GPS-Based Household Interview Survey for the Cincinnati, Ohio Region

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16. Abstract

Methods for Conducting a Large-Scale GPS-Only Survey of Households

Past Household Travel Surveys (HTS) in the United States have only piloted small subsamples of Global Positioning Systems (GPS) completes compared with 1-2 day self-reported travel inventory diaries. The Ohio Department of Transportation Research Division, in cooperation with the Ohio-Kentucky-Indiana (OKI) Council of Governments, in 2009 initiated the first exclusively GPS Household Travel Survey (HTS) (e.g., no diaries). In addition, the ODOT GPS-only HTS is one of a few initial US studies to successfully use a personal devise GPS. Most past subsample studies have installed GPS in vehicles for recording and comparison of auto travel only. Additionally, this study was one of the first completed address-based HTS, which includes cell only households, with Internet recruit available.

This research documents the protocols used for GPS deployment to all members of a household over 12 years old for a three-day recording period. Simplified diaries were provided for children under age 12. The main survey commenced in August of 2009. Recruitment of over 5,000 households progressed over a twelve month period, with proportional distribution. The highly stratified address-based sampling method used is described as well as the forms and materials, response rates for recruitment, and the compliance rates and experiences with households. Also described are the logistical challenges of getting 4+ persons households to all carry a GPS unit on a concurrent day and the challenge of loss rates on GPS units not returned.

This research documents the Internet-based prompted recall (PR) verification method used and its outcomes. The PR was essentially used to impute mode of travel and trip purpose from GPS recordings. These imputation methods and findings are described. Also presented and discussed is the depth and degree of accuracy of core trip variables obtained using GPS-only methods, including modes, travel time and distance, and purpose at locations. Lessons learned are recorded.

The primary conclusion to be drawn from this research is that it is feasible to undertake a GPS-only household travel survey, achieving a high standard of representativeness for the sample, while imputing mode and purpose at a sufficiently accurate level to support modeling work. The high level of accuracy attained in this survey for imputing mode and purpose with 96 percent on mode and around 90 percent on activity (other than detailed breakdowns of the "other" category) is far superior to self-report surveys. The richness of the "ground-truthing" of time, location, distance, speed, and route information from this survey surpasses what can be achieved from any other form of survey.

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Title Sheet

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GPS-Based Household Interview Survey for the Cincinnati, Ohio Region

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PROJECT BACKGROUND

Household travel surveys (HTS) are designed to provide information about daily travel patterns, including trip purposes, time of day decisions, mode choices, trip lengths and distances, activity locations, and routes taken. This information is typically gathered from self-reported information in a diary, with the information retrieved via a computer-assisted telephone interview (CATI), a web-based survey, or mailback of the completed diary. Unfortunately, it has been demonstrated that self-reporting leads to inaccuracies in travel information. The biggest short-coming is trip underreporting. For instance, recent work by Wolf et al., (2003), Pearson (2004) and others has shown that diary information retrieved through CATI when compared with GPS measured travel suggests trip under-reporting ranges from 20 to 30 percent. The diary approach has also shown time inaccuracies and origin-destination location errors; respondent fatigue often results in self-reporting human errors.

STUDY OBJECTIVES

As Global Positioning Systems (GPS) recordings become more accurate, reliable, and cost efficient, can they entirely replace travel diaries? By using GPS, the accuracy of spatial and temporal data collected on travel patterns can be greatly improved, and the duration of observation can be extended to better capture variability in travel. Respondent fatigue and corresponding errors are limited. However, to replace the travel diary method with GPS, both travel mode and trip activities/purpose have to be imputed from available data.

The goal of this research was to investigate whether such imputation methods can be sufficiently developed to justify replacing travel diary data collection methods with GPS. A secondary goal was to demonstrate that a fully representative sample of households will cooperate with GPS recording methods. This project was the first GPS-only full-scale household travel survey in the USA.

DESCRIPTION OF WORK

The project commenced in early 2009 with the conduct of a pilot survey, which helped establish various parameters and procedures for the main survey. The pilot survey has been documented elsewhere (Transportation Research Record, Journal of the Transportation Research Board, No 2176, Travel Forecasting, Volume 2, pp.26-34). Sampling for the pilot and the main survey used an address-based sampling procedure, with households contacted initially by a combination of mail and telephone.

The main survey commenced in August 2009 and was completed in August 2010. It was designed as a household travel survey to be collected steadily over a twelve-month period. Each household member over the age of 12 was asked to carry a personal GPS device with them everywhere they went for a period of 3 days. The household received travel packets two days prior to scheduled travel dates containing: a one-page GPS instruction sheet, household and person information forms, a GPS for each person aged 13+, 1 charger for every two devices, and postage-paid return mailing materials. Household members under the age of 13 received a simplified “child diary”, which was to be completed on the first day of the travel period. GPS units were set to collect data on a second-by-second basis (since this has been found to provide a superior basis for imputing stops and travel characteristics).

After the three-day collection period was completed, GPS units were retrieved from households, the data were downloaded, and processing of the data commenced. Household and person information forms sent to households were designed for respondents to indicate if they had or had not left home on any particular travel day, or if they carried or forgot to take the GPS with them on one or more days while they travelled. In addition, respondents were asked to provide workplace, school, and two most frequent shopping addresses for household members. Together with the home address of the household these addresses were geocoded and used in the GPS processing.

Figure ES1: The GPS Unit

The GPS unit shown in Figure ES1, is the GPS unit used. It is a personal device that can be carried in a pocket or purse, or clipped on a belt or wristband. It records all modes of travel including car, public transport, bicycle, and walk and can record inside many buildings. For the most part, the units recorded three days of travel. Once the units were returned, data were downloaded. Each data entry (GPS file, forms data, and household recruitment information) had an associated household and person ID. These data were compiled into a metadata file that was referenced to the GPS data.

The GPS unit records all location (latitude/longitude) data. The only errors that can occur in the location data are:

- Cold start problem – when the device does not find position until after a trip has actually started. The data processing software corrects for all except the first trip on the first day, which is corrected by the manual map editing.
- Lost signal – this is only a problem if it occurs near the end of a trip and results in a premature destination recording. This is also normally corrected during the manual map editing process.

Other errors in the GPS record arise if the person did not carry the device for the entire day, or if the battery ran out. In these cases, if the status form returned indicated that s/he forgot the device for part of the day or that the battery ran out, then that day was excluded from sampling for the PR survey. Battery problems turned out to be less than 5%.

The PR Survey
An Internet PR (PR) survey was conducted with respondents providing email addresses and based on Google® maps, providing a playback of the GPS records for one day of their travel. Respondents were asked to fill in certain information about their travel, including mode of travel between stops, purpose of stops, and which household members were with them. This information served two primary purposes: to validate the results of the processing software that imputed trip ends, mode, occupancy, and purpose; and to provide a means for improving the software by identifying those situations where the software did not perform as well as expected. In this report, the results of the PR survey are documented in terms of response rates and usability of the results from the survey.

The PR survey displayed the respondent's travel on a map in a common web interface (Google Maps®), and posed a series of questions regarding the respondent's travel, such as mode and trip purpose. The PR responses were then used to improve software to impute trip mode, purpose, and other missing data for the completed surveys. Only persons that completed at least one GPS recorded trip received the PR Survey.

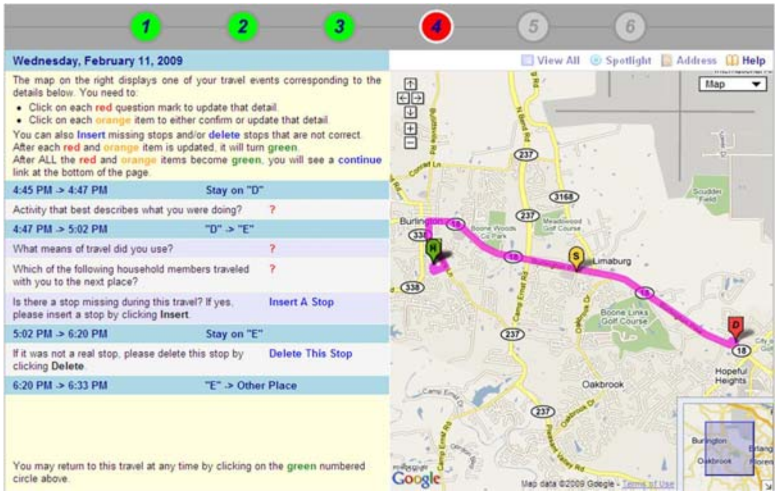

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Figure ES2: Example of PR Web Survey Format

RESEARCH FINDINGS & CONCLUSIONS

The major finding of the project was that it is now feasible to conduct household travel surveys by GPS. While the overall response rate from households was similar to that of more conventional methods of surveying in the US, some of the biases encountered in conventional diary surveys were not encountered and a representative sample of completed households was obtained.

A household was defined as complete only if all persons provided with GPS had at least one common day of travel data recorded, or a claimed no-travel day on that day. A total of 2,059 households provided fully completed GPS data, with an additional 737 incomplete households with significant GPS data. Of the 2,059, there were 17 one-person households that were GPS complete but where the household member did not travel. Hence, there are 2,059 households whose travel is reported in this section. A summary of the responses is provided in Table ES3. The completed households provided 3,849 GPS person records, exclusive of child diaries. Thus, an average of 1.88 persons per household carried a GPS on at least one common day.

The average trip rate of 4.61 trips per person per day for GPS recordings, or 8.62 trips per household per day, is higher than that usually measured in diary surveys (particularly when including only household members over 12 years old who carried GPS units.) The weekday trip rate is higher still at 5.06 trips per person or 9.46 trips per household. A limited analysis of child diary results is included in the report. Trip characteristics and final disposition of the completed sample are shown in Table ES3.

Table ES3: Disposition of the Final Sample

Statistic	GPS Complete		GPS Incomplete		TOTAL
	Number	Percent	Number	Percent	
Households	2,059	78.9%	549	21.1%	2,608
Persons	3,849	82.7%	807	17.3%	4,656
Travel Days	13,210	83.2%	2,670	16.8%	15,880
Trips	60,900	84.2%	11,336	15.8%	72,236
Average Daily Household Trip Rate	8.62	--	--	--	--
Average Daily Person Trip Rate	4.61	--	4.25	--	4.55
Average Weekday Household Trip Rate	9.46	--	--	--	--
Average Weekday Person Trip Rate	5.06	--	4.64	--	4.99
Average Trip Distance (all days)	6.11 miles	--	6.29 miles	--	6.14 miles
Average Trip Distance (weekdays)	6.21 miles	--	6.48 miles	--	6.25 miles
Average Trip Travel Time (all days)	0:13:07	--	0:13:17	--	0:13:09
Average Trip Travel Time (weekdays)	0:13:05	--	0:13:21	--	0:13:07
Average Daily Travel Time (all days)	01:22:11.1	--	01:19:27.1	--	01:21:44.4
Average Daily Travel Time (weekdays)	01:21:10.5	--	01:19:26.6	--	01:20:53.7

A total of 601 households completed the PR survey, comprising 989 persons, or 1.65 persons per household. This was lower than the number of GPS persons per household (which was 1.88); however, most households that completed the PR survey did so with all members of the household that carried a GPS completing the survey.

There are clear problems in the completion of the PR data. An in-depth analysis of the PR data revealed that about 6 percent of the responses of the mode of travel used appear to be highly questionable, and about 15 percent of the trip purposes identified also appear to be highly questionable. For mode, the most common issue was a trip claimed to be by walking at a speed beyond the capability of a human being. For purpose, the major issues relate to respondents combining two or more trips into one round trip or tour, and providing an incorrect purpose for the combination. As a general conclusion, the PR data are subject to almost all of the common problems found in self-report diaries, even though respondents have a map showing where the GPS says that they travelled and from which they just needed to fill in the details of their travel.

IMPLEMENTATION RECOMMENDATIONS

The primary conclusion to be drawn from this research is that it is feasible to undertake a GPS-only household travel survey, achieving a high standard of representativeness for the sample, while imputing mode and purpose at a sufficiently accurate level to support modeling work. The high level of accuracy attained in this survey for imputing mode and purpose with 96 percent on mode and around 90 percent on activity (other than detailed breakdowns of the “other” category) is far superior to self-report surveys. The richness of the “ground-truthing” of time, location, distance, speed, and route information from this survey surpasses what can be achieved from any other form of survey.

There are improvements that could be made, however, for future GPS-only HTS. The Abt/SRBI Team recommends including in the recruitment script the workplace and school location for every person in the household, as well as the household’s four most frequently visited site locations and names. The team also recommends that a longer period of measurement be used in future surveys. A full week (7 days) of GPS data will enhance the ability to identify work trips, as well as providing much richer data on the variability of travel from day-to-day. In addition, this would allow for a larger sample of weekend data, which may have significant future use in a number of policy areas. Finally, a better method than the PR survey is needed for obtaining ‘ground truth’ for further improvements in software processing; and detailed land use data should be compiled in digital GIS Open Streets Maps format for identification of “other” purposes such eating out, leisure, medical-related, and personal business.

I. Introduction: Overview of the Challenge and Research Approach

For the past decade, Global Positioning System (GPS) devices have been used increasingly as a means to validate household travel surveys. These devices provide measured versus reported travel activities thereby eliminating a variety of problems including under-reporting and misreporting of travel. Therefore, several recent studies are now looking into replacing, rather than supplementing, traditional diary based surveys. In 2009, the Ohio Department of Transportation (ODOT), in cooperation with the Ohio-Kentucky-Indiana Regional Council of Governments (OKI), the Metropolitan Planning Organization (MPO) for Cincinnati, initiated an exclusively GPS Household Travel Survey (HTS) using a personal GPS device to capture all modes of travel. A subsample of follow-up prompted recall surveys was conducted to allow respondents to review their GPS interpreted travel information for verification and to provide additional details not apparent from the GPS data.

Self-reporting of travel information, whether retrieved by mail, Computer-Assisted Telephone Interviewing (CATI), or Web-based formats, has been demonstrated to result in trip underreporting. For instance, recent work by Wolf et al., (2003), Pearson (2004) and others has shown that diary information retrieved through CATI suggest trip under-reporting ranges from 20 to 30 percent. In addition to the failure to report the number of trips correctly, it is known that respondents vary markedly in their ability to provide accurate information on other components of their travel. For instance, the tendency to round travel times to the nearest five, ten or fifteen minutes is well known. Non-motorized travel (particularly walking) is also thought to be poorly recalled compared to motorized travel, although the extent of this discrepancy has not yet been established scientifically. Location information tends to be even more problematic, with people rarely able to provide address information for even commonly visited destinations such as work, school and the local grocery store to the degree of specificity required for geocoding and planning purposes (Stopher, 2004). The situation is even more accentuated when trying to determine the route taken, with few people able to detail the route taken in terms of a sequence of street names.

An additional perceived problem with diary-based approaches, and for that matter any type of survey of this nature, is respondent burden. This burden obviously increases as the level of detail required and the numbers of days of observation increase. While most HTS are one or two day surveys, evidence suggests that extending the survey period for a week or even longer results in greater statistical efficiency and may significantly lower sample size and cost requirements (Richardson et al., 2003). However, in reality the drop-off in reporting after even one day has tended to undermine the utility of this in practice (PSRC, 2006 Household Activity Survey Report).

These issues aside, arguably the most pressing problem faced by *all* surveys is non-response. Starting with recruited households, while there is marked variability dependent on the exact strategies employed, as a rule response rates around 20-30 percent response from a mail-back survey, 40-60 percent from a telephone survey, and 60-75 percent for a face-to-face interview can be anticipated. However, non-response rates are not evenly distributed across the population, with certain groups (teenagers, larger and low-income households, and those who travel more) under-represented in surveys (Stopher and Greaves, 2007). This leads to the potential for significant bias, which can only partially be accounted for in post-survey factoring of survey results.

Recent evidence pointing to the inaccuracies of diary-based and other self-reporting approaches, concerns about respondent burden, and rising non-response necessitate a fundamental change in the way we conduct HTS. With the many recent developments in improving the capabilities and the user friendliness of small, portable GPS devices, the time appeared ripe to test the potential for GPS to replace travel diaries. A multi-day GPS Survey offers strong potential to tackle most, if not all, of the problems with self-reporting approaches. It also adds the capability to obtain multiple days of data from each person, something that is infeasible with self-report methods, especially diaries. This has two distinct advantages over a 1-day survey. First, it provides information on the day-to-day variability in travel, which is of increasing importance as we attempt to reduce both greenhouse gas emissions and the energy demands of day-to-day travel. Second, it enables acceptable levels of statistical accuracy in trip-making to be achieved with a substantially smaller sample size compared to a one-day sample.

GPS-based Household Travel Surveys can be further enhanced by recruiting from address-based samples rather than traditional Random-Digit-Dial (RDD) sampling frames. When all sources of undercoverage in RDD frames (i.e., households with no telephones, those in zero blocks, and cell-phone-only households) are considered, the percentage of US households not covered by RDD frames may be as high as 30-45%. Address-based sampling has the potential to improve the representativeness of HTS samples by including households that cannot be captured by land based phones. This approach also improves the ability to define specific geographic strata. Abt Associates, SRBI's parent company, has conducted extensive research on the migration from RDD sampling to address-based sampling for public policy research (Battaglia et al, 2007) and this effort sought to benefit from these experiences.

II. Objectives of the Research

This study is, in effect, a proof-of-concept study for replacing travel diaries with a multi-day GPS survey. The principle objectives were to collect multiple-day data from a large sample of households, using portable GPS devices, and then to improve existing processing software, so as to provide output data that are comparable in content to the data achieved from conventional diary surveys, and that can support current modeling approaches in the state of Ohio. Specifically, the GPS survey data will be used to update the Ohio-Kentucky-Indiana (OKI) regional travel demand model. A web-based prompted recall survey was sent to a large subsample of households to collect data that were not collected by GPS (primarily mode and purpose). The prompted recall interview was designed to allow for verification of trips from the GPS record, as well as to provide data for use in imputation of mode and purpose variables for the trip file. The effectiveness of this method of verification and imputation needed to be evaluated.

A key overall measure for the GPS-only survey will be the effect that the data collection approach has on travel demand modeling components for both trip-based models and tour-based/activity-based models. While the data needs for the different model types are similar, they have varying levels of susceptibility to the range of potential survey data limitations.

A secondary objective of this ODOT GPS-only HTS is to demonstrate that demographically representative samples of household travel inventories can be collected by GPS-only approaches. The question is: Will rare or traditionally difficult to interview households, such as low-income households, zero-vehicle households, and 4+ person households, participate adequately in a GPS-only travel inventory recording effort? Also, using an address-based sampling method and a GPS-only approach, will cell-phone-only households participate? (Cell phone-only households are primarily young adult households—age 18 to 35, who are traditionally undersampled in self-reported HTS). Finally, what strategies and levels of incentives are needed to secure the participation of these groups?

Finally, a goal of this large-scale GPS-Based HTS was to develop an efficient (low cost) means of deployment of the units to and from widely scattered sample households around the metropolitan region, because the costs of full personal courier delivery and collection are prohibitive. The survey procedure plan was to send out the GPS units and forms packages by Federal Express (at a government rate of approximately $8 per package). The outgoing package contained pre-paid return shipping labels and a return package that can be deposited in any Federal Express or US Postal Service drop box. Household respondents are also given the project 1-800 number to call to arrange a Fed Ex or personal courier pick-up if preferred. Extensive follow-up phone calls and Internet reminders were made to arrange courier pick-ups as needed, as the most difficult logistics challenge presented by GPS-based surveys can be an excessive loss of GPS units.

