately after ignition on, it may take anywhere between 15 seconds to 4–5 minutes for signal acquisition, depending on speed of movement and other extraneous factors, such as the presence of tree canopies and tall buildings (Stopher, 2004). The impact of the signal acquisition time on the quality of trip attributes recorded (especially trip-end locations and trip timing) is discussed in detail in Sections 3.3.1 and 3.3.2 of the next chapter.

The second important GPS unit specification is the *accuracy of the position and velocity recordings*. With the termination of selective availability in May 2000, the spatial accuracy of the GPS devices have increased substantially. Today, commercially available GPS devices are capable of providing a spatial accuracy of about +/- 10 meters (Stopher, 2004). The spatial accuracy of the GPS device is of particular interest when overlaying GPS streams on a GIS network map for visualization of travel patterns. The estimation of velocity may involve either computing the derivative of the position information or using the Doppler shift in the frequency of the signal due to the relative motion between the satellite and the GPS receiver. The Doppler-shift based algorithms for speed computation, which are independent of the position information, have been found to be significantly more accurate compared to those that use the position information (TRB NCHRP Synthesis, 2001). Most available GPS devices have velocity accuracy levels of +/- 0.1m/sec (Wolf, 2004a). The accuracy of velocity computations is of particular interest when the data-logging devices are programmed to record data only if the vehicle movement is detected (See Section 2.1.3 for further details). The velocity accuracy is also important from the standpoint of the trip-speed determination.

The third specification of interest is the *update rate*, i.e., how frequently the unit recomputes the position and velocity. Current GPS units are capable of recomputing and updating position and velocity information every second. Thus, GPS devices can record travel at a very fine temporal resolution.

2.1.2. GPS Receiver Output Formats

Most GPS receivers' output conforms to the National Marine Electronics Association's "NMEA 0183 GPS" message formats (Wolf, 2004). These formats represent the ASCII interface standards for marine electronic devices. The outputs are in the form of a continuous stream of "sentences," with each sentence composed of a number of predefined data fields separated by commas. The sentences begin with a "$" character and end with a "*" character, followed by check-sum, a carriage return, and a line feed. (The carriage return and line feed are control characters to signal sentence termination; see Wolf, 2000). The NMEA has prescribed the standard specifications for many different sentences types, with each sentence type providing different kinds of data.

The most relevant and commonly used sentence for travel survey purposes is the "GPRMC" (Wolf, 2004). The sentence specification for GPRMC is presented in a tabular format in Table 2.1. The GPRMC sentence contains all the necessary position, velocity, and time (PVT) information required by travel surveys. The position information is recorded in terms of latitude and longitude in fields 3 through 6. The recording of the latitude and longitude data follows the "ddmm.mmmm" format, in which the first two digits from the left are the degrees, the next two are the minutes, and the digits following the period are the decimal minutes. For example, the value 4533.35 indicates 45 degrees and 33.35 minutes, or equivalently, 45 degrees 35 minutes and 21 seconds. Velocity is recorded in fields 7 and 8. Field 7 records the speed in knots (1 knot = 1.5 mph), and the next field contains the direction of movement in degrees. The date and time are recorded as the Coordinated Universal Time (UTC) or the Greenwich Mean Time (GMT) in fields 9 and 1. The local time has to be subsequently derived from the UTC by applying appropriate correction factors. For example, Austin, Texas, is six hours behind the UTC during winter and five hours behind the UTC during the daylight savings period.

15

Table 2.1 Structure of the GPRMC Sentence

Field	Description	Format/ Value
0	The entry "GPRMC," indicating the GPS output sentence structure type	GPRMC
1	Time of position fix (in Coordinated Universal Time or Greenwich Mean Time)	hhmmss.ss
2	Status (A= valid, V = navigation receiver warning)	A/V
3	Latitude	ddmm.mmmm
4	Latitude hemisphere (N=North, S=South)	N/S
5	Longitude	ddmm.mmmm
6	Longitude hemisphere (E = East, W=West)	E/W
7	Speed over ground (in knots)	0.0 to 999.9
8	Course over ground (true degrees)	0.0 to 359.9 degrees
9	Date of position fix (in Coordinated Universal Time or Greenwich Mean Time)	ddmmyy
10	Magnetic variation	000.0 to 180.0 degrees
11	Magnetic variation direction (E=East, W=West) [west adds to true course]	E/W

In addition to the position, velocity, and time (PVT) data, it is also important to consider information on the reliability and accuracy of the PVT computations. In this regard, there are two measures of interest: (1) the number of satellites in view and (2) the horizontal dilution of precision (HDOP). The GPS units require signals from at least three satellites for a two-dimensional (i.e., latitude and longitude) position computation and signals from four satellites for a three-dimensional (i.e., latitude, longitude, and altitude) position computation (for further details on the position computation methodology, see Wolf, 2004). Hence, the number of satellites in view of the GPS antenna is often used as a measure of validity of the computed position information. Specifically, the computations are suspect when the number of satellites is less than three. The second measure of interest, i.e., the HDOP, is a measure of how the satellites are clustered in the sky as viewed from the GPS antenna when the PVT computations are made

(Stopher, 2004). HDOP can take values between 1.0 and 99.9 (Wolf, 2000). Lower values of HDOP indicate a wider dispersion of the satellites and hence greater reliability of the position computation. In contrast, higher values of HDOP indicate poor dispersion of the satellites (such as alignment immediately above the antenna or along the horizon; see Chung and Shalabay, 2004) and hence a lower reliability of the position computation. Data on the number of satellites in view are recorded in the "GPGSV" sentences, and the HDOP values are recorded in the "GPGSA" sentences.

2.1.3. Data-Logger Specifications

The second component of the equipment used for GPS travel surveys is a device that stores the periodic data outputs from the GPS receiver/antenna unit. This data-logging device can be a personal digital assistant (PDA), a rugged laptop, or a special purpose, purely-passive, data-logging device such as the GeoLogger (developed by GeoStats) or the GPS Data Logger (developed by the Institute of Transport Studies, ITS, The University of Sydney). There are two main specifications of the data-logging devices that are of interest. These are (1) data-logging formats and rules and (2) operational characteristics.

(1) Data-Logging Formats and Rules

The basic approach to data logging is to simply record the GPRMC sentences output by the GPS receiver. Hence, the format in which the data are recorded conforms to the GPRMC sentence specifications. In contrast to the simple recording of GPRMC streams, the GeoLogger and the GPS Data Logger are special purpose logging devices that have been developed to record accuracy measures such as the number of satellites in view and HDOP values along with the relevant fields from the GPRMC sentences (see Wolf, 2004, for GeoLogger output formats and Stopher, 2004, for GPS Data-Logger output formats). Further, the GeoLogger is also capable of being programmed to record position information in decimal degrees and speed and altitude information in metric units. This is important because the ability of the logging devices to process raw data from the receiver to generate readily usable outputs helps significantly reduce the preprocessing of data required before being input to the travel-diary generation software. The preprocessing of data is discussed in more detail in the next chapter.

In addition to alternate formats of data logging, both the GeoLogger and the GPS Data Logger are capable of being programmed to record data at various preset frequencies (e.g., 1

17

second or 5 seconds). In such a "frequency-based" logging approach, all valid data are recorded at the preset frequency, irrespective of whether the vehicle is moving or not. In addition, the GeoLogger is also capable of being programmed to record at the preset frequency only when movement is detected, i.e., when the speed is greater than 1 mph. This approach is called the "speed-checked" data logging. The reader will note that the ability to record data only when motion is detected helps enhance data storage efficiency. The implications of frequency-based versus speed-checked data logging for processing the data streams for trip-diary generation are discussed in the next chapter.

(2) Operational Characteristics: User-Flagged versus Purely-Passive Systems

The data logging devices are predominantly powered by their own internal source, such as a battery. In the case that the data logging device is a PDA or a laptop computer, it may not be desirable for the system to be powered on all the time. Hence, when such devices are used for data logging, the user is instructed to power the logger on at the start of the trip and off at the end of each trip. Such systems are referred to as the "User-Flagged" systems, as the driver flags the start and end of each trip. In such systems, the data points are necessarily logged only during the trip and not when the vehicle is at a stop (assuming that the driver diligently turns the PDA off and on). In contrast to PDAs and pocket PCs, the special purpose data recording devices developed by GeoStats and ITS Sydney, are constantly powered by internal batteries, and do not require the user to flag the recording device at the start and end of each trip. Hence, these systems are referred to as "Purely Passive" systems. In such systems, the data logger records the points (using any rules as prespecified) as long as the GPS receiver/antenna is powered on. Hence, in contrast to user-flagged systems, purely passive systems could also be recording points when the vehicle is at a stop. Thus, the choice of the data logging system has implications for the structure of the navigational streams recorded by the logging device.

2.1.4. Data Collection Protocols

In addition to equipment specifications and capabilities, GPS data recording patterns are also impacted by the data collection protocols as determined by the power system characteristics of the equipped vehicles. Wolf, 2000 and Bachu et al., 2001, have found that, particularly in American-made automobiles, the power to the cigarette lighter remains on even if the vehicle is powered off. Since the GPS receiver/antenna unit is typically powered by the vehicle's power

system using a cigarette lighter adapter, there can be two data collection protocols, depending on the automobile's power system characteristics, even when the same equipment is used. These are (1) the "continuous-power" system, in which the cigarette lighter is always powered on and hence the GPS receiver/antenna unit is also continuously powered on, and (2) the "switched-power" system, in which the GPS receiver/antenna is powered on and off by powering the ignition on and off, respectively.

The two data collection protocols have important implications for the nature and structure of the data outputs. *First*, the impact of GPS signal acquisition time on the data recordings is minimal in the case of continuous-power systems, as the GPS receiver is not turned off and on at each stop. However, for switched-power systems, the impacts of signal acquisition time must necessarily be considered. *Second*, in the case of switched-power systems, the data points are *not* logged when the vehicle has been powered off at a stop. On the other hand, in the case of continuous-power systems, the logging of data during the period when the vehicle is off depends on the logging device specifications. For example, if a user-flagged data logging method is used in a continuous-power system, then the data points are not recorded at the stops, because the user powers the data logger off. In contrast, if a purely-passive logger (such as the GeoLogger) is employed, the data points will be logged even when the vehicle is powered off, unless the device has been preset to employ speed checks during logging. Thus, the structure of the output navigational streams recorded by the GPS equipment also depends on the data collection protocols.

In general, the discussion presented here indicates that the choice of data logging equipment, along with the data logging rules, operational characteristics, and the data collection protocols, have a significant impact on the data elements recorded and the structure of the output. This can limit or enhance the ability of an analyst to convert GPS data into the more traditional travel survey diary format. GPS data processing algorithms must be designed to account for these different possible output patterns depending on the data collection protocols and equipment specifications.

2.2. Supplemental Data

The previous section provided a description of the navigational streams obtained from GPS devices, which form the fundamental inputs for trip-diary generation. While most of the

vehicle trip attributes can be derived from the position, velocity, and time information contained in the GPS data, the trip purpose is one very important attribute that cannot be determined solely from the GPS data. It is in this context that supplemental data becomes necessary. In addition to aiding activity/trip-purpose determination, supplemental data can also be used to enhance the trip-diary generation process by minimizing detection of false trips and by reducing the number of missed trips.

The supplemental data that have been used in prior GPS travel survey studies can be broadly divided into three categories: (1) respondent characteristics, (2) transportation network data, and (3) land use data. Of the three categories of data, respondent characteristics need to be elicited from the surveyed individuals, which contribute to respondent burden. In contrast, the other two types of data are typically available at the disposal of the analyst without further burden to the respondents. Each of these categories of data and their importance in GPS data processing is discussed below.

2.2.1. Respondent Characteristics

Since travel surveys using in-vehicle GPS devices focus on the collection of vehicular travel patterns, the survey respondent in this context is considered to be the primary driver of the vehicle equipped with the GPS device. In households with a single vehicle shared by multiple persons, each person is to be considered a respondent. The survey administrators typically collect data on respondent characteristics via a short survey during the installation/removal of the equipment or as part of a more formal telephone recruitment effort aided by CATI technology.

There are several respondent characteristics that substantially inform activity/trip-purpose identification efforts. Perhaps the most fundamental and important data in this context are the home and work locations of the respondent. As home and work form the majority of the trip-end locations, the knowledge of residential and work locations substantially reduces the effort in activity/trip-purpose identification (Wolf, 2000). Further, this is the minimum supplemental information required to classify the trips into the conventionally used aggregate trip-purpose categories of: home-based work, home-based other, work-based other, and other purposes. For the identification of more disaggregate activity/trip purposes, additional data are required in the form of further queries on frequently visited locations. For example, the Baton Rouge study queried the respondents for the locations of frequently visited shopping centers (Bachu et al.,

2001). Other US studies routinely collect the school address for each student in the household, which can help identify the most common drop-off/pick-up locations.

In addition to the location information, it is also useful to collect data on key demographic characteristics, such as the age and gender of the respondent. This information can provide additional insight to identify the activity type pursued by a respondent. The reader is referred to Section 3.2.4 for further details on the use of demographic data for activity/trip-purpose identification.

In future travel surveys using only the GPS component, supplemental data collection efforts on the respondent characteristics can be expected to be designed so as to balance respondent burden against data requirements for the desired level of disaggregate activity-purpose determination. Consequently, the GPS data processing software should also be designed appropriately and without being overly reliant on respondent characteristics.

2.2.2. Transportation Roadway Network Data

The transportation roadway network data as a Geographic Information System (GIS) layer is useful for GPS data processing in many ways. *First*, potential trip-end points identified from the GPS navigational streams can be overlaid on the GIS road network layer to determine whether they result from congestion delay or traffic signal points or are true activity stops (See Axhausen et al., 2004 and Section 3.2 of this report). *Second*, data on the roadway network are required for determining the trip route. Specifically, the GPS trace points can be overlaid on the GIS road network to identify the links traveled during the trip. Processing techniques that have been used to match GPS traces to network links are discussed in Section 3.3.5. *Third*, the availability of the roadway network data aids visualization of the travel patterns. The travel patterns plotted on a GIS map are very useful if the GPS travel survey also includes a subsequent prompted recall component for additional data collection (such as purpose and vehicle occupancy for each trip) and/or for the validation of the processed data by the respondent (such as verifying whether a trip end was really an activity stop or not). Such an approach was adopted in the recently conducted Kansas City Regional Household survey (Wolf et al., 2004; NuStats, 2004).

In general, in the United States, the road network GIS layer of the study region is readily available from local and/or state transportation planning organizations. In the absence of such

locally maintained data, one could use the roadway network from the Topologically Integrated Geographic Encoding and Referencing (TIGER) files (US Census Bureau, 2000). For example, the Baton Rouge (Bachu et al., 2001) and the Lexington (Batelle, 1997) studies used road network data built from these TIGER files. However, the road network data from the TIGER files are known to be, in general, less accurate and more error prone (Wolf et al., 1999; TRB NCHRP Synthesis, 2001). Commercially available roadway network databases such as the TeleAtlas' MultiNet shape file are built using the TIGER files along with aerial photography and GPS field surveys, thereby leading to enhanced positional accuracy. This database has been used in the SCAG vehicle activity study (see Stiefer et al., 2003).

The accuracy and scale required of the network data depends considerably on its use in the GPS processing analysis. Specifically, if the network is to be used primarily for visualization purposes, then the network maps could be of a lower accuracy and smaller scale. However, for use in trip detection analysis and trip route determination, more accurate data and larger scale maps are desirable. Further, in this case, it would also be desirable for the network layer to contain detailed roadway geometry information as opposed to only the representation of the center line.

2.2.3. Land Use Data

Land use data are required primarily for activity/trip-purpose identification. As already discussed, data on the respondents' home and work locations are adequate to classify the trips into the conventionally used aggregate activity/trip-purpose categories. However, for the determination of disaggregate activity/trip purposes (e.g., shopping, recreation, and personal business) GIS data on the regional land use are required. These data can be in one of two types: (1) facility location or points of interest (POI) data and (2) zoning data.

The POI data provide the spatial location of the major facilities such as shopping malls, hospitals, and schools within the region. Axhausen et al. (2004) have used such POI data in their activity/trip-purpose determination analysis in a study conducted in Europe. In the US context, the TIGER files provide such facility location data. However, there appears to be no documented use of this data in activity/trip-purpose identification efforts. Considering this issue, we present a preliminary analysis of the TIGER files and its applicability for our GPS data processing requirements in Chapter 4.

The second type of land use data, i.e., the zoning data, describes the land use pattern within each zone or parcel. The usefulness of this type of data depends on the spatial extent of each zone or parcel and the number of land use types into which these zones may be classified. The smaller the size of the zones and the greater the number of land use categories, the better are the data suited for activity-type identification. The research undertaken by Wolf (2000) used a parcel-level land use data in the proof-of-concept study of trip-purpose identification. This land use inventory is a database of property polygons and the property center point (when the polygon data was not available) and was developed by the researchers using tax-assessor property databases, property boundaries from the counties, and other data. (See Wolf, 2000, for a detailed description of the development of this land use inventory.)

If the trip-end location identified from the GPS streams can be associated with a specific facility from the POI data, or if the trip end falls within a zone with a single, well-defined land use, then the identification of trip purpose using the land use data becomes relatively straightforward. However, when the trip end is in a zone with mixed land use and/or the trip end cannot be associated with a unique facility, then the determination of trip purpose becomes more problematic. Section 3.3.3 in the next chapter presents a detailed discussion on how GPS data processing algorithms have used the POI and zoning data for trip-purpose determination.