III. Research and Analysis Description

A. Data Collection Methodology

A.1 Recruitment of Households and Deployment of GPS Units

The ODOT GPS-Based Household Travel Survey was developed using:

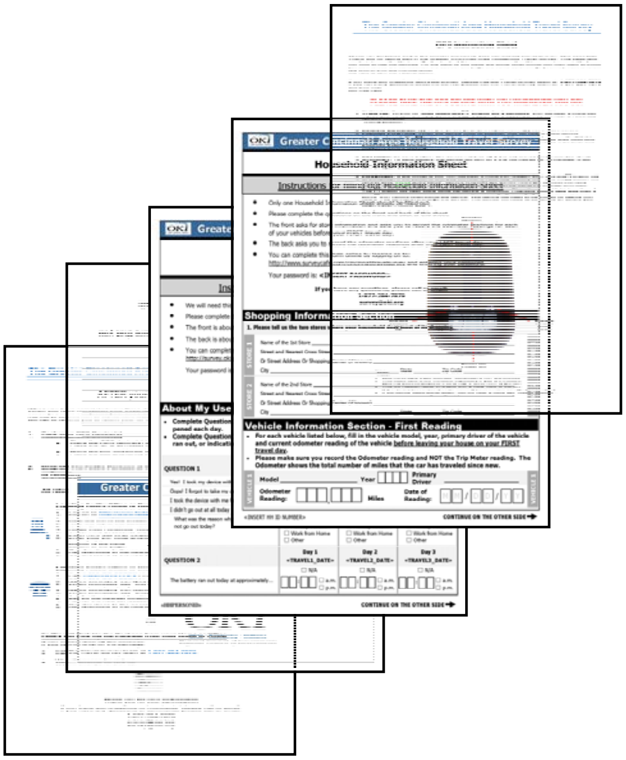
- An address-based sample frame, advance letters, and internet and phone recruiting and forms reporting,
- The requirement that every member of the household over 12 years old provide travel data via a personal GPS unit on a concurrent day, in order for the household to be considered a complete. (4+ person households could have one member missing GPS data),
- A simplified one-day diary for children under age 13 (see Appendix E),
- A one-year long data collection and processing window to ease GPS unit logistics and the implications,
- A follow up prompted recall survey for verification purposes and to develop imputation algorithms for secondary trip characteristics like purpose and mode, and
- Collection of multiple days of travel necessitated partly by GPS unit logistics but at the same time enabled by the lower respondent burden.

A peer-reviewed paper on the pilot survey and results has been separately filed with ODOT and the Transportation Research Board, and is included as Appendix A. For the main survey, an address-based sampling approach was used with addresses within the Cincinnati region randomly selected from the most current U.S. Postal Delivery Sequencing File (DSF), sorted by census block groups. Two geographically assembled groups were oversampled since these groups are important to travel modeling and often are undersampled. These groups are: 1) residential census blocks identified as having access to public transit (a proximity to transit stations or bus stops), and 2) block groups identified in residential areas as near major universities within the region, and therefore, having a higher propensity for student residential housing. Once the sample was designed and selected (see Appendix B: Task 4 Memorandum - Sampling Plan), address matching with land-based phone numbers was conducted. This resulted in a 55% match between addresses and land-based phone numbers over the approximate one-year long data collection period from August 2009 to September 2010. The 45% of households without a match to a land-based phone number were sent advance letters with an internet address for on-line recruitment and a phone number to call for CATI recruitment. The advance letters described the project, its importance, and was signed by the Director of OKI. The households with a matched phone number were also sent the advance letter. If the matched households did not complete the on-line recruitment, then they were called by phone. The recruitment interview consisted of assigning travel days for GPS recording (three consecutive/concurrent weekdays) for each member of the household over 12 years old, and collecting household and person demographic data.

Once recruited, GPS units and instructions, household and person forms, and simplified children's diaries (for those under 12 years old) were shipped via a Federal Express package—scheduled to arrive one to three days before the assigned travel days. The forms, as shown in Appendix D were designed to collect (1) work and school locations for each household member, (2) the household's two most frequent shopping locations, and (3) GPS usage status for each member, each day. Each person assigned a device was asked whether they carried the device all day, whether they forgot the device part of the day, whether the battery died during the day, whether the device was forgotten for the entire day, or whether they did not travel.

A reminder phone call or email was placed the day before the first assigned travel day. The forms and simplified children's diaries could be returned with the GPS units, or the information could be entered online—with a password provided.

Figure 1. Short-Form Materials Sent with GPS Units



The GPS devices used are personal units that can be carried in a pocket or purse, or clipped on a belt or wristband. Thus they record all modes of travel including car, transit, bike, or walk. For the most part, the units recorded three days of travel. Respondents were provided with battery chargers and instructions for use. Respondents were encouraged to charge the units each night.

Figure 2: Project Personal GPS Unit

The device used weighs less than 2 ounces. It has a memory of 8 megabytes, and runs on a cell phone battery. The device contains a vibration sensor, which turns the unit off if no vibration is sensed for 15 minutes, but turns the device back on immediately when new vibration is sensed. This serves to save power substantially, so that the current battery life could be on the order of 3 to 4 days if energy were conserved. The device has a very sensitive GPS chipset – capable of detecting GPS signals inside buildings (up to 2 floors below the roof), in buses, trains, and cars even when carried in a pocket or backpack, etc. The device can be recharged from a standard wall socket. It has both flashing lights and voice messages to inform the user of its status. When turned on, the device emits a green flash and states “satellites positioning.” When position is acquired, the device says “satellites fixed” and a red light flashes in addition to the green light. If the battery is close to running out of power, the device states “battery low.” In addition, if signal is lost during travel, the device will again say “satellites positioning” and will also say “satellites fixed” as soon as position is regained. This device is specially manufactured to specifications developed by PlanTrans and is not generally available commercially.

As stated above, to test economical means of shipping GPS units back to the project office within the Cincinnati area, respondent households were provided with pre-paid packaging to return the GPS units and forms via either Federal Express or U.S Postal Express. A series of follow-up phone calls were initiated when the GPS units and forms were not returned within a few days. The option of courier pickup was offered.

Once the units were received by Abt SRBI, data were downloaded and sent with the recruitment and entered personal/household travel forms data via ftp site to PlanTrans for processing. Each data entry (GPS file, forms data, and household recruitment information) had an associated household and person ID.

A. 2. PROMPTED RECALL INTERVIEW

For verification purposes as well as to provide data to improve the artificial intelligence software being developed by PlanTrans for mode and purpose identification, a web-based Prompted Recall (PR) survey was implemented. Abt SRBI pre-geocoded each household’s home address. Work and school addresses for all household members, and the addresses of the household’s two most frequent shopping locations were geocoded using information from the personal/household travel forms returned with the GPS units. This allowed for initial and quick representation of the respondents’ travel in Google Map format for the Prompted Recall interview. The most up-to-date GDT files for the OKI region (including the state of Ohio) were purchased from ESRI and were utilized by Abt SRBI for preliminary geocoding. All final coordinates provided in the trip files are as recorded by GPS.

The prompted recall survey displayed the respondent’s travel via their computer’s web browser on a map in a common web interface (Google Map), and asked a series of questions regarding that travel, such as mode and trip purpose. The prompted recall responses are then used to improve software to impute trip mode, purpose and other missing data for the completed surveys.

DESIGN PRINCIPLES FOR THE PROMPTED RECALL

The GPS devices record all location data. The only errors (provided that all downloading and processing is done correctly) that can occur in the location data are:

1. Cold start problem – the device is delayed in fixing position until after a trip has actually started. This is fixed for all except the first trip on the first day by the data processing software, and the first trip on the first day is fixed by the manual map editing that precedes setting up the internet address for each respondent for the PR survey.
2. Lost signal – this is only a problem if it occurs near the end of a trip and results in a premature destination recording. This should normally be fixed during the manual map editing process prior to setting up the PR survey.

The other things that could be wrong with the GPS record are if the person did not carry the device with them for the entire day, or if the battery ran out. In these cases, if the person marked on their form that they forgot the device for part of the day or that the battery ran out, then that day is excluded from sampling for the prompted recall survey. Apart from these issues, the start and end times of travel on the GPS record must generally be correct, and, provided that the travel is also along the street or rail networks, a trip must have taken place.

This leads to the assumption that the only things that may need to be corrected with the GPS record by prompted recall respondents are:

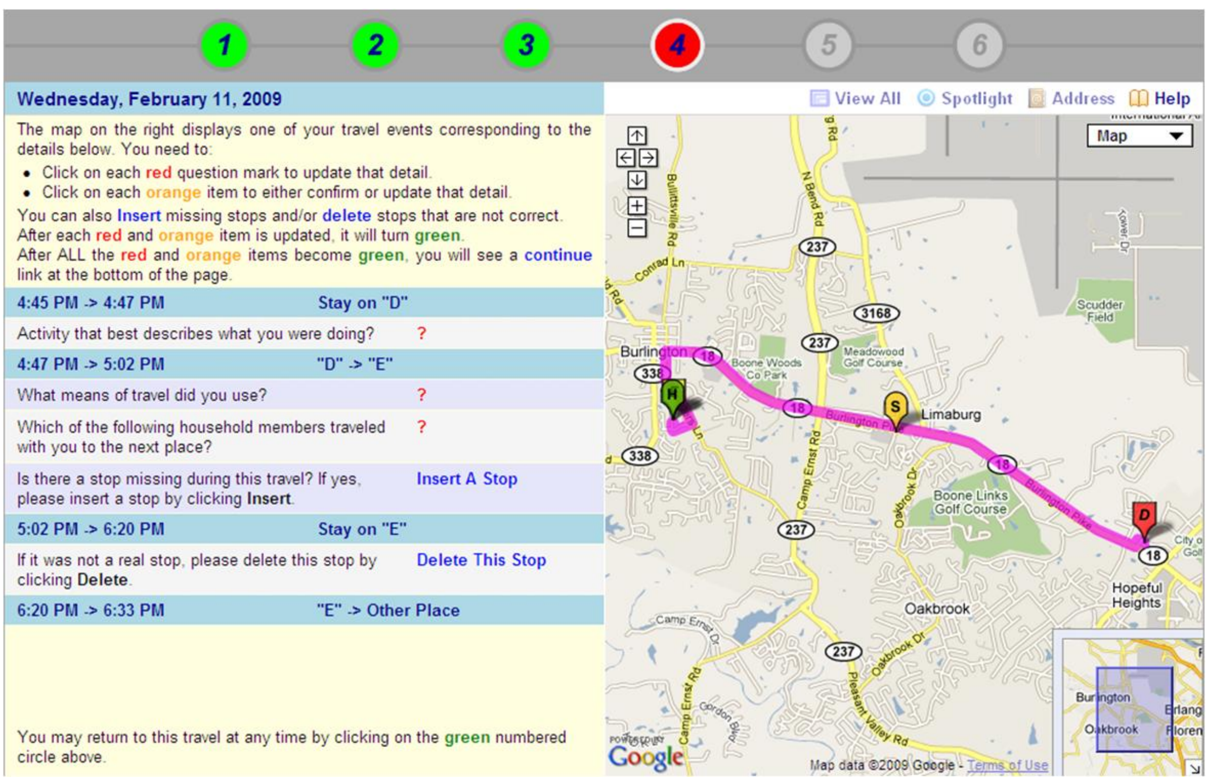
1. GPS processing has missed identifying a brief stop (usually one that lasted less than 120 seconds). In this case, the respondent is allowed to insert one or more stops, thereby splitting one trip into two or more trips.
2. GPS processing has identified as a stop what was actually just a traffic stop or other delay that lasted at least 120 seconds. In this case, the respondent is allowed to delete one or more stops, thereby linking together two or more travel episodes.

Based on these assumptions, questions regarding confirmation of the start and end times of each trip were not asked in the main PR Survey, although they were included during the pilot. In response to the first issue, to allow for the deletion of a stop, two consecutive trips are displayed to the PR respondent at a time. Because the respondent can see and edit both trips, he has the option of deleting the middle stop of the travel, thereby joining together the first and second travel events into a single trip.

To address the second issue, a question is included to ask whether the person traveled from the origin to the destination without stopping. If they respond no, then an edit box appears to allow them to insert the time they stopped and the time they started to travel again. If the respondent recalls reasonably accurately the time they stopped for each added stop, then the GPS record will allow identifying where the additional stop was with reasonable accuracy. Following completion of all of the other travel details (mode, companions and the nature of the stops), the respondent will click on continue, which will then display the next two trips. This continues in pairwise fashion to the end of the day.

A closing PR question asked whether there is any travel or any other stops that the respondent remembers making on that day that was not recorded on the survey. If so, they are asked to record stops and approximate times. The Prompted Recall survey is then complete. Figure 3 below provides an example page from the Prompted Recall Interview.

Figure 3: Example of Prompted Recall Web Interview Format



B. GPS Processing and Analysis

This section of the report covers several aspects of the Greater Cincinnati Area Household Travel Survey (GCAHTS) of 2010. Initially, the report describes the G-TO-MAP software that has been used and upgraded to process the data from the GPS devices. Second, the report describes the processes used to collect GPS data and to prepare the data for downloading. Third, the report describes the results of the processing of the data and also discusses a comparison of the GPS data with the Prompted Recall Survey results.

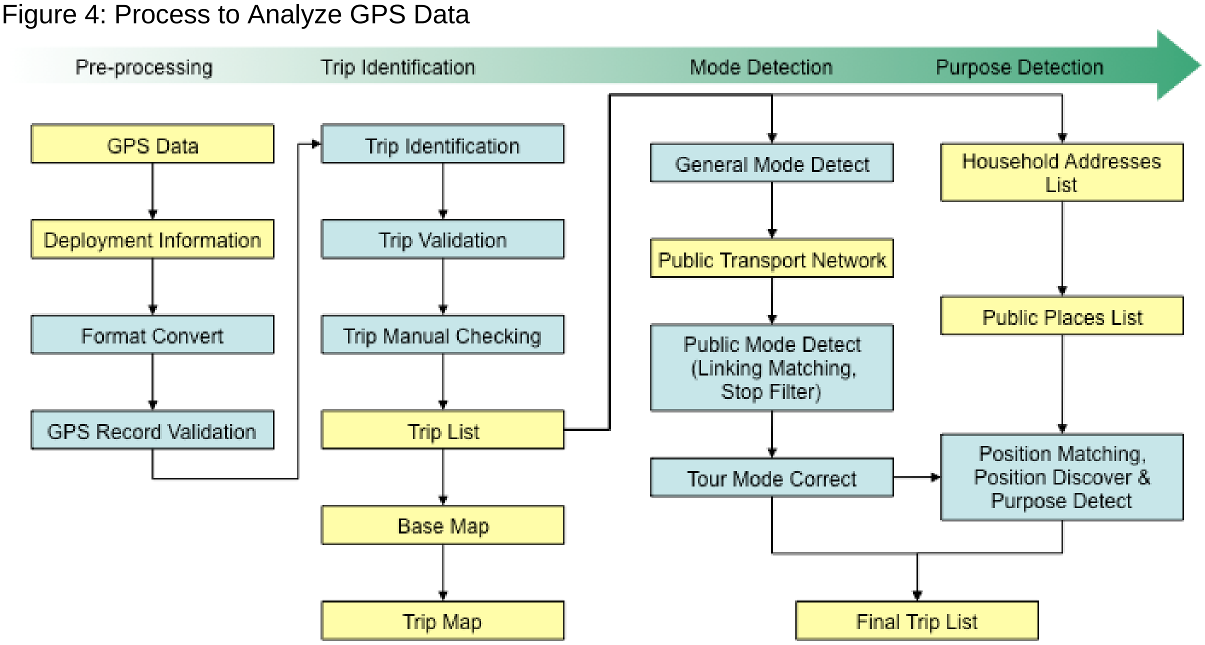
B.1 THE GO-TO-MAP SOFTWARE

The software developed by PlanTrans/ITLS is known as G-TO-MAP (GPS Trips, Occupancy, Mode and Purpose). It is written using a combination of the Python and GISDK development platforms, and operates on the TransCAD® software platform. TransCAD is used for the purposes of mapping and editing, and as a means to check for the accurate representation of travel. TransCAD manages the GIS layers needed in the processing, as well as providing a display of the resulting travel records. In addition, the latest version of G-TO-MAP permits output of maps to GoogleEarth, which has been found to be very helpful because of the ability to identify what exists in the immediate vicinity of the end of a GPS trip. G-TO-MAP utilizes the following data from the GPS-PPAL (GPS Personal Passive Activity Logger):

1. Date
2. Time
3. Position (latitude, longitude)
4. Speed (km/h)
5. Heading
6. Horizontal Dilution of Precision (HDOP)
7. Number of satellites in view

The steps involved in getting GPS data from its raw format to a format suitable for analysis is illustrated in Figure 4 (taken from Stopher, Clifford, Zhang and Fitzgerald (2008)).

Figure 4: Process to Analyze GPS Data



The whole process combines a number of automated processes with a few manual ones (described in more detail below). The strength of this is that the manual processes are applied early in the processing during the Trip Identification stage. This helps to filter out possible erroneous trips that may have been overlooked by the software, before imputation methods are applied. The weakness of this is that the manual process requires trained staff to inspect each day of travel. However, with the available tools, this process is now less laborious than before.

There are a few published papers on other imputation processes, which like PlanTrans/ITLS's papers, provide only sketchy details about the actual process (so that the authors retain IP over their processes) and so comparison to others is quite difficult. In terms of the imputation method, PlanTrans/ITLS uses a number of complex rules or heuristics combined with a probability matrix and GIS layers, similar to those reported by Bohte and Maat (2009), Chung and Shalaby (2005) and Tsui and Shalaby (2006). Tsui and Shalaby (2006) reported using fuzzy logic for imputation in a test setting and compared GPS/GIS imputation similar to PlanTrans/ITLS's with GPS/fuzzy logic imputation and showed little difference in imputation results between the two methods. More recently, Moiseeva, Jessurun and Timmermans (2010) reported on using Artificial Intelligence for mode and purpose imputation, but this method is still purely at a research stage.

The data processing and imputation process used in this study works as follows:

First, it must be remembered that the GPS device continues to record for at least 3 minutes after a person stops moving. This is necessary in order to not lose other valuable information and also to prevent the potential loss of position every time that a traffic stop occurs. Second, it is necessary to have GIS layers for the street network, the bus routes, (and train, when this is a potential mode), bus stops (and train stations), and, when available, land use by parcel. Third, to assist in purpose identification, we collect data on the workplace addresses of all household members, the addresses of educational establishments attended by all members of the household, and addresses of the two most frequently-used grocery stores. These addresses are geocoded at the outset of the analysis process.

B.2 TRIP IDENTIFICATION

The first step in the processing is to find locations where there is no movement recorded for at least 120 seconds. Because the position is not static, even when the device is stationary, it is not a straightforward procedure to identify lack of movement. However, in common with almost all processing software, a 120-second rule is used as the preliminary definition of a stop. Secondarily, the software looks for shorter stops with movement then continuing in the opposite direction within a matter of seconds. This will also usually identify a stop, such as a pick up or drop off, mailing a letter, etc. The software then looks for "clouds" of points usually generated by a stationary device, by looking at the heading (direction) of each point, speed, and total time and distance between the points. Such "clouds" of points are deleted and a determination made as to whether the cloud may have represented a stop. The software also compares traces between members of the same household and picks up any traces where it appears that two or more people have travelled together for part or all of a trip. This is used for two purposes. On the one hand, it is used to flag to the trained editors that two or more people from the household may have travelled together so that any editing changes are made consistently for each household member. Second, this provides information on the possible occupancy of a household vehicle and also helps to identify pick-ups and drop-offs that may otherwise be hard to find. The processing software also identifies, where possible, a change in average speed as a trip end, so that the trips are actually identified as trip segments (e.g., a walk to the bus stop is one trip segment, and travel on the bus is another trip segment).

At the end of this process, the identified trips are converted to traces on a TransCAD map or a Google Earth base, and are then visually examined by trained editors. In addition, an Excel file is produced summarizing the information on each identified trip (start time and location, end time and location, duration of trip, average speed, distance covered, etc.). The maps and Excel files are used to check that the trip identification appears reasonable. Warning messages are provided in the Excel table for situations where a trip appears to have ended in one location and the next trip starts at a different location. Other anomalies are also flagged by warning messages. The editors then make any necessary corrections in the Excel file and this information is passed back to the software.