2.3. Validation Data

Validation data are required for the purpose of validating the algorithms developed for processing the GPS streams. Data on the respondent-reported travel patterns can be compared to the derived GPS travel patterns to examine the performance of the developed automation procedures. Insights from such a comparative analysis can also be used for enhancing the GPS data processing algorithms. As already discussed, almost all GPS travel surveys to date have undertaken an exercise of comparing reported travel to derived trips. However, it is very important to note that the primary intent of these studies has not been the validation of general-purpose software for automating GPS data processing. Rather, the focus has been on auditing reported travel and examining the extent of underreporting of trips (e.g., Wolf, 2004b).

Comparing the derived trips (or machine-recorded trips) with reported travel for validation of the processing algorithms is not straightforward because of several reasons. *First,* the derived travel patterns are a record of vehicle trips, while the reported travel patterns are a

record of person trips. Unless each person uses his/her own vehicle and only makes vehicle trips during the travel period, matching derived and reported travel can be complicated. *Second*, the validity of the trips detected from GPS streams but not reported in CATI retrieval require manual investigation prior to being flagged as a trip end. Follow-up prompted recall surveys of the respondents may be required to validate such trips. Such an effort has been undertaken in the Kansas City Regional Household survey (Wolf et al., 2004). *Third*, there may be inherent differences between the recorded travel and the reported travel because of survey administration protocols. For example, in the Kansas City study (Wolf et al., 2004), persons who drove for a living were instructed not to report work-related travel in their travel survey. However, such trips are automatically recorded by the GPS device.

In summary, the above discussion suggests that the validation of the GPS processing algorithms may require not only reported travel data, but also a follow-up prompted recall data collection effort and a detailed knowledge of the self-reported and GPS-based travel survey administration protocols for definitive classification of nonreported "trips".

CHAPTER 3 PROCESSING GPS NAVIGATIONAL STREAMS

The previous chapter described the structure of the GPS navigational stream output as well as additional data that may be used by the analyst to enrich the generated trip diaries. This chapter focuses on the processing methods, which use one or more of the supplemental data to automate the process of deriving the trip sequences from the raw GPS streams. Specifically, this chapter identifies the major attributes of the trip-diary data to be derived, describes the algorithms used by past GPS travel survey studies in deriving each of these attributes of interest, and highlights the advantages and shortcomings of these approaches. At this juncture, it is useful to point out that the application of GPS to travel surveys is a relatively recent development in transport modeling. Many of the preliminary studies have used data from a small sample of vehicles for analysis and therefore have relied upon a mixture of manual and automated procedures for processing GPS data. With the study size increasing (from a few vehicles to hundreds and thousands of vehicles and from one-day to multiday data collection), there is a growing interest in the field to develop robust and efficient algorithms and software for processing and analyzing GPS data streams.

This chapter comprises three sections. Section 3.1 contains a discussion of preprocessing the raw data downloaded from the GPS devices and converting it into a format that is readily usable for further trip-diary generation analysis. This latter analysis procedure involves two major steps: (1) trip detection and (2) trip characterization. The first step involves the identification of individual trip segments (or equivalently, stops) from the continuous stream of GPS navigational data. The second step involves the characterization of each trip in terms of attributes such as location, timing, purpose, distance, speed, and route. It is useful to note here that trip detection and characterization are inherently interrelated steps. Specifically, characteristics of the identified trips might provide clues to the possible existence of other trips, which also need to be flagged as part of the trip detection processes. Alternatively, attempts to characterize a trip may suggest that the trip is infeasible and was falsely detected by the previous trip-identification algorithms. Although the interactive nature of these two steps is recognized, for ease of presentation, the trip detection and trip characterization methods are discussed separately in Sections 3.2 and Section 3.3, respectively. The interaction between the two steps will be suitably incorporated in the GPS-TDG software.

3.1. Preprocessing

As a first step toward deriving the trip sequences from the GPS navigational streams, the data downloaded from the logging devices is first converted to a format that is more readily usable for subsequent analysis. Typically, the data are downloaded as an ASCII text file that is then imported into a spreadsheet or a database file for input to trip-diary generation software. Additional processing of specific data elements may also be necessary, especially if the data logging simply involves the recording of GPRMC sentences. In this case, the preprocessing of data would entail: (1) conversion of latitude and longitude into decimal degrees, (2) conversion of speeds from knots to mph or metric units, and (3) conversion of date and time from UTC to local date and time. In contrast, when special purpose data logging devices, such as the GeoStats GeoLogger that can be programmed to record attributes in the required units are used, the preprocessing effort is minimized. Further, the GeoLogger outputs also include the number of satellites in view and the HDOP values for each record. In this case, the scope of the preprocessing task can be extended to flag and investigate the invalid and suspicious data points. For example, Chung and Shalaby (2004) delete records if the number of satellites is less than three or if the HDOP value is greater than five. The reader will note that, if only the GPRMC sentences are recorded, then the accuracy measures are not available. For purposes of this study, suspicious points will be flagged but not immediately deleted.

3.2. Trip Detection

Almost all earlier studies appear to have developed at least semiautomated procedures for identifying stops from the GPS navigational streams and breaking the streams into individual trip segments. A central idea to these procedures is the use of GPS data recordings to identify "dwell times," which are defined as periods of nonmovement of the vehicle. If the dwell time exceeds a certain threshold, called the dwell-time threshold, the presence of a stop and a corresponding trip is inferred. Thus, the fundamental trip detection procedure requires (1) the specification of a dwell-time threshold and (2) the logic to identify patterns in the GPS streams indicating nonmovement of the vehicle.

The dwell-time threshold should be chosen appropriately to identify even short duration stops (for example, stops for pick-up or drop-off), while at the same time guarding against detection of false stops (e.g., waiting at stoplights or congestion delays) (Wolf, 2000). It has been

found that for most urban areas, the use of 120 seconds as the dwell-time threshold is a reasonable rule for signaling a (potential) stop, i.e., if the period of vehicle nonmovement exceeds 120 seconds, then this indicates a stop (Stopher, 2004). However, dwell times of less than the threshold duration of 120 seconds could be quick stops for purposes such as pick-up or drop-off of passengers, which would be missed with a strict dwell time threshold for trip detection. To address these issues, the Trip Identification and Analysis System (TIAS) proprietary software developed by GeoStats (see Axhausen et al., 2004) uses three thresholds in its preliminary trip detection procedure. Specifically, the trips are classified as "confident" if the dwell times exceed 5 minutes, "probable" if the dwell time is between 2 and 5 minutes, and "suspicious delays" if the dwell time is between 20 seconds and 2 minutes. The "probable" and "suspicious delay" trip ends are subject to subsequent scrutiny based on the trip characteristics before being ultimately classified as a trip or not. The trip detection procedure developed by Stopher and colleagues (see Stopher et al., 2002) uses two thresholds; dwell times of 30 to 120 seconds due to engine turn-off are classified as "potential trip ends" and dwell times of greater than 120 seconds are designated as "trip ends". Again, as in the case of the TIAS approach, the "potential trip ends" are subject to further scrutiny.

The second facet of the trip detection procedure is the identification of nonmovement. As already discussed in the previous chapter, how vehicular movements and nonmovements are recorded depends on equipment specifications and data collection protocols. Specifically, there are two major ways in which nonmovement of the vehicle can be recorded. In switched-power data collection protocols, or when the logging device is user-flagged or uses speed check rules for data logging, the data recording stops when the vehicle is not moving. In these situations, extended periods of nonmovement are necessarily represented by breaks in the record streams. Therefore, nonmovement for long periods of time can be determined by simply looking for gaps in the time stamps between successive records (Wolf, 2000). In contrast, if a purely passive data logger without any speed check rules is used in a continuously powered data collection protocol, the above logic would not be applicable for detecting nonmovements. This is because, in this scenario, the data points are being continuously logged, even when the vehicle is at a stop and is powered off. Similarly, the logic of looking for gaps in the time stamps of the successive recordings cannot be applied in switched-power data collection protocols with frequency-based logging rules, to identify stops when the engine is not powered off. In these cases,

nonmovements have to be detected by explicitly examining the recorded position and speed data. Specifically, the detection of stops/trip ends involves identifying a sequence of data records over a certain period of time during which there is little change in the position of the vehicle and the speed is zero. The following approach[1] suggested by Stopher et al. (2002) can be used as the implementation logic: If the difference in successive latitude and longitude values is less than 0.000051 degrees (about 7.4 meters), the heading is unchanged or zero, *and* the speed is zero for a period of 120 seconds or more, then nonmovement is inferred. The reader will note that this algorithm cannot detect nonmovements of duration less than 2 minutes. Further, it is also not guaranteed that the detected nonmovement is necessarily a stop and not a congestion delay or a long wait at a signal.