IMPROVEMENTS TO TRIP IDENTIFICATION MADE DURING THE GCAHTS

During the GCAHTS and using information resulting from the Prompted Recall Survey, as well as more in-depth analysis of the results of the software, a few improvements were made to the Trip Identification process. First, a capability was introduced into the software to deal with the "clouds" of data points that occur when the person carrying the device is more or less stationary. Previously, these GPS point clouds (which arise because the GPS is continuously solving its position, and the position thereby moves within a relatively small area) had to be identified and edited manually. In place of that, the ability to locate such clouds and to remove and replace them with a single point that corresponds to the estimated end of one trip and beginning of the next was introduced into the software. This has resulted in some decrease in the effort required to map edit the data and has allowed some improvement to the location of the end of a trip.

A second improvement was to introduce a capability to map the resulting trips on Google Earth, instead of a TransCAD GIS map. This provides some improvement in the identification of actual stops, because Google Earth shows the actual buildings on the ground and may provide enhanced information around a potential trip end. It also allows more rigorous removal of "spurious traces" which are traces that occasionally occur from a stationary GPS device and usually run in straight lines. Because it can be seen more clearly that there is no transport facility available for such "spurious" traces, they are more readily eliminated in the map editing process.

A third improvement was to export, into the trip list that is used for map editing, information about any other household members that appeared to share the same trip or part of a trip. This was done to prevent inconsistent map editing, where two or more individuals in the same household apparently travelled together. In some cases, prior to this improvement, it was found that one of the companion trips had been deleted, while the other had not. The knowledge that two or more persons had travelled together provided a further check on the map editing process.

A fourth improvement was to regenerate the maps from the edited trip list, after map editing. This provides a means to double check that the map editing has been effective and is complete.

B.3 MODE OF TRAVEL

Using the edited traces, the next step is to identify the mode of travel. This is done by determining the speeds and acceleration/deceleration of the travel and also, in certain cases, by checking with the underlying GIS layers that are used in the processing. Speed, as measured by a Doppler process in the GPS-PPAL, is essential to accurate assessment of the mode. Walk is identified first, because this is most easily identified due to low overall speeds, low rates of acceleration and deceleration, and the fact that the trip does not necessarily stay on the road network. Second, if available in the metropolitan area under study, rail trips are identified next, because these trips are aligned with the rail lines, or, if the rail system is partly or entirely underground, because trips disappear at station locations and then reappear at station locations, or disappear after travelling along a rail alignment at a point where a tunnel begins, and reappear where the tunnel ends.

Again, there is an important issue relating to the GPS devices. Many GPS devices are slow to find position again after losing signal in a tunnel. At this time, the BTT-08M devices used in this project regain position within 1 or 2 seconds of emerging from a tunnel or other lost signal situation. This is of considerable importance for a tunnel situation, like IR 71 in downtown Cincinnati, because otherwise there is uncertainty as to where the survey subject actually got out of the underground system. Also, if there is significant delay in finding position again, the trip may end before the position is found and there will be no information on where the trip ended.

Next, trips by bus are identified. This is done by examining the speed of the trips, the number of stops that occur, the location of stops, and the location of the trip itself, the last of which must be entirely along bus routes in the GIS layer. The trip also starts and ends at a bus stop location, and is preceded and followed by a trip by a different mode (usually walk).

The remaining trips are bicycle and auto trips. All of the documented software procedures have noted difficulties in reliably separating bicycle and car, because bicycles travelling downhill can accelerate as fast as a car and may reach speeds comparable to a car, and cars in stop and go traffic may look like bicycles in terms of speed and acceleration/deceleration. The first step is to exclude bicycle as a mode if the household owns no bicycles. For households that own bicycles, the identification procedure uses speed, acceleration and deceleration, but averages these over the entire trip to help isolate real bicycle trips. The difficulty, however, in identifying bicycle trips remains one of the weaknesses of the software processing. In the future, a question on the frequency of use of a bicycle for those households that own bicycles is also expected to be helpful in resolving this issue.

IMPROVEMENTS TO MODE IDENTIFICATION MADE DURING THE GCAHTS

In the past, and as reported in the interim report on the Pilot Survey for GCAHTS, bus has not been identified well by the software. Part of the problem for this arises when there are incomplete GIS layers for bus routes, which has remained a problem for parts of the GCAHTS area. However, this has not been the only problem affecting identification of bus routes. Initially, the software used the fact that a trip began at or close to a bus stop and ended at or close to a bus stop and that the route was predominantly along a bus route as the primary identification of the mode being bus. However, it was found that this still resulted in some car trips being identified as bus and too many bus trips being identified as car. As a result, a modification was made in which the number of stops that coincide with bus stop locations are used to detect a bus trip.

However, in subsequent analysis, it was found that the stop search (which has to be circular in a GIS) was picking up bus stops on the wrong side of the road, and sometimes even on cross roads at intersections. So, two further changes have been made in this process. First, the search distance has been reduced from 45 meters (about 50 yards) to 15 meters (about 16 yards). Second, the search has been cut off on the left side of the path trajectory, so that only bus stops on the same side of the road as the traveler is moving can be picked up as qualifying bus stops.

A second and potentially more significant change has also been implemented in the final version of the software. In the preliminary results, too many bus trips and too many bicycle trips were being identified, where most such trips were actually car trips. An in-depth analysis of the GPS travel records showed that many of these bus and bicycle trips were appearing in the middle of a tour, where the rest of the tour took place either by walk or car. As a result, a module was introduced into the processing that links trips into tours and then examines the sequence of modes that have been identified for the tour. In the event that a single trip within a tour is identified as bus or as bicycle, it is usually replaced by either walk or car, according to the modes of the other trips in the tour. The actual rules employed are shown in Table 1.

Table 1: Rules for Replacing Mode in Tours

Tour Type	Mode Sequence	Corrected Mode Sequence
2 Trip Tour	Walk-Bicycle	Walk-Walk
	Bicycle-Walk	Walk-Walk
	Bicycle-Car	Car-Car
	Car-Bicycle	Car-Car
3+ Trips	Walk-Bicycle-Walk	Walk-Walk-Walk
	Car-Bicycle-Car	Car-Car-Car
	Bicycle-Car-Car*	Car-Car-Car
	Bicycle-Walk-Walk*	Walk-Walk-Walk

* Bicycle must be first in these sequences.

Another added improvement was the ability to identify school bus trips. This has been done by adding a module to the programming that specifically tests for a school bus, using several characteristics.

The 85th percentile acceleration and deceleration rates are also used to distinguish between bus, bicycle, and car. The rates are used by specifying in the software a maximum rate that is achievable by each of bus and bicycle. If the 85th percentile acceleration/deceleration rate is higher than the maximum for a bicycle or a bus, then the trip is identified as being by car. Similarly, if it is above the maximum rate for a bicycle, but below the maximum for a bus, and other characteristics suggest that this may be a bus trip, then it is assigned to bus.

Finally, the algorithm that uses the bus route network to detect a bus trip has been fine-tuned to improve detection of bus trips. This was found to be necessary because of signal inaccuracy at times along the route, which was having the effect of identifying the trace as not being along a bus route for a sufficient proportion of time.

B.4 TRIP PURPOSE

The final processing step is to identify the trip purpose. Purpose is identified mainly from the use of the collected addresses. Home is, of course, known; thus, all trips with one end at home can be so identified. This permits a clear distinction between home-based and non-home-based trips. Similarly, for those persons with a fixed work address, trips to and from work can be identified and classified as to purpose. This is also true for trips to and from school. Trips to and from a grocery store, if made to one of the two addresses provided, are also readily identified. All other trip ends are classified as "other". The software is able to identify home-based work trips, home-based school trips, some home-based shopping trips, non-home-based work trips, non-home-based school trips, some non-home-based shopping trips, and home-based other and non-home-based other trips. Additional purposes of 'Serve Passenger' and 'Mode Change' are also identified. Serve passenger is identified by finding locations where there is a change of occupancy of the vehicle. It will be effective only for multi-occupant trips from members of the same household. Mode change is identified from a sustained change in speed and also routing that indicates, for example, a change from walk to riding in a public transport vehicle and vice versa, entry into or exit from an underground or above-ground station, etc.

IMPROVEMENTS TO PURPOSE IDENTIFICATION MADE DURING THE GCAHTS

The capability to identify passengers from the same household, and to thereby identify a serve passenger purpose when the vehicle occupancy changes, was a capability that was added early in the process in GCAHTS. Along with this was also the identification of change travel mode as a purpose. These two purposes provided some significant improvement to the entire processing. By importing the mode identification results into purpose identification, the change travel mode activity could be identified correctly and remove some of the "other" trip purposes. Similarly, by building a "travel companion" database, serve passenger trips could be identified and this purpose also taken out of "other" and the subsequent purposes of the trip were able to be defined more correctly.

In the earlier version of our software, if a person had a geocoded workplace then the software checked to see if any trip made by that respondent originated or terminated within 200 meters (about 650 feet) of the workplace geocode. If so, the activity at that trip end was designated work. If no trips originated or terminated within that distance from the workplace geocode, a work trip end was not identified. In subsequent analysis, we found that this distance limitation was not sufficient to allow the workplace always to be picked up correctly, especially if the respondent might have left the GPS device in a parked car, or the GPS device did not record the walk from the car. If a respondent did not have a geocoded workplace, but was still recorded as a worker, then the software checked the length of time spent at work and also whether or not the respondent visited the same place on more than one day. The latter logic has been extended to include those with geocoded workplaces.

Further analysis of both the PR data and the 2009 National Household Travel Survey revealed that only school and work trips normally had an activity duration in excess of 4 hours (a very small number of work-related and school-related trips had a duration in excess of 4 hours, but less than 1 percent of any other purpose had a duration of this long). Based on this, a new rule has been implemented in which, if any activity time is in excess of 4 hours and the respondent is a worker (full-time, part-time, or volunteer), then the activity is defined as work; and a respondent who is a student (full-time or part-time) and has an activity of 4 hours or longer duration, this is defined as a school activity. This will misclassify a very small number of activities, but it is felt to be worthwhile to identify many more work and school activities correctly.

During this same analysis, it was noted that a number of respondents to the Prompted Recall Survey had designated a pick up or drop off activity at school as a trip with a school purpose. Because of this, it was also defined that any activity at a school that lasted less than 15 minutes before noon, or 30 minutes after noon would be classified as a pick-up/drop-off activity. From an analysis of the Prompted Recall data and comparison to GPS records, it was also found that family members traveling together often did not provide multiple GPS traces for the segment of travel made together with other household members. As a result, it has proven to be quite difficult to find where occupancy changes on multi-occupant trips, to identify a pick-up or drop-off activity.

Finally, in the earlier version of the purpose software, any multi-occupant travel not otherwise identified with a purpose was defined as social-recreational travel. This is actually not sound reasoning and this has been dropped from the present version of the software.

B.5. GPS Data Collection and Processing

As described elsewhere, GPS devices (PPALs) were distributed to all persons in sampled households over the age of 12 years. Each person provided with a PPAL was asked to carry it with them everywhere they went for a period of three days, beginning the day after the PPAL was received. Following the three-day recording period, the PPALs were to be returned by the household. In some instances household held onto their PPALs for much longer than intended and also sometimes continued to use the PPAL while they travelled, so that some people have provided more than three days of travel data.

Once the PPALs were returned to the SRBI offices, the data were downloaded and placed on an ftp site at the University of Sydney, where they were retrieved and run through the G-TO-MAP software. However, prior to software processing, it was also necessary that a metadata file was uploaded to the ftp site providing such items as the geocodes for the home, workplaces, schools, and shopping locations provided by the respondents in their self-administered survey forms. Other data required for the processing, including education levels of respondents and other family members, and bicycle ownership information were also included in the metadata file. All of the geocoding of addresses had to be completed, therefore, before processing could commence.

Once the GPS files and metadata were received, the data processing commenced. This involved initial software runs to convert the entire GPS trace for each household member into discrete trips by day. Checks were made to determine if all members of the household had reported travel for at least one common day. The GPS data were then map edited and the map-edited results were used to generate prompted recall survey data. For each household member, a selection was then made of one of the days of recording for the Prompted Recall survey. Once the data from a household were completed, URLs were generated for each household member and sent to SRBI in Ohio for transmission to the household by email. While prompted recall survey data were generated for all households received by PlanTrans/ITLS, only those households that provided email addresses to SRBI received URLs for the Prompted Recall Survey.

By completing the Prompted Recall Survey, the data about the trips shown on each sampled respondent day were recorded on the University of Sydney server. These data were then compiled and used for comparison with the results of further processing of the GPS data by PlanTrans/ITLS. The data were used to help identify shortcomings and errors in the output of the software. However, as is discussed subsequently, it also became apparent that respondents often provided incorrect information in the Prompted Recall Survey, similar to errors often noted in diaries, when these are compared to GPS results. These errors included providing a mode identification that was improbable or impossible, and also misidentifying trip purposes, partly because of a lack of understanding. In the pilot survey, it was found that a significant proportion of respondent errors arose from respondents defining a trip as a round trip, and attempting to combine trips that were separated by an activity at a place. This type of error still occurred in the Prompted Recall Survey for the main data collection, even though efforts were made to prevent respondents from being able to do so.

C. Quality Control and Reporting

Quality control for any data collection project includes well-designed sampling plans, survey instruments and materials, as well as carefully executed data collection operations. The elements of the project management plan for the Cincinnati GPS-Only HTS that were considered key to quality assurance included the following:

- The effective oversight involvement of the Technical/Liaison Panel to assure survey outcomes met modeling and clients' needs.
- Monitoring the many areas of design where biases and errors can creep in, including establishing detailed census-based sampling targets and continuous monitoring systems (see Appendices B and D).
- Establishing and maintaining a detailed project work schedule.
- Developing and maintaining detailed data collection formats and protocols for advance letters, the CATI and web-based recruitment interviews, and instructions for deployment and return of GPS units.
- Conducting a full pilot to evaluate whether survey design and data collection procedures are adequate for producing quality data outcomes.
- Monitoring survey labor and cost expenditures so that overruns in one area of the survey did not affect efforts and outcomes in other areas.
- Effective selection, training, and debriefing of recruitment phone interviewers, as well as GPS deployment technicians and GIS geocoding interns located in the Abt SRBI Erlanger, KY office (within the region). Their instruction included local geographic training.
- Project management staff periodic monitoring of recruitment interviews, in addition to continuous phone room supervisor monitoring. Feedback in the form of supplemental training.
- Electronic tracking of recruitment interviewers' performance – dialing statistics, completed interviews, refusals, non-contacts, average interviewer lengths, and asset management systems to track the deployment and return of GPS units.
- Implementing an appropriate public information effort and follow-up on respondent phone calls or emails to the survey help website or the survey 1-800 number provided.
- Establishing measures to protect respondents' privacy rights and to assure confidentially of survey data.
- Secure measures for downloading of GPS data and integration of this trip data with other household and person information collected during the recruitment by Internet or phone, or via the forms returned with the GPS units.

C.1 Specific HTS Quality Issues Addressed

Beyond these design and management elements, the project quality control plan specifically addressed and planned to correct for the most common errors and biases found in recent travel surveys conducted across the USA. These are:

1. Non-response bias in the form of underrepresentation of certain, often rare population groups such as 4+ person households, lower income and zero vehicle households, transit users, ethnic populations, etc.
2. Overrepresentation of certain populations that more readily cooperate with surveys such as retired households
3. Item non-response bias such as refusal to answer household income, employment, or other demographic information
4. Underreporting of trips, in this case not complying with GPS use procedures
5. Missing trip segments and links
6. Inconsistent reporting of trips where trip (tour) sequencing does not make sense
7. Inappropriate imputation of data

8. Data record and structure inadequacies
9. Failure to meet established weekly and monthly data collection targets

Five well developed work programs were necessary to assure that these quality control issues were addressed and corrected as data collection progressed. The programs are:

- *Continuous Data Flow Tracking System*
- *Automated Data Processing and Data Checking Systems*
- *Interim Reporting and Review System*
- *Corrective Actions Using Non-Response Design Interviewing Techniques*
- *Agreement on the Definition of a Completed Household.*

These five systems are briefly described below.

CONTINUOUS DATA FLOW TRACKING SYSTEM

A sampling plan (Appendix B) delineated monthly quotas for recruitment of households, travel day assignments, GPS household retrievals, and prompted recall follow-ups. This sampling plan, developed by Cambridge Systematics, was considered essential to quality control monitoring.

Quality control required that each household sample element be individually tracked through this process to completion or to final disposition of their status. This required Abt SRBI's electronic *Continuous Data Flow Tracking System* for travel surveys*,* customized to the needs of the Cincinnati GPS-Based Survey. This electronic sample management system provided the up-to-date status of each household sample element through approximately 15 steps of the survey process. Particularly important was tracking and reporting of the progress of households sharing the same specific travel days. The system generated continuous information to assure that each household received appropriate attention and that remedial action could be taken as needed. Timely contact increased response rates. Abt SRBI expended considerable time on developing customized sample tracking systems as the study progressed, so that continuously accessible and summary status reports (by household and person) could be generated from multiple sources (see Appendix F). Sources included sample data, web-based and CATI-based recruitment interviews and form input data, data downloads from GPS units, PR interview invitations and responses, and working out a process to determine the status of household completes.

Sample Monitoring: Throughout the data collection period, bi-weekly status tallies were provided to the Technical/Liaison Panel. The tallies tracked progress towards sampling targets by data cells as established by the Sampling Plan (Appendix B). Tracking included the number and percent of recruited and completed households by designated geographic sectors and by breakdowns of demographic variables of interest to travel, such as household size, number of workers, number of vehicles, and life cycle (households with and without children, students, and retirees), in addition to phone number matched vs. unmatched households. Within these tallies, sample demographic percentages were continually compared with available Public Use Microdata Samples *(*PUMS*)* data breakdowns as data collection progressed.

The Continuous Data Flow Tracking System included asset management software tracking of each GPS unit so its status and whereabouts were known and linked with the appropriate household at all times.

AUTOMATED DATA CHECKING AND DATA PROCESSING SYSTEMS

Abt SRBI's Computer-Assisted-Telephone-Interviewing (CATI) program and Resource Systems Group's Web-based interviewing program for recruitment interviews both had extensive in-system data checking capabilities to ensure such things as that the number of household members reported matched the reported person information. In-CATI checks and automated data-entry kept ranges and responses consistent and non-repetitive.

Automated Data Checks that have been developed for travel surveys by Abt SRBI for Household, Person, and Vehicles files were customized for the Cincinnati GPS-Based Survey**.**

INTERIM REPORTING AND REVIEW SYSTEM

A full pilot and evaluation report (see Appendix A), bi-weekly sample monitoring tallies (see example given in Appendix F) and quarterly interim reports as well as an interim dataset and presentation presented to the Panel in April of 2010 documented progress in meeting sampling goals and data requirements. (See Appendix G for April 27, 2010 Interim Report Presentation). This allowed for consideration of corrective measures (incentives, targeted sample, etc.) as the data collection progressed.

CORRECTIVE ACTIONS USING NON-RESPONSE DESIGN INTERVIEWING TECHNIQUES

To address non-response among hard to reach or rare populations, Abt SRBI employed a successful innovation to traditional household travel survey sample designs. This innovation is based on ideas on survey management developed by Heeringa and Groves, University of Michigan Institute for Survey Research (2004). Their approach is referred to as "responsive design". Modified approaches such as the use of differential incentives and oversampling of targeted low-income households (based on address-based sampling and census block data) were introduced as the data collection progressed, to ensure that rare populations were completed and that the resulting sample closely matched census PUMS data on key variables of interest for modeling. Throughout data collection, real-time sample monitoring tracked filling of data cells according to census/sampling data. When disproportionate recruiting or participation (retrieval) was identified within any of the targeted sampling data cells (documented by the bi-weekly sampling status tallies), the following responsive interviewing techniques were initiated with the Technical Panel's approval:

- Recruitment sample targets were adjusted based on the actual retrieval rates for different data cells;
- Full non-response, refusal conversions were attempted--with re-assignment of travel days for all households recruited in rare population data cells, when they did not comply with the GPS task;
- Differential incentives of $20 were introduced for underrepresented households, if all members of the household completed GPS recording on a concurrent day;

However, throughout the main survey, funds for differential incentives were only available for low-income households (under $25,000) and households with zero autos, and as the study proceeded, households recruited from the address-based sample unmatched with a phone number. The maximum incentive amount was $25 per completed household.