The above discussions have focused on using solely the GPS navigation data for trip detection. In this context, prior research has been largely successful in developing algorithms to identify stops of durations greater then a certain minimum dwell-time threshold (often 2 minutes). Stops of very short durations, however, are more difficult to identify, particularly when the vehicle is not powered off at the stop. Further, using only the GPS streams, it is not possible to guarantee that all trip ends identified are true stops (rather than congestion delays or wait times at the traffic signals). Supplemental data on transportation network characteristics can be used to alleviate these concerns and enhance trip detection by minimizing the number of missed trips and false trips. The TIAS software uses a GIS road network layer for trip-detection enhancement in two ways (Axhausen et al., 2004): *First*, "probable trip ends" and "suspicious delay" points identified from the preliminary trip-detection procedures are overlaid on the GIS road network, and those that fall within the last 1/3 of a road segment upstream of an intersection are classified as congestion delay and not considered as trip ends. *Second*, the software examines the travel paths for overlaps (i.e., loops in the travel path) and "circuity". Circuity is defined as a measure of the extent of directional change occurring during the trip and is computed as the ratio of the actual travel distance to the Euclidian distance between the trip ends. Points classified as "suspicious delay" from the preliminary analysis are reclassified as "trip ends" if they fall strategically on a path with high circuity or overlaps.

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[1] Stopher's study employed only switched-power data collection protocols. Hence, this methodology was developed specifically to determine stops occurring without engine power off.

Subsequent to trip detection, the next steps in the overall trip-diary generation methods focus on trip characterization. As already indicated, the characteristics of the identified trips might provide clues to the possible existence of other trips missed by the trip detection processes. For example, if the origin and destination locations of a trip are found to be the same, this suggests the possibility of a missed stop (although this could also be indicative of a purely recreational trip or an abandoned trip, i.e., a round trip with no apparent purpose; see Axhausen et al., 2004). In such a scenario, one could examine the specific trip further to determine if there was a missed stop. Another possible approach would be to examine if there is a reversal in direction of the vehicle along this trip. Stopher et al. (2002) provide an implementation definition of reversal as a change in heading between 178 and 182 degrees within 30 seconds. It is also possible that attempts to characterize a trip may suggest that the trip is infeasible and has been falsely detected by the previous trip-identification algorithms. Axhausen et al. (2004) reclassify a trip end as erroneous if the trip duration is less than 30 seconds, the average trip speed is greater than 50 kmph, or the trip distance is greater than 25 kilometers. Similarly, the SCAG vehicle activity study (Stiefer et al., 2003) required further examination of trips of duration less than 1 minute or greater than 1 hour and with average speeds less than 5 mph. or greater than 60 mph.

Finally, the above-described methods cannot be applied to scenarios in which stops occur during a period of signal loss. The following methodology to deal with such situations has been developed by Stopher et al. (2002):

1. The average speeds immediately before and after the period of signal loss is determined using the last 10 track points before the period of signal loss and the first 10 track points after the period of signal loss.

2. The estimated speed during the period of signal loss is determined using the straight-line distance between the location of signal loss and the location of signal reacquisition ("signal-loss distance") and the time period of signal loss.

3. If the estimated speed is considerably lower than the average speeds before and after the signal loss period, a potential stop is inferred.

4. If a potential stop is inferred, the expected time to traverse the signal-loss distance at the average speeds prior to the period of signal loss is computed. This is subtracted from the time period of signal loss to obtain an estimate of the stop duration. If this stop duration is

29

greater than 120 seconds, a stop is inferred; otherwise no stop is assumed to have occurred.

3.3. Trip Characterization

The second major step in the overall trip-diary generation procedure involves the characterization of the trips and stops identified by the first step of trip detection. The various trip attributes that may be derived from the GPS navigational streams and other supplemental data are the geographic location of the trip ends (Section 3.3.1), trip timing (Section 3.3.2), activity/trip purpose (Section 3.3.3), trip distances and speeds (Section 3.3.4), and route (Section 3.3.5). It is very important to note that the methods to determine each of these attributes could be potentially interlinked. For ease in presentation, we discuss the methods to derive each of these attributes in separate subsections below. However, the GPS-TDG software will suitably incorporate the linkages when determining the trip attributes, and also include routines to check for the reasonableness of the overall trip characteristics.

3.3.1. Trip-end (Stop) Locations

Origin and destination trip-end locations may be determined by reading the location information from the first and last records of the GPS navigational stream corresponding to the trip. However, when switched-power systems are used, the first valid point recorded may not be the starting point of the trip due to the time required by the GPS device to acquire a signal. The severity of this problem (i.e., the magnitude of the distance between the true origin and the recorded origin) depends on the signal acquisition time of the GPS device used and other factors (see discussion in Chapter 2). A signal-reception distance analysis undertaken by Bachu et al., (2001) indicates that the average distance traveled by a vehicle before the signal is first acquired is about 0.166 miles (the median value is 0.11 miles). However, this problem can be remedied by assuming that the origin location of a trip is the same as the destination location of the previous trip (Schonfelder et al., 2002).

A second issue with trip-end location identification arises specifically in the case of multiday data collection. When multiday travel data are analyzed, it is possible that the recoded coordinates of the trip ends are found to be different even if the actual trip destinations are the same. This could be because of use of different parking spots and/or inherent randomness in the GPS position determination. Schonfelder and Samaga (2003) have developed an algorithm to

identify the main destination locations from a clustered set of trip-end recordings. In this procedure, for each trip-end location, the distance to all other trip-end locations within a radius of 200 meters was computed. Those trip ends that have the most neighbors and the smallest average distance to these neighbors (i.e., the cluster centers) are classified as unique destination locations. For the remaining, non-central, trip ends (i.e., those trip ends that are not classified as a unique destination location from the previous step), the nearest cluster center is assigned as the destination location.

The discussion thus far has focused on the use of latitude and longitude to determine the trip-end locations. The second approach is to use land use parcel data at the trip end to identify a probable street address corresponding to the destination. For example, in a study undertaken by Wolf (2000), the trip-end location was overlaid on a GIS land use and network map to determine the likely land use parcel associated with the trip end and, hence, the address of the trip end. This procedure was manual and also involved the visual inspection of the aerial photographs for determination of trip-end location and examination of the road database to identify the nearest intersection for address assignment.

3.3.2. Trip Timing

The vehicle trip start time is primarily determined based on when the GPS device acquires its first fix after the start of the trip (i.e., from the time stamp on the first valid record for the trip). Similarly, the vehicle trip-end time is the time stamp on the last valid position assumed to be the end of the trip. Consequently, the determination of the correct trip start times can be impacted by the signal acquisition time, if switched power systems are used. Further, if there is a loss of fix at the end of the trip (e.g., driving into a parking garage), the recorded trip end may not be the true trip end. As a result of these issues, the recorded vehicle trip time can be expected to be systematically less than the actual vehicle trip time (and the reported person trip time), with the discrepancy being between several seconds to several minutes (Murakami and Wagner, 1999). Stopher et al. (2002) emphasize the need to develop interpolation methods to determine the true start times.

3.3.3. Trip and Activity Purposes

The identification of activity/trip purpose is perhaps the most challenging of all GPS data processing tasks. The first step in this direction was taken by Wolf (2000) in her dissertation

research. In this work, she proposed to use land use information at the trip end as the primary means to identify trip purpose. Specifically, this approach involves a "point-in-polygon" analysis to first match the trip-end location (a point) to a polygon-based land use inventory to determine the land use type at the trip end. Further, each land use type was associated with a primary trip purpose, and whenever possible, secondary and tertiary trip purposes were also identified. The study employed 25 land use type categories and 11 trip-purpose categories. The land use at the trip-end location along with the time-of-day of travel, and activity duration at the stop was used to *manually* assign trip purposes. The major problem encountered during this step was that it was not possible to associate certain land use categories (such as mixed-use land parcels and vacant lots) with a specific trip purpose. Further, the success of this methodology requires a very detailed land use GIS database at a fine spatial resolution, as was available in Atlanta where Wolf's study was undertaken.

The Swiss researchers (see Axhausen et al., 2004; Schonfelder and Samaga, 2003) have developed the most comprehensive approach for trip-purpose identification to date in the context of multiday travel-data collection. These researchers have used data on the demographic characteristics of the survey respondents, POI or facility location data, land use patterns, and national travel patterns to develop a probabilistic approach to trip-purpose determination. The overall methodology is summarized here:

1. For trip-end destinations that are within 200 meters of the driver's household location, the trip purpose is determined as "home".

2. For full-time workers, the trip purpose is assigned as work if (a) the destination location is the second most frequented of all, (b) the structural and temporal characteristics of the stop are consistent with those determined from the national travel surveys for the work purpose, and (c) the record is for a weekday.