AGREEMENT ON THE DEFINITION OF A COMPLETED HOUSEHOLD

Agreement on the definition of a "completed household" was important to final quality control. This was necessary so that households with significant missing or inconsistent data, or households not meeting sampling goals, could be corrected or replaced as the data collection progressed. This avoided discovering at the end that the data collection effort had not met modeling goals.

Criteria for determining what was to be considered a "completed household" for the Cincinnati GPS-Based HTS included:

- Tolerance for missing demographic information such as age and income below predetermined levels. If the variable was a sample control (geographic area, household size, number of vehicles), zero missing data was allowed; for other variables such as age, 3% to 5% was considered tolerable; income needed to be reported for at least 90% of the sample.
- Home, work, school, or trip locations were captured as part of the recruitment and forms returned with GPS units, for verification with GPS recorded data and for use in Prompted Recall mapping. Abt SRBI was responsible for geocoding these primary locations. It was anticipated that 100% of home addresses would be geocoded to x,y coordinates and 95% of school addresses to x,y coordinates. Likewise, 90% of work addresses (where a specific address was an appropriate response) were expected to be captured to x,y coordinates.
- If a household had 4+or more household members, the household could be considered a "complete", if only one household member's GPS-based travel inventory was missing.
- While not all persons or households travelled on any given day, when a household or a majority of members reported "no travel" for their assigned travel days, the entire household record was reviewed by PlanTrans, along with the reasons given on returned forms for no travel.

The definition of a “completed household” is a particularly complex issue for GPS-only based HTS as is documented in the Results section, since multi-day/concurrent recording are expected among all household members over 12 years old.

C.2 ISSUES AND CHALLENGES IDENTIFIED DURING THE DATA COLLECTION PERIOD

In May of 2010, and as a follow-up to the April 27, 2010 interim report (see Appendix G) and submission of draft interim data files, a comprehensive review of the GPS-only HTS progress was conducted by the Technical/Liaison Panel and ODOT, in conjunction with Abt SRBI and PlanTrans. Issues to be resolved were identified as follows:

1. Definitions of a GPS HH Complete and a PR Complete
2. Additional Documentation of Completes to be Provided in the Bi-Weekly Tallies
3. Problem of GPS Unit Loss and Its Implications
4. Schedule for Completes –Meeting Goals
5. Content of Draft Interim and Preliminary Data Files
6. Under Recruiting and/or Retrieval of Difficult to Reach Populations

RESOLUTIONS WERE AS FOLLOWS:

1. *The definition of a GPS Household complete, as agreed upon by the Panel,* is all members in a household over 12 years old (given a GPS unit), completing 1 concurrent day of full GPS recording. (If a household member did not travel on a day when the other(s) did fully record, it counts as a complete). GPS HH completes include households where 4+ persons were assigned a GPS unit and a single household member failed to record complete travel on a concurrent day.

The definition of a PR complete is a completed PR Survey from any member who completed a full day of travel, regardless of whether the member belongs to a GPS HH complete. A PR Survey complete from any member can be used for verification and imputation purposes.

*PlanTrans rationale for including persons in the PR Survey, irrespective of whether or not a household is a GPS complete was: “*There is a problem that we have noted from our other studies with the GPS device status. We have instances both in Ohio and in our other data sets where a person claims to have taken the GPS device with them all day and there were no data on the device, and other cases where they said they did not travel at all on a day, but we have GPS trips recorded. We are not sure what we should do in these cases. We have speculated that sometimes a person will mark that they have taken the GPS with them all day even though they did not leave home, simply because they know they didn’t forget to take it with them.”

2. *Added documentation to progress tallies.* Entries were added to the electronic tallies to help the Technical/Liaison Panel understand how many surveyed households were being completed.

(a) The number of Abt SRBI households sent in metafiles to PlanTrans that Abt SRBI estimated to be GPS HH Completes (all members assigned GPS units appeared to have one concurrent day of travel; or if 4+ members were assigned units—all but one recorded travel on a concurrent day).
(b) PlanTrans then provided feedback on the number of households in Abt SRBI metafiles, which were determined to be GPS HH completes, after their initial review of GPS data.
(c) These estimated completes were subsequently reported by Abt SRBI to the Panel in the tallies by sampling cell.

3. *Problem of GPS Unit Loss and Its Implications.* Abt SRBI provided a report on GPS Unit Loss at the Mid-Year April 2010 meeting with ODOT. As a result of unit loss, Abt SRBI implemented follow-up evening calls and final tracking calls by senior staff. The problem was one of late return of units as well as non-return. Additional private courier services were also utilized.

Note: For most subsample GPS HTS comparison studies conducted to date, the number of units distributed per household is limited to three. Additionally, households recruited for GPS deployment are prescreened by phone for their potential reliability in carrying out GPS tasks and returning units. The Cincinnati GPS-only effort is entirely a full sample deployment and to all members over 12 years old. In one case, eight units were lost by no-return by one household.

By the end of the project, starting May 2010 sufficient units were on hand to deploy to only 60% of households recruited. Priority in GPS deployment was given to recruitment and refusal conversions of households in underrepresented data cells. (See identification of these groups in 6 below.)

Clearly, GPS unit loss and slow returns were the primary survey methodology challenge for this GPS-only HTS. Implications and Recommendations are further examined in the Results section.

4. *Schedule for Completes – Meeting Goals:* The following table details the frequency and cumulative frequency of recruited households, participating households, completed households, partially completed households and completed prompted recall surveys. Participation was severely hindered by dwindling GPS unit supplies. The final totals are shown in Table 2.

Table 2: Frequencies and Cumulative Frequencies of Major Study Units by Project Schedule

Month	# of Weeks	HH Recruited	Cum. HH Recruited	HH Participated (Received Units)	Cum. HH Participated	HH Completed	Cum. HH Completed	HH Partial	Cum. HH Partial	HH PR Links Completed	Cum. HH PR Links Completed
Aug-09	4	223	223	223	223	91	91	33	33	39	39
Sep-09	8	510	733	474	697	219	310	76	109	88	127
Oct-09	12	519	1252	509	1206	285	595	89	198	46	173
Nov-09	16	458	1710	431	1637	233	828	76	274	15	188
Dec-09	20	452	2162	399	2036	212	1040	69	343	37	225
Jan-10	24	389	2551	355	2391	172	1212	37	380	63	288
Feb-10	28	420	2971	361	2752	179	1391	65	445	85	373
Mar-10	32	503	3474	376	3128	186	1577	60	505	28	401
Apr-10	36	500	3974	381	3509	175	1752	69	574	55	456
May-10	40	420	4394	265	3774	112	1864	44	618	42	498
Jun-10	44	500	4894	203	3977	80	1944	59	677	45	543
Jul-10	48	455	5349	206	4183	90	2034	49	726	49	592
Aug-10	52	215	5564	55	4238	25	2059	11	737	9	601

5. *Content of Interim and Preliminary Report and Data Files.* It was agreed that PlanTrans would provide interim GPS Trip Files without mode or purpose, as improvement to the mode and purpose processing was a part of the project, but not yet fully developed. Final data were to have all modes and purposes imputed from the revised process.

6. *Underrepresentation of Certain Targeted Data Cells.* Zero vehicle and low income households were receiving $25 incentives if all household members completed. There were insufficient funds to offer 3+ person households incentives.

7. *Additional Reminder Calls and Priority Allocation.* Increased numbers of reminder calls were implemented for low income and zero vehicle households. (Incentives had had marginal effect to this point).

8. *Priority Allocation.* A priority ranking methodology was introduced to ensure under-represented cells received GPS units to record travel on scheduled travel days. Targeted allocation of GPS deployments to the underrepresented groups, near the end of data collection, was necessitated by loss and late return of GPS units.

IV. Results: Findings of the Research Effort

A. The Impact and Logistical Challenges of GPS Loss and Slow Return Rates

One of the challenges of the project was ensuring that recruited households were properly supplied with GPS units. Demand for the units exceeded the supply due to two logistical issues: loss rates (failure to return) and longer-than-anticipated time between the shipping of the units and their return. Because this had an impact on the fielding of the study, this section examines the loss rates and return times in detail, and concludes with recommendations for improving the process in future efforts.

Note:
The protocol for this study required that each household member over 12 years old receive and return a GPS unit. The study was conducted continuously over a 12-month period.

Most subsample GPS diary/GPS comparison studies conducted to date have limited GPS deployment to a maximum of three units per household. Additionally these studies have prescreened recruited households by phone to determine their potential reliability for completing GPS tasks and returning units.

SUMMARY STATISTICS

- 700 GPS units were available at the beginning of study, plus 133 more mid-progress. A total of 833 units were deployed.
- The pre-test suggested a 2.7% loss rate for the project as a whole, but the rate in the actual study averaged 7% per month.
- 4,238 recruited households were sent GPS units; of them, 292 (6.8%) failed to send at least one of their GPS units back.
- 2,600+ households completed the GPS study, for a 61.3% response rate. A number of these households did not meet the complete household definition, so that the final number of completed households was 2,059. (A 48.6% completed household response rate for households deployed). . An additional 1,326 recruited households did not receive GPS units, because of unavailability of units (due to the high loss rate), resulting in an overall lower than targeted completion rate (target equaled 3,000 households).
- By study's end, 565 of the 833 units deployed were not returned (68%).
- 256 units lost (45%) were assigned to 4+ person households
- Because of lost units (and some which malfunctioned), the number of times which units were deployed ranged from once to 28 times (10 on average, median = 9).
- Some units were deployed only once because they were lost on the first mailing.
- The percentage of units lost in any given month ranged from about 3% to about 16%. The 16% maximum occurred in the final month. This percentage is based on units available at data collection end. It also includes units that were previously being tracked in anticipation of return, but at data collection end were considered lost. Aside from this final month, the maximum was about 10%.
- The average time between recruiting a household and receiving that household's units back in the actual study was 4-6 weeks. *(The average return time after receiving units was 25 days).* Over the course of a year, this allowed for approximately ten mailings per unit (52 weeks / 4-6 weeks). Without any losses or malfunctions, this would have allowed for a maximum of 7,000 people to carry 700 units in a year.
- The combination of limited GPS units, higher-than-expected loss rates, and longer-than-expected return cycles thus limited the number of households (and people) to whom GPS units could be deployed within any given month.

To complete 3,000 household given a 49-50% completion to deployment rate, approximately 6,000 households would need to be recruited and equipped with GPS units over the 12-month data collection period. This would mean that approximately 500 households would need to be provided GPS units per month and, at an average of 2 units per household, 1,000 units would need to be deployed per month; a total of approximately 12,000 unit deployments. However, with a loss (replacement) rate of 7% per month (70 units), over the course of 12 months a total of 840 replacement units would be needed (70 x 12=840). Thus a total of 1,840 units (1,000+840) would have been needed to complete 3,000 households using existing protocols.

DISCUSSION

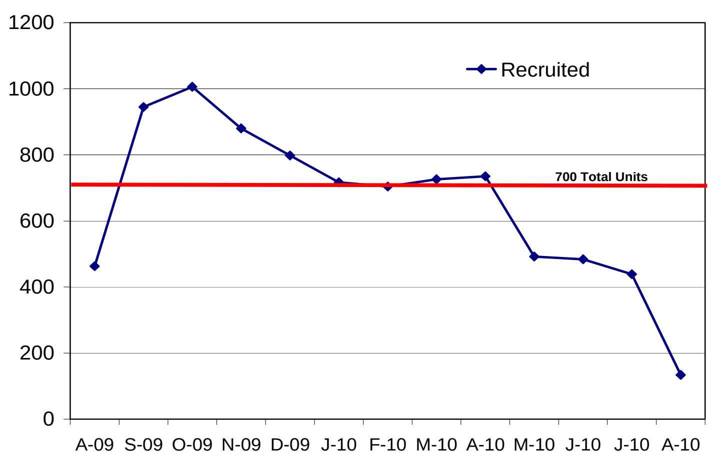
Pretest results suggested a loss rate of roughly 2.7% throughout the course of the project. This initial finding promised a return of 512 of the allocated units for the pretest. A total of 700 units were available for the project. PlanTrans shipped an additional 133 units to supplement the 700 units already in circulation. While this provided an immediate infusion, the additional units suffered the same fate as prior units. The following details the loss of units over the course of the project and provides recommendations to overcoming these challenges with retrieving GPS units in future studies.

GPS UNIT SUPPLY AND DEMAND

After a small pretest conducted in the summer and early fall of 2009, it was determined an expected loss rate for the project would be approximately 2.7% of units deployed. This loss rate was informed by a one recruit wave pretest. Had the pretest been carried out for more than one wave we may have anticipated the cumulative effects of GPS unit loss. That said, the expected loss rate was found to be multiplicative within the first few months of the project, as losses occurred with each mailing. Recruitment occurred in two waves during each month. Approximately 250 bi-weekly recruited households would require approximately two GPS units per household. In an average month this would mean approximately 1,000 units would need to be deployed and returned to fulfill the demands of recruitment.

Figure 5 shows the total number of monthly GPS deployments beginning in August 2009 to project end in August 2010. The demand for units exceeded the supply of units almost immediately. As of August, 692 units had been deployed, just under the total number of units available. By September, the number of units required exceeded the total number of units available for the project. Even with the influx of an additional 133 units by March 2010, the cumulative loss rate severely impacted our ability to meet the GPS unit demand (See the section GPS Units Lost for more detail). As described in the previous section (point 8, on page 24), starting in May 2010 deployment of available GPS units was allocated on a priority basis to recruited households in underrepresented data cells (low income, zero vehicles, 4+ person households, and the non-matched address-based sample households).

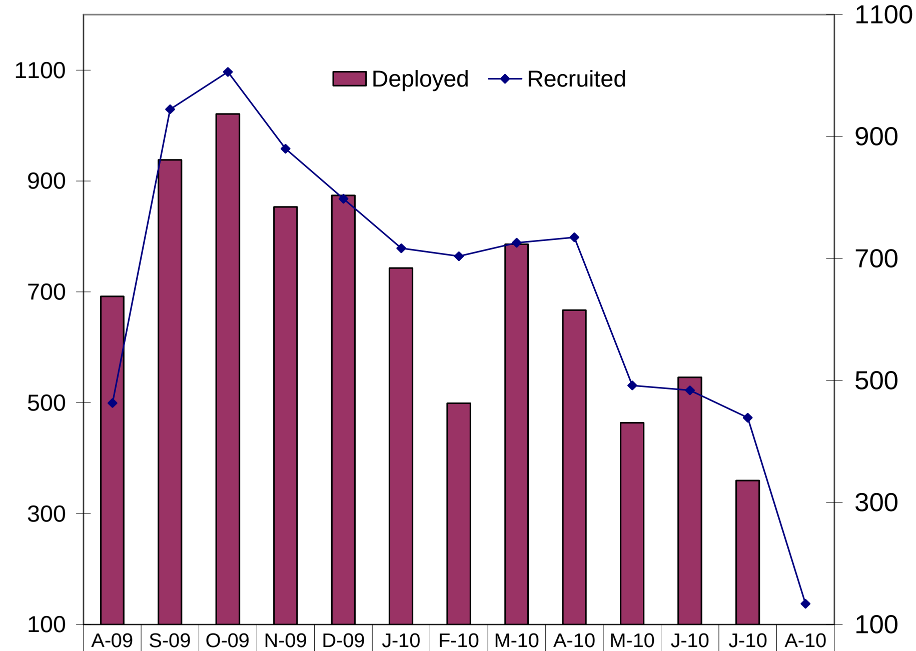
Figure 5: Monthly GPS Deployment



	A-09	S-09	O-09	N-09	D-09	J-10	F-10	M-10	A-10	M-10	J-10	J-10	A-10
Recruited	463	945	1006	880	798	717	704	726	735	492	484	439	134

While the pretest clearly established an expected loss rate, it underestimated the time required to retrieve GPS units. On average, return of the units, factoring time between recruitment and deployment, required four to six weeks. Compounding this lag in return was the cumulative loss rate. Figure 6 shows the number of units deployed factoring in the lag in retrieval and loss rate. Please note: due to end of month recruitment and travel required unit deployment and actual unit deployment may increase or decrease accordingly.

Figure 6: Monthly GPS Deployment, Accounting for Retrieval Lag and Loss Rate



	A-09	S-09	O-09	N-09	D-09	J-10	F-10	M-10	A-10	M-10	J-10	J-10	A-10
Deployed	692	938	1021	853	874	743	499	786	667	464	546	360	80
Recruited	463	945	1006	880	798	717	704	726	735	492	484	439	134

Note: "Deployed" is the Number of Units Available (August 2009) and Available and Deployed Thereafter

Recruitment demanded 11,118 household persons (5,564 households) receive a GPS unit. The compounding effects of lag and loss resulted in 4,238 households receiving units (8,523 persons).

The project was budgeted for 700 GPS units which would be deployed an average of 10 times (7,000 deployments). Mid-way in March of 2010 an additional 133 units were supplied by PlanTrans without additional charge, thus allowing for a total of 8,330 deployments. 8,523 deployments were actually achieved. However, as cited above main survey experience showed that 11,118 deployments would have been needed for 5,564 households to receive GPS units; so deployments with units available were 23% below the estimated need. At the end of April 2010 this dilemma was discussed with the ODOT Research Committee as part of an in-person mid-year report/presentation. Since budget and acquisition timing challenges were a barrier to acquiring more units through PlanTrans, it was decided that deployment would be targeted to the hard-to-reach households identified through recruitment and comparison with interim status reports. This assured a representative sample and the ability to weight and expand to key travel demand demographic variables. Since deployments of GPS units had to be decreased after April 2010, recruitments were correspondingly reduced thereafter.

GPS DATA RETRIEVAL

Nearly 93% of the people receiving units in a given month returned them, with or without data. On average, households recruited in the study had a household size of 2.34 persons, while households able to participate (units made available to them) averaged 2.41 household persons. This slight difference in household size between recruited and participating households is in part due to priority measures established to increase 4+ person households participation in the study. Approximately 2 persons in each participating household were eligible for carrying GPS units. The next section describes in detail unit circulation and profiles households failing to return units.

GPS UNIT CIRCULATION

The number of times a GPS unit was sent out ranged from once to 28 times (10 on average). This variation can be accounted for by the lag in unit return, the number of defective units being returned and the number of units lost over the course of the project. Table 3 shows the frequency of GPS unit circulation.

Table 3: GPS Unit Circulation Breakdown

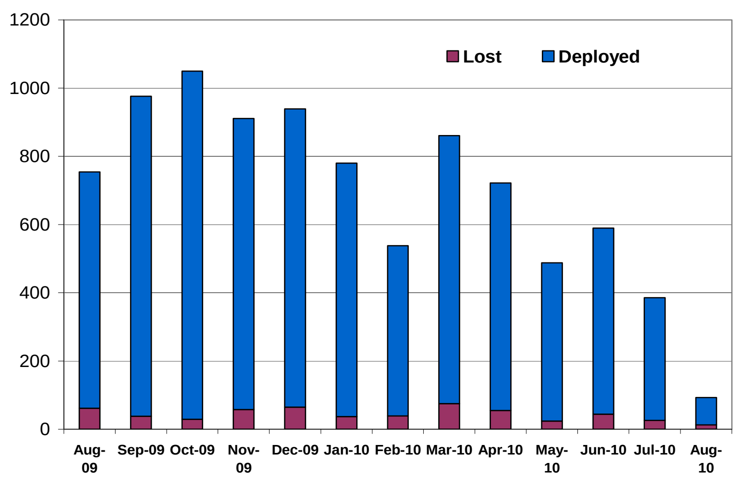
Circulation	# of Units	% of Units
Less than 5 times	269	32.3%
6 to 10 times	218	26.2%
11 to 15 times	147	17.6%
16 to 20 times	91	10.9%
More than 20 times	108	13.0%
Total	833	100.0%

Given the average circulation of one unit, a unit taken out of the rotation had significant impact on the number of people receiving units during the course of the study. For example, 7 units were removed from circulation due to malfunction or severe damage. These 7 units would have accounted for 70 people or approximately 30 households over the course of the study. As mentioned previously, lost units only partially account for the challenge of filling the GPS unit demand. Lag in unit return and lost units accounted for the greater share of difficulty in filling demand.

GPS UNITS LOST

There were 565 GPS units not returned over the course of the project. This accounts for nearly 68% of the total 833 units deployed from August 2009 to August 2010. Figure 7 shows the total number of units lost each month from the beginning of the project to the end.

Figure 7: Number of Units Lost Each Project Month

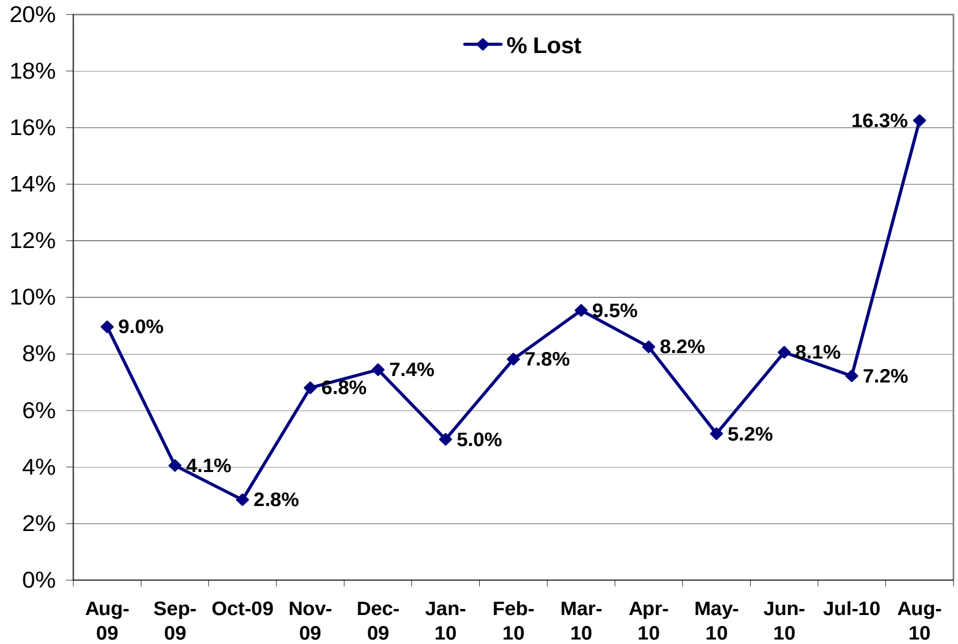


	A-09	S-09	O-09	N-09	D-09	J-10	F-10	M-10	A-10	M-10	J-10	J-10	A-10
Deployed	692	938	1021	853	874	743	499	786	667	464	546	360	80
Lost	62	38	29	58	65	37	39	75	55	24	44	26	13

Note: "Deployed" is the Number of Units Available (August 2009) and Available and Deployed Thereafter

The percentage of units lost in a month ranged from about 3% to about 16%. Figure 8 shows the number of units lost as a percent of the total deployed for each month of the project. The final 16%, occurring in the final month, is based on units at the end of data collection. Aside from that final month, the maximum in any month was 9.5%.

Figure 8: Number of Units Lost as a Percent of the Total Deployed, by Project Month



On average, 7% of the units were lost each month of the project, or approximately 44 units a month. If we take into consideration the average number of times a unit was deployed and assume the average unit was lost on its fifth deployment, we could have expected an additional 2,825 persons to have received units by project end (or 1,207 households). This would more than have exceeded the necessary number of households and persons recruited over the course of the project. Understanding then which sub-groups had the most difficulty in returning units provides some insight into future preventive measures.

GPS LOSS AMONG SUB-GROUPS

4,238 households were sent GPS units; of them, 292 (6.8%) failed to send at least one of their GPS units back. Of these 292 households, 96% did not send any of their units back; the 292 households collectively failed to return 565 GPS units, approximately 1.93 units per household. In part, the loss of GPS units may be a result of household dynamics. Table 4 shows a comparison of those households participating in the study and those where GPS units were lost.

Table 4: Comparison of Participating Households and GPS Lost Households by Household Characteristics

HOUSEHOLD INCOME	Participant HH N	Lost HH N	Part. HH %	Lost HH %
UP TO $25,000	912	106	21.5%	36.3%
OVER $25,000 TO $50,000	916	76	21.6%	26.0%
OVER $50,000 TO $75,000	732	43	17.3%	14.7%
MORE THAN $75,000	1,304	40	30.8%	13.7%
DON'T KNOW/REFUSED	374	27	8.8%	9.2%
TOTAL	4,238	292	100.0%	100.0%
HOUSEHOLD SIZE	**N**	**N**	**%**	**%**
1 PERSON	1,253	86	29.6%	29.5%
2 PERSONS	1,433	73	33.8%	25.0%
3 PERSONS	635	45	15.0%	15.4%
4+ PERSONS	917	88	21.6%	30.1%
TOTAL	4,238	292	100.0%	100.0%
NUMBER OF VEHICLES	**N**	**N**	**%**	**%**
0 VEHICLES	334	55	7.9%	18.8%
1 VEHICLE	1,329	117	31.4%	40.1%
2 VEHICLES	1,631	79	38.5%	27.1%
3+ VEHICLES	944	41	22.3%	14.0%
TOTAL	4,238	292	100.0%	100.0%
NUMBER OF WORKERS	**N**	**N**	**%**	**%**
0 WORKERS	1,270	94	30.0%	32.2%
1 WORKER	1,419	117	33.5%	40.1%
2 WORKERS	1,266	64	29.9%	21.9%
3+ WORKERS	283	17	6.7%	5.8%
TOTAL	4,238	292	100.0%	100.0%
HOUSEHOLD TYPE	**N**	**N**	**%**	**%**
ADULT HH	2,027	126	47.8%	43.2%
ADULT STUDENT HH	158	10	3.7%	3.4%
RETIREE	801	37	18.9%	12.7%
HH WITH CHILDREN	1,252	119	29.5%	40.8%
TOTAL	4,238	292	100.0%	100.0%

As can be seen from Table 4, a disproportionate number of units were lost by households with annual household incomes under $50,000, with nearly 36% of lost units or 203 units lost by households earning less than $25,000. Other notable characteristics include households with children, one-worker households, and one-vehicle households.

Table 5 shows a comparison between participating households and GPS lost households for notable study design characteristics.

Table 5: Comparison of Participating Households and GPS Lost Households by Study Design Characteristics

SAMPLE TYPE		Participant HH N	Lost HH N	Part. HH %	Lost HH %
	ADDRESS-BASED	3,589	229	84.7%	78.4%
	RANDOM DIGIT DIAL	649	63	15.3%	21.6%
	TOTAL	4,238	292	100.0%	100.0%
RECRUITMENT MODE		**N**	**N**	**%**	**%**
	TELEPHONE	3,652	270	86.2%	92.5%
	WEB	586	22	13.8%	7.5%
	TOTAL	4,238	292	100.0%	100.0%
TELEPHONE MATCHED		**N**	**N**	**%**	**%**
	MATCHED PHONE	3,646	268	86.0%	91.8%
	UNMATCHED PHONE	592	24	14.0%	8.2%
	TOTAL	4,238	292	100.0%	100.0%
INCENTIVES		**N**	**N**	**%**	**%**
	RECEIVED INCENTIVE	492	22	11.6%	7.5%
	NO INCENTIVE	3,746	270	88.4%	92.5%
	TOTAL	4,238	292	100.0%	100.0%

Table 5 shows only slight impacts on GPS loss rates due to study design characteristics. At first blush it appears incentives had the largest impact on deterring GPS loss but a deeper analysis indicates that offering incentives to unmatched households yielded no better return than not offering an incentive. This may in part be due to the level of engagement needed to initiate the process and complete the study.

Moreover, frequent contact with the households, either by phone or email, proved ineffective for these 292 households. This is significant. Future studies should account for a certain percentage of "non-responsive" households by budgeting additional units to be introduced at stages during the course of a project.

Lessons Learned and Best Practices Regarding GPS Deployment

Below details the lessons learned in GPS deployment and offers some best practices for consideration to agencies attempting an exclusively GPS Household Travel Survey.

- ***Less Aggressive Recruitment.*** The aggressive recruitment schedule of the project at least in part contributed to the difficulty in retrieving units in a timely manner. A less aggressive schedule would account for GPS unit retrieval lag and potentially additional reminder calls to households. Additional reminder calls may also be possible with an extended travel period. Taking into consideration study duration, sample size, and travel period it is recommended a recruitment of every other week, instead of weekly, with households traveling the following week. This would allow for a better rotation of units and build in additional time to control the return of units.

- ***Estimation of GPS Units Needed.*** Accounting for retrieval lag, loss rates, and defective units, having an abundance of units is advised. 833 units is approximately 20% of the total number of households recruited and able to participate and roughly 40% of completed households (n=2,059). To have reached 3,000 completed households would have potentially required more than twice the number of units (1,840) to achieve 3,000 completes (not including spares).

- ***Estimation of GPS Unit Circulation.*** GPS units could only be deployed an average of 10 times over the course of the project due to the time before their return. A conservative estimate of their time with each household would help ensure that an adequate number of units are planned for.

- ***Incentivize each Step of the Process.*** In this study, households were offered a one-time incentive of $25 to complete the entire study. This $25 incented recruitment, carrying and charging the units, filling out household and personal information forms, returning the units and potentially completing a prompted recall survey. Spreading incentives across each step of the project may improve retention of households to study's end. For example, offering $5 for completing the recruit, $10 for carrying the units, and $5 for filling out paperwork may add in retaining households. An increase in the incentive might also be considered, so each step of the process is attractive to households.

- ***Incentivize Based on Household Characteristics.*** Based on the outcomes of this study, we recommend not incentivizing unmatched households. Unmatched household engagement is higher than expected. Incentivizing households based on particular characteristics may yield greater returns.

- ***Expect Non-Responsive Households.*** Future GPS-only household travel surveys should estimate a certain percentage of households to be non-responsive or non-compliant with retrieval protocols. Seven percent of the 4,238 households that were recruited and able to participate in the study were non-responsive to retrieval protocols.

Follow-up note: *By the time of submission of this revised final report, Abt SRBI-PlanTrans completed 280+ household GPS completes within the Greater Minneapolis region for Met Council. Using the same definition for a completed household as used for the ODOT GPS-Based Only HTS, coupled with improved recontact procedures and a $25 incentive for households returning GPS units, the return rate for GPS units improved to nearly 90%.*

B. Can Representative Household Samples Be Collected via GPS-Only Data Collection?

The overall completed households sampling goal (using very strict criteria for a completed household – all members recording with a personal GPS unit on a concurrent day) was reduced as the study proceeded. This was due to loss of GPS units resulting in an inadequate number of GPS units available for deployment to the full sample of households recruited as the study progressed. Budget did not allow for full replacement of units as needed. At the same point-in-time, three-quarters of the way through the study and as would be expected, low completion rates were identified for certain hard-to-reach household categories (those with low incomes, those with zero vehicles, and those with 4+ person members). Thus, starting in May of 2010, distribution of GPS units was concentrated on recruited households meeting the undersampled criteria. Upon completion of the study, 2,059 households fully met the criteria for a completed household. Overall, units were deployed to 4,238 of the 5,564 households recruited (76%). Thus, the completion rate for those fully deployed was 48.6%.

Within the framework of the reduced sample size, a very representative sample was recruited and completed for all geographic and household demographic sampling variables. Given adherence to the address-based sampling approach, the completed sample was able to be fully weighted and expanded to year 2000 PUMS census data. (See Appendix I).

Over 12% of households completing the recruitment interview were recruited from the unmatched phone number portion of the address-based sample; only 7% of households considered full completes were unmatched households. However, these completed households were more likely to have incomes under $25,000 (21% vs. 16%), more likely to be student-headed households (34% vs. 26%), and much more likely to have persons 18 to 34 years old (28% vs. 11.5%). All of these households were recruited by an advance letter and web-based interview. The maximum incentive given to 76% of this sample was $25, and incentives were only given to the unmatched households if they met the criteria for low-income or zero-vehicle households. Trip rates for non-matched persons were almost exactly the same as for matched persons, 4.58 vs. 4.60.

It should be noted that the initial draft analysis of completed households had calculated 2,796 completed households. However, based on the strict agreed upon definition of a completed household, further analysis assigned a 0 to all persons whose device usage showed no travel for an assigned day when, in addition, their status form was missing. Thus full travel on a concurrent day could not be for 737 households under this definition. Results of this process are further shown and explained in Table 8 (page 41).

Table 6 shows counts and percentages for household completions (2,059 households). These percentages are compared with sampling plan (census-based) targets, which included adjusted geographically based oversampling for transit propensity households and households surrounding major universities.

Table 6: Analysis of Sample Representatives -- Based on 2,059 Completed Households Recorded by Abt SRBI

	Complete		Sampling Plan: Distribution of Households by Census PUMS 2000		Sampling Target W/ Oversample	Collapsed Oversample Categories	% Difference Completes/ Target
STUDY AREA HOUSEHOLDS	Frequency	Percent	HHs	Percent of Region	Percent		Percent
BUTLER	425	20.6%	123082	16.77%	NA		3.88%
CLERMONT	162	7.9%	66013	8.99%	NA		-1.12%
HAMILTON	954	46.3%	346790	47.24%	NA		0.91%
WARREN	167	8.1%	55966	7.62%	NA		0.49%
BOONE	83	4.0%	31258	4.26%	NA		-0.23%
CAMPBELL	82	4.0%	34742	4.73%	NA		0.75%
KENTON	149	7.2%	59444	8.10%	NA		-0.86%
DEARBORN	37	1.8%	16832	2.29%	NA		-0.50%
TOTAL	2059	100.0%	734127	100.00%			
SAMPLE TRANSIT TYPE	Frequency	Percent	HHs	Percent	Percent		Percent
Transit	320	15.5%	NA	10.39%	11.24%		4.30%
University	248	12.0%	NA	5.17%	22.52%		-10.47%
Other	1491	72.4%	NA	84.44%	66.24%		6.17%
TOTAL	2059	100.0%	NA	100.00%	100.00%		
HOUSEHOLD SIZE	Frequency	Percent	HHs	Percent	Percent		Percent
1 PERSON	669	32.5%	218622	27.27%	NA		5.22%
2 PERSONS	696	33.8%	256794	32.04%	NA		1.76%
3 PERSONS	278	13.5%	132757	16.56%	NA		-3.06%
4+ PERSONS	416	20.2%	193384	24.13%	NA		-3.93%
TOTAL	2059	100.0%	801557	100.00%			
NUMBER OF VEHICLES	Frequency	Percent	HHs	Percent	Percent		Percent
0 VEHICLES	91	4.4%	77555	9.68%	NA		-5.26%
1 VEHICLE	676	32.8%	258690	32.27%	NA		0.56%
2 VEHICLES	809	39.3%	311104	38.81%	NA		0.48%
3+ VEHICLES	483	23.5%	154208	19.24%	NA		4.22%
TOTAL	2059	100.0%	801557	100.00%			
NUMBER OF WORKERS	Frequency	Percent	HHs	Percent	Percent		Percent
0 WORKERS	573	27.8%	192037	23.96%	NA		3.87%
1 WORKER	704	34.2%	300001	37.43%	NA		-3.24%
2 WORKERS	643	31.2%	251120	31.33%	NA		-0.10%
3+ WORKERS	139	6.8%	58399	7.29%	NA		-0.54%
TOTAL	2059	100.0%	801557	100.01%			
HOUSEHOLD INCOME	Frequency	Percent	HHs	Percent	Percent		Percent
UP TO $25,000	344	16.7%	164803	20.56%	25.52%		-8.81%
OVER $25,000 TO $50,000	450	21.9%	201541	25.14%	27.48%		-5.63%
OVER $50,000 TO $75,000	395	19.2%	161650	20.17%	21.70%		-2.51%
MORE THAN $75,000	712	34.6%	273563	34.13%	25.30%		9.28%
DON'T KNOW/REFUSED	158	7.7%			0.00%		
TOTAL	2059	100.0%	801557	100.00%	100.00%		
HOUSEHOLD TYPE (LIFECYCLE)	Frequency	Percent	HHs	Percent	Percent		Percent
ADULT HH	1025	49.8%	368555	45.98%	43.64%		6.15%
ADULT STUDENT HH	83	4.0%	293541	2.86%	7.42%		-3.39%
RETIREE HH	377	18.3%	116567	14.54%	15.30%		3.01%
HH WITH CHILDREN	574	27.9%	22894	36.62%	33.64%		-5.76%
TOTAL	2059	100.0%	801557	100.00%	100.00%		
AUTOS VS. WORKERS	Frequency	Percent	HHs	Percent	Percent	Collapsed Oversample Categories	Percent
0 Autos, 0 Workers	61	3.0%	48513	6.05%	6.85%	0 Autos, 0 Workers	-3.89%
0 Autos, 1 Workers	27	1.3%	22171	2.77%	**4.06%**	**0 Autos, 1+ Workers**	**-2.60%**
0 Autos, 2 Workers	3	0.1%	5628	0.70%			
0 Autos, 3+ Workers	0	0.0%	1243	0.16%			
1 Auto, 0 Workers	310	15.1%	87473	10.91%	12.12%	1 Auto, 0 Workers	2.93%
1 Auto, 1 Worker	336	16.3%	142177	17.74%	20.06%	1 Auto, 1 Worker	-3.74%
1 Auto, 2 Workers	27	1.3%	25938	3.24%	**3.58%**	**1 Auto, 2+ Workers**	**-2.12%**
1 Auto, 3+ Workers	3	0.1%	3102	0.39%			
2 Autos, 0 Workers	162	7.9%	45332	5.66%	5.79%	2 Autos, 0 Workers	2.08%
2 Autos, 1 Worker	239	11.6%	101900	12.71%	12.61%	2 Autos, 1 Worker	-1.00%
2 Autos, 2 Workers	388	18.8%	153695	19.17%	16.91%	2 Autos, 2 Workers	1.94%
2 Autos, 3+ Workers	20	1.0%	10177	1.27%	1.09%	2 Autos, 3+ Workers	-0.12%
3+ Autos, 0 Workers	40	1.9%	10719	1.34%	1.39%	3+ Autos, 0 Workers	0.55%
3+ Autos, 1 Worker	102	5.0%	33753	4.21%	4.00%	3+ Autos, 1 Worker	0.95%
3+ Autos, 2 Workers	225	10.9%	65859	8.22%	7.09%	3+ Autos, 2 Workers	3.84%
3+ Autos, 3+ Workers	116	5.6%	43877	5.47%	4.45%	3+ Autos, 3+ Workers	1.18%
TOTAL	2059	100.0%	801557	100.00%	100.00%		
AUTOS VS. HOUSEHOLD SIZE	Frequency	Percent	HHs	Percent	Percent	Collapsed Oversample Categories	Percent
0 Autos, 1 HH Member	68	3.30%	45636	5.69%	6.61%	0 Autos, 1 HH Member	-3.30%
0 Autos, 2 HH Members	15	0.73%	15153	1.89%			
0 Autos, 3 HH Members	3	0.15%	7781	0.97%	**4.33%**	**0 Autos, 2+ HH Members**	**-3.22%**
0 Autos, 4+ HH Members	5	0.24%	8985	1.12%			
1 Auto, 1 HH Member	509	24.72%	144328	18.01%	24.76%	1 Auto, 1 HH Member	-0.04%
1 Auto, 2 HH Members	104	5.05%	64271	8.02%	8.55%	1 Auto, 2 HH Members	-3.49%
1 Auto, 3 HH Members	36	1.75%	25986	3.24%	**6.36%**	**1 Auto, 3+ HH Members**	**-3.30%**
1 Auto, 4+ HH Members	27	1.31%	24105	3.01%			
2 Autos, 1 HH Members	74	3.59%	23309	2.91%	**21.03%**	**2 Autos, 1-2 HH Members**	3.01%
2 Autos, 2 HH Members	421	20.45%	140850	17.57%			
2 Autos, 3 HH Members	123	5.97%	55814	6.96%	6.30%	2 Autos, 3 HH Members	-0.33%
2 Autos, 4+ HH Members	191	9.28%	91131	11.37%	9.94%	2 Autos, 4+ HH Members	-0.66%
3+ Autos, 1 HH Members	18	0.87%	5349	0.67%			
3+ Autos, 2 HH Members	156	7.58%	36520	4.56%	**4.67%**	**3+ Autos, 1-3 HH Members**	**9.42%**
3+ Autos, 3 HH Members	116	5.63%	43176	5.39%			
3+ Autos, 4+ HH Members	193	9.37%	69163	8.63%	7.45%	3+ Autos, 4+ HH Members	1.92%
TOTAL	2059	100.00%	801557	100.00%	100.00%		
HOUSEHOLD SIZE VS. WORKERS	Frequency	Percent	HHs	Percent	Percent	Collapsed Oversample Categories	Percent
1 HH Member, 0 Workers	327	15.88%	99428	12.40%	NA		3.48%
1 HH Member, 1 Workers	342	16.61%	119194	14.87%	NA		1.74%
2 HH Member, 0 Workers	206	10.00%	68965	8.60%	NA		1.40%
2 HH Member, 1 Workers	187	9.08%	82080	10.24%	NA		-1.16%
2 HH Member, 2 Workers	303	14.72%	105749	13.19%	NA		1.52%
3 HH Member, 0 Workers	21	1.02%	12849	1.60%	NA		-0.58%
3 HH Member, 1 Workers	79	3.84%	42406	5.29%	NA		-1.45%
3 HH Member, 2 Workers	126	6.12%	58714	7.32%	NA		-1.21%
3 HH Member, 3+ Workers	52	2.53%	18788	2.34%	NA		0.18%
4 + HH Member, 0 Workers	19	0.92%	10795	1.35%	NA		-0.42%
4 + HH Member, 1 Workers	96	4.66%	56321	7.03%	NA		-2.36%
4 + HH Member, 2 Workers	214	10.39%	86657	10.81%	NA		-0.42%
4 + HH Member, 3+ Workers	87	4.23%	39611	4.94%	NA		-0.72%
TOTAL	2059	100.00%	801557	100.00%			

While geographically based household goals for University areas were undersampled by 10.5% based on the established oversampling target, University area households captured as completes number 248 households, a sufficient sample size for independent statistical analysis, and at a percentage over twice their actual proportion of the total area population.