3. For the trip destinations not classified as either home or work, "most probable" trip purposes are determined in three different ways:

    a. For each trip destination, all points of interest within a catchment area of 300 meters are identified. Each POI is assigned an a priori probability of being associated with each of several trip purposes. The probability of each trip purpose is determined as the weighted sum of the individual trip-purpose probabilities

associated with each of the POIs within the catchment area. (POIs closer to the trip destination have a higher weight.) The most probable trip purpose is determined.

b. The land use patterns within 200 meters of each trip destination are examined. Each land use class is also assigned an a priori probability of being associated with each of several trip purposes. The trip-purpose probabilities of all the distinct land use classes found within the buffer zone are examined to identify the most probable trip purpose.

c. A third "most probable" trip purpose is determined using the characteristics of the driver (gender, automobile availability, and employment status) and the temporal characteristics of the stop (e.g., day of the week, activity start time, and activity duration). The national travel characteristics are used to develop rules of association between the demographic characteristics of the driver, the structural characteristics of the stop, and the trip purpose.

4. The final trip-purpose assignment is accomplished using the three probable trip purposes identified as follows:

a. If all the three approaches yield the same result for the most probable trip purpose, then the agreed purpose is assigned.

b. In case of any mismatch, the POI/land use categorization is preferred as the trip purpose, except when the trip purpose determined from the third method (i.e., using demographic characteristics of the driver and the structural characteristics of the stop) is "pick-up and drop-off," in which case, this is the assigned trip purpose.

c. If there is no clear POI/land use assignment possible, the categorization from the third method is used to determine the trip purpose.

3.3.4. Trip Distances and Speeds

There are two main approaches to determining trip distances from the GPS navigational data (Battelle, 1997). These are: (1) the point-to-point sum of distances (PP) over the entire trip

and (2) the link-to-link sum of distances (LL) over the entire trip after matching the GPS points to network links.

The first method, i.e., the point-to-point sum of distances, involves the computation of the distance between successive pairs of recorded locations. These pair-wise distances are then summed over the entire trip to determine the trip length. The computation of the distance between successive points may be accomplished using either the latitude and longitude information for the two points (the formula to calculate this distance is provided by Wolf et al., 2003) or as a product of the recorded instantaneous speed and the time gap between the successive data recordings (Wolf, 2000). The primary advantage of the PP approach is that the trip distance is determined without the use of any secondary data (as would be necessary in the LL approach discussed in the next paragraph). However, it has been found that the PP approach could result in the overestimation of trip distances, especially when the position information is used for computing the distance between successive points in a trip. Specifically, the positional errors associated with each data record could add up arithmetically leading to overestimation of the trip length. The magnitude of this error can be particularly large for trip segments through urban canyons, where multipath errors and satellite line-of-sight issues can significantly deteriorate the positional accuracy of the GPS points (Wagner et al., 1996). In this context, it has been suggested (see TRB NCHRP Synthesis, 2001) that the use of positional data recorded every 10 seconds instead of using the data recorded every second (which is the typical recording frequency) can help reduce the overestimation error by almost 50 percent.

The second method for trip distance computation, i.e., the link-to-link sum over the entire trip (the LL approach), requires that the GPS traces be matched to an underlying road network to identify the actual links traveled by the vehicle. The trip length is determined as the sum of the length of all the roadway links traveled. The advantage of this approach lies in its ability to accommodate loss of signals midtrip. Specifically, the distance computation using the LL approach can be accomplished, even when there is a loss of signal for a certain period during the trip, as long as there are adequate points to identify all the links that have been traversed. The accuracy of such an approach will depend on, among other factors, the quality and quantity of valid GPS points available for identifying the network links used (Murakami and Wagner, 1999).

The instantaneous speeds are also recorded by the GPS devices. Thus, the average trip speed and measures of variations in speed along the trip length can be determined in a straightforward manner from these instantaneous speed measurements.

3.3.5. Trip Route

The trip detection algorithms discussed in Section 3.2 are useful in identifying stops from the continuous GPS navigational streams. The stream of GPS data records between successive stops describes the path of vehicular movement during the trip. Hence, the trip route can be identified using map-matching procedures i.e., matching the GPS data points to appropriate links on an underlying GIS roadway network map. It is important to note that this matching is not trivial, as both the GPS data and the digital roadway-network data have different levels of spatial accuracy and inherent errors. Consequently, the development of map-matching algorithms is in itself a very vast and complex field of study. Researchers have developed a wide array of methods using deterministic, probabilistic, and fuzzy-logic-based approaches (see for example, TRB NCHRP Synthesis, 2001) for matching GPS traces to GIS maps. This report does not seek to present a comprehensive summary of map-matching procedures, as trip-route determination is not an objective of this current research project. The reader is referred to the following for some recent contributions in this area and further references: Chung and Shalaby (2004), Greenfeld (2002), TRB NCHRP Synthesis (2001), and Doherty et al. (1999).

To summarize, the details provided in this chapter highlight the feasibility of converting the GPS navigational streams into a more appropriate format for use in analysis of travel behavior. At the same time, these details also show the specific advantages and disadvantages of the various procedures available to accomplish the data processing and trip-diary data generation.

CHAPTER 4 DATA REQUIREMENTS AND ACQUISITION EFFORTS

The objective of this research effort is to develop the GPS-based Travel-diary Generator (GPS-TDG) software for processing navigational streams collected from in-vehicle GPS devices to identify trip sequences and various attributes of each vehicle trip, such as, trip-end locations (in terms of the Traffic Analysis Zones, or TAZs), trip timings, purpose, distance, and speed. The generated output will be stored in a conventional travel-diary format. The software will be capable of displaying the derived travel patterns of individuals either in a tabular format or on a GIS map. The software will also be designed to aggregate the derived travel patterns of several individuals to produce interzonal trip tables (by trip purpose and time of day) and network performance measures such as interzonal travel times, distances, and speeds (by time of day). Finally, the GPS-TDG will not be strictly tied to the processing of data from any single survey; rather, it is being developed as general purpose software that can be used for any future GPS travel survey.

This chapter identifies the data requirements for the development of the GPS-TDG and describes the efforts undertaken to date toward acquiring relevant data. Section 4.1 describes the GPS equipment and data collection protocols that we envision that the proposed software will be capable of handling. The structure of the raw GPS data that has been acquired is also described. Next, Section 4.2 focuses on supplemental data requirements for GPS-TDG. Finally, Section 4.3 describes the reported travel survey data acquired, which would be used for the validation of the algorithms developed.

4.1. GPS Equipment, Data Collection Protocols, and Data

The GPS-TDG will be designed to process navigational data collected using a GPS receiver/antenna with the following specifications:

1. Positional accuracy of 3–5 meters
2. Signal acquisition time: 1 minute (cold) and 15–30 seconds (warm)
3. Update rate of 1 second.

The software will be developed assuming that a handheld device will be used to record the GPRMC sentence outputs from the GPS receiver. Further, the data logging using the handheld device is also assumed to be of a "user-flagged" system, i.e., the driver turns the device

on at the start of the trip to initiate data recording and turns it off at the end of the trip to terminate data recording. These equipment and data logging specification assumptions are based on discussions between the research team and the project director, project coordinator, and other TxDOT staff involved in this project at a research meeting on December 1, 2004.

For the purposes of use in software development and refinement, we have acquired the raw GPS outputs from the recently conducted surveys in Laredo and Tyler/Longview. GPS data from over 100 households (more than 200 vehicles) are available from the Laredo survey, and data from over 200 households (more than 300 vehicles) are available from the Tyler/Longview survey. The GPS data for both studies were collected at 1-second logging frequencies, and all points were logged regardless of speed. The format of the output files is presented in Table 4.1 below (reproduced from the data documentation provided by TxDOT).

Table 4.1 Format of GPS outputs from Laredo and Tyler/Longview surveys

Item#	Variable Name	Variable Description	Data Type	Just.	Field Width	Coll. Stage	Values	Formal and Full Text
GR-1	RECTYPE	Record Type	I	RJ	1	A	GPS Record Type = 5	CORRECTED DATA
GR-2	GPS_ID	GPS Receiver Unit ID Number	I	RJ	3	GPS	0-999	
GR-3	HH_ID	Household ID Number	I	RJ	7	A		
GR-4	Veh_ID	Vehicle Number	I	RJ	2	A		
GR-5	GMT_DATE	Greenwich Mean Time Date Stamp	I	RJ	8	GPS	MM/DD/YY	
GR-6	GMT_TIME	Greenwich Mean Time Time Stamp	I	RJ	8	GPS	HH:MM:SS (Military Time)	
GR-7	LOC_DATE	Local Date Stamp	I	RJ	8	GPS	MM/DD/YY	
GR-8	LOC_TIME	Local Time Stamp	I	RJ	8	GPS	HH:MM:SS (Military Time)	
GR-9	LAT_RAW	Latitude	F	RJ	16	GPS	Decimal Degrees	XXX.XXXXXX deg
GR-10	LONG_RAW	Longitude	F	RJ	16	GPS	Decimal Degrees	XXX.XXXXXX deg
GR-11	ELEV_RAW	Elevation	F	RJ	16	GPS	Meters	
GR-12	VELOCITY	Velocity	F	RJ	8	GPS	Meters/Second	0..514.00m/s
GR-13	HEADING	Direction of Vehicle	F	RJ	6	GPS	True North	0.0..359.9 deg
GR-14	HDOP	HDOP (horizontal dilution of precision)	I	RJ	4	GPS	00.5-99.9	
GR-15	SATS	Number of Satellites	I	RJ	2	GPS	00-12	

It is important to note here that the GPS output formats from the two studies do not conform to the GPRMC specifications as the special purpose GeoLogger data logging device was used in these two studies. (See discussions in Chapter 2 for data logging specifications and

protocols.) Further, the data recorded by GeoLoggers are also considerably preprocessed, i.e., local dates and times are computed, velocity is converted to metric units, and latitude and longitude values are converted to decimal degrees. Hence, the use of these data for the development of preprocessing routines would be limited. We hope to acquire additional navigational data recorded in the GPRMC format using logging devices, which are expected to be used in future GPS travel surveys to be undertaken by TxDOT. This additional data will be used in the development of preprocessing routines. Further, the GPS data from the two travel surveys also contain measures on the quality of the GPS computations for each record, i.e., the HDOP measure and the number of satellites in view. These measures would not be available if only GPRMC output would be used in future GPS travel surveys. Hence, the use of these accuracy measures in our software development would be appropriately limited.

Both the Laredo and the Tyler/Longview surveys collected GPS travel data only for a single day. Consequently, our ability to develop algorithms that enhance trip detection and characterization by identifying and examining repetitive patterns from multiday travel-data collection efforts would be limited.

4.2. Supplemental Data

Based on the detailed discussions provided in the previous chapters, it is clear that the determination of trip purpose requires supplemental data. Further, the advantages of the use of supplemental data in enriching the travel-diary generation procedure have also been elaborated in the previous chapters. In the design of GPS-TDG, the goal is to balance the reliance on supplemental data (which may not always be possible to obtain or even necessary for the objectives of any given study) against the benefits (such as disaggregate activity/trip-purpose determination and enhanced reliability of trip detection) that could be achieved by using the extra data. Consequently, four categories of supplemental data are identified, two of which are required inputs for the software, and the other two of which are optional inputs. The required inputs are data on respondent characteristics and a GIS map of the TAZ boundaries. The optional inputs are the land use data and roadway network maps. Whenever available, the software uses these optional inputs to enhance trip detection and characterization. If these inputs are not provided, the software would still be capable of deriving the travel diary, but without disaggregate activity purposes and enhanced trip-detection checks. However, for the purposes of

software *development*, all four inputs are required. Each of the four input types is discussed below.

4.2.1. Respondent Characteristics

The most fundamental respondent characteristics required are the home and work locations, used to classify the trips into one of the four commonly used aggregate categories: home-based work, home-based other, work-based other, and other. TxDOT has provided household and personal characteristics data of the respondents participating in the Laredo and Tyler/Longview GPS surveys to the research team. The data sets were provided in an ASCII format, along with the record layout documentation necessary to import the data into analysis or mapping software. The demographic data, which consists of the household, person, and vehicle information, are nested in one file, with a record type indicator to help import the data correctly. The household file contains the home address zip code, the corresponding TAZ, and the latitude/longitude coordinate. The person file contains similar data for the work address. Thus, the most fundamental respondent characteristics required for aggregate trip-purpose determination are available. The demographic data files from the Laredo and Tyler/Longview surveys also include several household-level (such as number of vehicles, income, and tenure) and person-level (such as age, gender, and ethnicity) characteristics. The research team will examine these demographic data and identify the demographic attributes of primary interest for deriving the travel diaries in subsequent project tasks.

Finally, when collecting data on respondent characteristics, it would also be very useful to record whether the vehicle equipped with the GPS device has continuous power to the cigarette lighter or not. In the case of the Laredo and Tyler/Longview surveys, this information was recorded in "administrative data files," which are available to the UT research team.

4.2.2. TAZ Boundaries

A GIS map of the TAZ zone boundaries of the study is required for two purposes. *First*, the trip-end locations need to be characterized in terms of the TAZs, in addition to latitude and longitude, for subsequent use in travel modeling. *Second*, this GIS layer is also needed for the visualization of travel patterns. The GIS zone boundary layers for Laredo and Tyler/Longview study area will be acquired from TxDOT.

4.2.3. Land Use Data

The land use data are of primary importance for the purpose of disaggregate activity/trip-purpose determination. There are two types of land use data: (1) the zoning data and (2) facility location data. Based on preliminary investigations, it appears that land use data at the parcel level might be the best zoning data available for the purposes of this project. Efforts are underway to determine whether these data are available for the Laredo and Tyler/Longview study areas. Further, the research team will also investigate the availability of such data for other regions of Texas, including the typical land use classifications and data formats adopted by the different regions.

The second type of land use data are the facility location data (also called the points of interest data [POI]). In this context, the TIGER/Line files are relevant to this research project. These files constitute digital databases of geographic features (e.g., roads, railroads, rivers, lakes, legal boundaries, and census statistical boundaries) with latitude-longitude coordinates, feature name, and classification, etc. (US Bureau of Census, 2000). These files are available for most counties in the US. Among the 17 different TIGER/Line files available, the landmark file or Record Type 7 (US Bureau of Census, 2000) is of particular interest in the context of trip-purpose identification. Specifically, this file is a record of several regional landmarks, with each landmark characterized by the landmark name, its geographic location in decimal degrees, a feature class code, and an identification number. The landmark can either be a point, a line, or an area type, depending on the size of the feature and the depiction of the feature in the source document. For example, an airport might appear as a specific point, a line, or an area. Landmark names are not standardized and may be referenced by variant spellings or different census feature class codes (CFCC). The major CFCC categories are military installations, multi-household or transient quarters, custodial facilities, educational or religious institutions, transportation terminals, employment centers (including shopping centers and office parks), towers, open space, and special purpose landmarks, such as the post office and police station.

The benefits to using the landmark files for this project include the fact that these data are readily available for all counties in Texas and can be used by most GIS software packages. In contrast, a major shortcoming of these files is the omission of key landmarks. A review of the file for Travis County indicates that the data does contain many familiar landmarks like the Barton Creek Mall and various apartment complexes. However, the school listings are not

complete, nor are the hospitals. (Currently, there are 201 landmarks in all for Travis County; the entire table is included as Appendix A.) However, there is a project under way at the Census Bureau (MAF/TIGER Modernization Project) aimed at increasing the completeness of this file. A second major limitation of the landmarks file is that some addresses are geocoded to the centroid of the zip code. This causes several landmarks to be "stacked up" at a particular point. The research team will undertake a more comprehensive assessment to determine the applicability of the landmarks files for trip-purpose identification.

4.2.4. GIS Roadway Network Map

The next data requirement for the purposes of software development is the GIS roadway maps of the study regions. Determination of trip route is not a focus of this research project. Consequently, the predominant use of the road network data is to enhance trip detection by minimizing the detection of false trip ends (for example stoppage at a signalized intersection). The research team plans to acquire the roadway network maps developed by TxDOT for the two study regions (i.e., Laredo and Tyler/Longview) for the purposes of software development.

4.3. Self-Reported Travel Diaries: Validation Data

The final data requirement pertains to the validation of the procedures for the automation of travel-diary generation. For this purpose, the self-reported travel diaries of the respondents participating in the GPS and household travel surveys in the Laredo and Tyler/Longview study areas have been acquired. As discussed in Section 2.3, a detailed knowledge of the survey administration procedures for both the self-reported and GPS components is very important for developing validation rules. Correspondingly, the research team plans to acquire detailed documentation on the survey administration protocols from TxDOT. Finally, it is useful to point out here that the availability of GPS-recorded and reported travel data from two different studies provides us with a unique opportunity to test the transferability of our data processing algorithms. The reader will note that the transferability of the underlying algorithms is important to the successful development of such general purpose software as the GPS-TDG.

CHAPTER 5 SUMMARY AND CONCLUSIONS

Household travel survey data constitute a fundamental input to travel-demand model development for use in transportation planning and policy analysis. Although the design of surveys has been enhanced over the years to facilitate a more complete recollection of travel, and the advancements in the field of computers and telecommunications are being exploited to make data recording easier and more accurate, there are still several concerns about the data quality obtained from conventional household travel surveys. These concerns are primarily associated with the challenge of requiring respondents to record details about all trips and activities for the designated travel survey period.