Otherwise, the completed sample region-wide was very representative by county, household size, number of vehicles, and number of workers, with the exception that zero-vehicle households were under-represented in completes by 5.3%, despite $25 incentives for completion. Still, a statistically significant subsample of 91 zero-vehicle households was completed. Likewise, 4+-person households were only underrepresented by 4%. By income, as in diary-based household travel surveys, households with incomes under $25,000 were under-represented in completes (by 8.8%) with households with incomes over $75,000 over-represented by 9.3%. Only 7.7% of completed households refused or did not report income. Completes among households by lifecycle (adult households, adult student households, retirees, and households with children) were representative of census-based percentages. Additionally, the completed sample was very representative by the regional breakdown of categories of interest to travel analysis including: number of autos vs. number of workers, number of autos by household size, and household size by the number of workers. Thus, it was proved that a representative sample of completed households can be obtained using GPS-only and address-based sampling methodologies.

All of the above Table 6 variables were obtained as a part of the web/CATI recruitment interview. As previously noted, information on workplace address for each household member was collected through a “Person Information Form” sent out with each GPS unit, along with a child diary for every member of the household under 13 years old. In addition to workplace address, the Person Form collected GPS usage and status information for each household member for each assigned travel day. The “Household Form” sent with the units collected the two most frequent shopping locations for the household. These forms were to be either returned with the GPS units in the return, addressed shipping-paid box provided, or the information could be entered by connecting to the project’s website. Individual passwords were provided. The response rates for the return of these forms are shown in Table 7 below.

Table 7. Response Rates for Household, Person, and Child Diary Forms

	FORMS		
	HH	Person	Child Diary
	Completes/ Partials	Completes/ Partials	Completes/ Partials HHs
Number of Forms Sent (N)	2796	5716	1090
Number of Forms Returned (N)	2630*	4839*	525*
No Paperwork Returned (N)	166	877	565
Response Rate (%)	0.94	0.85	0.48

*Includes persons who returned forms but only partial information provided

Ninety-four percent (94%) of households who at least partially completed GPS recording submitted the Household Form; 85% of persons within complete or partially complete households completed the Person Form with workplace address and GPS usage/status data. Of the 1,090 completed or partially completed households with children, 48% returned child diaries.

An average of 5% of persons deployed with GPS units reported on each of the three travel recording days that they forgot to carry their unit for all or part of the day; an average of 6% on each travel day reported no travel; and an average of 3.4% persons on each travel day reported that their GPS unit battery gave out, starting at 2.5% of persons on the first day.

C. Definition of a Complete Household

One of the issues that has been noted in this survey is the rather substantial loss of households from the data set when the definition of a complete household has been imposed. A total of 2,796 households completed survey forms and carried GPS devices with them, but this total reduced to 2,059 GPS-complete households when the definition of what constitutes a complete household was imposed on the data. It was felt that this warranted some further investigation of the data to ensure that the definition of a GPS complete household was being implemented correctly and that it did indeed result in the loss of some 737 households.

The definition of a GPS complete household, as stipulated by ODOT was:

> "A GPS complete household is one where each person in that household over 12 years of age is GPS complete. A GPS complete person is one who has made at least one trip on the SAME day as the others in the household that is recorded by their GPS device. If a household participant claims to not have travelled that day (i.e., device usage status = 4 from the device usage status data (from person form)), they will be counted as a GPS complete. If GPS data for a participant is missing, they will count as a GPS non-complete member of the household unless their usage status indicates that they did not travel that day. However, if their usage data is missing, they will count as a GPS non-complete member of the household. A household with 3 or less people will be GPS complete if all participants in the household are GPS complete but in a household with 4 or more persons, one person can be GPS non-complete."

PROCESSING FOR DEFINITION OF A GPS COMPLETE HOUSEHOLD

Using this definition, we undertook two steps to determine if a household met the criteria of being a GPS complete household, as defined above. The two steps were as follows:

> Step 1: The number of GPS trips per person for each household was extracted. If all household members with GPS travel had travel on the same date, the household was classified as GPS complete. If the household had more than 3 members, then if no more than one person had missing GPS data on at least one common day, the household was classified as GPS complete. Households that did not meet these criteria were classified as GPS incomplete. This step was only carried out on those households that had GPS data.
>
> Step 2: GPS complete status determined from Step 1 was imported into the household metadata file and households with missing data were added. Each household was reinspected to see if there were other members in the household who had missing data. If missing data was due to a person not having travelled, as determined by their device usage status for the day of travel, the household was considered GPS complete if their original GPS complete status from Step 1 was complete, or if the household had more than 3 persons and their original GPS complete status was GPS incomplete. In all other cases, the household would be GPS incomplete. Households with no travel had their device usage inspected to determine if they were GPS complete or not. The same rule as above was applied except that a device usage status of 4 on the same day was compared.

The second step, however, was mainly a manual task and did not compare actual days of travel for which persons with missing data were supposed to travel. The device usage status for households and persons with missing data was applied as an average to the person or household's entire travel. In other words, device usage was not allocated to the scheduled dates of travel for persons with missing data, instead, if the person had at least one missing day of data with a device status indicating no travel, they were considered GPS complete. Results of this process are shown in Table 8 under the column titled "Original Calculation Manual".

The above process was simplified by combining the two steps and fully automating it. To do this, firstly, the number of GPS trips per day per person per household was extracted and usage data for each day of travel was assigned with the assumption that Day 1 of travel as indicated in the usage data corresponded to the first day for which GPS data was collected. Then all persons with missing data, including each person within households with missing data, were added to this list. For these persons with missing data, the scheduled days of travel were taken to be the actual days of the household travel. A trip count of 0 and device usage for that day was assigned to each scheduled day. Results of this process are shown in Table 8 under the column titled "Original Calculation Automated". Using this procedure, the results shown in Table 8 were achieved. The discrepancy of 20 households between the manual and automated process is due to the non allocation of travel dates to missing data as described in the manual process above, which could not be fully automated.

Table 8: Results of the Definition of a GPS Complete Household

Status	Original Calculation Manual	Original Calculation Automated
GPS Complete	2,059	2,079
Not GPS Complete	737	717
Total households	2,796	2,796

OTHER RESEARCH CONSIDERATIONS IN REGARD TO THE DEFINITION OF A COMPLETED HOUSEHOLD

While the definition of a completed household is the correct one for ODOT's travel modeling needs and is generally the one used by all travel demand modelers in the USA, it does result in a lot of "lost" person level data, which some researchers may want to explore. For this reason we have included the following section.

In a 2003 paper, Richardson and Meyburg made three relevant points about classifying responses as unit non-responses:

> "A very strict definition of 'acceptable response' (no missing data allowed in an acceptable household) results in a significant loss of data and a bias in retained households towards smaller households and less mobile households.
>
> "A more lenient definition of 'acceptable response' (twenty to fifty percent missing data allowed in an acceptable household) results in a very small loss of data, no bias in retained households towards smaller or larger households, and a slight bias towards more mobile households (mainly through the exclusion of totally immobile households).
>
> "On balance, it would appear that a more lenient definition of an 'acceptable response' would be much more cost effective (by not discarding data already collected) and would produce less bias in the characteristics of the retained households."

Along these lines, it was felt it to be appropriate to investigate what caused the loss of data in the GCAHTS.

TESTING OF MODIFICATION 1 OF THE DEFINITION OF A GPS COMPLETE HOUSEHOLD

The first modification proposed is to be more lenient, as suggested by Richardson and Meyburg (2003), and revise the definition of a GPS complete household to allow for 50 percent of the household members to have GPS travel or a no-travel day on the same day. Two versions of this definition were applied, one of which rounded down the number of household members that needed to be complete, while the other rounded it up for households containing an odd number of GPS-eligible persons. Thus, in the first version, a household of 1 person must have that 1 person providing GPS data on at least one day or not having travelled at all for the entire period of the GPS survey; a household with 2 or 3 persons eligible to carry

GPS devices must have 1 person with GPS data or not having travelled on any of the GPS days; a household with 4 or 5 persons eligible to carry GPS devices must have 2 persons who travelled on the same day (or had a no-travel day); and so forth. In the second version, a 1 or 2 person household must have 1 person who is GPS complete, while a 3 or 4 GPS-person household must have 2 GPS completes for the same day, etc.

The results of these two alternative versions are shown in Table 9.

Table 9: Results of the First Version of a GPS Complete Definition

Status	Modification 1: 50% rule rounded down	Modification 1: 50% rule rounded up
GPS Complete	2,718	2,597
Not GPS Complete	78	199
Total households	2,796	2,796

Clearly, this definition results in a far larger sample of households. It should be noted that we have not checked to see if the data are less biased.

TESTING OF MODIFICATION 2 OF THE DEFINITION OF A GPS COMPLETE HOUSEHOLD

The second modification was to return to the original definition, but relax the requirement that the members of the household that carried GPS devices must travel on the same day. Again, two versions of this definition were applied. In the first of these, the requirement was that all GPS-eligible members of the household had at least one trip recorded on any day, while the second version also implemented the more lenient requirement that in households with 4 or more GPS eligible persons, one GPS eligible person could have missing data for any day. The results of applying this definition are shown in Table 10.

Table 10: Results of the Second Version of the Definition of a GPS Complete Household

Status	Modification 2: Any person travel in all households	Modification 2: Any person travel in all households with 4+ person rule
GPS Complete	2,071	2,150
Not GPS Complete	725	646
Total households	2,796	2,796

As can be seen in Table 10, the improvement in the number of GPS Complete households is not very large in this case. This indicates that the major problem in the data is not that there are most GPS eligible household members with data for any day, but rather that the losses in sample stem from some members of the household not complying with the GPS task at all, while others did comply.

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D. GPS Data Collection Results

After all data checking and auditing were complete, a total of 2,059 households provided fully completed GPS data, with an additional 549 households completing significant GPS person recording, but not confirmed as meeting our strict project household complete definition of full recording for all members of a household over 12 years on a concurrent day. Of the 2,059, there were 17 one-person households that were GPS complete but where the household member did not travel. Hence, there are 2,042 households whose travel is reported in the following paragraphs. A summary of the unweighted responses is provided in Table 11. The completed households provided 3,849 person records. Thus, an average of 1.88 persons per household carried GPS devices on at least one common day.

Table 11: Disposition of the Final GPS Carrier Sample

Statistic	**GPS Complete**		**GPS Incomplete**		**TOTAL**
	Number	**Percent**	**Number**	**Percent**	
Households	2,059	78.9%	549	21.1%	2,608
Persons	3,849	82.7%	807	17.3%	4,656
Travel Days	13,210	83.2%	2,670	16.8%	15,880
Trips	60,900	84.2%	11,336	15.8%	72,236
Average Daily Household Trip Rate	8.62	--	--	--	--
Average Daily Person Trip Rate	4.61	--	4.25	--	4.55
Average Weekday Household Trip Rate	9.46	--	--	--	--
Average Weekday Person Trip Rate	5.06	--	4.64	--	4.99
Average Trip Distance (all days)	6.11 miles	--	6.29 miles	--	6.14 miles
Average Trip Distance (weekdays)	6.21 miles	--	6.48 miles	--	6.25 miles
Average Trip Travel Time (all days)	0:13:07	--	0:13:17	--	0:13:09
Average Trip Travel Time (weekdays)	0:13:05	--	0:13:21	--	0:13:07
Average Daily Travel Time (all days)	01:22:11.1	--	01:19:27.1	--	01:21:44.4
Average Daily Travel Time (weekdays)	01:21:10.5	--	01:19:26.6	--	01:20:53.7

The number of trips reported for persons in completed households totaled 60,900 as determined by the G-TO-MAP software, representing an average trip rate of 4.61 trips per person per day, or 8.62 trips per household per day. Given that these rates do not include children, both the person and household trip rates are higher than those usually measured in diary surveys. For the trips per person per day, the average trip distance was 6.11 miles with an average travel time of 13 minutes and 7 seconds. The minimum number of trips recorded for any individual was 0 and the maximum was 43. The trip file includes 27% of persons who claimed a no-travel day on at least one of the days that they carried GPS devices, and 18.5% of households where all household members claimed not to have travelled on one day. Each person spent an average of 1 hour, 22 minutes and 11.1 seconds in travel per day. Looking only at weekdays (i.e. excluding weekend days), the average trip distance is slightly longer at 6.21 miles, but the average travel time and daily travel time are each slightly less at 13 minutes and 5 seconds, and 1 hour 21 minutes and 10.5 seconds, respectively. The weekday trip rate is higher at 5.06 trips per person and a household trip rate of 9.46 trips per household.

These statistics indicate the greater completeness of GPS data compared to diary data and indicate the superiority that can be achieved using this method of data collection.

The prompted recall survey was sent out to all households that provided GPS data, unless the household did not provide an email address. A few households were not sent the prompted recall survey because the data were received so long after the GPS period that it was felt to be unwise to send the PR survey to these households. An incentive, in the form of a draw, was offered to encourage participation in the Prompted Recall Survey, and draw prizes were offered every three months. A total of 601 households completed the Prompted Recall Survey, comprising 989 persons, or 1.65 persons per household. This was lower than the number of trip completions per household (which was 1.88), however, most households that completed the Prompted Recall Survey did so with all members of the household that carried GPS devices completing the survey.

In the prompted recall survey, a more detailed list of modes was requested, and identification of driver and passenger. In addition, the total number of people on the trip was also ascertained. More detailed purposes were also collected. These data can be used in two ways. First, the data can be used to assist the improvement of the software, as has already been explained. Second the data can be used to check the results of the software processing and to suggest factoring of the software results where appropriate. However, considerable care must be taken in interpreting the prompted recall survey results, because the prompted recall survey data are not directly comparable to the full GPS data, as explained in the following subsection.

D. 1 Prompted Recall Survey Data

There are some fundamental differences between the Prompted Recall (PR) data and the full GPS data, which must be borne in mind when comparing the two, because direct comparison is actually not valid. In addition, an in-depth analysis of the PR data shows that these data are often not even close to the 'ground truth' that it is hoped that they would be. There is also an issue that needs to be kept in mind that there is much greater trip reporting from GPS than is customary from diary surveys. The following subsection discusses a number of issues relating to the PR data and also to comparisons between the PR data and the full GPS data. Following that, a brief analysis focused on work trips is reported that illustrates the dangers of comparing directly the PR and GPS data.

Prompted Recall Data

In considering the prompted recall data, there are some important issues that need to be understood. First, the full data include 4,064 no-travel days, whereas the PR data include 0 no-travel days. Of these no-travel days, 2,491 are on weekdays. Second, the distribution of weekdays and weekend days is radically different, with only 13 out of 4,831 trips (0.3 percent) in the PR data being on a Saturday and none on Sunday, compared to 1,921 (3.0 percent) in the full GPS data being on Saturday and 1,526 (2.4 percent) being on a Sunday. Thus, there is a much greater likelihood of weekday trips being reported in the PR data than in the full GPS data.

There are also clear problems in the completion of the PR data. As is noted later in this report, an in-depth analysis of the prompted recall data revealed that about 31 percent of the responses of the mode of travel used appear to be highly questionable, and about 18 percent of the trip purposes identified also appear to be highly questionable. Anecdotally, one can see an adult from a household who takes a child to school or picks a child up from school and reports this as a school trip for the adult. This also happens for some other purposes, where an obvious pick up or drop off activity is reported as having the purpose of the person picked up or dropped off, rather than the purpose of pick up/drop off. One can also find numerous instances of other respondents who make a pick up or drop off trip and combine the two trips into a single trip from home back to home. In other cases, trips with much longer activity durations are also combined into a single trip and the purpose information is not provided correctly. Indeed, in performing a match analysis between the GPS and PR data, it is found that the biggest cause of mismatch is people combining two or more separate one-way trips into a round trip or tour in the PR survey. As a result, the purpose and mode may then be recorded in error.

Other instances have also been found where a person claims to have travelled with other household members, but examination of the records of those other household members shows it to be impossible that those household members accompanied the respondent on the same trip. For example, a respondent claims three members of the household travelled with them on a shopping trip, while one of the household members reported being at work at that time, and the two others reported being at school at that time. In a few cases, respondents to the PR survey split a GPS trip into two, with at least one component having a duration of less than a minute. In all cases, these split trips appear unlikely to be correct, but it is puzzling as to what the reason was for the respondent splitting the trip.

As a general conclusion, we find that the PR data are subject to almost all of the common problems found in self-report diary data, even though respondents have a map showing where the GPS says that they travelled and from which they just need to fill in the details of their travel. Experience from the pilot, when respondents were allowed to change the trip times as well showed that respondents often have a completely incorrect idea of when the travel took place, as well as for what reason, with whom, and how the trip was undertaken.

While there is some proportion of the PR data that probably represents 'ground truth', there turns out to be a large amount of the data that are actually incorrect and unreliable. While an in-depth analysis can reveal some of the probable problems, through such analyses as are reported here, it is not possible to determine which prompted recall data are correct and which are incorrect at an overall level. Overall, the Prompted Recall survey data appear to be afflicted with many of the same problems as arise in self-report diary data.

PUTTING IT ALL TOGETHER

An example of the problems of comparing PR and GPS data is provided by looking at work trips. In the full GPS data, there are 2,868 workers. Of these workers, 2,160 provided sufficient workplace information to allow geocoding to their workplace. Of the remainder, 50 provided some information, but a geocode could not be established, and 658 failed to provide any address information. There are a total of 5,721 origins that were identified as work, and 5,814 destinations identified as work. For the workers, on average, they provided 3.89 days of data on their GPS devices, of which an average of 3.35 were weekdays. If each worker went to work once on each weekday, then this should produce approximately 7,236 origins and destinations that are work.