Advances in Global Positioning System (GPS) technology has provided transportation planners with an alternative and powerful tool for more accurate travel-data collection with minimal user burden and thereby address the concerns of the conventional household travel surveys. The data recorded by GPS devices, however, does not directly yield travel information; the navigational streams have to be processed and the travel patterns derived from it. The focus of this research project is to develop software, called GPS-TDG, to automate the processing of raw GPS data and to generate outputs of activity-travel patterns in the conventional travel-diary format. The software will identify trips, and characterize them by several attributes including trip- end locations, trip purpose, time of day, distance, and speed. The results will be presented to the analyst in a tabular form and/or on a GIS map, as desired. Further, the software will also be capable of aggregating the derived trip-diary data to produce trip tables and to compute inter-zonal network performance measures.

Within the overall focus of the research, this report presented a comprehensive synthesis of the state of the practice/art in collecting and processing GPS data. This synthesis is intended as the basis for developing input specifications and processing algorithms for our GPS-TDG software. A second objective of this report is to identify the data requirements for the software development purposes and document the efforts undertaken to acquire the data.

Chapter 2 presents an overview of the GPS outputs and other secondary data that has been used by past GPS travel studies in deriving the trip diaries. Specifically, the GPS equipment, data collection protocols, and the formats of the recorded navigational streams are discussed. Further, supplemental data such as respondent characteristics, land use patterns, and

roadway network data that have also been used by analysts for enhancing the trip identification and characterization are described. Finally, the data requirements for validating the algorithms developed for trip-diary generation are presented.

Chapter 3 presents a comprehensive synthesis of knowledge on the techniques that have been employed to convert the GPS streams into the travel-diary format. Specifically, we identify two major steps involved in the trip-diary generation procedure: (1) trip detection and (2) trip characterization. Trip detection involves the identification of individual trip segments (or equivalently, stops) from the continuous stream of GPS navigational data, whereas trip characterization determines attributes of the trips, such as location, timing, purpose, distance, speed, and route. The trip detection and trip characterization methods adopted by past research are discussed in detail. In addition, this chapter also discusses preprocessing routines required to convert the raw GPS streams downloaded from the data loggers to more readily usable formats for subsequent trip-diary generation analysis.

Chapter 4 focuses on the data requirements for the development of GPS-TDG. The GPS receiver/antenna and the data logger specifications supported by the software are first discussed. Next, supplemental data requirements are presented. In the design of GPS-TDG, we seek to balance the over reliance on supplemental data against the benefits that could be achieved by using the extra data. Consequently, we identify four categories of supplemental data, two of which are required inputs for the software application, while two are optional inputs. The required inputs are data on respondent characteristics and a GIS map of the TAZ boundaries. The optional inputs are the land use data and roadway network maps. In addition to the GPS and the supplemental data, we also require self-reported travel data from the GPS survey respondents for the purposes of validation of the algorithms developed. Chapter 4 also describes our data acquisition efforts to date. We have obtained the GPS navigational data, the corresponding reported travel diaries, and data on demographic characteristics of the respondents from the Laredo and the Tyler/Longview surveys. The research team has also undertaken a preliminary examination of the applicability of the facility location data from the US Census TIGER files for the trip-purpose determination. Efforts to acquire supplemental land use and roadway network data are under way.

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Appendix A
The Facility Location Data for the Travis County from the TIGER/Line Files

Record Type	Version	File (FIPS)	Landmark ID	Source	Census Feature Class Code	Landmark Name	LALONG	LALAT
7	1103	48453	69	J	D00	Austin State School		
7	1103	48453	58	J	D00	Texas State Health Dept		
7	1103	48453	77	J	D00	Travis State School		
7	1103	48453	55	J	D10	Camp Mabry Military Res		
7	1103	48453	153	M	D20	Willowbrook North Townhomes	-97719704	30374320
7	1103	48453	200	O	D21	Apartments	-97826396	30228965
7	1103	48453	182	M	D21	Arbors of Austin	-97699746	30369801
7	1103	48453	201	O	D21	Austin Trail Apartment	-97825338	30231189
7	1103	48453	197	O	D21	Canyon Creek Apartment	-97843753	30415197
7	1103	48453	156	M	D21	Centennial Place Apartment	-97780021	30188960
7	1103	48453	183	M	D21	Copper Mill Apartment	-97696107	30366480
7	1103	48453	186	M	D21	Country Place Apartment	-97699734	30370541
7	1103	48453	185	M	D21	Cross Creek Apartment	-97703837	30369709
7	1103	48453	170	M	D21	Edgecreek	-97697565	30408051
7	1103	48453	184	M	D21	French Embassy Apartment	-97700545	30372740
7	1103	48453	179	M	D21	Gateway Apartment	-97764590	30276556
7	1103	48453	163	M	D21	Gentrys Walk	-97705082	30395942
7	1103	48453	175	M	D21	Hunters Glen Apartment	-97806654	30209517
7	1103	48453	158	M	D21	Hunterwood Apartment	-97774939	30191790
7	1103	48453	167	M	D21	Limestone Ranch Apartment	-97680773	30479071
7	1103	48453	173	M	D21	Marbella Villas Townhomes	-97698379	30413293
7	1103	48453	164	M	D21	Monterey Ranch Apartment	-97838469	30233104
7	1103	48453	152	M	D21	Newport Apartment	-97716414	30372307
7	1103	48453	181	M	D21	Quail Run Apartment	-97702342	30371783
7	1103	48453	151	M	D21	Royal Crest Apartment	-97715465	30371926
7	1103	48453	187	M	D21	Runnymede Apartment	-97704254	30367396
7	1103	48453	196	O	D21	Sonterra 2 Apartment	-97840010	30428650
7	1103	48453	174	M	D21	The Huntingdon	-97695498	30410225
7	1103	48453	169	M	D21	The Lodge at Merrilltown	-97693458	30450354
7	1103	48453	172	M	D21	The Marquis	-97697000	30409963
7	1103	48453	171	M	D21	The Reserve at Northbend	-97696164	30412786
7	1103	48453	154	M	D21	Woodmark Apartment	-97718866	30381802
7	1103	48453	162	M	D21		-97723586	30242833
7	1103	48453	165	M	D21		-97859359	30372954
7	1103	48453	166	M	D21		-97855232	30375394
7	1103	48453	176	M	D21		-97693762	30443801
7	1103	48453	190	O	D23	Big Oaks Rv Park	-97877973	30514367
7	1103	48453	198	O	D23	Dessau Mobile Home Park	-97656689	30417052
7	1103	48453	157	M	D26	South Point Village	-97772220	30189514
7	1103	48453	168	M	D27		-97674849	30475430
7	1103	48453	73	J	D31	Austin State School		
7	1103	48453	155	M	D40	Anderson High School	-97754306	30374484
7	1103	48453	160	M	D40		-97852037	30154433
7	1103	48453	194	N	D43	Clint Small Middle School	-97841508	30233110
7	1103	48453	60	J	D43	Concordia College		

Record Type	Version	File (FIPS)	Landmark ID	Source	Census Feature Class Code	Landmark Name	LALONG	LALAT
7	1103	48453	161	M	D43	Mendez Middle School	-97742787	30188314
7	1103	48453	141	N	D43	Patton Elementary School	-97845163	30231818
7	1103	48453	65	J	D43	St Edwards University		
7	1103	48453	137	N	D43	Steiner Ranch Elementary Sch	-97883105	30380007
7	1103	48453	57	J	D43	Texas School for the Blind		
7	1103	48453	70	J	D43	Texas School for the Deaf		
7	1103	48453	61	J	D43	Texas School for the Deaf East		
7	1103	48453	59	J	D43	Univ of Texas Intramural Field		
7	1103	48453	6	J	D43	University of Texas Research C		
7	1103	48453	13	J	D43		-97928466	30525043
7	1103	48453	19	J	D43		-97469953	30401957
7	1103	48453	188	M	D43		-97833679	30177035
7	1103	48453	159	M	D44	Risen Savior Lutheran Church	-97836294	30179922
7	1103	48453	8	J	D44		-98040094	30508173
7	1103	48453	14	J	D44		-97395088	30406214
7	1103	48453	16	J	D44		-97456529	30391438
7	1103	48453	20	J	D44		-97486799	30405600
7	1103	48453	23	J	D44		-97442271	30317899
7	1103	48453	25	J	D44		-97481223	30255744
7	1103	48453	199	N	D51	Austin Bergstrom International	-97668390	30199349
7	1103	48453	64	J	D51	Austin Municipal Airport		
7	1103	48453	127	K	D51	Robert Mueller Muni Airport	-97700529	30298457
7	1103	48453	66	J	D51	Rusty Allen Lago Vista Airport		
7	1103	48453	35	J	D51	The Birds Nest Landing Strip		
7	1103	48453	9	J	D51		-98038308	30503304
7	1103	48453	45	J	D51			
7	1103	48453	5	J	D57	Austin-Bergstrom International		
7	1103	48453	93	K	D61	Allandale Shopping Center	-97740852	30333065
7	1103	48453	94	K	D61	Anderson Square	-97715123	30351953
7	1103	48453	95	K	D61	Barton Creek Square	-97808940	30253941
7	1103	48453	96	K	D61	Ben White Center	-97770323	30226177
7	1103	48453	97	K	D61	Ben White Plaza	-97779563	30228471
7	1103	48453	98	K	D61	Brykerwood Village	-97750864	30308206
7	1103	48453	99	K	D61	Cameron Village	-97708402	30311383
7	1103	48453	89	K	D61	Casis Shopping Center	-97766374	30301256
7	1103	48453	90	K	D61	Cherry Creek Plaza	-97798731	30215445
7	1103	48453	91	K	D61	Chimney Corners Shop Ctr	-97760404	30357650
7	1103	48453	92	K	D61	Corners	-97782467	30243104
7	1103	48453	100	K	D61	Creekside Square	-97740276	30361204
7	1103	48453	101	K	D61	Crestview Shopping Center	-97725615	30342805
7	1103	48453	102	K	D61	Delwood Shopping Center	-97718674	30295543
7	1103	48453	103	K	D61	Dobie Mall	-97741484	30283307
7	1103	48453	104	K	D61	Enfield Shopping Center	-97750323	30279332
7	1103	48453	105	K	D61	Ford Village Shopping Center	-97786611	30233933
7	1103	48453	106	K	D61	Gaston Place Shopping Center	-97688522	30313769