However, we also need to take into account the fact that the main study data include no-travel days, while the PR data includes no no-travel days. Therefore, it was determined what proportion of weekdays for workers were reported as no-travel days. There were a total of 1,575 no-travel days for workers on weekdays. This averages 0.55 no-travel days per worker, thereby reducing the number of actual days of travel per worker to 2.80. Using this figure and the number of workers who provided a workplace address that could be geocoded, the number of work trip ends that should be expected would be 6,048.

There were a total of 4,639 persons who carried GPS devices from the completed households, so that workers represented 61.8 percent of the total number of persons, and workers with a geocodable address comprised 46.6 percent of all persons carrying GPS devices.

In the PR data, there were 845 trips with an origin at work, and 861 with a destination at work. Out of the 989 persons who provided PR data from 601 households, 679 were workers, representing 68.7 percent, compared to 61.8 percent in the main data. All of their responses were on weekdays, so that it might be expected that there would be 679 trips with an origin at work and 679 with a destination at work, assuming that each worker went to work and returned from work on the PR day. In fact, on the weekdays for the PR survey, approximately 1.24 trip origins per worker were from work, and 1.27 trip destinations were at work.

Given this analysis, we can estimate the number of work trips that should have appeared in the processed full GPS data, compared to what was actually found. As determined above, in the full GPS data, there were 2,160 workers who provided a geocoded workplace address and who could therefore be expected to show work origins and work destinations. These 2,160 workers on average carried their GPS devices for 2.80 weekdays (so as to compare to the almost entirely weekday data of the PR data). Finally, from the PR data, it was found that the average worker made 1.24 work trip origins and 1.27 work trip destinations. Therefore, the expected number of workplace origins in the full data should be 7,500 and the number of workplace destinations should be 7,681. As is shown in Table 17, below, the actual numbers were 7,308 and 7,406, which are 2.5 and 3.6 percent low, respectively. In other words, better than 95 percent of work trip ends have been identified by the software.

A small sample analysis has revealed that approximately 16 percent of work trip ends begin or end more than 1/8 mile from the geocoded workplace, possibly in a parking lot or where the workplace is sufficiently large in area (like some shopping centres and industrial complexes) that the actual place of work is quite distant from the geocoded work location. If this statistic can be applied to all workplace locations, then this would reduce the expected number of origins and destinations by 16 percent, to 6,300 origins and 6,452 destinations. The actual number of such origins determined by the present version of the software is 5,721, which is 10 percent too low. Similarly, for destinations, the software determined 5,814 destinations, which is 11 percent too low.

This margin of error of around 10 percent, while higher than desired, is not disastrously large and, therefore, not large enough to warrant dismissing the data as unusable.

D.2 TRIP CHARACTERISTICS

Beyond the simple statistics provided above, some more detailed statistics are described in this section, both from the GPS and the Prompted Recall Survey. Table 12 provides a breakdown of trips by mode from the total completed sample and also provides a household trip rate by mode from the GPS data after processing.

Table 12: Breakdown of GPS Trips by Mode and Daily Household Trip Rate by Mode (Complete Households)

Mode of Travel	Number of Trips	Percent of Trips	Daily Household Trip Rate
Motor Vehicle	53,734	88.2	7.60
Bus	537	0.9	0.08
Walk	3,125	5.1	0.44
Bicycle	585	1.0	0.09
School Bus (GPS and Prompted Recall)	247	0.4	0.03
Unknown	2,672	4.4	0.38
TOTAL TRIPS	60,900	100.0	8.62

As expected, Table 12 shows that the majority of trips recorded were by car. Slightly less than 5 percent of trips could not be identified to a specific mode, usually as a result of a substantial part of the trip being missing, because the trip was inserted in map editing and there was no trace for the trip. There are also 4,101 no travel days within the data, for which, of course, there is no travel mode.

Table 13 shows a similar report for the Prompted Recall (PR) Survey.

The percentages of motor vehicle trips and bus trips are higher in the PR survey results than in the GPS survey, while bicycle trips are higher in the GPS survey results than the PR survey. The walk trips show approximately the correct percentage, based on the PR survey. However, the differences are very small. Trips by motor vehicle are 2.4 percent lower in the GPS data than the PR data, and total bus trips are 0.6 percent lower. Bicycle trips are 0.5 percent higher. Walk trips are 0.1 percent higher in the GPS data than in the PR data. The overall trip rate by households in the PR survey is lower than for the GPS survey, partly because of fewer persons per household completing the PR survey, and possibly also because those who did complete it may have been those with fewer trips in the sampled day. The high proportion of bicycle trips shows the often-reported problem of over-identification of bicycle from the GPS, because a car moving in congested conditions is not easily distinguished from a bicycle. The lower rate of bus trips shows that the software changes have solved the problem of estimating too many bus trips, but may have proceeded too far in reducing bus trips. However, overall, the percentage in the GPS data seems quite consistent with other bus ridership statistics for the region.

Table 13: Breakdown of PR Trips by Mode and Daily Household Trip Rate by Mode

Mode of Travel	Number of Trips	Percent of Trips	Daily Household Trip Rate
Driver of Auto/Van/Truck	3,816	79.4	6.39
Passenger of Auto/Van/Truck	452	9.4	0.76
Driver of Carpool	21	0.4	0.04
Passenger of Carpool	44	0.9	0.08
Passenger of Vanpool	9	0.2	0.02
Motorcycle/Moped	13	0.3	0.02
Total Motor Vehicle	4,376	90.6	7.31
Bus	62	1.3	0.10
School Bus	30	0.6	0.05
Total Bus	92	1.9	0.15
Taxi/Paid Limo	2	0.0	0.0
Walk	235	5.0	0.40
Bicycle	22	0.5	0.04
Other	83	1.7	0.14
Unknown	15	0.3	0.03
Total	**4,804**	**100.0**	**8.05**

Tables 14 and 15 show statistics that are not available for comparison from the GPS survey data, namely the split between drivers and passengers, and the number of people on the trip.

Table 14: Split Between Drivers and Passengers from the PR Data

Driver or Passenger	Number	Percent
Driver	3,853	79.8
Passenger	507	10.5
Not Applicable	468	9.7
Total	**4,828**	**100.0**

Table 15: Number of People on Trip from the PR Data

Number of People	Number	Percent
1	1,017	21.1
2	3,364	69.7
3	337	7.0
4	88	1.8
5	17	0.4
6	5	0.1
Total	**4,828**	**100.0**

The results shown in Table 15 are interesting, in that they show a much higher than usual number of people sharing a ride with at least one other person. Average vehicle occupancy would be considered abnormally high from these results, although it does cover all modes of travel. However, Table 16 shows the number of people on the trip by mode and shows further difficulties with the Prompted Recall data. The table shows that 193 car passengers were on their own (no driver?), and similarly 3 carpool passengers and 2 vanpool passengers were riding with no driver and no other occupants. For motorcycle/moped, 6 of 13 users reported being a party of 2. It is also at least curious that 20 out of 22 cyclists claimed to have been a party of two. These results must again raise some questions about the correctness of people's responses to the Prompted Recall survey.

Table 16: Number of People on Trip by Mode from the PR Data

Mode of Travel	Party Size						
	1	2	3	4	5	6	Total
Driver of Auto/Van/Truck	691	2,775	264	82	17	3	3,832
Passenger of Auto/Van/Truck	193	221	34	5	0	0	453
Driver of Carpool	5	9	7	0	0	0	21
Passenger of Carpool	3	26	16	0	0	0	45
Passenger of Vanpool	2	7	0	0	0	0	9
Motorcycle/Moped	7	6	0	0	0	0	13
Total Motor Vehicle	901	3,044	321	87	17	3	4,373
Bus	22	36	4	0	0	0	62
School Bus	0	27	3	0	0	0	30
Total Bus	22	63	7	0	0	0	92
Taxi/Paid Limo	2	0	0	0	0	0	2
Walk	60	174	5	6	0	2	241
Bicycle	1	20	1	0	0	0	22
Other	17	62	3	1	0	0	83
Unknown	14	1	0	0	0	0	15
Total	**1,017**	**3,364**	**337**	**88**	**17**	**5**	**4,828**

Table 17 shows the distribution of Origin and Destination Activities and rates of these per household per day from the GPS survey.

Because the G-TO-MAP software is provided principally with home, work, school, and some shopping locations, there will always be a large proportion of “Other” activities, these being those that cannot be classified to one of the other four purposes. With the most recent version of the software, work trips and school trips have increased as a percentage of total trips, and pick up/drop off trips increased significantly. Shopping trips remained approximately the same.

Table 17: Breakdown of Trips by Origin and Destination Activity and by Household Rate from the GPS Survey (Complete Households Only)

Purpose	Origin Activity			Destination Activity		
	Number	**Percent**	**Daily Rate**	**Number**	**Percent**	**Daily Rate**
At Home	15,419	25.3	2.18	15,155	24.9	2.15
Paid Work	7,308	12.0	1.03	7,406	12.2	1.05
School	1,871	3.1	0.27	1,905	3.1	0.27
Pick Up/Drop Off	2,243	3.7	0.32	2,224	3.7	0.32
Catch Bus/Train/Plane	1,552	2.5	0.22	1,548	2.5	0.22
Shop	14,452	23.7	2.04	14,457	23.7	2.04
Other	18,055	29.6	2.55	18,205	29.9	2.58
Missing	0	0	0	0	0	0
Total	**60,900**	**100.0**	**8.62**	**60,900**	**100.0**	**8.62**

Table 18 shows similar information for the Origin Activities as Table 17, but from the PR survey, with somewhat richer set of options for the Activities. The activities in Table 18 are grouped so as to make comparison to Table 17 easier. However, as noted in Section D.1, these are not strictly comparable, because there are no no-travel days in the PR data, and almost no weekend days. In addition, there is a larger proportion of workers in households that completed the PR survey, than in the GPS survey as a whole. However, the overall percentages now look quite close to what should be expected. The only figure that appears somewhat questionable here is that for shopping, which appears high, and may include some part-time retail workers who are misclassified, having not given a workplace address that could be geocoded and working for less than 4 hours per shift.

Table 18: Breakdown of Trips by Origin and Destination Activity and by Household Rate from the PR Survey

Purpose	**Origin Activity**			**Destination Activity**		
	Number	**Percent**	**Daily Rate**	**Number**	**Percent**	**Daily Rate**
At Home	1,376	28.7	2.31	1,360	28.3	2.28
Paid Work	842	17.5	1.41	858	17.8	1.44
School	136	2.8	0.23	128	2.7	0.21
Volunteer Work	56	1.2	0.09	56	1.2	0.10
Pick Up/Drop Off	227	4.7	0.38	222	4.6	0.37
Soc./Rec./Church	296	6.1	0.50	312	6.5	0.52
Catch Bus/Train/Plane	23	0.5	0.04	25	0.5	0.04
Transfer from a Bus/Train Plane to Another	35	0.7	0.06	33	0.7	0.06
Shop	622	13.0	1.04	621	12.9	1.04
Personal Business	322	6.7	0.54	327	6.8	0.55
Eat Meal	222	4.6	0.37	225	4.7	0.38
Go for a Drive	25	0.5	0.04	25	0.5	0.04
Work Related	162	3.4	0.27	155	3.2	0.26
School Related	57	1.2	0.10	58	1.2	0.10
Don't Know/Refused	388	8.1	0.65	380	7.9	0.64
Missing	0	0.3	0.03	0	0.3	0.03
Total	**4,804**	**100.0**	**8.05**	**4,803**	**100.0**	**8.05**

A comparison of Table 18 with Table 17 indicates that the proportion of trips originating and terminating at home is somewhat lower in the GPS software, while school trips are very close. Shopping is too high in the GPS data, which is surprising given that only two shopping locations were requested from each household and these were grocery-shopping locations. The rate of missing is much higher in the GPS software results. As noted below in the next section, one of the problems that arise is where the address given is actually a relatively large site, and the address is coded at a point that may be close to or on the road, or may be in the center of the site. This is particularly a problem for shopping and work trips. It must also be recalled, however, that there are very important differences between the prompted recall and the full GPS data, so that strict comparability would be highly unlikely in these statistics.

The in-depth analysis reported in the following section provides much greater insight into the reasons for a failure to match between the PR and GPS processed results. As is described there, a number of situations arise that make it impossible for the software to provide a match, while there are relatively few situations where the software could be improved. It is also extremely important to realize that respondents do not provide correct responses in a PR survey in all cases. Therefore, some fraction of the mis-matching reported here is a result of errors in the PR survey responses.

D.3 In-Depth Comparison of GPS and Prompted Recall Data

Two levels of analysis have been performed of the GPS versus the Prompted Recall data. The first analysis compares certain statistics for the entire PR sample with the corresponding day of data from the GPS. The second describes a much more in-depth, case-by-case analysis of certain of the households that provided both GPS and PR data.

Overall Analysis

First, we compare the quality of the PR data with the GPS data. As noted earlier, people make various errors in completing the Prompted Recall that are similar to errors made in completing self-report diaries. The first, and most obvious one, is linking individual trips together into tours and also omitting reporting on trips that are essentially claimed not to have been made. First, we note that there are 5,362 trips recorded by the GPS devices for the PR households, but PR respondents reported on only 4,827 trips. Further analysis shows that there were 24 trips reported by PR respondents that did not correspond to a GPS trip, while there were 554 GPS-recorded trips that did not correspond to a PR reported trip. In most cases, these 554 arose from situations where respondents grouped trips together from the GPS and called them a single trip. A few of these cases may be real situations where the GPS software identified a trip end that was actually not a trip end. However, many of these cases are where trips have been joined together. The "trip under-reporting" implied by these 554 trips is 10.3 percent, which is about half the rate of under-reporting in travel diary surveys. It must immediately call into question the reliability of the PR data.

A second part of this analysis was to look at trips that were reported as lasting longer than 1 hour. In the GPS data, there were 92 trips that lasted more than an hour. The range of trip durations was from 1 hour and 19 seconds to 5 hours, 46 minutes, 22 seconds. The mean was 1 hour, 39 minutes and 7 seconds, and the standard deviation was 50 minutes and 26 seconds. For the corresponding PR data, there were 199 trips that lasted over an hour, with a range from 1 hour and 19 seconds to 21 hours, 31 minutes, and 2 seconds. The mean travel time was 3 hours, 32 minutes, and 49 seconds, with a standard deviation of 3 hours, 24 minutes, and 57 seconds. These comparative statistics are further evidence of the joining together of trips that have a substantial activity duration between trips, and calling them a single trip.

Many of the 54 cases where the PR respondent stated that a trip was missing turn out to be cases where the PR respondent split a GPS trip into two, with one component of the trip being only a few seconds in length. This is shown rather clearly by the fact that there are 36 cases in the PR data of a trip of less than 30 seconds in duration, whereas there are only 11 trips of less than 30-seconds duration in the GPS data. Looking at the former, the range is from 0 seconds to 29.98 seconds with a mean of 10.8 seconds. For the latter, the range is from 10.97 seconds to 29.03 seconds with a mean of 22.1 seconds. In ten of the cases where the PR data has a less than 30-second travel time, the GPS data are missing, indicating that these are trips that have been split. Only 5 cases of the GPS data of less than 30 seconds correspond to missing trips in the PR data.

Notwithstanding these issues, we have compared the overall statistics of mode and activity at origin and destination between the PR and GPS data. The comparison of Mode is shown in Table 19.

Table 19: Comparison of GPS and PR Survey on Mode

Mode of Travel	**GPS Number of Trips**	**PR Number of Trips**
Driver of Auto/Van/Truck	--	3,816
Passenger of Auto/Van/Truck	--	452
Driver of Carpool	--	21
Passenger of Carpool	--	44
Passenger of Vanpool	--	9
Motorcycle/Moped	--	13
Taxi/Paid Limo	--	2
Total Motor Vehicle	4,437	4,357
Bus	54	62
School Bus	16	30
Total Bus	70	92
Walk	236	235
Bicycle	35	22
Other	--	83
Unknown	26	15
Total	**4,804**	**4,804**

From these data, it appears that the GPS processing has produced very close results. Total motor vehicle trips are overestimated by 80 trips (1.8 percent), and bus trips are underestimated by 22 trips, with the majority of these being school bus trips. Walk is almost exactly correct with 235 versus 236, while bicycle is still overestimated by the software by 13 trips. Overall, however, the results are remarkably close.

Because of the rather large number of trips recorded by the GPS that were grouped into a single trip or tour by PR respondents, and which therefore make direct comparison between the PR data and the GPS data rather questionable, Table 20 shows the distribution of trips by mode for the PR sample, as recorded by the GPS devices and processed by G-TO-MAP, together with the percentage splits in the PR data.

Table 20: Breakdown of GPS Trips by Mode for the PR Households, Compared to PR Percentages

Mode of Travel	Number of Trips	Percent of Trips	Percent from PR Responses
Total Motor Vehicle	4,773	89.0	90.6
Bus	59	1.1	1.3
School Bus	20	0.4	0.6
Walk	267	5.0	5.0
Bicycle	42	0.8	0.5
Other	0	0	1.7
Unknown	201	3.7	0.3
Total	**5,362**	**100.0**	**100.0**

It can be seen from Table 20 that, when comparing the results of the processing of the GPS trips against the percentage mode shares from the PR survey, the results are remarkably close, with motor vehicle underestimated by 1.6 percent, bus underestimated by 0.2 percent, School Bus also underestimated by 0.2 percent, walk is exactly correct, and bicycle is overestimated by 0.3 percent. There are 3.7 percent of trips that have an unknown mode, most of which are trips added by the GPS map editing, which had no traces and therefore could not be processed by G-TO-MAP.

Table 21 shows the comparison of the GPS processing of purpose by G-TO-MAP to the results of the PR survey on origin and destination activities. As for mode, Table 20 shows only those trips that more or less correspond between the GPS and PR survey, although it must be kept in mind here that, if two or more trips were combined by the PR respondent, the convention was used of matching the first GPS trip to the combined PR trip, which will lead to some anomalies in comparing purposes or origin and destination activities. For example, if, as happened a number of times, a respondent combined his or her trip to work with the one from work, then the combined trip is compared to the outward trip to work from the GPS.

The number of trips with an origin or destination activity at home is very close in the PR and GPS surveys. Pick-up and drop-off is identified lower in the GPS software than reported in the PR survey. However, some of these could also be confused with catching a bus, train, or plane in the GPS data, which could partially account for the too high frequency of this activity. Similarly, the GPS software cannot distinguish between catching a bus, train, or plane and transferring. In total, the software identifies 245 origins and 265 destinations that are either pick-up/drop-off, or catch or transfer between buses, trains, and planes. In comparison, the PR survey shows 285 origins and 280 destinations for these three activities, suggesting that overall, the software is doing a reasonable job on these activities. The shopping trips are the principal activity that is seriously overestimated. However, because of the fact that many supermarkets are within major shopping centers, and these centers may offer opportunities for both personal business and some social and recreational activities (such as a gym, movies, etc.), the over estimate is probably not unreasonable.

Table 21: Comparison of GPS and PR Survey Activities at Origin and Destination

Purpose	Origin Activity		Destination Activity	
	GPS Number	PR Number	GPS Number	PR Number
At Home	1,374	1,376	1,339	1,360
Paid Work		842		858
School		136		128
Volunteer Work	--	56	--	56
Pick Up/Drop Off	155	227	169	222
Soc./Rec./Church	--	296	--	312
Catch Bus/Train/Plane	90	23	96	25
Transfer from a Bus/Train Plane to Another	--	35	--	33
Shop	1,127	622	1,138	621
Personal Business	--	322	--	327
Eat Meal	--	222	--	225
Go for a Drive	--	25	--	25
Work Related	--	162	--	155
School Related	--	57	--	58
Don't Know/Refused	--	388	--	380
Other	1,241	0	1,245	0
Total	**4,804**	**4,804**	**4,803**	**4,803**

A more detailed examination of the work trips shows that about 180 of the work trip origins according to the PR data were categorized as 'other' by the GPS software and 98 were categorized as 'shop' trips, with figures of 192 and 109 respectively for destinations. Adding these numbers into the work plus volunteer work trips will actually produce larger totals of work trips than the PR survey measured, but is indicative of some of the reasons for difficulty in determining correctly the work activity.