Record Type	Version	File (FIPS)	Landmark ID	Source	Census Feature Class Code	Landmark Name	LALONG	LALAT
7	1103	48453	107	K	D61	Govalle Center	-97711674	30260095
7	1103	48453	108	K	D61	Hancock Shopping Center	-97720122	30299207
7	1103	48453	109	K	D61	Highland Mall	-97715315	30324360
7	1103	48453	110	K	D61	Highland Park West Shop Ctr	-97759483	30333205
7	1103	48453	111	K	D61	Lake Austin Shopping Center	-97775277	30283207
7	1103	48453	112	K	D61	Lakehills Plaza	-97791107	30236985
7	1103	48453	113	K	D61	Lamar Plaza	-97762291	30256184
7	1103	48453	114	K	D61	Lamar Village	-97743407	30306107
7	1103	48453	115	K	D61	Lantern Lane Shopping Center	-97750334	30327756
7	1103	48453	116	K	D61	Mesa Plaza	-97758045	30371316
7	1103	48453	117	K	D61	Montopolis Shopping Center	-97695225	30237132
7	1103	48453	118	K	D61	North Loop Plaza	-97741937	30326706
7	1103	48453	119	K	D61	North Village	-97732644	30352405
7	1103	48453	121	O	D61	Northfair Shopping Center	-97718027	30338471
7	1103	48453	122	K	D61	Northwest Hills Village	-97754492	30353638
7	1103	48453	123	K	D61	Northwest Shopping Center	-97740516	30335533
7	1103	48453	124	K	D61	Oak Hill Plaza	-97877397	30235615
7	1103	48453	125	K	D61	Plaza Balcones	-97758444	30336885
7	1103	48453	126	K	D61	River Hills Center	-97731188	30239642
7	1103	48453	128	K	D61	Shoppers World Center	-97740427	30326306
7	1103	48453	129	K	D61	South Congress Shopping Center	-97754322	30238869
7	1103	48453	130	K	D61	South Lamar Square	-97762411	30255722
7	1103	48453	132	K	D61	Town Lake Plaza	-97728554	30242523
7	1103	48453	133	K	D61	Twin Oaks Shopping Center	-97752498	30239495
7	1103	48453	135	O	D61	Violet Crown Shopping Center	-97721699	30334688
7	1103	48453	136	K	D61	Walnut Creek Village	-97681633	30305301
7	1103	48453	138	K	D61	Westgate Mall	-97798285	30231009
7	1103	48453	139	K	D61	Windsor Village	-97694562	30312053
7	1103	48453	177	M	D61		-97697094	30437548
7	1103	48453	180	M	D63	Walnut Creek Business Park	-97666642	30330410
7	1103	48453	178	M	D64		-97697209	30438744
7	1103	48453	195	N	D65	City Hall	-97944356	30308257
7	1103	48453	78	J	D81	Austin Country Club		
7	1103	48453	79	J	D81	Austin Country Club		
7	1103	48453	85	J	D81	Jimmy Clay Golf Course		
7	1103	48453	63	J	D81	Municipal Golf Course		
7	1103	48453	131	N	D82	Bee Cave Cemetery		
7	1103	48453	134	L	D82	Cemetery		
7	1103	48453	193	N	D82	Oliver Cemetery		
7	1103	48453	4	J	D82			
7	1103	48453	7	J	D82		-98044379	30509375
7	1103	48453	11	J	D82			
7	1103	48453	12	J	D82			
7	1103	48453	15	J	D82			
7	1103	48453	17	J	D82			

Record Type	Version	File (FIPS)	Landmark ID	Source	Census Feature Class Code	Landmark Name	LALONG	LALAT
7	1103	48453	18	J	D82		-97471602	30388915
7	1103	48453	22	J	D82		-97422214	30369423
7	1103	48453	24	J	D82			
7	1103	48453	26	J	D82		-97496640	30242068
7	1103	48453	29	J	D82			
7	1103	48453	36	J	D82			
7	1103	48453	54	J	D82			
7	1103	48453	68	J	D82			
7	1103	48453	72	J	D82			
7	1103	48453	87	K	D82			
7	1103	48453	33	J	D85	Arkansas Bend Park		
7	1103	48453	51	J	D85	Bull Creek Park		
7	1103	48453	42	J	D85	Cypress Creek Arm		
7	1103	48453	43	L	D85	Cypress Creek Park		
7	1103	48453	140	L	D85	Dragon Park		
7	1103	48453	142	L	D85	Lakeway City Park		
7	1103	48453	143	L	D85	Lakeway City Park		
7	1103	48453	144	L	D85	Lakeway City Park		
7	1103	48453	145	L	D85	Lakeway City Park		
7	1103	48453	146	L	D85	Lakeway City Park		
7	1103	48453	147	L	D85	Lakeway City Park		
7	1103	48453	149	L	D85	Lakeway City Park		
7	1103	48453	191	L	D85	Lakeway Park No 1		
7	1103	48453	32	J	D85	Malberger Park		
7	1103	48453	192	L	D85	Porpoise Park		
7	1103	48453	150	L	D85	Rebel Park		
7	1103	48453	52	L	D85	Sailfish Park		
7	1103	48453	31	J	D85	Sandy Creek Park		
7	1103	48453	47	J	D85			
7	1103	48453	62	J	D85			
7	1103	48453	120	N	D85			
7	1103	48453	148	L	D85			
7	1103	48453	189	M	D85			
7	1103	48453	53	J	H00	Bull Creek Arm		
7	1103	48453	39	J	H00	Cypress Creek Arm		
7	1103	48453	40	J	H00	Cypress Creek Arm		
7	1103	48453	41	J	H00	Cypress Creek Arm		
7	1103	48453	27	J	H11	Colorado River		
7	1103	48453	46	J	H11	Colorado River		
7	1103	48453	50	J	H11	Colorado River		
7	1103	48453	56	J	H11	Colorado River		
7	1103	48453	74	J	H11	Colorado River		
7	1103	48453	75	J	H11	Colorado River		
7	1103	48453	76	J	H11	Colorado River		
7	1103	48453	80	J	H11	Colorado River		

Record Type	Version	File (FIPS)	Landmark ID	Source	Census Feature Class Code	Landmark Name	LALONG	LALAT
7	1103	48453	81	J	H11	Colorado River		
7	1103	48453	82	J	H11	Colorado River		
7	1103	48453	83	J	H11	Colorado River		
7	1103	48453	84	J	H11	Colorado River		
7	1103	48453	88	J	H11	Colorado River		
7	1103	48453	3	J	H11	Pedernales River		
7	1103	48453	28	J	H11	Pedernales River		
7	1103	48453	30	J	H11	Pedernales River		
7	1103	48453	38	J	H11	Pedernales River		
7	1103	48453	86	K	H11	Pedernales River		
7	1103	48453	34	J	H31	Cypress Creek Arm		
7	1103	48453	21	J	H31	Harris Branch		
7	1103	48453	44	J	H31	Hurst Creek Arm		
7	1103	48453	49	J	H31	Lake Austin		
7	1103	48453	10	J	H31	Lake Travis		
7	1103	48453	37	J	H31	Lake Travis		
7	1103	48453	71	J	H31	Lake Travis		
7	1103	48453	2	J	H31	Pedernales River		
7	1103	48453	67	J	H31	Sandy Creek Arm		
7	1103	48453	48	J	H31	Walter E Long Lake		
7	1103	48453	1	J	H31			