Again, it seems useful to compare the percentages of trips from the GPS processing with the overall percentages from the PR data, using the percentages shown in Table 18 and comparing these to the percentages for the full 5,362 GPS recorded trips. The results are shown in Table 22.

Table 22: Breakdown of GPS Trips by Activity at Origin and Destination, Compared to PR Percentages

Purpose	Origin Activity			Destination Activity		
	Number	Percent	PR Percent	Number	Percent	PR Percent
At Home	1,501	28.0	28.7	1,484	27.7	28.3
Work	740	13.8	17.5	742	13.8	17.8
School	173	3.2	2.8	176	3.3	2.7
Pick Up/Drop Off	172	3.2	4.7	171	3.2	4.6
Catch Bus/Train/Plane	103	1.9	0.5	103	1.9	0.5
Transfer from a Bus/Train Plane to Another	0	0	0.7	0	0	0.7
Shop	1,275	23.7	13.0	1,279	23.9	12.9
Other	1,398	26.0	23.7	1,407	26.2	24.3
Don't Know/Refused	0	0	8.1	0	0	7.9
Missing	0	0	0.3	0	0	0.3
Total			**100.0**			**100.0**

A review of the numbers in Table 22 shows that trips with an origin or destination at home are correct to within about 0.7 percent. Work trips are underestimated by approximately 3.5 percent, while school trips are overestimated by about 0.4 percent. Pick up and drop off is underestimated by about 1.5 percent, and the combination of catching and transferring between bus, train, or plane is overestimated by 0.7 percent. Shopping is the most overestimated purpose, with an overestimate of around 10 percent, but much of this is likely to be personal business trips that would be easily confused with shopping trips and which comprise about 6.8 percent of trip activities according to the PR survey. Other purposes are slightly overestimated by about 2.1 percent, while the GPS results have no missing or refused/don't know results, which account for 8.4 percent of the PR total. Again, this comparison suggests that the processing results are relatively quite accurate and should be suitable to support most modeling applications.

DETAILED ANALYSIS

Following the completion of the various software improvements, a subsample of 41 households who made 429 trips was used to carry out an in-depth analysis of the results of the software processing in comparison to the Prompted Recall results. For this comparison, the focus was on mode and purpose.

Mode of Travel

For the 429 trips analyzed, 362 matched exactly after software processing. The reasons for mismatch are shown in Table 23. This represents an overall correct identification rate of 84.4 percent.

The first reason relates to instances where the Prompted Recall response was very questionable and probably wrong. The second reason represents situations where the rule based procedures are unable to handle the situation. Together with reasons 3 and 4, these represent areas where improvement could potentially be made in the future. The lack of prompted recall response is similar to the first reason and is a situation where a match is not feasible. When map editing required a trip to be inserted, this could not be shown on the prompted recall maps, because there is no available trace. Hence no mode could be identified. This means that the effective accuracy of mode identification is that 362 trips matched out of a total of 429 less 24 questionable PR responses, less 8 non-responses to the PR, less 9 inserted GPS trips, less 8 other modes, or 380 trips. This indicates 95.3 percent accuracy in this test.

Table 23: In-Depth Analysis of the Match Between Mode for PR and Software

Reasons for mode mismatch between PR and Mode detected results	**Number**	**%**
1. PR response questionable	24	35.8
2. Hard to distinguish between car and bus – e.g., a bus trip with no bus stops or < min. # bus stops	11	16.4
3. Mode Detection error - improvement needed?	2	3.0
4. Map editing error – e.g., trip not split	3	4.5
5. No PR Response	8	11.9
6. Inserted GPS Trip	9	13.4
7. Other Mode	8	11.9
8. GPS trip not shown on spreadsheet	2	3.0
Total	**67**	**100**

Trip Purpose

A similar analysis was performed with trip purpose. Of the 476 trips in this analysis, 232 matched on origin and 203 on destination. The reasons for mismatch are shown in Tables 24 and 25.

Table 24: In-Depth Analysis of the Match Between Origin Purpose for PR and Software

Reasons for Purpose mismatch between PR and Purpose Detected results at the Origin	Number	%
1. Geocoding error in MetaData	1	0.41
2. PR response questionable	55	22.54
3. Map editing error – e.g. trip not split	8	3.3
4. Purpose Detection correct based on available information (e.g. social recreational locations, elementary schools, work, and shopping locations not given in metadata)	131	53.7
1. Purpose Detection needs improvement	27	11.1
6. GPS trip insertion	20	8.2
7. No PR response shown	2	0.82
Total	244	100.7

One of the major problems found with purpose identification is where the address location is a large area. When an address was given for a workplace or shopping location or school, a single point was coded for the geographic location. The software identifies the location of the end of the trip if it is within 200 meters (1/8 mile) of the geocoded location. However, if the location is large, such as a shopping center, or large employment complex, the actual end of the trip may be much further away from the geocoded point than the maximum of 200 meters. The future potential solution to this problem would be to geocode large shopping, school, and work complexes to polygons rather than points.

Some examples of situations that led to the conclusion that the PR response was questionable include situations where the respondent combined multiple trips into a single trip and did not identify the purposes of intermediate trip ends. Another situation that was found was where the respondent coded the purpose as eat meal, when it was in fact a trip to home. In yet other cases, the respondent indicated a trip as having an origin of home, where the location was actually the workplace, not home.

Table 25: In-Depth Analysis of the Match Between Destination Purpose for PR and Software

Reasons for Purpose mismatch between PR and Purpose Detected results at the Destination	Number	%
1. Geocoding error in Metadata	1	0.37
2. PR response questionable	74	27.11
3. Map editing error	13	4.76
4. Purpose Detection correct based on available information (e.g. social recreational locations, elementary schools, work, and shopping locations not given in metadata)	143	52.38
5. Purpose Detection needs improvement	26	9.52
6. GPS trip inserted	11	4.03
7. No PR response	5	1.83
Total	273	100.00

In the case of destination activities, 27 percent of the prompted recall responses were questionable, and 2 percent were no response situations for the PR survey. Less than 10 percent of the destination problems indicated a need to improve the detection of destination activities.

As with mode, a significant number of the mismatches were due to external effects that could not be expected to be dealt with by the software. The geocoding errors, questionable Prompted Recall responses, addresses not given by the respondent in response to the questions, a GPS inserted trip, and no response in the PR survey account for 209 of the mismatches on origin and 234 for destination, suggesting that the actual correctness of the software in this case is 232 out of 267 for origins and 203 out of 242 for destinations. This represents 84 percent accuracy for both origins and destinations.

D. 4 Analysis of Child Diaries

From the survey sample, 1,090 households reportedly had 1,914 children. Out of these 1,090 households, 429 households (39.4 percent) with 724 children (37.8 percent) completed child diaries, 96 households (8.8 percent) with 149 children (7.8 percent) partially completed their diaries and 565 households (51.8 percent) with 1,041 children (54.4 percent) did not complete the diaries. Because a larger percentage of children had no diaries than the percentage of households with children, it can be assumed that households with more children were less likely to complete child diaries.

Out of the 429 households who completed child diaries, 28 did not have any GPS travel on the diary day. From the 401 households with child diary trips and GPS data, child diary trips for a subsample of 90 households were compared to GPS data from the same households. Within this subsample, there was a total of 149 children with 473 trips, averaging 5.25 trips per household and 3.17 trips per child.

From these trips, 384 trips from 77 households were claimed to have been made with other household members while 89 trips were claimed not to have been made with other household members. The trip rate for children who claimed to have travelled with other members of their household was 4.99 trips per household and 3.07 trips per child.

Child diaries only collected information for one day of travel, generally the first day. Information collected included place of start and destination, mode of travel, arrival time at destination, and whether a person travelled with another household member. The date of travel was not collected.

Comparisons between GPS records and child diary records were made by comparing the time of travel, that is, arrival time given in child diary records compared to arrival time recorded by GPS devices of household members. Tables 26, 27, 28 and 29 show the numbers of trips that matched or didn't match for each of time, origin, destination and mode attributes.

Table 26: Analysis of Child Diary Match on Time of Trip Start

Time match	**All trips N=473**		**Trips made with HH members N=384**	
	Frequency	**Percent**	**Frequency**	**Percent**
No match	153	32%	94	24.5%
Definite match (within 15 mins)	216	46%	197	51.3%
Possible match (over 15 mins but within 30 mins)	62	13%	54	14.1%
Possible match (over 30 mins but within 1 hour)	42	9%	39	10.2%
Total	473	100%	384	100.0%

Table 27: Analysis of Child Diary Match on Origin Location

Origin Match	All trips N=473		Trips made with HH members N=384	
	Frequency	Percent	Frequency	Percent
No match	194	41%	128	33.3%
Definite Match	168	36%	152	39.6%
Possible Match (New place)	111	24%	104	27.1%
Total	473	100%	384	100.0%

Table 28: Analysis of Child Diary Match on Destination Location

Destination Match	All trips N=473		Trips made with HH members N=384	
	Frequency	Percent	Frequency	Percent
No match	190	40%	123	32.0%
Definite Match	166	35%	152	39.6%
Possible Match (New place)	117	25%	109	28.4%
Total	473	100%	384	100.0%

38 trips (8%) matched on all of the four attributes: time, origin, destination, and mode matching. Of these, only one trip was claimed not to have been made with a household member. This trip was a school bus trip beginning at school and ending at home.

Table 29: Analysis of Child Diary Match of Mode of Travel

Mode Match	All trips N=473		Trips made with HH members N=384	
	Frequency	Percent	Frequency	Percent
No match	216	46%	141	36.7%
Definite Match	250	53%	236	61.5%
Possible Match	7	2%	7	1.8%
Total	473	100%	384	100.0%

COMMENTS

Some of the reasons for mismatches on any of the four attributes were seen as given below:

Mode mismatch:

- Missing mode information in child diary data
- Possible incorrect identification of mode as bicycle in GPS data

Time mismatch

- Incorrect times reported in child diary data e.g. PM written instead of AM or general misreporting of time (as some very similar trips were seen about an hour apart)

- Missing time values in child diary data
- Missing GPS travel data or missing GPS travel times

Origin/ Destination mismatch

- Home and work addresses being either missing, incorrect or incorrectly geocoded for GPS data
- Lack of retail addresses

The fact that 81.2 percent of child diary trips were claimed to be made accompanied by another household member indicates that the loss of data from children of 12 years of age and under not carrying a GPS is potentially quite small. However, as with the PR data, the child diary data show a number of problems of self-report diary data, which resulted in a failure to obtain matches more than about 60 percent of the time. However, it is notable that each time of the trip, origin, destination, and mode of travel were definitely or probably a match approximately 60 percent of the time (65 percent of those trips that were with another household member). It is disappointing, but not surprising, given the general problems associated with diary data and self-reporting, that approximately 30 percent of the trips with other household members provided no match on at least one of the four attributes.

V. Future Directions

PROMPTED RECALL SURVEY

The prompted recall survey had a primary purpose of providing "ground truth" for validating the GPS processing and helping to improve the results of the GPS processing, by providing data to identify shortcomings in the current results of processing. Even though the response rate to the Prompted Recall survey was not particularly high, more than enough data were gained to serve these purposes. It was also quite clear from the results of the Prompted Recall that it does not provide "ground truth", because people still misunderstand what is required and misremember what they did. This is clearly illustrated by the number of instances in which we found that the results of the Prompted Recall were not believable.

In the future, a small Prompted Recall survey would be useful to benchmark the results of processing. Probably a sample of 100 households or less performing the Prompted Recall would be sufficient for this purpose. A more substantial sample is not useful. Gaining a representative sample is also not important, because the focus here is on a comparison of trips from each of the GPS and the Prompted Recall survey. While it is unlikely to happen, it would be useful to consider whether there are ways in which the prompted recall survey could be changed to reduce self-report error. However, it is also quite possible that this is not achievable.

The other possibility is to seek other ways of obtaining "ground truth" about the travel of a small subsample. A process being investigated by the University of Sydney together with the University of Oxford (England) is the use of small cameras that take a picture every few seconds. The pictures are often quite revealing of what the respondent is actually doing and may potentially provide a better method to determine ground truth, particularly because the time-stamping of the pictures can be matched to times on the GPS device. However, this is still a research issue at this time.

ADDRESS AND GIS INPUTS

One of the major causes of error in the processing results turned out to be a lack of GIS land-use layers needed for processing trip purpose. In the case of GIS layers for trip mode, complete bus route and bus stop layers are essential for adequate identification of the bus as a mode of travel. In the case of Cincinnati, data were missing for certain parts of the region, with the result that bus could not be identified in those areas. Complete and up-to-date data are required on bus routes for mode identification. To improve purpose identification, a GIS of land use is needed. This GIS must be up-to-date and must provide detailed information about the actual land uses of every land parcel in the region. The data need to specify the land use to the same specificity as is required for purpose coding, e.g., retail, wholesale, service, education, recreation, etc. Software can then be improved to make use of these data and provide much more detail in the purpose.

SOFTWARE IMPROVEMENTS

The primary improvement in the software, apart from use of GIS parcel land use data, is to be able to use polygons rather than points in purpose identification. At present, the software uses a diameter of 200 meters around each address location as still corresponding to the address location (e.g. home, workplace, school, etc.). However, there are employment locations, shopping centers, schools, etc. where a diameter of 200 meters still does not cover the entire parcel and a destination or an origin can be misidentified as a result. Enlarging this diameter is not the solution, because this will then lead to losing some short trips, and also will compound the misidentification process. However, replacing the point information with a polygon that aligns with the boundaries of the developed parcel would solve the problem. How this could be implemented will need to be the subject of other research.

OTHER IMPROVEMENTS

In common with most other processing algorithms, the G-TO-MAP software has difficulty distinguishing between car and bicycle and sometimes bus. In the future, it would be useful to include in the web/telephone recruitment survey questions to ascertain frequency of bicycle and bus use by a household, in addition to ownership of bicycles. Indeed, there are some additional questions that would be extremely helpful in improving the mode identification. These are:

1. How many bicycles in working order are available to members of the household?
2. Which members of the household used a bicycle in the past week?
3. Which members of the household, if any, used a public bus in the past week?
4. Which members of the household, if any, used a school bus in the past week?

By asking these questions, it may be possible in many instances to rule out that any trips by a household are by bicycle or by bus or by school bus, and conversely, to identify households where trips by one or more of these modes are likely to be found. This would improve the accuracy of identification significantly.

WORKPLACE ADDRESS

As with the problem of accomplishing 100% return of even simplified (memory jogger) diaries for every household member over 12 years old with the return of personal GPS units, there is a problem with obtaining return of even more limited person information forms (for only workplace address and GPS daily usage status). For future GPS-only HTS the Abt SRBI/PlanTrans team recommends including the workplace address question for every person in the household as a part of the recruitment, whether the recruitment is conducted by web or CATI.

Abt SRBI does not usually recommend collection of this information in the recruitment because only the household contact person responds and does not always know detailed workplace address information for each household member. However, in the case of a GPS-only survey, it is recommended that, going forward, workplace address for each household member be asked of the contact person in the recruitment. Web and CATI interviewing can provide online geocoding/verification of the address. If the workplace address information cannot be provided or is insufficient for accurate geocoding, the household can be recontacted before mailing of the GPS units. If workplace address information is still insufficient for each worker in the household, the household should be considered a refusal at an early stage and replaced with an appropriate household within the same data cell.

An exception to this is if the person is “self-employed”. A small percentage of workers have no designated workplace. They go somewhere different everyday (maids, plumbers. etc.) so don’t report workplace, or don’t want to give a client’s address. Also, with high unemployment in Ohio during the survey period, there is likely a high degree of “black market” unreportable work activity. A respondent will report that they are working but refuse to give a workplace address—because they may also be drawing unemployment benefits from a permanent job layoff.

TECHNICAL IMPROVEMENTS

There are potentials to improve the software in other ways, but most will require significant research efforts to implement. For example, there is a PhD student at the University of Sydney who is embarking on research to do this, which is expected to take the next three years or so to complete. Included in this is investigation of the potential of using models such as discriminant analysis to produce probabilities of both modes and purposes through a classification process, and the introduction of the results of such probabilistic modeling into some form of fuzzy logic to select the most likely outcome. However, the research to accomplish this will take some time to complete. Nevertheless, the data obtained from the GCAHTS could well be sufficient to permit this research to proceed.

VI. Implementation Plan

This methodology was successful in its proof of concept that household travel survey data required for travel demand modeling can be collected by GPS-only. This approach substantially reduces the respondent burden associated with diary data collection, which has been proven leads to underreporting and inaccurate reporting of trips. GPS recording is the "ground-truth" for leave and arrival times (time stamps), distance, locations, acceleration, speed, and route, and this study has proven that travel modes and essential trip purposes can be imputed from GPS data at a sufficiently accurate level to support modeling work. Also, the project demonstrated that a high standard of representativeness can be achieved for a completed household sample using GPS-only.

Improvements that the Abe SRBI Team would recommend for future GPS-only HTS include:

- Capturing in the recruitment script (web or CATI) the workplace and school location for every person in the household, as well as the household's four most frequently visited locations. (In the GCHTS these addresses were provided on forms returned with the GPS units. This resulted in less than a 100% response.)

- Providing a longer period of measurement in future surveys. A full week (7 days) of GPS data will enhance the ability to identify work trips, as well as providing much richer data on the variability of travel from day-to-day. In addition, this would allow for a larger sample of weekend data, which may have significant future use in a number of policy areas.

- Developing a better method than the Prompted Recall (PR) Survey for obtaining validation and comparisons for further improvements in software processing—at least until recorded GPS data can be electronically captured. It takes an average of two weeks after the travel period to retrieve GPS units, so returning to respondents a format of their recorded trips, in a timely manner for recall is not likely. Especially when multi-method PR formats--web, CATI, mail are needed.

  Smartphone technology for GPS and text or verbal recording of locations, mode, etc at stops is not being proposed by the Abt SRBI team at this time, due to present barriers among which are:

  - Smartphone GPS recording is usually only to every 3-4 minutes. Not sufficient for short trips/stops.
  - Smartphone penetration is not yet sufficient—unrepresentative sample
  - Battery life in Smartphones is currently insufficient - GPs data recording 6 hours.
  - Only 50% of Smartphones have multi-tasking capabilities--GPS would compete.
  - Downloading/uploading apps requires early adapters capabilities
  - Data plan costs—who pays and how?
  - Capturing information in real-time—not post-processing--possible privacy concerns.
  - If you try to use text recording to capture activities at stops—possible driving safety hazards.

  Abt SRBI for now recommends a simplified child diary to collect locations, modes, occupancy in vehicles, and household car used. This very simplified format might be presented in a daily hourly timeline chart (rather than as a log) with spaces to fill in locations and travel mode between, who was with you, and vehicle used. While as few as 100 PR surveys may be needed for imputation purposes, collecting a simplified "diary" at the time of GPS unit return would increase the response rate.

- Compiling detailed land use data in digital GIS Open Street Maps format for identification of "other" purposes such eating out, leisure, medical-related, and personal business.

Explore use of polygons rather than points in purpose identification. At present, the software uses a diameter of 200 meters around each address location as still corresponding to the address location (e.g. home, workplace, school, etc.). However, there are employment locations, shopping centers, schools, etc. where a diameter of 200 meters still does not cover the entire parcel and a destination or an origin can be misidentified as a result (see page 58).

Improved use of trip chaining data and learning from multi-day activity patterns to improve purpose imputation.

- Including questions to ascertain frequency of bicycle and bus use by a household in the web/telephone recruitment survey, in addition to ownership of bicycles. There are some additional questions that would be extremely helpful in improving the mode identification. These are:

1. How many bicycles in working order are available to members of the household?
2. Which members of the household used a bicycle in the past week?
3. Which members of the household, if any, used a public bus in the past week?
4. Which members of the household, if any, used a school bus in the past week?

A long-term goal would be to develop a GPS device with front-end processing and GIS cross-checking to provide mode ready data.

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